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Efficiency of Emission Reduction Technologies for Residential Biomass Combustion Appliances: Electrostatic Precipitator and Catalyst

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Abstract: Residential biomass combustion has been pointed out as one of the largest sources of atmospheric pollutants. Rising awareness of the environmental effects of residential biomass combustion emissions boosted the development of different emission reduction devices that are currently available on the market for small-scale appliances. However, detailed studies on the efficiency of these devices in different combustion systems available in Southern European countries are lacking. In this study, two pollution control devices (catalytic converter and electrostatic precipitator) were tested in two different combustion systems (batch mode operated woodstove and automatically fed pellet stove) in order to assess the emission reduction potential of the devices. Pine firewood was used to fuel the woodstove. One commercial brand of pellets and an agricultural fuel (olive pit) were taken for the experiments in the pellet stove. While the efficiency of the electrostatic precipitator in reducing PM_{10} was only recorded for woodstove emissions (29%), the effect of the catalyst in decreasing gaseous emissions was only visible when applied to the pellet stove flue gas. For wood pellet combustion, reductions of CO and TOC emissions were in the range of 60–62% and 74–77%, respectively. For olive pit combustion, a lower decrease of 59–60% and 64% in CO and TOC emissions, respectively, was recorded.

Keywords: biomass; catalyst; electrostatic precipitator; emission factors; residential heating

Citation: Vicente, E.D.; Duarte, M.A.; Tarelho, L.A.C.; Alves, C.A. Efficiency of Emission Reduction Technologies for Residential Biomass Combustion Appliances: Electrostatic Precipitator and Catalyst. *Energies* **2022**, *15*, 4066. https://doi.org/10.3390/en15114066

Academic Editors: Albert Ratner and Adam Smoliński

Received: 21 April 2022
Accepted: 30 May 2022
Published: 1 June 2022

1. Introduction

Climate policies have promoted the shift from fossil fuels to renewable energies, such as biomass. The economic crisis of September 2008, and the consequent rise in the price of home heating oil, intensified the switch to wood and other biomasses [1]. More recently, as a result of the adoption of stay-at-home measures during the COVID-19 pandemic, there has also been an increase in the consumption of biomass for residential heating in many regions, whose emissions, especially particulate matter (PM), offset the decrease in traffic-associated pollution [2–5]. Most of the more than 70 million solid fuel appliances in Europe are outdated [6]. Fireplaces, traditional woodstoves, and other single-room appliances are often operated inadequately, and firewood is, in general, used in a very inefficient way. Thus, these small appliances have a tremendous impact on air quality. Residential biomass burning has been pointed out as one of the largest sources of atmospheric pollutants in the European Union [1,7–10]. These emissions contribute significantly to premature mortality and morbidity, particularly from cardiovascular and pulmonary diseases [11–16]. Research carried out in Athens concluded that wood burning stoves are responsible for almost half of people's exposure to the cancer-causing chemicals found in particle air pollution [17]. The same study showed that the level of carcinogenic pollution in Athens is of the same order of magnitude as that found in other European and North American cities, with much higher values usually reported for cities in China. A recent report by the European Environmental Bureau revealed that even new wood burning stoves meeting the

Ecodesign standard still emit 750 times more tiny particle pollution than a modern heavy goods vehicles [18]. The annual health-related financial costs per wood heater can reach EUR 8000 [19,20].

The growing awareness of the effects of residential biomass combustion has promoted studies aimed at implementing different emission reduction measures. These include both primary measures, focusing on preventing the formation of pollutants, and secondary measures employing depollution devices. The most investigated primary measures aimed at assessing the effect of air staging on emissions [21,22]. Additionally, the operating conditions of small-scale biomass combustion appliances (e.g., amount of fuel loaded, size of wood logs, ignition procedure, tray inclination, and air valve settings) have also been a topic of research [23–25]. To date, the most studied depollution devices are electrostatic precipitators (ESPs) [26–28] and catalysts [29–32]. Other studies have further looked at secondary measures to reduce particle emissions from residential biomass combustion systems. Messerer et al. [33] analyzed the possibility of using a heat exchanger for simultaneous heat recovery and particle deposition. The researchers reported particle deposition efficiencies up to 95% and observed that PM from two different appliances exhibited different deposition characteristics. Recently, Suhonen et al. [34] proposed a novel method to control PM emissions from small-scale combustion appliances based on an electrically insulated high-voltage electrode. This electrode collects particles that acquire the electrical charges, which are subsequently oxidized, reducing PM emissions. The authors reported that the efficiency of the method depended on the combustion stage, being more efficient during flaming conditions.

Particles from small-scale biomass combustion consist of three main fractions: (i) inorganic components (salts), (ii) soot, and (iii) condensable organic compounds [35]. The proportion of these three components considerably depends on the combustion technology and its efficiency. The electrical conductivity, which is a fundamental parameter for collection by ESPs, is significantly different for the three particle main fractions. While salts have been found to be ideal for ESP, the high conductivity of soot leads to the re-entrainment of agglomerated particles, and the low conductivity of condensable organic compounds may be related to back-corona, contributing to a sticky layer that is difficult to remove. Moreover, the concentration of H_2O, as well as of CO, CO_2 and O_2, can vary in a wide range, affecting the precipitation conditions in the ESP [35]. In the case of catalysts, during the start-up process and in the final stage of combustion, the species present in the fumes are at a too low temperature and may poison the active phase of the flue gas treatment device, especially by inorganic compounds. Furthermore, tars may condense on the catalyst, leading to its deactivation [36] (and references therein). To avoid this type of problems, flue gas treatment technologies are usually shut-off by researchers during transient conditions, such as the start-up phase. Thus, the reported removal efficiencies do not always represent those observed under real-life operating conditions.

Given that the efficiency of flue gas depollution technologies reported in the literature can be highly variable and sometimes lead to contradictory conclusions, the performance of ESPs and catalytic converters to reduce emissions from residential biomass burning should be the target of further studies before the large-scale use of these technologies. Additionally, considering that the type of combustion appliances and fuels highly affect the amount and composition of the released pollutants, which are key factors regarding the efficiency of depollution devices such as ESPs and catalysts, studies at the country level are important to assess the potential of these devices to reduce emissions from this source. This paper reports the results of a comparative study on the efficiency of a catalytic converter and an ESP in reducing gas and particulate emissions from biomass combustion in two household appliances (woodstove and pellet stove) representative of the small-scale units used in southern European countries.

2. Materials and Methods

2.1. Combustion Appliances and Fuels

The experiments were conducted at the combustion facility of the University of Aveiro (Portugal). Two small-scale combustion appliances representing traditional batch-mode operated and modern automatically fed combustion appliances were studied. Both appliances represented typical small-scale appliances in use in Southern Europe and were purchased from Solzaima. The traditional appliance consisted of a cast iron stove (model Sahara) with a manually controlled primary air supply at the bottom of the combustion chamber through the combustion grate. The fully automated top fed pellet stove (model Alpes) used in the present study can be set to operate at five different power output levels, in a range between 20 and 100% of the nominal heat capacity (9.6 kW), automatically adjusting the fuel feed rate and air flow. The stove provides combustion air staging with primary and secondary air supplied at the bottom and above the burner pot, respectively. A heat exchanger transfers the heat to a secondary air flow through an internal fan, which directs heated air into the room where the appliance is installed. A detailed description of the combustion appliance can be found elsewhere [37].

Pine (*Pinus pinaster*) wood logs were used in the batch-mode-fuelled appliance. For the combustion experiments in the pellet stove, bagged wood pellets were purchased locally. Additionally, an agro-fuel (olive pit) was also selected due to the increased interest in alternative biofuels for the residential heating sector. The fuel properties are presented in Table 1.

Table 1. Characteristics of the biofuels used in the experiments.

		Pellet Stove		**Woodstove**
		Wood Pellets	**Olive Pit**	**Pine**
Proximate analysis (wt.%, as received)	Moisture	8.4	12.9	9.9
Ultimate analysis (wt.%, dry basis)	Ash	0.73	0.66	0.4
	C	49.7	50.9	51.4
	H	6.9	6.59	6.2
	N	0.16	0.21	0.16
	S	<0.01	<0.01	<0.01
	O (by difference)	42.5	41.6	41.84

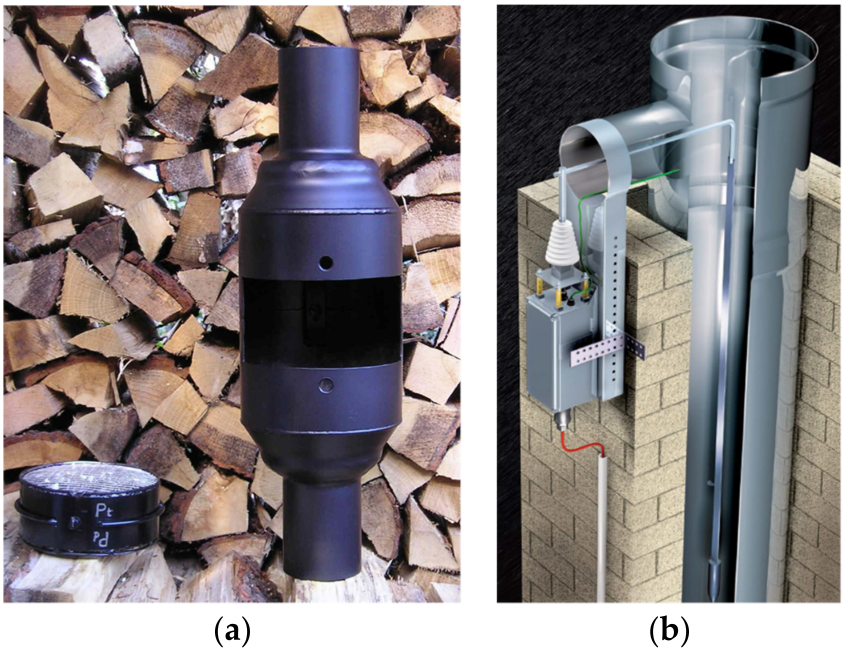
2.2. Test Procedure

The cold start experiments performed with the woodstove, with ignition from the bottom using pinecones and pine wood logs, were not included in the analysis. After the cold start experiment, pine wood logs with an average weight of 2 kg were added to the combustion chamber, placed on a bed of glowing charcoal. One combustion cycle lasted for about 45 to 60 min and started immediately after loading the appliance and closing the combustion chamber door. The air valve settings were fully open over the whole test duration. The fuel consumption over time was monitored through a weight sensor connected to the combustion grate of the woodstove. Six combustion experiments were carried out for each condition: catalyst (CAT), electrostatic precipitator (ESP), and reference (REF).

The wood pellets/olive pit were stored in the stove hopper to be continuously fed into the pellet stove burner pot. All combustion tests were performed after firing the stove for about 2 h in order to achieve steady state combustion conditions. The emissions produced by different operating conditions were evaluated: partial load (around 60% of the nominal power) and nominal load operation. The fuel consumption was determined a priori by weighing the fuel poured into the hopper before and after set periods of time for each fuel and operating condition. Three combustion experiments were carried out for each condition (CAT, ESP, and REF) at distinct operating conditions.

2.3. Depollution Devices

The catalyst (ABCAT$^{®}$) used in the combustion experiments (Ecolink Solutions, Wijk bij Duurstede, The Netherlands) contained a metal wire mesh covered with the catalytic material, platinum, and palladium (Pt50/Pd50). The catalytic material was attached to a round steel frame module, which was placed compactly inside the ABCAT housing (Figure 1a) installed in the lower part of the chimney. The ABCAT was also equipped with a build-in soot filter operating as a powerless electromagnetic filter using the Seebeck effect principle.



(**a**) (**b**)

Figure 1. Pollution control devices tested in the chimneys of a woodstove and a pellet stove: (**a**) platinum/palladium catalyst and (**b**) small-scale electrostatic precipitator.

A commercial chimney-top tubular electrostatic precipitator (OekoTube) with manual electrode cleaning was selected for the combustion experiments. The ESP, developed by Oekosolve, has a power consumption of 20–30 W during operation and a high-voltage power applied in the range of 15–30 kV. The precipitation electrode was inserted into the chimney and the control system and electronic circuit were installed outside (Figure 1b).

The removal efficiency was determined by comparing emissions from experiments with catalyst (CAT) or electrostatic precipitator (ESP) with those recorded without depollution device (REF). The evaluation of the performance of the pollution control devices (ESP and CAT) was performed by the calculation of the emission reduction percentages, as shown in Equation (1).

$$\% \text{ Reduction} = [(\text{EF REF} - \text{EF CAT or EF ESP})/\text{EF REF}] \times 100\% \quad (1)$$

where EF REF represents the emission factor (gaseous and PM_{10}) for the reference condition and EF CAT or EF ESP the emission factor with ESP or CAT.

2.4. Gaseous and Particulate Matter Measurements

The combustion flue gas was sampled from the stack through an insulated and externally heated (180 °C) line and carried to a multi-gas analyzer (Fourier transform infrared spectrometer, Gasmet, CX4000), which enabled the real-time and continuous monitoring of the gas composition. Particles were removed from the gas sample by a filter unit plugged at the tip of the sampling probe. Oxygen was measured with a paramagnetic gas analyzer.

Before particle sampling, the flue gases were diluted in a dilution tunnel (hood dilution). PM sampling was performed under isokinetic conditions, using a TCR TECORA operating at a 2.3 m^3 h^{-1} (STP). Quartz filters (Pallflex® 47 mm), thermally treated for 6 h at 500 °C, were used for the measurements. The PM_{10} mass was determined by weighing the filter with a microbalance (RADWAG 5/2Y/F) before and after sampling. To evaluate the background concentration, several blanks were taken in the dilution tunnel, which were subtracted from the measured amount.

A Pitot tube (Testo AG 808) and a thermocouple (type k) were used to measure the flue gas velocity and temperature inside the chimney and dilution tunnel. The temperature inside the combustion chamber was also monitored during the combustion experiments.

2.5. Statistical Analysis

Statistical analysis was performed using the IBM SPSS Statistics 26. Normality (Shapiro–Wilk test) and equality of variances (Levene's test) were evaluated before analysing the data. Emission factors from wood and pellet combustion with depollution devices (CAT and ESP) were compared with the reference condition (REF), without CAT or ESP, with the non-parametric Kruskal–Wallis test. All the differences were regarded as statistically significant at $p < 0.05$.

3. Results and Discussion

3.1. Woodstove

CO emissions using the catalyst (52.2 ± 4.16 g kg^{-1} of wood burned, dry basis) were slightly lower than those found for the reference condition (60.8 ± 6.18 g kg^{-1} of wood burned, dry basis) (Figure 2). The observed differences were not statically significant ($p = 0.142$). Although the catalytic converter was designed to clean the flue gas, most of the chemical compounds in wood smoke are only combustible at temperatures higher than 550–600 °C. When installed in the lower part of the chimney, connected to the outlet of the combustion chamber of small-scale traditional appliances, these temperatures are hardly achieved.

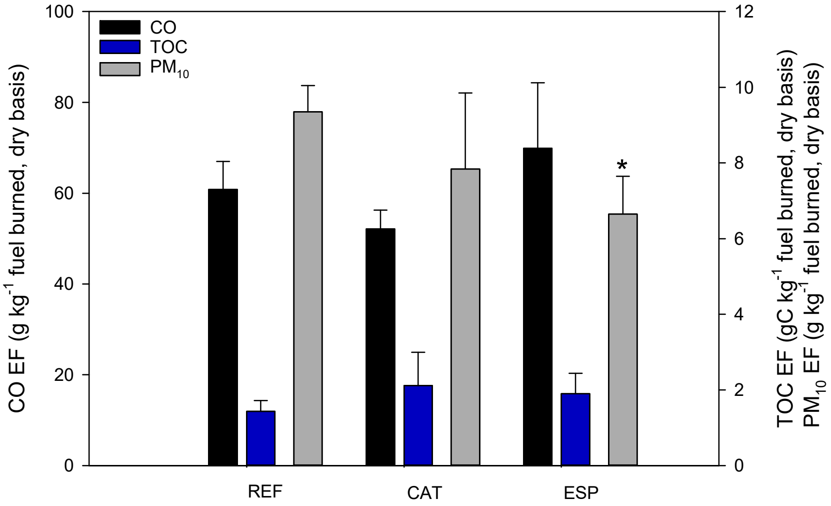


Figure 2. CO, TOC and PM_{10} emission factors from pine wood combustion with or without catalytic converter (CAT) and electrostatic precipitator (ESP). Asterisks indicate statistically significant difference compared to the reference condition (REF) ($p < 0.05$; Kruskal–Wallis test).

Reichert et al. [31] tested the impact of two types of honeycomb catalysts (ceramic and metallic honeycomb carriers coated with a wash coat of aluminium oxide (Al_2O_3) containing Pt and Pd) on wood combustion emissions and reported CO emission reductions above 80%. The main difference in the test procedure conducted by Reichert et al. [31] and the one carried out in the present study was the integration of the catalyst in the upper part of the combustion chamber, while in the current research, the catalyst was installed in the lower part of the chimney.

In the present study, the average temperature inside the combustion chamber ranged from 564 °C (REF) to 586 °C (CAT) (Table 2). In the chimney, much lower temperatures were recorded, hampering the efficiency of the device. Heating the catalyst externally (e.g., electrically) could be a possible solution to overcome this issue [36]. However, the extra cost and inconvenience to the end-users must be considered. Hukkanen et al. [30] tested a catalyst containing a metal wire mesh covered with the catalytic material (Pt/Pd) attached to a steel frame, which was inserted compactly inside the stack through an opening, similar to the configuration evaluated in the present study. The authors reported a reduction in CO concentration for the entire combustion cycle of 21%. They also reported that the reduction efficiency is affected by the load of the incomplete combustion products since the catalyst surface area is limited. Thus, the researchers documented lower reduction in CO and organic gaseous carbon (OGC) emissions during the gasification stage, when the emissions were higher. The catalyst efficiency depends not only on the catalyst material, but also on its construction (active surface, temperature, flow pattern, residence time, type of pollutants, etc.) [38]. Unproper catalyst operating conditions, such as low temperatures (below 400 °C), might result in deposited agglomerations on the catalyst's surface and in the risk of increased pressure drops [39]. The conversion rates of unburned pollutants have been also reported to be closely connected with the oxygen content in the flue gas [40].

Table 2. Operating parameters of the woodstove and CO, TOC, and NO_x emission concentration at 13% of oxygen.

	Woodstove—Pine Firewood		
	REF	**CAT**	**ESP**
O_2 (%)	13.5 ± 0.401	12.9 ± 1.80	13.6 ± 0.725
Temperature: chimney (°C)	162 ± 8.07	171 ± 19.5	157 ± 12.5
Temperature: combustion chamber (°C)	564 ± 22.4	586 ± 18.7	568 ± 32.6
CO (mg Nm^{-3}, dry basis, 13% O_2)	3299 ± 430	2814 ± 462	3075 ± 396
TOC (mgC Nm^{-3}, dry basis 13% O_2)	110 ± 34.1	133 ± 75.7	123 ± 24.9
NO_x as NO_2 (mg Nm^{-3}, dry basis, 13% O_2)	155 ± 23.7	98.1 ± 24.5	112 ± 18.8

The statistical analysis revealed no significant differences for total organic carbon (TOC) emissions (p = 0.200) (Figure 2). No significant differences ($p > 0.05$) were also observed between the emission factors of individual hydrocarbons (Figure 3).

PM_{10} emission factors from pine wood combustion ranged from 6.65 ± 1.00 (ESP) to 9.35 ± 0.697 g kg^{-1} (REF) of wood burned, dry basis (Figure 2). The use of the ESP generated significantly lower particulate emissions compared to the normal combustion condition ($p < 0.05$), i.e., without any depollution device, allowing an emission reduction of 29%. Carroll and Finnan [28] evaluated a chimney-top (OekoTube) with manual cleaning and an in-line wet ESP with automatic cleaning during the combustion of wood, willow and tall fescue. Although the authors reported that the chimney top ESP can achieve high efficiencies for willow (86%) and wood (69%) on a short-term basis, they also observed that after 10 h of operation during the combustion of tall fescue, the collection efficiency of the chimney top ESP decreased to zero. Brunner et al. [41] conducted a field monitoring of ESPs (two chimney-top and one inside version OekoTube ESPs) operation for residential wood heating systems. The study was conducted during two distinct heating seasons and different wood combustion appliances were evaluated (two wood boilers and one woodstove). In order to maintain the ESP performance over the heating season, additional cleanings by a chimney sweep were needed. The authors concluded that ESP models such as the OekoTube are suitable as retrofit units in old appliances and have potential to significantly reduce PM emissions from traditional wood combustion appliances. Additionally, they recommended that automated cleaning systems, to remove soot agglomerates from the

ESP surfaces, should be implemented. The main drawbacks pointed out regarding ESPs were the high investment costs and the need for regular cleaning and maintenance [26]. Studies have also shown that the PM toxicological properties might be altered after ESP. Kaivosoja et al. [42] evaluated the toxicity of particles from wood chips in a rotating grate combustion unit (nominal output of 10 to 15 MW), which included a cyclone and a single field ESP with horizontal flow fields. The authors found that, on an equal mass basis, the wood chip combustion particles collected after ESP were more cytotoxic than the ones collected before the ESP and attributed these findings to the altered chemical characteristics of the emissions in the ESP.

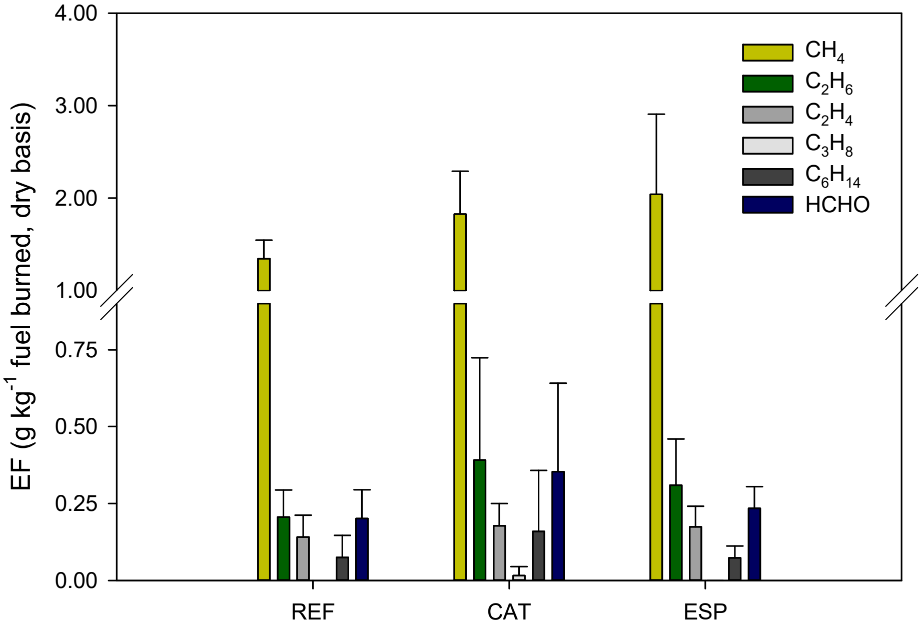


Figure 3. Emission factors of the individual hydrocarbons (CH_4, C_2H_6, C_2H_4, C_3H_8, C_6H_{14}, and HCHO) from pine wood combustion with or without catalytic converter (CAT) and electrostatic precipitator (ESP). Asterisks indicate a statistically significant difference compared to the reference condition (REF) ($p < 0.05$; Kruskal–Wallis test).

A decrease in PM_{10} EFs were also observed using the catalyst (16%), but the difference was not statistically significant ($p = 0.630$) (Figure 2). Catalytic effects on particle emissions, through the oxidation of condensable organic vapors and oxidation of soot particles, have been reported in previous works [30–32]. Reichert et al. (2018) found a reduction in PM emissions from firewood combustion of around 20% using two different catalysts. Higher reductions (30–40%) in PM emissions were reported by Wöhler et al. [32] and Hukkanen et al. [30]. Contrasting results were found by Klauser et al. [43] when they tested two commercially available oxidizing Pt/Pd catalysts with metallic and ceramic honeycomb carriers during the operation of a woodstove. The authors concluded that the tested catalysts cannot be recommended as an effective measure to reduce particulate emissions.

For the reference condition, the main compounds contributing to TOC emissions were methane (70.7%), ethane (11.2%) and ethylene (8.5%). Overall, a non-significant increase ($p > 0.05$) in individual hydrocarbons was observed using the catalyst (Figure 3). Propane, was either not detected or detected at low concentrations (no significant differences were found). Ryšavý et al. [40] tested two catalysts (honeycomb Pd catalyst and honeycomb Pd/Pt catalyst) installed at the exit of a woodstove. The authors reported that the palladium catalyst was almost ineffective (less than 10%) for C_3H_8 oxidation, and, in some cases, the conversion rate was negative. The C_3H_8 conversion rates recorded for the second catalyst tested (Pt/Pd) ranged between 0% and 85% and was strongly dependent on the combustion stage.

The CO average emission for the reference condition was more than double the one established by the Ecodesign directive for closed fronted heating devices (1500 mg Nm^{-3} at 13% O_2). Despite compliance with TOC emissions (120 mgC Nm^{-3} at 13% O_2), the levels recorded were at the upper limit. No significant differences were detected between REF, CAT and ESP conditions (Table 2). PM emissions were above the Ecodesign limit (5 g kg^{-1} of wood burned, dry basis), even when the ESP was used as retrofit unit in the traditional appliance. The NO_x emission limit (200 mg Nm^{-3} expressed as NO_2 at 13% O_2) set by the Ecodesign directive was met. The compliance with the regulated limits was expected since NO_x emissions from biomass combustion is mainly dependent on the fuel-bound nitrogen, which is low in woody fuels (Table 1).

3.2. Pellet Stove

For the reference condition, CO EFs ranged from 9.28 ± 0.637 g kg^{-1} fuel burned, dry basis, to 13.0 ± 0.429 g kg^{-1} fuel burned, dry basis, for the nominal and partial loads, respectively. TOC EFs were also higher under partial load operation (314 ± 0.576 mgC kg^{-1} fuel burned, dry basis) than under nominal load (165 ± 24.5 mgC kg^{-1} fuel burned, dry basis). Previous studies have indicated that even automatically fired appliances on the market fueled with wood pellets might fail to comply with the Ecodesign requirements for gaseous emissions [44]. In the present study, the use of the catalyst allowed to achieve significant CO and TOC reductions ($p < 0.05$), under nominal (60% and 77% reduction for CO and TOC EFs, respectively) and partial (62% and 74% reduction for CO and TOC EFs, respectively) combustion conditions, for wood pellet combustion (Figure 4).

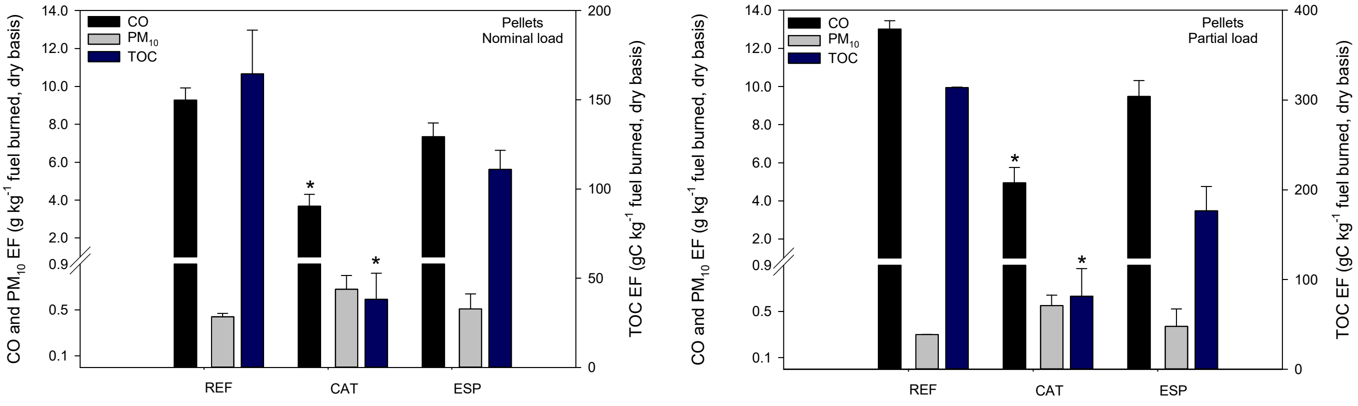


Figure 4. CO, TOC, and PM_{10} emission factors from wood pellet combustion at nominal and partial loads with or without catalytic converter (CAT) and electrostatic precipitator (ESP). Asterisks indicate a statistically significant difference compared to the reference condition (REF) ($p < 0.05$; Kruskal–Wallis test).

Despite the significant decrease achieved using the catalyst, CO concentrations were above the Ecodesign requirements (300 mg Nm^{-3} at 13% O_2, nominal load). TOC (60 mgC Nm^{-3} at 13% O_2) and NO_x (200 mg Nm^{-3} expressed as NO_2 at 13% O_2) concentrations were below the established emission limit for wood pellet combustion (Table 3). No significant differences were recorded in PM_{10} EFs using the catalyst or the ESP. Despite the inexistent reduction, PM (2.5 g kg^{-1} fuel burned, dry basis) emissions were below the regulated limit for this combustion appliance.

Table 3. Operating parameters of wood pellet combustion and CO, TOC, and NO_x emission concentration at 13% of oxygen.

	Wood Pellets—Nominal Load			Wood Pellets—Partial Load		
	REF	**CAT**	**ESP**	**REF**	**CAT**	**ESP**
O_2 (%)	17.7 ± 0.489	17.5 ± 0.482	17.2 ± 0.476	18.3 ± 0.477	18.0 ± 0.453	17.8 ± 0.428
Temperature: chimney (°C)	64.0 ± 1.35	65.0 ± 0.896	66.0 ± 0.990	53.6 ± 1.18	55.0 ± 0.980	56.8 ± 0.859
Temperature: combustion chamber (°C)	536 ± 56.5	556 ± 55.4	581 ± 55.4	498 ± 60.1	536 ± 59.8	549 ± 60.9
CO (mg Nm^{-3}, dry basis, 13% O_2)	905 ± 76.0	493 ± 89.0	648 ± 52.8	1277 ± 49.8	639 ± 91.8	836 ± 41.6
TOC (mgC Nm^{-3}, dry basis 13% O_2)	16.0 ± 2.93	5.08 ± 2.02	9.78 ± 0.732	30.7 ± 0.218	10.2 ± 3.45	15.5 ± 1.89
NO_x as NO_2 (mg Nm^{-3}, dry basis, 13% O_2)	179 ± 5.14	284 ± 16.0	181 ± 3.62	177 ± 13.3	291 ± 9.40	177 ± 6.08

Olive pit combustion generated CO and TOC emissions nearly one order of magnitude higher than wood pellets. The catalyst allowed a significant reduction ($p < 0.05$) of 59–60% and 64% in CO and TOC EFs, respectively (Figure 5). Despite the decrease, the emissions remained high under the nominal (36.4 ± 6.77 g kg^{-1} fuel burned, dry basis and 2553 ± 105 mgC kg^{-1} fuel burned, dry basis, for CO and TOC emissions, respectively) and partial load operations (33.3 ± 8.27 g kg^{-1} fuel burned, dry basis and 1710 ± 558 mgC kg^{-1} fuel burned, dry basis, for CO and TOC emissions, respectively).

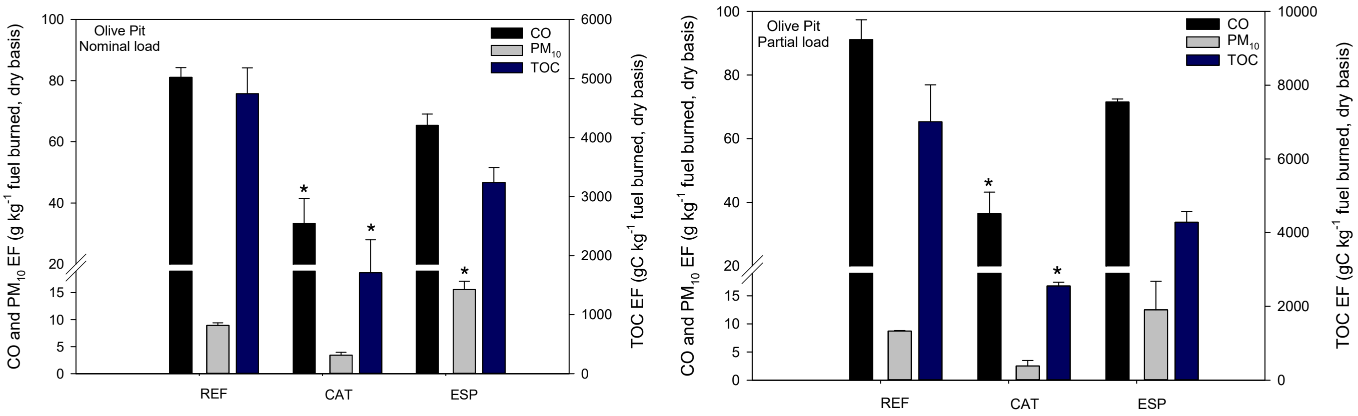


Figure 5. CO, TOC, and PM_{10} emission factors from olive pit combustion at nominal and partial loads with or without catalytic converter (CAT) and electrostatic precipitator (ESP). Asterisks indicate a statistically significant difference compared to the reference condition (REF) ($p < 0.05$; Kruskal–Wallis test).

Despite the catalyst's potential to reduce gaseous emissions, attention must be paid to the possible formation of hazardous pollutants. In the study of Kaivosoja et al. [45], despite reporting a reduction in CO, VOC, and PAH emissions from a sauna stove using a Pt/Pd catalyst placed in the chimney, the authors also observed an increase in chlorophenols and polychlorinated dibenzofurans emissions.

In the present study, emissions from olive pit combustion for the reference condition and using the depollution devices were well above the Ecodesign limits (Table 4).

Table 4. Operating parameters of olive pit combustion and CO, TOC, and NO_x emission concentration at 13% of oxygen.

	Olive Pit—Nominal Load			**Olive Pit—Partial Load**		
	REF	**CAT**	**ESP**	**REF**	**CAT**	**ESP**
O_2 (%)	18.3 ± 0.350	15.6 ± 1.25	17.9 ± 0.333	18.2 ± 0.197	15.5 ± 0.520	18.2 ± 0.176
Temperature: chimney (°C)	52.7 ± 1.80	117 ± 4.00	57.9 ± 1.56	48.3 ± 0.985	101 ± 8.77	50.3 ± 1.39
Temperature: combustion chamber (°C)	457 ± 76.1	665 ± 98.9	504 ± 57.9	458 ± 68.6	645 ± 69.6	411 ± 46.9
CO (mg Nm^{-3}, dry basis, 13% O_2)	6330 ± 304	2218 ± 552	4943 ± 280	7044 ± 594	2376 ± 212	6042 ± 291
TOC (mgC Nm^{-3}, dry basis 13% O_2)	370 ± 41.8	114 ± 37.2	245 ±19.2	542 ± 94.5	169 ± 24.1	353 ± 39.9
NO_x as NO_2 (mg Nm^{-3}, dry basis, 13% O_2)	268 ± 15.5	244 ± 39.6	245 ± 18.9	268 ± 47.7	235 ± 23.4	256 ± 14.8

No significant differences were recorded in PM_{10} EFs using the catalyst during the combustion of olive pit ($p = 0.061$ and $p = 0.539$ for partial and nominal load operations, respectively) (Figure 5). Under nominal load operation, a significant increase in PM_{10} emissions was recorded when ESP was used ($p < 0.05$). The re-entrainment of precipitated soot agglomerates from the filter surfaces has been reported to occur [41]. The efficiency of ESPs depends on dust resistivity. When the ratio of particulate carbon mass to particle mass is high, the re-entrainment of particles is expected to occur [26].

The main compounds contributing to TOC emissions (>76%) were methane (CH_4), ethane (C_2H_6) and formaldehyde (HCHO) for the combustion of wood pellets in the REF and ESP experiments. These were substantially reduced when using the catalyst ($p < 0.05$). The use of the catalyst reduced almost all the hydrocarbon EFs, except C_3H_8. Under partial load operation, the increase was significant compared to the REF condition ($p < 0.05$). For stove operation under partial load, reductions from 67.2% (C_6H_{14}) to 83.4% (C_2H_4) were recorded. Similarly, under nominal load operation, the highest reduction was recorded for C_2H_4 (91.9%) and the lowest for C_6H_{14} (37.3%). For the later hydrocarbon, the reduction was found to be non-significant ($p > 0.05$) under nominal and partial load operations (Figure 6). In the present study, the CH_4 reduction ranged from 81% (partial load) to 88% (nominal load).

For olive pit combustion, the main individual hydrocarbons contributing to TOC emissions were methane (CH_4), ethane (C_2H_6), and hexane (C_6H_{14}), comprising more than 75% and 68% of the emissions for stove operation under partial and full loads, respectively. Opposite to what was recorded for wood pellets, propane was not detected in olive pit combustion emissions using the catalyst. The compositional profile of TOC emissions using the catalyst remained roughly the same as in the reference condition. The reduction in individual hydrocarbons ranged from 58% (formaldehyde) to 72% (ethane) under the nominal load. For partial load combustion, the catalyst reductions were in the range from 36% (hexane) to 78% (ethane) (Figure 6).

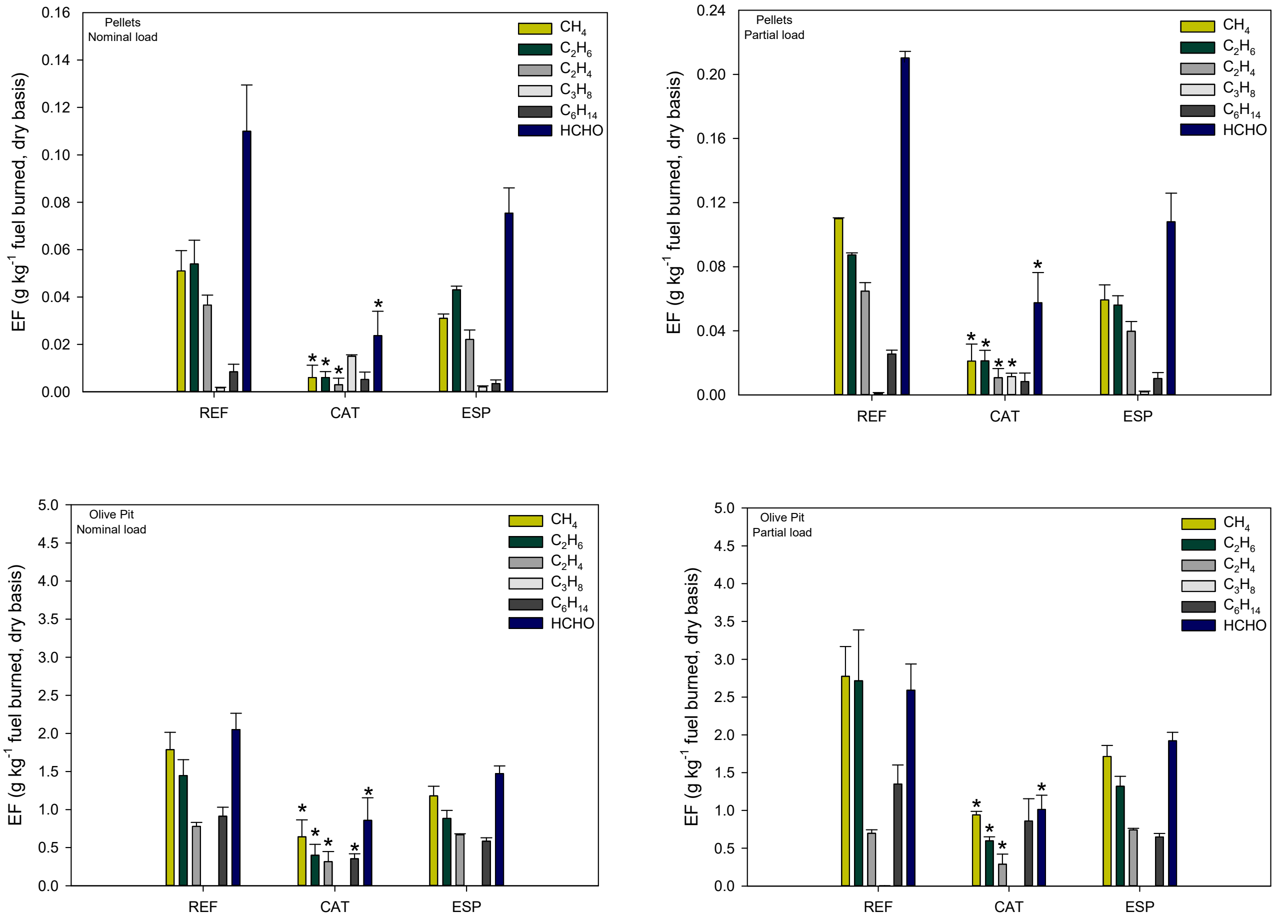


Figure 6. Emission factors of individual hydrocarbons (CH_4, C_2H_6, C_2H_4, C_3H_8, C_6H_{14}, and HCHO) from wood pellet and olive pit combustion at nominal and partial loads with or without catalytic converter (CAT) and electrostatic precipitator (ESP). Asterisks indicate a statistically significant difference compared to the reference condition (REF) ($p < 0.05$; Kruskal–Wallis test).

4. Conclusions

In this study, a commercial catalyst and electrostatic precipitator were applied to the flue gases of a traditional woodstove and a modern pellet stove in order to determine their effectiveness as a secondary emission reduction method for residential combustion appliances. The catalyst's effect on CO, TOC, and PM emissions from the woodstove was not statistically significant. The effect of the ESP on PM EFs was more visible and significant. A reduction of 29% was observed in PM EFs between the reference and the ESP condition. Nevertheless, the reduction was not enough to meet the Ecodesign limit for closed fronted heating devices.

For pellet and olive pit combustion, CO and TOC emissions underwent a statistically significant decrease during the experiments with the catalyst. On the other hand, none of the tested depollution devices showed effectiveness in removing particles. In fact, under the nominal load operation during olive pit combustion, a significant increase in PM_{10} emissions was recorded using the ESP, probably due to the re-entrainment of already precipitated particles. Since the efficiency of ESPs depends on dust resistivity, fuels must be carefully selected to ensure optimal performance of such devices. Additionally, the integration of automatic cleaning systems in such devices is of utmost importance to ensure optimal performance.

Retrofitting existing traditional small-scale combustion units can be a challenge due not only to high investment costs, but also to space constraints. While the commercial ESP selected in the present study was designed to be integrated directly into the chimney outlet, the catalyst needs to be attached to the early part of the chimney, which can be a drawback for end users. Additionally, Pd/Pt catalysts, such as the one tested in the present study, appear to be unsuitable as retrofit units in traditional combustion appliances since no significant reduction in gaseous and particulate matter emissions were recorded for the traditional woodstove. Given the results obtained and considering the investment costs, traditional combustion appliances should be replaced by modern devices, rather than installing flue gas depollution technologies.

The ageing and dirtying of the depollution devices were not studied. These devices require frequent cleaning and maintenance, which increases the costs for end-users. Considering the resulting inconveniences to homeowners, further research and development is required to prolong the maintenance intervals of reduction technologies. It should be also noted that the installation investment costs are high in comparison with those related to the combustion appliance. Thus, in addition to the technological requirements, legal and financial incentives will be needed to really achieve an effective market introduction.

Future work should focus on the effect of electrostatic precipitators on the chemical and toxicological properties of the released particles. Additionally, the catalyst's effect on hazardous gaseous emissions should be fully investigated.

Author Contributions: Conceptualization, C.A.A.; methodology, E.D.V., M.A.D., L.A.C.T. and C.A.A.; formal analysis, E.D.V.; writing—original draft preparation, E.D.V. and C.A.A.; writing—review and editing, L.A.C.T.; supervision, C.A.A.; project administration, C.A.A.; funding acquisition, C.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by AIRUSE–Testing and development of air quality mitigation measures in Southern Europe, LIFE 11 ENV/ES/000584. We acknowledge the Portuguese Foundation for Science and Technology (FCT) and the POHP/FSE funding program of the fellowship SFRH/BD/117993/2016. The financial support to CESAM by FCT/MCTES (UIDP/50017/2020 + UIDB/50017/2020 + LA/P/0094/2020), through national funds, is also acknowledged.

Data Availability Statement: Derived data supporting the findings of this study are available from the corresponding author upon request.

Conflicts of 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.

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