Chapter 1: Introduction

In this chapter, the background and motivation for investigating the performance, and optimization of gasification integrated internal combustion (IC) engine are presented. Furthermore, the objectives of the study and the methodology applied are explained, as well as a literature review. Finally, the outlines of the dissertation are mentioned.

1.1 Background and Motivation

Pollution is a terrible curse that the human race brings on itself as it seeks to increase the earth's living standard through exploitation. The world's population is also rapidly increasing and is projected to reach 9.7 billion by 2050 to 10.9 billion in year 2100 year [1], [2], and India is projected to be the most populated country, with 1.4 billion people [3]. Hence today, limiting global temperature increments under 1.5^{o}C and rapid depletion of conventional fuel mandated the efficient utilization of renewable forms of energy [1],[2]. Simultaneously, the fulfilment of energy demand for the increasing population is a gigantic global challenge. Figure 1.1 shows the trends of world energy and electricity demand along with the global CO_2 emission over the different periods. The trends in the figure clearly states that electricity has always been a key factor behind promoting developments in almost all facets of social sector. Furthermore, as outlined in the 2019 energy access report by the world bank, approximately one out of every seven individuals worldwide still does not have electricity access, predominantly in rural regions [3]. Besides, concerning access to electricity to increase economic development and productivity, 14% of the world's population still lacks electricity (around 1.06 billion people), of which approximately 239 million people belong to India [4]. Thus, in order to meet exploratory energy demand and successively pollution mitigation, several alternate resources are being identified worldwide. The most popular renewable energy (RE) sources include solar, wind, hydro, bioenergy, ocean energy, and geothermal. In 2021, RE accounted for about 29% of electricity generation, and further, it needs to be increased to target net zero emission by 2050, as its present percentage is very low to achieve [5]. In this context, biomass could be a promising renewable form of energy to solve a great extent of energy demand because it is abundant in availability and is a better prospect for environmentally friendly. The source of biomass is forests as India is the 9th rank to possess approximately 28.3% of forest land cover (about 68,434,000 ha land) and holds around 2800 million metric tonnes of carbon as forest biomass (India State of forest report, 2019) [6]. Moreover, the current availability of biomass in India is estimated about 500 million metric tonnes per year. Ministry of New and Renewable Energy has estimated surplus biomass availability at about 120 – 150 million metric tonnes per annum covering agricultural and forestry residues corresponding to a potential of about 17,000 MW. This apart, about 5000 MW additional power could be generated through bagasse-based cogeneration in the country’s 550 Sugar mills. However, the major challenges in RE application are operational issues like voltage fluctuation, power quality, frequency stability, resource selection, location, and social disputes, etc. However, it can be resolved by energy-efficient technology innovation and diversity, supply reliability, cost-effective price, market-sensitive intervention, public trust, etc [3]. Therefore, the present study focuses on the bioenergy RE sector to resolve issues like operational management, resource identification, and supply reliability for power sustainably through thermochemical-based gasification with engine integration technology for electricity/power generation. Therefore, the motivation of this study is to emphasise the use of alternative fuels in order to conserve conventional fuel and increase efficiency by utilising improved technologies and optimal operating conditions. In light of the aforementioned facts about the energy crisis and environmental safety, biomass-coal based producer gas into ICE (internal combustion engine) is one of the potential alternative gaseous fuels that may be used to produce power and to reduce global warming.

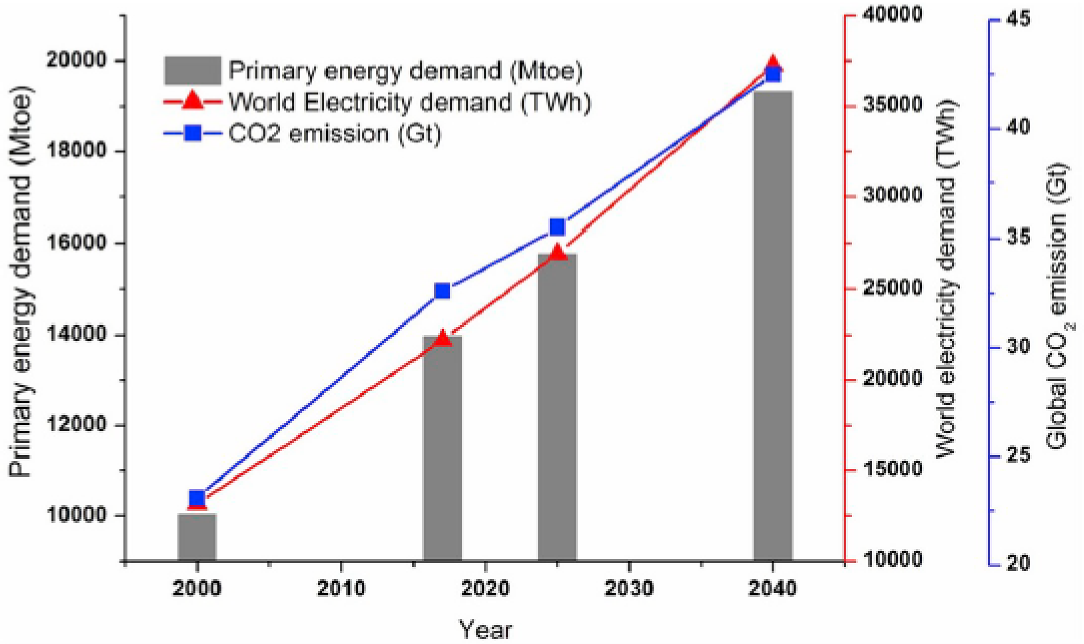

Figure 1.1. Trends of energy demand, electricity demand and CO_2 emission with years [7].

1.2 Biomass to fuel conversion technology

Biomass is the oldest source of energy and currently accounts for approximately 10% of total primary energy consumption. Many of the developing countries has growing their interest in biofuel development and providing greater access to clean liquid fuels while helping to address the issues such as increase in fuel price, energy security and global warming concerns associated with petroleum fuels. Abundant biomass is available throughout the world which can be converted into useful energy. Biomass is considered as a better source of energy because it offers energy security, rural employability and reduced greenhouse gas emission. Biomass is traditionally available in the form of solid. Solid biomass includes crops residues, forest waste, animal waste, municipal waste, food waste, plant waste and vegetable seeds. This biomass can be converted into heat and power by adopting appropriate method/technology. There are many methods to transform biomass into advantageous products having higher heating value. Figure

1.2 shows the conversion routes of biomass/ waste material, or industrial wastes to get various different possible liquid and gaseous fuel outputs. Wide variety of conversion technologies is available for the production of premium fuels from biomass. Conversion process generally depends on the physical condition of biomass and the economics of competing process.

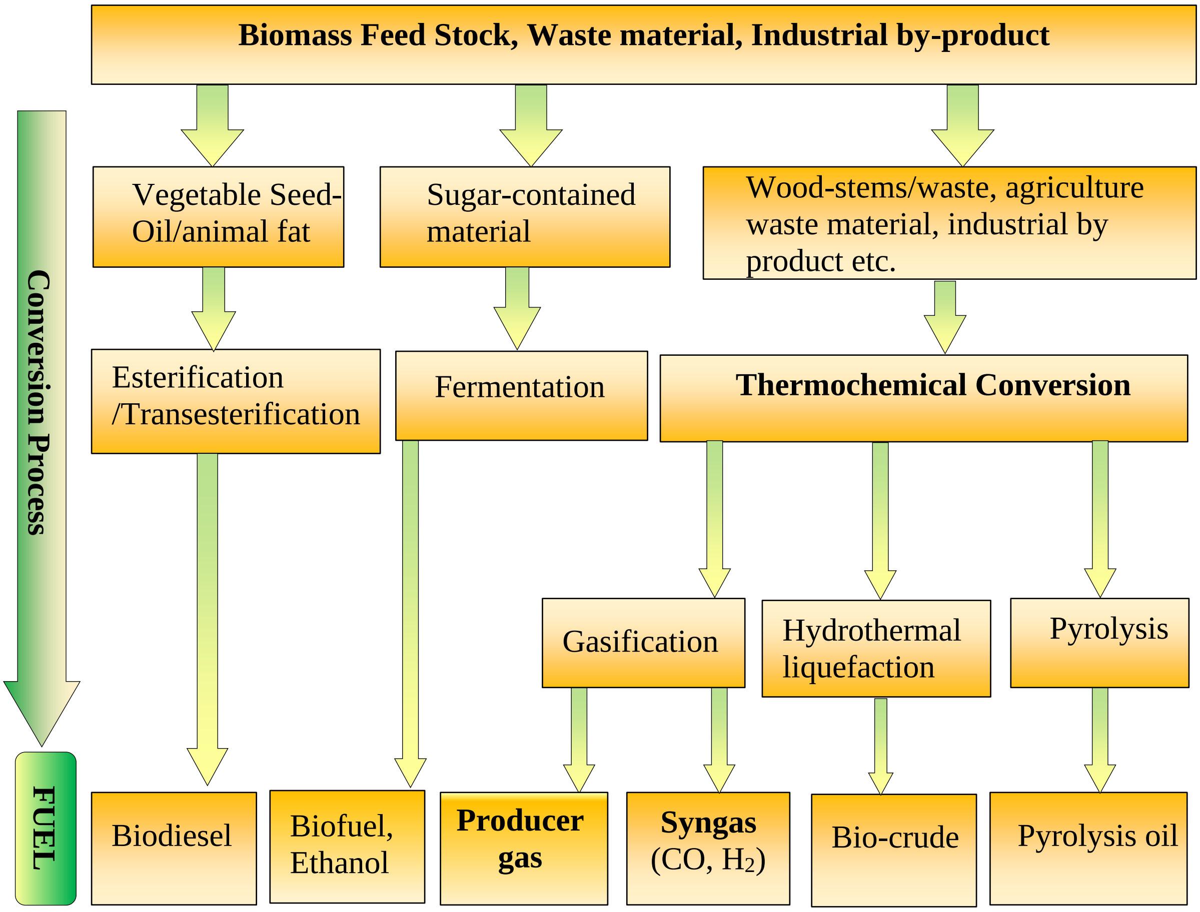

Figure 1.2. Biomass to fuel conversion routes

Regarding the aforementioned views and facts, numerous researchers are currently exploring to increase the yield of bioenergy through biomass conversion, as biomass availability is abundant and provides a better promise for ecologically friendly. It is reported that worldwide around 170 billion metric tons biomass produced annually, only 10 % of forest and agriculture residues are used for bioethanol production (233 billion litre), and in India approximately 400 million tonnes waste produces annually from agriculture activity [8],[9]. Moreover, it is possible to generate useful magnitude of energy from waste material like forest residue, agriculture residues, liquid waste, municipal solid waste, animal residue, farm residue, industrial waste, and sewage [9]. In order to utilize biomass waste easy to handle, the thermochemical process is an efficient technology for converting gaseous, liquid, and charcoal fuel components. Other biomass conversion route involves biomass combustion that leads to burning biomass directly to produce heat or electricity. The main products of combustion are heat, CO_2, water vapor, and ash. Pyrolysis of biomass can be a source of biochar, bio-oil liquid fuels [10]. Biomass gasification involves the partial oxidation of biomass to produce producer gas, distinguishing it from other biomass conversion techniques (like- combustion and pyrolysis) in terms of end products, oxygen presence, temperature, pressure, and applications. Moreover, among pyrolysis and gasification thermochemical processes, gasification has better biomass conversion efficiency [11]. Generally, biomass gasification carried out at high temperatures range (i.e., autothermal of 700–1200 ^{o}C temperature), comprises of drying zone (<200 °C), thermal decomposition or pyrolysis zone (200−500 °C), reduction zone (650−900 °C), and partial oxidation/combustion (800−1200 °C) [12]. Gasification takes place in a gasifier in the presence of limited gasification agents (air, O_2, steam, CO_2 and its mixture), and produces primarily PG, with tar and char as byproducts. The typical thermochemical properties of PG from air gasification has been reported as H_2 (13–19%), CO (18–22%), CH_4 (1–5%), CO_2 (9–12%), N_2 (45–55%), HC (0.2–0.4%) and calorific value (CV) 4–7 MJ/m^3 [13],[14],[15]. Since gasification is a partial oxidation reaction, factors such as biomass type and feeding size, mixture of feedstock materials, feed rate, mode of reaction agents, type of gasifier and design, and gasification equivalence ratio (GER) have a significant impact on the yield of gas produced as well as its CV and hydrogen content. [16], [17],[18]. Although, biomass is the fourth significant source after coal, petroleum and natural gas, but, due to inherent qualities of biomass such as high moisture content, low CV despite high hydrogen content, hygroscopic nature, and low density, pose challenges in transportation, storage, and preparation for gasification [19].

Nonetheless, gasification of any particular biomass presents challenges, like supply disruption owing to seasonal effects, dispersed distribution, and transportation expenses, and so far there is lack of developed market for biomass conversion to energy [20]. Therefore, coal, which has a higher CV, has been recognized for dual feedstock co-gasification with biomass. There are several merits and demerits in co-gasification. The comparison between sole gasification and co-gasification is shown in Table 1.1. The table depicts that there is significant lucrative while co-gasification is applied. Most research has identified that co-gasification is more beneficial than its application regarding dual feedstock gasification. Co-gasification could be helpful when non-availability issues of feedstock appear during individual gasification. Apart from these primary advantages and disadvantages, the performance of co-gasification is influenced by several factors, including the type and size of biomass feedstock, the coal biomass mixing ratio, the gasification medium, reactor design, and operational parameters [28]. It was reported that variation in coal and biomass properties strongly influences the yield of gaseous products and their quality in co-gasification [29], [30].

Table 1.1. Comparison of coal, biomass, and co-gasification.

Particular	**Gasification of Coal**	**Gasification of Biomass**	**Dual feedstock/ Co-gasification**	**Reference**
Remark	Non-renewable	Renewable	Sustainability and less reliance on fossil fuels	[21], [22]
Availability	Declining	Seasonal	Profitable	[21]
Operating cost	High	Reasonable	Low	[19]
Agglomeration, fused-ash slagging	Appears	No	Very less	[20]
Atmosphere pollution	More	less	Reduces CO_2, NOx, SOx, and volatile organic compounds	[21], [22],[23]

Particular	Gasification of Coal	Gasification of Biomass	Dual feedstock/ Co-gasification	Reference
Reactivity	Less	More	Less reaction time	[21], [23], [19]
Carbon conversion efficiency	Less	More	Increases	[21], [22],[23]
Gasification temperature	High	low	Lowers, Reasonable	[21], [22], [19]
Heating value (MJ/kg)	More	less	Enhances	[23],[19]
Gas Yield	less	More	Improves	[21], [23]
Tar formation	low	High	Less	[21], [23]
Char formation	Yes	No	Less	[21]

1.3 Literature Review

A brief review of existing literature on both the experimental and modelling work has been described. Complete literature survey has been categorised in the four subsections wherein first subsection depicts different types of biomass gasification taken for the investigation. Second subsection denotes the advantages of co-gasification taken for the experiment. Third subsection depicts the techno-economic analysis of waste biomass for the value-addition of biomasses in terms of briquette making plants for the gasification. Fourth subsection depicts the relevant research findings of utilizing producer gas from gasification units as an alternative fuel in engine applications. These research findings are the main novelty of the research work.

1.3.1 Works on gasification

The literature contains a wealth of review articles discussing gasification, particularly examining the impacts of coal, or biomass as feed materials in the gasification process. Studies have found that coconut shells can be effectively used to produce producer gas in a downdraft gasifier. In a study by Yahaya et al. [24], it was determined that the composition of the gas produced from coconut shell gasification included H_2 (8.20–14.6 % by volume), CO (13.0–17.4% by volume), CO_2 (14.7–16.7 % by volume), CH_4 (2.82–4.23 % by volume), and had a CV ranging from 4.01-5.39 MJ/Nm^3. In their experiments, Kim et al. [25] found that steam-based coal gasification resulted in a higher CV of 13.0-15.2 MJ/m^3 compared to air gasification, which yielded 6.3-10.6 MJ/m^3. This difference was attributed to an increase in hydrogen concentration in steam-based gasification. In a more recent study by Paul et al.[26], fluidized bed gasification at 950°C with a coal feed rate of 15 kg/h, an air to coal ratio of 1.5, and a steam to coal ratio of 0.2 produced gas with typical composition including H_2 (15-20%), CO (15-20%), CO_2 (10-12%), CH_4 (1-2%), and balanced N_2. Elita et al. [15] intensively reviewed and showed that the gasification of briquette non-woody waste offers promising alternative fuel sources for generating electric power and heat. Similarly, Saracoglu et al.[27] emphasized with an intensive SWOT analysis that wood briquettes will be tomorrow's fuel of Europe. Nerijus et al. [28] experimented with converting different types of briquette waste to gasification fuel. They revealed that the 2.06-3.11 Nm^3/kg gas yield of PG could be generated with a CV of 6.5-4.04 MJ/Nm^3. Dasappa et al. [29] studied the six types of agro-residues briquettes to gasification product and calorific value, as H_2 (17-88) vol%, CO (15-18) vol%, CO_2 (12-17) vol%, CH_4 (0.5-3) vol%, and 3.00-4.5 MJ/Nm^3 respectively. Indrawan et al. [30] experimented on the gasifier-IC engine using municipal solid waste (MSW) and agriculture waste and revealed that engine CO, CO_2, and NOx emissions were reduced, whereas SO_2 and HC emissions were raised while municipal solid waste fraction and load increased.

Moreover, the downdraft gasifier (DDG) offers a simple design, fabrication, and easily controllable operations [6]. Air as a reactive agent is fed into the oxidation zone by a nozzle located a certain distance above the grade level in an air-based DDG system. As gasification is based on partial oxidation thermochemical process, the magnitude of air supply and, subsequently, air-fuel equivalence ratio strongly influences the heating value of PG, its composition, temperature elevation, and generation of tar and char. The effective GER values lies within 0.2-0.4, rich mixture than stoichiometric combustion [31], [32], [33]. However, the optimum air-fuel equivalence ratio varies with types of feedstock gasification such as: 0.25 GER for wood coconut fibres pellet [34], 0.12 GER for low grade coal to IC engine [35], 0.21 ER for poultry litter at high gas yield [36], and in terms of excess air-fuel ratio (AFR) 0.63 for rice husk and 0.3 for rice husk pellet to higher CV [37]. Thus, the optimum GER depends on types of feedstocks and varies with target performance parameters like tar reduction, yield value, calorific value, composition, etc. Nevertheless, the number of review articles specifically addressing the utilization of feed material in combination with coal and biomass for co-gasification is currently limited.

1.3.2 Works on Co-gasification

Besides the comparative investigations (Table 1.1), several research investigations have been carried out regarding co-gasification as- sawdust and bituminous coal [17], rice husk and coal [18], coconut shells and sugarcane bagasse (SB) [19], sewage sludge and pine sawdust [20], poly-ethylene wastes and biomass [21],[22], refuse-derived fuels and bituminous coal [23], biomass and plastic wastes in fluidized bed reactor [24], Sanitary napkin with sawdust biomass [25], high-sodium coal and sewage sludge [26], sewage sludge and waste tire char [27], pellets of hens manure and wheat straw [28]. Ramos et al. [29] did a literature review and revealed some significant as- heating value of biomass/gasification has a negative relation with moisture content, increasing gasification temperature (700-900 ^{o}C) increases H_2 and CO species and lowers tar, longer residence time leads to an increase H_2, CO_2 and carbon conversion efficiency-gasification has a synergistic effect on thermochemical characteristics and conversion rate when compared to individual gasification. Inayat et al. [13] reported from a review that co-gasification reduces the seasonal availability problems with different combinations of feed material, and provides additional degree of compositional excellent by varying the fuel blend ratios. Kamble et al. [12] reported that, 50% blend of coal and biomass by weight provides lower activation energy than other blend, resulting in less quantity of gasification agents like air or oxygen. The most appropriate GER was found to be between 0.2-0.4 [30] [33]. Muhammad Awais et al. [38] experimented with the co-gasification of woodchips + corncobs, sugarcane bagasse + corncobs, and sugarcane bagasse + coconut shells (SB+CS). They observed that it has the potential for gasification to electric power generation, and (SB+CS) gasification results of CO and H_2 yield of 19.3-12.3 %, respectively. Thengane et al. [22] conducted an experiment on high ash biomass (garden waste pellets) to coal ratio gasification and reported that of 0.75 biomass ratio provides optimum CV and gasification efficiency (57.5 %). Mansur et al. [39] experimented with co-gasification of raw biomass and pre-treated biomass with coal and observed optimum H_2/CO ratio (1.58) and HHV syngas (6.072 MJ/Nm^3) at high GER (0.3). Basha et al. [40] performed air electrically heated co-gasification of palm kernel shell (PKS) and polystyrene plastic (PS) and found that CO and H_2 increase up to 900^0C temperature than decrease. As the PS blend increases, CO and H_2 gas percentage decreases in the produced gas at GER 0.27. Similarly, Barontini et al. [41] experimentally investigated the co-gasification of woodchips with sewage sludge, woodchips with organic fraction of municipal solid waste, and woodchips with hazelnut shells obtained LHV higher than 5.18-5.83 MJ/Nm^3. Moreover, they acknowledged that information on biomass and waste co-gasification is insufficient and requires further investigation of the characterization and conversion method [41]. Mallick et al. [42] have comprehensively reviewed the synergistic behaviour of several types of coal and biomasses gasification and suggested: that coal has low hydrogen and oxygen content, but high carbon promotes CO content in PG, silica content in coal efficiently cracks the heavy hydrocarbon molecules of biomass leads to increase H_2 content, resulting calorific value increases. However, PG composition varies due to governing factors such as temperature, heating rate, and individual composition feed materials. Table 1.2 depicts the effect of biomass in coal.

Table 1.2. Effect of biomass-coal based co-gasification.

Parameter	Feed-material	Gasifier-type	Remarks	References
General benefit	Coal, woody biomass, Plastic wastes, RDF, MSW	-Fixed bed -Fluidised bed gasifier	-Reduction in fossil fuel dependency, sustainability	[21], [22]
H_2	- Dealcoholized grape marc + coal	- Entrained flow gasifier - Fluidised Bed reactor	- Increase - Decrease	[43] [44]
CO	- Puertollano Coal + Pine - Dealcoholized grape marc + coal	- Entrained flow gasifier - Fluidised Bed reactor	- Increase	[43, 45]
CO_2	- Black Coal + Pine chips - Coal + Pine+ Bagasse - Pine chips +Black coal & Sabero coal	- Fluidised Bed reactor	- Increase - Decrease	[44] [45]
Tar content	- Coal + olive stones + chestnut - Bagasse + Colombian coal	- Fixed bed reactor	- Increase - Decrease	[21] [46]
Calorific value	- Coal + Wheat straw - Plastic + Coal + Biomass	- Entrained flow gasifier - Fluidised Bed reactor	-Decrease -Increase	[21, 47] [23, 48],[19]
CGE	- Mulia coal + Japanese cedar - Coal + Pine chips	- Downdraft gasifier - Fluidised Bed reactor	- Increase	[21],[45]
Yield	- Almond shells + olive stones + Eucalyptus	- Downdraft gasifier	- Increase	[21], [23, 49]
Carbon conversion	- Coal + Eucalyptus - Coal + Almond Shells	- Downdraft gasifier	- Increase	[49] [21], [23] [22]
Gasification Temperature	- Bituminous coal + olive stone + chestnut tree residue	- Fixed bed	- High	[21], [22]
Residence time	-Fabric fiber +wood chips + plastics -Sawdust, rice, or coffee husk + coal	- Updraft reactor - Fluidised Bed reactor	- Increase	[50, 51]

1.3.3 Economic viability of waste biomass

Biomass is a promising renewable form of energy. Biomass waste is derived from trees, crops and forestry operations; organic wastes; agro-industrial waste generated by wood conversion and paper industries; as well as household wastes [52],[53]. Among these, SB has been identified as a suitable renewable energy source [54]. Wood-based industries produce a massive quantity of saw-dust and discard it as waste material; eventually, it poses a threat to the environment. Moreover, considerable amounts of biomass and residues are usually discarded due to lower calorific value (CV). In this regard, blending with multiple biomass in a briquette form using an appropriate binder could be considered commendable for increasing energy density. Literature reveals that biomass briquette is formed by compressing biomass (compression strength of 121-305 MPa through mechanical piston and briquette presses or some screw extruders, density increases to range of 1200-1400 kg/m^3), which increases energy density (16-52 MJ/kg), durability, and combustion efficiency [55],[56],[15]. Furthermore, some researchers and industries are utilizing it as a source of energy or as a raw material for manufacturing, like particleboard, fine board, etc.[57]. As per the availability of biomass and residues, wood briquettes are being used as blending in co-firing power generation in Europe, North America, and Asia [58]. For India, Pallav & Vaibhav Chaturvedi [58] reported that growth in net residue availability for biomass briquette will be from 227 Mt (in 2010/11) to 281 Mt (in 2030/31). Beside unutilization of baggase, in the sugar mill, residual SB have an application in pulp and paper mills, where SB pith is a by product [59], [60]. In Egypt, the Bagasse pith is the leading waste by-product of the sugarcane industry that is available in large quantities at no cost [61]. Zanatta et al. [62] experimented and found a 16.103 MJ/kg HHV of SB, and Madlala et al. [63] reported that SB pith possesses energy contents of 15.74 MJ/kg. The SB or SB pith exists in the loosed energy density form, which creates difficulties in transporting, storing, and utilization. Thus, through the densification techniques, problems like biomass's handling, storing, and transportability can be improved efficiently [64]. Basically, briquetting is a high pressure compaction process for increasing the density of loosed biomass by mechanical, hydraulic, or a roller press type briquetting technique [65]. Briquetting requires compression in the range of 110-140 MPa, and during compression the temperature rises which melts the lignin content of biomass, that acts as binder to produce the final form of solid, stable fuel briquette [65],[56]. Usually, the bulk density of SB possesses approximately 68 kg/m^3 [15]. Anukam et al. [65] reported that densification through the screw press method reduced moisture content from 8-4%, bulk density increased from 200-1400 kg/m^3, and CV improved from 17.8-19.53 MJ/kg.

Further in the utilization phase, the briquette can be effectively used in rural and urban localities for domestic cookstoves, residential heating, steam generation, co-generation, gasification, and pyrolysis [56]. So far, finalizing the utilization aspect and initiation of small-scale industry, stable and profitable briquettes production must be ensured, particularly in developing nations due to their insecure economic condition. To identify the feasibility aspect, the positivity of net present value (NPV) and profitability index (PI) plays a significant role in the projection. Several authors have performed the economic viability of producing briquettes from biomass in the literature, with positive NPV and PI results. For example, studies in China and Poland found that using materials such as corn stalk, virginia mallow, willow, pine sawdust, and rape straw can lead to positive NPV of $1.5 million and briquette production costs ranging from 66.55 to 137.87 euro per ton. Researchers in China, led by Cheng Feng [66], conducted an economic analysis of producing briquettes from agricultural residues in an urban area over a span of 10 years. Through the use of sensitivity analysis, the study demonstrated that the production of briquettes can indeed be financially feasible. Additionally, the payback period for these investments was between 4.4 and 3.42 years, suggesting that these investments can be financially beneficial in the long run [67, 68]. Ifa et al. [69] performed the economic viability of cashew nut-shell briquette with an NPV of USD 147,402/year. Studies in Ghana performed sawdust briquette production with an NPV of GH¢ 4,724,130 and PI of 3.025, which is a positive indicator [70]. Sahoo et al. [71] performed a techno-economic analysis of portable briquette systems and found that utilizing forest residues to create valuable products could be economically viable, considering current market prices. Besides the briquetting of sugarcane baggase pith (SBP), as SBP root is biomass, a carbonaceous material, Hence, it can be converted to either liquid or gaseous fuel. Biochemical and thermochemical processes are the most efficient methods for transforming biomass residues into fuel. Even so, thermochemical-based gasification is the most flexible technique to produce clean energy because it has certain advantages, such as the complete biomass utilization, flexibility in feedstock choice, faster kinetics, and improved overall efficiency [72], [73]. Elita et al.[15] conducted a review and reported that gasifying non-woody waste briquettes could produce promising alternative fuel sources for generating both heat and electric power. Nerijus et al. [28] conducted experiments involving various types of waste briquettes gasification. Their findings revealed that the PG quality ranged from 2.06-3.11 Nm^3/kg gas yield, accompanied by lower CV ranging from 4.04-6.5 MJ/Nm^3. Moreover, Percy et al. [74] reported on the performance of a dual-fuel engine operated with different feedstock and compared NPV, payback period of gasification-diesel engine set. In his study on diesel-rubber shell PG, a NPV of Rs. 3,90,000 with payback period of 2.9 years was obtained. Similar study on diesel-PG set, a NPV of Rs. 2,80,000 with payback period of 6.4 years was observed [74].

1.3.4 Producer gas as a fuel in engine applications

Various factors impact the quality of producer gas, including biomass type and size, agent (steam, air, oxygen), gasifier type (downdraft, updraft, bubbling, fluidized, etc.), and AFR [16]. Biomass gasification provides a sustainable alternative to fossil fuels for power generation in IC engines. In terms of electric power generation driven by an ICE, besides the requirement of heating value and high H_2/CO ratio, tar content in PG should not be higher than 0.1 g/Nm^3 [75],[76], [77]. It is reported that downdraft gasifier is very suitable for the engine-electricity application because its PG contains tar quantity around 0.01-0.5 g/Nm^3, which is lower than updraft (30–150 g/Nm^3), counter current fixed bed (10–30 g/Nm^3), bubbling fluidized bed (1.5–10 g/Nm^3) and circulating fluidized-bed (5–50 g/Nm^3) [77]. However, tar produced from biomass gasification may lead to engine fouling and thus it requires additional cleaning and filtration systems before in engine applications. The review concludes with several authors, that coupling gasification with ICE successfully saves conventional fuel by 60-80% dual-fuel mode. Biomass gasification for IC engine applications offers several advantages, including the use of a renewable resource, reduced emissions, and potential for waste utilization. However, challenges such as feedstock variability, tar and particulate matter formation, and the need for gas cleanup and respective engine adaptation must be addressed to ensure reliable and economically viable operation. Because, performance of ICE significantly depends on PG composition, CV and tar presence. In attribution to the PG fuelled diesel engine, a significant diesel saving (DS) was obtained, for example, 26.47% from rice husk PG, 27.15% from coconut PG and 49.95% DS from rubber shell PG with 15.38 % to 19.44% BTE [78], 56% DS from redgram stalk PG [79], 45.7% at compression ratio (CR) 18 by SB and carpentry waste-PG [80], 64.3% at CR 18 by wheat-paddy PG [81], 49.05% at 18 CR by low-grade coal-PG [35], and 59.04% DS from biomass PG of 6.57 MJ/Nm^3 CV [82]. From these data, it could be observed that diesel saving highly depends on PG calorific value, biomass type, and engine operating condition such as CR, load, blend ratio etc. Furthermore, in terms of PG-fueled diesel engine performance in relation to gasifier-engine operating settings, trade-off characteristics have been observed between power-emission-fuel consumption. For example: while an engine's load and CR rise, BTE rises as well, but NOx emission also rises, which is undesirable [78], in addition, with PG-diesel duel fuel mode, both power and BTE decreases due to lower CV and increment in delay period interval, and NO_X reduces due to lower temperature elevation [78], [83]. Singh et al. [80] reported, brake power and BTE lowers by 16.67% and 24.56%, respectively, when the SB and carpentry waste PG-Diesel engine was running, but the advantage of 69.5% reduction in NOx. Regarding CO_2 and HC emission, PG-diesel mode engine release 65.8% and 24.6% more CO_2 and HC than neat diesel mode, respectively [84]. In terms of load variation during wallnut shell PG-diesel fueled, CO emission initially reduces to a specific level, then increases with load increment, and further decreases with CR, however its value is lower than neat diesel [85]. Moreover, the engine can be operated with minimum engine modifications; except for NOx and soot emissions, HC, CO emissions, and specific fuel consumption are more at part load condition [86],[87],[88],[89]. However, the gasification and ICE performance differ from other research work since their experimental procedure and operation variables differ.

Besides engine power-emission-fuel consumption parameters, engine noise is one of the most significant environmental issues. It contributes to around 40% of city environmental noise, which distresses comfort and human health and depends on fuel blend and combustion [90]. The noise generation during combustion is influenced by the rate of maximum pressure rise, which increases with pressure rise and short combustion duration, and elongated ignition delay at the first phase of combustion [91]. Moreover, blending in diesel fuel and improving cetane number and fuel oxygen content reduces sound levels [92]. So far, the parametric study of diesel with producer gas duel fuelled engine noise is inadequate. Lal et al. [81] observed a sound level variation of 81–89 db for diesel to 80.9–89.6 db for dual fuel mode at 3.2 kW. Sharma et al. [85] observed that the CI engine sound level at 18 CR reduced from 102.7 db to 99.84 db when the CI engine was run by neat diesel to dual mode (PG+ diesel).

Concerning SI engines, operating parameters such as blending ratio, CR, equivalence ratio and spark timing play a major role in the combustion, emission, fuel consumption, and power generation [93]. The blending ratio controls the blended form of calorific value for combustion, eventually heat release rate, rate of pressure rise, temperature rise, and emission formation. The Equivalence ratio significantly controls the thermal efficiency, power, and emission [94]. CR increment increases engine efficiency, and promotes temperature increment, however, it limits by knocking and NO emission. Spark timing controls the peak pressure and temperature of the inside cylinder, advancing of spark timing leads to a higher temperature for NO formation, over advance and retard reduces the brake torque of an engine. Therefore, optimum spark timing will be required for higher power, however, to reduce higher emission at optimum spark timing, little retarding is preferred from maximum brake-torque condition with bearing reduced power level [95]. Concerning the PG-based AFR in an engine, Gobbato et al. reported that more than 1.3 relative AFR decreases the flame speed and thus the fuel conversion efficiency [96]. Concerning PG blend with propane, Tsiakmakis et al. [97] introduced gasification of olive, grape, and peach kernels biomass, and suggested that due to the presence of N_2 and CO_2 in PG, CV reduces, and low pressure-temperature rise in cylinder contribute to low NO formation in SI engine. Babu et al. [98] experimented on bottle-based PG and suggested that enrichment of hydrogen significantly influences combustion, and reduces gaseous fuel consumption, however, CO and NO emission predominates. Thus, in view of the trade-off magnitude among the power, emission, and specific fuel consumption with respect to the input variable, it is mandatory to set the optimum input variable for the best performance and low emission of an SI engine. Most of the literature [37],[99],[100],[101],[102], intensively worked on gasifier-IC engine application and revealed the benefit, but, they have lacking to suggest cumulative optimum input variables to an engine for enhanced performance and low emission engine run. Yusri et al. [103] reported that the optimal balance between engine performance and exhaust emissions is one of the major challenges in automotive technology. Concerning these issues, it was found in the literature that the application of peach-based PG with propane blend in SI engine is not seen with a comprehensive approach to the optimization level. The peach (Prunus persica) is a deciduous tree. Worldwide, Peach-tree cultivation occurs in an area of around 1.54 million hectares, produces approximately 20-22 million tonnes of peach fruit [104], [105], thus its waste biomass could be one of the energy resources.

1.3.5 Parametric optimization of gasifier-engine system

Since there is a trade-off between gasifier-engine performance and emissions, so there is an utmost need of optimum responses corresponding to optimum input settings. Regarding previous work on optimization, Yusri et al. [106] concluded that artificial neural network (ANN) and RSM are better techniques for building the relationship between the output and input variables of SI and CI engine and optimizing. Although, the RSM model has been considered a better performance technique than the ANN approach [107]. RSM, leverages detailed statistics, modeling, and optimization to address various factors in large data set responses. Its popularity stems from its high accuracy and sensitivity, enabling a quick process completion by minimizing data sets. RSM also offers a suitable matrix for testing [107], [108], [109]. Regarding optimization tool as RSM, it was revealed in the literature that it is most compatible with engine applications and is popular due to its capability of high-level accuracy and sensitiveness to reach the collective results with less time and generate a suitable matrix for tests [106],[107],[110],[109]. Considerable works have been performed in the area of ICE performance optimization [111],[112],[113],[114], but few are from the gasification field [115]. Nonetheless, no research into the optimization of input parameters of coal- biomass gasification based PG with diesel mix engine performance response has been discovered in the literature. Moreover, the recent progress in optimization with gasification-engine application and the associated gap for the present work are shown in chapter 4.

In respect to above literature review, CI engines have been employed with producer gas, which is generated from a variety of feedstocks utilizing both solo and co-gasification. It can be seen that gasifier engine performance varies with feedstock type, its blending ratio, the calorific value of feed material, and the quality of PG. Moreover, there are a number of other types of biomasses that are also available in rural areas, and their waste-to-energy conversion and utilization are still lacking, and their versatility in terms of reports is still limited. It was discussed above that scarcity of feedstock availability due to a seasonal boundary can be solved mainly by co-gasification. Therefore, to determine the viability of effective utilization and wider applications, the performance of the gasifier-engine integration system must be studied in relation to the newly identified feedstock at various load conditions and with variable operating conditions. Simultaneously, it must be a comparative assessment and analysis of the optimum operating setting to obtain the optimal results in terms of power output and emissions.

1.4 Research gap

After conducting an extensive review of the existing literature, it has become evident that no previous authors have reached a conclusion regarding the combined impact of engine input variables on both performance and emissions. Therefore, there is a critical need to investigate the utilization of low-grade coal and biomass-gasified producer gas in conjunction with an IC engine to determine the optimal engine input parameters that can enhance engine performance and efficiency. This is particularly important because if a blended form of chemical energy is utilized for power generation in an engine without the optimization of its operating parameters, it can lead to reduced power output, increased fuel consumption, and higher emissions. In light of these considerations, the current thesis aims to address the following research gap-

- So far as the literature gap is concerned, it can also be deduced that the majority of prior research focused solely on examining the conventional operating parameters' influence on gasifier performance during gasification. Additionally, there is a paucity of information on the comparison of different feedstock in terms of purely and co-gasification comparison on a similar platform.
- No previous research has attempted a comparison of the sole and co-gasification performance of feedstocks like, coal-mahua-coconut shell-briquette and its blends in the

same gasifier-engine experimental setup. So far as sole feedstock and dual feedstock co-gasification coupled engine performance is concerned, due to composition and heating value variation, there will definitely be variations in power generation and trade-offs among power, efficiency, and emission parameters. Therefore, to achieve the best performance response, its operating variables must be optimized. There is an utmost need to determine the optimum operating parameters within which the gasifier and engine should run to achieve the enriched PG output with less engine emissions.

- Based on the reviews mentioned earlier and as far as the author's knowledge, there is no previous study available in the literature concerning the economic analysis of briquettes production from sugarcane bagasse pith, and subsequently, its applications for heating and power generation. In addition, very little literature has been addressed on briquette-based gasification and its PG utilization in the diesel engine.

1.5 Research aims and objectives

Considering the problem statement and the gap in existing research regarding an effective method for converting waste biomass into energy, it is evident that there has been limited investigation in the literature specifically focusing on the utilization of gas produced by gasifying biomass and low-grade coal, integrating it with a diesel-fuelled CI engine, and analyzing engine performance and emissions. To address this deficiency, the current Ph.D. thesis aims to fill this evident research gap. Thus, taking into account the literature review, and research gap, the following research objectives have been established for this Ph.D. study-

- The first objective of this study is to promote the waste-to-fuel conversion by utilization of available feedstocks (mahua tree, coconut shell, sawdust briquette, and blends with low-grade coal) for sustainable decentralized power generation.

- Experimental research involving a downdraft gasifier utilizing various biomass blends and subject to changing operational conditions in conjunction with a dual fuel ICE.
- To investigate the comparative assessment of gasifier-engine performance in terms of gasification efficiency, engine power, diesel saving, and emission with sole feedstock gasification and dual-triple feedstock co-gasification.
- To predict the optimum gasification-engine input parameters and optimum output responses for maximizing engine power, and minimizing engine emission and fuel consumption using the multi-objective RSM.
- To compare the optimization outcomes of the gasifier-engine operating settings for the best power and emission-balanced performance in the single and co-gasification modes utilizing the RSM optimizer tool.
- Comparative analysis of engine performance and emission with diesel to DF run CI engine.
- To study the economic viability of the small-scale briquette manufacturing plant in order to promote waste-to-fuel conversion through sugarcane bagasse pith briquette, and further to determine the experimental-based briquette gasification with engine-integrated performance, exhaust emission, sound levels, and diesel savings.

This thesis work supports the viability of biomass, and coal gasification/co-gasification for PG generation and simultaneous use in CI engine 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 coal/biomass-derived PG. Hence, this study will be a substantial reference platform for end-users and researchers with respect to economic analysis and valorization of waste biomass and subsequent gasification/co-gasification for engine applications. Further, this study will also 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.

1.6 Outline of the Thesis

Figure 1.3 shows a master chart presenting the work details of subsequent chapters of Ph.D. thesis. Moreover, the outlines of the current Ph.D. thesis work are as follows-

Chapter 1 Introduction. This chapter presented the background and motivation for investigating the performance, and optimization of gasification integrated internal combustion engine. In addition, a literature review was conducted. Furthermore, the research gap with aims and objectives of the study were stated. Finally, the outlines of the thesis were mentioned.

Chapter 2 State of the Art of the Gasification-integrated CI engine. This chapter has provided an overview of the gasification process and its components, including a summary of the different properties of feedstocks for gasification as well as the different components of the producer gas filtration process in terms of their characteristics and their variants. Furthermore, the details of fixed bed gasifier, VCR technology with its advantages are also discussed. Moreover, the optimisation of different operating variables for best response and economic analysis of briquetting system are discussed.

Chapter 3 Materials and methodology. This chapter included a brief description of the gasification-engine system on which this study is based. This section comprises of four subsections including experimental methodology, economical methodology, numerical methodology, and the optimization methodology used for gasification-IC engine.

Chapter 4 Results and Discussion. This chapter reported and discussed the results of the experimental and numerical simulation investigations. The experimental promotes waste-to-fuel conversion through gasification technology, and subsequently its application in heating and power generation in gasification-engine system. Further, this section also employs economic viability of waste biomass briquette manufacturing plant to have its usage as a fuel in gasifier-engine system. Additionally, the simulation work deals with the comprehensive quasi-dimensional thermodynamic numerical modelling and simulation analysis of the SI engine fuelled with producer gas and propane blend.

Chapter 5 Conclusions and Future work. This chapter consolidates the overall outcome of the investigation and describes the scope of future work.

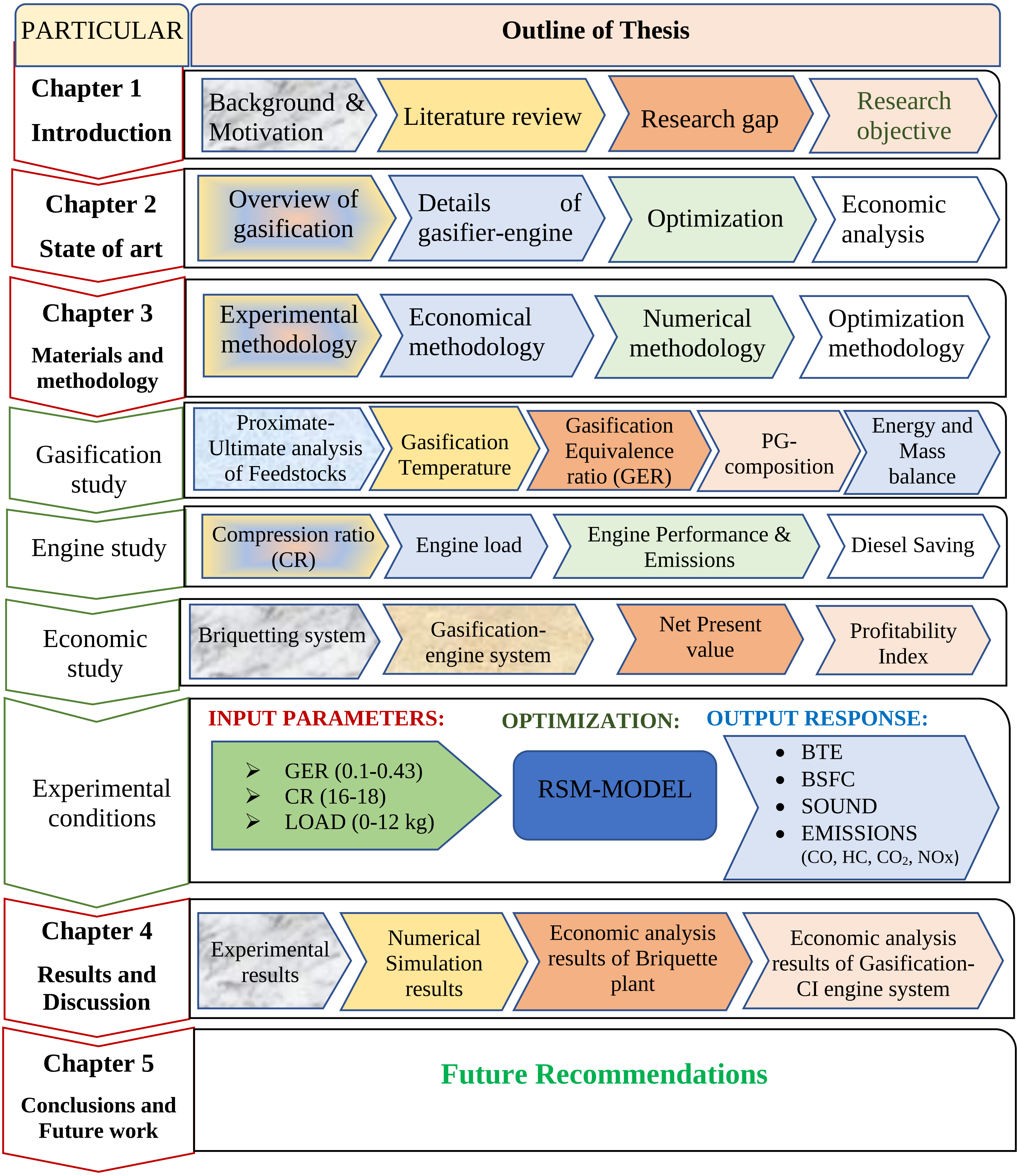

Figure 1.3. Outline of Thesis