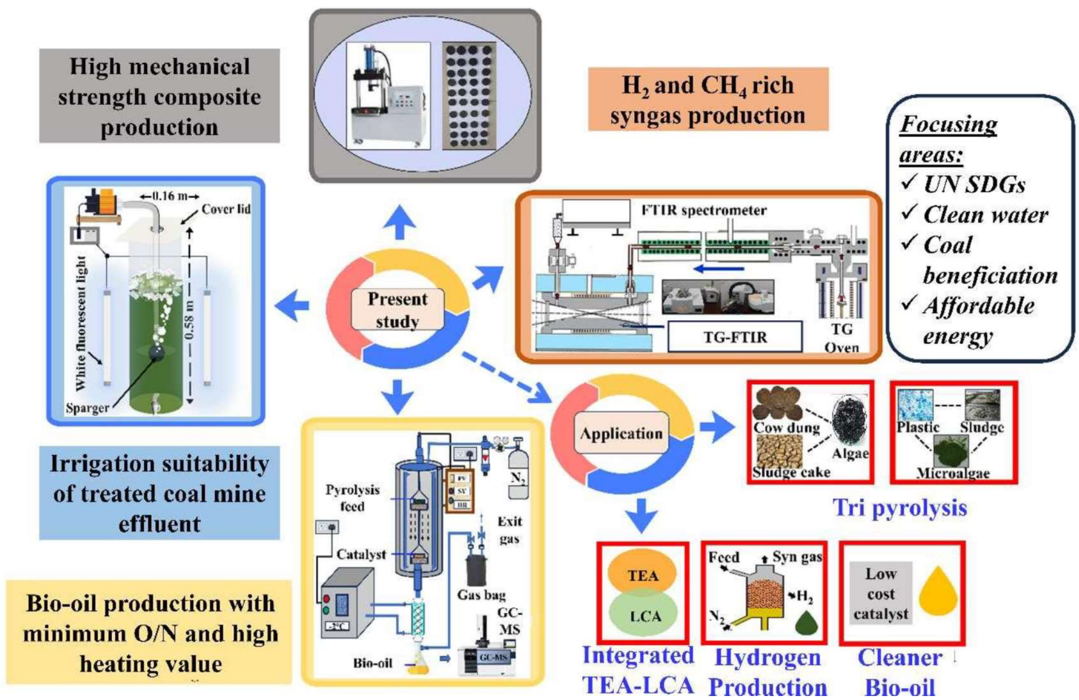
CHAPTER 8

Conclusion and future perspectives



8. Conclusion and future perspective

The microalgae assisted integrated approach of wastewater treatment and biofuel production facilitates sustainable advancement in coal mining industry in context of beneficial use of treated mine effluent for irrigation, direct CO_2 fixation and high value applications such as biofuel production. In present study, freshwater microalgae, *C. pyrenoidosa, C. minutissima, C. protothecoides* and marine microalgae, *C. vulgaris* and *Dunaliella* sp., were investigated for CME treatment. The selected candidate microalgae *C. pyrenoidosa* (NCIM 2738) showed maximum nutrient removal efficiency in terms of EC (86.9 %) and COD (89.8 %) with growth potential as μ_{net} of 0.33 d^{-1}. Fuel characteristic analysis interpretate *C. pyrenoidosa* as an appropriate pyrolysis feedstock with maximum HHV and LHV of 18.60 MJ Kg^{-1} and 17.14 MJ Kg^{-1}, respectively. In pyrolysis kinetic models, CR and DAEM model estimated apparent E_a of *C. pyrenoidosa* as 55.87±11.16 kJ/mol. Further, Conv1D-LSTM model is used to predict and verify microalgal thermal decomposition data which shows DNN6 as best DNN model with high regression coefficient ($R^2 > 0.997$) and minimum MSE of 10^{-6} for different heating rates of 10, 20 and 30 ºC/min.

In next stage, selected microalgae *C. pyrenoidosa* (NCIM 2738) was investigated to treat NSCME via semi-continuous cultivation mode at different HRTs of 4 d, 6 d and 9 d. The HRT 6 d presented maximum biomass concentration of 5.7 g L^{-1} and maximum biomass productivity of 950 mg L^{-1} d^{-1} in BCR. Although, HRT 9 d showed maximum COD removal efficiency (96.5 %) and maximum salinity removal efficiency (93 %) in BCR. Further, EDS results confirm excess salt ions (Na^+/ Mg^{2+}) as well as metal ions (Cu^{2+}, Cr^{2+}, Fe^{2+} and Pb^{2+}) accumulation in the microalgae sample, which indicates successful desalination from NSCME which was further reconfirmed by ICP-MS analysis. The transesterification of accumulated lipid to FAME shows biodiesel potentiality with CN of 53.94, SV of 193.33 and IV of 91.52.

The de-oiled microalgae have shown coal like fuel characteristics as high gross calorific value (18.62 MJ/kg), low ash content (18 %) and low sulfur content (1.45 %). Further, the blended composites of de-oiled microalgae and coal (20:80 ratio) showed fuel ratio (1.85), gross calorific value (19.0 MJ/kg) and sulfur content (< 1 %). The multi-objective optimization study results blended coal-microalgae composites production with compressive strength of 14.6 MPa and drop strength of 97.8 % at optimized conditions after model validation ($R^2 > 0.99$). These composites maintain ASTM standards of solid fuels. The improved thermal behavior of blended composites is confirmed by TGA-DTG-DTA analysis which showed notable shifting of ignition point from 335 °C (parent coal) to 301–299 °C (blended coal composites) and extended burnout temperature (47–82 °C higher than parent coal) of composite combustion.

In thermochemical conversion, a co-pyrolysis-based valorization of de-oiled microalgae and low rank coal blend is performed for syn-gas analysis which indicate the gradual addition of microalgae (0–100 %) in coal reduces E_a from 189.11–55.87 kJ/mol and 180.16–54.61 kJ/mol by KAS and STK method. In syn-gas emission, maximum hymethane carrying ratio defined as $(H_2 + CH_4)/(CO + CO_2)$ is observed as 2.51 and 3.51 at RSM and ANN-MOGA, optimized conditions respectively. The ANN-MOGA optimized conditions of blending ratio – 42.25 % and heating rate – 13.8 °C/min results maximum H_2 (54.5 %) in the syngas at mid pyrolysis stage (451 °C). Considering the particular benefits of ANN-MOGA over RSM, application of MOGA is highly recommended to modernize co-pyrolysis process for energy rich syngas production.

In the direction of cleaner co-pyrolysis strategy for high-quality bio-oil production, de-oiled microalgae-coal blends were pyrolyzed in presence of synthesized heavy metal-loaded Cu-Cr-ZSM-5 catalyst. The synthesized catalyst was characterised via XRD, SEM and TEM analysis which confirm synthesized catalyst as nano-crystalline of average size 7 nm. The microstructure of the synthesized catalyst shows stacked nanorods packing with connected intercrystal and intracrystal mesopores. Investigating product yield distribution results, non-catalytic microalgae pyrolysis has shown maximum bio-oil yield (35.7 %). The synergistic effect of nanorod morphology, active acid sites and excess mesoporosity of catalyst facilitates efficient deoxygenation, denitrogenation and aromatization of pyrolysis bio-oil with oxygen content from 2.1–3.1 %, nitrogen content 3.5–5.1 % and aromatic content 49.4–54.4 % at catalyst feed ratio of 1:1. The maximum obtained HHV of bio-oil from catalytic pyrolysis of coal (40.1 MJ/kg) followed by coal-microalgae (38.6 MJ/kg) and microalgae (36.5 MJ/kg) is very close to diesel oil with HHV (42–46 MJ/kg). This study encourages low-cost catalyst development, advancement in feed processing and application of thermocatalytic cracking as emerging efforts towards industrial-scale upgradation of bio-oil to engine fuels.

In the context of coal mining industries, present study offers exciting opportunities and potential benefits by integrating microalgae production facilities in coal mine discharges. These integrated approaches towards coal mine water treatment, resource recovery and biofuel production will lead towards implementing circular water economy in water and wastewater sectors. The highest possible management of coal mine water, cultivated microalgae, residual components and co-products suggest integrated circular economy approach in water and energy utilization. Mine locations with high solar radiation, adequate land and water resources facilitate microalgae production in coal mine sites. It may offer potential environmental, economic and social benefits such as saline mine water treatment, CO_2 fixation and high value products such as biofuel, biofetriliser and biochar production. Considering biodiesel as desired product from microalgal lipid, the de-oiled microalgae cake may be co-processed with low-cost fuel feedstocks as coal fines, cow dung and sludge cake to offer a diverse spectrum of biofuels, including bio-oil, biomethane, biogas and biohydrogen. These sustainable energy production approaches encourage co-pyrolysis (coal-microalgae) and tri-pyrolysis (coal-microalgae-waste) in pilot and plant scale implementation. Modernizing conventional pyrolysis with advanced feedstock processing and incorporating a multi-task machine learning algorithm to optimize specific applications as H_2 production will lead towards scale-up and commercialization of co-pyrolysis as an alternative to gasification. Further, catalytic co-pyrolysis offers upgraded quality and yield of bio-oil using effective, robust and multi-functional catalyst preparation, low-cost feed integration and catalyst regeneration. Integrated technoeconomic analysis and lifecycle assessment must be explored to determine interrelationship between technical, economic and environmental performance of microalgae assisted coal mine water treatment system for mine water treatment and biofuel production. Targeting sustainable energy solutions and different SDGs, present study develops integrated process strategy for coal mine water treatment and biofuel production following a closed loop process using microalgae platform.