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Development of a Low-Cost Biomass Furnace for Greenhouse Heating

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Abstract: The energy crisis and increasing fossil fuel prices due to increasing demands, controlled supplies, and global political unrest have adversely affected agricultural productivity and farm profitability across the globe and Pakistan is not an exception. To cope with this issue of energy deficiency in agriculture, the best alternate strategy is to take advantage of biomass and solid waste potential. In low-income countries such as Pakistan, the greenhouse heating system mostly relies on fossil fuels such as diesel, gasoline, and LPG. Farmers are reluctant to adopt greenhouse farming due to the continuously rising prices of the fossil fuels. To reduce reliance on fossil fuel energy, the objective of this study was to utilize biomass from crop residues to develop an efficient and economical biomass furnace that could heat greenhouses to protect the crop from seasonal temperature effects. Modifications made to the biomass furnace, such as the incorporation of insulation around the walls of the furnace, providing turbulators in fire tubes, and a secondary heat exchanger (heat recovery system) in the chimney, have increased the thermal efficiency of the biomass furnace by about 21.7%. A drastic reduction in hazardous elements of flue gases was observed due to the addition of a water scrubber smoke filter in the exit line of the flue. The efficiency of the biomass furnace ranged from 50.42% to 54.18%, whereas the heating efficiency of the diesel-fired heater was 71.19%. On the basis of the equal heating value of the fuels, the unit material and operating costs of the biomass furnace for wood, cotton stalks, corn cobs, and cow dung were USD 2.04, 1.86, 1.78, and 2.00 respectively against USD 4.67/h for the diesel heater. The capital and operating costs of the biomass furnace were about 50% and 43.7% of the diesel heater respectively, resulting in a seasonal saving of about 1573 USD. The produced smoke was tested as environmental friendly under the prescribed limits of the National Environmental Quality Standards (NEQS), which shows potential for its large-scale adoption and wider applications.

Keywords: biomass; furnace; greenhouse; efficiency; economics

1. Introduction

Energy requirements in the future are certain to increase drastically with the ever-growing global population. In the coming years, more people will require the excess of energy that is presently available from different sources [1,2] Generally, energy is considered the main pillar of the economic growth of a country as most of the industries run on energy, which is playing remarkable role in socio-economic growth [3]. Energy is first and foremost a requirement for sustainable development. In terms of energy mix, Pakistan's energy sector heavily depends on thermal energy which consists of imported coal, local coal, re-gasified liquid natural gas, and natural gas that constitute about 58.4% of the total energy mix. The share of different sources such as hydroelectric, thermal, nuclear, and renewable is 30.9, 58.4, 8.2, and 2.4%, respectively. From the energy mix, the contribution of renewable energy needs to be enhanced as uncontrolled burning of fossil fuels is leading to increased environmental pollution by the release of greenhouse gases [4]. Moreover, a substantial potential for renewable energy is present in the country. All these aspects demand switching to renewable energy resources, which will help reduce the gap between energy supply and demand in Pakistan [5,6]. Table 1 shows that there is a large potential for biomass-based renewable energy in Pakistan. Renewable energy sources like solar, geothermal, and biomass are commonly used in greenhouse heating [7]. During the winter season, the increased demand for heat energy to keep the temperature of the greenhouses at the desirable level for crop production is essential. Hence, a proper greenhouse heating system is unavoidable for healthy and optimum crop production [8].

Table 1. Calculation of estimated annual surplus biomass production [9].

Crop Type	Estimated Crop Production (000 tons/year)	Crop Residue Ratio (CRR)	Estimated Biomass Production (000 tons/year)	Estimated Surplus Biomass (000 ton/year)
Sugarcane	65,257	0.12	7831	2552
Cotton	14,531	3.40	49,405	5039
Wheat	34,581	1.00	34,581	5689
Rice	16,754	1.00	16,754	6534
Maize	4260	1.25	5325	680
Total	135,383		113,896	20,494

Renewable energy sources like solar, geothermal, and biomass are commonly used in greenhouse heating [7]. To cater for the increasing energy demands, developed nations are continuously making efforts to explore alternate energy sources and coin new methods and technological innovations for energy conservation and efficiency improvement [10,11]. The literature has provided information about the application of heating and cooling devices for use in food and agriculture sectors in Portugal [12]. However, these studies do not provide the latest research and development framework and modalities that could help towards the design of a low-cost furnace or hot air generators for the agriculture sector, especially, when talking about remote locations. However, these studies discussed the utilization of renewable energy to provide hot air for the agriculture sector, in detail. Some studies suggested a methodology for analyzing the regional potential for developing biomass district heating systems based on forestry biomasses [13–15].

In consideration of a holistic and cost-effective approach, the overall energy price tag on greenhouses comes around 10–15% of its total cost of production. The profit margins of greenhouse farming have decreased due to rising energy costs, which have doubled over the last two decades [16]. Most greenhouse heating systems in Pakistan rely on electricity or fossil fuels, the prices of which have remained volatile and are continuously rising. Therefore, farmers are reluctant to adopt greenhouse farming due to decreasing profit margins. Higher energy costs in greenhouse farming have motivated the farmers to explore alternative means to reduce energy costs. Many growers use firewood for the heating of greenhouses, the cost of which is also rising. However, being an agrarian economy, Pakistan produces a large mass of crop residues annually [17,18]. The estimated production of major crop residues of cotton stalks, wheat straw, rice straw, sugarcane trash, and corn stalk in Pakistan are 49.4, 34.581, 16.75, 7.83, and 5.325 million tons per annum, respectively [2]. These crop residues are abundantly available in the country and require a viable strategy to be utilized in an efficient way, as compared to direct land filling and open air burning which is the current practice [2,19,20].

Generally, farmers are very cautious in exploring new sources of energy for their agricultural operations. Most farmers understand that firewood is the best option and low-cost source for thermal heating at the farm level [16]. Two types of biomass boilers and furnaces are currently used in the world on the basis of manual fuel feeding and automated feeding. Manually loaded boilers and furnaces are mostly run on waste wood whereas automatically fueled boilers run on different biomass sources like wood chips, biomass pellets, wood biomass, grain, and bagasse [21,22].

As per author information, there is no comprehensive study in Pakistan that has developed an indigenous waste fuel-based furnace in the agricultural sector for better and improved thermal applications. In this study, we developed a biomass/solid waste fuel furnace that can be helpful for thermal applications in the agriculture sector for better and improved production purpose. The objective of the study was to utilize biomass/solid waste in an efficient and economical way as a greenhouse heating system. The produced heat can be utilized for greenhouse heating to maintain optimal temperature during winter season.

2. Materials and Methods

2.1. Design Parameters

The biomass furnace for greenhouse heating was designed and developed at the Faculty of Agricultural Engineering, Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Pakistan. The important design considerations included simple design, local manufacturing, light weight, portability, economics, and ease of operation. The 1st prototype model of the biomass furnace was installed in a 30.48 × 12.19 m^2 greenhouse tunnel for further testing and evaluation. Biomass furnaces work on the principle of a boiler, where the direct burning of biomass takes place in the burning chamber. The clean and hot air moves in a separate enclosure surrounding the hot air tubes. A typical biomass furnace consists of a combustion chamber, primary heat exchanger, chimney, secondary heat exchanger, water scrubber smoke filter, air distribution system, automatic air temperature control system, ash chamber, axial fan, blower for combustion, and temperature gauges. The basic design considerations for the design and development of the biomass furnace for greenhouse heating included:

1. It should be simple, light weight, portable, and easy to operate.
2. It can be manufactured using indigenous material and local technology.
3. It should be affordable (economical) and efficient.

The important parameters for the design of a biomass furnace for greenhouse heating are described hereunder.

2.1.1. Equation (1): Volume of the Targeted Tunnel

$$\text{Volume} = \text{Length} \times \text{Width} \times \text{Height} \tag{1}$$

2.1.2. Equation (2): Energy Required to Heat the Targeted Tunnel

$$Q = m \times C_p \times \Delta t \tag{2}$$

where m = mass of air in the tunnel, Cp = specific heat of air (1.008 kJ kg^{-1} K^{-1}), and Δt = the difference in final and initial temperature inside the tunnel.

2.1.3. Equation (3): Biomass Required to Maintain the Required Heat in the Targeted Tunnel

$$\text{Biomass required} = \frac{\text{Heat Required}}{\text{Calorific value of biamass}} \tag{3}$$

2.1.4. Heat Exchanger Design

Equations (4) and (5): The heating surface required is computed by:

$$A = \frac{Q}{U \times \Delta t_m} \tag{4}$$

$$Q = U \times A \times \Delta t_m \tag{5}$$

where A = heat transfer area (m^2), Q = heat transfer rate, kJ h^{-1}, U = overall heat transfer coefficient, kJ h^{-1} m^2 °C (for air 28.58 kJ h^{-1} m^2 °C), Δt_m = Log mean temperature difference (°C), which is given by Equation (6):

$$\Delta t_m = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \frac{(T_1 - t_2)}{(T_2 - t_1)}} \tag{6}$$

where T_1 = inlet fire tube temperature (°C), T_2 = outlet fire tube temperature (°C), t_1 = inlet shell side air temperature (°C), and t_2 = outlet shell side air temperature (°C).

Equation (7): The heat transfer rate can be measured as:

$$Q = m \times C_p \times \Delta t \tag{7}$$

where m = mass flow rate of air (kg hr^{-1}), and C_p and Δt are as specified above.

The schematic diagram of the biomass furnace is presented in Figure 1 and its isometric view is presented in Figure 2, whereas the connectivity of biomass furnace with the greenhouse tunnel is shown in Figure 3. The design final parameters of the biomass furnace are outlined in Table 2.

Table 2. Specification of biomass furnace.

Parameters	Values
Length of furnace	168.0 cm
Width of furnace	108.0 cm
Height of furnace	183.0 cm
Fuel loading capacity	50 kg/batch
Construction material	MS steel
Volume flow rate	0.17 m^3/s
Heat exchanger area	5 m^2
Cross-sectional area of exhaust	0.0046 m^2
Volume of tunnel	1303.6 m^3
Mass of air in tunnel	1469.16 kg
Efficiency	54%
Total weight	400 kg
Price USD	1562.5

2.2. *Fabrication of Biomass Furnace*

Apart from design parameters, fabrication material is the most important aspect of the biomass furnace that directly affects its thermal efficiency and capital cost. A multitude of fabrication materials (silver, copper, brass, iron, steel) with varying thermal conductivities (406, 385, 109, 80, 50 W/mK) and melting points (962, 1085, 930, 1538, 1450 °C), respectively, are in use across the world. However, their manufacturing industry and capital costs limit their wider-scale adoption. Pakistan is a low-income agrarian economy and the manufacturing sector is still at its infancy but has tremendous growth potential. For fabrication of the prototype type biomass furnace designed in this study, we selected easily available and the lowest cost material, i.e., mild steel. A local vendor (M/S Malik Engineering and Works, Rawalpindi) was hired for the fabrication of the biomass furnace in a precise manner to ensure the precision of all the design parameters. Figure 4 displays the different views of the fabricated biomass furnace.

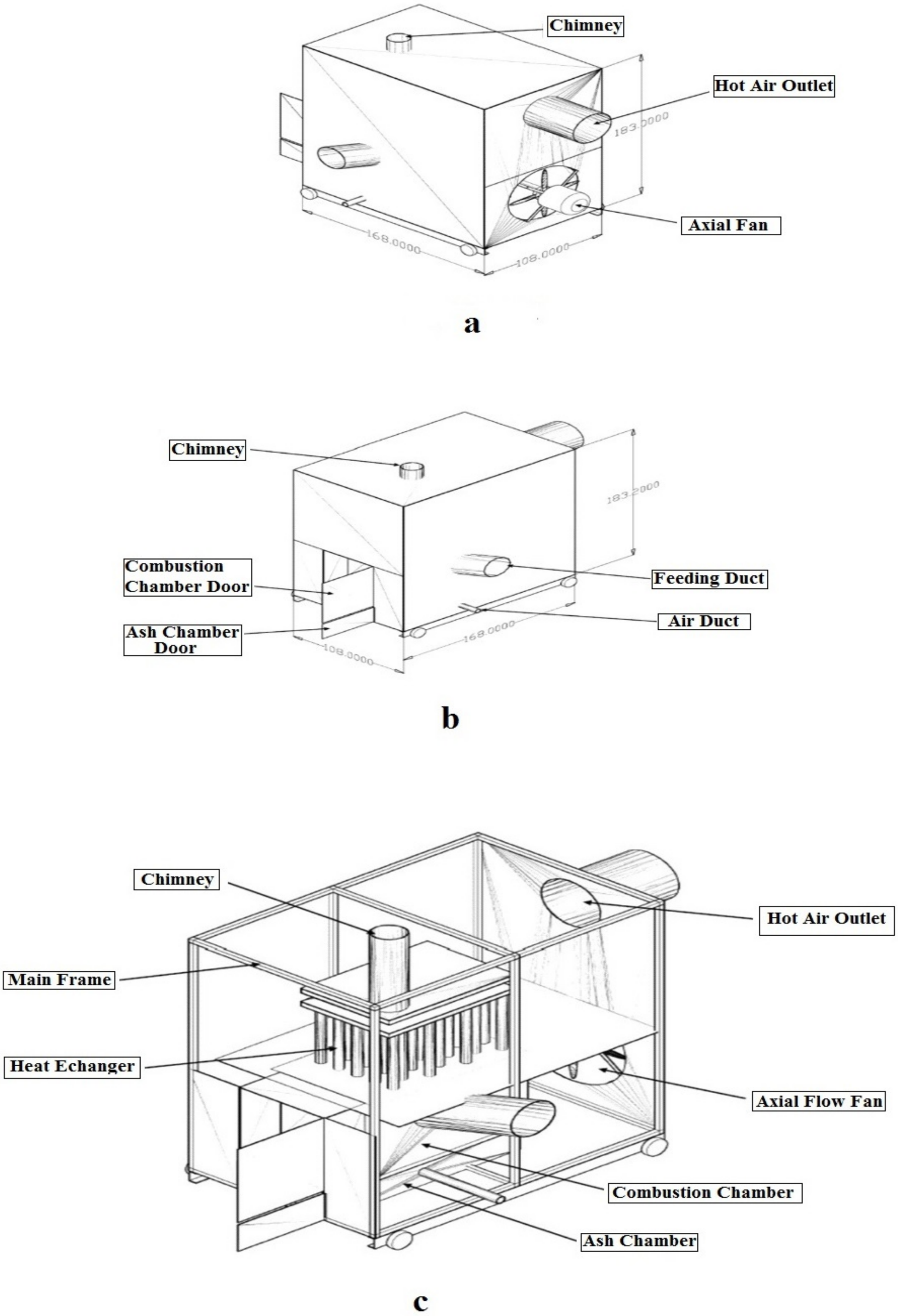

Figure 1. Schematic diagram of biomass furnace (**a**) back view (**b**) front view, and (**c**) cross-sectional view.

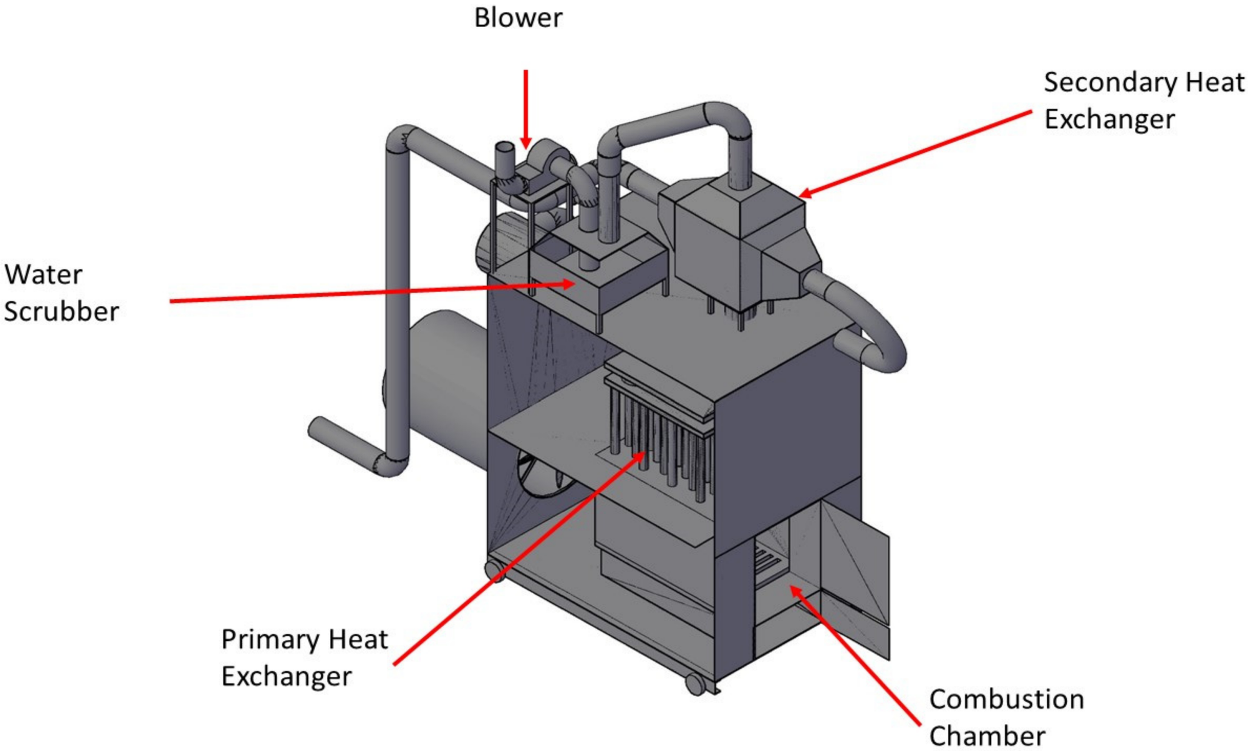

Figure 2. Isometric view of biomass furnace.

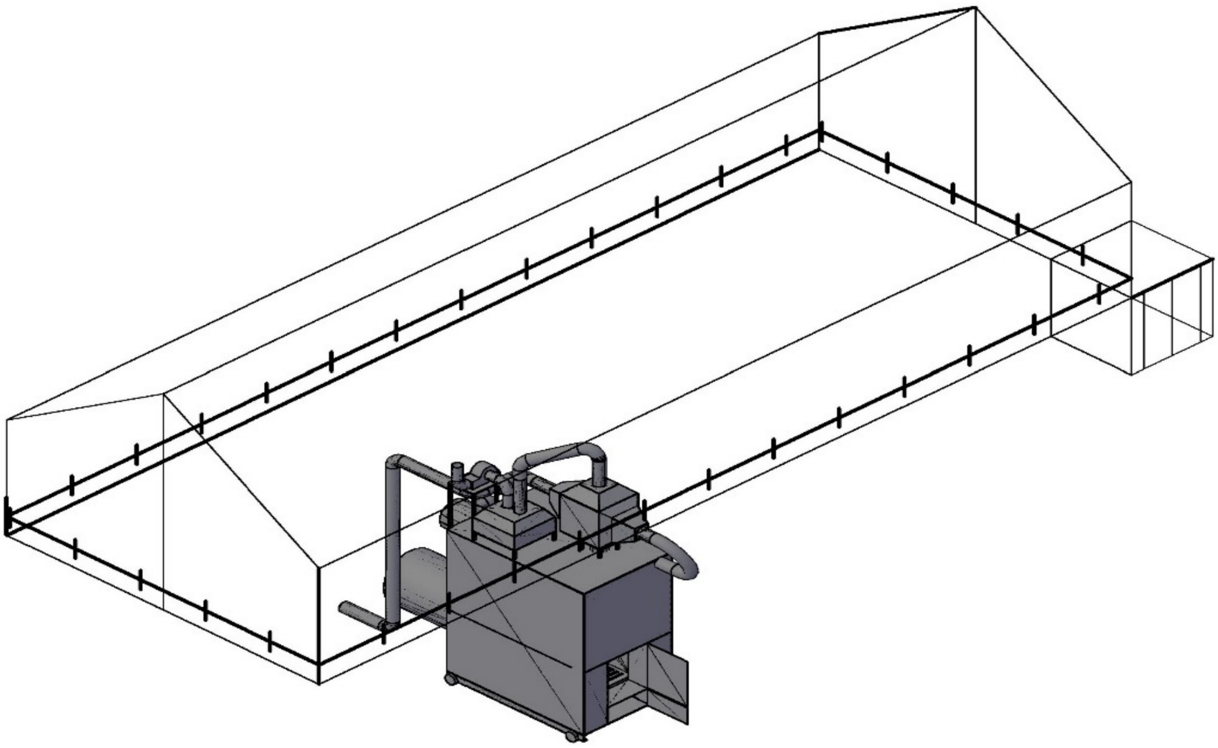

Figure 3. Connectivity of the biomass furnace to the greenhouse tunnel.

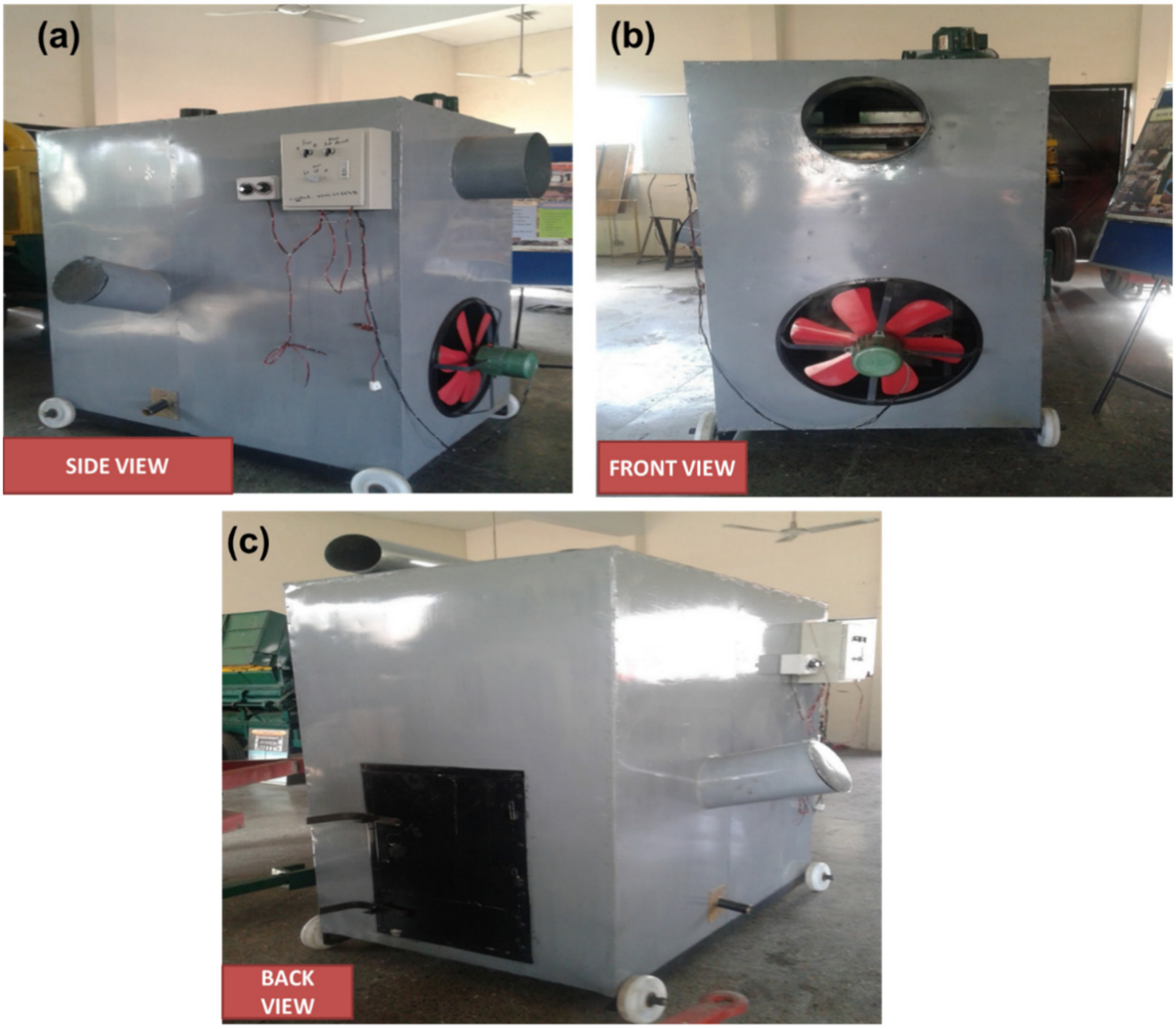

Figure 4. Different views of fabricated biomass furnace. (**a**) side view. (**b**) front view. (**c**) back view.

A variable flow blower is provided in the combustion chamber for the mixing of the stoichiometric air-fuel ratio for optimum combustion. The combustion gases move in a network of parallel vertical tubes provided with spiral baffles for delaying the passage of gases in the tubes. The heat is transferred from biomass flames to fire tubes through the radiation and convection principles of heat transfer, while from inner surfaces to the outer surfaces of tubes heat is transferred through the conduction principle. The hot air passing from all fire tubes gets very hot and exits from one end, which directly opens into the greenhouse or tunnel. Processed air passes through a zigzag having different baffles for getting maximum heat transfer from the hot air tubes to the processed air. An auxiliary suction fan is provided at the exit of the hot air for getting the maximum amount of hot air for drying purposes.

2.3. Biomass Collection and Preparation

Biomass residue samples (wood, cotton stalk, corn cob, and cow dung) were collected from farmers' fields in the surrounding areas. The moisture content affects the heating value of a biomass fuel. For a moist fuel, the heating value decreases because a portion of the heat is used to evaporate the water present in the biomass. The collected biomass was sun-dried to lower the moisture content (10%). Thereafter, the biomass was converted into pellets, chips, and briquettes for greenhouse heating using a biomass furnace. Therefore, almost no cost was incurred to dry the biomass used for this study. However, the conversion of biomass to pellets, chips, and briquettes were prepared manually with a labor cost of USD 0.375/day.

2.4. Evaluation of the Biomass Furnace

The prototype biomass furnace unit was evaluated at the National Agricultural Research Centre, Islamabad using different feed rates of wood. The biomass furnace was operated continuously for 10 h, while the air flow rate of the blower was fixed at 0.17 m^3/s during the entire testing period. The thermal efficiency of the furnace was recorded for each feed rate of the firwood. The pretesting indicated considerable heat losses in the walls of the combustion chamber and through the hot flue gases releasing from the exhaust vent. Therefore, the design and fabrication of the prototype biomass furnace unit was further modified to increase its thermal efficiency and make it environmentally friendly.

3. Results

3.1. Pretesting of the Biomass Furnace

The prototype biomass furnace was pretested using firewood feed rates of 8, 10, and 12 kg/h. The prototype biomass furnace was transported to the engineering workshop of the National Agricultural Research Centre (NARC), Islamabad for its pretesting, evaluation, and further modification (Figure 5). Data were collected on ambient air temperature, furnace temperature, exhaust temperature, heated air temperature, tunnel temperature, output heat flow rate, efficiency of the furnace, and heating time during the different tests (Table 2). The efficiency, input and output power, and operational cost of the furnace were determined to make the comparison between different feed rates of wood (8, 10, and 12 kg/h). Based on input and output powers, the average efficiency of the furnace increased linearly with the feed rate of the firewood (Table 3). Thermal efficiency was calculated with the ratio of output heat flow rate to input heat flow rate. The output heat flow rate was calculated using Equation (8):

$$Q_{output} = m \times (kg) \times Cp. \times \Delta T \quad (8)$$

where Q = energy flow rate (kW); m (fan speed) = mass flow rate (0.1008 kg/s); Cp = specific heat of air (1.012 KJ/kg·k); ΔT = temperature difference ($T_2 - T_1$); T_2 = final temperature; T_1 = initial temperature.

Table 3. Temperature, flow rate, and efficiency of wood at different feed rates during pretesting of the biomass furnace.

Biomass Type and Feeding Rate (kg/h)	Amb. Air Temp. (°C)	Furnace Temp. (°C)	Exhaust Temp. (°C)	Heated Air Temp. (°C)	Tunnel Temp. (°C)	Output Heat Flow Rate (kW)	Thermal Efficiency η (%)
Wood 8	10.2	247.7	191.3	98.5	26.4	14.30	42.89
Wood 10	13.8	300.1	211.8	126.8	33.5	18.30	43.91
Wood 12	9.5	318.8	229.4	146.1	34.1	22.12	44.24

The input heat flow rate is the product of a biomass burnt per hour and the calorific heating value of that biomass, i.e., Q_{input} = m, the calorific or heating value of biomass multiplied with quantity used per hour. However, the increase in efficiency was disproportionate with the increase in the feed rate of wood. Nevertheless, pretesting of the prototype biomass furnace suggested its larger suitability for greenhouse heating in cold environments.

Figure 5. Pretesting of the biomass furnace at NARC.

The design of a diesel heater is relatively better due to its better engineering, and copper material having good thermal conductivity (385 W/m K). However, the material of the biomass furnace was mild steel, which possesses relatively lower thermal conductivity (64.8 W/m K). The design temperature of exhaust gas was assumed to be 373.15 K, but the actual values always differ from the design values because in theoretical design, mostly ideal conditions are assumed while the actual conditions are always different from the theoretical. This fact leads to lower actual efficiency of the machine than the theoretical efficiency.

3.2. Modification of the Prototype Biomass Furnace

The major deficiencies identified during the pre-testing of the prototype biomass furnace unit were its low thermal efficiency due to considerable heat losses from furnace walls as well as from the vent. The risk of environmental pollution due to the uncontrolled emission of toxic flue gases was another drawback of the prototype furnace. To cater for these issues, the design and fabrication of the furnace was modified by providing insulation work inside, installing turbulators in the heat exchanger tubes, adding a secondary heat recovery unit, and installing a water scrubber smoke filter in the furnace to reduce environmental pollution.

The insulation work was carried out by providing a thick layer of glass wool across the walls of the furnace as a barrier to reduce thermal losses during the operation of the biomass furnace. Hot air turbulators are commonly used for enhancing the thermal efficiency of boilers, air heaters, and heat exchangers. They retain hot air for longer durations inside the heat exchanger, resulting in saving fuel and increasing thermal efficiency. The air turbulators in the modified biomass furnace were provided inside the heat exchanger and heat recovery unit. A significant volume of precious hot air was wasted through the vent located at the top of furnace. To address this issue, a secondary heat exchanger was provided on top of the vent as a heat recovery unit. The flue gases again passed through this secondary heat exchanger unit or heat recovery unit, which contained tubes and a convection chamber for further recovery of heat from the flue gases. The addition of this heat recovery unit considerably improved the thermal efficiency of the furnace and reduced exhaust temperature. The emission of raw flue gases from the furnace into the atmosphere is detrimental to environment. A wide variety of exhaust emission control devices such as venturi wet scrubbers, packed tower wet scrubber, impingement wet scrubbers, and catalytic converters are used in industrial applications to control environment pollutions, but these devices are very costly and not affordable to the common farmer. To address this problem, a simple and economical water scrubber smoke filter device was designed, developed, and tested for the cleaning of flue gases emitting from the biomass furnace developed in this study. This modification added 312.5 USD more in capital cost of the furnace. It was provided on the top of the furnace from where flue gases pass through before mixing into the environment. The water scrubber smoke filter controls air pollution and removes particulate matter by dissolving it in liquid. The smoke filtering device is very useful for reducing air pollution and is also used for the reduction of many exhaust gases, which include CO, NO, NO_2, H_2S and SO_2 [23,24]. To monitor the exhaust flue gases, the US-EPA and PAK-EPA certified TESTO-350 flue gas analyzers were used. The modified biomass furnace is shown in Figure 6.

Figure 6. Side view of the modified biomass furnace.

3.3. Testing of the Modified Biomass Furnace

The modified biomass furnace was shifted to the field and installed outside an existing greenhouse/tunnel with the dimensions 30.48 m × 12.19 m × 4.26 m. The heating efficiency of the biomass furnace was evaluated by varying three feeding rates of wood biomass, e.g., 8, 10, and 12 kg/h. The efficiency and economics of the modified biomass furnace was also evaluated for common types of crop residue-based biomasses (cotton stalks, corn cobs, and cow dung), as well as diesel, which is the standard fuel for greenhouse heating in Pakistan. Data were collected on furnace parameters, such as ambient air temperature, furnace inside temperature, heated air temperature, furnace exhaust temperature, tunnel temperature, heat flow rate, and furnace efficiency. The furnace was operated continuously for 10 h, while the air flow rate of the furnace was kept constant at 0.17 m^3/s during the entire testing period. The initial performance of the prototype biomass furnace was poor due to considerable heat loss from the furnace walls and the vent. However, a considerable reduction in heat energy dissipated from the exhaust vent and significant increases in the furnace temperature, heated air temperature, output heat flow rate, and thermal efficiency were observed after modification of the biomass furnace (Tables 3 and 4).

Table 4. Temperature, flow rate, and efficiency of wood at different feed rates after modification of the biomass furnace.

Biomass Type and Feeding Rate (kg/h)	Amb. Air Temp. (°C)	Furnace Temp. (°C)	Exhaust Temp. (°C)	Heated Air Temp. (°C)	Tunnel Temp. (°C)	Output Heat Flow Rate (kW)	Thermal Efficiency η (%)
Wood 8	6.0	371.4	149.0	122.0	15.0	17.33	51.98
Wood 10	5.8	394.5	158.3	153.0	15.9	22.20	53.28
Wood 12	7.1	404.8	174.4	183.7	16.4	27.09	54.18
Cotton Stalks 13.0	7.2	389.2	155.4	174.6	15.0	25.84	51.71
Corn Cobs 13.0	6.3	388.9	158.9	178.7	15.3	26.46	52.33
Cow Dung 23	5.4	364.2	161.3	169.8	14.1	25.21	50.42
Diesel fuel 4 L/h	7.1	477.4	107.5	129.4	27.5	36.09	72.19

4. Discussion

4.1. Efficiency of the Modified Biomass Furnace

Modification in the design and fabrication of the biomass furnace resulted in significant improvements in its performance under different feed rates of firewood. On average, the furnace temperature increased by 36.1%, heated air temperature by 23.4%, output heat flow rate by 21.7%, and thermal efficiency by 21.7%, and exhaust temperature reduced by 23.8% over the prototype biomass furnace (Figure 7). These improvements were achieved with a nominal increase in the capital cost of the modified biomass furnace.

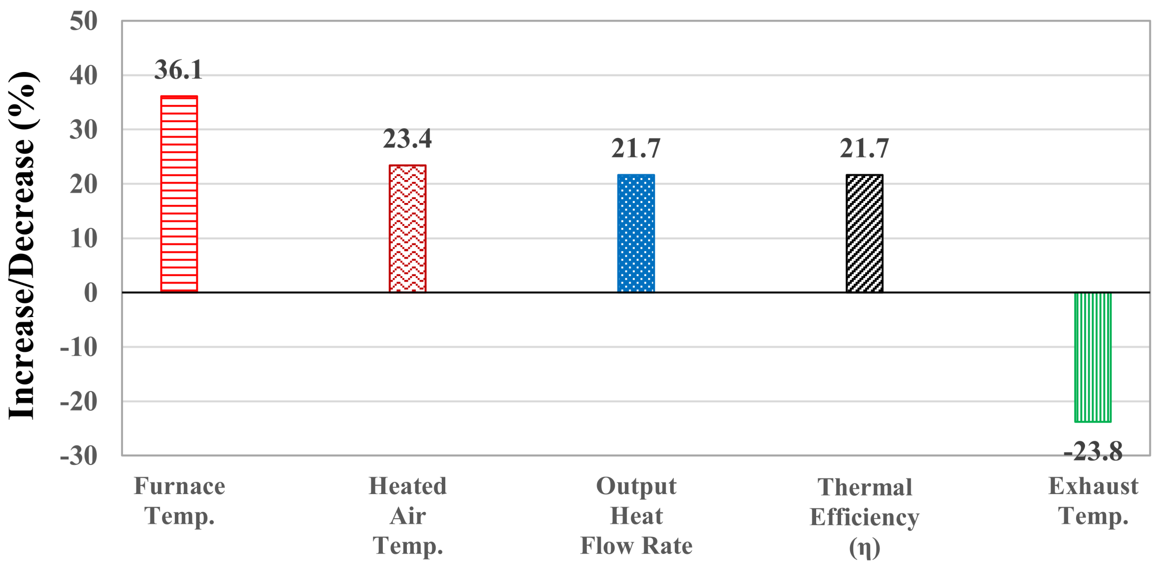

Figure 7. Improvements in various parameters after the modification of the biomass furnace.

4.2. Efficiency of Different Biomasses Relative to Diesel

Diesel is the standard and most widely used fuel for greenhouse heating in Pakistan. However, due to its increasing price, greenhouse growers are continuously searching for viable alternatives for heating of their greenhouses. As such, the efficiency of different biomass fuels used in this study was compared with respect to the heating value of the diesel fuel. The average heating value of 4 L diesel fuel is about 45 MJ/kg. The feed rates of the selected biomass fuels were adjusted to meet the reference heating value of diesel fuel. During the tests, three feed rates of wood viz. 8.0, 10.0, and 12.0 kg/h were used, whereas one feed rate for cotton stalks (13.0 kg/h), corn cobs (13.0 kg/h), and cow dung (22.5 kg/h) was used for testing purpose. The biomass furnace was operated continuously for 10 h under all diesel and biomass fuel tests. The idea behind this was to explore economic and viable solutions for greenhouse heating so that the growers could use their crop residues for this purpose.

Table 4 shows average efficiencies of the modified biomass furnace for different biomasses and diesel fuel. Based on input and output powers, the efficiency of the diesel fuel was 72.19%, which is higher than the efficiency of different biomasses. The reason is that there were still many heat losses from the biomass furnace. In contrast, the diesel-fired heater had minimal heat loss from the heating surface.

4.3. Economics of Biomass Furnace for Greenhouse Heating

The economic analysis of the biomass furnace for greenhouse heating is the most important factor for farmers, as well as end users, in order to understand the cost of greenhouse heating that they have to pay by adopting this innovative technology. Therefore, an economic comparison of the biomass-based heating of greenhouse tunnel with a commercially available diesel-fired heater was carried out. The following assumptions were made in order to make an economic comparison of the two system:

1. It was assumed that both systems would be operated for 600 h per annum.
2. Labor cost as well as man-hours were assumed to be equal for both systems.
3. The life of the system was assumed to be equal for both systems.
4. The feeding rate of biomass (wood) for the furnace was fixed with the fuel consumption of the diesel heater. For example, 4 L/h was the fuel consumption of diesel heater. The calorific value of diesel was 45 MJ/Kg. This makes 12 kg/h of wood equal to the heating value of diesel.

Following Kepner et al. [25], the cost analysis based on fixed and variable costs of the biomass furnace for greenhouse heating is presented in Table 4. The purchase price (capital cost) of the new biomass furnace for greenhouse heating was estimated as USD 1562.50, whereas the market price of the diesel-fired heater was assumed to be USD 3125, and the useful life of the both systems was taken as 15 years. The annual fixed cost and variable cost of the biomass furnace for greenhouse heating was calculated to be USD 398.44 and USD 828.11, respectively. This made the total cost (fixed + variable) equal USD 1226.55. The cost of wood fuel consumption in an hour of furnace operation was USD 0.75, whereas for diesel heater it was USD 2.78. The repair and maintenance costs were USD 0.13/h for the biomass furnace and USD 0.42 for diesel heater. The electric load of the furnace was calculated as 1000 watts per hour whereas that of the diesel heater was 420 watts.

Apart from the capital cost, the operating cost of the biomass furnace is the most important economic consideration for the selection of greenhouse heating system. Table 5 shows the detail comparison of operational costs per day and per season of the biomass furnace using different biomass sources. The economic cost analysis presented in Table 6 indicates that the adoption of the biomass furnace as a greenhouse heating system could save about 1573.09 USD annually for each greenhouse grower. This means that the diesel heater is 2–3 times more expensive than the biomass furnace. Thus, the biomass furnace is economical and environmentally friendly as compared with the diesel-fired heater.

Table 5. Comparison of operational cost of biomass furnace using different biomass fuels with the diesel heater.

Fuel Source	Unit Calorific Value MJ/kg	Estimated Unit Cost (USD)	Biomass Feeding Rates Equivalent to 4 L Diesel Heating	Operational Cost (USD/h)	Operational Cost (USD/Season)	Net Seasonal Saving over Diesel Heating (USD)
Diesel	45.00	0.63	4.0 lit	4.67	2799.64	NIL
Wood	15.00	0.06	12.0 kg	2.04	1226.55	1573.09
Cotton stalks	14.00	0.04	13.0 kg	2.04	1117.80	1681.84
Corn cobs	14.00	0.04	13.0 kg	1.78	1069.05	1730.59
Cow dung	8.00	0.03	22.5 kg	2.00	1198.43	1601.21
Rice husk	15.00	0.05	12.0 kg	1.89	1136.55	1663.09
Wood chips	18.00	0.05	10.0 kg	1.79	1076.55	1723.09

Operational cost is determined by following Kepner et al. [25].

Table 6. Cost analysis of a biomass furnace for greenhouse heating.

Item	Diesel Heater	Biomass Furnace
Basic information		
Purchase price (USD)	3125	1562.5
Annual usage (hr)	600	600
Life (yrs)	15	15
Life (hrs)	9000	9000
Salvage value (USD)	312.5	165.25
Fixed cost		
Depreciation (USD/hr)	0.31	0.16
Interest (USD/hr)	0.86	0.43
Insurance (USD/hr)	0.05	0.03
Tax (USD/hr)	0.05	0.03
Shelter (USD/hr)	0.05	0.03
Sub-total (USD/hr)	**1.33**	**0.66**
Variable cost		
Electricity cost (USD/hr)	0.13	0.13
Cost of diesel/wood (USD/hr)	2.78	0.75
Labor cost (USD/hr)	0.38	0.38
Repair and maintenance (USD/hr)	0.42	0.13
Sub-total (USD/hr)	**3.34**	**1.38**
Total Cost (USD/hr)	**4.67**	**2.04**
Operating cost (USD/day)	**46.66**	**20.44**
Saving over diesel heater (USD/hr)		**2.62**
Saving over diesel heater (USD/day)		**26.22**
Saving over diesel heater (USD/Season)		**1573.13**

Conversion rate is based on 1 USD being equal to PKR 160.

4.4. Emissions of Flue Gases

One of the major drawbacks of the conventional greenhouse heating systems is the emission of a higher concentration of greenhouse gases into the atmosphere. The emission of four flue gases (carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon dioxide (CO_2)) was monitored before and after the installation of the water scrubber smoke filter over the top of the furnace. In case of no water scrubber, excessive (greater than National Environmental Quality Standards-NEQS limits) carbon monoxide (CO) was only detected for cotton stalks and cow dung. The concentrations of the remaining three flue gases remained well below the NEQS limits, which are specified as 698, 649, and 638 ppm for CO, SO_2, and NO_2, respectively, whereas such a limit is not specified for

CO_2. Nevertheless, the provision of a water scrubber smoke filter significantly reduced the concentrations of the emitting flue gases into the atmosphere (Figure 8).

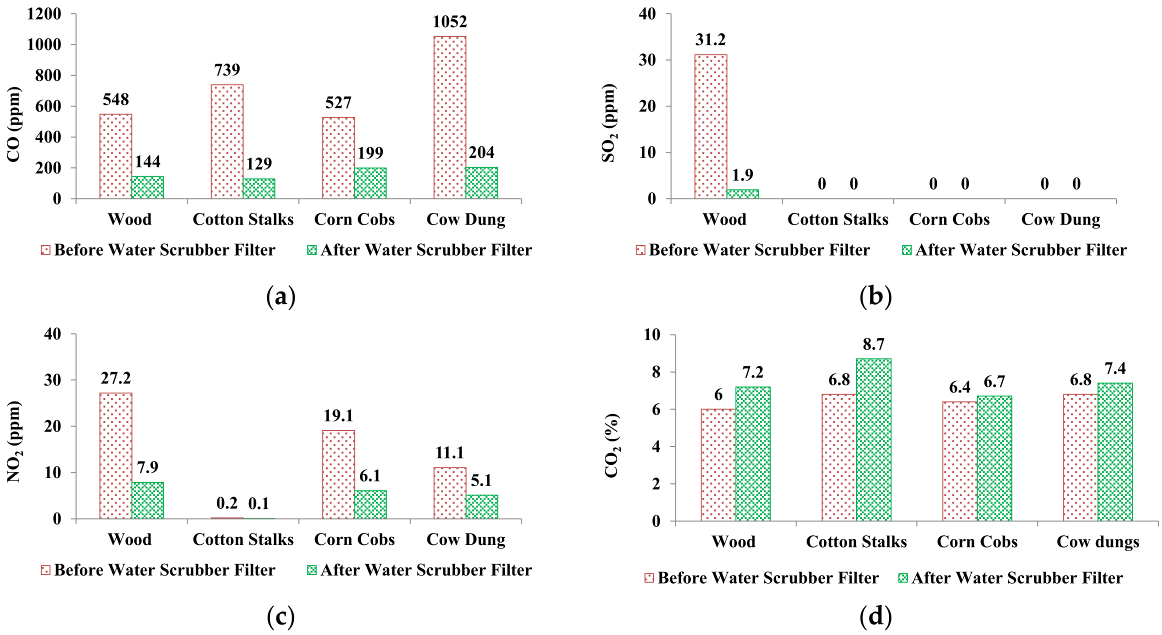

Figure 8. Flue gas concentrations of different biomass fuels before and after the water scrubber. (**a**) Carbon monoxide (CO). (**b**) Sulphur dioxide (SO_2). (**c**) Nitrogen dioxide (NO_2). (**d**) Carbon dioxide (CO_2).

The provision of the water scrubber smoke filter reduced CO concentrations by 73.7% from wood, 73.9% from cotton stalks, 62.2% from corn cobs, and 80.6% from cow dung, while 99.4% of the SO_2 was removed from wood. Sulfur dioxide was in considerable concentration only in wood, whereas in cotton stalks, corn cobs, and cow dung, it could not be detected. Similarly, the removal of NO_2 concentration was about 71.0% for wood, 50.0% for cotton stalks, 68.1% for corn cobs, and 54.1% for cow dung. It is worth noting that the addition of the water scrubber smoke filter did not reduce the emission of CO_2; rather its concentration was slightly increased due to the reaction of CO with water to form CO_2. The elevated levels of CO emissions from cotton stalks and cow dung were efficiently lowered to meet the NEQS.

5. Conclusions

A biomass furnace was successfully designed and developed at the Faculty of Agricultural Engineering and Technology, PMAS-AAUR, with the aim of utilizing biomass (crop residues) in an efficient and economical way as an alternative energy source to fossil fuels for greenhouse heating. Based on the experimental results, the following conclusions were drawn:

i. A biomass furnace is an efficient and attractive heating system for greenhouse heating and has great potential for similar uses like the heating of farmhouses, poultry sheds, and water; and the drying of grains, fruits, and vegetables.
ii. The designed biomass furnace is lightweight and portable, which enhances its practical utility.
iii. Modifications made to the biomass furnace, such as the insulation of the outer walls of the furnace, the provision of turbulators in fire tubes, and the addition of a secondary heat exchanger (heat recovery unit) in vent/chimney increased the thermal efficiency of the biomass furnace by 21.7% (from 43.68% to 53.15%).
iv. The thermal efficiency of the biomass furnace can be increased considerably by using fabrication materials with greater thermal conductivities (e.g., silver, copper, brass, etc.) and by installing the furnace inside the tunnel.

v. The thermal efficiencies of the biomass furnace with different biomasses were lower than the diesel-fired heater and ranged from 50.42% to 54.18% against 71.9% by diesel fuel. In terms of equal calorific value of 4 L diesel, the thermal efficiencies of different biomasses vary slightly with the highest efficiency for wood followed by corn cobs, cotton stalks, and cow dung.
vi. The designed biomass furnace is significantly more economical as compared to a commonly used diesel heater. Its capital cost is only 50% and operational cost is about 43.7% of the traditional diesel fuel heater. Hence, a seasonal saving of 1573 USD over the diesel heater can be achieved by using a biomass furnace.
vii. The seasonal operating cost of the biomass furnace is about 50% of the diesel heater (1562.5 USD against 3125 USD).
viii. The produced smoke was tested as environmentally friendly under the prescribed limits of the National Environmental Quality Standards (NEQS), which shows potential for its large-scale adoption, and wider applications can be a source of safe disposal of agricultural wastes.

Keeping in view the increasing rates of fossil fuels and easy availability of crop residues at the farms, the designed biomass furnace displays a very high potential for its large-scale adoption in the heating of various systems. However, the lack of policy framework, adequate research and development, market development, commercial services, farmer awareness, trainings, demonstration, and legal and regularity issues are the major bottlenecks in the utilization of these biomass resources within the country.

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