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# Co-Combustion of Blends of Coal and Underutilised Biomass Residues for Environmental Friendly Electrical Energy Production

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**Citation:** Kanwal, F.; Ahmed, A.; Jamil, F.; Rafiq, S.; Ayub, H.M.U.; Ghauri, M.; Khurram, M.S.; Munir, S.; Inayat, A.; Abu Bakar, M.S.; et al. Co-Combustion of Blends of Coal and Underutilised Biomass Residues for Environmental Friendly Electrical Energy Production. *Sustainability* **2021**, *13*, 4881. https://doi.org/10.3390/su13094881

Academic Editor: Adam Smoliński

Received: 7 March 2021
Accepted: 21 April 2021
Published: 27 April 2021



**Abstract:** This study investigated the co-combustion of the blends of coal and biomass residues from poplar sawdust, rice husk, pine nut shells, and sunflower residues for ecofriendly energy production. Proximate and ultimate analyses and calorific values of the coal and biomass residues were also carried out to evaluate the properties of the coal and biomass residues. The volatile matter in coal was reported as 43.38 wt% and ranged from 56.76 wt% to 80.95 wt% in the biomass residues. The ultimate analysis reported the carbon and sulfur content of coal as 68.7 wt% and 5.5 wt%, respectively. The coal and biomass blends were prepared using different ratios on the thermal basis of coal and biomass given as 100:0, 90:10, 80:20, 70:30, 60:40, and 50:50 by weight percentage. The consequent stoichiometric air requirements for all the blends were also calculated. The results revealed that the combustion of 60:40 of coal and sunflower residue blend was the most efficient blend, resulting in less emission of $NO_x$, $SO_x$, and $CO_2$ in the flue gas compared to the combustion of pure coal. The study revealed a great perspective of the selected biomass residues to blend with coal for environmentally friendly and sustainable energy production.

**Keywords:** eco-friendly combustion; coal; biomass residues; biomass blending ratios; combustion efficiency

## 1. Introduction

The global economy and energy consumption have been rapidly increasing over the last century due to the increase in industrialization, which increases dependence on fossil energy sources and causes serious environmental pollution [1–4]. Energy is vital to the socio-economic development and modern life [5,6]. Without reliable and affordable sources of electricity, it is difficult to progress in the modern era [7–9]. Currently, coal-fired power plants generate almost 41% of the total required global electricity [10]. The combustion of coal is one of the most substantial causes of greenhouse gases (GHGs) emissions into the atmosphere. During combustion, the sulfur and nitrogen contents in coal are oxidized to $SO_x$ and $NO_x$, which cause acid rain, depletion of the ozone layer, photochemical smog, and several adverse health impacts [11,12]. Along with the hazardous of GHGs, the releases of fine particulate matter from the combustion of coal is also a challenge that needs to be addressed [13]. Many solutions, such as improving the energy efficiency of the current running systems and use of renewable resources to contribute for energy needs can help to mitigate the aforementioned challenges [14,15].

Stakeholders are contemplating sustainable and renewable techniques and technologies that can be utilized to protect the environment. The European Union has fixed a mandatory target of getting 20% share of renewable resources in the energy mix by 2020 [16]. Among various available renewable resources, such as solar, hydro, and geothermal; biomass presents a viable substitute owing to its availability and capability of meeting diverse energy needs, including electricity generation, vehicle fueling, and domestic heating [17,18]. Biomass is considered to be the fourth largest fuel after coal, oil, and natural gas, and compared to fossil fuels, biomass is termed as carbon-neutral [19,20]. It also contains fewer sulfur and nitrogen components. Biomass is easily accessible worldwide, and people in many underdeveloped, developing, and developed countries consume biomass for energy production. Moreover, the utilization of renewable resources as fuels is required to combat the increasing environmental pollution due to the combustion of fossil fuels [21,22].

Co-firing of biomass with coal provides a good alternative to minimize the environmental pollution, as this can reduce the $NO_x$, $SO_2$ and $CO_2$ emissions and helps in consuming the biomass resources for energy production. The other possible way to reduce the atmospheric pollution caused by the combustion of coal is via coal cleaning and installation of low-emission appliances, but these methods are expensive. The co-combustion of coal and wheat straw in power plants has been considered as a possible way to reduce $CO_2$ emissions [23]. The decrease in $NO_x$ and $SO_x$ was measured while increasing the fraction of straw in the fuel. The net reduction in NO and $SO_2$ emissions were observed for blends of up to 20% straw (thermal basis) with Canadian coal [23]. Another study reported the co-combustion of Polish bituminous coal, lump wood, pine sawdust, and briquettes [24]. Online monitoring of the flue gas composition was proceeded via infrared analysis for CO, $CO_2$, $SO_2$, and NO. The $NO_x$ and $SO_2$ levels were significantly lower for biomass than for coal, and the levels of CO were also reduced [24]. The co-combustion of Duki coal with bagasse showed a decrease in CO and $NO_x$ emissions with increasing the blending ratio [25]. However, $SO_2$ emission levels were increased as the blending ratio was increased. A blending ratio of 40% was found to be optimum, because it afforded the minimum emissions of $NO_x$, $SO_2$, and CO [25].

The co-combustion of biomass residues with coal has gained more attention recently owing to its cost-effectiveness, value-added benefits, and sustainable nature [26–29]. The co-combustion of coal and biomass can be implemented in existing facilities by considering a few minor modifications. This method is cost-effective, and it reduces the emissions of net $CO_2$ and other hazardous pollutants to the environment. This study investigated the effects of co-combustion the coal with underutilised lignocellulosic biomass residues on flue gas emissions. Moreover, the combustion efficiencies and overall effectiveness of the blends for cleaner combustion were also studied. The biomass residues included poplar sawdust, rice husk, pine nutshells, and sunflower residues, which are abundantly available globally and are typically underutilized, and to the best of the authors knowledge, the selected biomass residues have not been previously studied for blending with coal in the proposed scheme for efficient and eco-friendly energy production.

## 2. Materials and Methodology

### 2.1. Feedstock Selection and Sample Preparation

The biomass samples were collected from the residue stocks of pine nut shells, sunflower leftovers, rice husk, and poplar sawdust. The coal samples were obtained from coal mines located in Lakhra district, Sindh, Pakistan. Both the coal and biomass samples were crushed separately using a jaw crusher and were grounded in a disc pulverizer to get sieved particles passing through the size-60 mesh number.

### 2.2. Analysis of Coal and Biomass

The proximate analyses of the coal and the biomass samples were carried out to determine the moisture, volatile matter, ash content, and fixed carbon following the ASTM standard methods ASTM D3175-07, ASTM 3174-04, and ASTM D-3172-13, respectively [30–32]. Ultimate analysis was carried out to find the elemental chemical constituents such as carbon, hydrogen, nitrogen, and sulfur in the samples used, while the oxygen content was measured by calculating the difference. The carbon and sulfur contents in the samples were monitored using a carbon/sulfur analyzer (Model no Leco SC-144 DR), and the nitrogen content was measured using Flash EA 1112 Series elemental analyzer from CE Instruments, Thermo-Quest. The gross calorific values (GCVs) of the samples were determined using a bomb calorimeter following the ASTM method ASTM-D 5865-13 [33].

### 2.3. Blending of Coal and Biomass on a Thermal Basis

To study the co-combustion of coal and biomass samples, the blends were prepared using different biomass blending ratios on a thermal basis of coal:biomass (wt%) given as 100:0, 90:10, 80:20, 70:30, 60:40, and 50:50, as mentioned in Table 1. The co-combustion was studied in a total oxidative environment. This reaction was continuous; thus, less conversion occurred due to less residence time. For complete burning, an excess ratio of air/fuel was provided throughout the co-combustion. Stoichiometric air was also calculated for the co-combustion of coal and biomass, as shown in Table 1.

**Table 1.** Blending ratios for coal and biomass used along with stoichiometric air requirement for each biomass blending ratio (BBR).

| Coal | Biomass | Coal and Poplar Sawdust (lit/min) | Coal and Rice Husk (lit/min) | Coal and Pine Nut Shell BBR (lit/min) | Coal and Sunflower Leftovers BBR (lit/min) |
|---|---|---|---|---|---|
| | | 1.44 (4.52:0) | 1.44 (4.52:0) | 1.44 (4.52:0) | 1.44 (4.52:0) |
| 90 | 10 | 1.34 (4.07:0.92) | 1.38 (4.07:0.76) | 1.37 (4.07:0.6) | 1.34 (4.07:0.83) |
| 80 | 20 | 1.31 (3.61:1.84) | 1.34 (3.61:1.53) | 1.33 (3.61:1.19) | 1.28 (3.61:1.66) |
| 70 | 30 | 1.27 (3.16:2.77) | 1.31 (3.16:2.29) | 1.30 (3.16:1.79) | 1.22 (3.16:2.49) |
| 60 | 40 | 1.22 (2.71:3.69) | 1.29 (2.71:3.06) | 1.26 (2.71:2.38) | 1.15 (2.71:3.32) |
| 50 | 50 | 1.16 (2.26:4.61) | 1.26 (2.26:4.61) | 1.23 (2.26:2.98) | 1.10 (2.26:4.14) |

### 2.4. Combustion and Flue Gas Emissions

The co-combustion of samples was studied in a tube furnace. The flue gases from the combustion of coal and different coal–biomass blends that were prepared by mixing in accordance with the thermal basis of parent coal and biomasses were analyzed. The tube furnace was connected to an air compressor and had a rotameter to control and maintain the specified flow rate of air during the combustion. A portable flue gas analyzer (model Teledyne PEM 9002) was used to monitor the produced $NO_x$, $CO_2$, $O_2$, and $SO_2$. A precisely measured weight of 1 g sample of each blend was placed in the tube furnace at an initial temperature of 100 °C. The probe of the flue gas analyzer was inserted into the exit of the tube furnace. The readings of $NO_x$, $CO_2$, $O_2$, $SO_2$, and CO emissions were noted down after the temperature intervals of 50 °C and continued until the temperature reached 950 °C for each experimental run. After completion of the co-combustion, the blend residue was left in the tube furnace for 1 h to allow the complete conversion of biomass to ash. The ash was then analyzed to determine the contents of carbon and sulfur using the carbon/sulfur analyzer. The ultimate analysis of ash was used to estimate the unburned carbon in the ash and calculate the combustion efficiency of the blends.

## 3. Results and Discussion

### 3.1. Proximate and Ultimate Analysis

The characteristics of feedstock coal and biomass samples were assessed by determining the calorific value and performing proximate and ultimate analyses, as shown in Table 2. The proximate analysis indicated that the moisture content and amount of fixed carbon in coal were higher than in the biomass residues. The percentage of the volatile matter was higher in the biomass samples as compared to coal, which indicated that the biomass residues were more combustible than pure coal. The results of the ash content in the biomass and coal samples were random. The ultimate analysis is helpful in estimating the air requirements for the combustion and co-combustion of the fuels. Carbon and sulfur were the main targets in this study because sulfur causes slagging and corrosion, as well as the as $SO_x$ emissions during the combustion. The GCV of coal was reported to be higher than that of the biomass residues, which was attributed to the higher carbon content in coal, and it could be of great advantage in energy production by increasing the GCV of the blended fuels.

**Table 2.** Thermochemical properties of the coal and biomass residues.

| | **Proximate Analysis** | | | | | | **Ultimate Analysis** | | **GCV** |
|---|---|---|---|---|---|---|---|---|---|
| **Samples** | **Moisture (wt%)** | **Volatile Matter (wt%)** | **Ash Content (wt%)** | *** Fixed Carbon (wt%)** | **Carbon (wt%)** | **Sulphur (wt%)** | **Nitrogen (wt%)** | *** Others (H and O) (wt%)** | **(Kcal/Kg)** |
| Poplar Sawdust | 4.76 | 80.95 | 4.72 | 9.57 | 36.30 | 0.32 | 0.27 | 63.11 | 3061 |
| Rice Husk | 5.40 | 58.46 | 18.00 | 18.14 | 48.80 | 0.31 | 0.35 | 50.45 | 3625 |
| Pine Nut Shell | 5.97 | 56.76 | 5.61 | 31.66 | 42.80 | 0.42 | 0.31 | 56.47 | 4620 |
| Sunflower leftovers | 3.86 | 71.84 | 17.64 | 6.66 | 30.10 | 0.31 | 0.38 | 68.79 | 3281 |
| Coal | 15.00 | 43.38 | 7.02 | 34.60 | 68.70 | 5.50 | 2.56 | 23.44 | 5587 |

* Calculated by the difference.

### 3.2. Flue Gas Emissions

The flue gases released from the co-combustion of samples were balanced at a rate of 6% $O_2$ by applying the correlation stated by Munir et al. reported elsewhere and given in Equation (1) [16].

$$SO_2 \text{ @ } 6\%\ O_2 = (20.9 - 6\%)/(20.9 - O_2\%) \times SO_2 \quad (1)$$

The co-firing of biomass and coal reduces the $CO_2$ and $SO_2$ emissions, may reduce the $NO_x$ emissions, and represents a near-term, low-risk, low-cost, and sustainable energy development. Different gases are emitted in flue gases such as $NO_x$, $SO_x$, CO, $CO_2$, and $O_2$, which indicate the consumption of $O_2$ in the oxidation reactions during the combustion, which resulted in the breakdown of carbon bonds and production of carbon oxides. The sulfur content in coal and biomass reacts with $O_2$ to form sulfur oxides, mostly $SO_2$, while the nitrogen content mostly reacts with $O_2$ to form $NO_x$ (NO, $NO_2$). During the initial stage of combustion, the $O_2$ levels were maximum but started to drop at 350 °C, which increased the concentration of $CO_2$, as shown in Figure 1a.

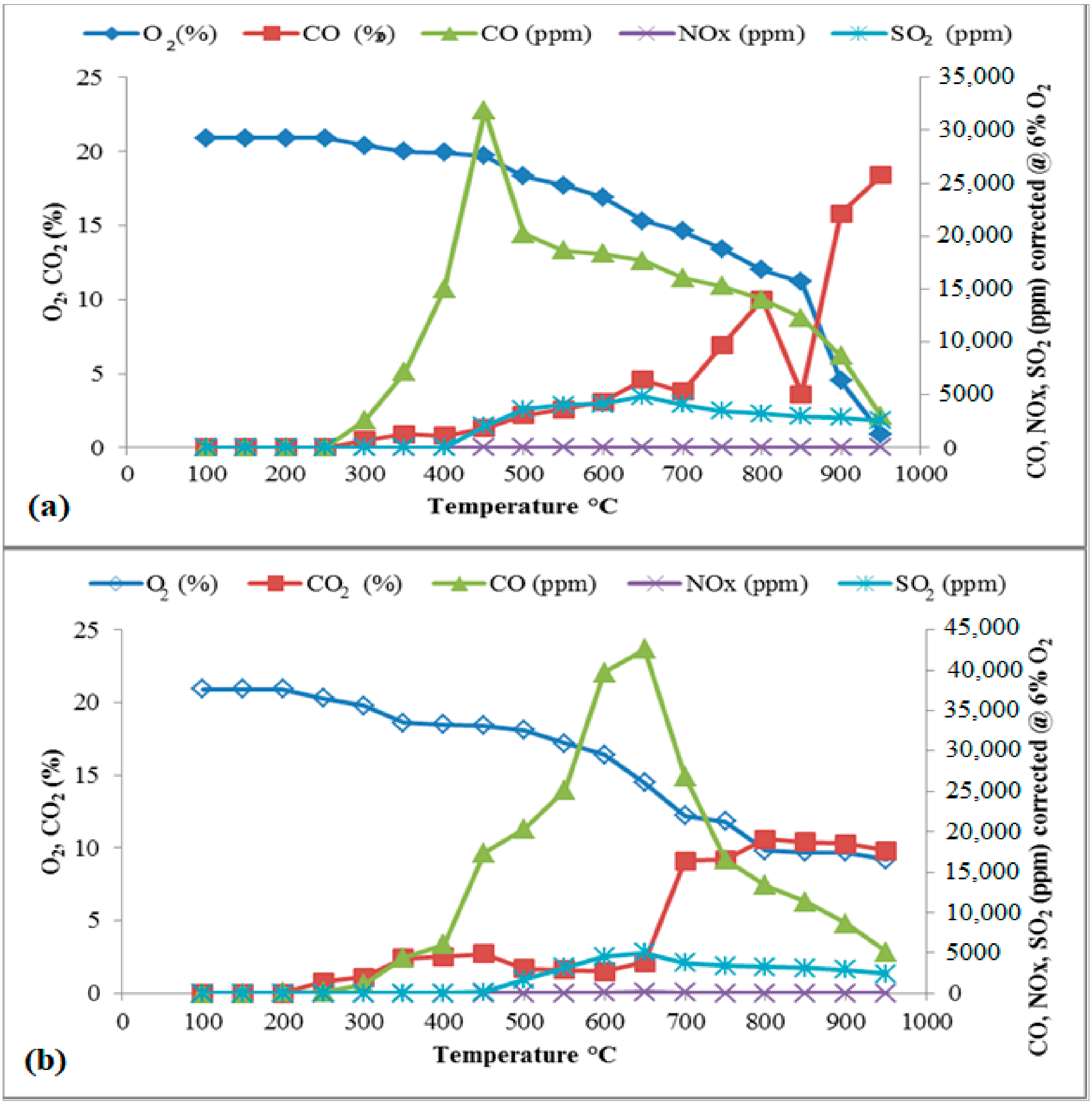


**Figure 1.** Emission profiles from the combustion of (**a**) 100% coal, (**b**) 90% coal and 10% poplar saw-dust.

At 450 °C, the CO emissions level was found to be at its peak with a value of 31,836 (±5%) ppm. When CO emissions were high, the $CO_2$ emissions were low. This could be attributed to the devolatilization of coal. After this step, the concentration of CO started to decrease, and that of $CO_2$ increased, which could be due to the start of char oxidation. Coal and biomass residues were co-combusted up to 950 °C. Therefore, fuel $NO_x$ emissions were released, but there were no thermal $NO_x$ emissions generated because the thermal $NO_x$ is generated at a temperature of approximately 1400 °C and above [34,35]. The maximum level of $NO_x$ emissions was reported as 34 ppm (±5%) at 700 °C. The sulfur content was higher in coal, as shown in Table 2, which resulted in 7452 (±5%) ppm emissions of $SO_2$ from the combustion of coal. At 950 °C, the $CO_2$ emissions were maximum, because the volatile matter of blends was fully combusted but fixed carbon was still burning.

The emissions analysis from the co-combustion of coal and poplar sawdust are shown in Figures 1–3. The co-combustion of coal and poplar sawdust blend (90:10) produced a maximum CO concentration of 42,571 (±5%) ppm at 650 °C. When the CO level was high, the $CO_2$ level was low, but the $O_2$ level was high. When the CO level started to decrease, the $CO_2$ level started to increase. This gradual change in CO, $CO_2$, and $O_2$ can be observed in Figure 1b. The maximum $NO_x$ emission observed was 138 (±5%) ppm at 650 °C, whereas the maximum measured value of $SO_2$ was 5033 (±5%) ppm at 650 °C.

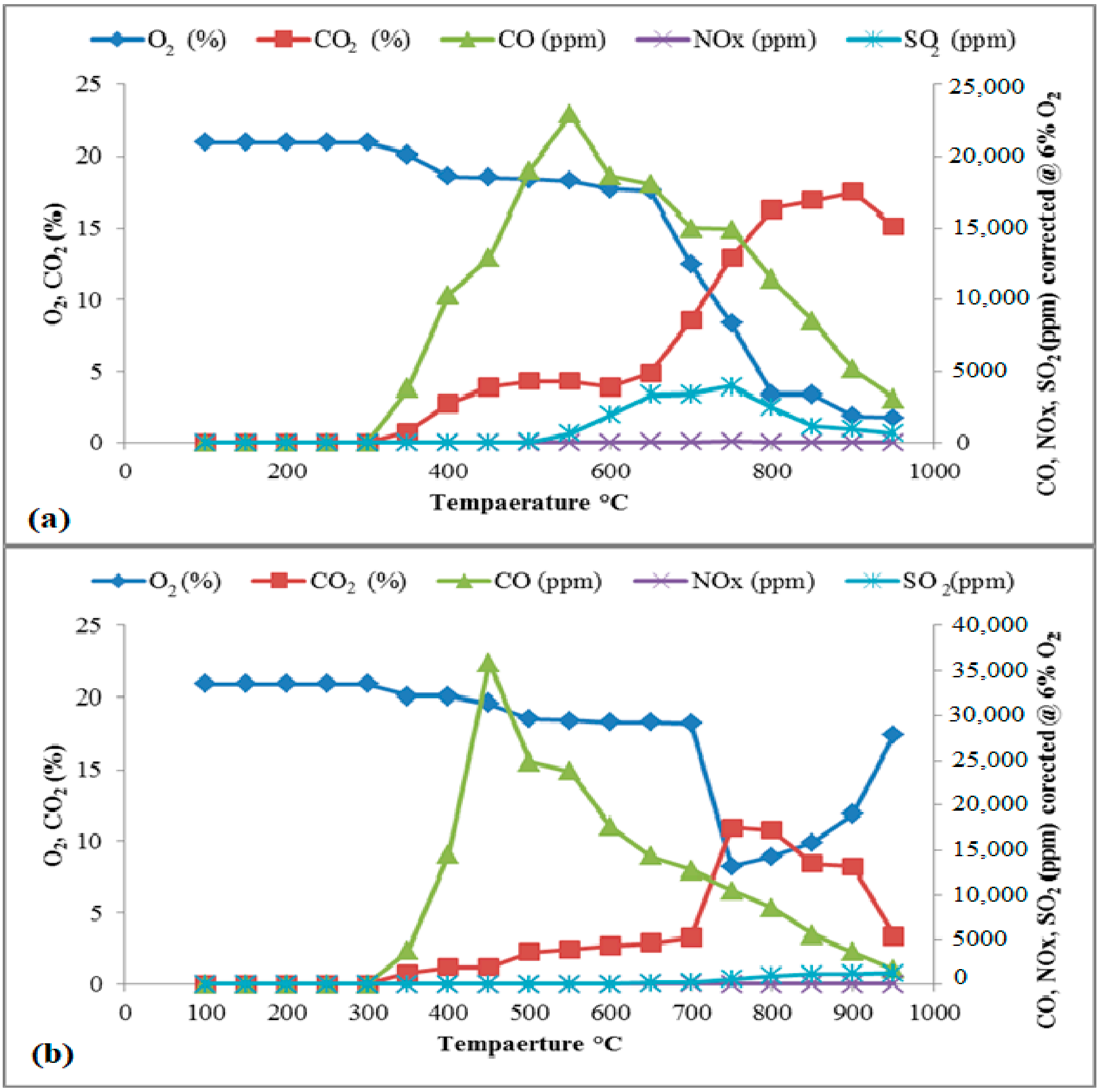


**Figure 2.** Emission profiles from the combustion of (**a**) 80% coal and 20% poplar sawdust, (**b**) 70% coal and 30% poplar sawdust.

The 80% coal and 20% poplar sawdust blend produced a maximum CO level of 22,920 (±5%) ppm at 550 °C. The maximum $NO_x$ level was reported as 95 (±5%) ppm at 750 °C, and the maximum $SO_2$ level was reported as 3948 (±5%) ppm at 750 °C (Figure 2a). When 70% coal and 30% blend of poplar sawdust was co-combusted, a sudden increase in the concentration of CO was observed. At 450 °C, the CO concentration reached its maximum value of 35,846 (±5%) ppm, and it gradually decreased with an increase in temperature. When the CO level was high, the $CO_2$ and $O_2$ levels were 1.3% and 19.6%, respectively. These readings revealed the devolatilization and char oxidation of the coal and biomass blends, as shown in Figure 2b. At 700 °C, the maximum $NO_x$ level was reported as 77 (±5%) ppm, whereas that of $SO_2$ was reported as 1247 (±5%) ppm at 950 °C.

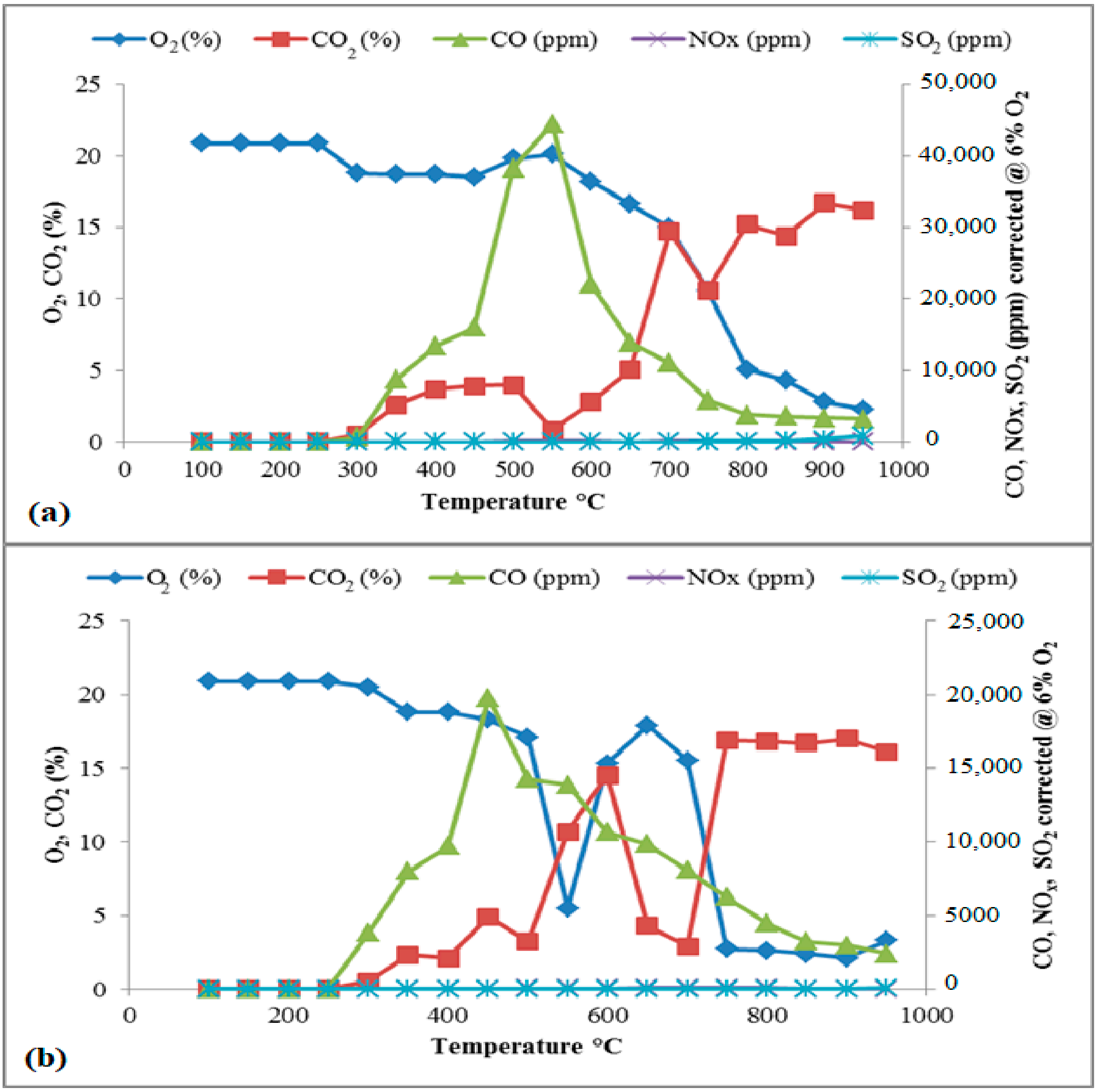


**Figure 3.** Emission profiles from the combustion of (**a**) 60% coal and 40% poplar sawdust, (**b**) 50% coal and 50% poplar sawdust.

Moreover, when 60% coal and 40% poplar sawdust blend was studied, the level of CO suddenly increased to 44,500 (±5%) ppm at 550 °C. At this level, the percentage of $O_2$ decreased from 20.9% to 18.1%, and a slight increase in the $CO_2$ level was observed. The maximum $NO_x$ level was 47 (±5%) ppm at 700 °C, whereas the maximum $SO_2$ was 871 (±5%) ppm, as shown in Figure 3a. When the 50% coal and 50% poplar sawdust blend was co-combusted, the maximum CO emission was reported as 19,788 (±5%) ppm at 450 °C, the $O_2$ level was 18.3%, and $CO_2$ was 2.6%. The maximum $NO_x$ concentration was 89 (±5%) ppm at 650 °C and the maximum $SO_2$ concentration was found to be 66 (±5%) ppm at 950 °C (Figure 3b).

The emissions analysis from the co-combustion of coal and rice husk are shown in Figures 4–6. The co-combustion of 90:10 coal and rice husk biomass revealed a maximum CO level of 10,620 (±5%) ppm at 400 °C. When the CO level was high, the $CO_2$ level was low, but the $O_2$ level was high. When CO emission level started to decrease, the $CO_2$ level started to increase. This gradual change in CO, $CO_2$, and $O_2$ can be seen in Figure 4b.

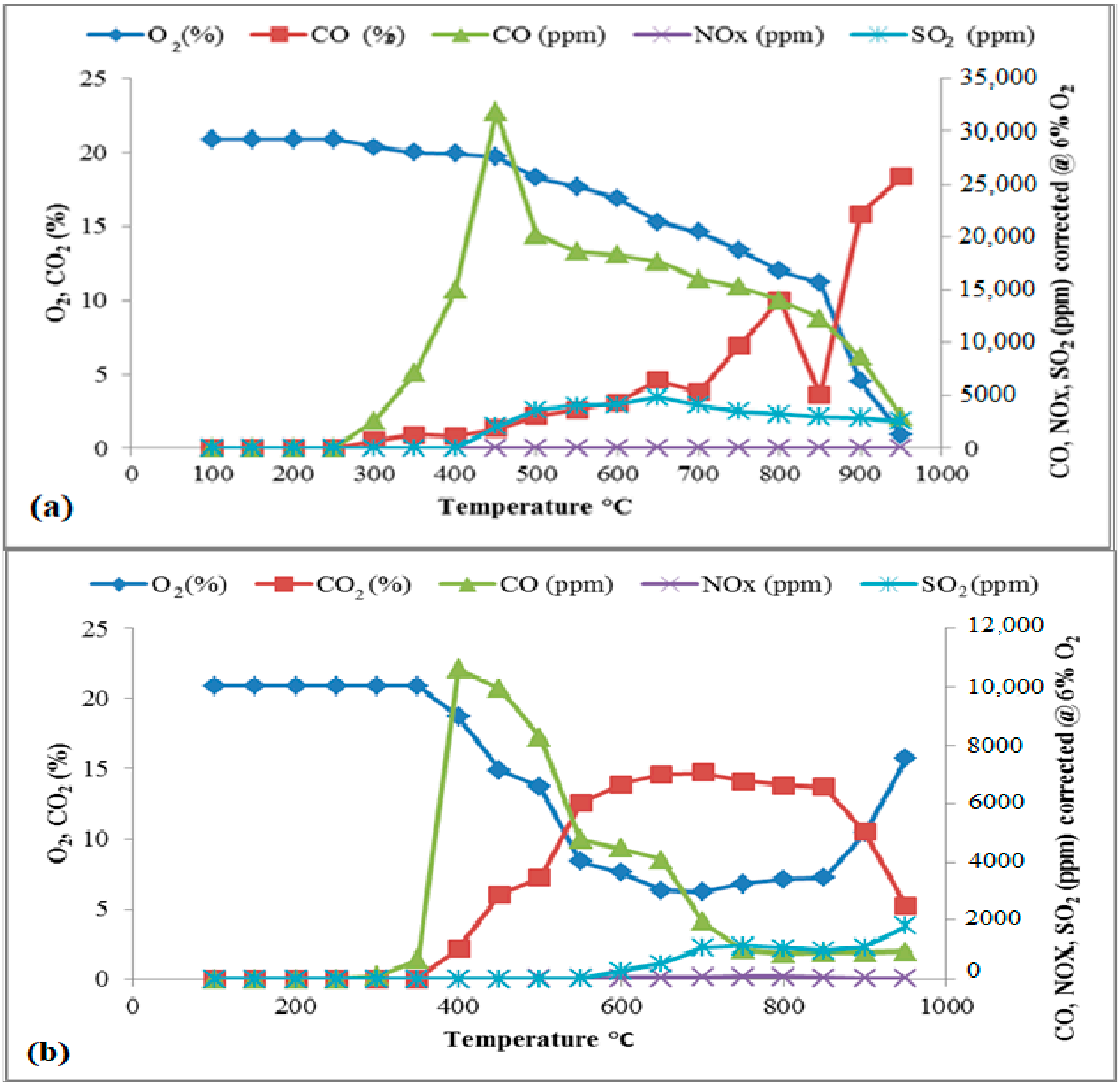


**Figure 4.** Emission profiles from the combustion of (**a**) 100% coal, (**b**) 90% coal and 10% rice husk.

The maximum $NO_x$ emission level was reported as 70 (±5%) ppm at 750 °C, while the maximum concentration of $SO_2$ was reported as 1117 (±5%) ppm at 750 °C. Furthermore, for the 80% of coal and 20% rice husk co-combustion, a sudden increase in the CO emission level was observed, and at 600 °C, it reached a maximum value of 13,244 (±5%) ppm and gradually decreased with an increase in the temperature. At 750 °C, the maximum $NO_x$ level was reported as 32 (±5%) ppm, whereas the emission of $SO_2$ was reported as 611 (±5%) ppm, as shown in Figure 5a.

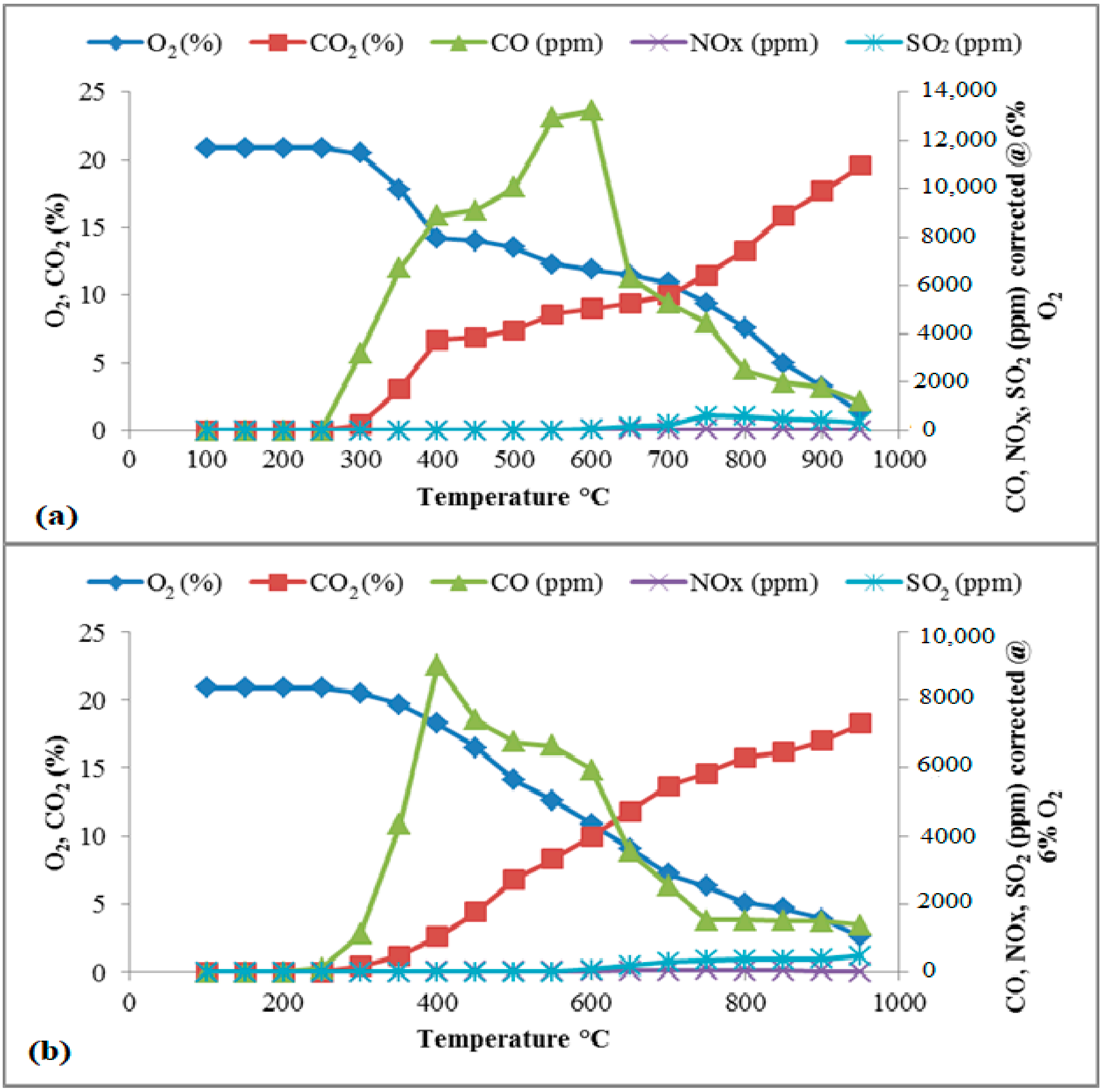


**Figure 5.** Emission profiles from the combustion of (**a**) 80% coal and 20% rice husk, (**b**) 70% coal and 30% rice husk.

The co-combustion of 70% coal and 30% rice husk generated 9030 (±5%) ppm of CO at 400 °C. The maximum amount of $NO_x$ produced was reported as 51 (±5%) ppm at 750 °C, whereas the measured $SO_2$ was 472 (±5%) ppm at 950 °C, as shown in Figure 5b.

When 60% coal and 40% rice husk blend was combusted, the amount of CO emissions was 11,480 (±5%) ppm at 400 °C. At this level, the amount of $O_2$ decreased from 20.9% to 15.5%, and a slight increase in the $CO_2$ level was observed, as shown in Figure 6a. Moreover, the maximum amount of $NO_x$ was 90 (±5%) ppm at 650 °C, whereas the maximum $SO_2$ emissions were 409 (±5%) ppm at 750 °C. When the 50% coal and 50% rice husk blend was combusted, the CO emissions peaked at 19,240 (±5%) ppm at 500 °C. In this case, the maximum $SO_2$ released was 928 (±5%) ppm at 750 °C, whereas the maximum $NO_x$ was 928 (±5%) ppm at 750 °C, as shown in Figure 6b.

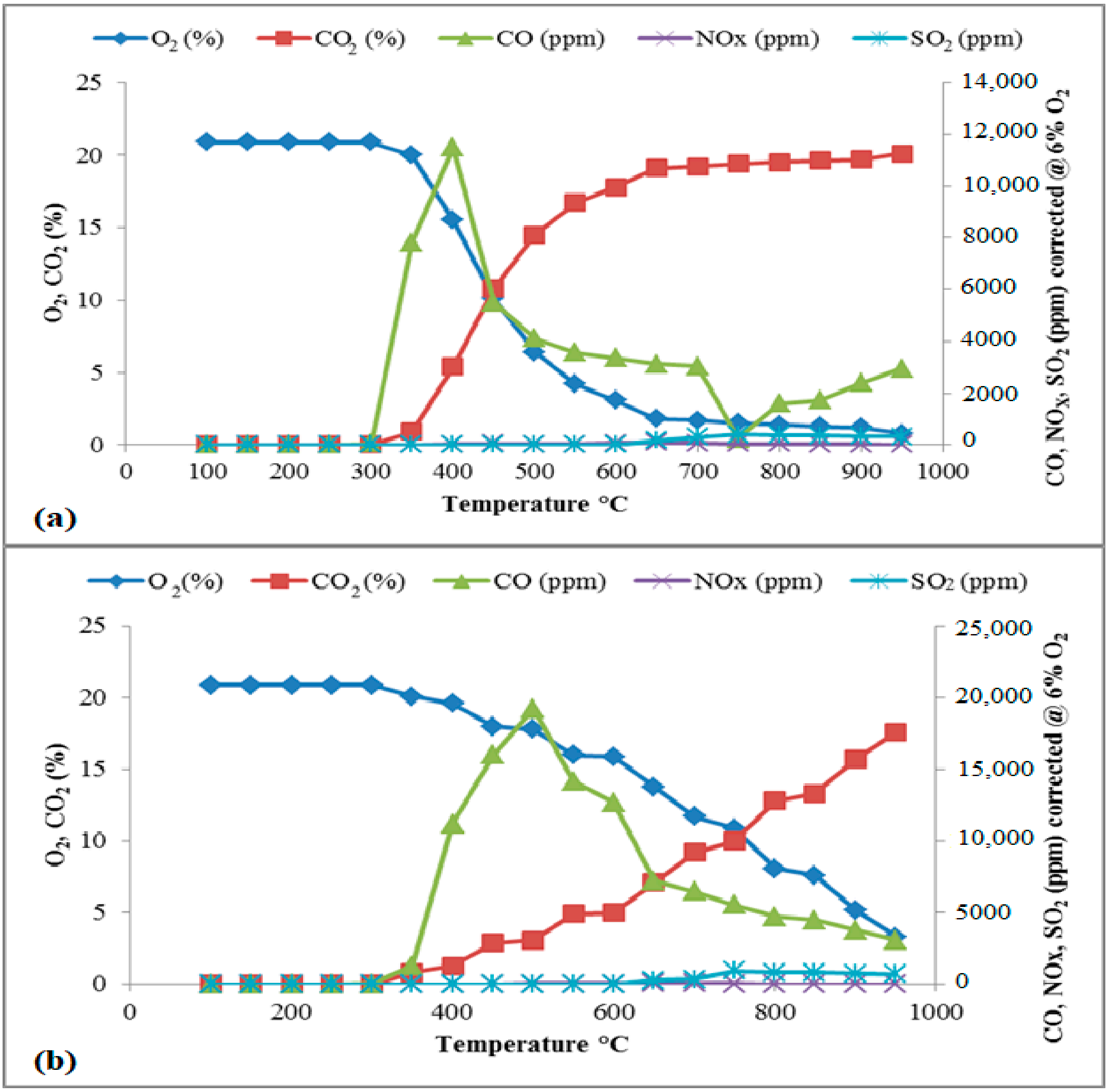


**Figure 6.** Gaseous profiles from the combustion of (**a**) 60% coal and 40% rice husk, (**b**) 50% coal and 50% rice husk.

The emissions analysis from the co-combustion of coal and sunflower are shown in Figures 7–9. When 90% coal and 10% sunflower residue blend was used, the maximum amount of CO emission was reported as 9773 (±5%) ppm at 400 °C with $O_2$ was 18.2%, and $CO_2$ was 2.6%. The maximum amount of $NO_x$ was reported as 22 (±5%) ppm at 800 °C, whereas the maximum $SO_2$ emissions were 942 (±5%) ppm at 700 °C, as shown in Figure 7b.

The use of 80% coal and 20% sunflower leftover exhibited a sudden increase in CO emissions to 13,860 (±5%) ppm at 450 °C, which was then gradually decreased by an increase in the temperature. When the CO emissions level was high, $CO_2$ was only 4.3% and $O_2$ was 16.6%, which revealed the devolatilization and char oxidation reaction of the coal and biomass blend, as shown in Figure 8a.

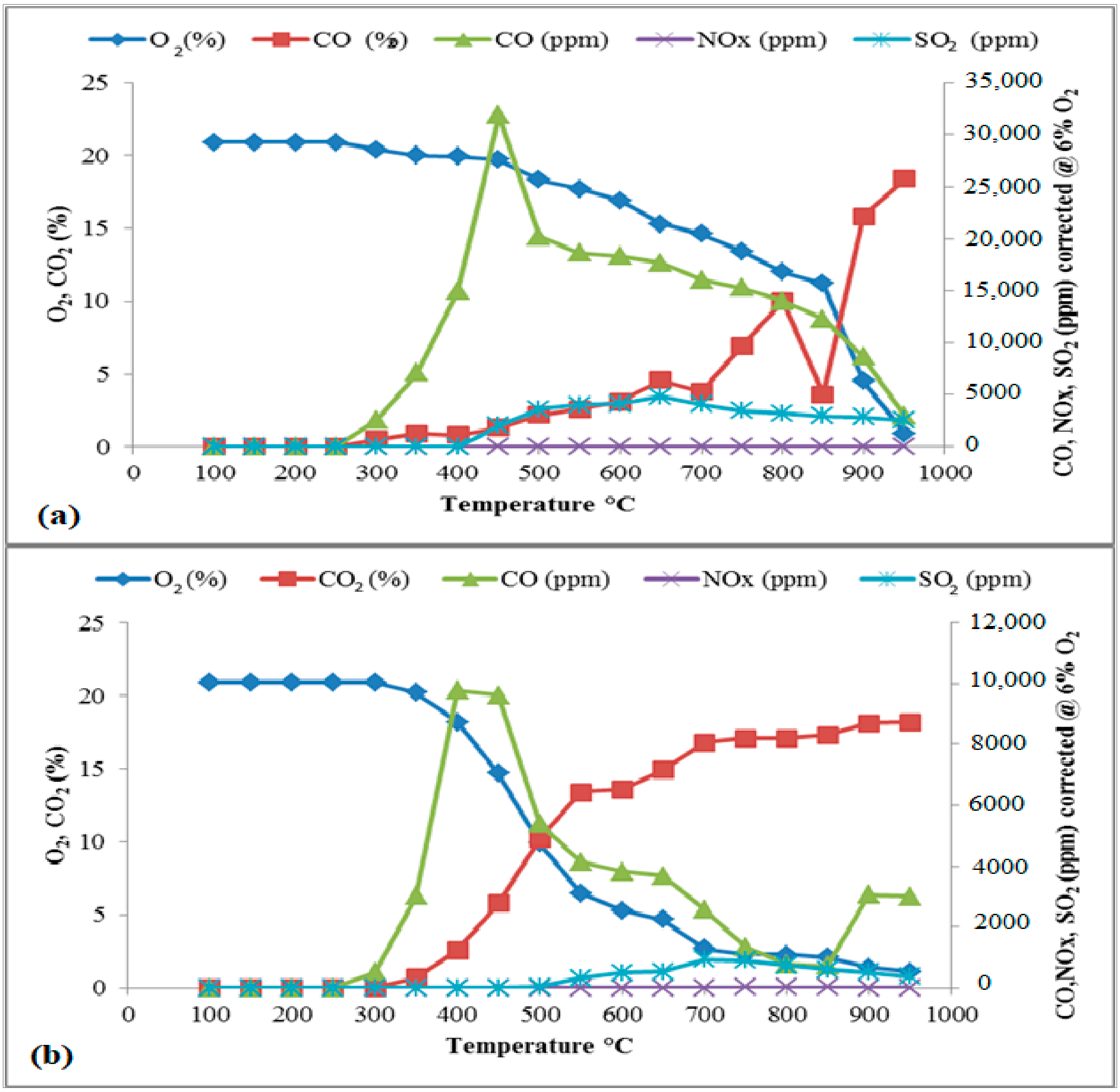


**Figure 7.** Emission profiles from the combustion of (**a**) 100% coal, (**b**) 90% coal and 10% sun-flower residues.

At 750 °C, the maximum amount of $NO_x$ was 36 (±5%) ppm, whereas that of $SO_2$ was 775 (±5%) ppm at 900 °C. Furthermore, when 70% coal and 30% sunflower residue were combusted, the amount of CO suddenly increased to 15,618 (±5%) ppm at 400 °C. At this level, the amount of $O_2$ decreased from 20.9% to 19.8%, and a minor increase in $CO_2$ was observed, as shown in Figure 8b. The maximum amount of $NO_x$ was 18 (±5%) ppm at 700 °C, whereas zero $SO_2$ emissions were detected in this case.

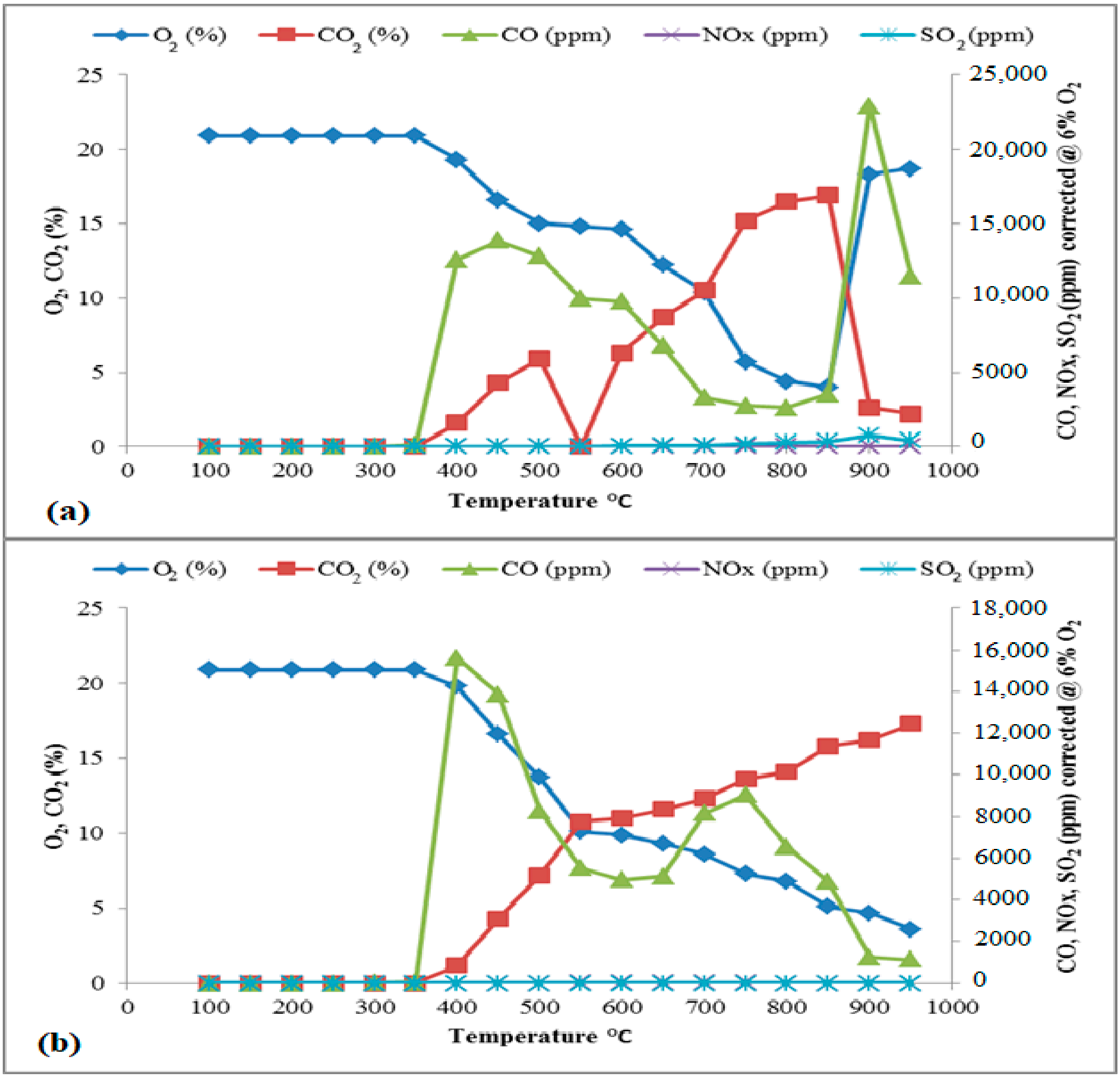


**Figure 8.** Emission profiles from the combustion of (**a**) 80% coal and 20% sunflower leftovers, (**b**) 70% coal and 30% sunflower residues.

The co-combustion of 60% coal and 40% sunflower resdues produced a maximum CO level of 8638 (±5%) ppm at 400 °C. When the CO level was high, the $CO_2$ level was low, but the $O_2$ level was high as well. When the CO level started to decrease, the $CO_2$ level started to increase, and this gradual change in CO, $CO_2$, and $O_2$ can be seen in Figure 9a. The maximum $NO_x$ emissions were 48 (±5%) ppm at 700 °C, and the maximum amount of $SO_2$ was 28 (±5%) ppm at 950 °C. When the 50% coal and 50% sunflower leftover blend was combusted, the peak value of CO was 10,643 (±5%) ppm at 350 °C. In this case, no $SO_2$ was observed, whereas the maximum amount of $NO_x$ was 50 (±5%) ppm at 600 °C, as shown in Figure 9b.

The emission analyses of the co-combustion of coal and pine nut shells are given in Figures 10–12. A blend of 90% coal and 10% pine nut shells produced a maximum CO level of 16,865 (±5%) ppm at 400 °C.

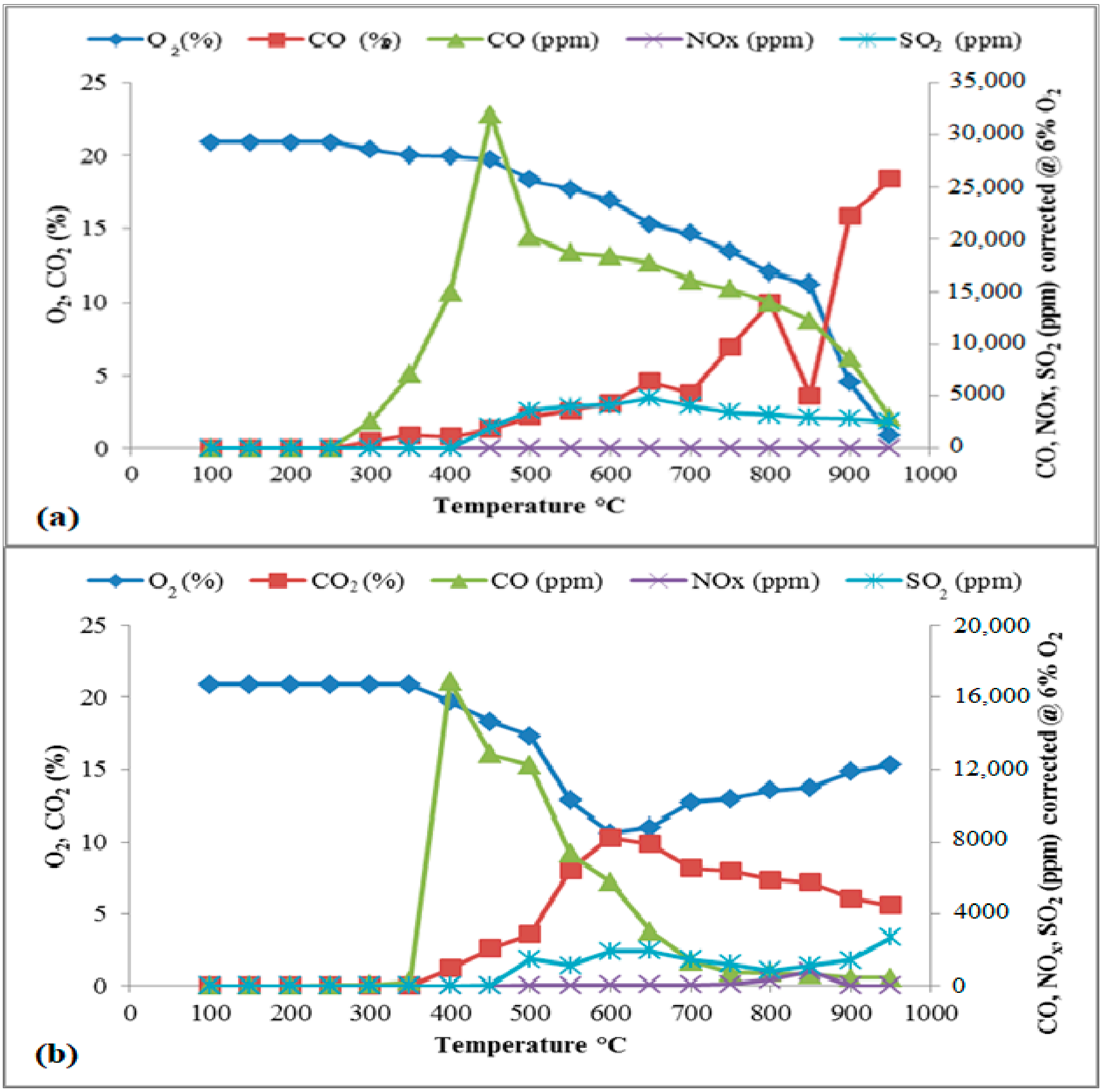


**Figure 9.** Emission profiles from the combustion of (**a**) 100% coal combustion, (**b**) 90% coal and 10% pine nut shell.

Meanwhile, when the CO and $O_2$ levels were high, the $CO_2$ level was low. As the CO level was decreasing, the $CO_2$ level started to increase, and this gradual change in CO, $CO_2$, and $O_2$ can be seen in Figure 10b. The maximum amount of emitted $NO_x$ was 817 ppm at 850 °C, whereas that of $SO_2$ was 1962 (±5%) ppm at 650 °C.

When the 80% of coal and 20% PNS blend was combusted, the amount of CO increased suddenly to 11,729 (±5%) ppm at 400 °C, and it gradually decreased with an increase in the temperature. When the CO level was high, the $CO_2$ level was only 4.3% and $O_2$ was 16.6%, as shown in Figure 11a. These findings revealed the devolatilization and char oxidation reaction of the coal and biomass blend. At 700 °C, the maximum amount of $NO_x$ was 28 (±5%) ppm, while that of $SO_2$ was 1237 (±5%) ppm.

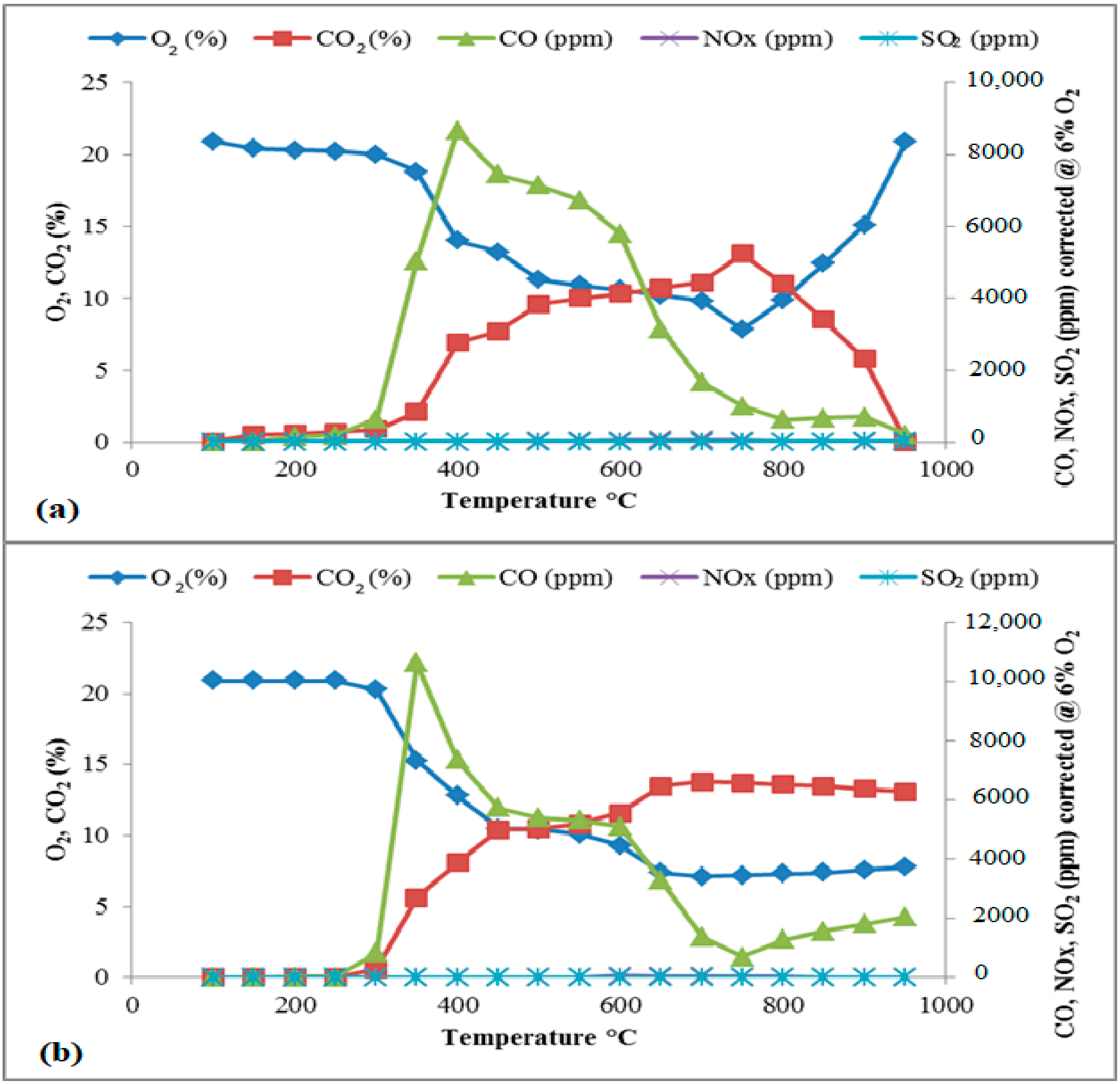


**Figure 10.** Emission profiles from the combustion of (**a**) 60% coal and 40% sunflower leftovers, (**b**) 50% coal and 50% sunflower leftovers.

The co-combustion of 70% coal and 30% PNS generated 10,102 (±5%) ppm of CO at 550 °C, as shown in Figure 11b. The maximum amount of $NO_x$ was 28 (±5%) ppm at 750 °C, while the amount of $SO_2$ was 561 (±5%) ppm at the exit (950 °C).

The co-combustion of 60% coal and 40% PNS generated 14,766 (±5%) ppm of CO at 350 °C. At this stage, the amount of $O_2$ decreased from 20.9% to 17%, and a slight increase in $CO_2$ emissions was observed, as shown in Figure 12a. The maximum amount of $NO_x$ was 68 (±5%) ppm at 700 °C, whereas the maximum amount of $SO_2$ was 371 (±5%) ppm at 900 °C.

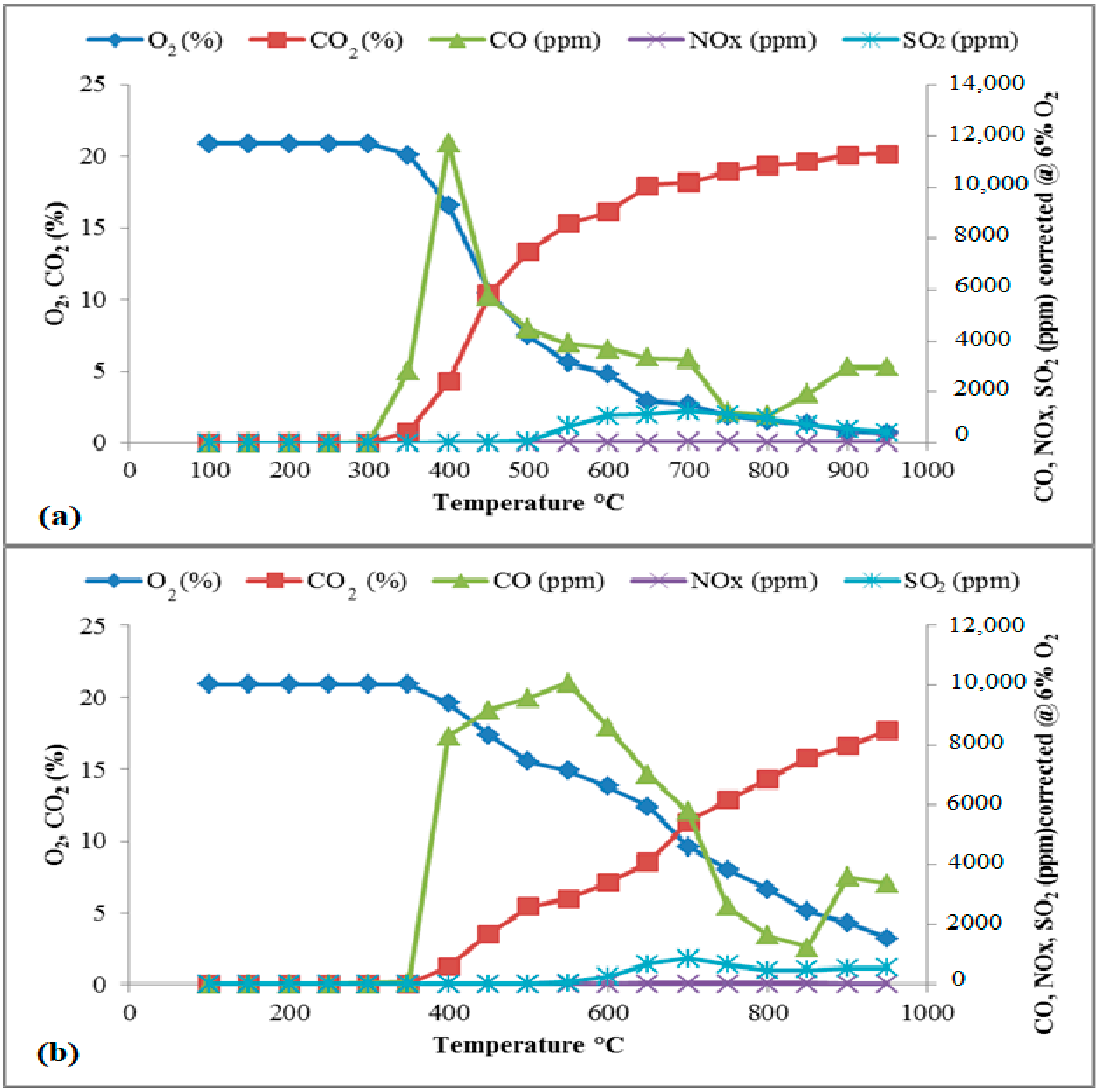


**Figure 11.** Emission profiles from the combustion of (**a**) 80% coal and 20% pine nut shell, (**b**) 70% coal and 30% pine nut shell.

When 50% coal and 50% PNS blend was combusted, the CO emissions peaked at 22,923 (±5%) ppm at 700 °C. In this case, no $SO_2$ was generated, and the maximum $NO_x$ was 16 ppm at 950 °C. Furthermore, $O_2$ was less used; the minimum percentage of $O_2$ was 17.2%, so less $CO_2$ was produced, and the maximum CO was 3.7% (Figure 12b).

When coal is added to biomass, the volatilization rate is modified, the released heat is affected, and the combustion residue is reduced under the same final combustion temperature. Thus, the combustion efficiency is increased [36]. Guo et al. also showed that biomass and coal blends directly dominated by the heating temperature and the heat released by the biomass combustion, which increases the conversion rate of the coal [14].

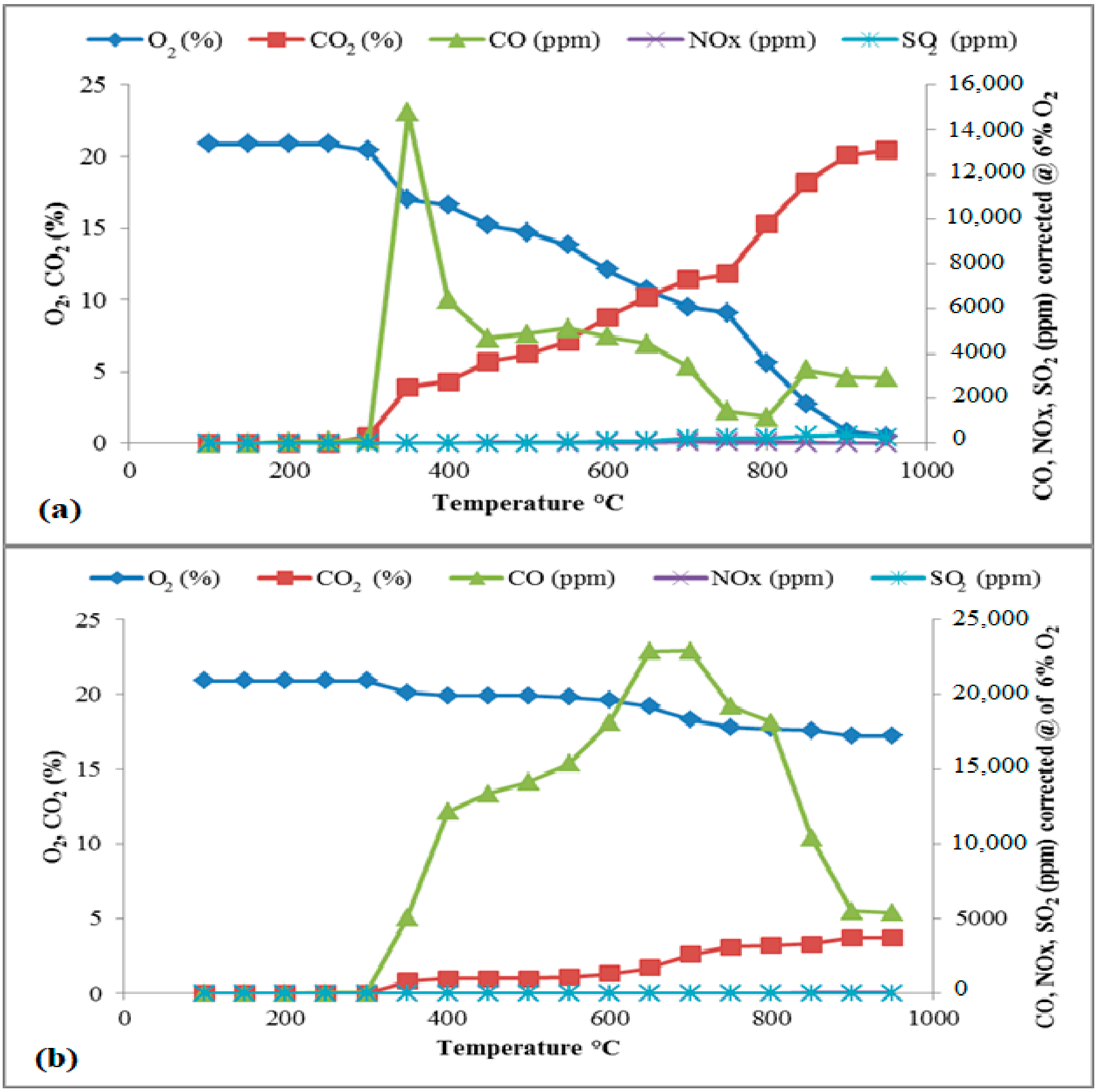


**Figure 12.** Emission profiles from the combustion of (**a**) 60% coal and 40% pine nut shell, (**b**) 50% coal and 50% pine nut shell.

Moreover, co-firing with biomass residues is the best approach among the studied alternatives for maximizing the savings of both fossil energy and greenhouse gases. Compared to the coal-fired base case, 20% co-firing with logging residues reduces the fossil energy consumption per kWh of electricity generated by 26% and decreases emissions of $CO_2$ by nearly 20%. In general, the biomass from wood showed a slight advantage over the biomass from switch grass [37].

### 3.3. Comparison of Emission Concentrations from Different Biomass Blending Ratios

Figure 13 shows a comparison between the concentrations of emissions from different biomass blending ratios (BBRs) that can be used to determine the emitted flue gases. When 90% coal and 10% poplar sawdust blend was co-combusted, the concentrations of released CO, $NO_x$, and $SO_2$ were 42,571, 138, and 5033 ppm, respectively. The volumes of CO, $NO_x$, and $SO_2$ produced from the co-combustion of 80% coal and 20% poplar sawdust were 22,920, 95, and 3948 ppm, respectively. Moreover, the volumes of CO, $NO_x$, and $SO_2$ generated from the co-combustion of 70% coal and 30% poplar sawdust were 35,846, 77, and 1247 ppm, respectively. For 60% coal and 40% poplar sawdust, the volumes of CO, $NO_x$, and $SO_2$ were 44,500, 93, and 871 ppm, respectively. When the BBR was 50%, the amounts of CO, $NO_x$, and $SO_2$ were 19,788, 89, and 66 ppm, respectively. In this study, a BBR of 50:50 was found to be the optimum BBR, because it produced 38% less CO and 99% less $SO_2$ than those of pure coal combustion. When 90% coal and 10% rice husk were co-combusted, 10,620, 70, and 1810 ppm of CO, $NO_x$, and $SO_2$ were released, respectively. The amounts of CO, $NO_x$, and $SO_2$ emitted from the co-combustion of 80% coal and 20% rice husk were 13,244, 32, and 611 ppm, respectively. Moreover, the amounts of CO, $NO_x$, and $SO_2$ emitted from the co-combustion of 70% coal and 30% rice husk were 9030, 51, and 472 ppm, respectively. For 60% coal and 40% rice husk, the amounts of CO, $NO_x$, and $SO_2$ were 11,480, 90, and 409 ppm, respectively. When the BBR was 50%, the amounts of CO, $NO_x$, and $SO_2$ were 19,240, 71, and 928 ppm, respectively. The comparison between different BBRs is shown in Figure 13b. In this case, the BBR of 70:30 was determined to be the optimum, as it produced 72% lower CO and 90% lower $SO_2$ emissions than those of pure coal combustion.

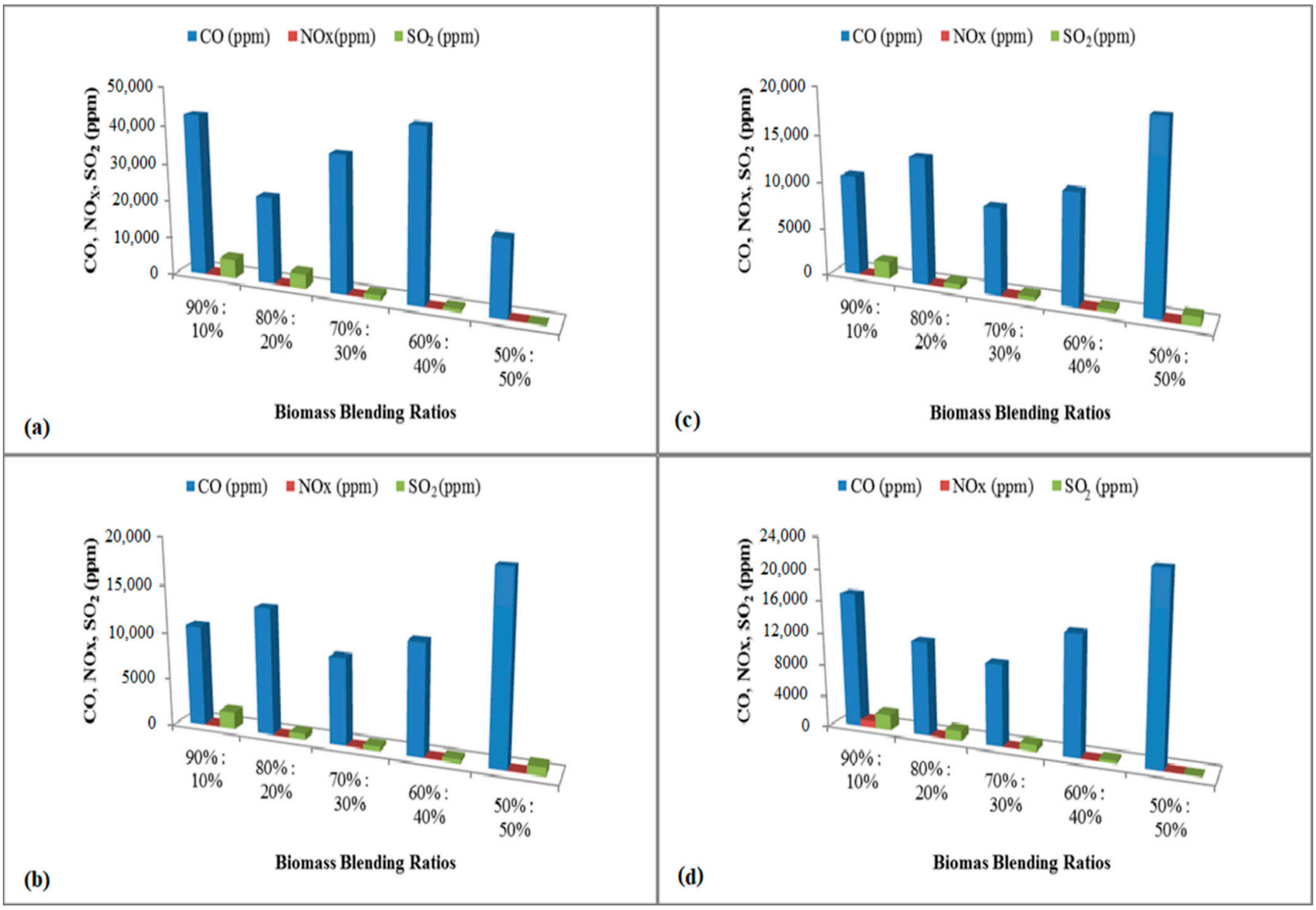


**Figure 13.** Comparison of emissions concentration of BBR of coal and biomass (**a**) poplar sawdust, (**b**) rice husk, (**c**) sunflower leftovers, and (**d**) pine nuts shell.

Kwong et al. also reported that the co-combustion of coal and rice husk caused a reduction in emissions by 10–30% [38]. The co-firing of coal and hydrothermally treated municipal waste has also been reported to reduce the emissions of a 70:30 blend [39]. Similarly, when 90% coal and 10% sunflower leftovers were co-combusted, the amounts of CO, $NO_x$, and $SO_2$ were reported as 9973, 22, and 942 ppm, respectively, as shown in

Figure 13c. The amounts of CO, $NO_x$, and $SO_2$ released from the co-combustion of 80% coal and 20% sunflower leftovers were 13,860, 36, and 775 ppm, respectively. Moreover, the amounts of CO, $NO_x$, and $SO_2$ released from the co-combustion of 70% coal and 30% sunflower leftovers were 15,168, 18, and 0 ppm, respectively. For 60% coal and 40% sunflower leftovers, the amounts of CO, $NO_x$, and $SO_2$ were 8638, 48, and 28 ppm, respectively. When the BBR was 50%, the amounts of CO, $NO_x$, and $SO_2$ were 10,643, 50, and 0 ppm, respectively. In this case, a BBR of 60:40 was determined to be the best choice, because the co-combustion of this blend generated 73% less CO and 99% less $SO_2$ than the combustion of 100% coal.

When Duki coal and bagasse blends were co-combusted, a BBR of 60:40 was found to be the optimum [25]. Finally, when 90% coal and 10% pine nut shells were co-fired, the amounts of CO, $NO_x$, and $SO_2$ released were 16,865, 817, and 1962 ppm, respectively, as shown in Figure 13d. At a BBR of 80:20, the amounts of CO, $NO_x$, and $SO_2$ were 11,729, 28, and 1237 ppm, respectively. The amounts of CO, $NO_x$, and $SO_2$ released from the co-combustion of 70% coal and 30% pine nut shells were 10,102, 28, and 871 ppm, respectively. Moreover, the amounts of CO, $NO_x$, and $SO_2$ released from the co-combustion of 60% coal and 40% pine nut shells were 14,766, 68, and 371 ppm, respectively. When the BBR was 50%, the amounts of CO, $NO_x$, and $SO_2$ were 22,923, 16, and 0 ppm, respectively, and the comparison between different BBRs can be seen in Figure 13d. In this case, a BBR of 70:30 was determined as a good option, because it generated 68% less CO and 82% less $SO_2$ than those of pure coal. Thus, based on the above discussion, a BBR of 60–40% coal–sunflower leftover was the best among all tested BBRs, producing 73% less CO and 99% less $SO_2$ than those of pure coal. Guo et al. showed that the excessive amount of biomass and coal blends have advantages to the co-combustion process. They reported the optimum blending ratio of 30% for the composite biomass pellets (CBPs) and coal blends [18].

### 3.4. Combustion Efficiency

Combustion efficiency is an important factor that needs to be addressed. When 100% coal was combusted, the percentage of unburned carbon in the ash was 8.3%, whereas in the ash of the 50:50 coal–poplar sawdust, the unburned carbon was 7.11%, which means that this blend showed 14.33% better combustion efficiency than pure coal did. The percentage of unburned carbon in the ash of 70% coal and 30% rice husk was 5.18%, which indicated better combustion efficiency than that of pure coal by 37.57%. The unburned carbon of 60% coal and 40% poplar sawdust was 0.45%, which means that this blend showed 94.57% better combustion efficiency than pure coal did. The unburned carbon in the ash of 70% coal and 30% pine nut shells was 7.20%, which means that the combustion efficiency of this blend was 13.25% better than that of pure coal. Therefore, the combustion of coal and biomass blends was more efficient than the combustion of pure coal.

Moreover, based on the comparison of the combustion efficiencies of all the BBRs, it was established that the combustion efficiency of 60% coal and 40% sunflower leftovers was the highest, and this blend emitted less flue gas among all the blends studied. The blend of 40% coal and 60% straw produced the lowest levels of $SO_2$ and $NO_x$ emissions, but the total $CO_2$ emissions increased constantly when increasing the content of coal [36]. Yang et al. studied the behavior of NOx emissions for the co-combustion of biomass and pine sawdust that showed a good agreement with this study. They reported that the maximum reduction of NOx could be achieved with 50% biomass and 50% coal combustion [40]. Sahu et al. concluded that during the co-combustion of biomass and coal, the GHGs and flue gases, particularly NOx and Sox, are reduced by increasing the amount of biomass reasoned for the lower sulfur content in biomass feedstock compared to the sulfur content in the coal [40]. Su et al. studied the co-combustion of food waste with lignite coal and their blends using non-isothermal thermogravimetric analysis coupled with Fourier-transform infrared spectroscopy set on a mass basis as 1:6, 2:6, 3:6, 4:6, and 5:6 [41]. It was reported that $CO_2$, $SO_2$, and HCl were the main gaseous pollutants produced during the co-combustion.

The ratio of 4:6 was reported to be the optimum for the co-combustion of coal and food waste because the $SO_2$ and HCl emissions decreased at this ratio [41].

## 4. Conclusions

This study examined the effects of the co-combustion of coal with different underutilized biomass residues based on flue gas analysis and combustion efficiencies. The blend of 60% coal and 40% sunflower residue was found to be the optimum blend with 73% less CO and 99% less $SO_2$ emissions compared to the combustion of pure coal. Furthermore, the same blend exhibited the most efficient combustion. The biomass and coal blends reduced the flue gas emissions and their combustion was more efficient than that of coal. The study concluded that the blending of biomass with coal can be greatly beneficial in reducing the emissions of harmful gases, improving the combustion efficiencies and reducing the particulate matter emissions to the environment. Moreover, the inclusion of biomass for energy production by blending with coal can make the process more sustainable.

**Author Contributions:** F.K., A.A., and F.J. and developed the conceptualization and methodology of the study. S.R., H.M.U.A. provided valuable research insights. M.G. and M.S.K. provided the supervision and research insights along with helping in review the manuscript, S.M. (Shahid Munir) provided the analysis support. A.I., M.S.A.B., and S.M. (Surendar Moogi) provided valuable insights and help in editing and review the manuscript. S.S.L. and Y.-K.P. provided valuable feedback and helped in publishing. All authors have read and agreed to the published version of the manuscript.

**Funding:** The support from the Department of Chemical Engineering COMSATS University Islamabad Lahore Campus is acknowledged. Furthermore, the financial support from the National Research Foundation of Korea under the project NRF-2020R1I1A1A01072793 and NRF-2020M1A2A2079801 are acknowledged.

**Data Availability Statement:** Data are provided within the article.

**Conflicts of Interest:** The authors declare no conflict of interest.

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