Waste to Energy: Air Pollutant Emissions from the Steam Boilers Using Recycled Waste Wood

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ABSTRACT

In Taiwan, combustible wood mostly comes from waste pallets and scrap packaging materials discarded by factories, which produced a total of 278,067 tons of waste wood in 2019. In this study, the heat value of waste wood was 18.3 ± 1.07 MJ kg⁻¹. The measured volatile fraction was $76.5 \pm 7.34\%$, the fixed carbon was $15.7 \pm 3.19\%$, the ash content was $2.96 \pm 2.45\%$, and the moisture content was $21.6 \pm 10.2\%$. The proportions of the elemental constituents in the waste wood were $45.3 \pm 4.95\%$, $46.9 \pm 3.94\%$, $5.9 \pm 0.44\%$, $0.21 \pm 0.17\%$, $0.29 \pm 0.26\%$, and $0.02 \pm 0.02\%$ for carbon, oxygen, hydrogen, sulfur, nitrogen, and chlorine, respectively. The average boiler capacity was 11.5 ± 6.84 ton hr⁻¹, the average fuel consumption of the boilers was 1.47 ± 1.81 ton hr⁻¹, the average operating temperature of the boilers was $853 \pm 228^\circ\text{C}$, the average steam generation of the boilers was 7.63 ± 5.97 ton hr⁻¹, and the average exhaust flow rate was 246.6 ± 200.9 m³ min⁻¹. The main air pollution control systems used in the waste wood combustion boilers were systems combining a cyclone, a baghouse and a scrubber (37.8%), a cyclone and a baghouse (28.4%), a cyclone and a scrubber (10.2%), and systems using a baghouse only (9.8%). Based on our fuel consumption data, the air pollutant emission factors were 0.71 ± 1.44 kg per ton of wood for PM, 0.86 ± 1.47 kg per ton of wood for SO_x, and 5.24 ± 9.56 kg per ton of wood for NO_x. In July 2022, new emission standards for boilers will be implemented, and emission reductions of at least 30% for PM, 35% for NO_x and 7% for SO₂ will be required.

Keywords: Waste wood, Boiler, Air pollution control system, Emission factor

1 INTRODUCTION

Biomass, with its very specific properties, has been used as a source of energy for thousands of years. However, interest in biomass has been decreasing for some time due to the potential use of fossil fuels such as oil, coal and natural gas as energy sources, with their prime characteristics of high calorific values, ease of transportation, and ease of storage. However, the resulting appetite for fossil fuel resources has led to their depletion, which experts predict will occur very rapidly within the next 40–50 years (Saidur *et al.*, 2011). Therefore, their market price is increasing annually. Biomass is now being considered as a renewable energy source that can replace fossil fuels. In fact, carbon dioxide (CO₂) emissions can be significantly reduced if biomass is used to generate electricity instead of fossil fuels. Indeed, unlike fossil fuels, burning renewable biomass

OPEN ACCESS

Received: November 2, 2021
Revised: November 19, 2021
Accepted: November 21, 2021

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Publisher:
Taiwan Association for Aerosol
Research
ISSN: 1680-8584 print
ISSN: 2071-1409 online

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is thought to be GHG-neutral.

In 2016, bioenergy was the world's fourth-largest energy source after coal, oil and natural gas, occupying 9.5% of the global primary energy supply and 69.5% of the global renewable energy supply (IEA, 2018), and in 2017 it was the third-largest energy source domestically after coal and oil, accounting for 15% of energy consumption (BP, 2018). A recent study suggested that the potential of the world's biomass resources will be around $100\text{--}600 \times 10^{18}$ J by 2050 (Slade *et al.*, 2014), which corresponds to 15–65% of the demand for primary energy, based on estimates from the IEA (2014). According to life-cycle analyses, bioenergy can reduce air pollution emissions by a maximum of 4.9–38.7 GtCO₂e, or, stated otherwise, to 9–68% of the emissions resulting from the production of fossil fuel-derived electricity and heat, and the use of liquid fuels. In addition, replacing conventional sources of electricity and heat with bioenergy is, on average, 1.6–3.9 times more effective in terms of reducing emissions than the carbon offset resulting from the use of liquid fuels (Staples *et al.*, 2017).

Compared to coal, biomass has low sulfur and ash content and is carbon-neutral. It is highly flexible as compared with other renewable energy sources, and it can be used to generate electric power (Pfeiffelmann *et al.*, 2021).

In the United States in 2016, biomass and waste fuels were used to produce 71.4×10^9 kWh of electricity, which was the equivalent of 2% of the total power generation (U.S. EIA, 2017). This figure is expected to slowly increase to 5.39×10^{15} Btu by 2050 (U.S. EIA, 2021). Based on Global Bioenergy Statistics 2020, Europe, the United States, Asia (China and Taiwan) are leading the trend toward the use of biomass for renewable heat production.

In China, biomass accounted for 2.4–2.8% of total energy consumption (Alliance experts, 2021). The generation of power from biomass in China increased from 1.4 Gigawatts (GWs) in 2006 to 14.88 GWs in 2017, and the installed capacity can be raised to 30 GW by 2030 (Fernandez, 2019; Danish and Ulucak, 2020).

In Europe, 43% of solid biomass-generated energy was consumed by the residential sector in EU28 in 2017 (Malicoet *et al.*, 2019). In addition, the European Union (EU) has set a target of using renewable sources to produce 32% of energy by 2030. Therefore, the consumption of biomass to satisfy energy demand may increase in the future.

In Taiwan, the use of biomass and waste as sources of energy is expected to increase from 727 MW in 2016 to 813 MW in 2025 (BOE, 2021). Biomass and waste fuels currently account for 1.1–1.3% of the primary energy supply in Taiwan (BOE, 2021). In addition to hydropower, wind power and solar energy, biomass is another option that is available to help the Taiwanese government achieve its energy goal of obtaining 20% of its energy from renewables by 2025.

With the global demand for energy increasing and social pressure to decrease the use of fossil fuels, governments and various energy companies are exploring many renewable energy alternatives. Commercial crops and biomass waste streams together are considered to be one of the most reliable sources of alternative energy (Zhou *et al.*, 2019). Unfortunately, because of the variability in the composition of fuel, these fuel sources suffer from low combustion stability and poor boiler efficiency (Demirbas, 2005).

In Taiwan, the availability of wood as a biomass source of energy is limited, and most of the wood that is consumed is imported (> 99%). Therefore, waste wood is burned in combustion boilers to produce the steam required by nearby industrial facilities. In Taiwan, wood waste mainly comes from waste pallets, packaging materials, and some construction waste. The combustion process is commonly employed to deal with this waste; however, the air pollution produced as the biomass is incinerated in a boiler is a matter of concern.

In order to reduce particulate matter (PM) emissions, biomass boilers are equipped with air pollution control devices, such as cyclones or multi-cyclones, fabric filters, scrubbers, and electrostatic precipitators (Strand *et al.*, 2002; Pagels *et al.*, 2003; Wierzbicka *et al.*, 2005; Lim *et al.*, 2015; Bianchini *et al.*, 2016; Nussbaumer *et al.*, 2016; Mertens *et al.*, 2020; Cornette *et al.*, 2020). These boilers produce small fluctuations in NO_x emissions and have low DeNO_x efficiency. In addition, burning wood chips has been shown to achieve low precipitation efficiencies ranging between 30 and 50% (König *et al.*, 2018). Because of the low sulfur content of wood, PM and NO_x emissions are a particular source of concern related to the use of wood-fired combustors.

Biomass combustion can cause the formation of particulate matter and the emission of ash particles, the prevention of which is one of the most pressing challenges related to the use of

biomass-fired utility boilers. Biomass combustion has been shown to be an important source of air pollution in northern China (Xu *et al.*, 2017, 2020; Xu *et al.*, 2021) and in Europe (EEA, 2013; Bourguignon, 2015). Many studies have focused on the emissions of NO_x and other pollutants (CO, VOCs, PAHs, and metals in PM) (Vamvuka *et al.*, 2020; Poláček *et al.*, 2021; Zhang *et al.*, 2020; Kong *et al.*, 2021; Jaworek *et al.*, 2021). In order to address the problem of pollution and to reduce emissions, it is important to take into consideration combustion efficiency, operating conditions and air pollution control devices (Caposciutti *et al.*, 2020; Oluwoyea *et al.*, 2020).

Emission factors of fine particulate matter are highly correlated with fuel characteristics and burn conditions. Conversely, fuel moisture content and burn conditions have been shown to determine the emission factors of specific organic chemicals (Guillén and Ibargoitia, 1999; Khalil and Rasmussen, 2003).

In this study, wood combustion boilers were investigated to determine how the composition and calorific value of waste wood, the boiler operating parameters, and the air pollution control devices in the boilers affect air pollution emissions. Then, the operating conditions were evaluated in terms of their potential for improving combustion efficiency and reducing air pollution emissions in the future.

2 EXPERIMENTAL PROCEDURES

2.1 Proximate Analysis

A proximate analysis was conducted to identify the levels of moisture, ash, and volatile matter in the biomass. The fixed carbon content was determined based on the percentages obtained for ash and volatile matter using an empirical expression. Each sample was analyzed at least three times to show the reproducibility of the results. The proximate analysis followed the testing procedures set out in the Taiwan Environmental Protection Administration (EPA) regulations and the Chinese National Standards. All the analytical procedures were similar to those proposed by the American Standard for Testing Materials (ASTM).

2.1.1 Moisture

The moisture in the biomass was measured after each sample had been air-dried for 2–3 days. The experimental process involved measuring the weight difference in a stove, putting the weighted samples into crucibles, and drying the samples in an oven at temperatures fixed between 120 and 150°C for 3–4 h with a weight difference under 10 mg. The moisture of the samples was determined as follows (ASTM, 2019a):

$$M(\%) = \frac{W_i - W_f}{W_i - W_c} \times 100 \quad (1)$$

where M is the moisture, W_i is the initial weight of the sample, W_f represents the weight of the sample after drying in the oven to remove moisture, and W_c is the container weight.

2.1.2 Ash content

The ash content was determined using the ASTM E1534 standard test method (ASTM, 2019b). A crucible with the dried sample was placed in a furnace at 580–600°C for 3–4 h. Then, the crucible was taken out of the furnace, put into a desiccator, and cooled down to room temperature. Afterwards, the crucible containing the sample was weighed once more. The ash content was calculated using the formula below, where W₁ is the initial combined weight of the dried sample and the crucible, W₂ stands for the combined weight of the crucible and the sample after the ashing procedure, and W_c represents the weight of the crucible.

$$\text{Ash}(\%) = \frac{W_2 - W_c}{W_1 - W_c} \times 100 \quad (2)$$

2.1.3 Volatile matter

Volatile matter was analyzed using the ASTM E872 standard test method (ASTM, 2019c) (The control temperature was set at $950 \pm 20^\circ\text{C}$). The weight loss was calculated using the following formula:

$$A(\%) = \frac{W_i - W_f}{W_i - W_c} \times 100 \quad (3)$$

where W_i represents the initial combined weight of the sample and the crucible with a cover, W_f stands for the final combined weight of the sample and the crucible with a cover after being heated in a furnace, and W_c represents the weight of the crucible and the cover. $A(\%)$ expresses the weight loss as a percentage terms. The value of $A(\%)$ is used in the following formula to calculate the content of the volatile matter (VM):

$$VM(\%) = A - B \quad (4)$$

where B is the percentage of moisture in the sample, as determined with the ASTM E871 standard test method.

2.1.4 Fixed carbon (FC) percentage

In this study, the released moisture content was included as part of the percentage of volatile matter. The fixed carbon content was measured according to the formula $FC = 100 - (\% \text{ Ash} + \% \text{ VM})$, where FC stands for the percentage of fixed carbon, and VM is the measurement of volatile matter obtained earlier.

2.1.5 Combustible solid fractions (Fixed carbon)

The content of other combustible solid fractions $FC(\%)$ was determined based on the following equation:

$$FC = 100 - M - A - V \quad (5)$$

where M is the moisture content (%), A is the ash content (%), and VM is the volatile matter content (%) in the sample.

2.1.6 Calorimetry

The heat value of the waste wood was determined with a static bomb calorimeter (IKA-Calorimeter C4000, IKA-Analysentechnik Heitersheim)

2.2 Ultimate Analysis

An elemental analyzer (Elementar Vario EL cube MICRO, Elementar Americas Inc. New York, USA) was employed to determine the levels of the carbon, hydrogen, nitrogen, sulfur, and oxygen constituents in the waste wood (ASTM D5373, 2016). Chlorine levels were determined using an electrical furnace in which the furnace gas was absorbed with 3% H_2O_2 and analyzed by means of Ion Chromatography (ASTM D7359, 2018).

2.3 The TEDS Emission Data

The Taiwan Emission Data System (TEDS) was established in 1992 and is updated every three years. TEDS 10.1 was used in this study. In 2016, its emission data were employed to check and adult the consistent with standard flue gas emissions tests.

2.4 Regular Testing for PM, NO_x and SO_x

Based on permit licenses, the boilers were selected based on the steam generated from waste wood combustion. About 100 waste wood boilers were tested to measure their emissions of PM, SO_x , and NO_x according to the methods proposed by the National Institute of Environmental Analysis

(NIEA), under the Taiwan Environmental Protection Administration (TEPA). The NIEA methods A101.76C, A411.75C and A413.75C, are based on the United States EPA Methods 5, 7E and 6C, respectively (U.S. EPA, 2004, 2006, 2019). The permits for the boilers were checked, and their operating conditions were inspected in the field as part of the regulatory testing to determine the representativeness of our samples. The data from the regular testing reports were obtained from the TEPA, and the data sheets were rearranged and checked.

2.5 Emission Factor

Emission factors were determined based on air pollution emissions and activity (wood combustion or steam generation).

$$EF = E_i / (AC) \quad (6)$$

where EF is the emission factor (gram of pollution emission from one ton of wood combustion or steam generation, g ton-wood^{-1} or g ton-steam^{-1}); E_i is the i specie pollutant emissions (i is PM, SO_x , or NO_x in grams), and AC is the activity (wood combustion or steam generation in tons).

3 RESULTS AND DISCUSSION

3.1 Waste Wood Characteristics

In Taiwan, combustible wood mainly comes from waste pallets and scrap packaging materials discarded by factories, materials from used decorations, and pruned tree branches. Based on the TEPA data, the sources of waste wood are shown in Fig. 1(a). There were 278,067 tons of waste wood in 2019. Most boilers for waste wood combustion are regarded as waste treatment systems and are used to produce steam. These boilers are used in food and animal feed manufacturing (32%), wood and bamboo product manufacturing (18%), agriculture and animal husbandry (12%), pulp, paper and paper products manufacturing (9%), textiles mills (5%), the laundry industry (5%), the electricity and gas supply (5%), and others (see Fig. 1(b)). Therefore, waste wood shows potential as an energy source and for disposing of excess waste materials after being properly processed.

The moisture content was $21.6 \pm 10.2\%$ (in the range of 10.41–38.8%) (see Fig. 2(a)). The volatile fraction was in the range of 64.7–85.7% (the average was $76.5 \pm 7.3\%$), and the fixed carbon was $15.7 \pm 3.19\%$ (in the range of 10.2–19.0%). The ash content was $2.96 \pm 2.45\%$ (in the range of 0.29–7.9%). The heat value of the wood was $18.34 \pm 1.07 \text{ MJ kg}^{-1}$ (in the range of 16.29–19.85 MJ kg^{-1}).

Fig. 2(b) shows the values for the major elemental compositions values of the waste wood. The elemental constituents were $45.3 \pm 4.96\%$ for carbon (ranging from 36.0–56.6%), $46.9 \pm 3.94\%$ (ranging from 38.1–53.0%) for oxygen, $5.96 \pm 0.44\%$ (ranging from 4.94–6.90%) for hydrogen, $0.21 \pm 0.17\%$ (ranging from 0.02–0.59%) for sulfur, $0.29 \pm 0.26\%$ (ranging from 0.081–0.900%) for nitrogen, and $0.02 \pm 0.02\%$ (ranging from 0.0016.0–0.0624%) for chlorine. Some chloride was detected in the waste wood, which could be a sign that some plastic was mixed in with the wood or that chlorinated preservatives have been used on the wood (U.S. EPA, 2021).

Table 1 shows the characteristics of the waste wood used in this study compared with the results of other studies. Our results indicated that the components of the waste wood matched the carbon and hydrogen constituents of spruce pellets and beech wood (Poláčik *et al.*, 2021), certified and uncertified pellets (Vicente *et al.*, 2020), and agricultural residues (Vamvuka *et al.*, 2020). However, a higher moisture content was found in the waste wood as a result of their sources and the fact that it was stored in the open before being used as feedstock in boilers. In addition, highly variable characteristics have been measured for biomass (Saidur *et al.*, 2011) and for forest and biomass (García *et al.*, 2012). Recently, solid recovered fuel (SRF) has been considered as an alternative to using waste wood as biomass. However, there are standards for the allowable quantities of trace elements ($\text{Cl} \leq 0.03\text{--}0.1\%$, $\text{As} \leq 2.0 \text{ mg kg}^{-1}$, $\text{Cd} \leq 1.0 \text{ mg kg}^{-1}$, $\text{Cr} \leq 15 \text{ mg kg}^{-1}$, $\text{Cu} \leq 20 \text{ mg kg}^{-1}$, $\text{Pb} \leq 20 \text{ mg kg}^{-1}$, $\text{Hg} \leq 0.1 \text{ mg kg}^{-1}$, and $\text{Zn} \leq 200 \text{ mg kg}^{-1}$) present in wood pellets (ISO, 2021) which cannot be ignored. Such high limits for trace element content could be a limitation to the use of waste wood. In addition, the moisture levels measured in this study were

rather high (moisture $\leq 0\%$), which can reduce the heat value, reduce the boiler combustion efficiency, and increase the emission of air pollutants.

EPCM: Electronic Parts and Components Manufacturing,
CP, FM, SR, PRM: Chemical Products Manufacturing, Fertilizers Manufacturing, Synthetic Resin, Plastic and Rubber Materials Manufacturing,
WRDI: Waste Removal and Disposal Industry,
MVPM: Motor Vehicles and Parts Manufacturing,
FMPM: Fabricated Metal Products Manufacturing,
PCPM: Petroleum and Coal Products Manufacturing,
BMM: Basic Metal Manufacturing,
NMPM: Non-metallic Mineral Products Manufacturing,
TM: Textiles Mills,
CI: Construction Industry,
PPM: Plastic Products Manufacturing,
CEPM: Computers and Electronic Products Manufacturing, Others.

Fig. 1(a) Sources of waste woods used as biomass energy in Taiwan.

FAFM: Food and animal feed manufacturing,
WBPM: Wood and bamboo products manufacturing,
AAH: Agriculture and animal husbandry,
PPPPM: Pulp, paper and paper products manufacturing,
TM: Textiles mills,
EGS: Electricity and gas supply,
LI: Laundry industry, and others.

Fig. 1(b). Sources of boilers for waste wood combustion.

Fig. 2(a). Approximate analysis of waste woods from 100 industrial-sized wood combustion boilers.

Fig. 2(b). Elemental constituents of waste woods from 100 industrial-sized wood combustion boilers.

3.2 Characteristics of Boilers

Table 2 shows the characteristics of the boilers. The average boiler capacity was $11.5 \pm 6.84 \text{ ton hr}^{-1}$, and their cumulative capacity of 10 to 90% ranged from 5.00 to 17.00 ton hr^{-1} . The fuel consumption of the boilers was $1.47 \pm 1.81 \text{ ton hr}^{-1}$, and their cumulative consumption from 10 to 90% was from 0.20 to 3.06 ton hr^{-1} . The average exhaust flow rate was $246.6 \pm 200.9 \text{ m}^3 \text{ min}^{-1}$, and the cumulative rate of 10 to 90% ranged from 69.4 to 450.6 $\text{m}^3 \text{ min}^{-1}$.

The average operating temperature of the boilers was $853 \pm 228^\circ\text{C}$, and their cumulative temperature of 10 to 90% ranged from 500–1200°C, reflecting a 2.4-fold difference. The average temperatures were slightly lower than the typical temperatures for biomass combustion in fluidized bed boilers (900–1000°C) (Vakkilainen *et al.*, 2017).

The average steam generation of the boilers was $7.63 \pm 5.97 \text{ ton hr}^{-1}$, and their cumulative generative capacity of 10 to 90% ranged in the range of 1.50–14.0 ton hr^{-1} , reflecting a 9.3-fold

Table 1. Physiochemical characteristics of scrap wood and biomass used in 100 industrial-sized wood combustion boilers.

Items	Biomass	Forest and biomass	Agricultural Residues	Certified and uncertified pellets	Spruce pellets and Beech wood	Waste wood
C	38.45–57.00	24.51–97.18	46.5–49.5	48.7–49.7	42.7–43.7	45.34 ± 4.96
H	4.50–10.20	0.27–11.55	5.7–6.3	6.1–6.3	5.5–5.7	5.96 ± 0.44
S	0.01–0.60	0.10–1.48	< 0.05	< 0.01	0	0.213 ± 0.173
N	0.1–3.4	0.07–3.94	0.8–2.2	0.71–1.02	0.6–0.7	0.288 ± 0.255
Cl	0.01–1.50	–	–	–	–	0.022 ± 0.017
O	33.9–47.1	0–73.80	36–43	42.5–43.7	40.3–41.2	46.95 ± 3.94
Ash %	0.10–20.26	0–22.9	1.4–7.3	0.43–0.84	0.3–2.3	2.96 ± 2.45
Volatile fraction (%)	57.2–87.4	26–86.5	72.1–81.4	–	–	76.5 ± 7.34
Fixed carbon (%)	7.42–29.30	1.0–50.17	13.11–26.5	–	–	15.7 ± 3.19
Calorific Value (MJ kg ⁻¹)	8.0–22.08	11.87–23.0	17.5–20.4	18.47–18.53	18.04–18.24	18.34 ± 1.07
Moisture %	5.43–9.53	5.10–43	–	7.2–8.0	7.9–9.5	21.55 ± 10.21
Remark	Saiduret <i>al.</i> , 2011	Garćiaet <i>al.</i> , 2012	Vamvukaet <i>al.</i> , 2020	Vicente <i>et al.</i> , 2020	Poláčiket <i>al.</i> , 2021	This study

Table 2. Operation parameters of boilers.

Parameters	Boiler capacity (ton hr ⁻¹)	Operation temperature (°C)	Fuel consumption (ton hr ⁻¹)	Steam generation (ton hr ⁻¹)	Flue gas flow rate (Nm ³ min ⁻¹)
10%	5.00	500	0.20	1.50	69.35
25%	6.00	600	0.38	3.70	111.75
Median	12.00	900	0.82	5.50	189.20
75%	15.00	1050	2.00	10.80	327.77
90%	17.00	1200	3.06	14.00	450.57
Min–Max	1.80–40.00	500–1,200	0.02–15.00	0.06–38.0	10.6–1,282.1
Mean	11.50	852.5	1.47	7.63	246.59
Standard deviation	6.84	228.2	1.81	5.97	200.96

difference. Based on the calculations related to wood consumption and steam generation, the level of energy efficiency was approximately 76%, which is slightly lower than the typical level of 80–94%. This discrepancy could be explained by the moisture content of the wood pellets and the operating conditions of the boilers (Scottish Forestry, 2021).

3.3 Air Pollutant Concentrations and Emission Factors

The average concentrations of PM, SO_x and NO_x emissions are shown in Fig. 3. The average fuel consumption was 1.47 ± 1.81 ton hr⁻¹, and the cumulative consumption of 10 to 90% ranged from 0.20 to 3.06 ton hr⁻¹, reflecting a 15.3-fold difference. The average concentration of PM was 36.3 ± 36.0 mg Nm⁻³ and the cumulative concentration of 10 to 90% ranged from 3.0 to 86.9 mg Nm⁻³, reflecting a 29.0-fold difference. The SO_x concentration was 17.4 ± 20.8 ppm, and the cumulative concentration of 10 to 90% ranged from 3.0 to 38.6 ppm (8.6–110.3 mg Nm⁻³), reflecting a 12.9-fold difference. The NO_x concentration was 126.4 ± 60.1 ppm, and the cumulative concentration of 10 to 90% ranged from 60.4 to 211.2 ppm (124.0–454.2 mg Nm⁻³ as NO₂), reflecting a 3.5-fold difference. The emissions from the combustion of wood chips of PM were 16–18 mg Nm⁻³ and the emissions of NO_x were 101–122 mg Nm⁻³ with an O₂ content of 10.8–10.9% and an exhaust temperature of 154–179°C (König *et al.*, 2018). The concentrations of emissions from the waste wood combustion boilers used in this study were higher than those identified in other studies (König *et al.*, 2018).

Calculated over an entire year, the level of air pollutant emissions was 2.38 ± 4.40 ton yr⁻¹ for PM, 4.03 ± 7.25 ton yr⁻¹ for SO_x, and 24.9 ± 34.7 ton yr⁻¹ for NO_x. The cumulative emission level

Fig. 3. PM, SO_x, and NO_x concentration distribution.

of 10 to 90% ranged from 0.06 to 5.36 ton yr⁻¹ for PM, from 0.04 to 10.34 ton yr⁻¹ for SO_x, and from 2.04 to 64.11 ton yr⁻¹ for NO_x. There was an 85.2-fold difference for PM, 271-fold difference for SO_x and 31.5-fold for difference NO_x.

The quantity of air pollutants based on the level of fuel consumption can be expressed as 0.71 ± 1.44 kg ton-wood⁻¹ for PM, 0.86 ± 1.47 kg ton-wood⁻¹ for SO_x, and 5.24 ± 9.56 kg ton-wood⁻¹ for NO_x. The cumulative emission factor of 10 to 90% ranged from 0.01 to 1.51 kg ton-wood⁻¹ for PM, from 0.01 to 2.04 kg ton-wood⁻¹ for SO_x and from 0.80 to 10.76 kg ton-wood⁻¹ for NO_x. There was a 178.7-fold difference in PM, 212.2-fold difference in SO_x, and a 13.5-fold difference in NO_x. With a calorific value of the waste wood of 18.3 MJ kg⁻¹, the air pollutant emission factors were converted to 38.7 mg MJ⁻¹ for PM, 46.9 mg MJ⁻¹ for SO_x, and 285.7 mg MJ⁻¹ for NO_x. The level of emissions of PM was lower than that found in another study (51–53 mg MJ⁻¹ for PM) and 2.98–3.86 fold of NO_x emission factor (74–96 mg MJ⁻¹ for NO_x) (Win, 2015). Based on the AP-42 emission factors, the value for PM was 0.22–0.56 lb MMbtu⁻¹ (0.511–1.301 g MJ⁻¹), the value for NO_x was 0.22–0.49 lb MMbtu⁻¹ (0.511–1.138 g MJ⁻¹), and the value for SO_x it was 0.025 lb MMbtu⁻¹ (0.058 g MJ⁻¹) (U.S. EPA, 2001).

In terms of steam generation, the emission factors were 0.21 ± 0.89 kg per ton of steam for PM, 0.29 ± 0.66 kg per ton of steam for SO_x, and 1.09 ± 2.92 kg per ton of steam for NO_x. The cumulative emission factor of 10 to 90% ranged from 0.0018 to 0.197 kg ton-steam⁻¹ for PM, from 0.0017 to 0.309 kg ton-steam⁻¹ for SO_x, and from 0.121 to 1.688 kg ton-steam⁻¹ for NO_x. There was a 111.4-fold difference for PM, a 186.1-fold difference for SO_x and a 14.0-fold difference for NO_x.

Fig. 4(a) shows the correlations among boiler capacity, fuel consumption and steam generation. The results indicate strong correlations between the boiler capacity, and both waste wood feedstock ($r^2 = 0.57$) and steam production ($r^2 = 0.64$).

Fig. 4(b) shows correlations of $r^2 = 0.41$ between the PM emission factors (based on steam production) and the level of SO_x emissions and $r^2 = 0.81$ between the PM emission factor and the level of NO_x emissions. The results indicate a strong correlation between the PM emission factors and the level of NO_x emissions in relation to steam generation.

3.4 Air Pollution Control System

The air pollution control devices used in this study are shown in Fig. 5. Boiler exhaust control systems typically include a combination of various types of equipment. The most common combination includes a cyclone, a baghouse and a scrubber (39.5% of systems), followed by the combination of a cyclone and a baghouse (29.6%), a cyclone and a scrubber (10.6%), and systems using only a baghouse (10.2%).

Fig. 4(a). Relationship of boiler capacity with wood consumption and steam generation.

Fig. 4(b). Relationships of PM emission factor with NO_x and SO_x based on steam generation.

The cyclone pressure drop was 169 ± 104 mmH₂O, and the inlet exhaust temperature was $151 \pm 86^\circ\text{C}$. The liquid-to-gas (L/G) ratio of the scrubber was 6.5 ± 6.1 L m⁻³, the median value was 4.60 L m⁻³ and the pressure drop was 131 ± 97 mmH₂O. The inlet exhaust temperature was $131 \pm 82^\circ\text{C}$. The L/G ratios of the scrubber were in the range of 0.5–3.0 L m⁻³ (Richards, 1995). Some operating conditions may increase the L/G ratios by as much as 5.35–20.0 L m⁻³ (40–150 gal (1000 scfm)⁻¹) for high efficiency or toxic mercury (U.S. EPA, 2002).

The air-to-cloth ratio of the baghouse was 1.92 ± 2.29 m min⁻¹, the median value was 1.18 m min⁻¹, and the pressure drop was 229 ± 97 mmH₂O. The inlet exhaust temperature was $143 \pm 66^\circ\text{C}$.

Fig. 5. Waste combustion boiler air pollution control system.

Table 3. Air pollutant emission concentrations for different control systems.

APCD	PM ($\mu\text{g m}^{-3}$)	SO _x (ppm)	NO _x (ppm)
Cyclone + Scrubber + Baghouse	33.2 ± 39.9	17.9 ± 24.7	132.6 ± 65.5
Cyclone + Baghouse	32.4 ± 32.3	17.4 ± 21.0	111.4 ± 49.0
Cyclone + Scrubber	49.1 ± 29.1	12.2 ± 11.4	99.6 ± 46.2
Baghouse	29.1 ± 33.1	22.0 ± 14.6	163.3 ± 59.0
Scrubber	77.6 ± 19.4	11.5 ± 12.4	110.9 ± 26.2
Cyclone	55.7 ± 34.8	17.3 ± 4.3	134.3 ± 39.0
Scrubber + Baghouse	58.8 ± 22.5	26.4 ± 4.4	144.2 ± 35.9

Generally speaking, the analysis of cyclones has shown them to have a lower control efficiency for particle sizes smaller than 5 μm , and the Venturi scrubber has proven to be effective for particles larger than 1 μm (approximately 96% efficient) (Wakelin *et al.*, 2008). In addition, a baghouse and electrical precipitation have been shown to be effective at removing particles with sizes in the submicro range (approximately 95–97% efficient) (Wakelin *et al.*, 2008).

Table 3 shows the concentrations of PM, SO_x and NO_x emissions after the air pollution control system was utilized. In the system combining a cyclone, a baghouse, and a scrubber, the average concentrations of PM, NO_x and SO_x were $33.2 \pm 39.9 \text{ mg Nm}^{-3}$, $132.6 \pm 65.5 \text{ ppm}$ (average concentration: 272.3 mg Nm^{-3}) and $17.9 \pm 24.7 \text{ ppm}$ (average concentration: 51.1 mg Nm^{-3}), respectively. For the system combining a cyclone and a baghouse, the average concentrations of PM, NO_x and SO_x were $32.4 \pm 32.3 \text{ mg Nm}^{-3}$, $111.4 \pm 49.0 \text{ ppm}$ and $17.4 \pm 21.0 \text{ ppm}$, respectively. For the baghouse system, the average concentrations of PM, NO_x and SO_x were $29.1 \pm 33.1 \text{ mg Nm}^{-3}$, $163.3 \pm 59.0 \text{ ppm}$ and $22.0 \pm 14.6 \text{ ppm}$, respectively. For the system combining a cyclone and a scrubber, the average concentrations of PM, NO_x and SO_x were $49.1 \pm 29.1 \text{ mg Nm}^{-3}$, $99.6 \pm 46.2 \text{ ppm}$ and $12.2 \pm 11.4 \text{ ppm}$, respectively.

The temperature of the flue gas, the boiler's inlet and outlet water temperatures, and the gaseous emission rates were scaled to specific feed and air flow rates when combustion and efficiencies of boiler were controlled. Throughout the entire operation, the CO and NO_x emissions from all fuels were below regulatory limits, while SO₂ emissions were insignificant because of the low sulfur content of wood. Combustion efficiencies were satisfactory, ranging between 84 and 86% (Vamvukaet *et al.*, 2020).

In relation to the PM_{2.5} removal efficiency, results indicate the PM_{2.5} concentration was $141 \pm 5.18 \text{ mg Nm}^{-3}$ for the washing tower, $81 \pm 6.74 \text{ mg Nm}^{-3}$ for the bubble-column scrubber, $78 \pm 7.85 \text{ mg Nm}^{-3}$ for the Venturi scrubber, and $10\text{--}20 \text{ mg Nm}^{-3}$ for the combined Venturi and bubble-column scrubber (Bianchini *et al.*, 2016). The results indicate that the PM concentration was $77.6 \pm 19.4 \text{ mg Nm}^{-3}$ for the system using only a scrubber, which was lower than the findings of other studies on systems incorporating a washing tower, a bubble-column scrubber, and a Venturi scrubber.

The emission concentration of NO_x was $150\text{--}195 \text{ mg Nm}^{-3}$ and that of SO₂ was $2.9\text{--}5.0 \text{ mg Nm}^{-3}$ for a medium-scale boiler at a rated power of 5.0 MW_{th} that was equipped with a multi-cyclone

followed by a baghouse filter (Cornette *et al.*, 2021). These SO_x and NO_x concentrations were higher than those found in other studies (Cornette *et al.*, 2021).

The current boiler emission standards for Taiwan of 30 mg Nm⁻³ for PM, 50 ppm for SO_x, and 100 ppm for NO_x were announced on July 1, 2020 and will be implemented on July 1, 2022. The regular testing of boilers shows emissions of 45.5% for PM, 59.8% for NO_x and 6.1% for SO_x, which are in excess of the new emission standards. Therefore, revised emission reduction and control strategies are required to address these unacceptably high levels of emissions. In order to comply with these stringent emission standards, emission reductions of 137 ton yr⁻¹ (a 30% reduction) for PM, 1690 ton yr⁻¹ (a 35% reduction) for NO_x, and 25 ton yr⁻¹ (a 7% reduction) for SO_x should be made.

According to the new emission standards, the operating conditions of the air pollution control systems on the boilers (including the frequency of filter cake removal and filter bag replacement for the bag filter, inspection and maintenance schedules, etc.) should be modified to improve the PM control efficiency. Using a bag filter can be sufficient to prevent PM emissions under the proper conditions, especially when combined with the pretreatment of the cyclone for the removal of large PM during wood boiler combustion. In this study, there was no proper treatment system for NO_x. Therefore, equipping boilers with a dedicated NO_x removal system such as selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) might make it possible to reduce NO_x emissions to fewer than 100 ppm.

The 100 industrial-sized wood combustion boilers investigated in this study operated in the range of 3 to 86.9 mg Nm⁻³ (10–90% cumulative concentrations) with an average of 36.3 ± 36.0 mg Nm⁻³. Since the average particle size of combustion particulates is fine, mechanical collectors like cyclones typically cannot achieve emission levels lower than 30 mg Nm⁻³ for wood combustion (using a grate or suspension burners). The cost of the air pollution control equipment (an electrostatic precipitator, ESP, or a fabric filter) may exceed the cost of the combustor for smaller combustion boiler units. In this study, the waste wood combustion boilers were equipped with a combined air pollution control device for PM emissions control. However, the concentration of PM emissions was still high. The results suggest that regularly inspecting and maintaining the devices, employing experienced operators, and optimizing the operating conditions could significantly improve the combustion efficiency of the boilers and the efficiency of the air pollution control system.

Therefore, regulating the air-fuel ratio, maintaining good combustion conditions, and using high quality wood low moisture content are methods that have been proposed to mitigate the impacts of the direct exposure of an urban population to the pollution produced by wood combustion boilers (Sarigiannis *et al.*, 2015). For example, it costs 2.5 times as much as a boiler at 1.5 MW, while the costs of the air pollution control systems and the combustors were close at 5.5 MW (Wakelin *et al.*, 2008). In this study, approximately 65% of the boilers were larger than 5.5 MW. This suggests that boilers are more sensitive to increasing the number of air pollution control devices required and the cost of pollution reduction. This accounts for 50% or more of the associated capital costs compared to larger-sized boilers.

The wood used in this study was obtained from construction and/or demolition waste, which may have affected the fuel characteristics and made it impossible to stay under the low emission limits.

High-performance flue gas cleaning equipment, ESPs, and fabric filters seem inappropriate for use with smaller applications. Current technologies are available to reduce particulate emissions to extremely low levels. However, the optimization and maintenance of the boiler combustion system and the air pollution control system are crucial to being able to achieve low emission targets. The significance of employing experienced operators to ensure good control and to carry out proactive maintenance duties becomes more important as allowable emission limits decrease. Conversely, smaller installations become more difficult to adapt under these conditions because of escalating costs.

4 CONCLUSIONS

The most common sources of combustible waste wood are waste pallets and scrap packaging materials discarded by factories, used decorative materials, and pruned tree branches. Most

waste wood is consumed by food and animal feed manufacturing (32%), manufacturing of wood and bamboo products (18%), agriculture and animal husbandry (12%), and manufacturing of pulp, paper, and paper products (9%). In this study, we examined waste wood combustion boilers used for steam generation, with particular attention placed on the functioning of the air pollution control system. The results showed that air pollution emissions were high, with an average PM concentration of $36.3 \pm 36.0 \text{ mg Nm}^{-3}$, a SO_x concentration of $17.4 \pm 20.8 \text{ ppm}$, and a NO_x concentration of $126.4 \pm 60.1 \text{ ppm}$. A portion of the boiler emissions (45.5% of PM emissions, 59.8% of NO_x , and 6.1% of SO_x) exceed the new emission standards (PM: 30 mg Nm^{-3} , NO_x : 100 ppm, and SO_x : 50 ppm). NO_x control devices such as SCR and SNCR are necessary to reduce NO_x emissions to below 100 ppm. In addition, the cyclone and the baghouse system appear to reduce PM emissions to less than 30 mg Nm^{-3} under optimal operating conditions. Otherwise, it would be necessary to use more effective PM removal devices to reduce emissions. Based on our fuel consumption data, the air pollutant emission factors were $0.71 \pm 1.44 \text{ kg}$ per ton of wood for PM, $0.86 \pm 1.47 \text{ kg}$ per ton of wood for SO_x , and $5.24 \pm 9.56 \text{ kg}$ per ton of wood for NO_x . In July 2022, new emission standards for boilers will be implemented, and emission reductions of at least 30% for PM, 35% for NO_x and 7% for SO_2 will be required.

ACKNOWLEDGEMENTS

The authors express their sincere thanks to the Ministry of Science and Technology, Executive Yuan, Republic of China (Taiwan) for research funding (MOST 109-2622-E-224-014).

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