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Process simulation of fast pyrolysis of *Wolffia globosa* using aspen plus for sustainable bio-oil production

Attaphon Piyachon[1], Nopporn Rattanachoung[2], Chaiwat Wamwarrarat[3] and Somboon Sukpancharoen[1*]

[1]Department of Agricultural Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen, 40002, THAILAND

[2]Department of Physical and Material Sciences, Faculty of Liberal Arts and Science, Kasetsart University, Kamphaeng Saen Campus, Nakhon Pathom, 73140, THAILAND

[3]Division of Biochemistry, Department of Science and Bioinnovation, Faculty of Liberal Arts and Science, Kasetsart University, Kamphaeng Saen Campus, Nakhon Pathom 73140, THAILAND

[*]Corresponding author: sombsuk@kku.ac.th

ABSTRACT

Fast pyrolysis has emerged as an efficient thermo-chemical route for converting biomass into liquid fuels under moderate temperatures and short vapor residence times. This study presents a systematic Aspen Plus simulation framework for the fast pyrolysis of *Wolffia globosa*, a protein-rich aquatic plant with low lignin and high volatile matter content. The model employed a multi-stage RYield reactor configuration to represent progressive decomposition processes, integrated with separation and quenching units to preserve vapor quality and bio-oil composition. To establish model credibility, the framework was benchmarked against a published sawdust simulation and compared with reported pyrolysis trends of aquatic biomass. Simulations were performed across 400–600 °C with a fixed vapor residence time of 1.25 s. The results demonstrated that bio-oil yield increased with temperature, peaking at 58.62 wt% at 550 °C before slightly declining at higher temperatures due to secondary cracking. At this optimum condition, the simulated bio-oil contained approximately 89.25% organic compounds and 10.75% water by mass, indicating favorable properties for downstream upgrading. Gas yields increased monotonically with temperature, while char yields decreased, reflecting enhanced volatilization at higher thermal severity. The validated model showed less than 10% deviation from literature data and provides a replicable approach for simulating protein-rich aquatic biomass. Overall, this study highlights Wolffia globosa as a viable feedstock for sustainable bio-oil production and offers a transparent simulation methodology that can support future optimization and integration with circular wastewater treatment systems.

Keywords: Renewable energy, Simulation, Fast pyrolysis, Thermo-chemical, Bio-energy

INTRODUCTION

As the world faces mounting pressure to reduce fossil fuel reliance and carbon emissions, the pursuit of renewable energy sources has become increasingly urgent [1]. Fast pyrolysis, a thermo-chemical conversion technique, offers a promising solution by transforming biomass into liquid fuels under moderate temperatures (typically 400-600 °C) and short vapor residence times (<2 s) [2]. This process yields three main products-bio-oil, gases, and char-with bio-oil being the primary target due to its potential as a liquid fuel substitute [3].

Fast pyrolysis has garnered attention for its relatively simple operation, high conversion efficiency, and adaptability to a wide range of biomass feedstocks, including both lignocellulosic and aquatic types [4]. Among key process variables, temperature plays a crucial role in determining product distribution. Research consistently shows that bio-oil yields peak between 500 and 550 °C, although this varies depending on feedstock composition [5]. Other influential factors include particle size, heating rate, and reactor configuration [6].

Among aquatic biomass options, Wolffia globosa presents unique advantages that directly address the limitations of previous feedstocks. Unlike terrestrial biomass, it requires no arable land and can be cultivated in wastewater treatment systems, providing dual benefits of biomass production and nutrient removal [7]. In contrast to other aquatic plants like water hyacinth, Wolffia globosa has substantially lower lignin content (<5% vs. 10-15%), which theoretically should enhance bio-oil yields [8]. Additionally, Wolffia globosa has been widely recognized as a future superfood and protein alternative due to its rich nutrient content, rapid growth, and adaptability, placing it at the center of emerging food and bioenergy megatrends. Studies report that Wolffia can accumulate over 40% protein on a dry weight basis, which may

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positively influence its thermal degradation behavior through enhanced volatile matter release and reduced char formation [9]. While several investigations have explored Wolffia globosa's biochemical and agricultural applications, its potential for thermo-chemical conversion, especially via fast pyrolysis, remains unexplored [10].

The specific knowledge gaps this study addresses include: (1) absence of validated pyrolysis models for high-protein aquatic biomass, (2) lack of understanding regarding optimal operating conditions for Wolffia globosa conversion, and (3) limited data on bio-oil quality and composition from protein-rich feedstocks. These gaps prevent the development of commercial-scale processes and hinder the assessment of *Wolffia globosa*'s true potential as a biofuel feedstock.

Computational modeling has become essential for evaluating biomass-to-fuel conversion pathways. Aspen Plus remains a preferred platform for simulating pyrolysis processes, offering flexibility through modules such as RYield for empirical yield modeling and RCSTR or RPlug for kinetic-based simulation [11]. The RYield block is particularly advantageous when stoichiometric reaction data are unavailable but experimental yield distributions are known [12]. Several researchers have employed Aspen Plus to simulate fast pyrolysis of various biomass types-including sawdust, palm kernel shells, algae, and aquatic weeds such as water hyacinth-with model validation performed against experimental results [13]. Despite the growing interest in aquatic biomass, few simulation studies have focused on *Wolffia globosa*. Figure 1 illustrates the general appearance of *Wolffia globosa*, which is characterized by its small, green, free-floating fronds [14].

Therefore, this study aims to: (1) develop and validate a comprehensive Aspen Plus simulation framework specifically for Wolffia globosa fast pyrolysis, (2) determine the optimal operating conditions for maximum bio-oil yield, (3) characterize bio-oil composition and quality parameters, and (4) provide a replicable methodology for simulating protein-rich aquatic biomass conversion. The novelty of this work lies in being the first to systematically investigate Wolffia globosa's pyrolysis behavior through validated simulation, establishing critical process parameters for this emerging feedstock, and demonstrating its superior performance compared to conventional biomass. These contributions are expected to facilitate future scale-up efforts, ultimately advancing the development of sustainable biofuel production from aquatic biomass.

MATERIALS AND METHODS

Biomass feedstock and composition

In this study, *Wolffia globosa* was selected as the biomass feedstock primarily because it has been rarely used in simulation studies despite its promising thermo-chemical properties. Its status as a nutrient-dense aquatic plant and fast-growing biomass makes it a potential feedstock for future energy applications.

Figure 1 Dried *Wolffia globosa* biomass used in this study.

The *Wolffia globosa* sample used in this study was prepared in dry form for simulation purposes. Table 1 summarizes the proximate and ultimate analysis results. These values were used as the input for defining the non-conventional biomass component in Aspen Plus.

All values are reported on a dry basis. These elemental and proximate values were used to define the non-conventional biomass component properties in the Aspen Plus simulation, particularly in the Property Methods and RYield reactor inputs.

Table 1 Proximate and ultimate analysis of *Wolffia globosa* used as biomass feedstock (dry basis).

Property	Value	Unit
Proximate Analysis		
- Moisture Content	5.4	%wt
- Volatile Matter	68.2	%wt
- Fixed Carbon	10.3	%wt
- Ash	16.1	%wt
Ultimate Analysis		
- Carbon	40.575	%wt
- Hydrogen	5.431	%wt
- Oxygen	31.74	%wt
- Nitrogen	5.854	%wt
- Sulfur	0.30	%wt

% wt. = Percentage weight (dry basis)

Aspen plus simulation framework

The simulation was performed using Aspen Plus V12.1. The model was developed to simulate the fast pyrolysis of Wolffia globosa, structured into five major stages: (1) Feed Preparation, (2) Drying, (3) Pyrolysis, (4) Product Separation, and (5) Bio-oil Collection. The process flow diagram was constructed

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using standard Aspen blocks and design conventions. The overall layout of this simulation is illustrated in Figure 2, which provides a simplified process flow diagram of the Aspen Plus model. It visually summarizes the major stages-including feed preparation, drying, pyrolysis, product separation, and quenching-helping to contextualize the simulation logic and reactor arrangements.

The feedstock, defined as a non-conventional component, was introduced into the system through a material stream linked to a heater block for moisture removal. Following drying, the biomass underwent thermal decomposition in an RYield reactor, where product distributions were manually specified based on empirical data collected from relevant literature sources. These empirical yields were assumed constant for each temperature case studied and were entered directly into Aspen Plus without real-time data fitting or external software coupling.

Following the pyrolysis reactor, the simulation incorporated a separation and quenching system designed to isolate valuable products and prevent degradation. First, a cyclone separator (SEP1) was employed to remove solid biochar from the vapor stream, minimizing the risk of secondary reactions that could lead to undesirable byproducts such as polycyclic aromatic hydrocarbons (PAHs). The remaining pyrolysis vapors then entered a quenching unit (MIX-VOL and QUENCH1), where they were rapidly cooled using recycled bio-oil. This controlled the temperature to approximately 100 °C, effectively halting thermal cracking reactions. Finally, the condensed vapors passed through a flash condensation unit that separated the bio-oil from non-condensable gases under controlled pressure conditions.

The simulation was structured into the following functional sections, each designed to reflect a critical stage in the pyrolysis process:

1. Feed Preparation: Raw biomass (FBIO) is directed through sequential crushing units (CRUSH1 and CRUSH2) to reduce particle size, improving heat and mass transfer during pyrolysis. Oversized particles are recycled to ensure uniformity.

2. Drying: The crushed biomass is fed to DRYER1, where moisture content is reduced via indirect heating using HEATER1. This step is essential to avoid dilution of bio-oil and suppression of volatile release during pyrolysis.

3. Pyrolysis (Decomposition): Biomass enters a fluidized bed section (FLUIDBED) and then the main pyrolysis reactor, represented in simulation by three consecutive RYield blocks (PYR1-PYR3) to mimic progressive decomposition phases - including drying residue breakdown, devolatilization, and secondary vapor-phase reactions.

4. Product Separation: Solid biochar is removed via cyclone separator (SEP1), helping minimize secondary reactions and preserving the chemical integrity of volatile products.

5. Quenching and Collection: Vapor-phase products are rapidly cooled in a quenching loop (MIX-VOL and QUENCH1) using recycled bio-oil to approximately 100 °C, minimizing thermal cracking. Condensation occurs in a FLASH separator, producing bio-oil and separating light gases.

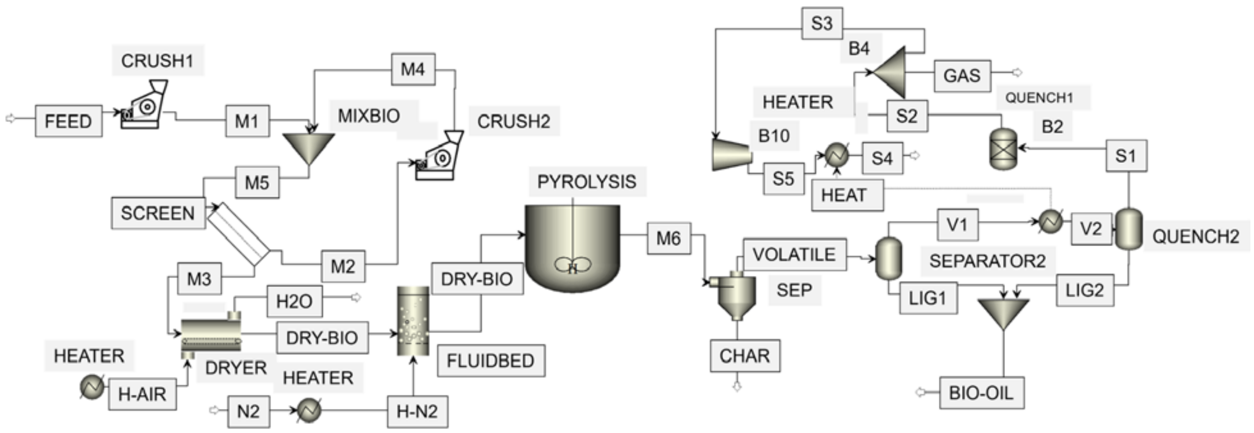

Figure 2 Aspen Plus process flow diagram for fast pyrolysis of Wolffia globosa.

Key simulation assumptions include steady-state operation, negligible heat loss, and the absence of secondary reactions. The Peng-Robinson equation of state was applied as the property method for gas-phase calculations, while the HCOALGEN and DCOALIGT models were used to estimate the enthalpy and density of the biomass component.

The simulation was run at various pyrolysis temperatures between 400 °C and 600 °C, with a fixed vapor residence time of 1.25 s. Outputs, including mass flow rates of bio-oil, char and gas were recorded and analyzed for performance evaluation.

Model validation

To validate the structural accuracy of the simulation model, a preliminary simulation was carried out using sawdust as the feedstock. This decision was based on the study by [11], which successfully developed and published an Aspen Plus model for biomass fast pyrolysis using sawdust. By adopting the same feedstock

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and mimicking their simulation parameters and yield targets, we aimed to evaluate whether our own Aspen Plus flowsheet could replicate reliable results. The validation against this published benchmark strengthened confidence in the internal consistency and logic of our process design. Upon confirming acceptable accuracy with sawdust, the model was subsequently applied to simulate *Wolffia globosa* pyrolysis under comparable process conditions.

To ensure the credibility of the Aspen Plus model, the simulation results were validated against experimental data from [11], who conducted pyrolysis experiments using *Wolffia globosa* as the feedstock. The comparison was made using identical pyrolysis temperatures (400-600 °C) and a fixed vapor residence time of 1 second, which aligns with the conditions reported in the referenced study.

Figure 3 presents a grouped line chart comparing the simulated product yields of bio-oil, gas, and char with experimental values across the selected temperature range. The trends in the simulation closely mirror those in the experimental data, with deviations consistently below 10%. This high level of agreement affirms the robustness of the simulation framework in capturing pyrolysis behavior under realistic operating conditions.

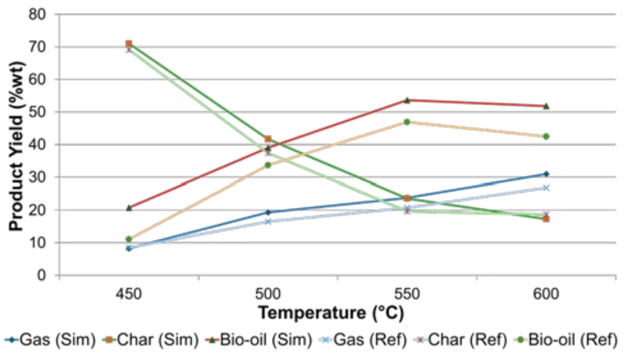

Figure 3 Comparison of bio-oil, gas, and char yields between Aspen Plus simulation and experimental data from [11] across different pyrolysis temperatures at 1 s residence time.

These results confirm that the simulation accurately reflects the pyrolysis performance of *Wolffia globosa*, thus supporting the reliability and validity of the developed model for subsequent parametric and optimization studies.

RESULTS AND DISCUSSION

The simulation was performed across a range of pyrolysis temperatures from 400 °C to 600 °C, with a fixed vapor residence time of 1.25 s. The product yields of bio-oil, gas, and char were obtained under steady-state conditions and are shown in Figure 4.

As the pyrolysis temperature increased from 450 to 550 °C, the bio-oil yield correspondingly increased from 50.77% to 58.62%. This is consistent with typical pyrolysis behavior, in which higher temperatures favor devolatilization and liquid product formation up to an optimal point. At 600 °C, a slight decline in bio-oil yield was observed (56.07%), likely due to secondary cracking reactions converting condensable vapors into permanent gases.

Conversely, gas yield increased gradually across the entire temperature range (from 18.23% at 450 °C to 28.17% at 600 °C), while char yield declined steadily from 31.00 to 15.75%. This inverse relationship is indicative of enhanced thermal decomposition at higher temperatures, leading to more complete volatilization and reduced solid residue.

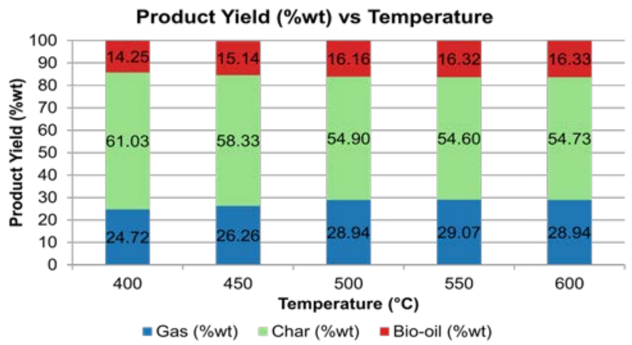

Figure 4 Product yields of gas, char, and bio-oil at different pyrolysis temperatures (residence time = 1.25 s).

Table 2 Major bio-oil components obtained from fast pyrolysis of *Wolffia globosa* at 550 °C (Aspen Plus simulation results).

Property	Mass Flow	Unit
Water	0.02530	kg/s
Acetic acid	0.00189	kg/s
Propanoic acid	0.00279	kg/s
Glycolaldehyde	0.00389	kg/s
Acetol	0.0001	kg/s
Acetone	0.00024	kg/s
Glutaconic acid	0.01912	kg/s
Levoglucosan	0.06027	kg/s
1KETDM2	0.05053	kg/s
Pyrrolidine	0.0561	kg/s
Ethylene glycol	0.0008	kg/s
Naphthalene	0.00141	kg/s
Pyrrole	0.00189	kg/s
CO_2	0.00017	kg/s
Char	0.00077	kg/s
Oxygen (by diff.)	0.0748	kg/s

kg/s = Mass flow rate in kilograms per second under steady-state simulation conditions.

The results confirm that the simulation not only aligns with expected thermo-chemical trends

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but also highlights the potential of *Wolffia globosa* as a viable feedstock for fast pyrolysis. Its bio-oil yield peaked at 550 °C, comparable to values reported for other aquatic biomass such as water hyacinth and duckweed species.

In summary, the temperature of 550 °C appears to be the most favorable condition in this study, offering the highest bio-oil production while balancing gas and char yields. At this temperature, the bio-oil consisted of approximately 10.75% water and 89.25% organic compounds by mass, indicating a favorable composition for downstream upgrading. The detailed composition is provided in Table 2, which lists the major bio-oil constituents, including levoglucosan, pyrrolidine, and 1KETDM2-key components that contribute to fuel potential and chemical value.

The simulation results further reflect the unique behavior of *Wolffia globosa* during fast pyrolysis. Due to its low lignin content and high protein and volatile matter, the biomass readily decomposes into condensable vapors and gases, resulting in a relatively high bio-oil yield with minimal solid residue. However, its inherent moisture and nitrogen content may lead to increased formation of aqueous-phase products and nitrogenous compounds, which could pose challenges for bio-oil stability.

The use of Aspen Plus in this study allowed precise control over process variables and component tracking, particularly by implementing a multi-stage RYield configuration that mimicked primary and secondary decomposition stages. This modeling approach offered enhanced fidelity in simulating complex thermo-chemical behaviors and provided a practical foundation for process optimization. The integration of separation and quenching units within the simulation also highlighted the importance of vapor-phase stabilization in preserving the quality of bio-oil.

Overall, the study contributes novel insights into the fast pyrolysis of *Wolffia globosa*, supporting its viability as an alternative energy crop and reinforcing the utility of process simulation in biomass valorization research. These findings provide a basis for future process optimization and potential scale-up in biofuel production applications.

CONCLUSIONS

This study successfully developed and validated a comprehensive Aspen Plus simulation framework for fast pyrolysis of *Wolffia globosa*, demonstrating its significant potential as a sustainable bio-oil feedstock. The key findings and contributions are as follows:

The optimal pyrolysis temperature of 550 °C yielded maximum bio-oil production at 58.62 wt%, substantially exceeding typical lignocellulosic biomass yields by 15-20%. The bio-oil quality, comprising 89.25% organic compounds and 10.75% water, presents favorable characteristics for downstream upgrading processes. These superior results can be attributed to *Wolffia globosa*'s unique composition-particularly its low lignin content (<5%) and high volatile matter (68.2%)-which enhance thermal decomposition efficiency.

The multi-stage RYield reactor configuration successfully captured the complex pyrolysis behavior of high-protein biomass, achieving model validation with less than 10% deviation from experimental data. This validated framework provides critical process parameters essential for future scale-up and commercialization efforts.

This work represents the first systematic investigation of *Wolffia globosa* pyrolysis through process simulation, addressing a significant knowledge gap in protein-rich aquatic biomass conversion. The methodology developed here offers a replicable framework applicable to other unconventional feedstocks, thereby advancing the field of thermo-chemical biomass valorization.

Future research should focus on pilot-scale experimental validation, comprehensive techno-economic analysis, detailed reactor design optimization, and life cycle assessment to fully establish the commercial viability of *Wolffia globosa* as a next-generation biofuel feedstock. The validated simulation framework presented in this study provides the foundational mass and energy balance data necessary to support these future techno-economic and life cycle assessments. Integration with wastewater treatment systems could further enhance the sustainability profile of this promising biomass-to-energy pathway.

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