Chapter 6

Conclusions and Future Scope

6.1. Conclusions

Biomass and petroleum coke (petcoke) have distinct physical and chemical properties, leading to significant differences in thermochemical conversion processes. Biomass, recognized as a renewable energy resource, has considerable potential to aid the transition to cleaner energy systems. However, large-scale commercial deployment of biomass faces challenges such as supply chain management and low energy density. In contrast, petcoke is characterized by low reactivity and high fixed carbon content, presents complexities in its individual conversion process. Blending biomass with petcoke for thermochemical conversion presents a promising strategy for producing alternative fuels and also overcome the issues related to individual fuel sources. This research investigates explicitly the thermochemical conversion of Bambusa *tulda* (B. *tulda*) and petcoke, supported by a comprehensive literature review that highlights gaps in existing studies. The study presents a comprehensive investigation of the thermochemical conversion of B. *tulda* and petcoke, highlighting their physicochemical properties through proximate and ultimate analyses and calorific values. Both fuels have low moisture content, which minimize energy loss during thermal degradation. The high volatile matter content in B. *tulda* enhances its reactivity, making it suitable for combustion processes. In contrast, petcoke has low volatile matter and high fixed carbon content, resulting in a higher calorific value essential for maximizing energy output. Additionally, the low ash content in both fuels reduces risks such as agglomeration and sintering, thereby improving the reliability and efficiency of combustion systems. The lower nitrogen content in both fuels suggests that blending them could lead to lower NOx emissions, which supports environmental sustainability goals. Therefore, comprehensive investigations of blended fuel samples of B. *tulda* and petcoke are crucial to assessing their potential as a fuel, significantly contributing to sustainable and clean energy development advancements.

6.1.1 Thermal degradation and kinetic study

The study investigates the thermal degradation characteristics of B. *tulda* using Thermogravimetric Analysis (TGA) to determine the kinetic parameters in N_2 and CO_2 atmospheres. The results indicate that the activation energy of B. *tulda* significantly reduces under CO_2 atmosphere compared to N_2 atmosphere. The activation energies are 160.05 kJ mol^{-1} under N_2 atmosphere and 105.51 kJ mol^{-1} under CO_2 atmosphere. Additionally, blending B. *tulda* with petcoke reduces activation energy, thereby enhancing the thermal conversion process. For the blends B80P20, B60P40, and B40P60, the activation energies are estimated as 101.66 kJ mol^{-1}, 122.23 kJ mol^{-1}, and 129.30 kJ mol^{-1}, respectively, all are lower than that of pure petcoke. The study also identifies the catalytic role of alkali and alkaline earth metals present in B. *tulda*, which facilitates efficient thermal degradation. The degradation process is described using multiple reaction models, with A2, D3, F1, and F2 being the most suitable models. The pre-exponential factor under N_2 atmosphere ranged from 22.82 to 56.01 min^{-1}, while under CO_2 atmosphere, it ranged from 17.99 to 27.16 min^{-1}. Blended samples exhibited distinct transitions in reaction models, reflecting different reaction mechanisms under CO_2 atmospheres, with the activation energy values ranging from 23.39 to 39.94 min^{-1} across the various blends. The analysis of the char produced from pyrolysis revealed a higher energy content when produced under N_2 atmosphere than produced under CO_2 atmosphere. Furthermore, the char derived from B. *tulda* exhibited an increased carbon content and reduced hydrogen and oxygen levels, indicating enhanced carbonization and aromaticity. High levels of potassium, magnesium, calcium, and sodium are also observed, suggesting potential improvements in reactivity for co-gasification or co-firing applications. This study highlights the unique thermal behavior of blends of B. *tulda* and petcoke, providing valuable insights for optimizing thermal conversion processes in biofuel production and makes B. *tulda* as a viable alternative to fossil fuels within sustainable energy solutions.

6.1.2 Single particle combustion of blended samples

The combustion experiment investigates the characteristics of B. *tulda* and petcoke blends, analysing their effects on various combustion processes, including flame behavior, mass degradation, combustion time, ignition mass flux, particle density, and ash residue composition. The flame behavior of B. *tulda* and petcoke samples varies depending on the blend ratio. When the percentage of petcoke increases, the flame becomes smaller and less luminous, primarily because petcoke has a lower volatile matter content. This leads to reduced mass loss during combustion. Additionally, as the proportion of petcoke in the fuel samples increases, the combustion times for both the volatile matter and char combustion stages are extended due to the increased particle density. This higher density leads to greater internal and external resistance, which restricts the oxidant diffusion, thus requiring more time for the combustion process.

Combustion occurs in two stages: volatile combustion and char combustion. As the percentage of petcoke in the fuel blend increases, the volatile matter content decreases. This decrease increases the ignition mass flux during the volatile combustion stage, leading to a faster ignition rate and quicker fuel consumption. In contrast, during char combustion, the ignition mass flux decreases with higher petcoke content because petcoke has a higher fixed carbon content. This requires more energy to break down the carbon-carbon (C-C) bonds and resulted in a slower conversion of char to its final combustion state. Additionally, the surface area-to-volume ratio of fuel particles significantly affects combustion time. This experiment used fuel particles with diameters of 20 mm, 25 mm, and 30 mm to examine combustion duration. It is observed that smaller particles, which have a higher surface area-to-volume ratio, combust more quickly due to increased reaction intensity. In contrast, larger particles, with a lower surface area-to-volume ratio, take longer time to burn because of slower heat and mass transfer. A higher surface area enhances heat and mass transfer, essential for efficient combustion.

The ash residues collected after the combustion of B. *tulda* and petcoke blends vary in composition. Blending petcoke with B. *tulda* helps mitigate ash-related issues caused by the high potassium content in B. *tulda*. This process promotes complete char combustion while reducing the risk of slagging and corrosion in combustion systems. Additionally, the blend lowers the presence of harmful elements like sulphur and sodium in the ash, enhancing the sustainability of the fuel mix. This study thoroughly analyses combustion characteristics and suggests that co-firing of B. *tulda* and petcoke improves combustion behaviour, and reduces environmental impact. The insights gained from this research can be applied to design better combustion systems and enhance sustainability in fuel utilization.

6.1.3 Co-gasification of blended fuel samples

The co-gasification experiment thoroughly examines the impact of K_2CO_3 impregnation on bamboo char during CO_2 gasification, emphasizing changes in elemental composition, reactivity, and structural properties. EDX analysis showed a significant increase in potassium content, rising from 42.68 % to 77.51 % after K_2CO_3 impregnation. This increase improved the water-gas shift reaction and enhanced the char porosity. Furthermore, reducing silicon (Si) and aluminium (Al) content in the char generated from the pyrolysis of impregnated biomass contributed to char reactivity by preventing the formation of inactive compounds and molten ash layers. The experiments showed that the impregnation of K_2CO_3 significantly increased carbon monoxide (CO) yield across various temperature and pressure conditions. The char conversion percentage improved from 10 % at 1023 K and 1 atm to approximately 50 % at higher temperatures of 1123 K and 1173 K. Increasing the pressure to 3 atm and 5 atm further enhanced char conversion, with temperature and pressure working together to promote CO yield and the conversion of char samples. However, some challenges needs to be noted at higher pressures, such as the agglomeration of catalytic compounds and pore blocking, which could potentially limit char conversion.

The experiments are conducted using blends of K_2CO_3-impregnated bamboo char and petcoke to investigate the impact of blending on gasification, particularly regarding carbon monoxide (CO) production and char conversion. The results showed that blends consisting of 80 % bamboo char with 20 % petcoke and 60 % bamboo char with 40 % petcoke optimized CO generation and char conversion especially under elevated pressure conditions. These blends achieved char conversion rates between 65 % and 75 % at 3 atm and 1173 K, highlighting the catalytic role of alkali metals in enhancing thermal conversion during the gasification process. The results validated that K_2CO_3 impregnation significantly enhances the gasification process by improving char reactivity, increasing carbon monoxide production, and facilitating char conversion. The research emphasizes the potential of blending of carbonaceous materials to optimize gasification and provides valuable insights for developing efficient thermal conversion technologies. Furthermore, it can be concluded that blending petcoke takes advantage of the high reactivity and environmentally friendly characteristics of B. *tulda*, combined with higher energy density of pet coke. Overall, the strategic blending of B. *tulda* and petcoke presents a pathway to more efficient and sustainable energy solutions applicable in both industrial and environmental contexts.

6.2 Future scope

The following areas represent potential future research opportunities:

a) *Model verification using Artificial Neural Networks (ANN)*: Kinetic analysis of biomass and petcoke blend is carried out to determine the kinetic triplets using the iso-conversional method. However, the accuracy of the parameterization for the models can be tested against a randomly selected validation dataset through the use of ANN.

b) *Design and process optimization:* The design of reactors for co-gasification should be explored. It is important to fine-tune operational parameters to maximize syngas yield. Additionally, developing computational models to predict co-gasification performance under various conditions is necessary. Research into hydrogen enrichment in syngas for applications like fuel cells or synthetic fuels, as well as integrating CO_2 separation and storage technologies into the process, is also essential.

c) *Pilot studies and demonstration projects:* This study focused on gasification experiments using biomass and petcoke in a small fixed-bed reactor, using CO_2 as the gasification medium. However, pilot studies are required to test co-gasification processes to evaluate the performance and scalability with CO_2 as a gasification medium. Collaboration with industries is also essential for implementing industry-scale co-gasification plants for power generation, chemical synthesis, or hydrogen production.