EFFECT OF RESIDENTIAL STOVE TECHNOLOGY ON GASEOUS EMISSIONS FROM BIOMASS COMBUSTION

EFEITO DA TECNOLOGIA DE FOGÕES RESIDENCIAIS NAS EMISSÕES GASOSAS DA COMBUSTÃO DA BIOMASSA

EFECTO DE LA TECNOLOGÍA DE ESTUFA RESIDENCIAL EN LAS EMISIONES GASEOSAS DE LA COMBUSTIÓN DE BIOMASA

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ABSTRACT

The growing use of biomass for cooking and heating raises environmental concerns about atmospheric air pollution from flue gases emitting during its combustion. In this work, the gaseous emissions from two residential wood stoves were examined. Emissions from conventional single-stage and triple-stage combustion logwood stoves were compared using Eucalyptus grandis (EUG) and Pinus elliottii (PIE) woods as fuels. Temperature, humidity, CO, CO2, total volatile organic compounds (TVOC) and formaldehyde (HCHO) content of the release gases were determined at the outlet of each chimney. Carbon monoxide emissions were reduced in 102% and 240%, when PIE and EUG wood logs were burned in triple-stage combustion stove. The triple combustion system showed total volatile organic compounds and formaldehyde emissions higher than obtained in conventional system possibly due to the mixture of both gaseous emissions with water vapor releasing during combustion. The results indicated that the utilization of triple combustion stove with some adjustments would be beneficial to local air quality, individual health and reduced global climate change.

KEYWORDS

Wood; combustion; gaseous emissions; residential stove; triple combustion system.

RESUMO

A crescente utilização da biomassa para cozimento e aquecimento acarreta no aumento das preocupações ambientais quanto à poluição do ar atmosférico pelos gases emitidos durante sua combustão. Neste trabalho foram examinadas as emissões gasosas de dois fogões a lenha residenciais. Comparam-se as emissões de fogões a lenha convencionais de estágio único e de estágio triplo utilizando como combustível as madeiras de Eucalyptus grandis (EUG) e Pinus elliottii (PIE). Foram determinadas a temperatura, umidade, CO, CO2, compostos orgânicos voláteis totais (TVOC) e teor de formaldeído dos gases liberados na saída de cada chaminé. As emissões de monóxido de carbono foram reduzidas em 102% e 240% quando as toras de madeira de PIE e EUG foram queimadas em fogão de combustão tripla. O sistema de combustão tripla apresentou emissões totais de compostos orgânicos voláteis e formaldeído superiores às obtidas no sistema convencional, possivelmente devido à mistura de ambas as emissões gasosas com vapor de água durante a combustão. Os resultados indicaram que a utilização do fogão de combustão tripla, com algumas adaptações, seria benéfica para a qualidade do ar local, saúde individual e para redução das mudanças climáticas globais.

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PALAVRAS-CHAVE
Madeira; combustão; emissões gasosas; fogão residencial; sistema de combustão tripla.

RESUMEN
El creciente uso de biomasa para cocinar y calentar genera una mayor preocupación ambiental con respecto a la contaminación del aire atmosférico por los gases emitidos durante la combustión. En este trabajo se examinaron las emisiones gaseosas de dos estufas de leña residenciales. Se comparan las emisiones de estufas de leña convencionales de una y tres etapas que utilizan madera de Eucalyptus grandis (EUG) y Pinus elliottii (PIE) como combustible. Se determinó la temperatura, humedad, CO, CO2, compuestos orgánicos volátiles totales (COVT) y contenido de formaldehído de los gases liberados a la salida de cada chimenea.Las emisiones de monóxido de carbono se redujeron en un 102 % y un 240 % cuando se quemaron troncos de madera PIE y EUG en una estufa de triple combustión. El sistema de triple combustión presentó emisiones totales de compuestos orgánicos volátiles y formaldehído superiores a las obtenidas en el sistema convencional, posiblemente debido a la mezcla de ambas emisiones gaseosas con vapor de agua durante la combustión. Los resultados indicaron que el uso de la estufa de triple combustión, con algunas adaptaciones, sería beneficioso para la calidad del aire local, la salud individual y para reducir el cambio climático global.

PALABRAS CLAVE
Madera; combustión; emisiones gaseosas; estufa residencial; sistema de triple combustión.

1. INTRODUCTION

Increasing world energy demands estimated in 50% from 2020 and 2050 (KISTLER et al., 2012) associated with climatic effects from fossil fuel combustion are the driving force to accelerating the need for sustainable energy sources. Biomass has become a possible alternative source of energy. At around 26% of the domestic applied thermal energy in European Union households comes from renewable sources. Biomass combustion represent 98% of this total (KISTLER et al., 2012). In Canada, every year, over 100 petajoules of energy from wood are consumed in the residential sector, which represented more than 7% of residential energy used (GOVERNMENT OF CANADA, 2017). In 2018, the energy from biomass represented 9% of all electrical energy generated in Brazil (BRAZIL, 2021).

Nonetheless, biomass is generally used for cooking and heating in several low- and middle-income countries, such as, India, China and Brazil. Globally, at around 2.4 billion people relied on theses fuels for domestic cooking, and this value is expected to little change until 2030. However, the incomplete combustion of biomass fuel, usually in low-efficiency stoves, emits large amounts of gaseous pollutants and particulate matter, which can be causing various diseases (ZHAO et al., 2022).

Thereby, while wood is a potential renewable and sustainable energy source, it is also a source of hazardous gaseous emissions in low-efficient stoves in many households around the world. Residential wood combustion contributes significantly with the urban air pollution and gaseous particulate emissions (WIN and PERSSON, 2014). The incomplete combustion products present in wood smoke such as CO, CH4, particulate matter, volatile organic compounds (VOC), including toxic and carcinogenic constituents, mainly polycyclic aromatic hydrocarbons, causing environmental pollution and also global warming (ZHAO et al., 2022; WIN and PERSSON, 2014).

The emissions during wood combustion depend on fuel type, combustor type, combustion technology and individual parameters, such as lighting the fuel and operation habits (KISTLER et al., 2012). Due to wood availability and low cost when compared to others fuels, residential wood heating probably will persist in the near future in many parts of the world (BHATTU et al., 2019). However, manually operated small units, such as fireplaces and stoves, are potential emitters of incomplete combustion products (KISTLER et al., 2012). Therefore, a development of a combustion technology improving the process control and performance has become a necessity due to stringent emission legislations. The reductions of gaseous and particulate emissions from solid fuel combustion stimulated the development of various improved stoves in recent decades, such as downdraft stoves, gasifier stoves, rocket stoves, catalytic stoves and forced-air stoves (ZHANG et al., 2021).

Brazil has an economy dependent on the primary sectors of agricultural and forestry production, explaining the significant representativeness of biomass within the national power matrix (SILVA et al., 2018). The average production of primary energy in Brazil was made up of 54.2% non-renewable sources and 45.8% of renewable sources between 2006 and 2015 (SILVA et al., 2018). The renewable sources were composed by hydroelectric power (13.4%) and biomasses such as sugarcane products (18.1%) and firewood (10.7%) (SILVA et al., 2018). Biomasses come from silvicultural sector or as residues from some agricultural production chain. The Brazilian woody biomass is consumed directly as fuel in power generation or as raw material in the carbonization process of charcoal production. The Brazilian production is mainly supplied by plantations of eucalyptus, followed by pine wood (SILVA et al., 2018). However, in low income households the usage of wood wastes to prepare meals in low-effectively or primitive stoves has increasing. The Brazilian Institute of Geography and Statistics point out that in Brazil 14 million households used wood or coal to prepare their meals in 2018, which represented an increase of 20% when compared with 2016 (BRAZIL, 2021).

The present study compares two residential stoves manually operated with different combustion technologies. A conventional single-stage and a triple-stage combustion logwood stoves using eucalyptus and pine wood species as fuels. First, we characterized both wood species used during combustion. Secondly, we evaluated the effect of stove technology on the gaseous emissions during the combustion cycle and compare these emissions with those from both devices tested in this study and literature values.

2. MATERIAL AND METHODS

2.1. Material sampling

Wood samples were obtained from a lumber industry located at Bento Gonçalves, Rio Grande do Sul, Brazil. The Eucalyptus grandis (EUG) and Pinus elliottii (PIE) were used as fuels in both stoves tested.

2.2. Stove operation and gas emission measurement

Conventional single-stage combustion and triple-stage combustion logwood residential stoves were used. The combustion air is provided through a grate in the bottom of the single-stage combustion residential stove while airflow is controlled manually via a front opening valve. The triple-stage combustion residential stove operates with three combustion zones. The combustion air is also provided through a grate in the bottom (primary air), similar to the single-stage combustion stove. The secondary air insertion occurs by means of slits located in the back wall, applying air at a higher temperature than the primary air. The air is sectioned through a tube, using the pressure difference between the external environment and the interior of the stove to insert the oxygen in the system. The tertiary entrance the air is also inserted behind the equipment, but as the tube is longer, it passes above the burn, thus raising its temperature optimizing the combustion system. In both stoves tested the exhausted gases leaving the stove by a chimney.

Each load consisted of around 1.5 kg of wood composed by 2 or 3 wood logs sized on the average 5x5x25 cm. After setting fire to each wood sample, in each of the evaluated stoves, 30 minutes were waited before carrying out the measurements, in order to provide uniformity of wood burning. Measurements were performed in quintuplicate at the outlet of each chimney. The air quality meter from Dongguan Jinlide Electronic Technology Company, model JD-3002, was used to measure temperature and humidity of the release gases, carbon dioxide (CO2), total volatile organic compounds (TVOC) and formaldehyde (HCHO) emissions. Carbon monoxide (CO) emission levels were measured using a CO meter from Next Instruments, model NCO-01.

2.3. Characterization of wood

The determination of wood components, such as extractives, cellulose, hemicellulose, lignin and inorganic content were carried out in triplicate. The determination of extractives followed the TAPPI T204 cm 97 standard using ethanol/benzene in the proportion 1:2 v/v as extractor solution. Lignin determination was performed according to TAPPI T222 om-02 standard. The determination of cellulose and hemicellulose followed the modified Van Soest method (SILVA and QUEIROZ, 2009).

Immediate analysis of wood was carried out according ASTM D1762 standard. Moisture, volatile matter and ash contents were determined in triplicate. The fixed carbon content in the samples was calculated by difference.

The thermogravimetric analysis (TGA) was performed in oxygen atmosphere using a TGA 50 Shimadzu. The flow gas rate was 50 ml.min-1. The temperature ranged from 25°C to 800°C with a heating rate equal to 10°C.min-1.

	Biomass	Moisture (%)	Extractives (%)	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
This study	*Pinus elliottii*	13.16±0.25	10.29±0.73	40.89±1.54	9.47±2.02	25.58±1.51	0.59±0.09
	Eucalyptus grandis	12.00±0.38	8.12±0.70	32.30±1.56	7.03±1.00	39.30±1.34	0.93±0.06
Rowell (2005)	*Pinus elliottii*	-----	10.30	46.00	11.00	27.00	0.30
Jones et al., (2006)	*Pinus taeda*	-----	------	36.17±2.36	23.11±1.43	28.28±1.22	-----
Rowell (2005)	*Eucalyptus gigantea*	-----	4.80	49.00	14.00	22.00	0.40
Ramírez et al., (2009)	*Eucalyptus globulus*	-----	1.80±0.30	62.6±1.90	11.9±1.70	26.60±1.00	-----

Table 01: Wood components and its comparison with others values from the literature.
Source: Authors.

3. RESULTS AND DISCUSSION

3.1. Wood components

The chemical composition of PIE and EUG samples was determined based on the extractives, cellulose, hemicellulose, lignin and ash contents. Table 01 presented the wood components of both wood species used in this work and compared these results with others from the literature. Both species presented higher moisture content. However, some studies indicate that the moisture content of air-dried wood varies from 13% to 18% (RODOLFO JÚNIOR, 2005). Higher moisture content can reduce the temperature in the combustion chamber due to water evaporation, which may result in incomplete combustion (BHATTU et al., 2019).

PIE presented higher quantity of extractives. Pinus is a resinous wood specie, which should explain the higher quantity of extractives in this wood when compared to a hardwood specie. On the other hand, the amount of extractives removed from the wood depends on several factors, such as the species, age and original location of the wood sample in the tree (SHEBANI et al., 2009). The content of extractives, in general, varies between 2-5%, but can exceed 15% in species from tropical climates (GUO et al., 2010; MÉSZÁROS et al., 2007).

The higher lignin content in EUG indicates a higher concentration of aromatic structures (POLETTO et al., 2012) in this species when compared to PIE. The lignin content can vary between 25-35% and, due to its complex structure; its components tend to a slow degradation process, being more resistant to high temperatures than hemicelluloses and cellulose (SHEBANI et al., 2009). Cellulose and hemicellulose contents are lower in EUG, possibly due to higher lignin content in this wood specie. Hemicellulose promotes the thermal degradation of wood at low temperatures, while cellulose increases its thermal stability due to its higher molar mass ((SHEBANI et al., 2008). Based on the ash content, EUG has a higher amount of inorganic compounds in its constitution.

3.2. Immediate analysis results

Table 02 presented the results of immediate analysis of both wood studied. A comparison with immediate analysis results of others wood species were also provided.

The moisture content obtained by the immediate analysis corroborate with those obtained in wood chemical composition presented in Table 1. As discussed in the previous section, the moisture content of air-dried wood can vary between 13% and 18%, depending on the equilibrium point obtained with the relative humidity of the drying air environment (RODOLFO JÚNIOR, 2005). The high content of volatile matter is typical from biomass, as can be seen in the values obtained by others authors in Table 2.

In general, the ash content obtained in the immediate analysis are also similar to those observed in wood chemical composition. Differences may be associated with variations in procedures for determining ash content. TAPPI T 211 om-02 standard, used for determined the chemical composition of wood, suggest a temperature of 575±25ºC for 3 h to obtain the ash content. ASTM D 1762, used in the immediate analysis, indicates that ash content must be obtained after 6 h

	Biomass	Moisture (%)	Volatile matter (%)	Ash (%)	Fixed carbon (%)
This study	Pinus elliottii	13.30±0.10	79.40±0.50	0.80±0.30	6.60±0.20
	Eucalyptus grandis	13.50±0.10	80.60±0.70	0.20±0.04	5.70±0.70
Borghetti (2022)	Pinus elliottii	5.25	82.17	1.01	16.82
Kumar et al., (2010)	Eucalyptus globulus	5.00	89.00	0.80	5.20
Guerrero et al., (2005)	Eucalyptus globulus	7.70	74.90	0.98	16.40

Table 2: Immediate analysis results and its comparison with others values from the literature.
Source: Authors.

at 750°C. The fixed carbon content for PIE was slightly higher than that obtained for EUG.

3.3. Thermogravimetric analysis

Figure 01 shows the weight loss curves obtained during the pyrolysis of PIE and EUG in an oxidative atmosphere. Both samples presented a thermal decomposition behavior typical of lignocellulosic materials.

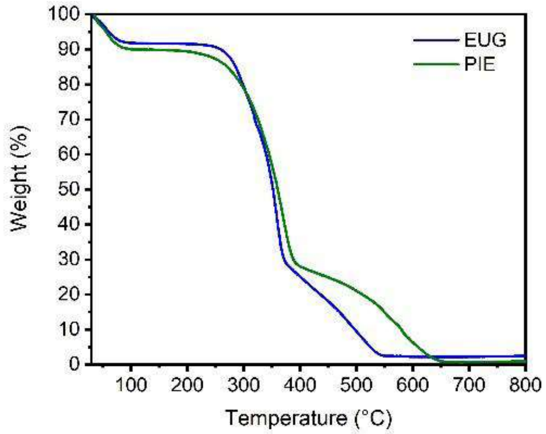

Figure 01: Thermogravimetric curves of PIE and EUG wood samples.
Source: Authors.

Both wood species presented a mass loss at temperatures below 100°C. This behavior may be related to the loss of accumulated water inside the wood, as well as the volatilization of extractives. Popescu et al (2011) determined values of moisture loss up to 140ºC for wood, where all species showed different percentages of weight loss due to the elimination of water and extractives. During the thermal decomposition process of wood, molecules with low molar mass suffer degradation followed by formation of volatile gases such as CO2 and water vapor (SHEBANI et al., 2009; POPESCU et at., 2011) at temperatures that can vary between 30 and 150ºC.

The wood species present three stages of mass loss, as can be seen in Figure 1. The first stage is associated with loss of moisture and volatilization of the extractives and occurs up to approximately 100°C. The second may be related to the decomposition of hemicellulose and cellulose present in wood, as well as the slow degradation of lignin, starting at approximately 220°C and extending up to 400°C. The last stage starts at 400°C and extends to 550°C for EUG and 650°C for PIE. At this stage, the greatest degradation of lignin and aromatic compounds formed during the degradation of the evaluated wood species may occurs (POPESCU et at., 2011).

3.4. Temperature and humidity of the release gases

Figure 02 shows the temperature of the gases releasing by chimney for both wood species evaluated in the two types of stoves studied.

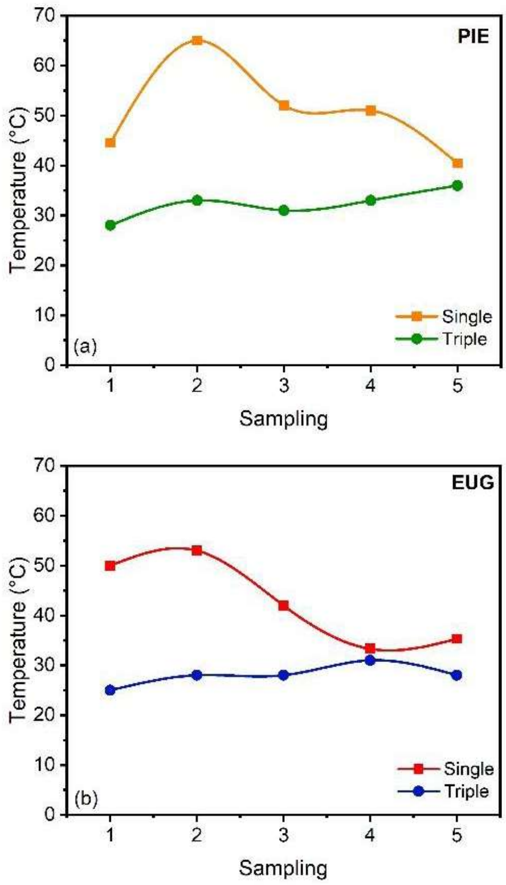

Figure 02: Temperature of gases releasing by chimney for PIE (a) and EUG (b).
Source: Authors.

As can be seen in Figure 02, the gases from single combustion logwood stove presented higher temperature those from triple combustion logwood stove. Possibly the triple combustion system allows an additional burning of the combustion gases and, in this way, increases the heat exchange in the internal environment of the furnace and, therefore, the gases releasing the combustion chamber with a lower temperature. When compared both wood species, the temperature of the exhaust gases is higher for PIE wood. This result may be associated with the resinous characteristic of this softwood. After wood ignition, the resin burns fast and may accelerate the burning of wood. In addition, this behavior is also in agreement with the higher amount of extractives obtained for PIE wood, as presented in Table 1. Vicente et al (2018) obtained temperatures at around 50°C for gases releasing by the chimney in Portuguese charcoal barbecue grills. This value is similar to the mean temperature value obtained for the single stove tested in this work.

The humidity of the exhaust gases measured in chimney outlet are show in Figure 03. In general, the gases from triple combustion system presented higher humidity those from conventional stove.

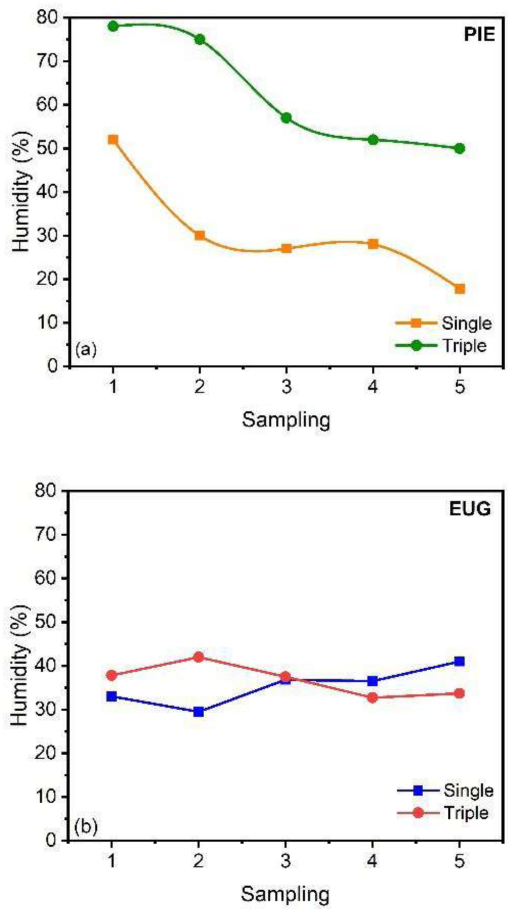

Figure 03: Humidity of the exhaust gases from PIE (a) and EUG (b) in both stoves tested.
Source: Authors.

The higher quantities of water leaving the combustion chamber in the triple combustion stove may indicate that wood is more efficiently converted in carbon dioxide, water and energy. This implies in a more efficient combustion system. The secondary and tertiary air insertion burning the volatile gases, such as CO and CH4, releasing after wood burning. A similar result was obtained by Cardoso and coworkers (2010). The authors observed an increased in the humidity of the exhausted gases after burning the gases releasing during Eucalyptus sp. combustion.

The triple combustion stove presented lower CO emissions for both wood tested, as can be seen in Figure 4. The CO emissions were greatly reduced probably because of their higher burnout in triple combustion stove with high furnace temperature and sufficient air supply (ZHANG et al., 2021; SARAVANAKUMAR et al., 2022). In the conventional stove CO is not totally burned. Carbon monoxide is formed from incomplete combustion of the fuel and is affected by several parameters such as, non-optimized air flow rate, insufficient residence time, non-perfect mixing of air and flue gas in post combustion, among others (OLAVE et al., 2017; KHODAEI et al., 2017; THIRUGNANASAMBANTHAM et al., 2020).

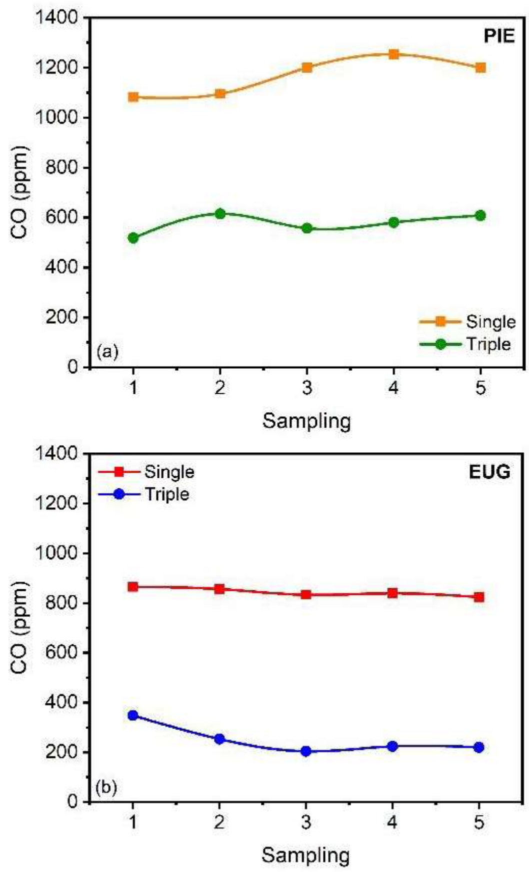

Figure 04: CO emissions in ppm after combustion of PIE (a) and EUG (b).
Source: Authors.

There was a reduction in CO emissions for both wood species tested during combustion in the triple combustion stove. This reduction was approximately 102% when PIE was used as fuel and reaches 240% when EUG was tested. The reduction in CO emission might be associated with the triple burning system. The gases released after combustion are trapped on the combustion chamber, which makes possible promotes a secondary and tertiary combustion with the insertion of air in three different zones into the chamber, as showed in Figure 05.

The combustion sequence occurs in three distinct stages. The first combustion occurs in the same way as in single combustion stoves, where basically the primary air

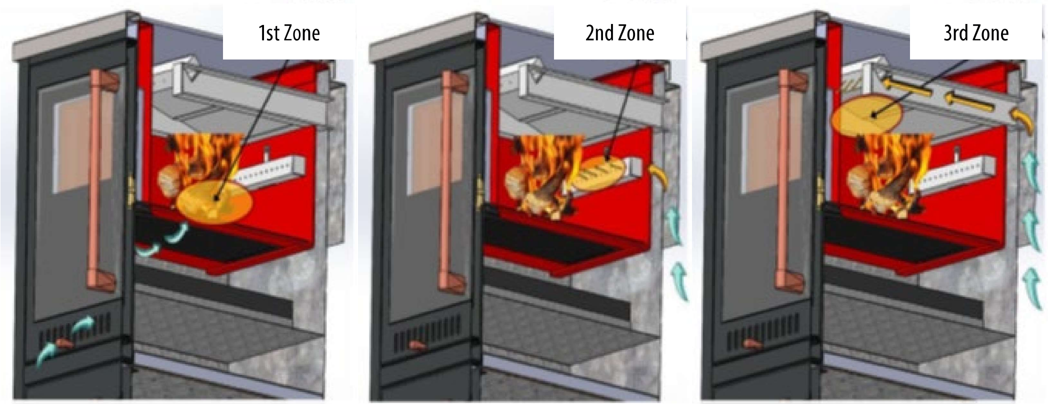

Figure 05: Side view of the combustion chamber in triple combustion stove showing the three zones of air insertion.
Source: Authors.

enters through the front of the equipment, at room temperature being inserted below the wood. The second air insertion occurs behind the equipment, applying air at a higher temperature than the first, where basically the air is sectioned by means of a tube, using the pressure difference between the external environment and the interior of the equipment to air. In the third zone, the air is also inserted behind the equipment, but as the tube is longer, it passes above the burn, thus raising its temperature and making the other stages higher. So, an increased in flue gas temperature may be ignite the volatiles released during combustion (BHATTU et al., 2019). These three steps result in a more efficiently combustion system when compared to conventional single combustion stoves. Zhang et al. (2021) observed a reduction of 96% in CO emissions comparing a traditional domestic stove and a proposed stove based on three combustion technology.

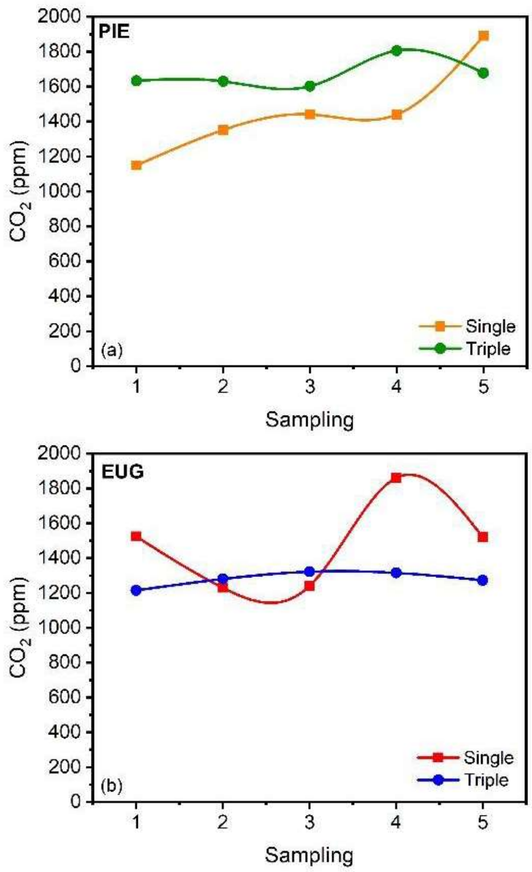

Figure 06: CO2 emissions in ppm after combustion of PIE (a) and EUG (b) in both stoves tested.
Source: Authors.

The CO2 emission was higher for PIE than EUG wood, as can be seen in Figure 06. It is also possible observed in Figure 6 that some CO2 measurements are higher in triple combustion system for PIE than EUG. This behavior may be related to the subsequent burning of gases in the three combustion zones, which results in the conversion of carbon monoxide, and other volatile gases into carbon dioxide. The fuel oxidation reaction is improved and approaches to complete combustion (SARAVANAKUMAR et al., 2022). This result is in agreement with the reduction of CO emission observed in Figure 04(a)

Figure 07 showed the TVOC results obtained during the combustion of PIE and EUG. The TVOC emissions are similar in both systems evaluated, showing small variations throughout the measurements performed. In general, triple combustion system showed TVOC concentrations higher than those obtained in conventional system, with is an unexpected result.

Ruling out possible experimental errors, volatile organic compounds (VOCs) are substances that may evaporate at low temperatures, and therefore could be leaving the system through the chimney. Křůmal et al. (2019) suggest that wet wood ignites and burns more slowly than dry wood. So, when burning dry wood volatile matter is releasing more easily than from wet wood. Therefore, the combustion process can rapidly develop and further combustion is limited by the supply of oxidant.

In case of a high rate of volatile matter released and a lack of oxidant, the volatile matter cannot burn out

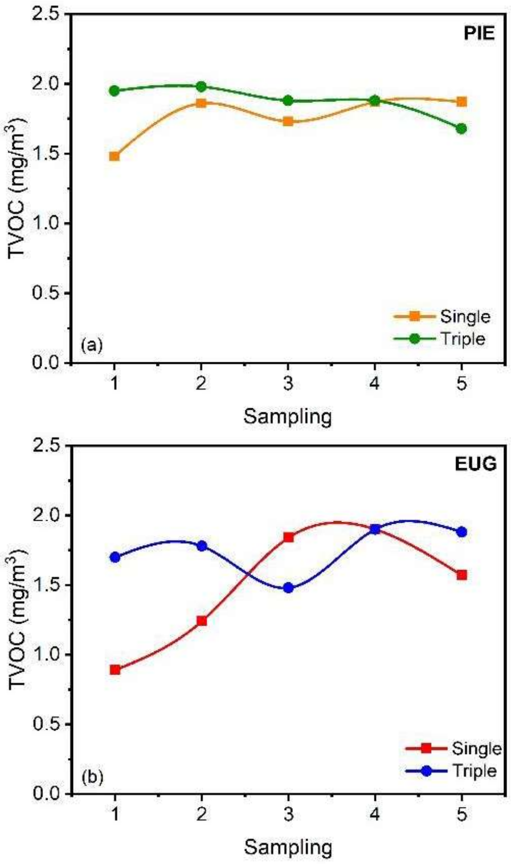

Figure 07: TVOC emissions after combustion of PIE (a) and EUG (b) in both stoves tested.
Source: Authors.

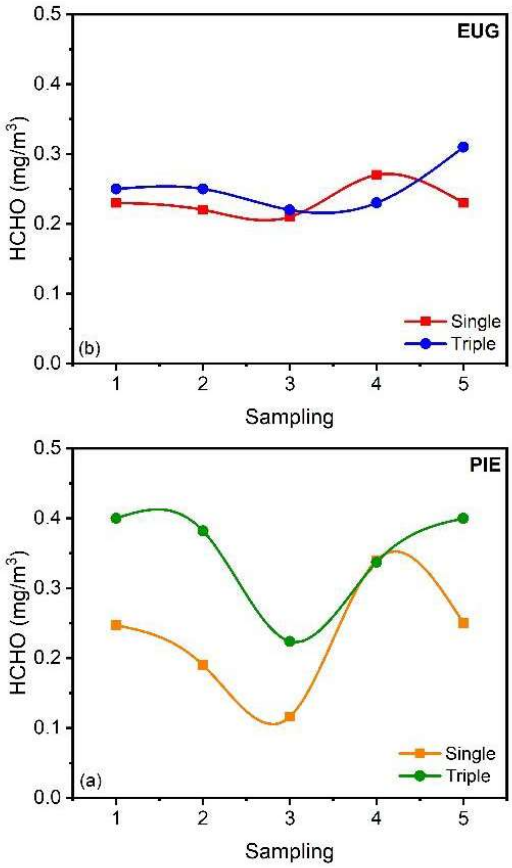

Figure 08: HCHO emissions after combustion of PIE (a) and EUG (b) in both stoves tested.
Source: Authors.

despite the sufficient temperature in the combustion chamber (KŘŮMAL et al., 2019). As a result, volatile matter leaves the combustion chamber without burning out which can generate higher emission of pollutants.

The HCHO emissions obtained during the combustion of PIE and EUG are shown in Figure 08. In general, the formaldehyde concentration was higher in triple combustion system, when compared to conventional system, which is also an unexpected result. Formaldehyde is a colorless gas with an irritating odor and high solubility in water. HCHO is also soluble in most common organic solvents, which can be explained due to its polarity (RUSSEL, 1994). As shown in Figure 03, the humidity of the gases from the triple combustion system are higher than that obtained from the single combustion system. Thus, given the high water solubility of formaldehyde, it may be releasing from the combustion chamber along with water vapor, which could explain the higher HCHO content in the gases generated in triple combustion stove.

5. CONCLUSION

The temperature of the gases emitted by the chimney in triple combustion system is lower than that of the gases emitted from conventional system, possibly due to efficiently burning of gases generated during combustion. However, the humidity of the gases generated in the triple combustion system is higher than that observed in the single combustion system. There was a reduction in the CO content emitted between the two stoves analyzed for the two wood species evaluated. An increase in CO2 emissions were observed in the triple combustion system, which may be directly related to the more efficient burning of carbon in this stove. The triple combustion system showed concentrations of TVOC and HCHO higher than those obtained in the conventional stove. In fact, this result was not expected, since the triple combustion system, in theory, would provide burning of gases released in combustion chamber. However, both TVOC and HCHO are composed of volatile gases that may not be trapped in the second combustion chamber of the triple combustion stove, being expelled through the chimney. In general, the results demonstrated that triple combustion system is more efficient that conventional single combustion stove. However, based on the TVOC and HCHO results the triple combustion stove still has potential for some adjustments, so that it may be able to demonstrate more positive results regarding the emission of harmful gases.

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