Theoretical simulation of olive pomace pyrolysis for biomass energy: a sustainable approach to waste reduction and energy efficiency

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Abstract. This scientific investigation explores the conversion of olive pomace waste from Moroccan oil mills into valuable biomass energy via pyrolysis. The study involves three pivotal parts: Our research encompasses a multifaceted approach, beginning with a comprehensive review of olive pomace, pyrolysis, gasification, and biomass combustion to establish a robust foundational knowledge base. Following this, we embark on developing a physical and mathematical model for pyrolysis alongside determining crucial thermo-physical properties, thus setting the stage for subsequent simulations. In the final phase, our study conducts intricate simulations of the pyrolysis process, precisely calculating gas and solid temperatures at multiple pivotal points while accounting for fluctuations in solid temperature due to gas interactions. Employing a TDMA (Thomas Algorithm) approach to iteratively solve the system's equations, we simultaneously derive temperature values for both gas and solid phases. Notably, our research integrates critical thermal data, including the initial assumption of a uniform solid temperature at 293 K, an incoming gas temperature of 600 K, and an existing gas temperature post-pyrolysis of 514.52 K, while considering non-uniform solid temperatures. This comprehensive research underscores the potential of pyrolysis as a sustainable biomass energy source, addressing waste management concerns and championing environmental sustainability.

1. Introduction

In the contemporary landscape of escalating energy demand, our world faces a critical juncture characterized by the unsustainable exploitation of natural resources and the ensuing widespread environmental degradation. This pressing challenge necessitates a paradigm shift toward renewable and environmentally sustainable energy sources. Such sources, often called renewable or green energies, are characterized by their capacity to meet energy needs without depleting finite natural resources, harnessing elements that naturally regenerate. Among these sources, biomass holds significant promise.

This research is founded upon the central notion of valorizing the often-overlooked by-products of the olive oil industry, focusing on Morocco. The process of olive oil extraction in this region yields substantial quantities of by-products, principally comprising vegetable waters (in liquid form) and pomace (a pasty residue). Approximately 100 kilograms of olives yield an average of 35 kilograms of pomace and 100 liters of vegetable water. While the potential uses for raw olive pomace are manifold, it remains an environmental concern due to its chemical composition, which retains valuable edible oil, cellulose, and nitrogenous materials. However, the detrimental environmental impact of these by-products primarily stems from their polyphenol content, notorious for its resistance to biodegradation. Beyond olive pomace, the industry also generates "margins" – liquid discharges from olive oil production – which, when discarded into rivers and sewers, pose severe threats to aquatic ecosystems owing to their high levels of soluble phenolic compounds. These aromatic compounds have a deleterious effect on soil, impairing its capacity to support life and inhibit the growth of organisms.

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We offer an overview of key findings from various sources, each contributing unique insights into the diverse applications of olive pomace. Some studies [1] delve into the biotechnological valorization of olive pomace as a substrate for entomopathogenic fungal biomass production, achieving impressive biomass yields. Others [2] focus on the physicochemical attributes of olive pomace, unveiling its potential as a high-energy, sustainable fuel source. Another set of investigations [3] introduces torrefaction as a pre-treatment method, revealing the value-added compounds that can be derived from olive pomace. Meanwhile, [4] explores the utilization of olive pomace for fast pyrolysis, highlighting the role of inorganic metals in influencing product distribution. Additionally, research [5] delves into the efficient drying kinetics of olive pomace using solar convective dryers, optimizing energy consumption. Further studies [6] investigate the hygroscopic behavior of raw olive pomace during convective drying, focusing on its thermodynamic properties and kinetic measurements. In parallel, [7] examines the combustion dynamics of pulverized olive cake, showing the impact of excess air ratios on emissions and temperature distribution in a vertical furnace. Subsequently, [8] analyzes biomass flame behavior with olive waste, emphasizing the strong influence of air mass flow on ignition and combustion behavior, revealing distinct phases. Together, these diverse findings establish a comprehensive foundation for our scientific article, elucidating the multifaceted potential of olive pomace in biotechnology, energy production, and environmental sustainability. Lastly, we draw insights from [9], which investigated the slow pyrolysis characteristics of food wastes, specifically acorn cups, acorn pericarp, almond shells, and nut shells, highlighting differences in thermal behavior and gas products formed during pyrolysis. Furthermore, [10] emphasizes the production of renewable biochar from peanut shell waste and sugar cane bagasse at different pyrolysis temperatures, improving calorific value and morphology of the biochars. Together, these diverse findings establish a comprehensive foundation for our scientific article, elucidating the multifaceted potential of olive pomace in biotechnology, energy production, and environmental sustainability.

Considering these challenges, our research delves into olive oil by-products' environmental and energy aspects. We investigate the transformation of olive pomace, the solid residues from oil extraction, into biomass energy through pyrolysis. Pyrolysis, involving the thermal degradation of organic matter without oxygen, yields a range of valuable products, including solid carbon-rich compounds and condensable (tar) and non-condensable (hydrocarbons) gaseous compounds. Our study is organized into three key chapters: the first provides a comprehensive review of literature on olive pomace, pyrolysis, gasification, and biomass combustion; the second details the development of physical and mathematical models, along with the characterization of thermo-physical properties of the biomass; and the final chapter is dedicated to the simulation of the pyrolysis process, featuring the presentation of a custom C-program and a comparative analysis of results with ANSYS Fluent. Through this research, we aim to elucidate the potential of pyrolysis as a sustainable approach to convert waste into valuable biomass energy, ultimately contributing to waste reduction and environmental sustainability.

2. Equipment and methods

2.1. Description of the prototype description and dynamic modeling

Our physical model consists of a boiler, temperature-measuring instruments, and a gas inlet with an adjustable flow.

Figure 1: Physical model [8]
1. Flue gas outlet
2. Fuel bed
3. Temperature acquisition T1-17
4. Data analysis and visualization
5. Grate
6. Primary air
7. Air flow meter
8. Pressure regulator
9. Air Compressed

Then, the gas inlet is at the bottom of the boiler. The gas (CO₂ and N₂) enters with a speed of 0.25 m/s. It carries a temperature of around 600 K at the level of our biomass (the pomace of’olive), which is at room temperature 293 K, then we will have pyrolysis in a porous medium.

The boiler contains a grate (circular hole with a diameter of 4 mm) and a cylindrical shape, height of 450 mm and diameter of 124 mm, and the boiler bed has a height of 95 mm.

2.2. Assumptions

In scientific inquiry, the intricacies of physical phenomena often present formidable challenges. The complexity inherent in these phenomena necessitates recourse to mathematical equations as a means of description and analysis. However, grappling with these intricate systems invariably demands the employment of simplifying assumptions. These assumptions serve as indispensable tools in our quest to distill the complexity of real-world phenomena into tractable mathematical frameworks, enabling the application of analytical or numerical techniques for problem-solving. While simplifying assumptions is essential for advancing our understanding and facilitating practical solutions, they also invoke a crucial caveat – the need for vigilance in assessing the implications of these
simplifications on the accuracy and validity of our models and predictions. As such, the judicious selection and critical evaluation of simplifying assumptions stand as paramount considerations in pursuing scientific knowledge and the advancement of our comprehension of the physical world.

- The steady state
- Constant thermophysical properties
- We concede that our system is one-dimensional.

The general equation for the Solid in a Steady-state:

\[ 0 = \frac{d}{dx} \left( (1 - \varepsilon_s) \lambda_s \frac{dT_s}{dx} \right) - h_c A_{spec} (T_s - T_g) \]  

(1)

where \( \varepsilon_s \) stands for porosity, \( \lambda_s \) is solid conductivity, \( T_s \) is solid temperature, \( A_{spec} \) is the volumetric surface, and \( x \) corresponds to bed thickness.

The general equation for the gas in one-dimensional and Steady-state:

\[ \frac{d}{dx} \left( \rho_g u_g h_g u_g \right) = \frac{d}{dx} \left( \varepsilon_g \lambda_g \frac{dT_g}{dx} \right) + h_c A_{spec} (T_s - T_g) \]  

(2)

where \( \rho_g \) stands for density, \( h_g \) is heat transfer coefficient, \( u_g \) is gas velocity, and \( \lambda_g \) corresponds to gas conductivity.

**2.3. Treatment methodology needs**

Physics, the bedrock of scientific inquiry, seeks to fathom the universe's natural phenomena, encompassing its myriad forms, laws, and evolutionary patterns. When theoretical calculations become impractical, numerical methods become indispensable tools, spanning physics, biology, technology, economics, and social models. These methods drive the development of computational codes and fuel simulations in meteorology, particle physics, aeronautics, and the nuclear industry. Their central advantage lies in their ability to yield numerical solutions for virtually any problem grounded in a mathematical model, forging an inseparable alliance with computer science, thus propelling scientific understanding and technological progress.

The finite volume method, a specialized weighted residual technique, discretizes the study domain by dividing it into elementary volumes surrounding central nodes. These volumes are defined by interfaces—two in one dimension (e,w), four in two dimensions (e,w,s,n), and six in three dimensions (e,w,s,n,t,b). The method integrates the governing differential equation, approximating the unknown variable using interpolation functions between adjacent nodes in each volume. This integration yields discrete algebraic equations formed by nodal values, providing a versatile approach for numerical simulations and modeling in various scientific and engineering contexts.

Our computational approach involved programming the four equations derived from the digital processing of gas and solid interactions, incorporating the TDMA method for solving our system of equations. This iterative process was essential since solid temperatures are interdependent with gas temperatures, necessitating a loop to achieve convergence through a specific number of iterations.

**3. Results and discussion**

**3.1. Computational Results and Validation**

After conducting 100 iterations of our C program, we obtained the temperature values for both the gas and solid phases. Then, we imported the computed data into the origin software to visualize and analyze the results effectively, enabling the generation of gas and solid temperature profiles.
In this study, we initially assumed a uniform solid temperature of 293 K. At the same time, the incoming gas had a temperature of 600 K. Upon concluding the pyrolysis process, we observed that the exiting gas registered a temperature of 514.52 K, accompanied by non-uniform solid temperatures. For instance, at the terminal point of the bed \((x = 0.0079 \text{ m})\), the system reached a state of thermal equilibrium with a temperature close to 514 K. These temperature variations can be attributed to the convective exchange phenomenon between the solid and gas phases, which plays a pivotal role in the observed thermal transformations.

### 3.2. Dynamic modeling

Employing our laboratory simulation tool, we have derived the following outcomes:

In this study, we observed a significant convective exchange phenomenon that strongly influences gas and solid temperatures along the spatial dimension, denoted as \(x\). Specifically, this phenomenon led to a noteworthy trend wherein gas temperature exhibited a decreasing profile with respect to the spatial coordinate \(x\). Conversely, solid temperature demonstrated a consistent increase in correlation with \(x\). This observation underscores a fundamental
dynamic in which the gas phase imparts thermal energy to the biomass, resulting in a progressive reduction in gas temperature as a function of position.

Our decision to employ our laboratory simulation tool was driven by the primary objective of validating the outcomes generated by our in-house program. Subsequently, our observations revealed remarkable consistency in equilibrium temperatures between Fluent and our program. Specifically, solid temperature consistently increased with a parallel slope in both simulations. However, a noteworthy distinction arose in gas temperature dynamics, as it decreased rapidly. The state of equilibrium for gas temperature occurred at \( x = 0.018 \) in Fluent, while our program achieved equilibrium at \( x = 0.035 \).

4. Conclusion

In this study, we explored the conversion of olive pomace waste from Moroccan oil mills into valuable biomass energy through the pyrolysis process. Recognizing the pressing need for sustainable energy solutions amid growing demand and environmental concerns, we turned our attention to the potential of biomass, specifically olive pomace. Although often disregarded, this waste holds promise despite the environmental challenges posed by its polyphenol content.

Our investigation focused on pyrolysis, a thermal process that converts organic matter into biomass energy without oxygen. We conducted an exhaustive literature review to establish the foundation. The second phase involved the development of a physical and mathematical model for pyrolysis, an essential step to ensure precise simulations. In the third phase, we conducted pyrolysis simulations using our custom C program, demonstrating the capabilities of our model.

In conclusion, our study underscores the potential of pyrolysis as a sustainable solution to convert olive pomace waste into biomass energy, bridging the gap between waste management and energy production. As we progress towards a future marked by energy security and environmental responsibility, pyrolysis offers a promising avenue for sustainable biomass energy production, aligning with our commitment to a more responsible and sustainable world.

References