AGRICULTURAL SCIENCES JOURNAL VOL(2025)7-(2): 1-18

Agricultural Sciences Journal
Available online at http://asj.mnsuam.edu.pk/index.php
ISSN 2707-9716 Print
ISSN 2707-9724 Online
https://doi.org/10.56520/asj.v7i2.514

Research Article

DESIGN, CONSTRUCTION AND PERFORMANCE EVALUATION OF INDIGENOUS HEATING SYSTEM FOR HYDROPONICS GREENHOUSES

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Abstract

Hydroponic farming enables year-round vegetable production, however, it requires specific temperature and humidity control for optimal plant growth. In winter, when ambient temperatures drop below 16 °C, supplemental heating becomes essential. To address this challenge, an indigenous air-heating system was developed and evaluated for its effectiveness in three greenhouse types including glasshouse, fiberglass house and polythene house. Three types of fuels (wood, crop residues and solid waste) were used during experimentation. Wood shown better performance for heating of greenhouse as compared to its competitors (crop waste, solid waste) because of its higher calorific value. However, crop waste and solid waste fuels were more economical as well as abundantly available. Results showed that the glasshouse provided the most effective temperature regulation due to its higher heat transfer efficiency under higher temperature gradients. The fiberglass house demonstrated moderate performance with an average heat output of 26,000 Btu, while the polythene house was least effective, producing only 18,000 Btu with poor heat distribution. Inadequate heating in the polythene house delayed plant growth and fruit ripening. Overall, the study highlights the importance of greenhouse design in achieving efficient heating for hydroponic crop production under cold climatic conditions.

Keywords: *Fiberglass house, Greenhouse, Hydroponics, Heating system, Heat transfers, Polythene house.*

(Received: 03-July-2025 Accepted: 27-Aug-2025) Cite as: Raza, S. M., N. A. Rai., U. H. Zia., W. Ahmad., A. Tajwar., A. K. Aksar, H. B. Mirza., 2025. Design construction and performance evaluation of indigenous heating system for hydroponics greenhouses. Agric. Sci. J. 7(2): 1-18

1. INTRODUCTION

The escalating demand for food production, coupled with the growing awareness of sustainable agricultural practices, has driven the development of innovative greenhouse technologies, particularly those integrating hydroponics and advanced environmental control systems. Hydroponics, a soilless cultivation technique, provides advantages such as efficient water usage, reduced land requirements, and higher crop yields. However, the successful implementation of hydroponics in greenhouses, especially in regions with fluctuating climates, depends on maintaining optimal environmental conditions, with temperature regulation being a primary factor. Greenhouse systems have evolved to create controlled environments that promote plant growth, with automation playing a central role in improving productivity. Automation in greenhouses began in the 1950s with simple thermostat-based temperature control and has since expanded to encompass structural design, environmental regulation, and sustainability features (Teruel, 2010).

Greenhouse cultivation has become an essential component of modern agriculture,

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particularly in regions where climatic conditions are not favorable for year-round crop production. In recent years, hydroponics has gained attention as a soil-less cultivation method that enhances water and nutrient use efficiency while maximizing crop yield in controlled environments (Jensen, 1997). However, maintaining optimal environmental conditions especially temperature is critical for successful hydroponic greenhouse operations, particularly during cold seasons.

Traditional heating systems used in greenhouses often rely on fossil fuels, which can be expensive and environmentally unsustainable (Abdel-Ghany and Al-Helal, 2011). In developing countries, limited access to high-tech heating systems and energy sources makes it difficult for small-scale farmers to sustain greenhouse productivity during winter. To address these challenges, there is a growing interest in developing indigenous, low-cost, and energy-efficient heating systems using locally available materials and technologies (Khalil and Mirza. 2009).

Temperature control directly influences plant physiological processes, including nutrient uptake, photosynthesis, and respiration. Sub-optimal root zone and air temperatures in hydroponic systems can lead to stunted growth, nutrient deficiencies, and poor fruit development (Resh, 2013). Thus, maintaining a suitable thermal environment is not only crucial for plant health but also for optimizing hydroponic system efficiency and reducing energy consumption.

Several researchers have explored alternative heating approaches such as solar thermal systems, compost heating, geothermal heating, and biomass-fueled systems to reduce greenhouse energy dependency (Hashem *et al*., 2012; Aldrich and Bartok, 1994). However, these solutions often require technical expertise and capital investment, making them less feasible for low-resource settings. Indigenous heating systems, when properly designed and implemented, offer a sustainable and context-sensitive solution by utilizing locally available fuels such as agricultural residues, wood chips, or biomass waste (Shukla *et al*., 2014).

An indigenous heating system for hydroponics greenhouses necessitates careful consideration of several design parameters, including heat source selection, heat distribution methods, insulation strategies, and control mechanisms. The choice of heat source profoundly impacts the system's efficiency, cost-effectiveness, and environmental footprint. Solar energy represents a particularly attractive option, offering a renewable and sustainable alternative to fossil fuel-based heating systems concentrated solar power systems can be used to control greenhouse climate (Sonneveld *et al*., 2014).

The present project has been developed to design an indigenous heating system for a hydroponic greenhouse using farm waste, solid waste, raw wood and /or any other source of cheaper fuel, depending on their availability and cost.

Greenhouse temperature and humidity definitely need to be regulated for proper crop development. Both lower and upper extremes of these parameters prove dangerous, for instance, during low temperatures, the pollination of flowers retards due to slowed bumblebee activity. As a result, ripening of the crop is delayed, fruit size is reduced and ultimately, the crop yield is curtailed. Therefore, the hydroponic growers arrange heating systems near the sheds to maintain their temperature and humidity. All these demands require considerable energy for what the managers have to plan for energy generation and energy saving techniques. The literature reveals that people have worked on this aspect throughoutout history and have come up with many and varied greenhouse heating methods. Even in Pakistan, farmers hesitate to listen to hydroponic farming, considering it a luxury of the developed nations, since the initial cost of the system is too high in addition to the the energy costs involved in greenhouses. In spite of the fact that hydroponics pays back its initial investment just in one year. Previous studies and experiences of the researchers suggest that there are techniques like energy release from biodegradation of wastes that are almost free of costs burdens that can be profitable used for heating the hydroponic greenhouses. Similarly the use of farm wastes, for burning and heating of air is also a cheaper option that needs to be developed under the field conditions of Pakistan for heating tunnels there are several types of crops wastes at Pakistan farms such as rice straw, shelled corn cobs leaves of potatoes, groundnuts crops, sugarcane straws etc. in case of hydroponic farming considerable crop wastes from de-leafing activity is also procured that can be beneficial used for biodegradation and heat generation or the same can be used for burning and heating the air entering into greenhouses. The objective of this study is to design, construct, and evaluate the performance of an indigenous heating system for a hydroponics greenhouse. The system aims to ensure adequate heat delivery, maintain root zone temperatures within optimal ranges, and improve overall energy efficiency using simple mechanical components and accessible fuel sources. The study also assesses the thermal distribution within the greenhouse and examines the system's suitability under varying environmental conditions. In view of this, the present study has been planned to burn farm wastes and heat up the air entering greenhouses.

2. MATERIALS AND METHODS

This research work was conducted at Rawat Hydroponics Station of PMAS Arid Agriculture University Rawalpindi. An indigenous Masonry Kiln was designed and constructed for heating air passing through a loop of pipes over the flames of burning materials in the system. It was planned to locate the kiln near to existing greenhouses at the Farmers Market Private Limited, Rawat. Research area required for the kiln and storage of burning materials was estimated to be 4046 m^2 for each system of heating.

Design and construction of indigenous air heating system

This indigenous air heating system included: a fire chamber, a cold air intake chamber, a hot air delivery chamber, ash collecting chamber, blower, and chimney. The installation and construction of heating system is described in Figure 1 and 2.

An indigenous air heating system was developed for greenhouse heating, comprising a fire chamber, cold air intake chamber, hot air delivery chamber, ash collecting chamber, blower, and chimney. The air intake chamber, built with concrete walls (2.13 m × 0.60 m × 0.45 m), holds 0.57 m^3 of cool air drawn from the greenhouse. This air feeds into 22 small pipes and a large 10 cm looped pipe above the fire chamber for heating. The fire chamber (0.7 m^3) has two sections, separated by a grill: the lower ash chamber and the upper combustion chamber, where combustibles like wood, crop waste, or domestic waste are burned. Heated air flows into the hot air delivery chamber (2.13 m × 0.60 m × 0.45 m, 1.03 m^3 capacity), which connects to a blower (3.7 kW, 2850 RPM, 50 m^3/min). The blower draws in heated air, creates vacuum pressure, and distributes hot air through main pipes with nozzles spaced at 7.62 m intervals inside the greenhouse. The chimney (30 cm diameter, 3.05 m height) safely vents flue gases like CO, CO_2, and SO_2, placed higher than the greenhouse roof to avoid contamination. Ash is collected and reused as organic fertilizer. Each fuel type's heating efficiency is tested over 12 hours.

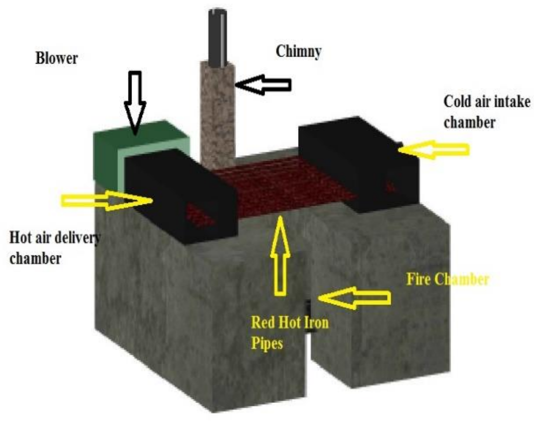

Figure 1: Cold and hot air chambers of indigenous heating system

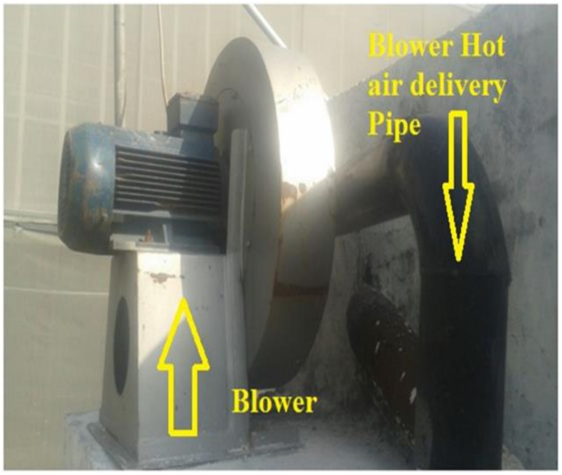

Figure 2: Blower of air heating system

Working process of proposed system

The study measured daily temperature, humidity, and heat transfer into greenhouses clad with glass, fiberglass, and polythene using three fuels: wood, crop waste, and solid waste. The air heating system includes cool air intake, fire, and hot air delivery chambers. Air circulates from the greenhouse through intake pipes, passes over red-hot iron pipes in the fire chamber, and is pushed back by a blower through a 4" main pipe with 24 delivery valves. Typically, 12 valves are used alternately. A furnace operator feeds combustibles and manages the fire chamber door to reduce heat loss and improve efficiency.

Table 1: Specifications of indigenous air heating system

Sr. No	Components	Dimensions (m)
1	Fire chamber	1.21 x 1.21 x1.21
2	Cool air feeding chamber	2.13m x 0.76m x 0.60m
3	Hot air delivery chamber	2.28 x0.76 x 0.60
4	Blower	3.7 kw, CFM (1765)
5	Looping pipe	0.11 dia , 6.70 length
6	Rectangular box with air resistance plates	0.45 x 0.60 x0.30
7	Chimney Pipe	0.45 dia , 3.04 length
8	Ash collecting chamber	1.21 x 1.21 x1.21
9	Outer bricks boundary	3.65 x 3.65
10	Semicircular roof dome	1.21 dia,3.04 length

For investigating the performance efficiency of the designed heating system, it was desired to understand the heating values of various fuels, and similarly, heat-retaining efficiency of various cladding materials. Therefore, three different materials with varying heat values were selected. The materials selected were wood logs, domestic solid waste and farm wastes. The cladding materials for covering the greenhouses were tempered glass, fiberglass and polythene. The factors and their levels included in the experiment are tabulated (Table 2).

Table 2: Factors and their levels

Factors	Levels
Cladding materials	Tampered glass
	Fiberglass
	Polythene
Combustibles materials	Wood logs
	Domestic solid wastes
	Crop wastes

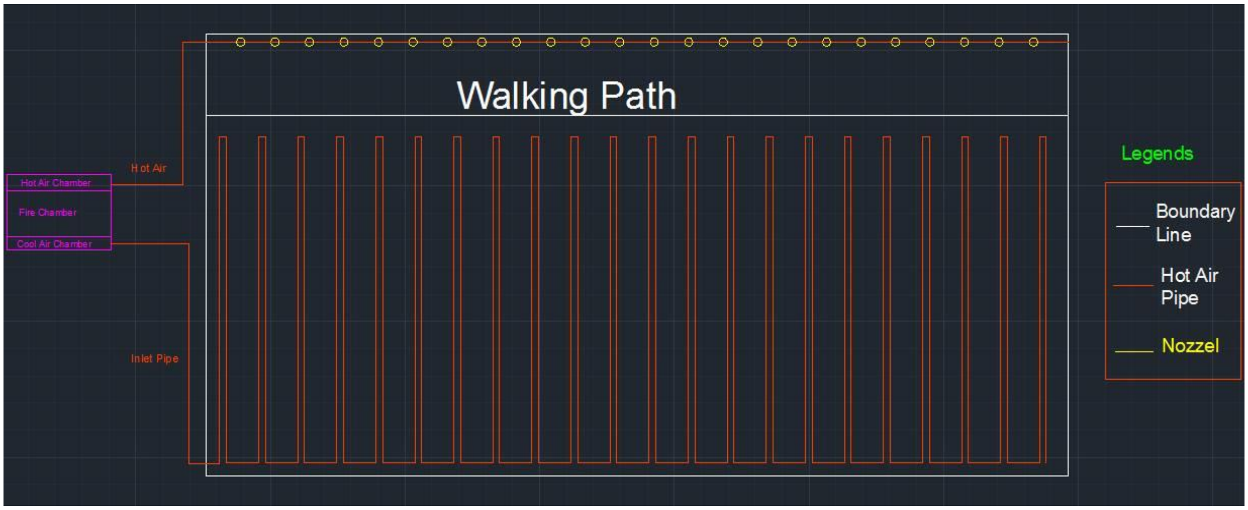

Figure 3: Top view of whole installed air heating system

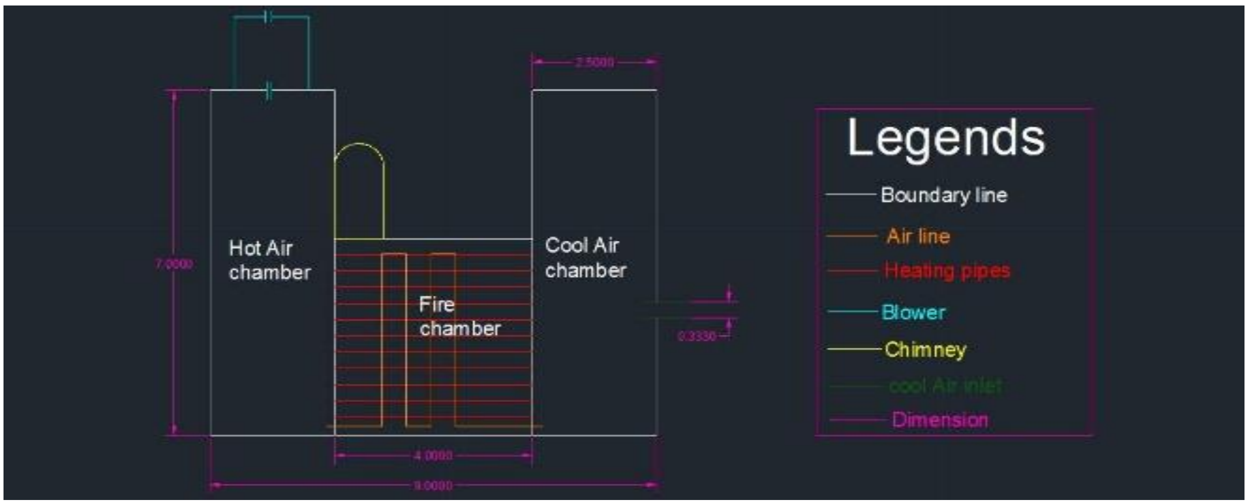

Figure 4: Top view of Furnace

Performance of the Indigenous Air Heating System was evaluated using average temperature, humidity, and heat (Btu) data over 30 days for three fuels. Thermometers placed at three points in each greenhouse recorded temperature/humidity. Heat gain was calculated using $Btu = K \times V \times (T_2 - T_1)$

Where;

V = Volume of air (ft^3/min) T_2=Temperature of air entering the greenhouse (centigrade) T_1=Tempeature of air leaving the greenhouse (centigrade)

K=Constant (1.08) for conversion of heat value in btu

Separate furnaces for each greenhouse was tested simultaneously.

3. RESULTS AND DISCUSSION

This chapter covers results and discussion for the indigenous air heating system at the three different greenhouses, each using three different combustibles for heating purposes.

An indigenous air heating system was designed to address low temperature conditions in greenhouses. The impact of the air heating system was studied by measuring the three main environmental variables, such as temperature, humidity, and total heat entering the greenhouses. Each of the greenhouses was spread over different areas, that is, one acre, one-fourth (1/4) of an acre, and one-eighth (1/8) of an acre. Different data were collected under variable conditions of various three greenhouses as outlined next.

Feeding of Burning Fuels

Three different types of combustibles were burnt, i.e., wood, solid waste, and crop waste in the fire chamber. The start and end times were the same for each type of greenhouse i.e., from 06:00 pm to 06:00 am. Temperatures of heated air and cold air were recorded at intervals of two hours throughout the operational periods. The temperature differences were further calculated.

Treatment No. 1

In this treatment, Greenhouse type different but burning fuel was kept constant. The observations against the climatic variables were recorded in the below mentioned tables.

Temperature difference measurements

In this treatment, the impact of greenhouse fuel was tested and noticed that greenhouse made of glass has more average temperature difference than the other two greenhouses made of fiber and polythene respectively. It was quite clear that glasshouse had more average temperature differences values than the other two greenhouses. The graphical representation temperature difference is shown in Fig. 5.

Fig. 5 showed temperature variations among greenhouses under the same ambient conditions. The glasshouse consistently exhibited higher average daily temperatures due to its superior heat retention. From Dec 25 to 28, temperatures rose across all greenhouses as ambient temperature increased (5.63 °C to 6.73 °C). Subsequently, a decrease in ambient temperature led to declining internal differences. The glasshouse showed the highest average temperature difference, peaking at 6.46 °C, and dropped to 4.45 °C by day 10. The fiberglass greenhouse followed a similar pattern with differences ranging from 3.6 °C to 4.5 °C initially and dropping to 2.9 °C. The polythene house showed the lowest heat retention, with a peak of only 2.22 °C and a minimum of 0.98 °C. Overall, internal temperature differences closely followed changes in ambient temperature, and performance varied significantly by cladding material. The glasshouse performed best, while the polythene house showed minimal heat retention efficiency. In this treatment, the impact of greenhouse material was tested, and noticed that the greenhouse made of glass has a greater average temperature difference than the other two greenhouses made of fiber and polythene, respectively. It showed the observations for average temperature differences of greenhouses.

The graphical representation of average temperature difference is shown in Fig. 6. Fig. 6 showed temperature variations among greenhouses under the same ambient conditions. The glasshouse consistently recorded the highest average daily temperatures due to its superior heat retention. From January 4 to 7, 2016, temperature differences rose across all greenhouses as ambient temperature increased from 5.25 °C to 7 °C. From the 4th to 6th day, temperature differences dropped (6.05 °C to 4.38 °C) with a decrease in ambient temperature (7 °C to 6.54 °C). From day 6 to 9, the difference rose again (4.38°C to 5.5 °C), followed by a decline (5.5 °C to 4.95 °C) on day 10 as the ambient temperature fell (6.98 °C to 5.8 °C). In the fiberglass house, the trend followed a similar pattern, with temperature differences ranging from 3.2 °C to 4.5 °C and a low of 3.38 °C.

In Fig. 6, the polythene house showed the lowest heat retention, with fluctuations from 1.73 °C to 2.5 °C. Overall, the glasshouse maintained the highest temperature difference (6.05°C), and the polythene house had the lowest (1.066 °C).

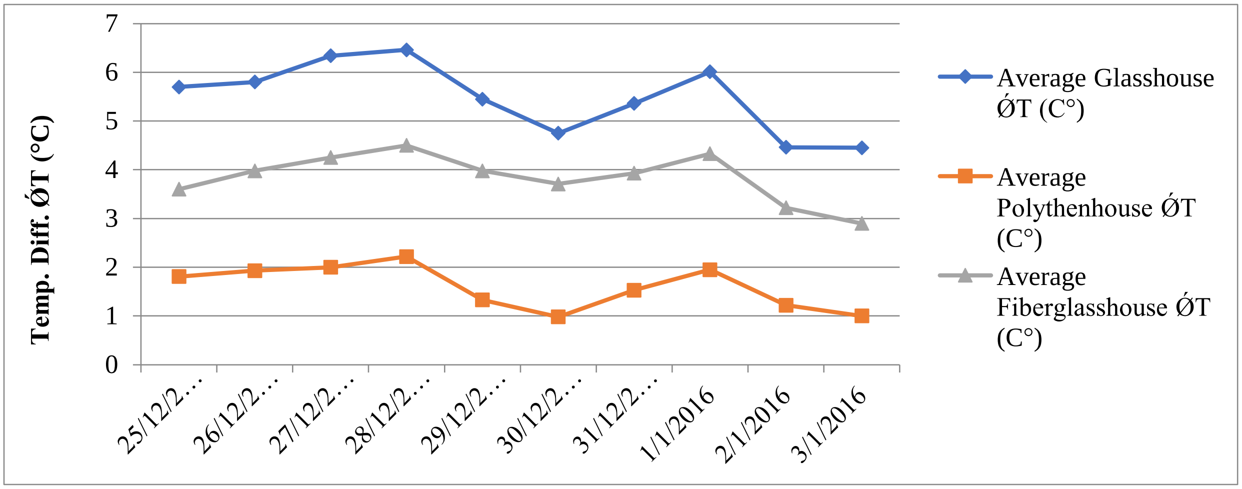

Figure 5: Average temperature differences for Greenhouses when "Wood" was used as burning fuel

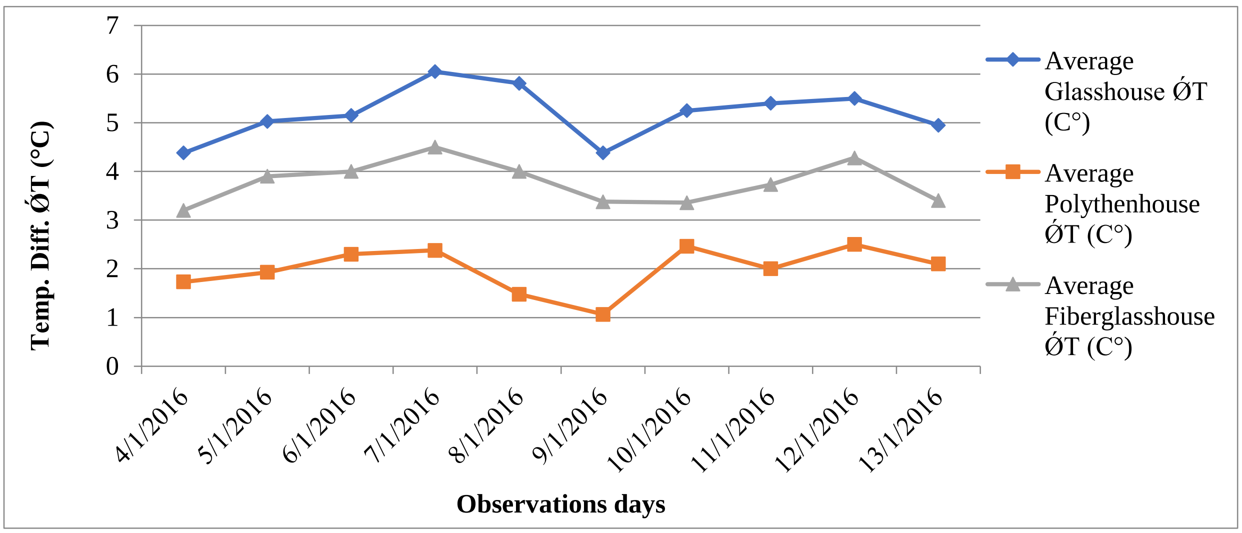

Figure 6: Temperature differences between Greenhouses when "Solid waste" was used as burning fuel

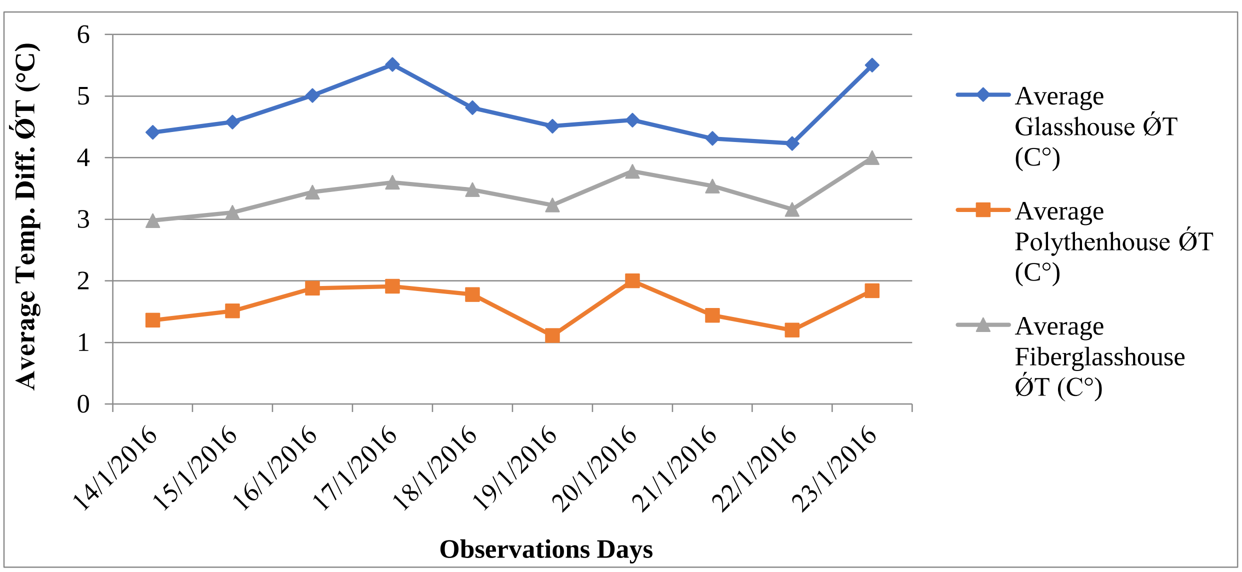

Figure 7: Temperature differences between Greenhouses when "Crop waste" was used as burning fuel

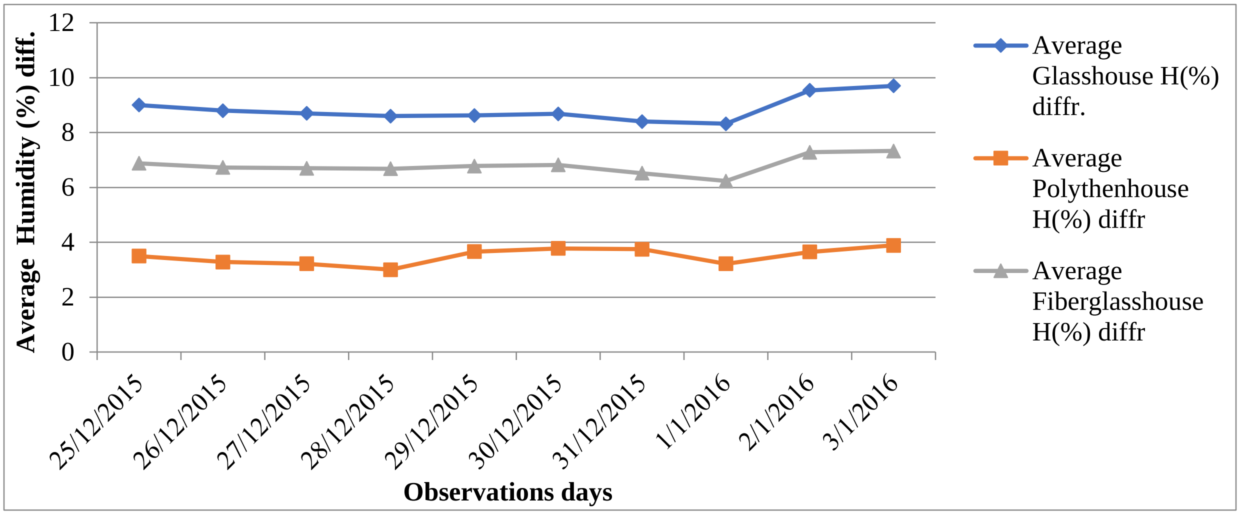

Figure 8: Humidity differences for all Greenhouses when "Wood" was used as burning fuel

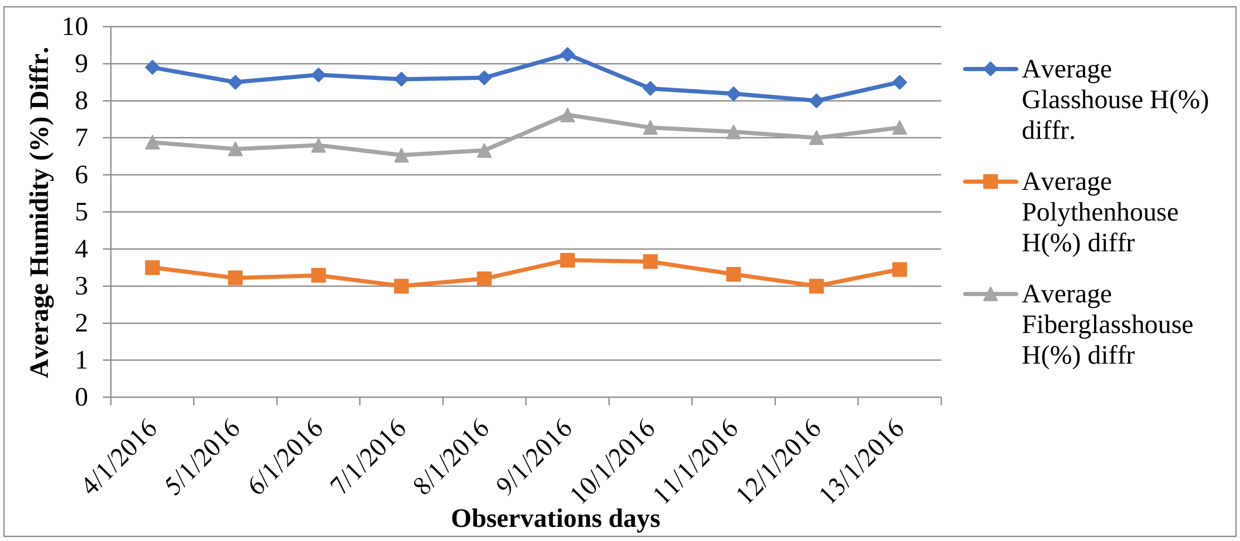

Figure 9: Humidity differences between Greenhouses when "Solid Waste" was used as burning fuel

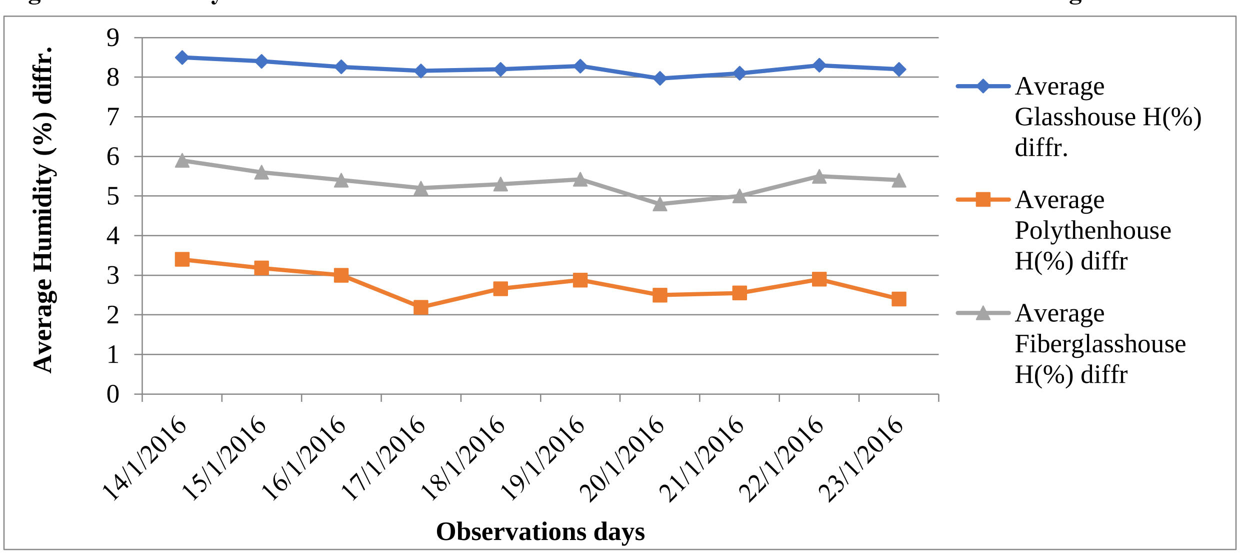

Figure 10: Humidity variations for Greenhouses when "Crop waste" was used as burning fuel

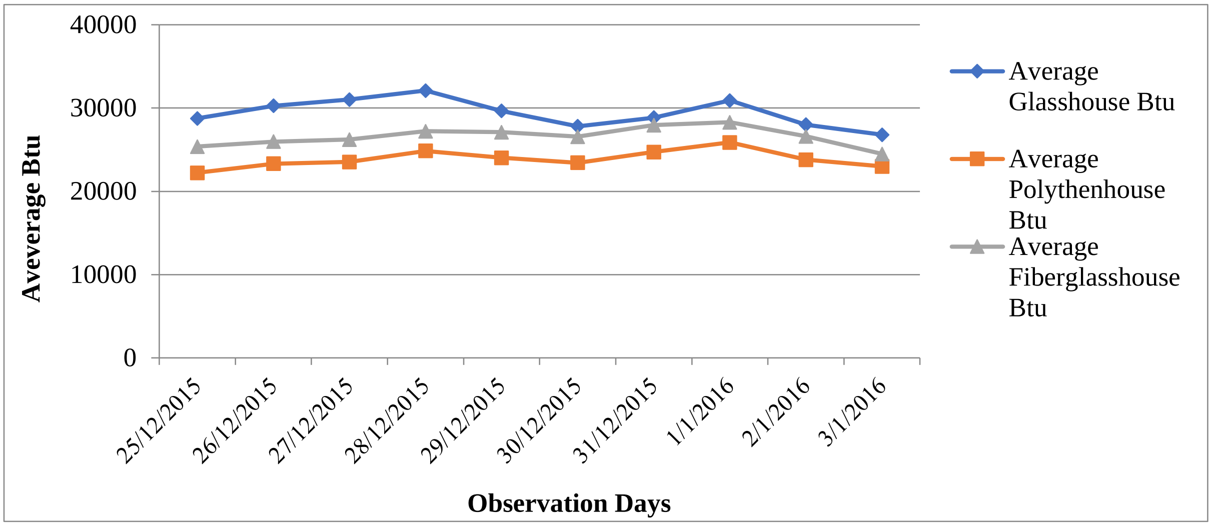

Figure 11: Btu values between Greenhouses when "Wood" was used as burning fuel

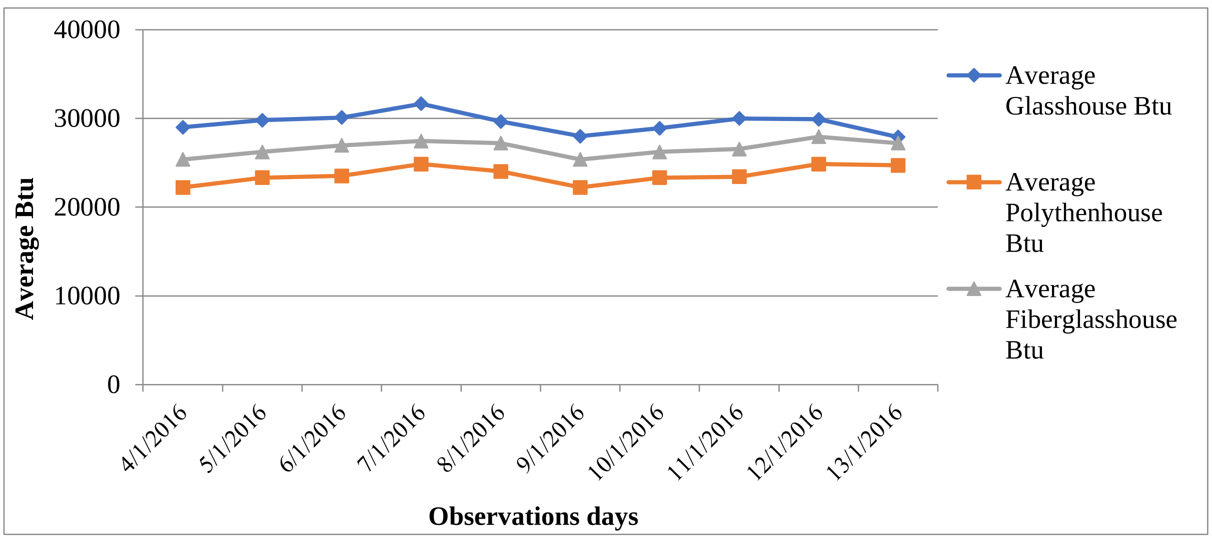

Figure 12: Btu values between Greenhouses when "solid waste" was used as burning fuel

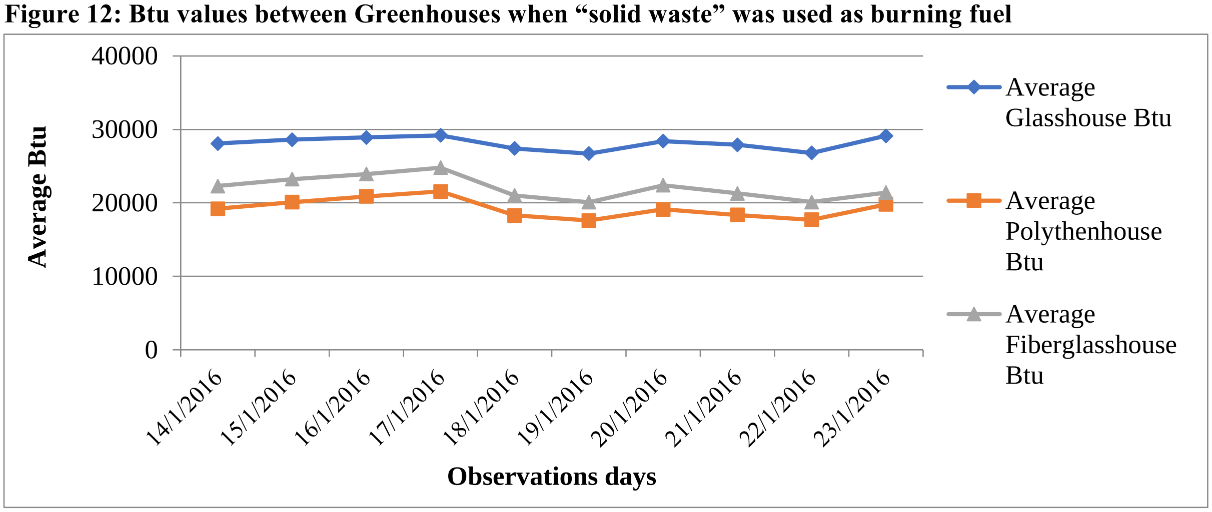

Figure 13: Btu values between Greenhouses when "Crop waste" was used as burning fuel

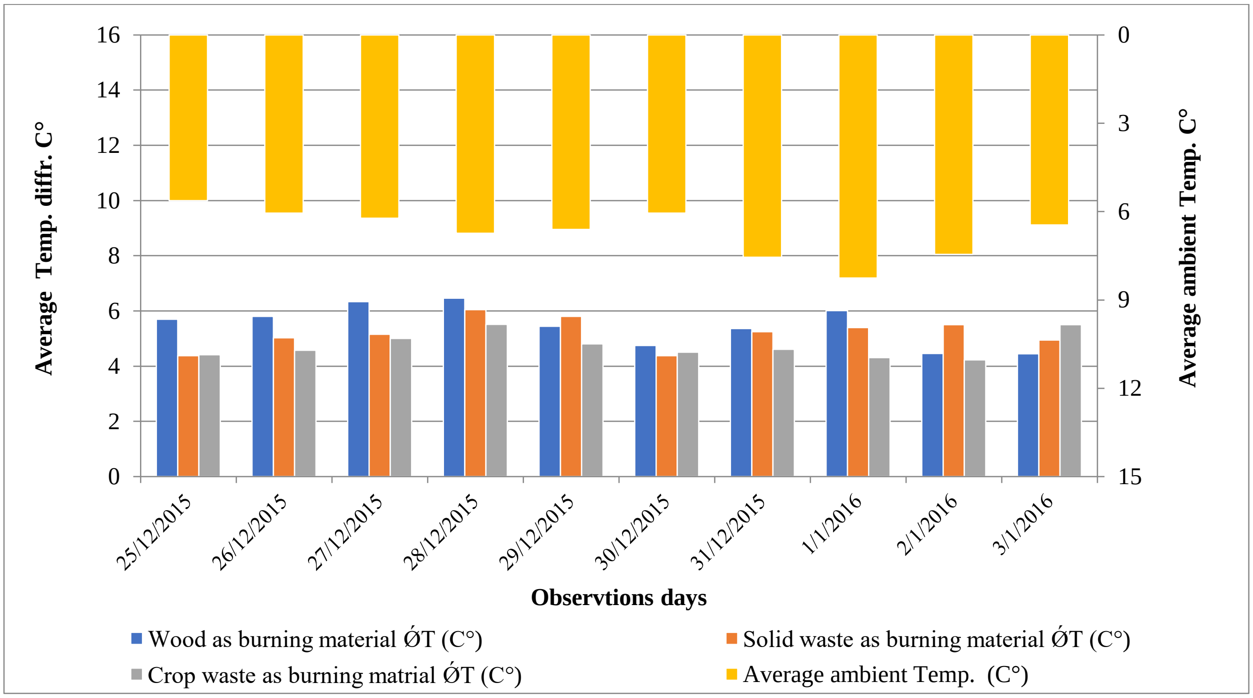

Figure 14: Graph of Temperature differences within the glasshouses against burning fuels (wood+solid waste+Crop waste) in furnace of Glasshouse

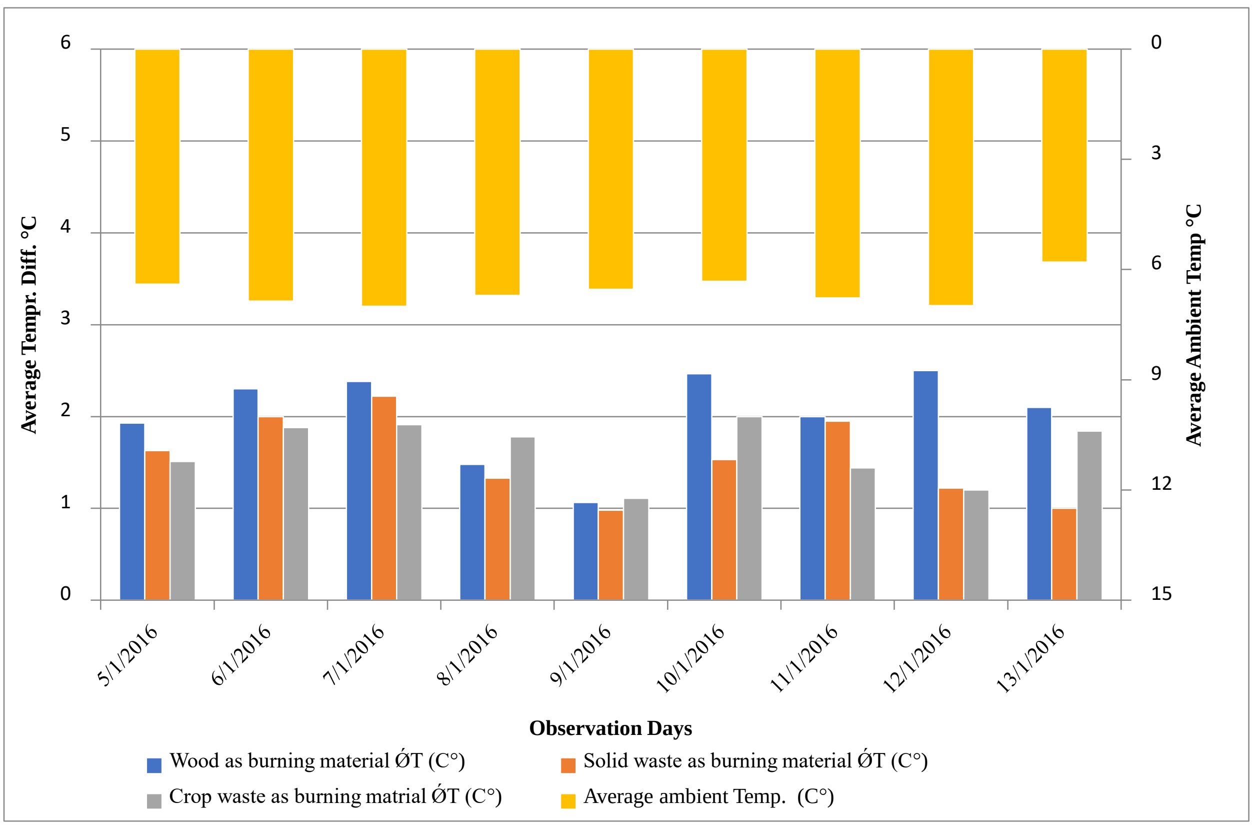

Figure 15: Graph of Temperature differences maintained by burning fuels (wood +solid waste+ Crop waste) in furnace of polythene house

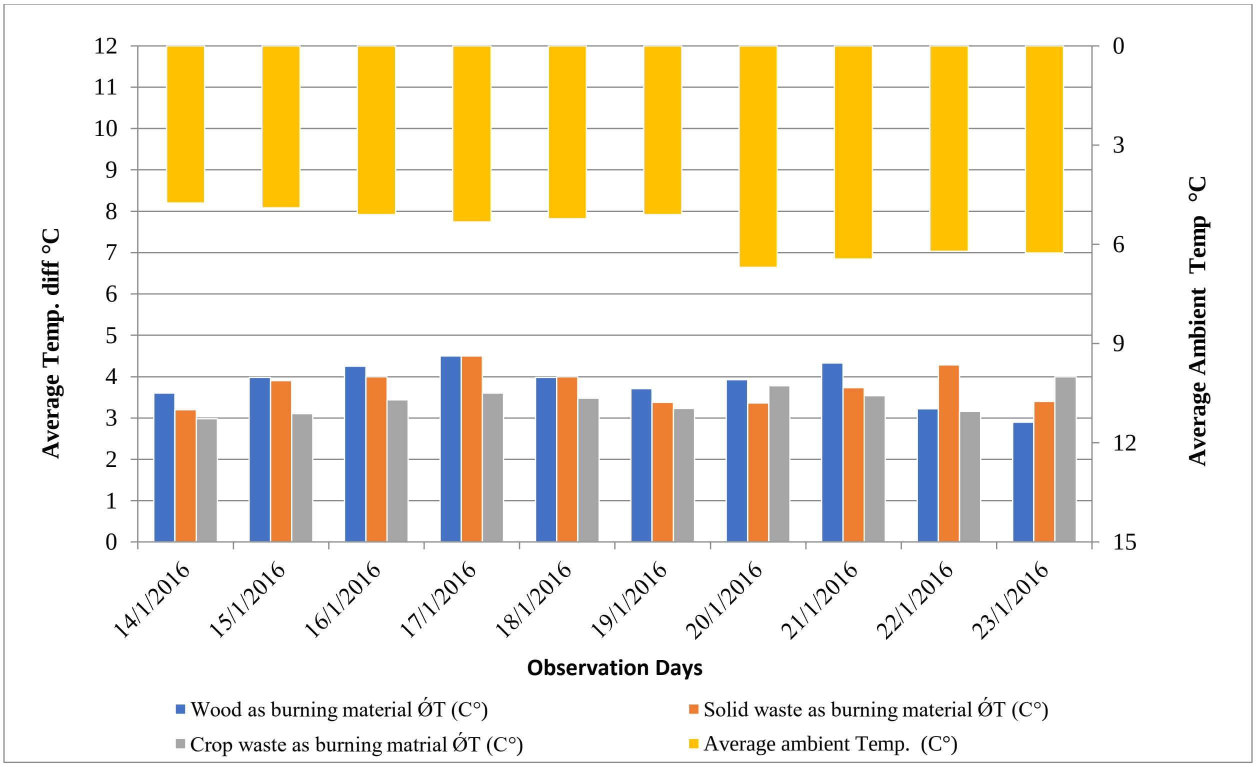

Figure 16: Graph of Temperature difference by burning fuels (wood solid waste crop waste) in furnace of fiberglass house

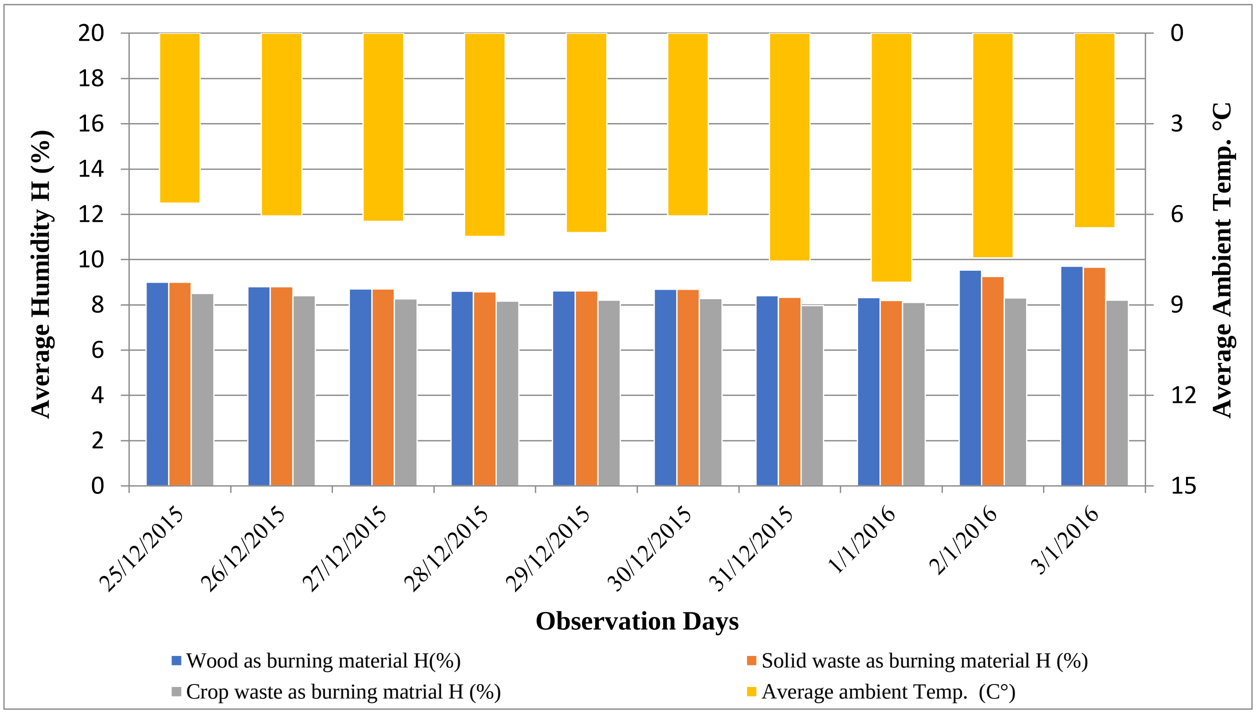

Figure 17: Graph of Humidity (%) differences by using all burning fuels (wood solid waste Crop waste) in furnace of glasshouse

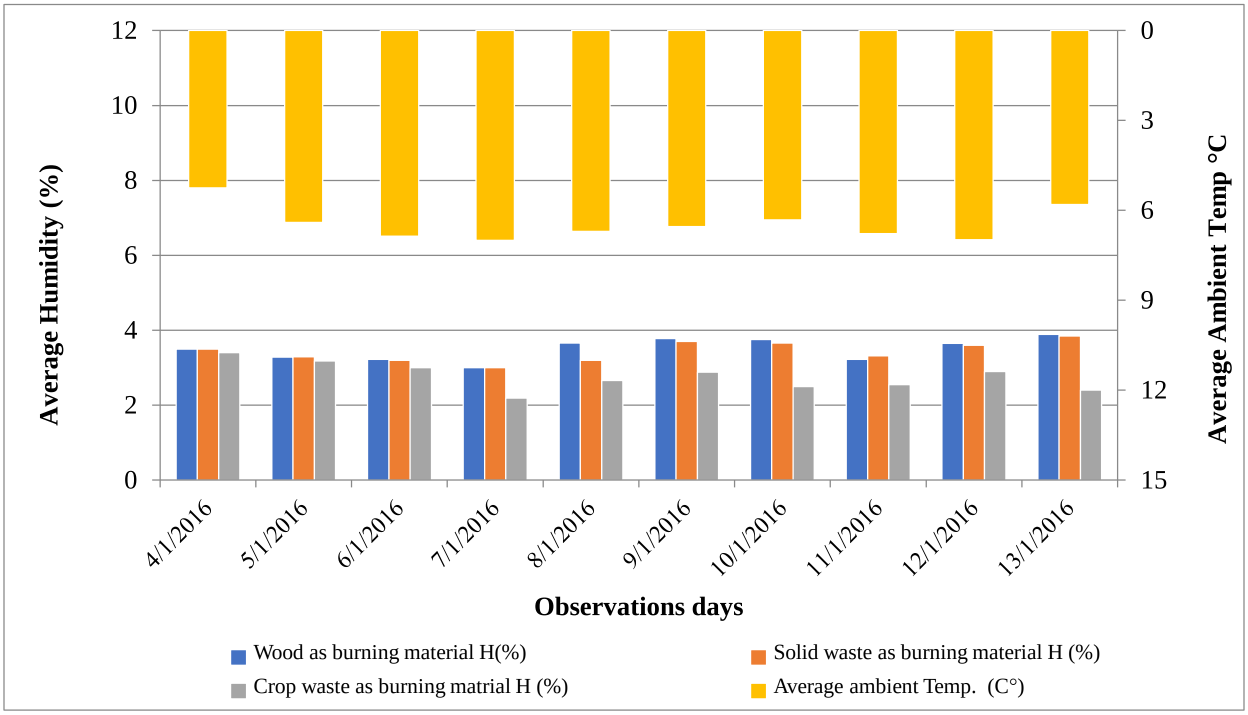

Figure 18: Graph of Humidity (%) differences by using all burning fuels (wood solid waste Crop waste) in polythene furnace

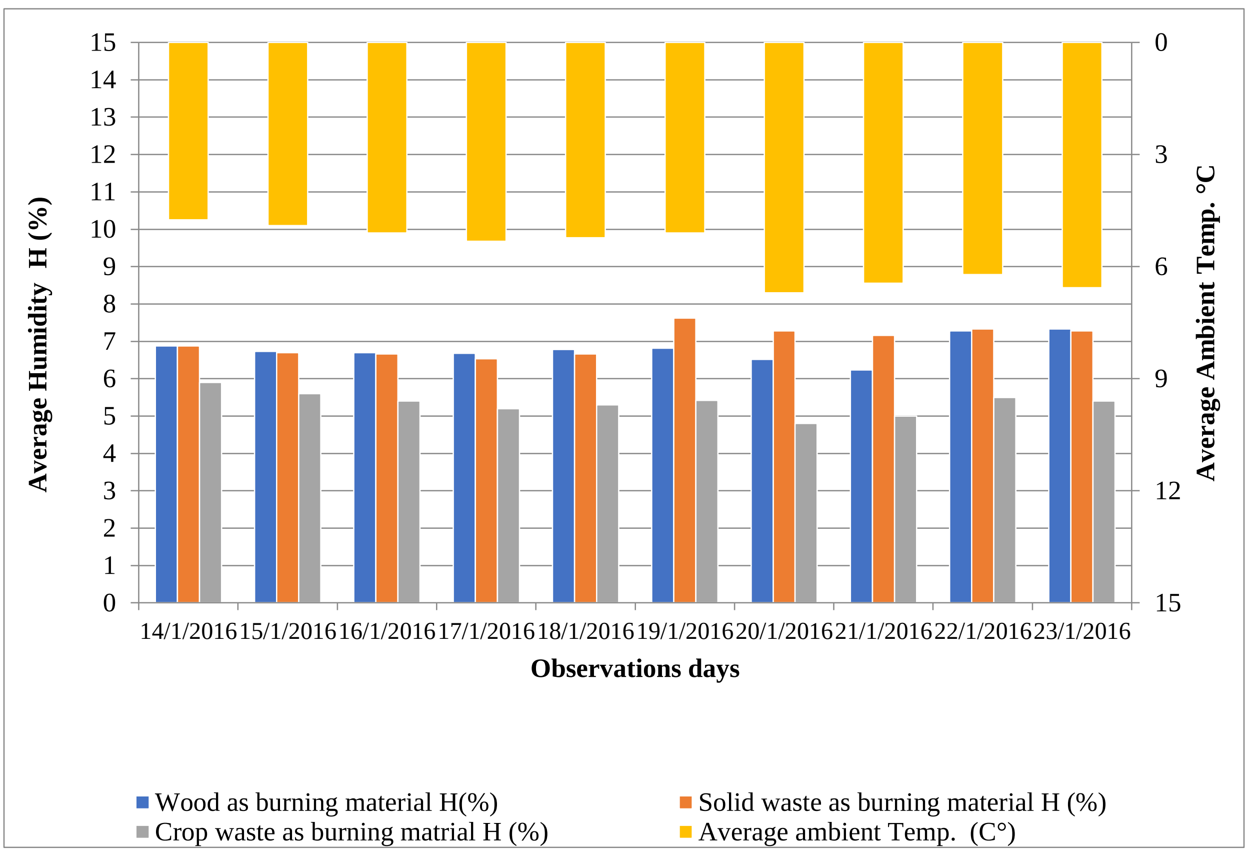

Figure 19: Graph of Humidity (%) differences managed by burning fuels (wood solid waste Crop waste) in furnace of fiberglass

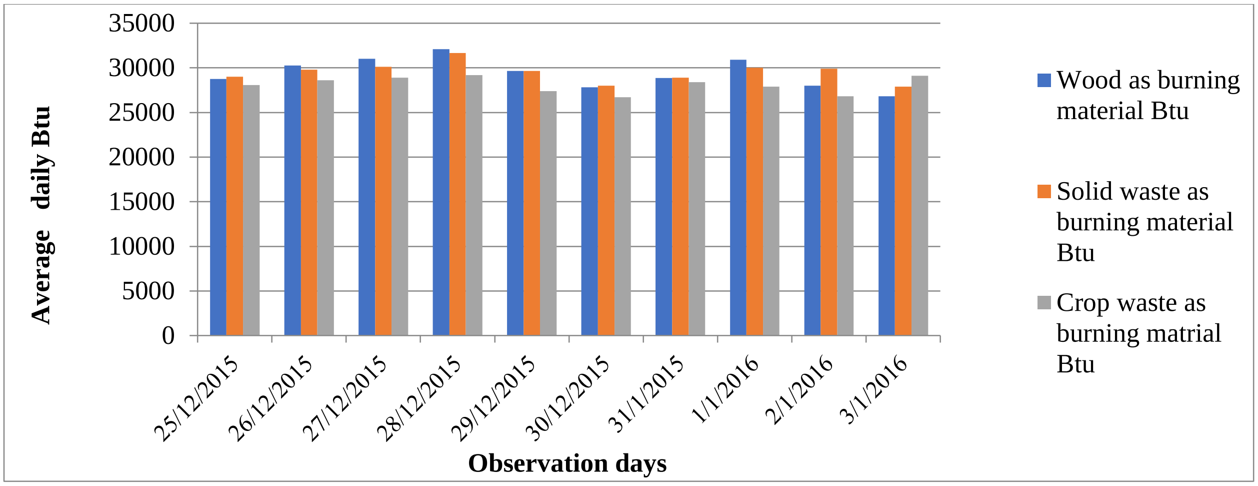

Figure 20: Graph of Btu imparted by burning fuels (wood, solid waste, Crop waste) within the furnace of Glasshouse

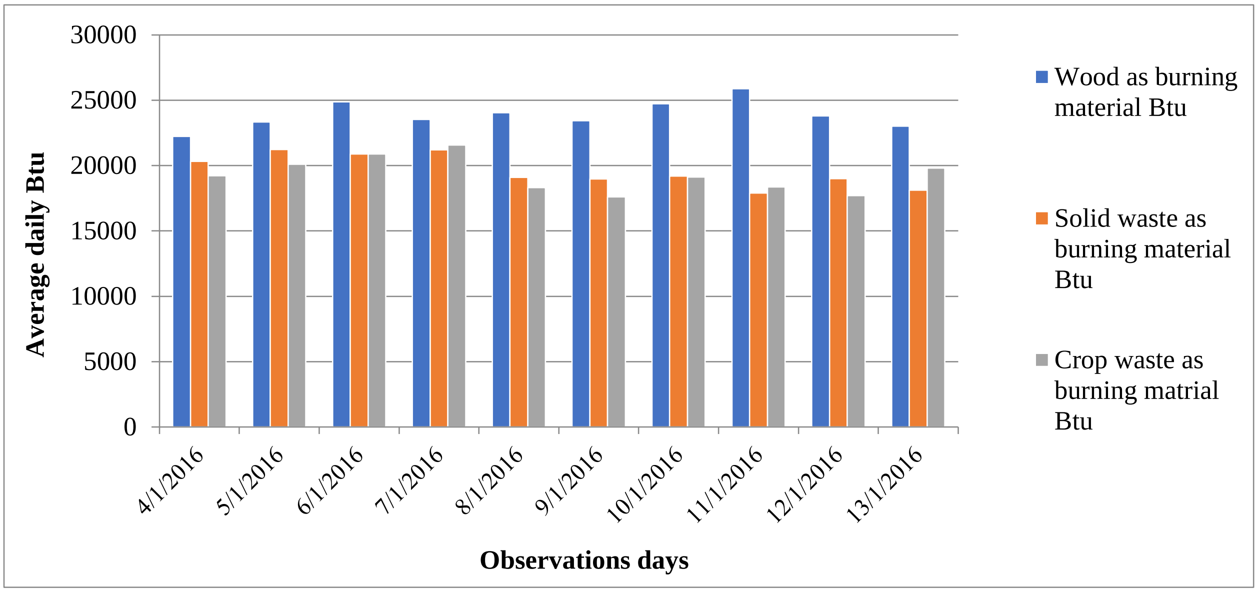

Figure 21: Btu values imparted by furnace when all fuels were used in Polythene house furnace

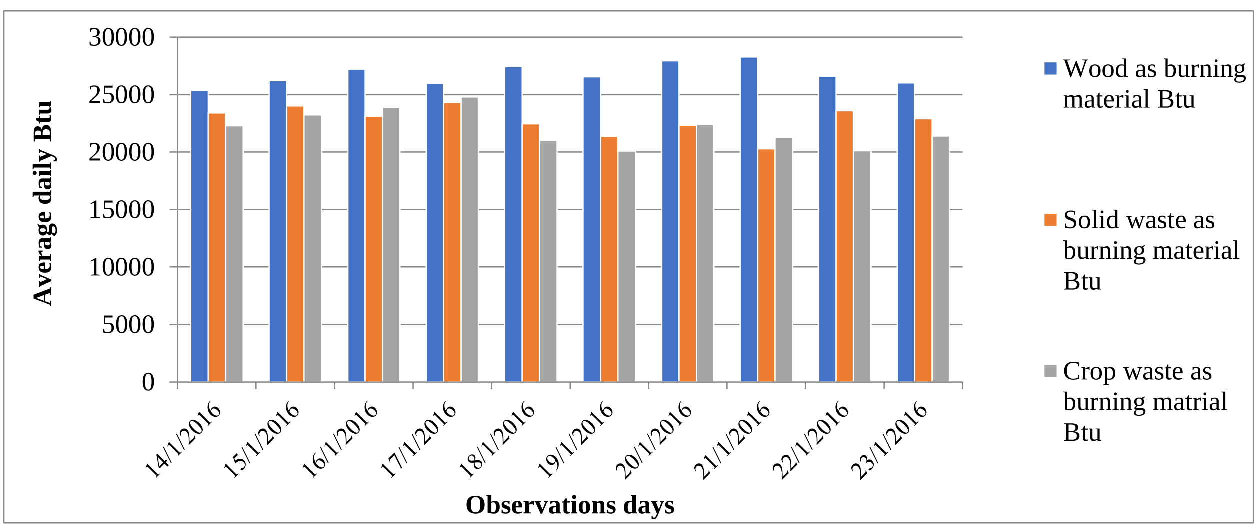

Figure 22: Btu values imparted by furnace when all fuels were used in fiberglass house furnace

In this treatment, the impact of greenhouse material was tested, and noticed that the greenhouse made of glass has a greater average temperature difference than the other two greenhouses made of fiber and polythene, respectively. It showed the observations for average temperature differences of greenhouses. From Table 4.10, it was quite clear that the glasshouse has more average temperature difference values than the other two greenhouses. It was analyzed that there was a significant effect of the nature of the material used in greenhouses. The graphical representation of the average temperature difference is shown in Fig. 4.7.

Fig. 7 illustrate temperature variations among greenhouses under similar average ambient conditions. The glasshouse consistently showed higher internal temperatures due to its superior heat retention. From January 14-17, 2016, average temperature differences rose from 4.41°C to 5.51°C, corresponding with an increase in ambient temperature from 4.75°C to 5.32°C. A decline followed from the 4th to 6th day (5.51°C to 4.51°C), linked to a drop in ambient temperature. Similar trends were observed in the fiberglass house (2.98°C to 4°C) and polythene house (1.36°C to 1.84°C), with minor fluctuations influenced by ambient temperature changes. The polythene house showed irregular behavior due to its lower thermal mass. Overall, internal greenhouse temperatures were directly related to ambient temperature, increasing or decreasing accordingly. The glasshouse retained the highest average temperature difference (5.51°C), while the polythene house showed the lowest (1.2°C). The type of construction material significantly influenced heat retention performance.

In this treatment, the impact of greenhouse material was tested and noticed that greenhouse made of glasshouse has more average humidity variations than the other two greenhouses made of fiber and polythene, respectively. It showed the observations for average humidity variations of greenhouses. The graphical representation of the average temperature difference is shown in Fig. 8.

Fig. 8 shows humidity variations in greenhouses under similar ambient temperatures. The glasshouse had the highest humidity due to better heat retention. From Dec 25-28, 2015, humidity decreased as temperature rose, then fluctuated with cooling and warming cycles. Polythene and fiberglass houses showed similar but lower humidity changes. Overall, humidity inversely correlated with ambient temperature. The greenhouse material influenced internal conditions, with glasshouses showing the largest humidity variation compared to fiberglass and polythene greenhouses. The graphical representation of the average temperature difference is shown in Fig. 9.

Fig. 9 illustrated humidity variations across greenhouses under similar ambient temperatures. The glasshouse showed the highest humidity due to better heat retention. From January 3 to 6, 2016, humidity decreased as temperature rose: in the glasshouse, it dropped from 8.9% to 8.58%, then rose to 9.25% as temperature fell, followed by fluctuations ending at 8.5%. The polythene house had lower humidity, ranging 3% to 3.7%, while fiberglass showed moderate variation between 6.53% and 7.62%. Overall, humidity inversely fluctuated with temperature, with glasshouse having the greatest retention and polythene the least. Greenhouse material impacts humidity variation.

Fig. 10 showed humidity variations in greenhouses using crop waste fuel under similar temperatures. The glasshouse retained the highest humidity due to better heat retention, with values decreasing from 8.5% to 8.16%, then slightly rising before settling at 8.2%. The fiberglass house had moderate humidity changes (5.9% to 5.2%), while the polythene house showed the lowest variation (3.4% to 2.4%). Overall, the glasshouse maintained superior humidity control, preventing fungal diseases. The maximum humidity difference was 9.2% in the glasshouse and the minimum was 2.5% in the polythene house, showing material impacts on humidity management.

Btu measurements

In this treatment, the impact of greenhouse material was tested, and noticed that the greenhouse made of glass has more average Btu variations than the other two greenhouses made of fiber and polythene, respectively. It showed the observations for average Btu variations of greenhouses.

Fig. 11 showed Btu variations among greenhouses under similar ambient temperatures. The glasshouse recorded the highest Btu due to superior heat retention, rising from 28,763.9 to 32,098.1 Btu as temperature increased (5.63°C to 6.73°C). It later fluctuated with temperature changes, dropping to 26,800.18 Btu by Day 10. The fiberglass house showed moderate Btu values, while the polythene house had the lowest, reflecting weaker thermal performance. Overall, greenhouse type significantly affects heat retention, with the glasshouse proving most efficient in conserving energy.

In this treatment, the impact of greenhouse material was tested, and noticed that the greenhouse made of glass has more average Btu variations than the other two greenhouses made of fiber and polythene, respectively. It showed the observations for average Btu variations of greenhouses. The graphical representation of the average temperature difference is shown in Fig. 12.

Fig. 12 showed variations in Btu values among greenhouses under similar ambient temperatures. The glasshouse exhibited the highest average daily Btu values due to better heat retention. From Jan 4 to Jan 7, 2016, Btu values increased in all greenhouses with rising ambient temperature. In the glasshouse, Btu rose from 29,008.1 to 31,663.9 Btu as temperature increased (5.25°C to 7°C), then dropped to 28,006.45 Btu with falling temperatures, followed by a rise and final drop to 27,900.18 Btu. Similar trends were observed in the fiberglass and polythene houses, though with lower Btu values. For example, in the fiberglass house, Btu ranged from 25,385.74 to 27,942.47 Btu, while in the polythene house, it varied between 22,219.71 and 24,866.82 Btu. The glasshouse showed the greatest temperature differences, making it the most effective at heat retention. Maximum Btu (31,663.9) was recorded in the glasshouse; minimum (21,223.71) in the polythene house.

In this treatment, the impact of greenhouse material was tested, and noticed that the greenhouse made of glass has more average Btu variations than the other two greenhouses made of fiber and polythene, respectively. It showed the observations for average Btu variations of greenhouses. The graphical representation of the average temperature difference is shown in Fig. 13.

Fig. 13 showed Btu variations in greenhouses under similar ambient temperatures during crop waste burning. The glasshouse had the highest average Btu due to better heat retention. From Jan 4-17, 2016, Btu values generally followed ambient temperature trends. In the glasshouse, Btu ranged from 28080.18 to 29200.17 Btu. In the fiberglass house, Btu rose from 22300.74 to 24800.73 Btu, then declined and fluctuated with temperature. Polythene house values ranged from 19213.71 to 21560.44 Btu, showing similar patterns. Overall, the glasshouse consistently showed higher Btu values and greater temperature differences, confirming it as the most effective structure. The maximum Btu was 29200.17 Btu (glasshouse) and the minimum was 17606.05 Btu (polythene house).

Treatment No. 2

In this treatment, the greenhouse type was kept constant, and the fuel nature was varied.

Temperature measurements

Three burning fuels were burned in furnaces respectively. It was observed that the burning fuel of wood produces more average temperature variations as compared to the other two burning fuels.

Fig. 14 showed temperature variations using three different burning fuels (wood, crop waste, solid waste) under similar ambient conditions in a glasshouse from Dec 25-28, 2015. Wood generally showed slightly higher average temperature differences due to its higher calorific value. On day 5, solid waste produced the highest temperature due to low moisture. From days 6-8, wood again led due to increased ambient temperature and dryness. On day 9, solid waste regained the lead, while crop waste had the highest on day 10. Overall, temperature differences among fuels were minor and mainly influenced by fuel quality and quantity. With proper adjustments, the performance of all fuels can be optimized to achieve desired temperature levels.

Fig. 4.15 showed temperature differences from burning solid waste, wood, and crop waste in a polythene house. From days 1-4, temperature differences rose steadily with ambient temperature (5.25°C to 7°C), with wood performing best due to low moisture and high calorific value. On days 5-6, crop waste outperformed others due to lower moisture. Day 6 showed lower differences for all fuels due to low ambient temperature. Wood led again on day 7 but had poor combustion. From days 8-10, solid waste gave the highest temperature differences due to low moisture. Overall, differences among fuels were small and primarily driven by moisture and quality. Solid and crop waste can effectively replace wood if material conditions are optimized.

Figure 16 illustrates temperature differences using wood, solid waste, and crop waste in a fiberglass house. From days 1-4, temperature differences steadily increased (4.75°C to 5.32°C), with wood and solid waste performing well due to low moisture. From days 5-6, both fuels maintained high values due to dryness. A slight decline occurred on day 7 due to low ambient temperature, then increased again with better ambient conditions. On day 9, solid waste outperformed due to low moisture, while wood and crop waste showed similar results. On day 10, crop waste led, followed by solid waste. Moisture and fuel quality primarily affected performance. The graph suggests solid and crop waste can replace wood, offering similar temperature management under proper material conditions.

Figure 17 showed that from days 1-6, average humidity differences remained constant across all fuels under steady ambient temperatures (5.63°C to 6.73°C). This pattern continued from days 7-9, even under varying conditions. On day 10, crop waste showed better results than solid waste, which had lower values due to low moisture. Overall, humidity differences among fuels were minimal, mainly influenced by fuel quantity and quality. Adjusting these factors can help achieve desired humidity and temperature control in greenhouses.

Figure 18 shows that from days 1-3, humidity differences decreased in the polythene house, indicating poor humidity control. From days 4-6, wood and solid waste showed constant humidity behavior. From days 6-10, humidity differences increased due to rising ambient temperatures and fuel dryness, suggesting that wood and solid waste offered better humidity management with strong combustion properties.

Figure 19 showed that from days 1-6, average humidity difference remained constant (0.30) under steady ambient temperatures (4.75°C to 5.32°C), with wood showing slightly better humidity control due to higher calorific value. From days 7-10, humidity differences increased, with solid waste performing best. All fuels followed similar patterns, with only slight variations due to moisture content and calorific value. Solid waste proved effective and economical, offering an eco-friendly use of discarded materials. Overall, humidity differences among fuels were minimal and manageable by adjusting fuel quantity and quality to achieve desired greenhouse conditions.

Figure 20 showed that from days 1-3, wood burning produced the highest Btu values, followed closely by crop waste. Over five days, both fuels slightly outperformed solid waste. From days 4-7, wood and crop waste maintained similar Btu levels, supporting good crop growth and fruit ripening under stable ambient temperatures (5.63°C to 6.73°C). By days 9-10, Btu values from wood and solid waste were nearly equal, indicating solid waste as a cost-effective alternative to wood for greenhouse heating.

Figure 21 shows that from days 1-6, wood burning consistently produced the highest Btu values, followed by solid waste. From days 6-8, wood remained dominant, while solid and crop waste showed similar Btu performance under stable ambient temperatures (5.25°C to 6.54°C). From days 8–10, Btu from wood decreased due to falling ambient temperatures (6.7°C to 5.8°C), while solid and crop waste maintained steady output. Solid waste proved to be a cost-effective alternative to wood for maintaining greenhouse heating efficiency.

Figure 22 showed that wood burning consistently produced the highest Btu values from days 1–10. Wood and solid waste outperformed crop waste, with wood leading throughout. Ambient temperature remained relatively stable, influencing similar Btu trends in all fuels.

CONCLUSION:

The study concludes that newly developed furnace performed most effectively in glasshouse compared with fiberglass and polythene cladded greenhouses primarily due to superior heat retention properties of tempered glass. Conversely, inadequate heating in polythene-cladded greenhouse resulted in delayed plant growth and fruit ripening. These findings highlight importance of greenhouse cladding material in ensuring efficient heat management and sustaining optimal crop performance under cold climatic conditions. Wood shown better performance for heating of greenhouse as compared to its competitors (crop waste, solid waste) because of its higher calorific value.

ACKNOWLEDGEMENT

This research didn’t receive specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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Mirza Hussain Baig: Formatting the manuscript

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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