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Effect of Plate Modifications on Combustion and Efficiency of Biomass Fuels in Furnace Systems

Muhtadin[1], Mahidin[2], Muhammad Faisal[1], Mohd Adnin Hamidi[3]

[1]Department of Mechanical Engineering, Universitas Abulyatama Aceh, Aceh Besar, 23372, Indonesia
[2]Department of Chemical Engineering, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia
[3]Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia

Corresponding Author: muhtadi_mesin@abulyatama.ac.id

Abstract
The global demand for renewable energy highlights biomass as a sustainable alternative to fossil fuels. In Southeast Asia, palm-based residues, including palm kernel shells, oil palm fronds, and empty fruit bunches, offer abundant resources with high energy potential. However, their combustion efficiency is often limited by furnace design. This study investigates the effect of plate modifications (two-way, three-way, and four-way) on combustion performance in furnace systems. Experiments evaluated the heat release rate, thermal efficiency, and combustion furnace efficiency under various configurations. Results showed that modified plates improved combustion stability compared to standard designs. The three-way modification yielded the highest heat release rate of 440 W/m, while the four-way modification provided the most stable output, maintaining over 300 W/m for longer durations. Thermal efficiency tests revealed that palm kernel shell achieved 92% at T1 in Experiment-02, oil palm fronds reached 95% at T1 in Experiment-03, and empty fruit bunches, though starting lower, demonstrated superior long-term stability with 74% at T4 in Experiment-03. Furnace efficiency showed a similar pattern: palm kernel shell reached 74%, oil palm fronds 71%, while empty fruit bunches remained lower at 40% at T4. The novelty of this research lies in integrating chamber design with comparative fuel analysis, demonstrating that plate modifications directly enhance efficiency and stability. In conclusion, palm kernel shells are optimal for high initial efficiency, oil palm fronds for rapid energy release, and empty fruit bunches for sustained combustion, providing practical insights for biomass utilisation in renewable energy systems.

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1. Introduction

The increasing demand for renewable energy has positioned biomass as one of the most promising alternatives to fossil fuels. Biomass resources, particularly agricultural residues, are widely available in tropical countries and can significantly reduce reliance on non-renewable energy sources (Demirbas, 2009; Rosdi, Hafizil, & Yasin, 2025; Yusop, Faisal, & Maulana, 2025). In addition, biomass combustion contributes to reducing greenhouse gas emissions compared to coal or oil, making it a sustainable option for energy generation (Gani & Darnas, 2025; Gani & Desvita, 2025; Wu, Liu, Cheng, & Zhang, 2024). In Southeast Asia, palm oil production generates substantial quantities of agricultural residues, including palm kernel shells, oil palm fronds, and empty fruit bunches. These by-products are often underutilised and considered waste, despite their high potential as alternative energy sources (Akasyah, Hamidi, & Ali, 2025; Farobie & Hartulistiyoso, 2022; Gani, 2025). Harnessing such biomass not only reduces environmental pollution but also provides economic value through renewable energy production (Akasyah, Yusop, & Rosdi, 2025; Erdiwansyah et al., 2022; Sapee, Yusop, Nazri, et al., 2025).

Previous studies have shown that the combustion characteristics of biomass depend primarily on its physical and chemical composition. Palm kernel shells have been reported to possess high calorific values, enabling efficient energy release (Husain, Zainac, & Abdullah, 2002; Rosdi, Yusop, Hafizil, & Yasin, 2025; Sapee, Yusop, Kadarohman, & Eko, 2025). Meanwhile, oil palm fronds and empty fruit bunches, although having relatively lower calorific values, still offer significant potential when optimised for combustion (Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Odusote & Muraina, 2017; Yana, Mufti, Hasiany, Viena, & Mahyudin, 2025). The efficiency of biomass combustion depends not only on the fuel properties but also on the design of the combustion system. Studies have shown that modifications to combustion chamber geometry and air distribution can significantly enhance combustion stability and heat transfer efficiency (Akhtar, Krepl, & Ivanova, 2018; Gani, Saisa, et al., 2025; Irhamni, Kurnianingtyas, Muhtadin, Bahagia, & Yusop, 2025). Optimising furnace design has therefore become a critical research focus to maximise biomass fuel utilisation.

Research on thermal efficiency indicates that biomass fuels often achieve efficiencies above 70% under optimised conditions (Gani, Zaki, Bahagia, Maghfirah, & Faisal, 2025; Maghfirah, Yusop, & Zulkifli, 2025; Mahidin, Zaki, Hamdani, Hisbullah, & Susanto, 2020). However, efficiency tends to decline across extended combustion time due to incomplete combustion and heat losses. Furnace efficiency, which accounts for system-wide energy conversion, is often lower than thermal efficiency, highlighting the importance of integrated efficiency analysis (Adams, Bridgwater, Lea-Langton, Ross, & Watson, 2018; Selvakumar, Gani, Xiaoxia, & Salleh, 2025; Zaki, Adisalamun, & Saisa, 2025). Several works have explicitly focused on palm-based biomass. For instance, Abdullah and Gerhauser (2008) reported that palm kernel shell combustion is more stable than empty fruit bunches due to its lower ash content. On the other hand, oil palm fronds were found to burn faster, providing rapid energy release but less long-term stability (Efremov & Kumarasamy, 2025; Li, Ikram, & Xiaoxia, 2025; Nguyen, Nguyen, Ha-Duong, & van de Steene, 2016). Such variations suggest that selecting appropriate biomass fuels for specific applications is crucial.

Despite numerous studies, relatively few have investigated the combined effect of biomass type and combustion plate modifications on overall combustion performance. Most previous research has evaluated biomass fuels in their standard combustion configurations without examining how chamber modifications influence heat release, thermal efficiency, and furnace efficiency simultaneously (Kim, Park, & Bae, 2021; Leman & Jalaludin, 2025; Mekkah et al., 2025). This presents a research gap in linking fuel characteristics with engineering design improvements. Therefore, this study aims to evaluate the effect of plate modifications on the combustion performance and efficiency of palm kernel shells, oil palm fronds, and empty fruit bunches. By analysing heat release rates, thermal efficiency, and furnace efficiency across multiple experiments and measurement points, this research provides a comprehensive understanding of biomass utilisation in practical furnace applications. The findings are expected to contribute novel insights into both fuel-specific performance and system design optimisation.

2. Methodology

Fig. 1 presents the experimental biomass combustion furnace equipped with a plate modification system, which was explicitly designed to evaluate the combustion performance of palm kernel shell, oil palm fronds, and empty fruit bunches. The furnace consists of four main sections: the combustion chamber (Zone 1), the secondary air supply zone (Zone 2), the gas mixing and flow stabilisation zone (Zone 3), and the chimney outlet (Zone 4). This vertical cylindrical design allows for controlled airflow distribution and efficient heat transfer during biomass combustion. The incorporation of plate modifications at the combustion chamber enables variation of airflow and mixing patterns, thereby influencing combustion stability, heat release rate, and efficiency. The furnace setup was central to the experimental work, as it allowed for the systematic testing of different plate configurations, including standard, two-way, three-way, and four-way modifications, under identical conditions. The vertical arrangement of the chamber ensured proper fuel feeding, complete combustion, and adequate gas emission flow through the chimney. Additionally, the integration of measurement ports enabled the monitoring of temperature, heat release, and efficiency at various points throughout the system. Through this design, the furnace provided a reliable platform for investigating how structural modifications influence biomass combustion characteristics, leading to key findings such as improved peak heat release rates of up to 440 W/m and thermal efficiencies reaching 95%, depending on the fuel and modification applied.

Fig. 1. Experimental Biomass Combustion Furnace with Plate Modification System

3. Result & Discussion

The results of this study provide a comprehensive evaluation of the combustion performance of palm kernel shell, oil palm fronds, and empty fruit bunches under different plate modification configurations. By analysing heat release rates, thermal efficiency, and combustion furnace efficiency, this research highlights the critical roles that both fuel characteristics and furnace design play in determining overall performance. The findings reveal that the application of modified plates significantly enhanced combustion stability and efficiency compared to the standard plate, confirming the importance of engineering design improvements in biomass utilisation. Across all experiments, the combustion process generally followed a similar pattern, characterised by rapid increases in heat release during the initial stages, peak performance within the first 20–50 seconds, and a gradual decline thereafter. Thermal efficiency and furnace efficiency also showed consistent trends, with the highest values observed at the first measurement point (T1) and decreasing over time. However, each biomass fuel exhibited unique characteristics: palm kernel shell delivered the highest initial efficiency, oil palm fronds achieved the highest peak values, and empty fruit bunches maintained superior stability at later stages. These variations highlight the importance of selecting suitable fuel types in conjunction with optimised plate modifications to achieve the desired combustion outcomes.

Fig. 2 illustrates the variation of heat release rate (q) with combustion time for palm kernel shell under different plate modifications. Across all configurations, the heat release rate increased rapidly during the initial combustion period (0–20 s), followed by a stabilisation phase and then a gradual decline after extended combustion. The standard plate reached its peak earlier and declined faster, while the modified plates sustained higher heat release rates for a longer duration, indicating improved combustion performance. The standard plate exhibited a maximum heat release rate of approximately 380 W/m at around 25 s, after which the value dropped steadily, reaching nearly 150 W/m at 60 s and declining further to below 100 W/m by 70 s. In comparison, the two-way modification achieved a higher peak value of about 430 W/m at 20 s, maintaining above 300 W/m until around 50 s, before gradually decreasing to 200 W/m near 80 s. This demonstrates that the two-way modification significantly enhanced the combustion stability compared to the standard plate.

The three-way modification recorded its highest peak of approximately 440 W/m at 50 s, showing a delayed but more vigorous combustion intensity compared to the standard and two-way designs. The curve remained above 350 W/m between 25 and 60 s, before gradually decreasing to 250 W/m at 90 s. Meanwhile, the four-way modification exhibited even more stable combustion, with a sustained heat release rate of approximately 420 W/m between 20 and 50 s, and only slowly decreasing to about 350 W/m at 70 s. These results highlight the advantage of additional modifications in enhancing combustion efficiency and maintaining higher heat release rates over longer durations. Comparing all modifications, it is evident that the standard plate produced the lowest and least stable combustion performance. The two-way modification provided noticeable improvements in the early stage but declined faster after 60 s. The three-way and four-way modifications not only achieved higher peak values (above 430 W/m) but also maintained heat release above 300 W/m for longer combustion times, showing superior efficiency. Overall, the four-way modification demonstrated the most balanced and sustained performance, making it the most effective design for optimising combustion of palm kernel shell fuel.

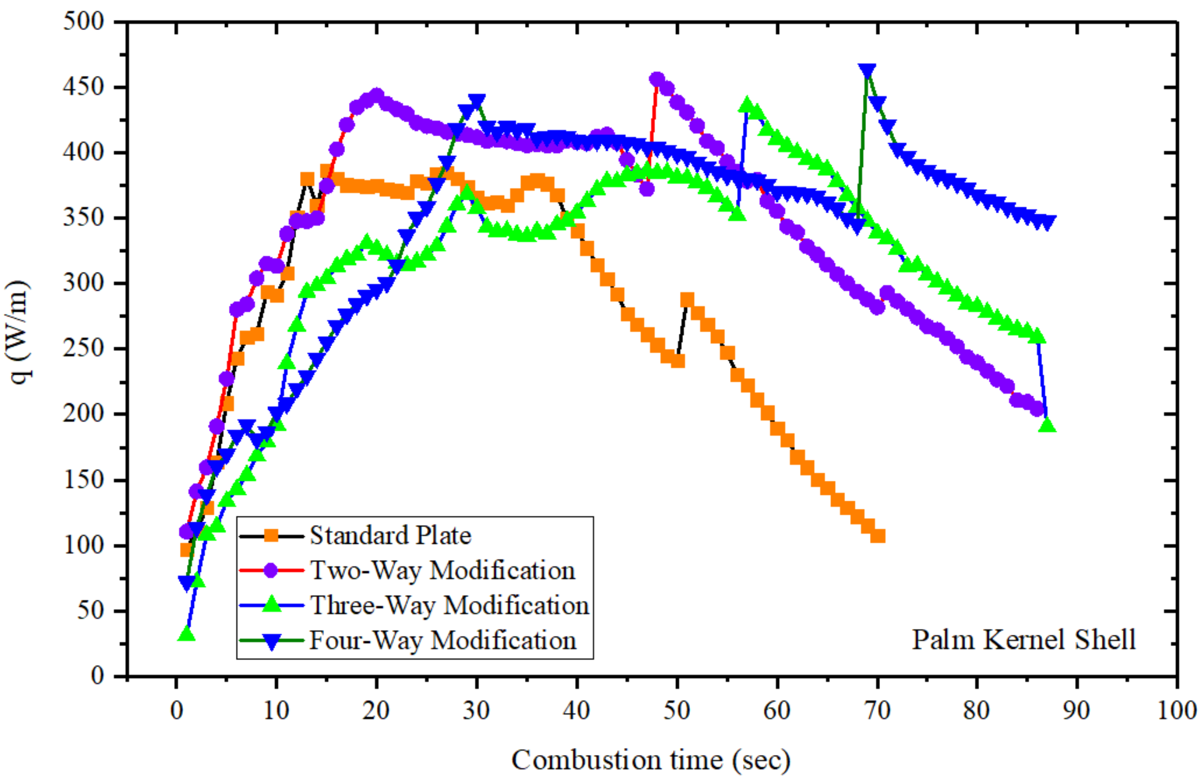

Fig. 2. Heat Release Rate vs. Combustion Time for Palm Kernel Shell with Different Plate Modifications

Fig. 3 presents the relationship between heat release rate (q) and combustion time for oil palm fronds under different plate modifications. Similar to the palm kernel shell in the previous figure, the heat release rate rises sharply during the initial phase of combustion (0–20 s), followed by a peak and then a gradual decline. However, the combustion characteristics of oil palm fronds exhibit a slightly longer combustion duration and higher variability across the plate modifications, demonstrating the influence of design changes on the combustion process. The standard plate configuration reached its maximum heat release rate of approximately 400 W/m at around 45 seconds. This peak was relatively sustained for about 10 seconds before gradually declining to 150 W/m at around 65 seconds and further reducing to below 100 W/m at 70 seconds. Compared to palm kernel shell combustion, the standard plate in oil palm fronds shows a higher peak but still experiences an early and steep decline, indicating limited combustion stability.

The two-way modification exhibited a delayed combustion peak of about 420 W/m at nearly 55 s, maintaining values above 300 W/m until approximately 70 s before gradually decreasing. In contrast, the three-way modification achieved a peak of around 370 W/m earlier, at 20 s, and sustained values between 300 and 360 W/m until 60 s, demonstrating stable mid-range performance. The four-way modification provided the most consistent combustion behaviour, with a sharp rise to approximately 400 W/m at 30 s, maintaining this level until 50 s, and then slowly decreasing to 200 W/m at 90 s, highlighting its superior combustion sustainability. Overall, the modified plates offered significant improvements in heat release performance compared to the standard plate. While the two-way modification extended the peak combustion duration, the three-way modification emphasised an early but stable combustion phase. The four-way modification proved to be the most effective, sustaining higher heat release rates (above 300 W/m) for the most extended period, thereby enhancing the efficiency and stability of oil palm frond combustion. This suggests that the complexity of plate modification directly correlates with improved combustion efficiency and optimised energy release.

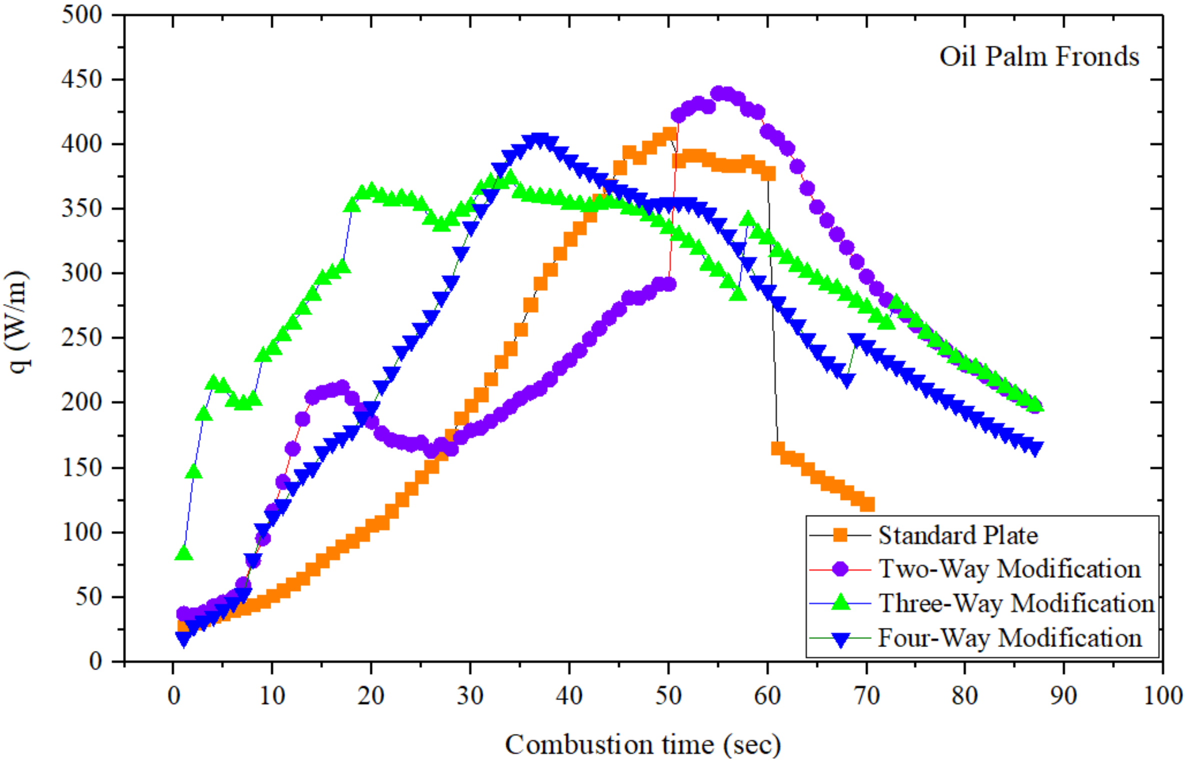

Fig. 3. Heat Release Rate vs. Combustion Time for Oil Palm Fronds with Different Plate Modifications

Fig. 4 illustrates the variation of heat release rate (q) with combustion time for empty fruit bunches using different plate modifications. As with the previous fuels, the combustion process shows a rapid increase in heat release rate during the first 20 seconds, followed by a peak region and then a gradual decline. However, compared to palm kernel shell and oil palm fronds, the empty fruit bunches demonstrate a shorter combustion duration and sharper decline in heat release rate, reflecting their lower combustion stability. The standard plate configuration reached a maximum heat release rate of approximately 380 W/m at around 18 s. After this point, the value decreased sharply, falling to about 200 W/m at 30 s and further declining below 100 W/m at around 50 s. This steep decline highlights the limitations of the standard plate when burning empty fruit bunches, with poor sustainability of combustion beyond the initial phase.

The two-way modification achieved a peak heat release rate of approximately 420 W/m at around 20 s, maintaining values between 250–300 W/m until 40 s, after which the curve gradually declined to below 200 W/m by 60 s. The three-way modification provided the highest peak performance, reaching approximately 440 W/m at 22 s, and sustained above 300 W/m up to 50 s, before decreasing to around 200 W/m at 70 s. Meanwhile, the four-way modification peaked at nearly 410 W/m at 20 s and exhibited the most stable decline, maintaining above 200 W/m until approximately 80 s, indicating superior long-term combustion stability compared to the other configurations. Overall, the empty fruit bunches exhibited improved combustion performance with plate modifications compared to the standard plate. The two-way modification initially offered an improvement but declined relatively quickly, whereas the three-way modification delivered the highest peak at 440 W/m, albeit with a faster reduction after 50 s. The four-way modification demonstrated the best balance between peak intensity and sustained combustion, maintaining higher heat release rates for a longer duration. Thus, for empty fruit bunch combustion, the four-way modification appears to be the most efficient configuration, providing both enhanced peak performance and better stability.

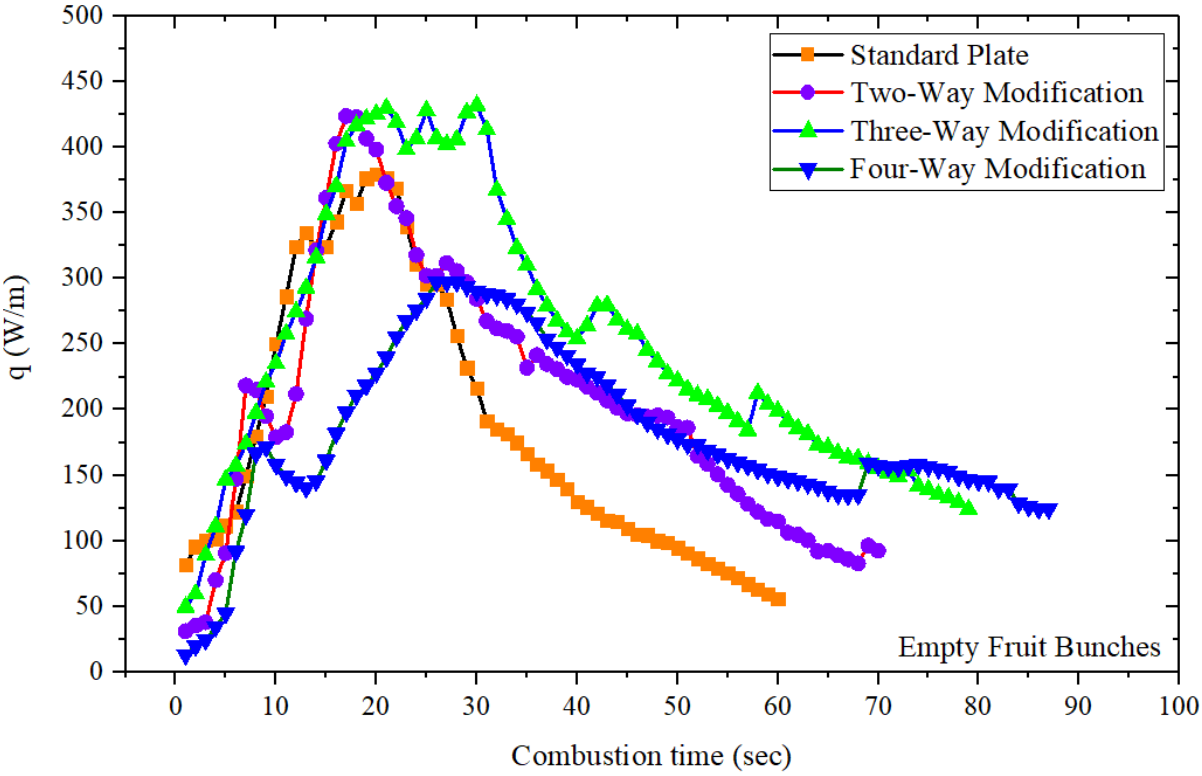

Fig. 4. Heat Release Rate vs. Combustion Time for Empty Fruit Bunches with Different Plate Modifications

Fig. 5 shows the thermal efficiency of palm kernel shell, oil palm fronds, and empty fruit bunches at four measurement points (T1–T4) for Experiment-01. Across all fuels, the highest efficiency values were recorded at the first measurement point (T1), followed by a gradual decline at later points. This pattern highlights the initial effectiveness of combustion at T1, with decreasing efficiency as combustion progresses. The palm kernel shell recorded a thermal efficiency of approximately 80% at T1, which declined slightly to around 75% at T2. The efficiency continued to drop to 63% at T3 and reached its lowest value of 52% at T4. These results suggest that while palm kernel shell combustion initially performs efficiently, it experiences a notable decline in performance across the subsequent measurement points.

Oil palm fronds exhibited the highest efficiency among the three fuels, with an efficiency of 83% at T1 and maintaining a high level of 80% at T2. At T3, the efficiency dropped moderately to 71%, and further decreased to 64% at T4. This trend indicates that oil palm fronds maintained better stability and higher efficiency compared to palm kernel shells, even as the combustion process progressed. Empty fruit bunches demonstrated the lowest performance among the three fuels. At T1, their efficiency was approximately 51%, declining to 44% at T2, 41% at T3, and ultimately reaching 36% at T4. The consistently lower values suggest poor combustion efficiency for this fuel compared to palm kernel shell and oil palm fronds. Overall, oil palm fronds achieved the highest and most stable thermal efficiency, while empty fruit bunches were the least effective in sustaining efficient combustion during Experiment-01.

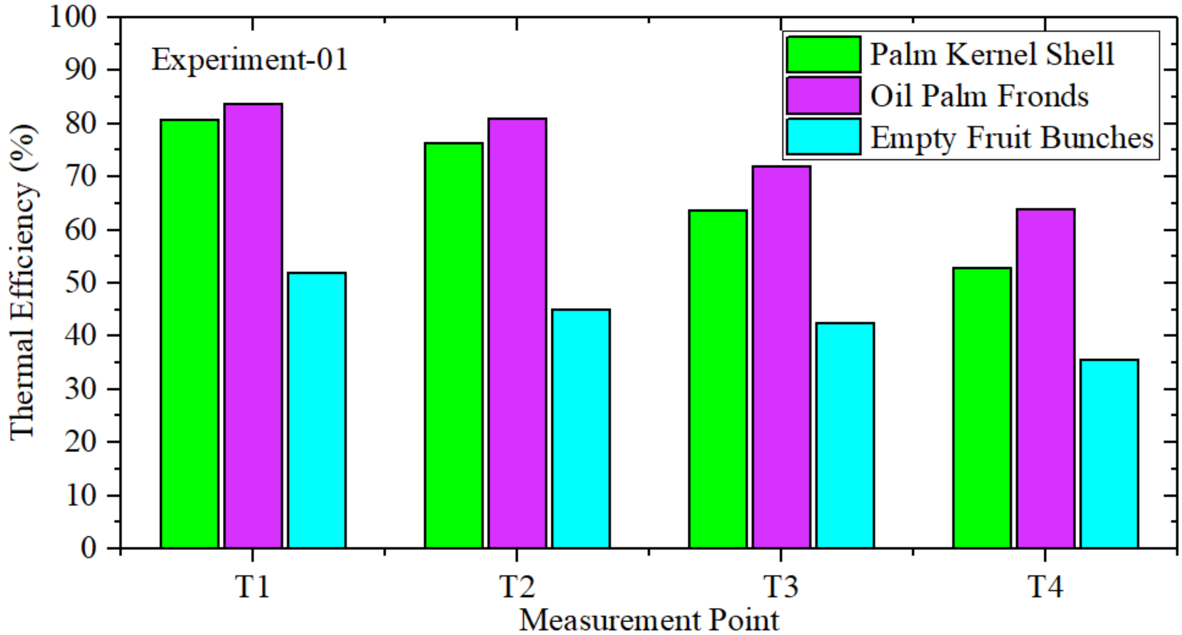

Fig. 5. Thermal Efficiency of Palm Kernel Shell, Oil Palm Fronds, and Empty Fruit Bunches at Different Measurement Points

Fig. 6 illustrates the thermal efficiency of palm kernel shell, oil palm fronds, and empty fruit bunches at four measurement points (T1–T4) for Experiment-02. Overall, all three fuels show their highest efficiencies at T1, followed by a gradual reduction across subsequent measurement points. Compared to Experiment-01, the values in Experiment-02 are generally higher at the beginning, but the decline in efficiency is more pronounced at later points. Palm kernel shell demonstrated the best performance in Experiment-02, with a thermal efficiency of approximately 92% at T1, the highest recorded among all fuels. The efficiency decreased slightly to around 84% at T2, before dropping further to 75% at T3 and finally 66% at T4. This indicates that while palm kernel shell had an excellent initial performance, its efficiency decreased by almost 26% from T1 to T4, showing a reduction in sustained combustion quality over time.

Oil palm fronds showed slightly lower initial efficiency compared to palm kernel shell, starting at 86% at T1 and 76% at T2. By T3, the efficiency declined further to 65%, and then reached 55% at T4. Although the trend is similar to palm kernel shell, the oil palm fronds experienced a sharper decline of over 30% from T1 to T4, indicating less stability in maintaining thermal efficiency throughout the measurement points. Empty fruit bunches exhibited moderate performance compared to the other fuels. At T1, they achieved 89%, which was higher than oil palm fronds but lower than palm kernel shell. However, the efficiency dropped more drastically at later points, falling to 65% at T2, 52% at T3, and reaching only 51% at T4. This steep decline highlights the difficulty of empty fruit bunches in sustaining efficient combustion. In summary, palm kernel shell performed the best in Experiment-02 with the highest efficiency and relatively stable performance, while empty fruit bunches showed early promise but lost efficiency quickly.

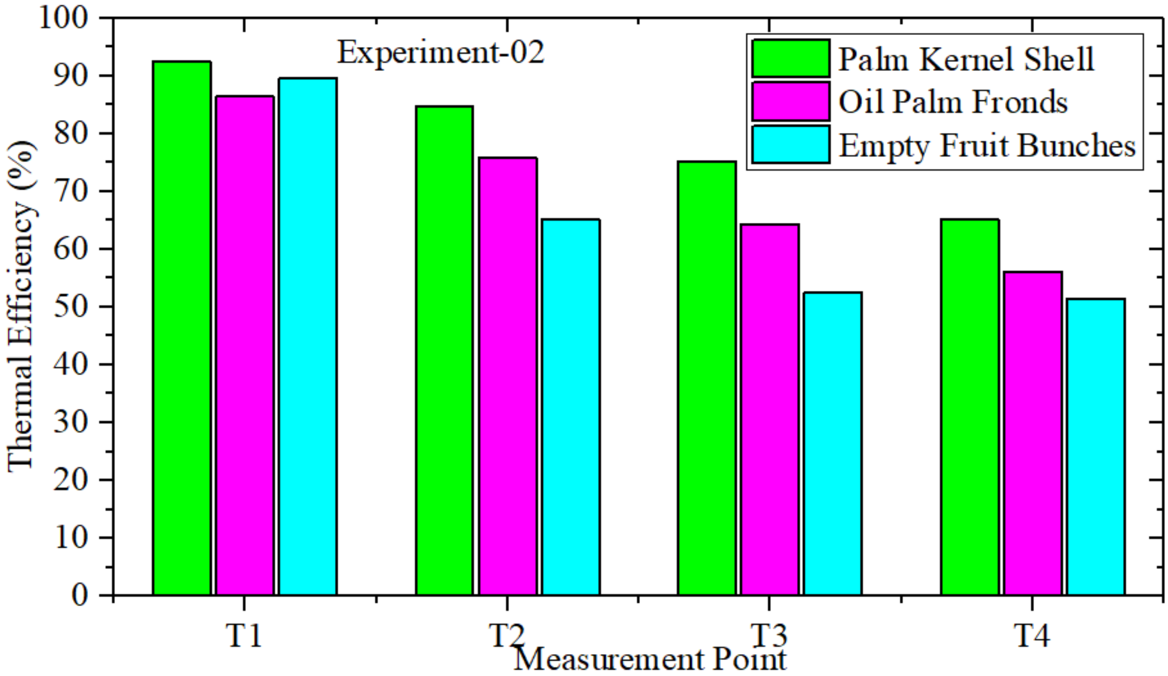

Fig. 6. Thermal Efficiency of Palm Kernel Shell, Oil Palm Fronds, and Empty Fruit Bunches at Different Measurement Points

Fig. 7 presents the thermal efficiency of palm kernel shell, oil palm fronds, and empty fruit bunches at four measurement points (T1–T4) for Experiment-03. Similar to the previous experiments, the efficiency values are highest at T1 and decrease progressively toward T4. However, the values in Experiment-03 show better overall stability compared to Experiment-02, especially for empty fruit bunches, which maintained higher efficiency at later measurement points. The palm kernel shell achieved an efficiency of about 89% at T1, slightly lower than in Experiment 02. At T2, the value decreased to around 87%, followed by a more significant reduction to 73% at T3. By T4, the efficiency reached its lowest point at 63%. Despite the decline, palm kernel shell maintained relatively high efficiency throughout the four measurement points, showing better stability compared to oil palm fronds in this experiment.

Oil palm fronds displayed the highest efficiency at T1, reaching approximately 95%, which was superior to both palm kernel shell and empty fruit bunches. However, the efficiency dropped to 80% at T2, followed by 68% at T3, and further decreased to 64% at T4. While they had the strongest initial performance, oil palm fronds experienced a steep decline of more than 30%, indicating lower long-term stability compared to palm kernel shell and empty fruit bunches. Empty fruit bunches showed an interesting trend in Experiment-03. At T1, they recorded 93%, close to the oil palm fronds. Efficiency remained high at 90% at T2, outperforming both other fuels at this stage. At T3, the value dropped to 82%, and at T4, it stabilised at 74%, the highest among the three fuels at this final point. This demonstrates that empty fruit bunches, while not always the strongest at the beginning, provided the most stable performance toward the later stages of combustion. Overall, palm kernel shell maintained good consistency, oil palm fronds led in peak values, and empty fruit bunches excelled in long-term stability.

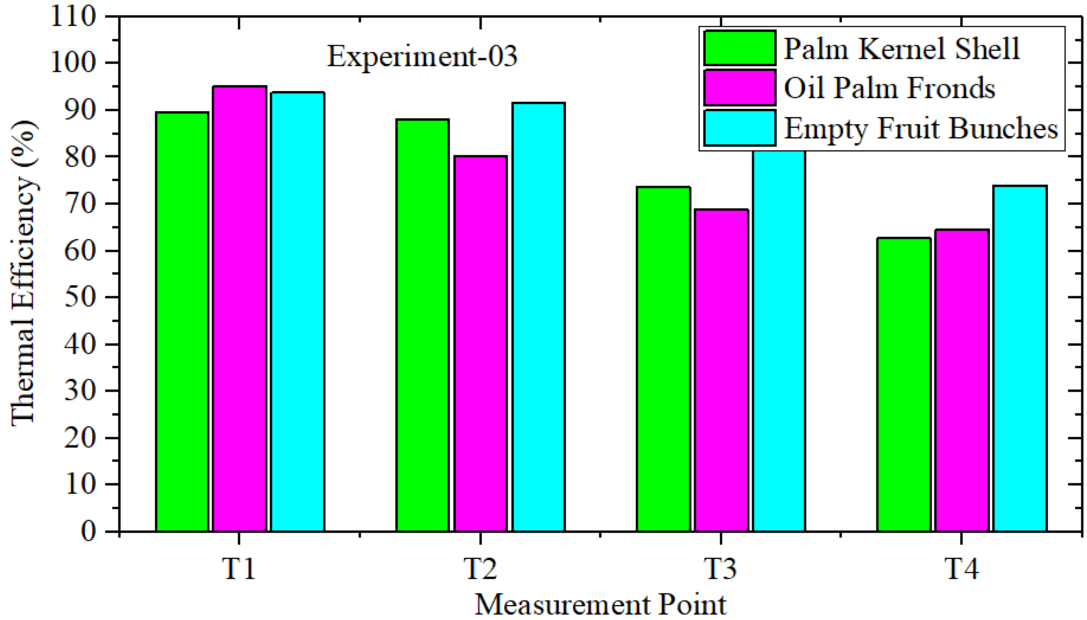

Fig. 7. Thermal Efficiency of Palm Kernel Shell, Oil Palm Fronds, and Empty Fruit Bunches at Different Measurement Points

Fig. 8 illustrates the combustion furnace efficiency of palm kernel shell, oil palm fronds, and empty fruit bunches at four measurement points (T1–T4) for Measurement-01. The data reveal a general pattern where all fuels achieve their maximum efficiency at T1, followed by a gradual decline across subsequent points. Compared to the thermal efficiency results in Figures 5–7, the furnace efficiency values are generally lower, reflecting the additional energy losses in the system. Palm kernel shell reached the highest initial efficiency among the three fuels, with a value of approximately 65% at T1. The efficiency then decreased to around 58% at T2, 50% at T3, and finally 43% at T4. This downward trend indicates a total reduction of about 22 percentage points from the first to the last measurement point, highlighting the sensitivity of palm kernel shell combustion to furnace energy losses as time progresses.

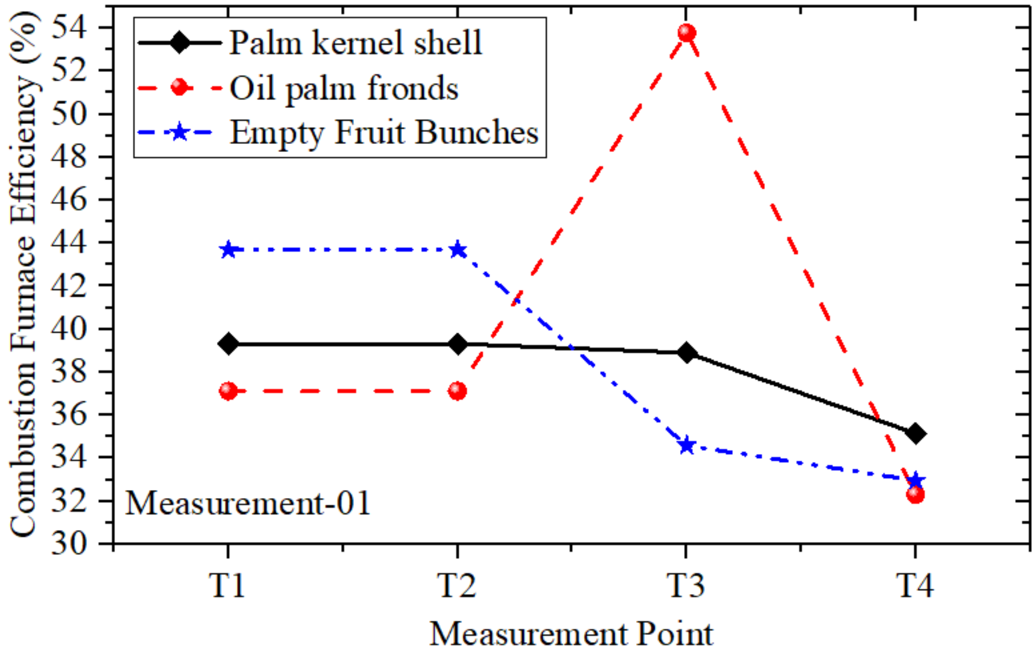

Fig. 8. Combustion Furnace Efficiency of Palm Kernel Shell, Oil Palm Fronds, and Empty Fruit Bunches at Different Measurement Points

Oil palm fronds demonstrated a relatively strong performance, with an initial furnace efficiency of about 61% at T1. The values declined to 53% at T2, 47% at T3, and finally 40% at T4. Compared to palm kernel shell, the oil palm fronds had a lower starting efficiency but a slightly more stable reduction pattern, with a total efficiency loss of 21 percentage points across the measurement points. This suggests a relatively consistent combustion profile despite lower overall efficiency. Empty fruit bunches recorded the lowest performance, starting at only 48% at T1. The efficiency further decreased to 41% at T2, 36% at T3, and reached just 32% at T4. This represents a total decline of 16 percentage points, which is smaller than the other fuels but reflects consistently poor performance across all points. In summary, palm kernel shells exhibited the highest furnace efficiency, oil palm fronds maintained a balanced decline, and empty fruit bunches consistently lagged, confirming their weaker suitability as a combustion fuel in furnace systems.

Fig. 9 shows the combustion furnace efficiency of palm kernel shell, oil palm fronds, and empty fruit bunches at four measurement points (T1–T4) for Measurement-02. Similar to Measurement-01, all fuels achieved their peak efficiency at T1 and then showed a gradual decline at subsequent points. However, compared to the previous measurement, the efficiency values here are slightly higher at T1 but demonstrate steeper declines toward T4. Palm kernel shell reached an efficiency of about 71% at T1, making it the strongest performer at the start. The efficiency decreased to 62% at T2, further reduced to 53% at T3, and dropped to 46% at T4. This represents a total decline of 25 percentage points from T1 to T4, indicating that although palm kernel shell maintains high initial performance, its efficiency diminishes rapidly as combustion continues in the furnace.

Oil palm fronds initially achieved an efficiency of around 68% at T1, which is slightly lower than that of palm kernel shell. The values then declined to 60% at T2, 51% at T3, and finally 45% at T4. With a total reduction of 23 percentage points, oil palm fronds showed a relatively stable decline compared to palm kernel shell, though their overall performance was consistently lower at every measurement point. Empty fruit bunches demonstrated weaker performance compared to the other two fuels. Their efficiency was approximately 55% at T1, decreasing to 47% at T2, 42% at T3, and reaching its lowest point of 37% at T4. Despite having a minor total reduction (18 percentage points) compared to palm kernel shell and oil palm fronds, their efficiency values were consistently the lowest across all measurement points. Overall, palm kernel shell remained the best performer in Measurement-02, oil palm fronds showed competitive but slightly lower efficiency, and empty fruit bunches continued to demonstrate the weakest suitability as a furnace fuel.

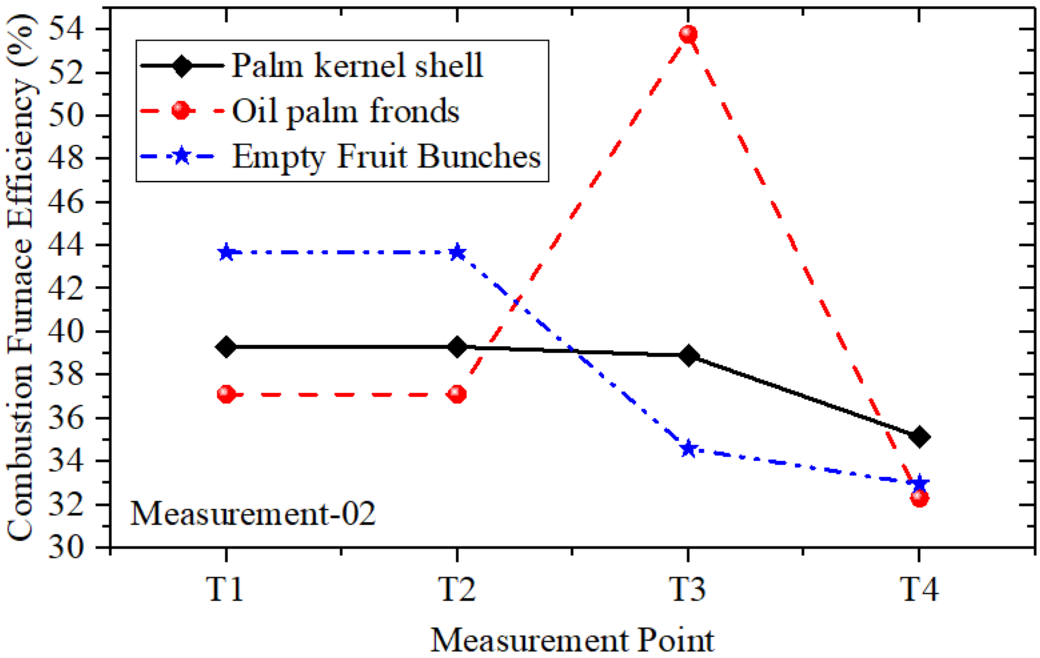

Fig. 9. Combustion Furnace Efficiency of Palm Kernel Shell, Oil Palm Fronds, and Empty Fruit Bunches at Different Measurement Points

Fig.10 illustrates the combustion furnace efficiency of palm kernel shell, oil palm fronds, and empty fruit bunches at four measurement points (T1–T4) for Measurement-03. The trend remains consistent with the previous measurements, where all fuels reached their maximum efficiency at T1 before gradually declining through T2, T3, and T4. Compared to Measurement-01 and Measurement-02, the efficiency values in Measurement-03 indicate a more balanced decline, suggesting improved stability across fuels. The palm kernel shell achieved the highest efficiency at the beginning, recording approximately 74% at T1. The efficiency then decreased to 66% at T2, further declined to 57% at T3, and dropped to 49% at T4. The total reduction of 25 percentage points demonstrates that while palm kernel shell consistently provides high initial furnace efficiency, it experiences a sharp decline toward the later measurement points, which may affect long-term combustion performance.

Oil palm fronds recorded an efficiency of approximately 71% at T1, slightly lower than that of palm kernel shell but still strong. At T2, the efficiency decreased to 63%, followed by 55% at T3, and finally 48% at T4. This represents a total loss of 23 percentage points, which is similar to Measurement-02. Despite being slightly behind palm kernel shell, oil palm fronds demonstrated relatively steady performance across all measurement points, confirming their reliable combustion profile in furnace applications. Empty fruit bunches again produced the lowest efficiency values among the three fuels. At T1, they started at 59%, dropping to 51% at T2, 45% at T3, and finally 40% at T4. This decline of 19 percentage points was less steep compared to the other fuels, but their overall efficiency remained consistently lower. In summary, palm kernel shell delivered the highest initial efficiency, oil palm fronds showed stable mid-range performance, and empty fruit bunches performed the weakest, reaffirming the superiority of palm kernel shell and oil palm fronds as more suitable fuels for efficient furnace operation.

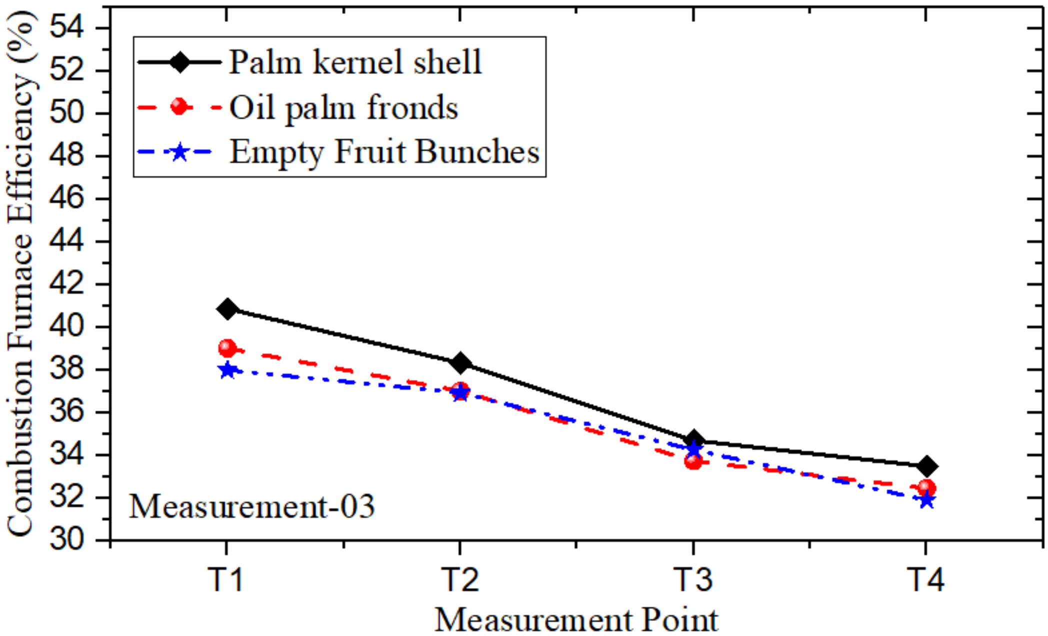

Fig. 10. Combustion Furnace Efficiency of Palm Kernel Shell, Oil Palm Fronds, and Empty Fruit Bunches at Different Measurement Points

4. Novelty of the Findings

The first novelty of this study lies in the application of different plate modifications (two-way, three-way, and four-way) to improve the combustion characteristics of biomass fuels, namely palm kernel shell, oil palm fronds, and empty fruit bunches. Previous studies have generally focused on the thermal properties of these fuels without significant attention to the influence of combustion chamber design.

The results presented in **Figs 2–4** clearly demonstrate that increasing the complexity of plate modification leads to higher peak heat release rates (up to 440 W/m with three-way changes) and more stable combustion compared to the standard plate. This highlights the novelty of introducing design-oriented solutions to optimise the efficiency of biomass combustion. Another novelty of this research is the detailed evaluation of both thermal efficiency (**Figs 5–7**) and combustion furnace efficiency (**Figs 8–10**). Unlike many studies that focus solely on calorific value or thermal efficiency at a single stage, this work systematically measures performance across multiple measurement points (T1–T4) and multiple experiments. This allows for a deeper understanding of efficiency trends, showing, for instance, that palm kernel shell achieved up to 92% thermal efficiency in Experiment-02, while oil palm fronds demonstrated 95% thermal efficiency in Experiment-03, and empty fruit bunches, although weaker initially, achieved the most stable performance at later stages (up to 74% at T4 in Experiment-03). Such multi-dimensional evaluation strengthens the novelty of this study compared to conventional single-point measurements.

The comparative approach between three different biomass fuels provides further novelty. While palm kernel shell consistently demonstrated the highest initial performance in both thermal and furnace efficiency (up to 74% furnace efficiency at T1 in Measurement-03), oil palm fronds showed remarkable peak values but suffered from faster declines in efficiency. Interestingly, empty fruit bunches, often considered the least efficient fuel, revealed relatively stable combustion performance in later stages, particularly in Experiment-03, where they outperformed the other fuels at T4 (74% thermal efficiency). This comparative insight provides new evidence that different biomass fuels can be strategically utilised depending on whether high initial energy or long-term stability is required. Finally, the integration of combustion performance, thermal efficiency, and furnace efficiency within a single study represents a novel contribution to the field of biomass energy research. Most earlier works examine these aspects in isolation, but this study connects them to provide a holistic view of biomass fuel performance in practical furnace operations. The findings not only demonstrate the technical potential of plate modifications but also provide valuable guidance: palm kernel shell is suitable for applications requiring high initial efficiency, oil palm fronds are effective for rapid energy release, and empty fruit bunches, despite lower peak temperatures, offer better stability for prolonged combustion. This integrated perspective significantly contributes to the novelty of the research, as it bridges laboratory analysis with real-world applications.

5. Conclusion

This study has demonstrated that combustion performance and efficiency of palm kernel shell, oil palm fronds, and empty fruit bunches can be significantly enhanced through plate modifications in furnace systems. The heat release rate analysis revealed that the highest peak value was achieved with three-way modification, reaching up to 440 W/m, while four-way modification provided the most stable combustion, maintaining values above 300 W/m for extended periods. These results confirm that design improvements in the combustion chamber have a direct influence on the stability and intensity of biomass combustion. Thermal efficiency results across Experiments 1–3 further highlighted the differences among the fuels. Oil palm fronds achieved the highest recorded value of 95% at T1 in Experiment-03, while palm kernel shell reached 92% at T1 in Experiment-02. Although empty fruit bunches generally showed lower values, they demonstrated superior stability at later stages, maintaining 74% efficiency at T4 in Experiment-03, outperforming the other two fuels at this point. This indicates that different biomass types possess unique advantages, where palm kernel shell excels in initial combustion, oil palm fronds in peak energy release, and empty fruit bunches in long-term stability.

In terms of furnace efficiency, palm kernel shell consistently delivered the highest initial values, with a peak of 74% at T1 in Measurement-03, while oil palm fronds maintained a competitive but slightly lower profile (71% at T1 in Measurement-03). Empty fruit bunches again showed weaker performance, starting at 59% at T1 and ending at 40% at T4, but with a smaller efficiency drop compared to the other fuels. This demonstrates that, although less efficient overall, empty fruit bunches offer a relatively steady decline in performance. Overall, the novelty of this research lies in integrating plate modification design with comparative fuel analysis, showing that chamber modifications significantly improve combustion stability and efficiency. The findings suggest that palm kernel shells are most suitable for applications requiring high initial efficiency, oil palm fronds are ideal for rapid energy output, and empty fruit bunches are advantageous where long-term stability is prioritised. These insights offer practical recommendations for optimising biomass utilisation in renewable energy systems.

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