Chapter 5: Conclusion and Future work

In order to reduce the emissions and dependency on fossil fuels, and subsequently to promote the production of producer gas through gasification process, this thesis work includes the performance and optimization of commercial scale gasifier-engine setup. In this regard, this conclusion section has been categorised into two units wherein first unit deals with the conclusions obtained from the experimental section. Second unit includes the concluding specific statement pertaining to the numerical modelling and simulation. Further, the future recommendations are also mentioned to emphasize on various issues related to the possibilities, problem identification, and prospects of utilizing gasification technique in better way so that the infrastructural problems of fuel oil scarcity, economics and environment degradation could be squarely met.

In this chapter, the producer gas fuel generation from different waste biomass feed materials are concluded to have significant economic potential to substitute conventional diesel fuel through Gasifier-Engine integration system. Moreover, numerical modeling and multi-objective optimizations to determine the best response of the performance and emission parameters of SI engine fuelled with producer gas and propane blends proved to be a valuable tool for the guidance of experimentation with reduced time and resource needs. The conclusion of experimental works contains six subsections namely (a) Comparative performance and Optimization analysis of biomass gasification-CI engine, (b) Co-gasification of Low-grade Coal with Mahua Biomass and dual-fuelled engine performance, (c) Co-gasification of Mahua Biomass- Saw dust briquette and dual-fuelled engine performance, (d) Co-gasification of Triple feed materials and dual-fuelled engine performance, (e) Comparative analysis of gasification/co-gasification on CI engine performance, and (f) Economic analysis of sugarcane bagasse pith briquette production and its application in gasifier-engine system. In each sub-sections, conclusions regarding maximum engine performance with minimum emissions are presented for different solo and co-gasification feed materials. Additionally, optimum operating settings are also concluded for best performances and optimum economic feasibility of waste biomass are also suggested in context of waste-to -fuel conversion through briquette plant.

5.1 Experimental work conclusion

5.1.1 Comparative performance and Optimization analysis of biomass gasification-CI engine

Successful experimental studies were carried out on a downdraft gasifier with a DF mode CI engine, incorporating varying CR and BP. The PG was produced by gasification of Briquettes, Mahua wood, and Coconut shell, and the performance of PG-diesel fuelled engines performance (power, emission, and diesel saving) was investigated. The RSM optimization tool was used to find the optimal input configuration for the best performance response. The RSM-based results suggest that the quadratic model was prominent for quantification using ANOVA, F-values, and P-values. The prediction accuracy in terms of R^2 was found to be higher than 85%. Based on the experimental and RSM optimization approach, the following conclusions can be drawn:

- Briquettes-based PG DF engines were found to have the highest BTE (25 %), followed by coconut shells (24.1 %) and Mahua wood (17 %).
- Coconut shell-based PG DF engines were found to have the maximum diesel saving (57.83 %), followed by Briquette (52.5 %) and Mahua wood (50.9 %).

- During DF engine run, a rise in CR leads to an increase in CO_2, i.e., for Mahua-PG 1.1-2.2% vol., Briquette-PG 1.2-2.3 %vol., Coconut shell-PG 1.5-3.8 %vol.. Similarly, NOx increases with CR as Briquette-PG 6-31ppm, coconut shell-PG 6-56ppm, and Mahua-PG 40-220 ppm.
- During DF engine run, as engine BP increases, CO and HC emissions decreases correspondingly for all biomass PG blends.
- The RSM-based optimum input setting for the Briquette PG-operated DF engine was found to be 16.34 CR with 2.78 kW BP.
- The optimal RSM-based input setting for the Mahua PG-powered DF engine was determined to be 16 CR with 3.30 kW BP.
- The RSM-based optimal input setting for the DF engine powered by coconut shell PG was observed to be 16.04 CR with 3.20 kW BP.
- Briquette, Mahua wood, and Coconut shell have composite desirability functions of 0.85, 0.76, and 0.91, indicating good reliability of the model.
- RSM-predicted performance responses were compared experimentally at optimized input conditions and found to be a 6.6% maximum error.

In conclusion, this study supports the viability of Briquette, Mahua wood, and coconut gasification for PG generation and simultaneous use in CI engines as gaseous fuel to operate engines in DF mode. Additionally, this research develops a platform to run with optimal operating settings for the best performance and emission characteristics of a DF engine using biomass-derived PG.

5.1.2 Co-gasification of Low-grade Coal with Mahua Biomass and dual-fuelled engine performance

This study investigated the influence of different ratios of mahua wood biomass and low-grade coal in co-gasification fuel blends for the power generation purpose in dual fuel mode engine run. This research intends to perform experimental parametric impact and RSM based optimization of three operating parameters i.e., gasifier equivalence ratio, engine load, and compression ratio, to get a better knowledge of the output parameters, such as efficiency, diesel saving and emission parameters i.e., NOx, CO_2, UHC, and CO emissions. The following conclusions were drawn from this experimental analysis:

- In the co-gasification engine run, as mahua blend fraction increases, engine BTE decreases. Maximum optimised magnitude of BTE observed was 27 % at 0% mahua blending when running the engine at higher CR and load condition.
- Maximum diesel saving obtained is 54.16 % at CR 18 with no-load condition, when 100% mahua biomass was employed in co-gasification.
- Increasing Mahua biomass blend in coal from 0% blend to 25% biomass blend, the CO_2 emissions increases, and the Minimum magnitude of CO_2 concentration obtained was 0.8 % vol. at 75 % blending, 12 kg load, CR16, and GER 0.43. However, the optimised CO_2 concentration obtained was 0.64 % vol. at 75% blending, 12 kg load, CR16, and GER 0.1.
- The minimum magnitude of HC i.e., 1 ppm is observed at 75 % blending at CR 18, having 0.43 GER, and running at maximum load.
- The optimised magnitude of NO_x exhaust emission observed was 9.86 ppm at 0% mahua biomass, 0.10 GER, CR17 at full load.

- Co-gasification decreases the CO engine emission as compared to single feedstock coal gasification. Maximum CO emission observed was 0.67 % volume at 0 % mahua blending, 0 kg load, GER 0.43, and CR 18.

Conclusively, it could be suggested that integration of gasifier-engine system offers better performance parameter for engine power and emission mitigation with 0-50 % mahua blend co-gasification. Further, this study will provide a base for academician to extend research and development, and supportive for the small-scale industries to adopt this system to save conventional fuel and the environment.

5.1.3 Co-gasification of Mahua Biomass- Saw dust briquette and dual-fuelled engine performance

Based on the experimental analysis and RSM optimization tool to analyze the impact of independent parameters, ER, CR, and BP on the performance and emission parameters of diesel and dual-fuel mode VCR engines following conclusions are drawn:

- The fuel conversion efficiency is low for the dual-fuel mode, but it can save more diesel fuel and has a low sound.
- In Dual fuel engine operation, the maximum percentage of diesel saving was found to be 44.76%, 54.28%, and 62.75% at compression ratios of 16, 17, and 18, respectively.
- Maximum Brake thermal efficiency during dual-fuel mode attained was 20.44 % at ER 0.21, CR 18, and BP 3.5kW.
- Dual fuel mode engine run is advantageous as it produces 0-3.19% less sound than diesel mode. The maximum sound level recorded during dual fuel mode was 95.8db at ER 0.1, CR 18, and BP 3.5 kW.

- According to 0.838 cumulative composite desirabilities, RSM optimization results predict the optimal operating parameters as ER 0.10, CR 16, and BP 3.18 kW. Corresponding to these optimal operating setting, output responses were found as BSFC 0.165 kg/kWh, BTE 17.41 %, sound intensity 91.74db, CO 0.017 %vol., HC 3.83 ppm, CO_2 3.11 %vol., and NO_x 1.85 ppm, respectively, for dual mode.
- CO, HC, and CO_2 emissions were observed to be higher for the dual-fuel mode engine. However, the minimum CO and HC emissions during dual fuel mode were observed at 3.5 kW, CR 18, and ER 0.43 of magnitude 0.05 % vol. and 15 ppm vol., respectively; and

minimum CO_2 emission observed was 2.1 % vol. at 3.5 kW, CR 16, and ER 0.43.

- A dual-mode engine run is advantageous in terms of NO_x reduction. The NO_x emission during dual fuel operation was 50.81-86.95% lower than in diesel mode. Maximum NO_x emission noted during dual fuel mode was 99ppm vol. at ER 0.21, CR 17, and 0.1 kW.

In summary, the biomass co-gasifications with engine integration have the potential to replace diesel with the lowest possible exhaust emissions. Additionally, this research develops a platform to run with optimal operating settings for the best performance and emission characteristics of a dual fuel engine using co-gasification derived PG.

5.1.4 Co-gasification of Triple feed materials and dual-fuelled engine performance

Based on the outcomes of the experiment of triple feedstocks, i.e., low-grade coal and biomass (Briquette + Mahua wood) blend co-gasification, a conclusion was drawn that the process is regarded as an innovative, promising way of non-renewable diesel fuel saving and reduction of NOx emission to a great extent. Additionally, running the CI engine on both diesel and dual (diesel + PG) mode and analyzing the RSM-based optimization of operating and response parameters, the following conclusions are also being drawn:

- A maximum diesel saving of 59.5% was achieved at CR 18.
- Maximum BTE obtained was 29.69% and 27.30% in diesel and dual fuel (Diesel + PG) mode, respectively, at higher load conditions, i.e., 12kg.
- The sound coming out while running the engine on dual mode was 7.03% less than that of the diesel mode engine run. The Minimum optimized sound recorded during dual mode was 90.21db.
- With 0.72 composite desirabilities, the optimum value of input parameters was- gasifier ER 0.43, CR 16, and engine load 100% (i.e., 12kg).
- The optimum magnitude of engine performance (BP, BSEC, BTE, and GSR) obtained were 3.5kW, 34.16 MJ/kWh, 21.02%, and 49.39%, respectively.
- The optimum magnitude of engine emissions (CO, HC, CO_2, and NO_x) obtained were 0.0918 %vol., 17.4144 ppm, 2.0575 %vol., and 4.5538 ppm, respectively.
- 90-95% reduction in NO_x emission was achieved during the dual fuel mode engine run.

Thus, the successful conduction of the experiment and favorable results of lab-scale gasifier - Engine coupling could be a good reference for the research and development of large-scale gasifiers.

5.1.5 Comparative analysis of gasification/co-gasification on CI engine performance

A feasibility study using coal and different biomasses (briquette, coconut shell, and mahua wood) as a gasification/co-gasification feedstock was carried out using a scaled-up downdraft gasifier. Coal and biomasses as a feedstock were studied at 1, 1:1, and 1:1:1 co-gasification ratios. Further, the outcomes from experimental investigations and optimization through RSM studies were obtained by conducting performance and emission tests on a 4-stroke, single-cylinder, CI engine employing the gasifier-PG and diesel/B20 biodiesel oil (blended with mahua-based PG) on a dual fuel mode engine. The results from gasification-integrated CI engine were analyzed for CR 18. Furthermore, the techniques applied in RSM to optimize the performance of IC engines operating in DF mode were found consistent. The combination of experimental results and the RSM optimization strategy led to the following conclusions:

- Volatile matter in case of biomass is more than the coal, whereas the ash content in coal is higher than the biomasses. Moreover, the PG composition results suggest that as the biomass ratio is decreased during co-gasification, the hydrogen content increases. Co-gasification of 1:1:1 triple feedstock (coal+ briquette+ mahua wood) leads to higher hydrogen gas production of 18.5 % volume.

- Coal-based PG has the minimum gasification and carbon conversion efficiency. However, the co-gasification of respective biomass with coal leads to a decrease in gasification and carbon conversion efficiency. Maximum gasification and carbon conversion efficiency were observed for mahua wood-based PG as 85.24 %, and 95.42 %, respectively.

- Engine BTE increases with an increase in engine load. However, the engine BTE decreases with a decrease in GER for gasification, or biomass co-gasification of briquettes-based PG. Maximum BTE of 27.6 % was obtained at 100 % engine load, and GER 0.43 for briquette+

mahua wood-based PG integrated CI engine. While a maximum BTE of 28.37 % at 100 % engine load was obtained during diesel mode operation.

- Gasification of coconut shell-based PG leads to maximum diesel saving of 63.44 % at 33.33 % engine load and GER 0.24 as compared to other gasification feedstocks-based CI engine.
- Co-gasification of coal+ briquette+ mahua wood-based PG emits highest engine CO_2 and HC, CO emissions of 7.5 %vol., 381 ppm, and 1.21 %vol. respectively at 0% engine load and GER 0.43. A maximum of 1.6%vol. CO_2, 19 ppm HC, and 0.04%vol. CO was obtained at 66.66% and 33.33% engine load during diesel mode engine run.
- Gasification of mahua wood, or co-gasification of coal+ mahua wood integrated CI engine emits highest engine NO_X emission as compared to other gasification feedstocks. A maximum 311 ppm NO_X was obtained at 66.66 % engine load and GER 0.24 during DF engine run for mahua wood-based PG. The maximum engine NO_X during diesel mode obtained was 402 ppm at 100% engine load.
- Engine CO emissions decreases with increase in load percentage and decrease in GER. for co-gasification of 1:1:1 (coal+ briquette+ mahua wood) based PG integrated CI engine.
- RSM-based optimization results suggests optimum input conditions for coal, briquette, (coal+ briquette), coconut shell, (coal+ coconut shell), mahua wood, (coal + mahua wood), (briquette+ mahua wood), (coal+ briquette+ mahua wood), (mahua wood+ B20 biodiesel) as GER 0.15, 0.10, 0.20, 0.12, 0.24, 0.43, 0.43, 0.10, 0.22, and 0.10 respectively at 100% engine load except for 80.80 % engine load for (coal+ briquette). The optimum maximum emissions of CO, HC, CO_2, and NO_X obtained are 0.15 %vol., 39.09 ppm, 3.77 %vol., 206 ppm respectively.

- The composite desirability of RSM model lies in the range of 0.75-0.98 for all gasification/co-gasification based CI engine suggesting a good reliable model.
- Experimental comparison was conducted to assess RSM-predicted performance responses under optimized input conditions, revealing a maximum error of 5.78%.

In summary, this research affirms the feasibility of utilizing coal, biomasses, and its different blends gasification as sources for producing PG. This PG can be employed as gaseous fuel in CI engines, enabling them to operate in DF mode. Furthermore, the study establishes a framework for achieving optimal operational parameters, enhancing both the performance and emission traits of a DF engine powered by PG derived from biomass.

5.1.6 Economic analysis of sugarcane bagasse pith briquette production and its application in gasifier-engine system

The current study aims to analyze the production cost, the economic viability of small-scale sugarcane bagasse pith (SBP) briquetting and gasification-engine unit, experimentation on gasification of SBP for PG generation, and PG-Diesel blend DF mode engine run for power generation. Experimentally, different engine parameters such as CR, GER, and engine load were varied to obtain performance characteristics (i.e., BTE, exhaust, EGT, and sound emission) with dual fuel mode engine run and compared with standard diesel alone. According to the study, it was observed that SBP-briquette production is a profitable business, and the producer gas produced during the gasification of SBP-briquettes has a significant potential for use as an alternative fuel for IC engine run. In conclusion, the following major findings were derived from this research:

- The cost of SBP-briquette production significantly depends on repayment of bank loans, property taxes, maintenance costs, and operator costs. Despite these factors, the economic evaluation indicators for producing SBP's briquettes, i.e., NPV and PI, are positive with Rs. 4964379.5 (≈0.06 million USD) and 1.98, respectively, over a 20-year timeframe. Moreover, a 14 kW downdraft gasifier-engine set become financially attractive upto discount percent of 9% and capital cost of Rs.10 lac with a positive NPV and PI values for electricity line distribution.

- The maximum cylinder pressure was found to be decreased in DF mode as compared with a neat diesel-fuelled run. The maximum values for 16, 17, and 18 CR were 58.99, 62.76, and 70.71 bar for neat diesel mode and 57.47, 58.22, and 64.08 bar for dual mode, respectively.
- Maximum diesel saving observed was 66.15 %, 38.27 %, and 30.33 % at compression ratios 16, 17, and 18, respectively.
- Maximum BTE observed was 29.69 % and 27.4 % for neat diesel and DF mode, respectively, at maximum engine load.
- The intensity of sound recorded during dual fuel mode was low as compared to diesel mode at full load condition. The highest noise level recorded during the diesel mode engine run was 96.2 db, whereas in DF mode, the maximum sound recorded was 94.7 db at GER 0.21, CR 17.
- The minimum HC and CO emission was observed at 0.43 GER, CR 18, and 12 kg load with DF mode run. However, its value is higher than neat diesel mode, such as 27 ppm HC for DF and 16.0 ppm HC for neat diesel, 0.08 %vol CO for DF, and 0.02 %vol CO for neat diesel.
- Minimum CO_2 emission was found to be 2.0 %vol at 0.43 GER, CR 16, and 12 kg load at dual fuel mode, while at neat diesel was 1.6 % vol.

- Minimum NO_X emission was observed at 12 ppm at 0.1 GER, CR 16, and 8 kg load at dual fuel mode, while at neat diesel was 291 ppm.
- RSM results predicted optimum output responses aiming to maximize the performance (power, efficiency) and minimize the emission (CO, HC, CO_2, NO_X, sound) as 27.18 % BTE, 91.21 db Sound, 0.10 %vol CO, 53.19 ppm HC, 2.33 %vol CO_2, and 8.43 ppm NO_X, respectively, at optimal operating settings of 0.10 GER, 16 CR, and 9.93 kg.

Hence, utilizing biomass gasification for IC engine applications have potential benefits in terms of less annual greenhouse gas emissions and annual conventional diesel fuel savings. In the biomass gasification-CI engine application, 1.88 tonnes of annual CO_2 was released during DF mode engine run which was much lesser than 5.13 tonnes of annual CO_2 during neat diesel mode engine operation. However, this carbon emitted is offset by the carbon absorbed during the biomass's growth phase. Furthermore, during DF mode engine run, NO_X emission was 65-85% less than diesel mode engine run. However, PG based CI engine leds to slight decrease in BTE of CI engine as compared to neat diesel engine run. Additionally, another potential benefit was annual fuel saving costs of Rs. 109226.25 during DF engine operation, thus, it can be revealed that this system will be very suitable for further implementation and adoption.

The study provides important insights into the production of biomass briquettes and its implications for researchers, investors, technical operators, and decision-makers. It offers valuable knowledge that can aid in a better understanding of the challenges and opportunities in briquette production and its application to cooking, heating, and IC engines for power generations with a significant proportion of diesel savage.

5.2 Numerical simulation work conclusion

In the current research work, numerical modeling and multi-objective optimizations were performed to determine the best response of the performance and emission parameters of SI engine fuelled with peach-based PG and propane blends. To this end, first of all quasi-dimensional computational simulation model was developed on FORTRAN code, then results of the computational simulation model were validated with the experimental cylinder pressure trace from the earlier work. Afterward, this model was used to investigate the operating condition such as equivalence ratio, blending percentage, and SOI timing on engine performance and emission of PG-propane dual fuel SI engine. Subsequently, applying RSM-Design expert simulation tools, operating variables were optimized based on maximizing BP, BTE, and minimizing BSFC, CO and NO emission. The main conclusive results of this study are summarised as follow.

- A comprehensive quasi-dimensional (burn and unburn zone) thermodynamic model has been developed and successfully validated to simulate the performance and emission of dual fuel SI engine
- Regression models created from the ANOVA results were found to be accurate in predicting output response variables.
- The optimal values of independent parameters i.e., equivalence ratio, blending percentage, and SOI timing are found to be 1.002, 90 vol.%, and, 33.83 bTDC using the response optimizer.
- The optimum values of dependent parameters i.e., BP, BSFC, BTE, CO, and NO are found to be 2.41 kW, 0.3003 kg/kWh, 27.19 %, 0.809 vol%, and 2026.05 ppm respectively.

- The composite desirability observed was 0.868 which depicts a favourable outcome for all the responses as a cumulative.

Conclusively, in view of validation, prediction, and optimization, the present model proved to be a valuable tool for the guidance of experimentation with reduced time and resource needs. In the future, it can be adopted for the use of other different types of gaseous fuel and its blends. On other hand, peach-based PG and propane blends were revealed to be profitable resources for power generation. It was found that blending, ER, and spark timing significantly trade-offs the power and emission, therefore the engine operating condition must be adjusted in order to allow the balance between power and exhaust emission. So far adoption is concerned, the minor modification at inlet manifold of IC engine and respective operating setting is cost effective and compatible with biomass gasification.

Conclusively, it was found that PG fuel generation from different biomass waste feed material and non-woody material have significant economic potential to substitute conventional fuel like diesel through Gasifier-Engine integration system. Consequently, this study proves that it will be a significant tool for rural development with respect to socio-economic growth, and subsequently it could be a substantial mode to rise the GDP of the nation. Moreover, the implications of current study's findings suggest the broader adoption and commercialization of biomass gasification for IC engine applications, as this technology contributes to energy security, especially for regions with abundant biomass resources and environmental benefits with global efforts to reduce carbon footprints and combat climate change. Successful optimization and commercialization can create new markets for biomass-derived fuels and gasification technologies. Commercializing biomass gasification for IC engines not only addresses waste management issues but also adds value to materials that would otherwise be discarded. Further, this study will provide a base for the end-users and researchers to adopt a gasifier-IC engine integration system, which will provide a feasible approach toward utilizing low-grade coal and waste biomass in air gasification through a downdraft gasifier.

5.3 Scope for Future work

The experimental and numerical investigations carried out in this research activity have provided a base to address the fuel dependence of engine performance and a generic methodology to address alternate fuels in a systematic manner. Furthermore, enhancing the understanding and application of biomass gasification for IC engine applications is a dynamic field with several potential future research directions. Some of the areas that researchers might explore to advance this field are as below-

- Exploring the potential of unconventional biomass sources, such as algae, or dedicated energy crops.
- Exploration of advanced combustion strategies, such as stratified combustion or homogeneous charge compression ignition (HCCI), for improved efficiency.
- Exploring ways to efficiently recover waste heat from gasification and engine processes for additional energy generation or other applications.
- Development of catalytic integrated air-steam gasifier for the gasification of agriculture waste and valorization of gasified fly ash on concrete work will be the future scope of the present work.
- Development of highly efficient modified downdraft gasifier which can able to produce high quality of Producer gas with minimum magnitude of tar content inside the reactor.
- Gasification can also be integrated into hybrid systems, combining it with other renewable energy sources like solar and wind to provide a stable and continuous power supply.

- Techno-economic analysis of gasification integrated IC engine can be performed for electricity line distributions.
- Development of highly efficient system for carbon capture from producer gas and enriched hydrogen production.
- Implementation of Artificial intelligence algorithms to optimize gasification processes by continuously analyzing and adjusting parameters in real-time.
- Utilization of Machine learning models to predict optimal operating conditions based on historical data, helping to maximize efficiency and minimize emissions of gasifier-engine system.

Thus, continued research in these areas will contribute to a deeper understanding of biomass gasification for IC engine applications and drive the development of more efficient, sustainable, and economically viable energy solutions.