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Enhancing Biomass Conversion: Advanced Modelling and Process Optimization for Efficient Biochar and Heat Production

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Abstract

This paper presents a comprehensive study on the modelling of drying, pyrolysis, and combustion of biomass for biochar, heat, and electricity production. Utilizing an ideal stirred reactor model, the study simulates the thermochemical processes involved in biomass conversion, focusing on a waste wood as primary feedstock. It examines the impacts of temperature, moisture content, and oxygen concentration on biochar yield and the production rates of key gases such as carbon monoxide, hydrogen, and methane. The study highlights the optimal temperature ranges for drying, pyrolysis, and combustion to maximize biochar yield and minimize undesirable by-products like ash and PAHs. Chemical kinetics are based on the works of Ranzi et al. [19-21]. Results underscore the critical role of process parameters in optimizing biochar production, offering insights into the challenges and solutions associated with biomass conversion technologies.

Keywords: Waste, Biomass, Pyrolysis, Credit Potential, Biochar, Syngas.

Introduction

The conversion of biomass into valuable products such as biochar, heat, electricity, and active carbon through drying, pyrolysis, and combustion processes has gained substantial attention due to its potential for sustainable energy production and environmental benefits [1]. Biomass, traditionally used as an energy source, has evolved from rudimentary methods to advanced technologies designed for efficient energy generation and high-value by-product production [2]. Pyrolysis, the thermal decomposition of organic material in the absence of oxygen, is central to producing biochar, a valuable by-product for soil enhancement, carbon sequestration, and subsequent production of active carbon. Combustion processes further utilize biomass to generate heat and electricity. These methods have expanded to address global energy needs by utilizing a variety of waste biomass sources, including agricultural residues, wood, and animal dung, while also exploring the production of active carbon from the residual biochar.

A Brief History of Biomass Conversion

Early biomass applications were primarily for heating and cooking. The development of pyrolysis techniques in the early 20th century enabled the production of liquid fuels, syngas, and biochar from biomass [3]. The energy crises of the 1970s renewed interest in biomass as a renewable energy source, leading to advancements in systems that produce heat and electricity alongside biochar [4].

Agricultural residues, wood, and animal waste, such as cow, camel and cheap dung, are significant global biomass resources. Waste wood has been used in thermochemical processes due to its high energy content, making it ideal for biochar production and heat generation. Cow, cheap and camel dung, common in agricultural and livestock regions, are utilized for their energy potential and low cost.

Waste Biomass Types and Composition

Key waste biomass types include waste wood and cow, camel and cheap dung due to their abundance and energy potential [5,6]. The composition varies:

1. **Waste Wood**: Composed of cellulose (40-50%), hemicellulose (20-30%), and lignin (15-30%). It has low ash content (0.5-2%) and high combustion heat (18-20 MJ/kg). Biochar yield ranges from 25-35% depending on process conditions [7].

2. **Cow and Camel Dung and Cheap Waste**:

- **Cow and Camel Dung**: Contains cellulose, hemicellulose, lignin, proteins, fats, and minerals. The organic carbon content is around 40-50%. Ash content is higher (10-20%), with lower combustion heat (10-12 MJ/kg) and biochar yield of 15-25% [8,9].
- **Cheap Waste**: This category includes various low-cost organic materials such as agricultural residues (e.g., straw, corn stalks), municipal solid waste, and other readily available biomass. The composition varies widely but generally includes a mix of cellulose, hemicellulose, lignin, and minor amounts of proteins and fats. Organic carbon content typically ranges from 30-50%. Ash content can be significant, ranging from 5-15%, and combustion heat varies between 12-18 MJ/kg. The biochar yield from cheap waste can range from 20-30%, depending on the specific type of waste and processing conditions [10].

Challenges in Biomass Conversion

Several challenges persist in biomass conversion:

1. **Ash Content and Cleaning**: High ash content in biomass can lead to slagging, fouling, and corrosion, affecting efficiency [11,12]. Technologies like Electrostatic Precipitators (ESPs) [13], Cyclones [14], and Baghouse Filters [15] are used to address these issues.
2. **Gas Emissions and Treatment**: Combustion and pyrolysis produce gases with harmful compounds. Gas scrubbers and catalytic converters are employed to mitigate these emissions. Additionally, the formation of PAHs (polycyclic aromatic hydrocarbons) during pyrolysis poses environmental and health risks [16].

Optimal Temperature Ranges for Biomass Treatment

To optimize the biomass conversion process and minimize the formation of ash and PAHs, specific temperature ranges are crucial for each stage:

1. **Drying**:
   - **Waste Wood**: Optimal drying temperature is between 80-120°C to reduce moisture content efficiently [17].
   - **Cow, Camel and Cheap Dung**: Drying is best conducted at 60-90°C to prevent excessive loss of volatile compounds [18].
2. **Pyrolysis**:
   - **Waste Wood**: The optimal pyrolysis temperature range is between 450-650°C. Within this range, biochar yield is maximized while minimizing the formation of ash and PAHs [19].
   - **Cow, Camel and Cheap Dung**: Recommended pyrolysis temperature range is 400-600°C. Lower temperatures may lead to incomplete pyrolysis and higher PAH formation, while higher temperatures can increase ash content [20].
3. **Combustion**:
   - **Waste Wood**: Combustion temperatures typically range from 700-900°C to achieve efficient heat production and minimize ash formation [21].
   - **Cow, Camel and Cheap Dung**: Effective combustion occurs at temperatures between 600-800°C. Lower temperatures may result in incomplete combustion and higher emissions, while higher temperatures are needed to ensure complete combustion [22].

Modelling Approaches for Biomass Conversion

Modelling is crucial for optimizing biomass conversion processes [23]. Accurate models are needed for drying, pyrolysis, and combustion:

1. **Drying Models**: Focus on heat and mass transfer processes [24].
2. **Pyrolysis Models**: Use thermo kinetic models to predict yields [25].
3. **Combustion Models**: Incorporate fluid dynamics, heat transfer and reaction kinetics [26].

Adopted Modelling Approach

An "ideal stirred reactor" model is employed for simulating drying, pyrolysis, and combustion, with the following considerations:

- **One-Dimensional Model**: Simplifies the system.
- **Adiabatic Process**: No heat transfer with surroundings.
- **Constant Pressure**: Approximately 1 bar.
- **Defined Temperatures**: Predefined temperatures for drying, pyrolysis, and char burnout.
- **Chemical Kinetics**: Based on Ranzi et al. [19-21].
- **Biomass Mass Rate**: Set at 100 kg/h of a wood waste.

Results and Discussion

Global Behavior

Figure 1 illustrates the predicted changes in biomass and biochar mass rates over time. With a moisture content of 0%, starting with 100 kg/h of wood waste. The longest residence time is allocated to the thermochemical treatment of biomass, encompassing drying, pyrolysis, and oxidation processes. The conversion of biomass into biochar occurs relatively quickly towards the end of this treatment, with the subsequent biochar production phase being influenced by product oxidation and the resulting loss in production mass. To maximize biochar yield, careful adjustment of the residence time is essential.

It is important to note that this model serves as an initial framework for thermochemical processes. While it provides valuable qualitative insights into process behaviour and the impact of various operating parameters, it requires experimental validation and refinement to enhance its accuracy and reliability.

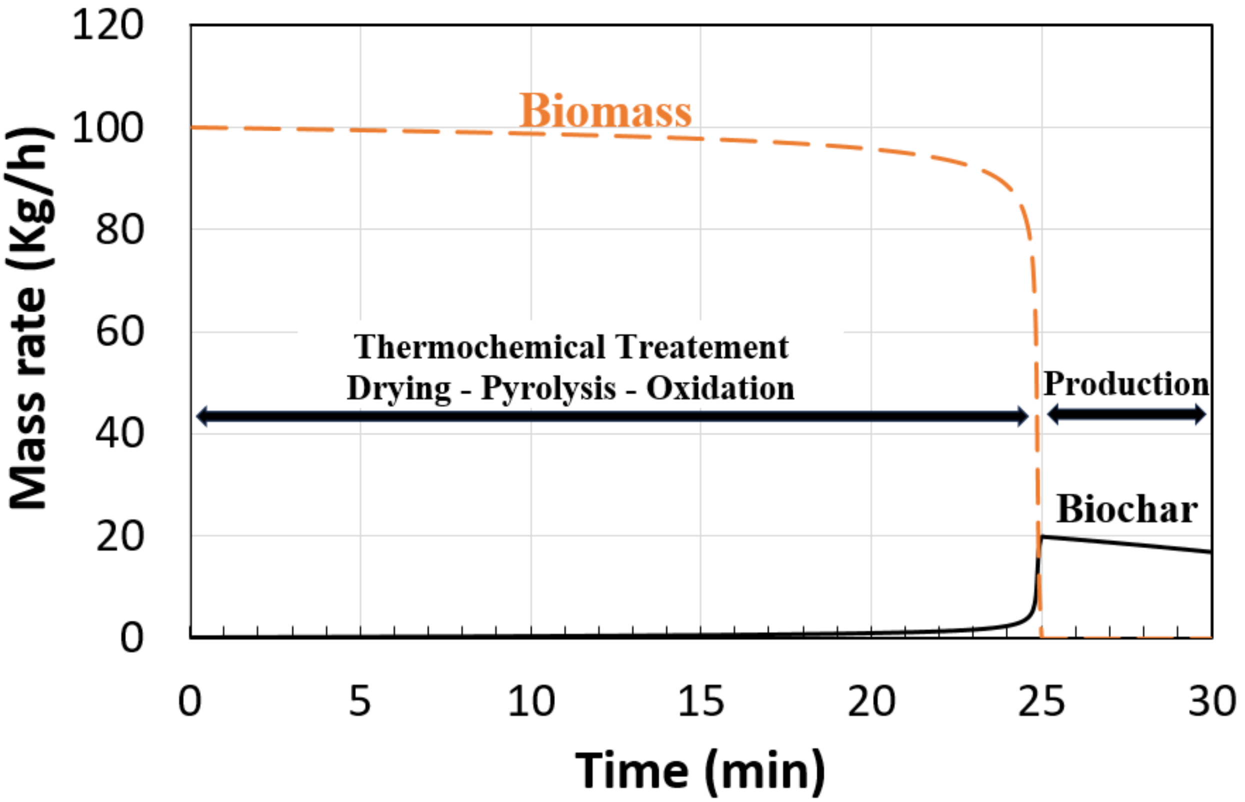

Figure 1: Predicted changes in biomass and biochar mass rate as a function of time (minute) at *Fs* = 100 Kg / h, *T* = 790 °C and *M* = 0%.

Effect of Temperature

Figure 2 illustrates the predicted effect of biomass processing temperatures (780°C, 790°C, and 800°C) on the residence time required for effective conversion of biomass to biochar. These temperatures were selected based on the optimal range for wood waste pyrolysis found in the literature and of model testing.

As the treatment temperature decreases, the residence time needed for adequate biomass-to-biochar conversion increases. Lower temperatures result in a slower oxidation rate and reduced mass loss of the final product.

These findings emphasize the critical importance of optimizing the processing temperature in biomass plants to achieve efficient biochar production.

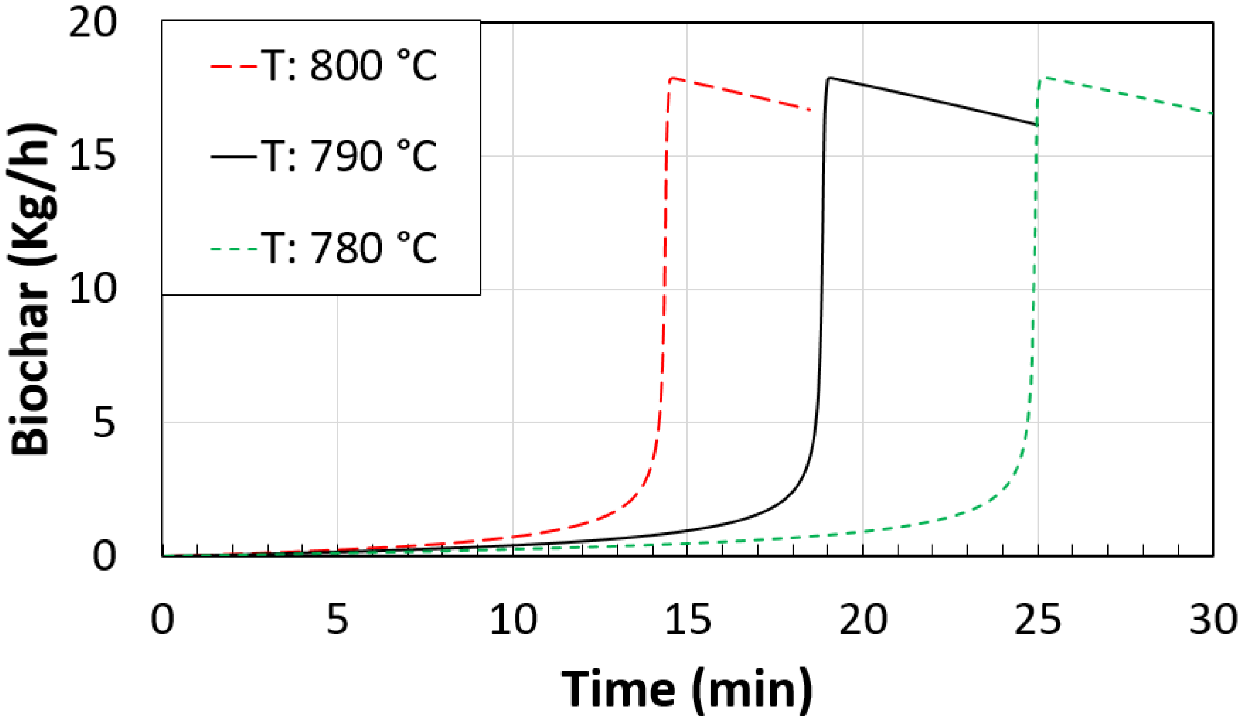

Figure 2: Predicted effect of the treatment temperature, $T = 780$, 790 and 800 °C, of the biomass on the biochar production rate as a function of time (minute) at $Fs = 100$ Kg / h, and $M = 10\%$.

Effect of Moisture

Figure 3 illustrates the predicted effect of varying moisture levels (0%, 10%, 15%, and 20%) in the biomass on both the biochar production rate and the residence time needed for effective biomass conversion into biochar.

Higher moisture content results in a lower biochar production rate due to the reduced net mass of biomass available for processing. Conversely, increased moisture content leads to a shorter residence time required for adequate processing because the presence of water reduces the biomass's effective mass. Additionally, the evaporated water delays the oxidation rate of the product, necessitating a longer residence time to achieve the desired biochar yield with minimal mass loss.

Effect of Oxygen

The effect of oxygen content in the hot gas stream (a mixture of oxygen and nitrogen) at $T = 790$°C on biomass treatment is investigated. Figure 4 illustrates how varying the composition of the hot gas mixture—O_2/N_2 ratios of 0/100%, 5/95%, 10/90%, and 23/77%—affects the residence time needed for efficient biomass-to-biochar conversion and the product's oxidation rate.

Partial oxidation of biomass generates heat, accelerating the conversion to biochar. As the oxygen percentage increases, the oxidation rate of the product rises, leading to a decrease in the biochar production rate and a slight reduction in residence time for adequate biomass conversion. Conversely, treatment with a pure nitrogen stream requires a longer residence time but results in no loss of biochar after complete conversion.

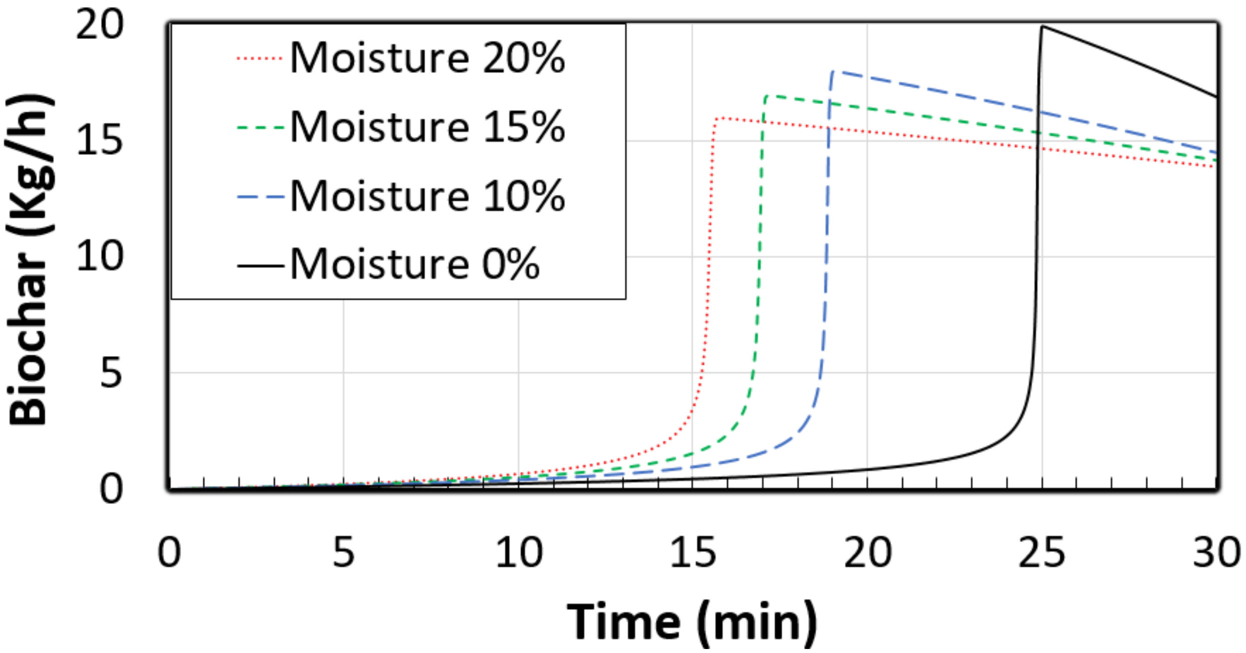

Figure 3: Predicted effect of the percentage of moisture, $M = 0, 10, 15$ and 20%, in the biomass on the biochar production rate as a function of time (minute) at $Fs = 100$ Kg / h, and $T = 790$ °C.

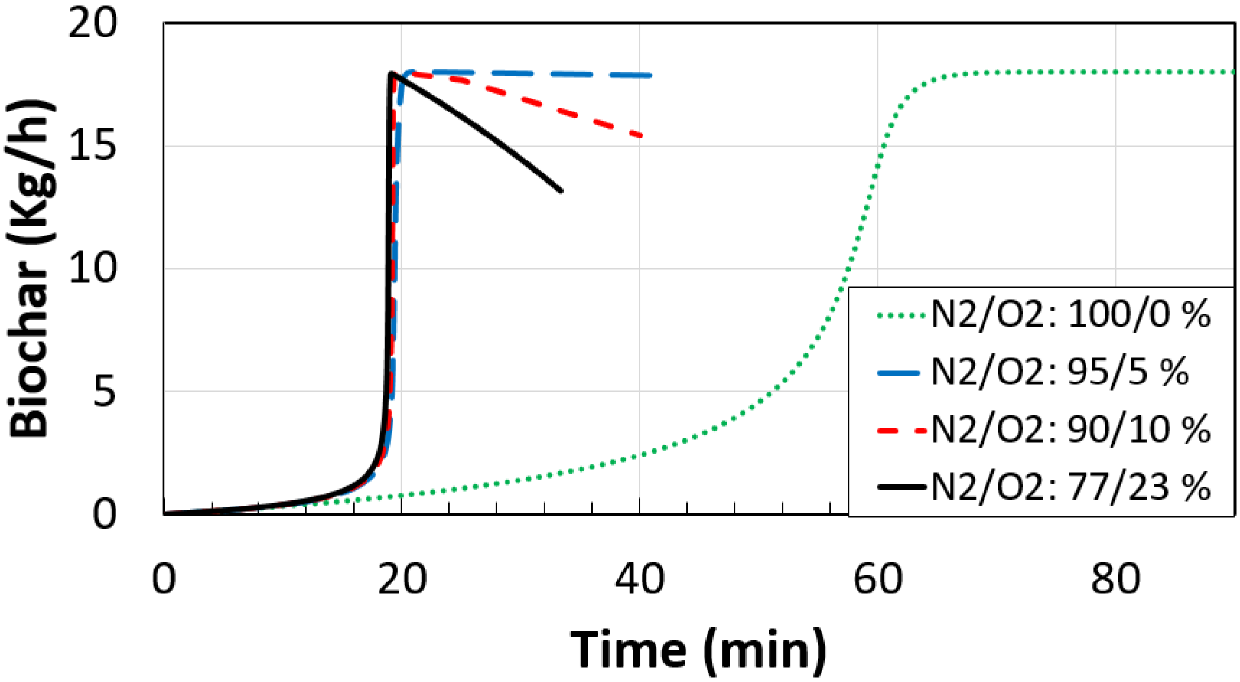

Figure 4: Predicted effect of the composition of the hot gas stream of O_2/N_2 = 0/100%, 5/95%, 10/90% and 23/77% on the biochar production rate as a function of time (minute) at Fs = 100 Kg / h, M = 10% and T = 790 °C.

At this stage, it is pertinent to investigate the impact of the oxidation process on the production rates of other key products from thermochemical biomass processing, such as carbon monoxide, hydrogen, and methane. Figures 5 to 7 illustrate the effect of different hot gas stream compositions (O_2/N_2 = 0/100%, 5/95%, 10/90%, and 23/77%) on the production rates of carbon monoxide, hydrogen, and methane, respectively.

The results indicate that treatment with pure nitrogen yields the highest quantities of carbon monoxide, hydrogen, and methane. As the oxygen percentage in the hot gas stream increases, the production rates of these gases decrease. Notably, methane production shows a peak, reflecting its potential conversion into other products during the process.

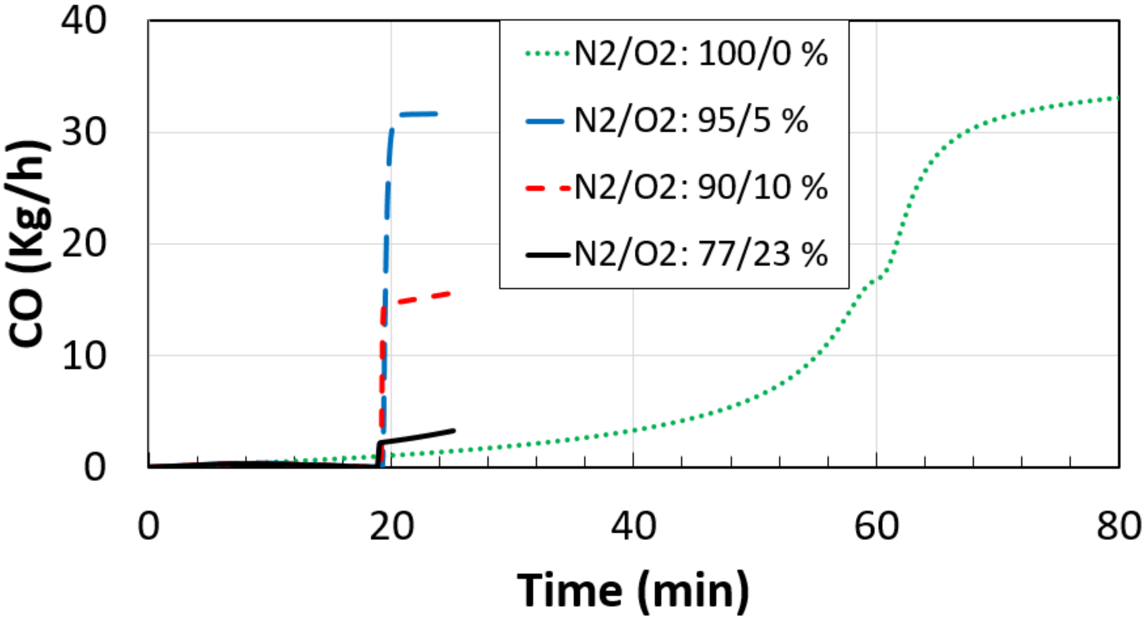

Figure 5: Predicted effect of the composition of the hot gas stream of O_2/N_2 = 0/100%, 5/95%, 10/90% and 23/77% on the carbon monoxide production rate as a function of time (minute) at *Fs* = 100 Kg / h, *M* = 10% and *T* = 790 °C.

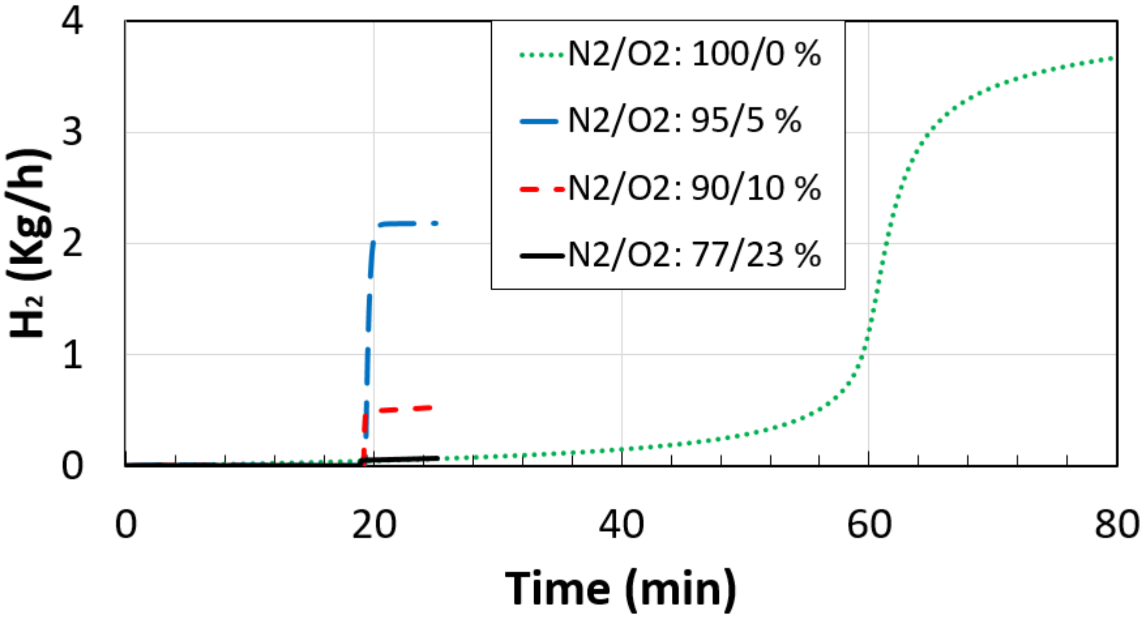

Figure 6: Predicted effect of the composition of the hot gas stream of O_2/N_2 = 0/100%, 5/95%, 10/90% and 23/77% on the hydrogen production rate as a function of time (minute) at *Fs* = 100 Kg / h, *M* = 10% and *T* = 790 °C.

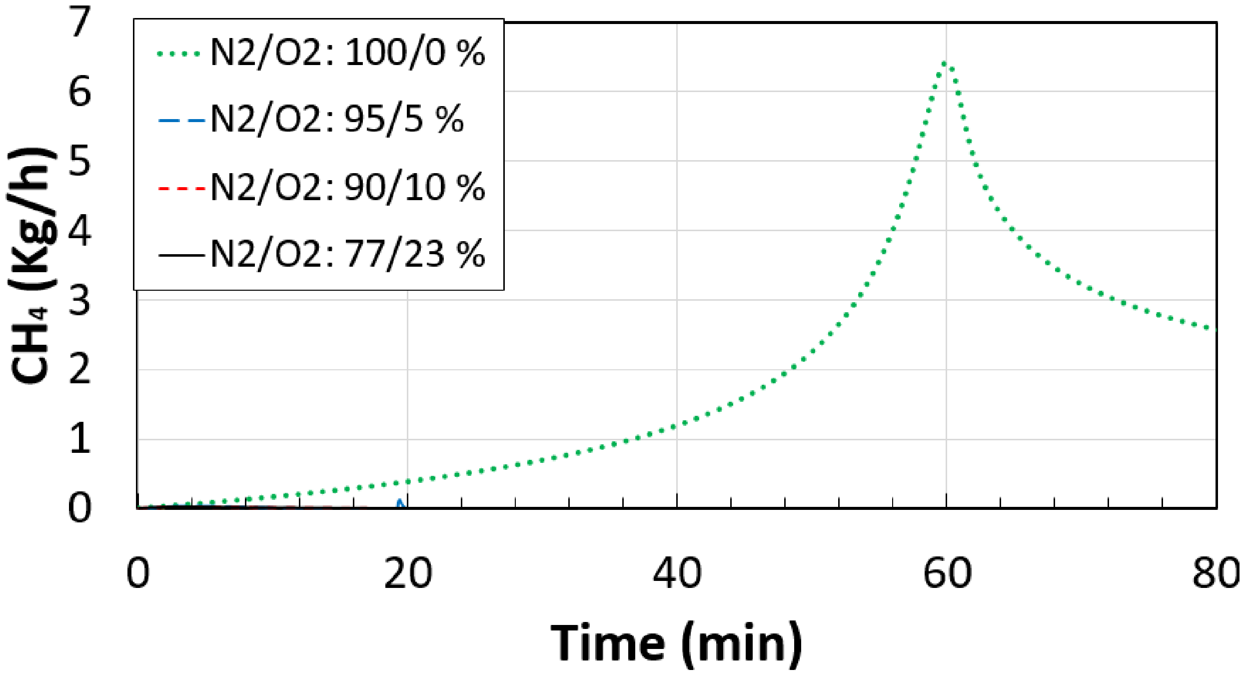

Figure 7: Predicted effect of the composition of the hot gas stream of O_2/N_2 = 0/100%, 5/95%, 10/90% and 23/77% on the methan production rate as a function of time (minute) at *Fs* = 100 Kg / h, *M* = 10% and *T* = 790 °C.

Conclusion

Optimizing a biomass conversion process involves balancing residence time, temperature, moisture content, and oxygen levels. Advanced modelling techniques and optimization algorithms can enhance process efficiency [27,28]. By integrating temperature control strategies with measures to minimize ash and PAH formation, the study provides a comprehensive approach to improving biomass conversion technologies. However, it is essential to validate this model experimentally and develop similar validated models for other biomass types, including plant waste, and cow, cheap, and camel dung. Addressing the technical challenges associated with implementing effective technologies will be crucial for ensuring high performance, minimizing maintenance, and extending the operational lifespan of biomass conversion plants.

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