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Performance evaluation of a small scale palm fruit biomass-fired autoclave boiler

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Abstract

Different fuel mixture (empty fruit bunch, fiber and shell from palm kernel) at different ratios were used to fire an existing boiler to determine the most efficient fuel mixture composition for an improved performance of the boiler. This was carried out to determine the effects of the different types of fuel mixture (at different proportions) on the steam temperature, pressure, rate of steam production and boiler efficiency of the boiler. It was discovered that fuel mixture with higher percentage of fibre cum palm-kernel shells produced the best results for high combustion rate and steam generation. The result of the steam temperature, pressure and enthalpy results for all the fuel combinations ranges between 141 to 161°C, 3.7 to 6.34 bar, and 27.351 to 27.591 MJ kg^{-1}, respectively. Fuel combination ratio 1:8:1 produced the best result in terms of rate of steam generated while the fuel mixture ratio 1:2:7 produced the highest value for boiler efficiency (74.2%). The boiler consumed more fuel with combinations that have high percentage of fibre content (2:7:1) due to the physical and combustion properties of fibres but fuel combinations with higher shell content in the mixture (1:1:8) burns longer in the combustion chamber than mixtures with higher percentages of other fuel. The fuel mixtures produced high temperatures with ranges of 602 to 738°C for processing operation which indicated the suitability of these fuels as good potentials for boilers. These results indicates that preparation of the waste product from palm oil processing as fuel to fire the boiler have the capacity to supply the energy required in the mill in order to boost the extraction efficiency and oil quality of the small scale palm fruit processors upon incorporation into their process line.

Keywords: Small-scale boiler, Biomass-fired boiler, Fuel combinations, Boiler efficiency, Steam production, Efficiency

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INTRODUCTION

The production of palm oil can be grouped (according to their throughput and degree of complexity) into traditional methods, small-scale mechanical units, medium-scale mills and large industrial mills. Of all the methods of production, steam remains a vital resource which can either be produced manually or with the use of steam generators, otherwise called boilers (Jack *et al.*, 2024). The importance of boilers in the industry has led to the development of series of models of boilers which has also been scaled down to the different methods of palm oil production. FAO (2002) classified a plant capacity that can process about 2 tons of fresh palm fruits in an hour, 3-8 tonnes per hour and more than 10 tonnes per hour as small scale, medium-scale and large-scale respectively. Regardless of this classification, the basic unit operations which involves fruit loosening, fruit sterilization, digestion, oil extraction, clarification and packaging (Salako *et al.*, 2014) requires the function of a boiler for smooth running of the plant and desired output (Winarto and Sari, 2024). A boiler generates steam required through the chemical energy stored in the fuel (Labibah *et al.*, 2024; Mohammed *et al.,* 2021) which must have sufficient calorific value for improved efficiency of the boiler (Agustiar *et al.,* 2022). Erivianto and Dani (2024) reported that the moisture content of palm oil waste used as fuel materials for boilers is a major factor that affects the calorific value of the waste (fuel) which in turn add economic values to the system if the waste are properly managed. The major component of a boiler system is the combustion chamber and the evaporator. The combustion chamber produces the heat energy while the evaporator produces the steam which is channelled to the required area for palm oil processing (Nugroho et al., 2021).

For quality palm oil production, ('Quality' is entirely subjective and depends on the demands) there must be a low content of free fatty, low content of products of oxidation and readily removed colour for increasing commercial values of the products. To achieve this, bunch sterilization immediately after harvest, effective clarification and drying of the crude oil after extraction are important but remains a major mirage at the small and medium scale of palm fruit processing and the role of steam generation cannot be underestimated (Maulana *et al.,* 2016)

The extraction efficiency and quality of oil produced by small and medium scale processors (who are major key players in the Nigerian palm oil industry) are very low while majority of the wastes generated from these mills tends to be a waste and a huge source of pollution in the industry (Syukry, 2016). Drop in temperature of the fruit mash due to the time lag from one processing stage to the other has been identified as the major factor affecting the extraction efficiency and quality of the oil produced. Timely processing of fresh palm fruit bunch can only be possible with the inclusion of boiler in the process line. Also, indiscriminate dumping of palm fruit co-product around the mill constitutes serious environmental hazard and therefore has to be effectively utilised by ploughing it back into the mill (Agustiar *et al.,* 2022; Owolarafe, 2015).

In Nigeria, boilers being utilised by large scale plant (mostly imported) are usually expensive and beyond the reach of small scale processors. In order to bridge the gap, a small scale boiler that utilizes the palm fruit wastes as fuel to supply the steam required at high pressure to sterilise the fresh fruit bunch (FFB) thereby achieving substantial fruit recovery, high oil extraction efficiency as well as ensuring production of high quality oil is urgently required (Winarto and Sari, 2024; Salako *et al.,* 2014). These boilers are designed to utilize the biomass generated from palm oil processing as a means of fuel as Indonesia significantly identify the potential of biomass as a viable source of fuel for boilers (Yus *et al.,* 2018; Sam. 2016). Steam boilers today ranges in size from those required to heat a small-size home to the very large ones used in large scale processing industries. The fundamental requirement for a boiler system is how to ensure the smooth and continuous energy flow which may vary in capacity and pressure of the steam produced (Muzaki and Mursadin, 2019). To satisfy this requirement, it is desirable that the rate and quality of steam generation be properly controlled so that the production and consumption of steam energy can be maintained in equilibrum at all times (Mahlia *et al.*, 2003). Figure 1 shows the boiler developed in previous study to enhance the productivity of the processors but its performance needs to be optimised.

MATERIALS AND METHODS

Composition of Fuel for Boiler

Palm fruit biomass was combined differently to determine the best proportion for optimum boiler performance. Table 1 below shows the different combinations of the biomass that were considered in this study to provide an insight into the effect of utilizing these co-products on the qualitative and quantitative properties of the steam produced, boiler efficiencies, flue gas temperature profile, rate of fuel consumption amongst other variables. 36 different combination proportions were used which more consideration on the traditional methods of combinations by end users or processors.

Boiler Evaluation Procedure

The fuel materials were combined in 36 different proportions to determine the effects of the properties of steam (temperature, pressure, enthalpy, entropy and specific volume) on the boiler efficiency, rate of steam production, rate of the boiler fuel consumption and the core temperature of the furnace while monitoring the temperature profile of the flue gas. The various fuel proportions were fed into the system based on the different burning characteristics of the composition of the fuel material. The theoretical and the excess air required for complete combustion of the various fuel materials were determined and a thermocouple was used in measuring the temperature profile of the steam as well as the flue gas.

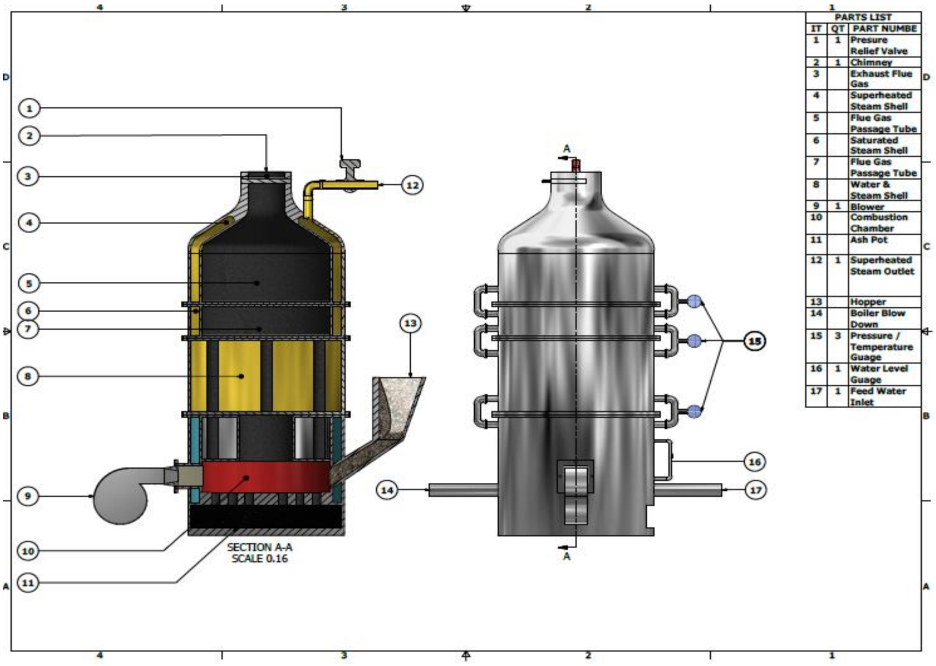

Figure 1. Detailed labelled view of the modified biomass fired boiler

Table 1. Combinations of the palm fruit biomass in different proportions

S/No	Fuel Combinations (EFB:Fiber:Shell)	S/No	Fuel Combinations (EFB:Fiber:Shell)	S/No	Fuel Combinations (EFB:Fiber:Shell)
1	0.1 : 0.1 : 0.8	**13**	0.3 : 0.6 : 0.1	**25**	0.2 : 0.3 : 0.5
2	0.1 : 0.8 : 0.1	**14**	0.6 : 0.1 : 0.3	**26**	0.2 : 0.5 : 0.3
3	0.8 : 0.1 : 0.1	**15**	0.6 : 0.3 : 0.1	**27**	0.3 : 0.2 : 0.5
4	0.1 : 0.2 : 0.7	**16**	0.1 : 0.4 : 0.5	**28**	0.3 : 0.5 : 0.2
5	0.2 : 0.7 : 0.1	**17**	0.1 : 0.5 : 0.4	**29**	0.5 : 0.2 : 0.3
6	0.7 : 0.1 : 0.2	**18**	0.4 : 0.1 : 0.5	**30**	0.5 : 0.3 : 0.2
7	0.1 : 0.7 : 0.2	**19**	0.4 : 0.5 : 0.1	**31**	0.2 : 0.4 : 0.4
8	0.2 : 0.1 : 0.7	**20**	0.5 : 0.1 : 0.4	**32**	0.4 : 0.2 : 0.4
9	0.7 : 0.2 : 0.1	**21**	0.5 : 0.4 : 0.1	**33**	0.4 : 0.4 : 0.2
10	0.1 : 0.3 : 0.6	**22**	0.2 : 0.2 : 0.6	**34**	0.3 : 0.3 : 0.4
11	0.1 : 0.6 : 0.3	**23**	0.2 : 0.6 : 0.2	**35**	0.3 : 0.4 : 0.3
12	0.3 : 0.1 : 0.6	**24**	0.6 : 0.2 : 0.2	**36**	0.4 : 0.3 : 0.3

RESULT AND DISCUSSION

The results of the combination of the fuel samples (EFB, Fibre and Shell) in different proportions on the properties of steam produced, boiler efficiency, rate of steam production and flue gas temperature profile are presented as follows;

Effect of Fuel Combination on Rate of Steam Temperature

Fuel samples produces heat energy in the combustion chamber while the evaporator produces the steam required for the process of palm oil production. It was discovered that the rate of the temperature of the generated steam varies according to the fuel types and composition (Figures 2a – 2f). The highest steam temperature of 161°C was achieved at a fuel combination ratio of 3:5:2, closely followed by fuel combination ratio of 2:6:2 with a steam temperature of 160 °C. The ANOVA result (Table 2) indicated that the heating values of the various fuel compositions have direct effect on the resulting steam temperature as fuel combinations with higher proportion of fibre were observed to produce the best result in terms of steam temperature. This might be due to the percentage of carbon content in the fibre (Fitria *et al*., 2022; Sari *et al*., 2016, 2017). Similarly, the least value for steam temperature of 141 °C was obtained at fuel combination 1:2:7. The effect of the different fuel combinations were observed to significantly ($p < 0.05$) affects the steam temperature profile of the boiler. This result is corroborated by the findings of Salako *et al.* (2014) and also the findings of Oladosu *et al.* (2018). Generally, fuel combination with higher proportion of fiber reaches boiling point faster but burns quickly in the furnace which can result to drop in the temperature if corresponding rate of fuel input into the furnace is not maintained. On the other hand, fuel combination with higher shell proportion burns longer in the furnace therefore the frequency of fuel input is lower compare to fiber and EFB.

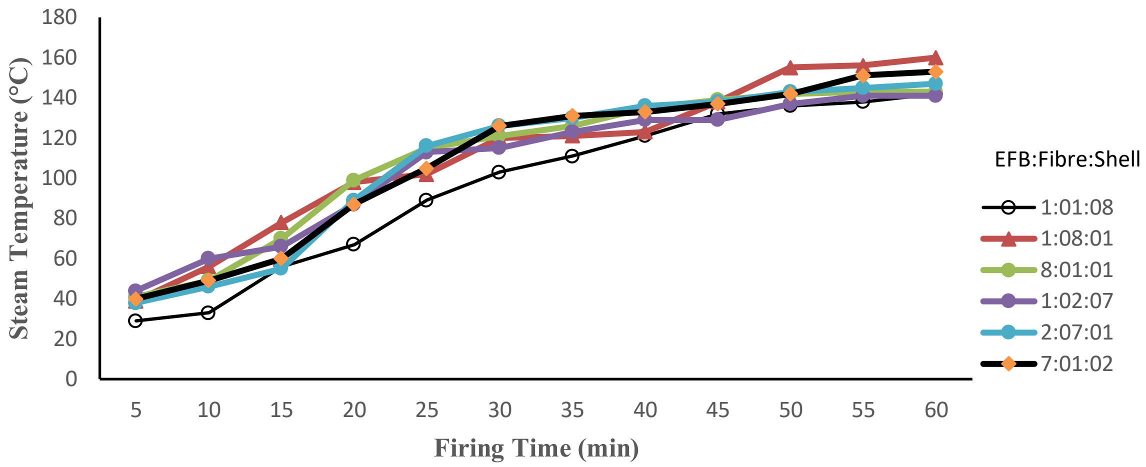

Figure 2a. Effect of Fuel Combination on Steam Temperature

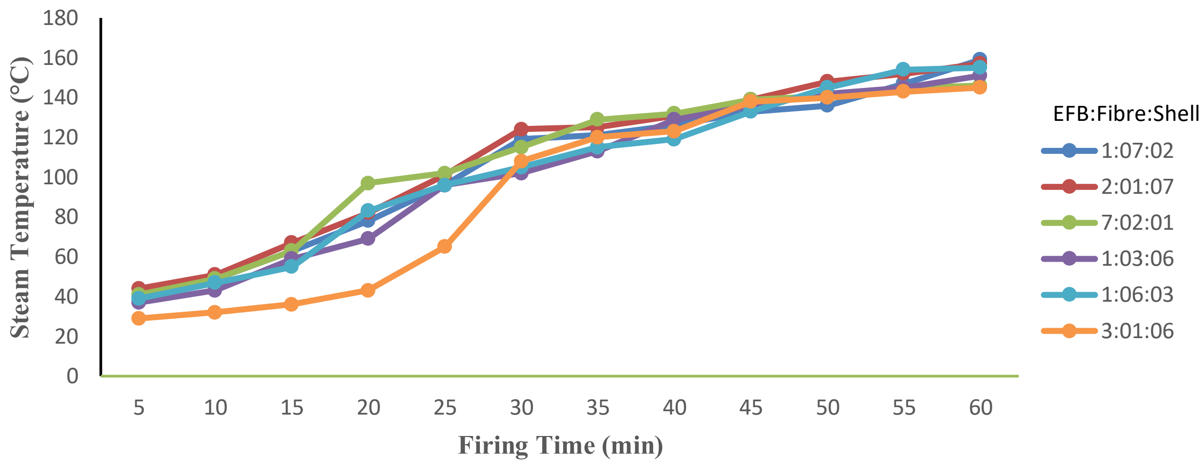

Figure 2b. Effect of Fuel Combination on Steam Temperature

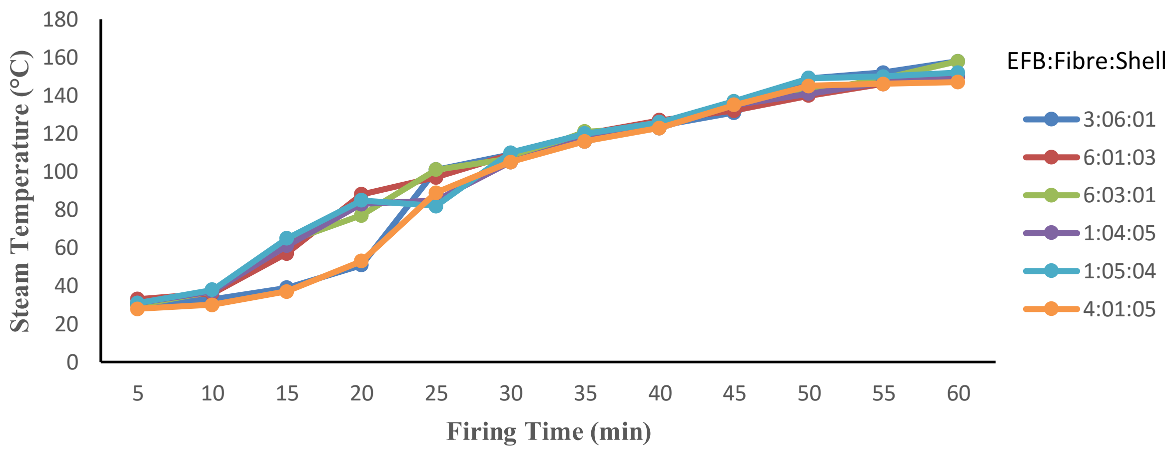

Figure 2c. Effect of Fuel Combination on Steam Temperature (*contd.*)

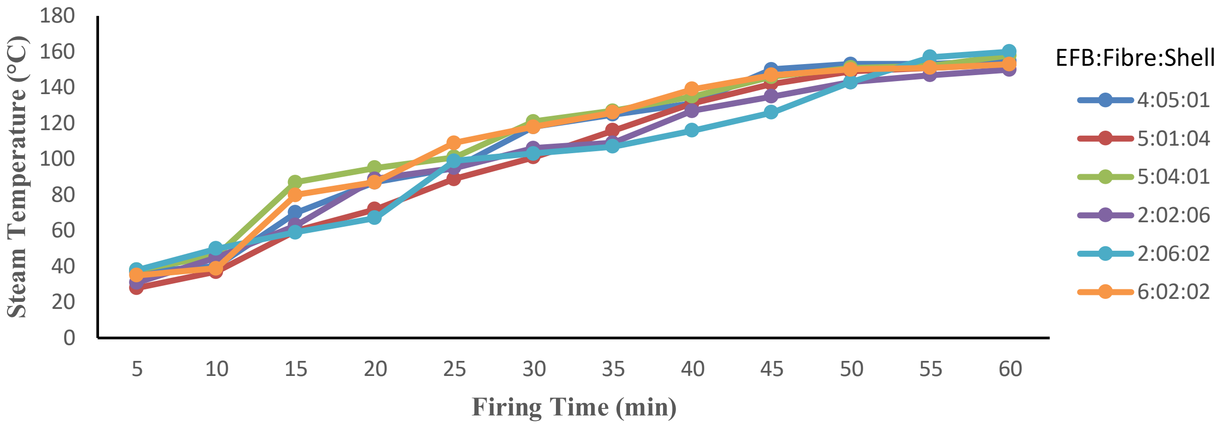

Figure 2d. Effect of Fuel Combination on Steam Temperature (*contd.*)

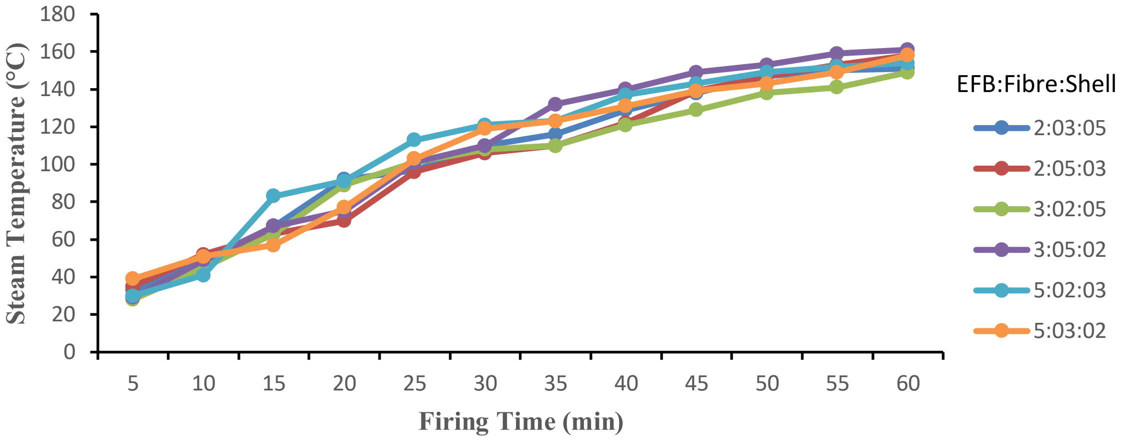

Figure 2e. Effect of Fuel Combination on Steam Temperature (*contd.*)

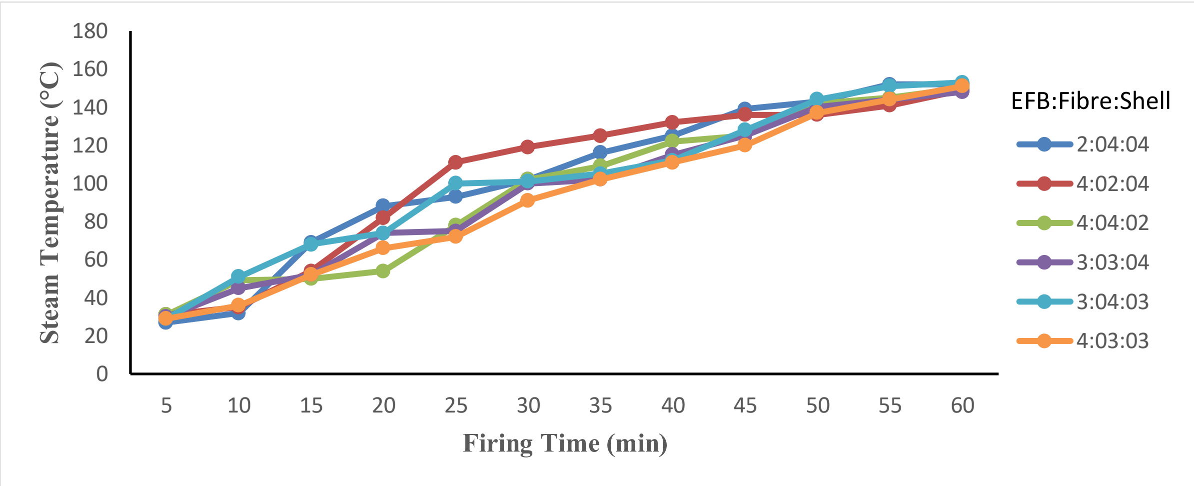

Figure 2f. Effect of Fuel Combination on Steam Temperature (*contd.*)

Table 2. ANOVA Table Showing Effect of fuel combinations on Steam Temperature

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F	at P<0.05
FuelType	5	23077.3393	4615.4679	766.86	<.0001	s
Time	11	139432.2446	12675.6586	2106.06	<.0001	s
FuelType×Time	50	35739.7107	714.7942	118.76	<.0001	s
Model	66	187909.6343	2847.1157	473.05	<.0001	s
Error	134	806.5000	6.0187			

Effect of Fuel Combination on the Steam Pressure

For all the fuel samples, the steam pressure was observed to be increasing over time. At 25 to 30 mins, pressure builds up in the boiler was about 100 kPa but later increased rapidly as shown in Fig. 3 (a – f). The vapour pressure turned to have a direct relationship with the rate of fuel consumption at the combustion chamber of the boiler. The pressure of the steam when fired with fuel combination 3:5:2 reached the maximum of 6.34 bar closely followed by fuel combination 2:6:2 with 6.18 bar at 60 minutes firing time. The vapour pressure builds up slowly but more sustained when fired with fuel combination with higher proportion of shell in comparison with fibre and EFB. Similarly, the least value for steam pressure of 3.72 bar was also obtained at fuel combination 1:2:7. The change in fuel combination has significant effect ($p < 0.05$) on the steam pressure, this result follows the trend reported by Oladosu *et al.* (2018) while evaluating the performance of a palm kernel shell-fired boiler, and also supported by the findings of Salako *et al.* (2014).

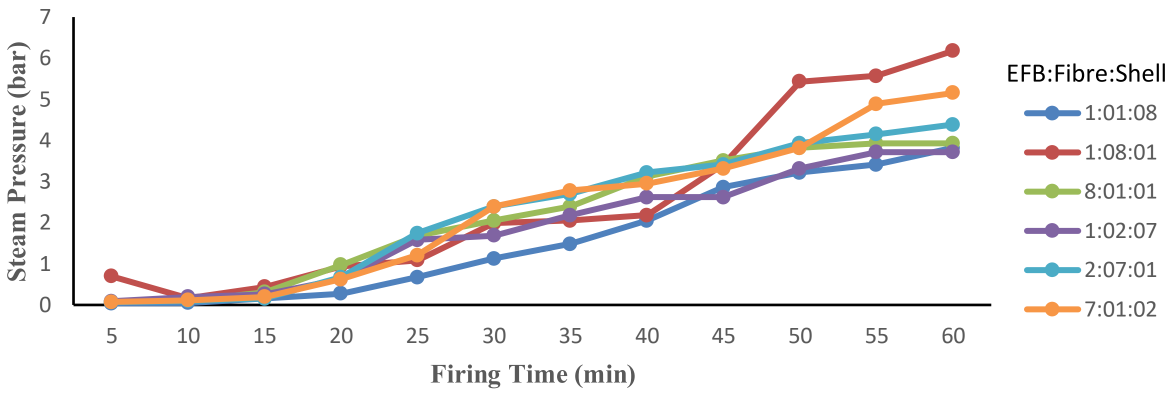

Figure 3a. Effect of Fuel Combination on Steam Pressure

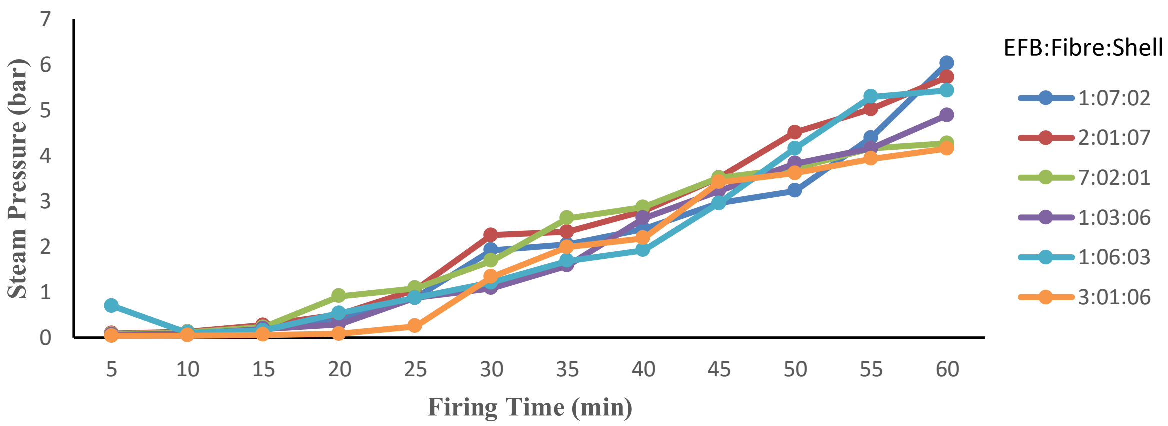

Figure 3b. Effect of Fuel Combination on Steam Pressure (*contd.*)

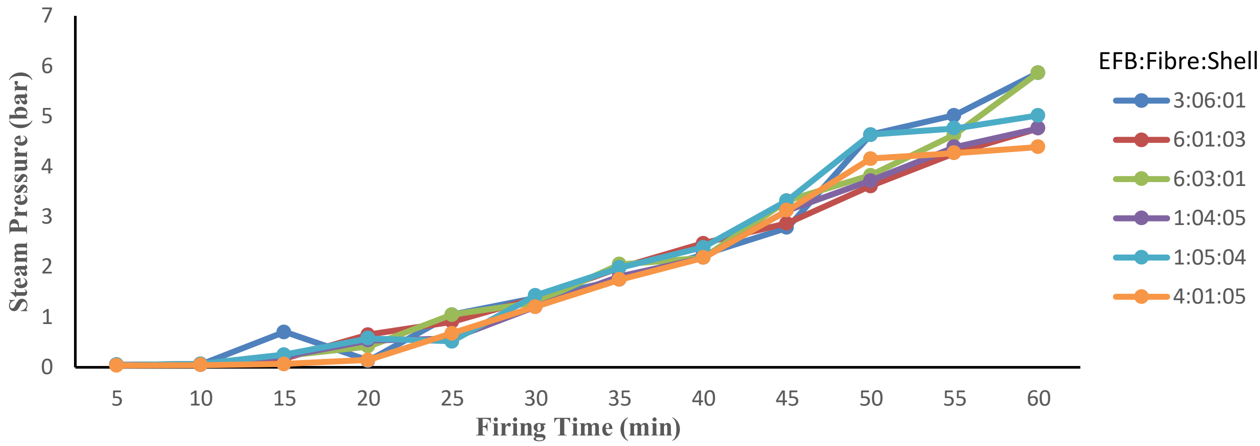

Figure 3c. Effect of Fuel Combination on Steam Pressure (*contd.*)

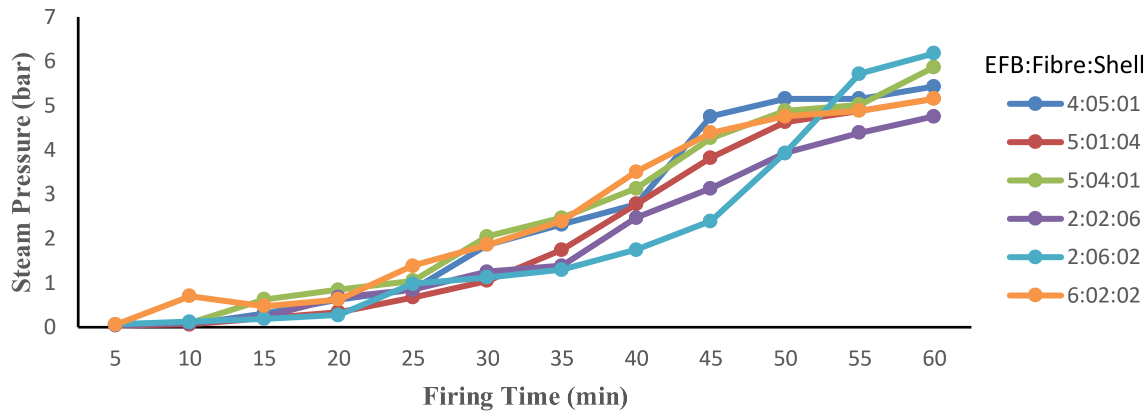

Figure 3d. Effect of Fuel Combination on Steam Pressure (*contd.*)

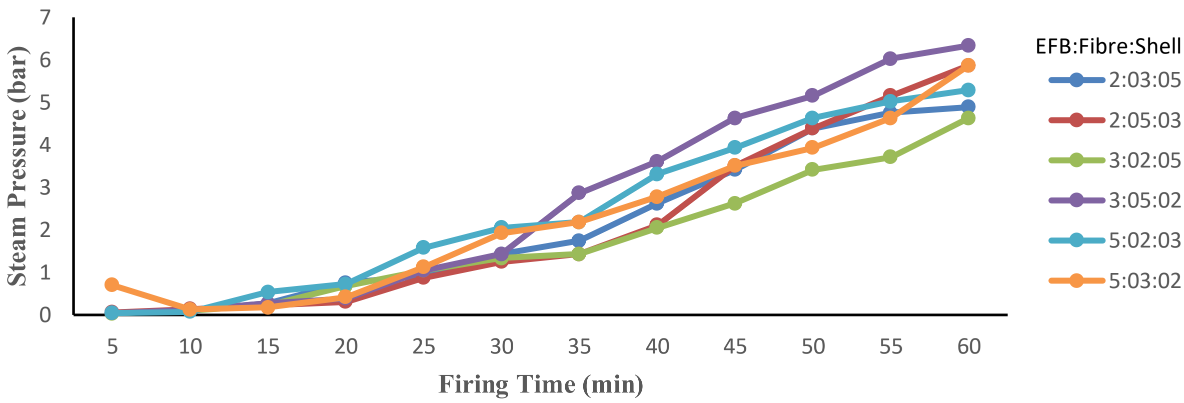

Figure 3e. Effect of Fuel Combination on Steam Pressure (*contd.*)

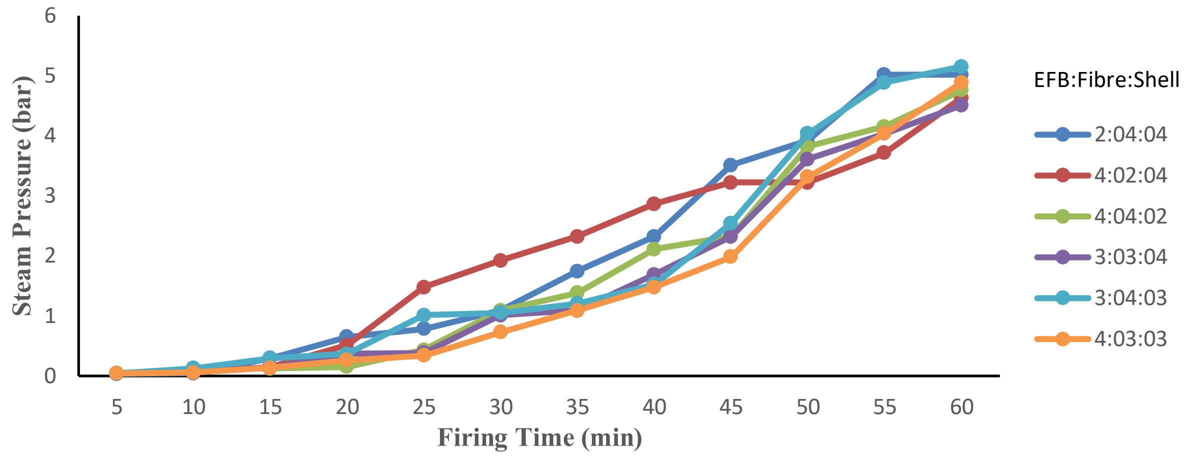

Figure 3f. Effect of Fuel Combination on Steam Pressure (*contd.*)

Table 3. ANOVA Table Showing Effect of fuel combinations on Vapour Pressure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F	at P<0.05
FuelType	5	347096.385	69419.277	1549.87	<.0001	s
Time	11	1230371.448	111851.950	2497.24	<.0001	s
FuelType×Time	50	487107.861	9742.157	217.51	<.0001	s
Model	66	1924911.945	29165.333	651.15	<.0001	s
Error	134	6001.894	44.790			

Effect of Fuel Combination on Rate of Steam Enthalpy

The effect of the fuel material on enthalpy of the saturated vapour is as shown in Figure 4 (a – f) and this shows the significance at ($p < 0.05$) according to the ANOVA result (Table 3). The highest steam enthalpy value of 27.591 MJ kg^{-1} was achieved at fuels combination ratio of 3:5:2, while fuel combination ratios of 2:6:2 and 1:8:1 yielded almost the same value (27.580 MJ kg^{-1}). The heating value of the various fuel compositions has a direct effect on the resulting steam enthalpy as in the case of steam temperature and pressure. Fuel combination with higher proportion of fibre was observed to produce the best steam enthalpy value while the least value for steam enthalpy of 2735.1 MJ kg^{-1} was obtained at fuel combination 1:2:7. The result obtained follows the trend reported by Salako *et al.* (2014). This affirms that the combination of these palm fruit biomass (shell, efb and fibre) in different proportions produces viable fuel source or energy needed in the palm oil processing industry.

Effect of Fuel Combination on Rate of Steam Production

Fuel mixture with higher percentage of fibre produced the highest quantity of steam followed by fuel mixture with higher percentage of EFB. This may be due to the combustion property of fibre over the other materials. Over 111 kg of steam were produced per hour at fuel combination ratio of 1:8:1 and 2:7:1 (EFB, Fibre and Shell), while the lowest quantity of steam generation was attained for fuel ratio 1:1:8. The result has a direct correlation with the findings of Salako *et al.* (2014). The indicate that fuel combinations ratios have significant effect on the rate of steam production ($p < 0.05$).

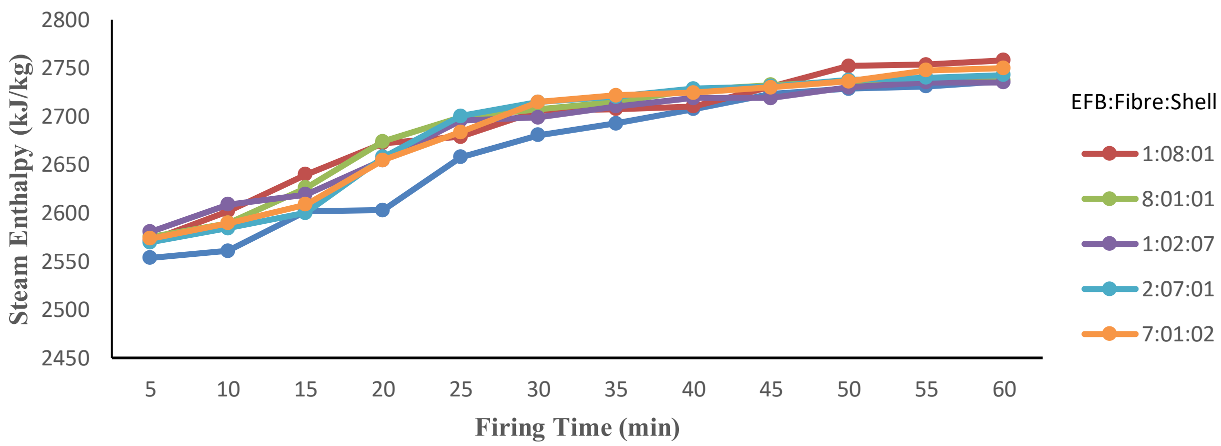

Figure 4a. Effect of Fuel Combination on Steam Enthalpy

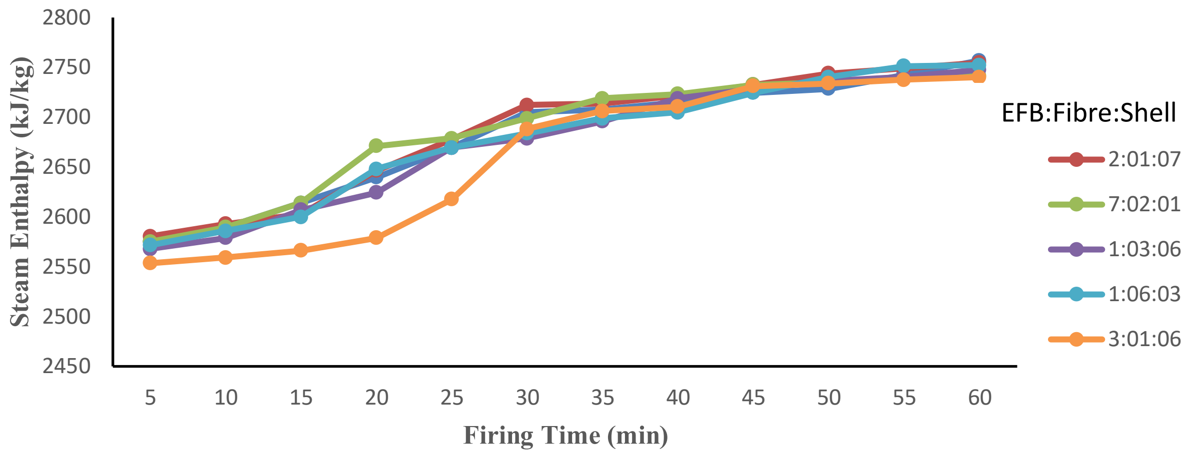

Figure 4b. Effect of Fuel Combination on Steam Enthalpy (*contd.*)

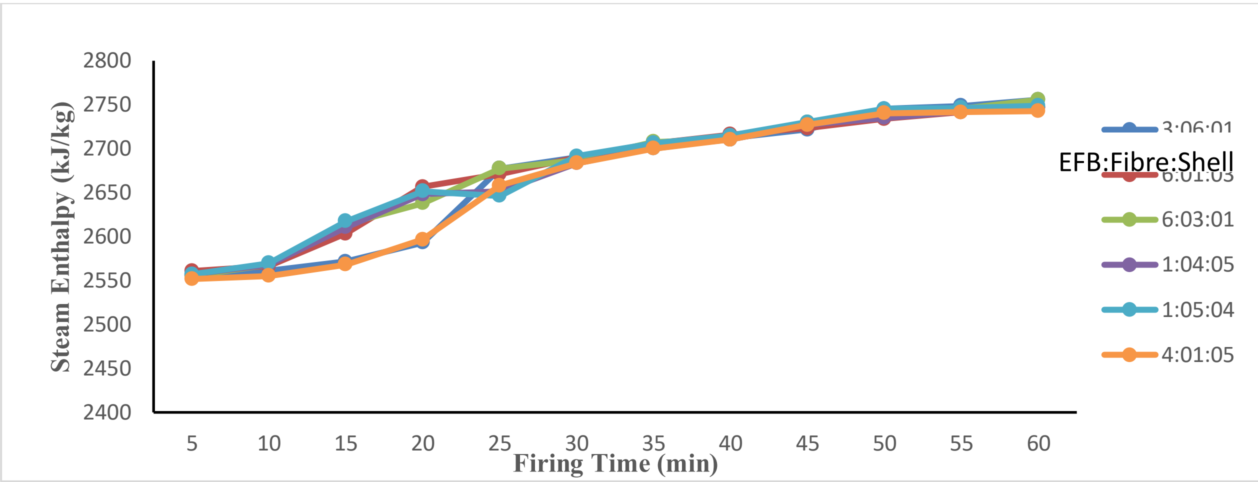

Figure 4c. Effect of Fuel Combination on Steam Enthalpy (*contd.*)

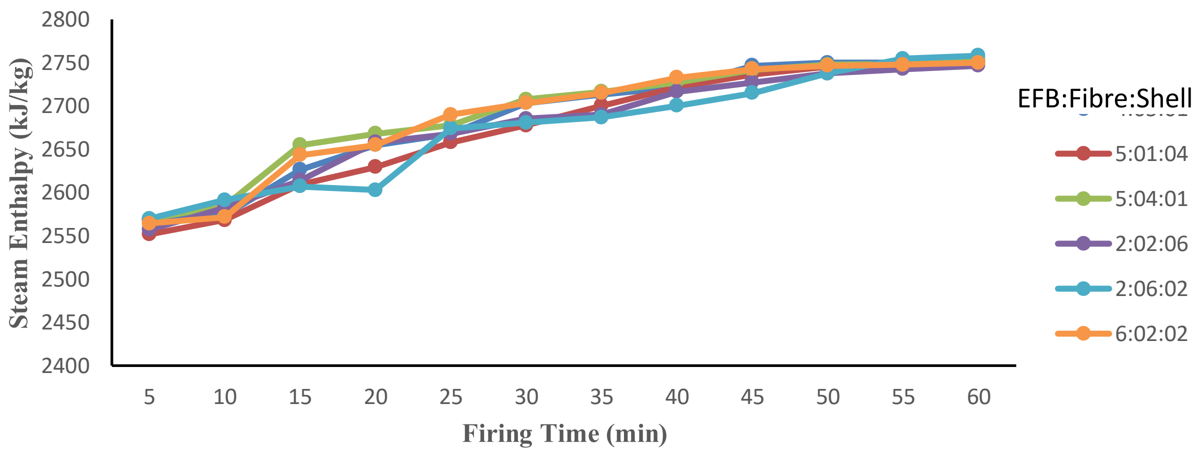

Figure 4d. Effect of Fuel Combination on Steam Enthalpy (*contd.*)

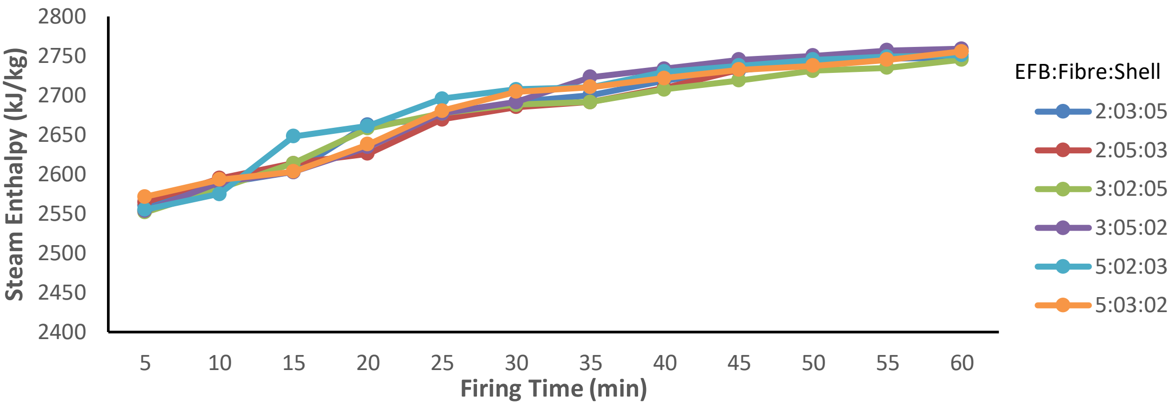

Figure 4e. Effect of Fuel Combination on Steam Enthalpy (*contd.*)

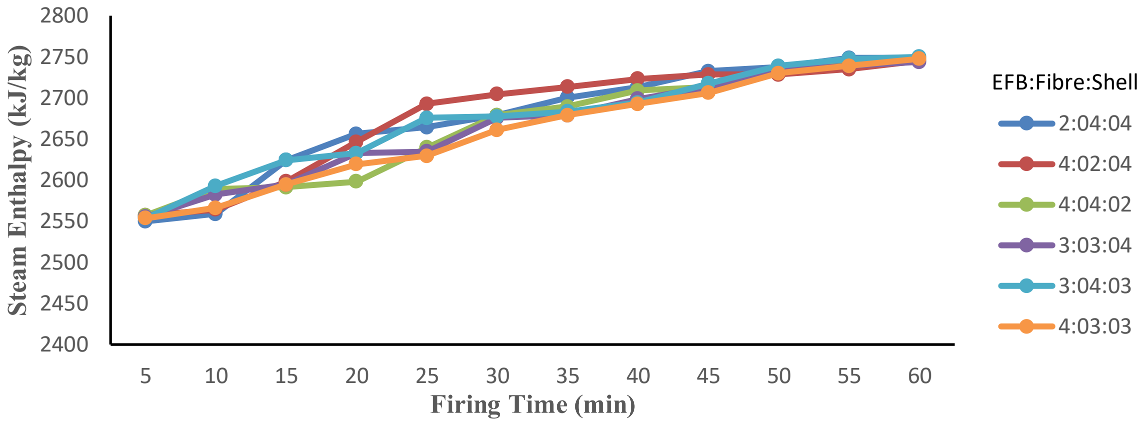

Figure 4f. Effect of Fuel Combination on Steam Enthalpy (*contd.*)

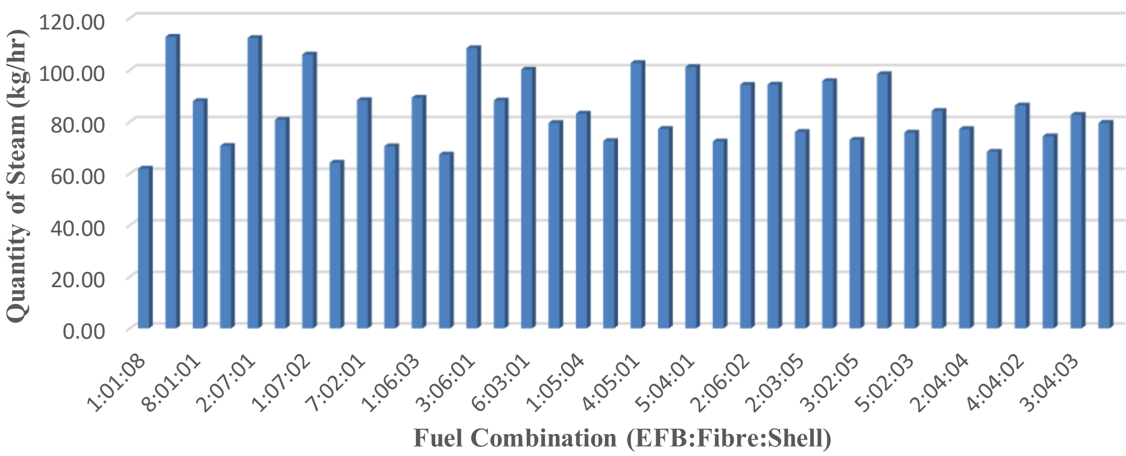

Figure 5. Effect of fuel combination on the rate of steam production

Effect of Fuel Combination on Rate of Boiler Efficiency

The efficiency of the machine varied differently when fired with the various combination of the palm fruit biomass. Fuel mixture with highest percentage of shell composition (1:2:7) produced the highest boiler efficiency (74.2%) while the least efficiency (69.4%) was produced at a fuel combination of 3:5:2. This position fuel materials with high shell composition as a potential when mixed with fibre due to its combustion property. This result is in consonance with the reports of Sivabalan (2013), Oladosu *et al.* (2018) and also Salako *et al.* (2014) who also confirmed that fuel combinations affects has a significant effect on the boiler efficiency.This shows (Figure 6) a better result compared to other fuel materials and position palm fruit biomass as a potential to supply the energy required by a boiler for palm oil production.

Effect of Fuel Combination on the Rate of Fuel Consumption

The rate of fuel combustion is the ratio of the total mass of fuel used in the firing process to the burning time. The different burning characteristics of the composition of the fuel material and the low heating values resulted to the variation in the rate of fuel consumption of the boiler (Hartanto *et al.,* 2020) which also influences the boiler efficiency (Winarto and Sari, 2024).

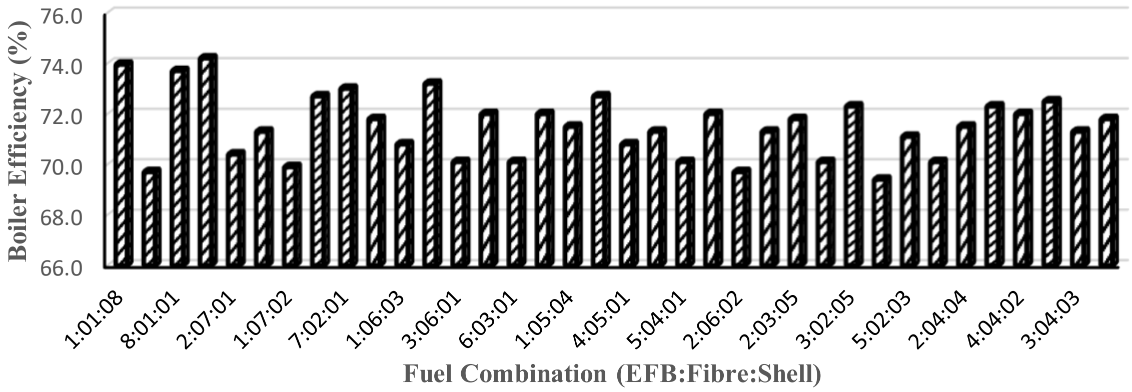

Figure 6. Effect of fuel combination on the boiler efficiency

According to the result, fibre has the highest potential in terms of heat released but shell has the longest burning time, followed by the EFB and fibre in that order. The longer burning time of the uncrushed raw palm shells used for the experiment can be attributed to its physically hard property that requires more time for char combustion to be achieved over the entire particle, while the EFB were dried quartered bunches. This submission is corroborated by Ilmi *et al.* (2013) and also in accordance with Hasibuan and Napitupulu (2013) who affirmed that fuel with low heating values affects the rate of fuel consumption and boiler efficiency. The burning rate of the char depends on both the chemical rate of the carbon-oxygen reaction at the surfaces and the rate of boundary layer and internal diffusion of oxygen. Fuels with higher densities typically has lower oxygen diffusion rate. This surface reaction generates primarily CO, which then reacts with free oxygen or other formed substances outside the particle to form CO_2. As obtained in the result, fuel combination with higher composition of fibre requires larger quantity of fuel in order to maintain steady rate of combustion and heat supply to the heat exchangers. Therefore, as shown in Figure 7, as much as 21 kg of fuel was utilized when fired with a 2:7:1 and a combination of 1:1:8 only requires 12.5 kg of fuel. The result obtained is also in line the findings of Sivabalan, (2013) and Oladosu *et al.* (2018).

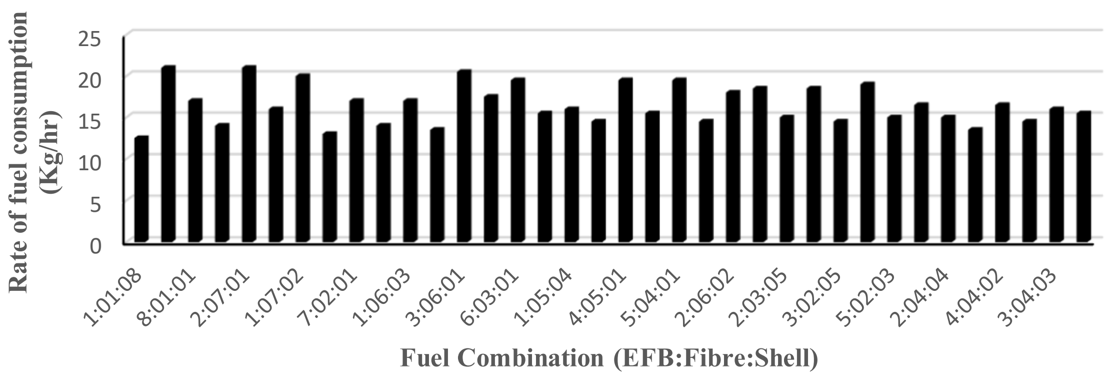

Figure 7. Effect of fuel combination on the boiler rate of fuel consumption

Effect of Fuel Combinations on the Flue Gas Temperature Profile of the Boiler.

Temperatures of the flue gas at all the sections increases with time due to steady in-flow of fuel material and decreases along its flow path (Figure 8). This shows that a rapid cooling rates along the direction of travel of the combustion towards the exhaust. From the high range of temperature obtained (602-738°C), fuel samples with higher concentration of fiber produced the peak result but more fuel were consumed during the process due to the percentage of carbon content in the fibre (Fitria et al., 2022; Sari et al., 2016, 2017) and its physical properties. This result is in line with findings of Najmi *et al.* (2008). The average temperature difference between the saturated tube, superheated tube and the exhaust gas at the chimney was also estimated to be about 15°C.

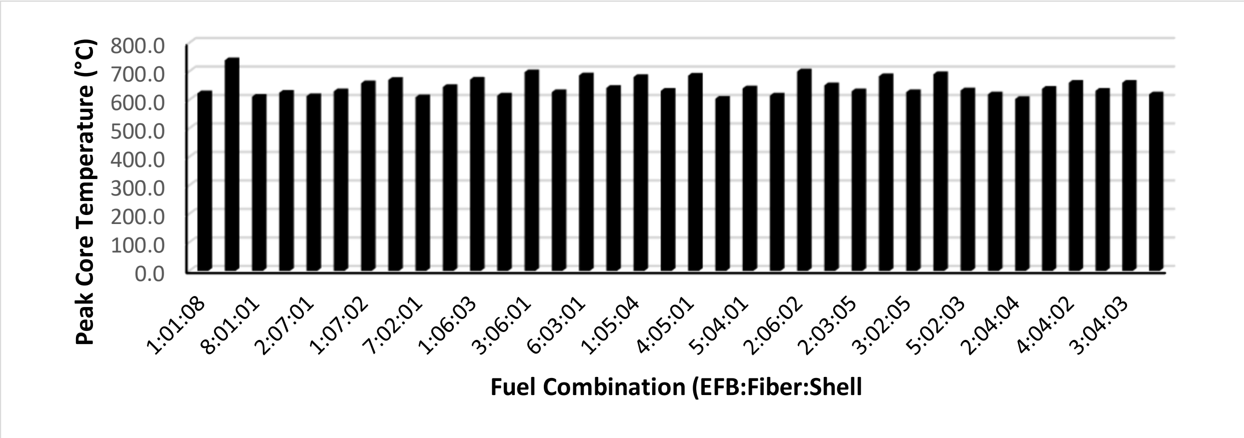

Figure 8. Effect of fuel combination on the peak core temperature of the boiler

CONCLUSION

The mixture of Palm fruit biomass (EFB, Fibre and Shell) is found to be a viable fuel to fire a boiler. These materials can generate required steam by any small or medium scale boiler for various special palm oil processing operations. Fuel mixture of palm kernel shell and fibres are best to produce sufficient energy required by boilers for special palm oil production due to the combustion properties of the fibres which tends to compliments the useful properties of the palm kernel shell. This study signifies the importance of palm oil biomass as fuels for boilers that are designed for palm oil processing. This will add more economic values to the production of palm oil and develop the appetite of more processors to the production of valuable oil from palm kernel.

Compliance with Ethical Standards

Peer-review

Externally peer-reviewed.

Author contribution

The contribution of the authors to the present study is equal. All the authors read and approved the final manuscript.

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