One-step microwave pyrolysis of sago bark waste for rapid pyrolytic oil production: a response surface methodology approach

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Abstract

Purpose – This study employed microwave pyrolysis using palm kernel shell activated carbon (POAC) as an absorber to maximize the output of pyrolytic oil from sago bark (SB).
Design/methodology/approach – Using a central composite rotatable design in response surface methodology (RSM), 17 experiments were conducted to examine the combined effects of temperature, sample mass and

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POAC loading. The physicochemical characteristics were thoroughly studied, and the main components of the resulting oil were identified by gas chromatography–mass spectrometry (GC–MS) analysis.

Findings – In the microwave pyrolysis at 400 °C, the addition of 35% POAC increased the oil output to 29.63%. The oil's calorific value was 21 MJ/kg, density was 2 g/cm^3 and the phenolic compounds accounted for 57.6% of the oil content.

Practical implications – The findings demonstrate an efficient way to convert sago bark waste (SBW) into pyrolytic oil through an optimized process. Pyrolytic oil's characterization offers insights into the specific refining processes for its potential utilization as a sustainable biofuel.

Originality/value – This research is a distinct exploration of the application of POAC as an additive to optimize the pyrolytic oil yield. The optimized synthesis and the characterization of the oil demonstrate POAC benefits as an absorber and highlight the potential of SB as a bio-oil feedstock.

Keywords Biomass, Bio-oil, Microwave pyrolysis, Pyrolytic oil, Response surface methodology

Paper type Research article

1. Introduction

Global energy consumption has significantly increased as a result of rapid industrialization and population growth (Badza *et al.*, 2024). Despite dominating the energy landscape for more than a century, fossil fuels, though dominant for over a century, pose major challenges due to their limited availability and significant environmental impacts, such as carbon emissions and global warming (Foong *et al.*, 2024). To support sustainable development, the Paris Agreement sets a target for a worldwide commitment to reduce greenhouse gas emissions and keep global warming below 2 °C, ideally 1.5 °C, by 2100 (Imran-Shaukat *et al.*, 2025a). Despite initiatives to meet these goals, reliance on fossil fuels remains a significant challenge (Fang *et al.*, 2024). According to the International Energy Agency, between 30 and 40% of the energy used worldwide comes from oil alone (Kashif *et al.*, 2024). The rapid population growth in recent years has significantly driven up global energy demand (Palla *et al.*, 2024). With increasing ecological degradation, pollution and resource depletion, renewable energy is emerging as a crucial alternative to fossil fuels (Yue *et al.*, 2024). Renewable energy sources include hydropower, geothermal, solar and biomass (Palla *et al.*, 2024).

Biomass is the fourth-largest renewable energy source under the waste-to-energy strategy, accounting for 14% of global energy consumption and reinforcing its role in the global energy matrix (Muniyappan *et al.*, 2023). Resources derived from non-food sources, such as lignocellulosic materials (wood, plants and leaves) and carbohydrates from crops and vegetables (Allende *et al.*, 2023a). It also includes organic, industrial and household waste, algae and municipal waste, which are all considered biomass (Shahnouri *et al.*, 2024). Various thermochemical techniques – such as gasification, hydrolysis, liquefaction, pyrolysis and hydrothermal carbonization-are employed to convert biomass and solid waste into sustainable fuels and energy products (Badza *et al.*, 2024; Sidabutar *et al.*, 2024). Key biomass conversion technologies include direct combustion (Palla *et al.*, 2024), gasification (Qiu *et al.*, 2024), liquefaction, hydrolysis (Badza *et al.*, 2024), torrefaction (Sidabutar *et al.*, 2024) and pyrolysis (Kashif *et al.*, 2024).

Pyrolysis, a thermochemical process carried out in an inert or low-oxygen atmosphere, is particularly appealing due to its low pollutant emissions and diverse product yield (Fernández *et al.*, 2024). Depending on the properties of the feedstock and the process parameters, particularly temperature and residence time, it can yield three distinct products: solid char, liquid fuel and syngas (Hanafi *et al.*, 2024a). Pyrolysis is typically conducted at temperatures between 400 °C and 1,200 °C to optimize the product yield and quality (Allende *et al.*, 2023a). Higher temperatures generally enhance syngas production, whereas lower temperatures favor char formation, depending on the feedstock type (Fang *et al.*, 2024). Pyrolysis of biomass at approximately 500 °C primarily yields bio-oil as the main product (Makepa *et al.*, 2023). Each pyrolysis product holds distinct value and serves specific functions across various applications (Hanafi *et al.*, 2024b).

During pyrolysis, biomass undergoes a series of reactions, including the breaking of large molecular bonds, polymerization of small molecules and isomerization, ultimately forming low molecular weight volatile components such as bio-oil, gas and char (Ke *et al.*, 2024; Wahi