KINETICS EVALUATION OF NON-ISOTHERMAL MICROWAVE-ASSISTED TORREFACTION OF OIL PALM FIBRE: EFFECT OF MICROWAVE POWER LEVEL

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This study investigates the non-isothermal microwave-assisted torrefaction of oil palm fibre, focusing on the effect of microwave power levels on reaction kinetics and biochar yield. Microwave-assisted torrefaction (MAT) offers rapid volumetric heating and energy efficiency, making it a promising alternative to conventional thermal methods for biomass valorization. A modified kinetic model based on di Blasi and Lanzetta was applied to simulate the decomposition pathway, incorporating heating rate (β) and multi-step reactions involving biomass (A), intermediate product (B), final product (C), and volatile components (V_1, V_2). Experimental data revealed that increasing microwave power from 400 W to 800 W enhanced heating rates and volatile release, but reduced solid residue yield, indicating intensified thermal decomposition. The kinetic parameters and statistical validation (R^2, RMSE, SSE) confirmed the model's robustness, particularly at 400 W. These findings demonstrate that MAT can be tuned to optimize biochar properties for multifunctional applications, such as carbon sequestration and thermal energy storage, contributing to climate mitigation and sustainable biomass utilization.

Keywords: kinetics, microwave, non-isothermal, oil palm fibre, torrefaction

INTRODUCTION

Carbon dioxide (CO_2) emissions, the primary driver of global climate change, reflecting the rising use of fossil fuels, increased by 0.8% to reach 37.8 Gt in 2024.[1–3] The implementation of Thermal Energy Storage (TES) systems is a key option for integrating renewable energy sources and achieving efficient, sustainable, and effective thermal systems that reduce CO_2 emissions.[1,4–8] Mobilized TES has even been shown to reduce CO_2 emissions by 93%.[9,10] TES implementation contributes to the achievement of Sustainable Development Goals 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 (Addressing Climate Change).[9]

TES technologies facilitate the capture and reuse of excess thermal energy, which improves grid reliability, decreases dependence on fossil fuels, and aids in decarbonizing industrial, residential, and agricultural sectors. Within this framework, biochar, a carbon-rich byproduct produced from biomass pyrolysis or torrefaction, has surfaced as a versatile material with valuable uses in TES systems.[11,12] While it has been traditionally acknowledged for its benefits in soil improvement and carbon storage, biochar's porous nature, thermal stability, and adjustable surface

chemistry render it an ideal medium for the integration of Phase Change Materials (PCMs), which are substances that store and release latent heat during phase transition processes.[11,13,14] Latent TES uses phase-change materials (PCMs) capable of storing 5–15 times more energy than sensible heat storage.[15] Other advantages of PCMs include their molecular heat transfer, high heat storage density, low cost, flexible design, and reduced energy consumption.[4,11,16]

In tropical areas such as Indonesia, oil palm fiber serves as a significant biomass source with significant potential for producing biochar. Traditional torrefaction techniques, although effective, frequently encounter challenges like slow heating rates, inconsistent thermal distribution, and limitations in scalability. Torrefaction methods can generally be classified into conventional thermal torrefaction and advanced techniques, such as microwave-assisted torrefaction (MAT).[17,18] Conventional torrefaction typically involves gradually heating the biomass in an inert atmosphere at temperatures ranging from 200–300 °C, resulting in partial devolatilization, increased energy density, and improved hydrophobicity.[18–20] While this method is effective, it often faces challenges like uneven heat distribution, lengthy residence times, and considerable energy requirements, particularly for larger particles. To overcome these challenges, researchers are investigating innovations, such as oxidative, steam, and microwave-assisted torrefaction, each presenting distinct thermal and processing characteristics.[18,19,21]

Microwave-assisted torrefaction (MAT) is notable for its quick volumetric heating and energy efficiency.[18,19] Unlike traditional external heating methods, microwaves penetrate the biomass and produce heat internally through dielectric heating, leading to consistent thermal profiles and shorter processing durations.[22–24] This approach allows for improved management of devolatilization reactions, better product consistency, and a reduction in excessive char production.[25] MAT is particularly beneficial for treating fine powders or wet biomass, as it is more efficient in moisture management.[26] Its flexibility and compatibility with continuous processing systems position it as an encouraging option for decentralized bioenergy generation, complementing the sustainable use of biomass and the growing demand for low-carbon energy solutions.[27,28]

Microwave-assisted torrefaction (MAT) stands out due to its rapid volumetric heating and energy efficiency.[18,19] In contrast to conventional external heating techniques, microwaves penetrate the biomass and generate heat internally through dielectric heating, resulting in uniform thermal profiles and reduced processing times.[22–24,28,29] This facilitates better management of devolatilization reactions, enhances product uniformity, and minimizes the chances of excessive char formation.[25] MAT is particularly advantageous for processing fine powders or moist biomass, as it more effectively manages moisture.[26] Its adaptability and compatibility with continuous processing systems make it a promising candidate for decentralized bioenergy generation, aligning well with the sustainable utilization of biomass and the increasing need for low-carbon energy alternatives.[27,28]

Despite these advantages, the fundamental kinetic behavior of biomass under MAT conditions remains insufficiently understood, particularly under non-isothermal regimes where heating rates vary dynamically with microwave power. Kinetic studies are essential because they provide quantitative insights into reaction pathways, activation energies, and decomposition rates, which are critical for designing scalable thermochemical conversion systems. Previous models, such as single-step or consecutive reaction schemes, often oversimplify the complex multi-step decomposition of lignocellulosic biomass. The di Blasi and Lanzetta model, later modified to incorporate heating rate (β), offers a more realistic framework by accounting for sequential transformations of biomass into intermediates, volatiles, and stable carbonaceous products. Recent developments in microwave-assisted torrefaction have shown greater energy efficiency, quick heating, and improved control over reaction kinetics, making it an appealing alternative for decentralized biochar production systems.

This study therefore investigates the non-isothermal microwave-assisted torrefaction of oil palm fibre, focusing on how varying microwave power levels influence reaction kinetics and product yield. By applying a modified kinetic model and validating it against experimental data, we aim to clarify the decomposition pathways and quantify the trade-offs between biochar quality and yield. Understanding these kinetic dynamics is crucial not only for optimizing biochar properties for TES and carbon sequestration, but also for advancing decentralized bioenergy systems in tropical agro-industrial contexts. In doing so, this research addresses both the scientific gap in kinetic

modeling of MAT and the broader sustainability imperative of valorizing agricultural residues for climate mitigation.

EXPERIMENTAL

Materials

The oil palm fibre was sourced from plantations in Sumatra, Indonesia. Following collection, the fibre was sun-dried, chopped, and ground into powder, which was subsequently screened to a 60-mesh size. To further reduce residual moisture and ensure sample consistency, the sun-dried powder was re-dried at 105 °C for 10 minutes prior to use. The measured moisture content of the prepared oil palm fibre was 11.2%.

Torrefaction procedure

The powdered oil palm fibre was processed in a microwave-assisted torrefaction system comprising a nitrogen cylinder, microwave unit, reactor, digital scale, data logger, thermocouple, sample container, and personal computer. Nitrogen gas was continuously supplied to displace oxygen, thereby maintaining the oxygen-deficient atmosphere required for torrefaction. The microwave employed was an Electrolux model EMM2308X, while the digital scale had a capacity of 0.25 kg with a precision of 0.0001 g. For each run, 15 g of fibre powder was placed in a Pyrex container and heated for 1,800 s. A nitrogen flow rate of 2 L/min was maintained, and the microwave operated at an output power of 400 W, 600 W, or 800 W depending on the experimental condition. Experiments began at ambient temperature and continued until the maximum temperature was reached. The maximum temperatures obtained were 283.79 °C at 400 W, 288.46 °C at 600 W, and 337.50 °C at 800 W. The sample mass (M_t) was continuously monitored online during torrefaction using a digital scale (capacity 0.25 kg, precision 0.0001 g) connected to a data logger. This ensures that mass loss data were directly recorded during the process. The recorded mass values were subsequently used to calculate the relative mass ratio $\frac{M_t}{M_0}$, where M_t denotes the sample mass at time t and M_0 represents the initial mass.

Kinetic modelling

The kinetic model applied in this research was the model developed by di Blasi and Lanzetta and modified by Harun *et al*. for the heating phase.[30] On the isothermal kinetics reaction for the non-isothermal phase, Harun *et al.* included the heating rate (β) in the model equations.[30] The reaction scheme is illustrated in Figure 1. It is assumed that, initially, biomass A is converted into B, an intermediate solid, and a volatile V_1; the intermediate solid then generating a final product C and a volatile V_2.

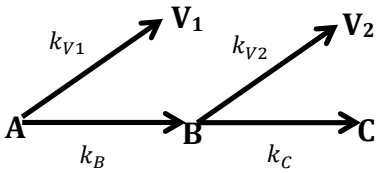

Figure 1: Torrefaction reaction scheme

The rate equations for the reaction scheme are presented in Equations 1-5:

$$\frac{dA}{dt} = \frac{1}{\beta}.-(k_B + k_{V1})[A] \quad (1)$$

$$\frac{dB}{dt} = \frac{1}{\beta}(k_B[A] - (k_C + k_{V2})[B]) \quad (2)$$

$$\frac{dC}{dt} = \frac{1}{\beta}k_C[B] \quad (3)$$

$$\frac{dV1}{dt} = \frac{1}{\beta}(-(k_B + k_{V1})[A]) \quad (4)$$

$$\frac{dV2}{dt} = \frac{1}{\beta}(-(k_B + k_{V1})[A]) \quad (5)$$

The simultaneous differential equations of the models were numerically solved by Euler's method to obtained the calculated mass fraction of A (biomass), B (intermediate solid), C (final product), V_1 (volatile product obtained from the conversion of A) and V_2 (volatile product obtained from the conversion of B). The step size (t) for the numerical solution is set to 1s. Four kinetic model parameters, that is, k_B, k_C, k_{V1} and k_{V2}, were determined by fitting to the experimental data of the relative mass sample $\frac{M_t}{M_0}$, which represents the ratio of M_t as the sample mass at time t, and M_0 as the intial sample mass. Meanwhile, the calculated relative mass sample was calculated as the sum of the mass of A, B and C. The fitting was based on minimization of the sum of square error (SSE), as in Equation 6:

$$SSE = \sum_{i=1}^{N}\left(\frac{M_t}{M_0}_{exp,i} - \frac{M_t}{M_0}_{calc,i}\right)^2 \quad (6)$$

The performance of the torrefaction model was also evaluated by calculating several statistical parameters, including coefficient of determination (R^2), Chi-square (X^2), Root Mean Square of Error (RMSE), and Mean Square Error (MSE), by Equations 7-10:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(\frac{M_t}{M_0}_{exp,i} - \frac{M_t}{M_0}_{calc,i}\right)^2}{\sum_{i=1}^{N}\left(\frac{M_t}{M_0}_{exp,i} - \frac{M_t}{M_0}_{ave,i}\right)^2} \quad (7)$$

$$X^2 = 1 - \frac{\sum_{i=1}^{N}\left(\frac{M_t}{M_{0exp,i}} - \frac{M_t}{M_{0calc,i}}\right)^2}{N} \quad (8)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(\frac{M_t}{M_{0exp,i}} - \frac{M_t}{M_{0calc,i}}\right)^2}{N-n}} \quad (9)$$

$$MSE = \frac{\sum_{i=1}^{N}\left(\frac{M_t}{M_{0exp,i}} - \frac{M_t}{M_{0calc,i}}\right)^2}{N-n} \quad (10)$$

RESULTS AND DISCUSSION

Effect of microwave power level

Thermogravimetric analysis (TGA) is a fundamental technique used to study the thermal stability and compositional characteristics of materials by monitoring changes in weight as a function of temperature or time under controlled atmosphere. Widely applied in biochar and biomass research, TGA enables precise identification of moisture content, volatile components, decomposition stages, and ash residues.[31,32] In this research, the TGA data was recorded and the final solid residue mass was used to determine the yield of the process. The yield of the solid residue obtained from the microwave assisted torrefaction of oil palm fibre is depicted in Figure 2.

Figure 2 shows that the yield of solid residue obtained from the microwave-assisted torrefaction of oil palm fibre ranged between 63.83% and 83.87%. This range is comparable to the findings of Harun *et al*., who reported solid residue yields of 78–50% for empty fruit bunch (EFB) and 52–82% for palm kernel shell (PKS) under conventional torrefaction at temperatures of 240 °C, 270 °C, 300 °C, and 330 °C.[30] In contrast, Khamwicit *et al.* reported a significantly higher yield of 97.36%, when palm fibre was torrefied at 200 °C for 30 minutes.[33]

The differences in yield across these studies highlight the strong influence of operating conditions, particularly temperature, heating method, and residence time, on torrefaction outcomes. The relatively high yield observed in our microwave-assisted experiments suggests that MAT promotes efficient energy transfer, which reduces excessive devolatilization, compared to conventional methods. However, the lower yield compared to Khamwicit *et al*.[33] can be attributed to the higher operating temperatures in our study (up to 337.5 °C), which accelerate decomposition and volatile release, thereby reducing the solid fraction.

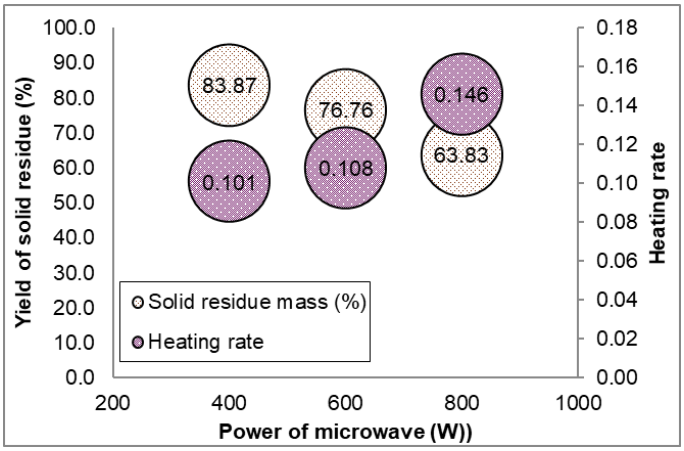

Figure 2: Yield of solid residue obtained from the microwave-assisted torrefaction of oil palm fibre at different power levels of the microwave

Figure 2 also highlights the effect of microwave power on the yield of solid residue and heating rate during thermochemical conversion. The experimental results reveal a clear inverse relationship between the microwave power level and the yield of solid residue during non-isothermal microwave-assisted torrefaction of oil palm fibre. As microwave power increased from 200 W to 600 W, the solid residue mass decreased significantly from 83.87% to 63.83%, indicating enhanced thermal decomposition and volatilization of organic components. This trend suggests that higher microwave power accelerates the breakdown of hemicellulose and cellulose fractions, leading to greater mass loss and increased biochar porosity.[19] Concurrently, the heating rate exhibited a positive correlation with microwave power, rising from 0.101 to 0.146, which reflects the rapid energy transfer and localized heating effects characteristic of

microwave irradiation.[22] These findings align with previous studies that emphasize the role of microwave-induced dipole rotation and ionic conduction in intensifying thermal reactions within lignocellulosic biomass.

The reduction in solid residue yield at elevated power levels implies a trade-off between biochar quantity and quality, particularly in applications targeting carbon retention versus surface functionality. Higher heating rates may promote the formation of micro- and mesopores, enhancing the material's suitability for adsorption or TES composite integration, especially when paired with PCMs. However, excessive power could risk structural collapse or reduced fixed carbon content, necessitating careful optimization for targeted end-use. From a kinetics perspective, the non-isothermal conditions and variable power inputs complicate activation energy estimation, but they offer valuable insights into reaction dynamics under scalable, energy-efficient processing. These results underscore the importance of power modulation in tailoring biochar properties for multifunctional applications, including soil amendment, carbon sequestration, and thermal energy storage. Overall, microwave-assisted torrefaction presents a promising pathway for valorizing oil palm fibre into high-performance biochar, contributing to both waste reduction and climate mitigation strategies.

Kinetics of torrefaction

In terms of energy recovery, the kinetics of biomass torrefaction is of great importance. The assesment of the torrefaction kinetics was intended to obtain basic data for the design of thermochemical conversion system, as well as to get a better insight into the evoluion of the torrefaction process.[34] In the development of the mathematical modelling of the torrefaction process, a variety of models have been proposed due to the physical and chemical mechanism complexity involved in thermochemical reactions of torrefaction. Thus, there are torrefaction kinetic models proposed for biomass or biomass components based on a single reaction, several consecutive reactions, or complex reactions.[20,35]

The initial work that proposed a single step model of torrefaction was reported by Coats and Redfern in 1964.[36] The biomass was assumed to be converted into solid residue and gas in a single reaction. The reaction can follow either first- or n^{th}-order kinetics.[20,36] Further, Kilzer and Broido proposed the torrefaction consecutive reaction scheme showing the conversion of cellulose into chars and low molecular weight volatiles in their work in 1969-1975.[35] Nowadays, most of the models proposed are multiple step models, in which the solid residue produced from the first reaction is converted into a new solid one. The volatile can also be produced from both reactions. Due to its simplicity and accuracy, the two-step model proposed by di Blasi and Lanzetta is often preferred.[20,30,37,38]

The torrefaction process in this work is a non-isothermal one. The kinetics model applied is the model developed by di Blasi and Lanzetta, and modified by Harun *et al*. for the heating phase.[30] In the non-isothermal phase, Harun *et al.* included the heating rate (β) in the model equations.[30] The validation of the torrefaction model presents the profile of the calculated relative mass of the sample, including the mass fractions of biomass (A), intermediate solid (B), final product (C), volatile components (V_1), and a second volatile fraction (V_2), as illustrated in Figure 3.

The mass fraction data shown in Figure 3 demonstrates the transformation of biomass during microwave torrefaction at three distinct power levels, providing insights into decomposition behavior, product yield, and the evolution of volatiles. The mass fraction profiles obtained from the microwave-assisted non-isothermal torrefaction of oil palm fiber reveal a multi-step decomposition pathway, marked by specific changes in the biomass structure. Figure 3 also presents the mass loss patterns for both experimental and calculated $\frac{M_t}{M_0}$. The correspondence between the experimental ($\frac{M_t}{M_0}\,exp$) and calculated ($\frac{M_t}{M_0}\,calc$) profiles confirms the model's validity. This assertion is further substantiated by the statistical parameters presented in this research (Table 1).

The initial decomposition of A is related to the degradation of hemicelluloses and the release of loosely bound moisture, succeeded by the formation of intermediate products (B), where the degradation of cellulose prevails. The final product (C) signifies the stabilization of carbon-dense biochar, with mass loss reaching a plateau as recalcitrant lignin structures resist further volatilization. The presence of two distinct volatile phases (V_1 and V_2) indicates the sequential release of light and heavy volatiles, probably associated with microwave-induced selective heating and dipole activation.

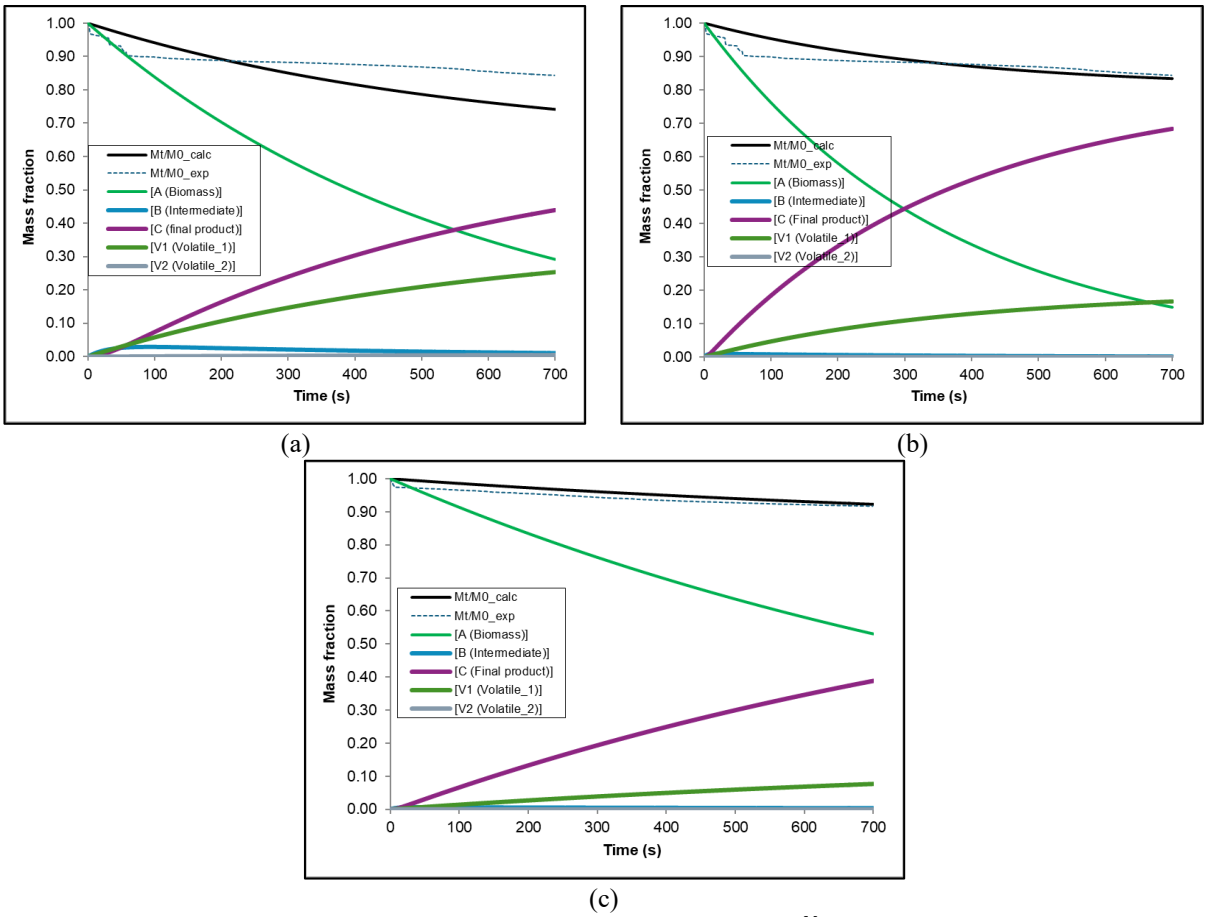

Figure 3: Mass fraction profile of obtained data of the relative mass sample ($\frac{M_t}{M0}$exp), calculated relative mass sample ($\frac{M_t}{M0}$calc), biomass (A), intermediate product (B), final product (C), volatile 1 (V_1) and volatile 2 (V_2) of the torrefaction of oil palm fibre performed at microwave power levels of (a) 800 W, (b) 600 W, and (c) 400 W

Table 1
Kinetics and statistical parameters

Kinetics parameter	400W	600W	800W
k_B	0.000076	0.000237	0.000164
k_C	0.063696	0.080133	0.038296
k_{V1}	0.000015	0.000057	0.000092
k_{V2}	0.000239	0.000224	0.000331
Beta	0.101000	0.108000	0.146000
R^2	0.907195	0.799911	0.820419
MSE	0.000125	0.000263	0.000236
RMSE	0.011164	0.016227	0.015373
X^2	0.000125	0.000263	0.000236
SSE	0.336534	0.710933	0.638069

These findings highlight the complex thermal behavior of oil palm fiber under microwave treatment, where power variation directly affects reaction kinetics and product distribution. The existence of intermediate and final product stages suggests that microwave-assisted torrefaction allows for controlled carbonization, crucial for customizing biochar properties for specific uses, such as thermal energy storage or soil enhancement. The pattern of dual volatile release may improve energy recovery potential, particularly if captured and repurposed. Additionally, the close alignment between experimental and calculated mass fractions

reinforces the reliability of the kinetic model, providing predictive capabilities for scaling up and optimizing the process. Overall, the results accentuate the potential of microwave-assisted torrefaction for not just efficient biomass conversion, but also for producing high-quality biochar with multifunctional benefits in climate-resilient systems.

The kinetic assessment across different microwave power levels illustrates varying thermal decomposition characteristics of oil palm fiber during non-isothermal torrefaction. At 600 W, the highest rate constant for intermediate product formation (k_B = 0.000237) and cellulose degradation (k_C = 0.080133) indicates more intense thermal reactions, likely a result of enhanced dipole rotation and localized heating. Notably, although 600 W facilitates fast decomposition, the rate of final product formation (k_C) decreases significantly at 800 W (0.038296), suggesting potential structural collapse or over-carbonization limiting stable biochar creation. The kinetics of volatile release (k_{V1} and k_{V2}) also change with power level, with k_{V2} reaching its peak at 800 W (0.000331), indicating a higher release of heavier volatiles under intense energy conditions. These differences emphasize how sensitive biomass transformation routes are to microwave intensity, necessitating optimal power adjustment to balance decomposition efficiency with product integrity.

From a modeling performance viewpoint, the goodness-of-fit metrics (R^2, MSE, RMSE, SSE) indicate that 400 W presents the most statistically sound condition (R^2 = 0.907, RMSE = 0.011), implying that lower power levels produce more predictable and stable reaction profiles. Conversely, the lower R^2 at 600 W (0.799) and 800 W (0.820) reveals heightened variability, potentially due to non-uniform heating or secondary reactions. The heating rate (β) escalates with power, hitting 0.146 at 800 W, which correlates with increased mass loss but also brings about modeling difficulties. These observations suggest that while higher microwave power boosts reaction kinetics, it may also jeopardize model precision and biochar consistency. Consequently, the range of 400–600 W seems to provide a suitable kinetic performance.

In this study, applying the two-step kinetic model to describe the torrefaction kinetics of palm fibre produced moderate coefficients of determination (R^2). This outcome suggests that although the model successfully captured the overall decomposition trends, its statistical fit was weaker than that reported in several earlier studies. For instance, Barcelo *et al*. applied the two-step model to the torrefaction of *Caryocar brasiliense* (pequi) seed and achieved highly accurate predictions with R^2 values exceeding 0.99, demonstrating the model's strong capability under their experimental conditions.[37] Similarly, Jamin *et al*. reported a close correlation between experimental and modeled residual mass in green waste torrefaction using the same framework.[38]

The differences observed in model performance can be linked to the distinctive behavior of microwave-assisted torrefaction. Unlike conventional thermal systems, microwave heating introduces additional complexities, such as non-uniform energy distribution, particle size variation, and residual moisture, all of which can disrupt uniform heating and reduce the accuracy of kinetic predictions. These factors often lead to deviations from the assumptions underlying simplified kinetic models, thereby lowering the statistical fit.

Microwave irradiation is particularly prone to producing localized hot spots and uneven heating patterns, which generate steep temperature gradients within the biomass.[39] At higher microwave power levels, these gradients can intensify, resulting in the formation of hot and cold regions, concentrated heating zones, and edge or corner overheating. In extreme cases, this phenomenon may trigger thermal runaway, further complicating the predictability of reaction kinetics.[39,40]

Despite these limitations, the moderate R^2 values obtained here remain informative. They provide meaningful insights into the sequential transformation of biomass into intermediates, volatiles, and solid residue, and allow comparative evaluation across different microwave power levels. The model thus remains a useful tool for identifying trends in product distribution and reaction pathways.

Moreover, Table 1 also shows a low value of Chi-square (X^2). The low value of Chi-square (X^2) indicated that the model fits well the experimental data and the low value of SSE quantifies the total deviation of the calculated values from the experimental data.[41,42] Moreover, the lower RMSE and MSE are also an indicator of the good fit of the model to the experimental data. The evaluation of the torrefaction kinetics also reveals the profile of the predicted mass fraction of the biomass (A), intermediate solid (B), final product (C), volatile

(V_1) and the mass fraction of volatile 2 (V_2) (Fig. 4).

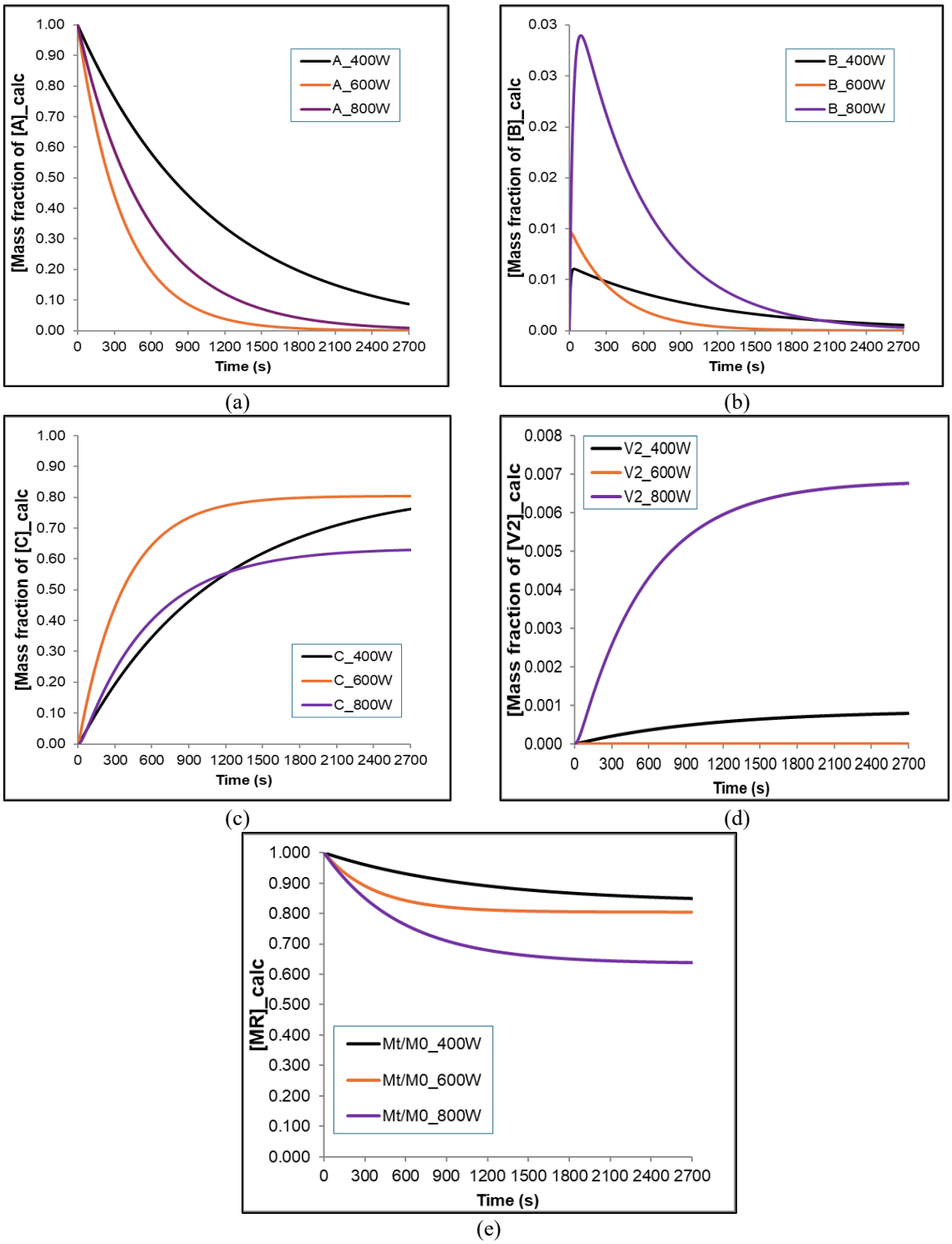

Figure 4: Mass fraction profile of calculated: (a) biomass (A), (b) intermediate product (B), (c) final product (C), (d) volatile 1 (V_1), and (e) volatile 2 (V_2) of the torrefaction of oil palm fibre

The calculated mass fraction profiles in Figure 4 provide a detailed view of the thermal decomposition pathway of oil palm fibre under microwave-assisted torrefaction. The evaluation of torrefaction kinetics provides insight into the thermal decomposition behavior of oil palm fibre under microwave-assisted conditions. As illustrated in Figure 4, the predicted mass fraction

profiles of biomass (A), intermediate solid (B), final product (C), volatile 1 (V_1), and volatile 2 (V_2) reveal the sequential transformation of the material during the torrefaction process.

The biomass fraction (A) shows a rapid decline in the early phase, indicating the breakdown of hemicelluloses and partially of cellulose at lower temperatures. This is followed by the formation of intermediate products (B), which peak before transitioning into stable carbonaceous structures (C). The final product fraction (C) stabilizes as the reaction progresses, suggesting the formation of biochar with high fixed carbon content and reduced volatile matter. These transitions reflect the sequential nature of biomass degradation, where microwave energy accelerates molecular vibration and dipole rotation, enhancing reaction kinetics compared to conventional heating.

The volatile release profiles (V_1 and V_2) further support the staged decomposition mechanism. Volatile 1 (V_1), likely composed of light oxygenated compounds, emerges during the initial breakdown of biomass, while Volatile 2 (V_2), associated with heavier hydrocarbons and lignin derivatives, appears later in the process. The distinct timing and magnitude of V_1 and V_2 suggest that microwave power influences not only the rate of decomposition, but also the composition of evolved gases. This has implications for energy recovery and emission control, as selective capture of volatiles could enhance process efficiency and reduce environmental impact. Moreover, the M_t/M_0 curve closely follows the expected mass loss trajectory, validating the kinetic model and confirming the reliability of the simulation in predicting real-world behavior.

A comparison across the three microwave power levels highlights the influence of energy input on decomposition kinetics. At 400 W, the maximum temperature reached was 283.79 °C, resulting in slower biomass degradation and a more gradual release of volatiles. At 600 W, the maximum temperature increased slightly to 288.46 °C, producing a modest acceleration in volatile formation, but still maintaining a relatively balanced conversion pathway. At 800 W, the maximum temperature rose significantly to 337.50 °C, leading to faster biomass decomposition, a sharper decline in the intermediate fraction, and a more pronounced release of volatiles. This higher power level enhanced the yield of biochar (C) while intensifying volatile production, indicating stronger microwave absorption and more efficient heat transfer.

From an application standpoint, the formation of stable final products with reduced volatile content is advantageous for further utilization of the biochar, such as TES. The controlled release of volatiles and the preservation of carbon-rich structures indicate that microwave-assisted torrefaction can be tuned to produce biochar with desirable thermal and structural properties. This aligns with broader sustainability goals, as valorizing oil palm fibre into functional materials supports waste reduction, energy resilience, and climate mitigation. The insights from Figure 4 reinforce the importance of power modulation and kinetic modeling in optimizing biochar production for multifunctional use, particularly in tropical agro-industrial contexts where biomass availability is high and energy demands are growing.

A limitation of this study is the absence of proximate and ultimate analysis data for the oil palm fibre used in the experiments. Parameters such as moisture content, volatile matter, fixed carbon, ash, and elemental composition are well known to influence microwave absorption, dielectric properties, heating rate, and decomposition pathways. Without these data, it is not possible to establish direct correlations between fibre composition and the kinetic constants obtained. Given this constraint, the kinetic modeling results presented here should be interpreted primarily as trends associated with microwave power levels, rather than absolute relationships tied to biomass composition. Even so, the continuous online mass measurements employed in this work provide reliable information on decomposition dynamics and product distribution under different operating conditions.

Future studies will incorporate proximate and ultimate analyses to enhance the mechanistic interpretation of microwave absorption and reaction pathways. Such characterization will enable a more comprehensive understanding of how fibre composition interacts with microwave energy, thereby improving the predictive accuracy of kinetic models and strengthening the reproducibility of torrefaction research.

CONCLUSION

This research explored the non-isothermal microwave-assisted torrefaction of oil palm fibre, focusing on how different microwave power levels influence decomposition kinetics and biochar yield. The results showed that increasing

microwave power from 400 W to 800 W accelerated heating rates and volatile release, but simultaneously reduced solid residue yield, indicating more intense thermal breakdown. The modified two-step kinetic model effectively described the sequential conversion of biomass into intermediates, volatiles, and stable carbonaceous products, with the strongest statistical agreement observed at 400 W (R^2 = 0.907). Although the coefficients of determination were lower than those reported in conventional torrefaction studies, the model still provided meaningful insights into reaction pathways and product distribution under microwave conditions.

The study highlights the distinctive nature of microwave heating, where localized hot spots and uneven energy distribution introduce variability, but also enable rapid energy transfer and efficient biomass conversion. These findings emphasize the need to optimize microwave power to balance biochar yield, structural stability, and functional properties. Overall, microwave-assisted torrefaction emerges as a promising approach for converting oil palm fibre into biochar.

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REFERENCES

[1] T. Martins, A. C. Barreto, F. M. Souza and A. M. Souza, *Environ. Pollut.*, **291**, 118093 (2021), https://doi.org/10.1016/j.envpol.2021.118093

[2] International Energy Agency, Global Energy Review 2020, OECD Publishing, Paris, https://doi.org/10.1787/a60abbf2-en

[3] M. Kabir, U. E. Habiba, W. Khan, A. Shah, S. Rahim *et al.*, *J. King Saud Univ.-Sci.*, **35**, 102693 (2023), https://doi.org/10.1016/j.jksus.2023.102693

[4] Y. Li, X. Zhao, D. Li, X. Zuo and H. Yang, *Compos. Part A Appl. Sci. Manuf.*, **185**, 108331 (2024), https://doi.org/10.1016/j.compositesa.2024.108331

[5] Z. Said, A. K. Pandey, A. K.Tiwari, B. Kalidasan, F. Jamil *et al.*, *Prog. Energ. Combust. Sci.*, **104**, 101162 (2024), https://doi.org/10.1016/j.pecs.2024.101162

[6] M. Morciano, M. Fasano, E. Chiavazzo and L. Mongibello, *Energ. Convers. Manag. X*, **25**, 100862 (2025), https://doi.org/10.1016/j.ecmx.2024.100862

[7] L. J. R. Nunes, *Environments*, **10** (2023), https://doi.org/10.3390/environments10040066

[8] D. Das, O. Masek and M. C. Paul, *J. Energ. Storage*, **84**, 110995 (2024), https://doi.org/10.1016/j.est.2024.110995

[9] M. Zadshir, B. Kim and H. Yin, *Materials (Basel)*, **17**, 1 (2024), https://doi.org/10.3390/ma17194816

[10] K. Du, J. Calautit, P. Eames and Y. Wu, *Renew. Energ.*, **168**, 1040 (2021), https://doi.org/10.1016/j.renene.2020.12.057

[11] M. Katish, S. Allen, A. Squires and V. Ferrandiz-Mas, *Clean. Mater.*, **14**, 100274 (2024), https://doi.org/10.1016/j.clema.2024.100274

[12] J. O. Ighalo, J. Conradie, C. R. Ohoro, J. F. Amaku, K. O. Oyedotun *et al.*, *Ind. Crop. Prod.*, **204**, (2023), https://doi.org/10.1016/j.indcrop.2023.117300

[13] A. C. Sparavigna, *SSRN Electron. J.*, (2022), https://doi.org/10.2139/ssrn.4310141

[14] R. A. Mondragon, S.Boonyubol, S. Cheng and J. S. Cross, *ASEAN J. Chem. Eng.*, **23**, 77 (2023), https://doi.org/10.22146/ajche.80081

[15] B. Kalidasan, *Prog. Mater. Sci.*, **101380** (2025), https://doi.org/10.1016/j.pmatsci.2024.101380

[16] A. Anand, M. Mansor, K. Sharma, A. Shukla, A. Sharma *et al.*, *Alexandria Eng. J.*, **112**, 254 (2025), https://doi.org/10.1016/j.aej.2024.10.054

[17] S. W. Yen, W. H. Chen, J. S. Chang, C. F. Eng, S. R. Naqvi and P. L. Show, *Sustainability*, **13**, (2021), https://doi.org/10.3390/su13084246

[18] N. A. Mohamad Aziz, H. Mohamed, D. Kania, H. C. Ong, B. S. Zainal *et al.*, *Renew. Sustain. Energ. Rev.*, **191**, 114097 (2024), https://doi.org/10.1016/j.rser.2023.114097

[19] P. F. Prashanth, L. Gurrala, R. V. Mohan, K. Sarvanakumar and R. Vinu, *IET Renew. Power Gener.*, **16**, 2964 (2022), https://doi.org/10.1049/rpg2.12445

[20] A. Soria-Verdugo, E. Cano-Pleite, A. Panahi and A. F. Ghoniem, *Energ. Convers. Manag.*, **267**, 115892 (2022), https://doi.org/10.1016/j.enconman.2022.115892

[21] A. Andersone, A. Arshanitsa, Y. Akishin, A. Semenischev and G. Telysheva, *Chem. Eng. Trans.*, **86**, 109 (2021), https://doi.org/10.3303/CET2186019

[22] M. Agung, I. Rahim and F. Amir, *AIP Conf. Proc.*, **2630** (2023), https://doi.org/10.1063/5.0125902

[23] I. Hartati, H. Sulistyo, W. B. Sediawan and M. M. Azis, *ACS Omega*, (2021), https://doi.org/10.1021/acsomega.1c01084

[24] W. B. Sediawan, I. Hartati, H. Sulistyo, M. M. Azis and U. Rahma, *Int. J. Technol.*, **14**, 310 (2023), https://doi.org/10.14716/ijtech.v14i2.5381

[25] E. Valdez, L. G. Tabil, E. Mupondwa, D. Cree and H. Moazed, *Energies*, **14** (2021), https://doi.org/10.3390/en14144298

[26] P. N. Y. Yek, M. S. Osman, C. C. Wong, C. S. Wong, S. H. Kong *et al.*, *Mater. Sci. Energ. Technol.*, **3**, 742 (2020), https://doi.org/10.1016/j.mset.2020.08.004

[27] A. S. Lozano Pérez, J. J. Lozada Castro and C. A. Guerrero Fajardo, *J. Manuf. Mater. Process.*, **8**, (2024), https://doi.org/10.3390/jmmp8030121

[28] L. K. Mangalla and T. A. Kurniawan, in "Microwave Engineering - Foundational Studies and Multifarious Applications", edited by K. Ho Yeap, S. Qi Ping and V. Dakulagi, IntechOpen, 2025,

http://dx.doi.org/10.5772/intechopen.1008872
[29] I. Hartati, H. Sulistyo, W. B. Sediawan and M. M. Azis, *Iran. J. Chem. Chem. Eng.*, **44**, 1482 (2025), https://doi.org/10.30492/ijcce.2025.2019962.6385
[30] N. H. M. Harun, N. A. F. Samad and S. Saleh, *Energ. Proc.*, **105**, 744 (2017), https://doi.org/10.1016/j.egypro.2017.03.385
[31] R. K. Kottala, B. K. Chigilipalli, S. Mukuloth, R. Shanmugam, V. C. Kantumuchu *et al.*, *Energies*, **16** (2023), https://doi.org/10.3390/en16052187
[32] Q. V. Bach, W. H. Chen, C. F. Eng, C. W. Wang, K. C. Liang *et al.*, *Fuel*, **251**, 118 (2019), https://doi.org/10.1016/j.fuel.2019.04.024
[33] A. Khamwichit, J. Kasawapat, N. Seekao and W. Dechapanya, *Energies*, **17** (2024), https://doi.org/10.3390/en17092192
[34] M. Chai, L. Xie, X. Yu, X. Zhang, Y. Yang *et al.*, *Renew. Sustain. Energ. Rev.*, **143** (2021), https://doi.org/10.1016/j.rser.2021.110962
[35] M. González Martínez, C. Dupont, A. Anca-Couce, D. da Silva Perez, G. Boissonnet *et al.*, *Energy*, **210** (2020), https://doi.org/10.1016/j.energy.2020.118451
[36] A. Coats and J. Redfern, *Nature*, **201**, 68 (1964), https://doi.org/10.1038/201068a0
[37] R. Barcelo, G. C. Lamas, P. P. D. O. Rodrigues, G. F. Ghesti, S. Luz *et al.*, in *Procs. 31st European Biomass Conference and Exhibition*, 5-8 June 2023, Bologna, Italy, 2023, https://doi.org/10.5071/31stEUBCE2023-1DV.1.9
[38] N. A. Jamin, F. A. Samad and S. Saleh, *IOP Conf. Ser. Mater. Sci. Eng.*, **702** (2019), https://doi.org/10.1088/1757-899X/702/1/012008
[39] M. U. H. Joardder and M. A. Karim, *Food Eng. Rev.*, **17**, 946 (2025), https://doi.org/10.1007/s12393-025-09426-5
[40] L. Yan, C. Wang and X. Yin, *Microwave*, **1**, 12 (2025), https://doi.org/10.3390/microwave1030012
[41] R. Rusdimansyah, K. Khasrad, J. Jaswandi, R. Rusfidra and D. Aulia, *Biodiversitas*, **25**, 2478 (2024), https://doi.org/10.13057/biodiv/d250616
[42] K. A. Hagig, B. Acar, A. Dağdeviren, E. Taşkesen and M. Özkaymak, *J. Therm. Eng.*, **9**, 876 (2023), https://doi.org/10.18186/thermal.1327094