

Chapter 1. Introduction

1.1. Background and motivation

Worldwide, one of the major environmental concerns and sources of pollution is the improper management and unsafe disposal of huge sewage sludge volumes, that get generated from the industrial, domestic, and commercial activities. The rapid rise in population, urbanization, and civil development are the significant factors contributing its generation [1]. On the other hand, the exhaustible reserves of conventional fossil fuels have already alarmed us to switch to alternative fuels either through sole or blended mode applications. Sewage sludge (SS) is a solid waste, generated majorly from industrial and municipal wastewater treatments. Its annual production rate is about 0.1-30.8 kg per population equivalent [2]. Current global SS production estimations are reportedly around 100 million tons (Mt), and is predicted to increase to 175 Mt/year by 2050 [3, 4]. However, even today, the foremost sewage sludge treatments include disposal into oceans, landfills, or incineration. Therefore, these approaches are neither environmentally friendly nor cost-effective[5]. Alternatively, SS is also detected to be a potential renewable and sustainable resource for energy production [6]. Based on the reviewed proximate and ultimate analysis reports of SS, it is found to possess as much as 11.1~ 22.1 (MJ/kg) High heating value (HHV) [4, 7]. Chen et al., studied the SS composition as: 49% volatile matter, 40.3% ash and 10.7% fixed-carbon (dry basis wt.%, proximate analysis), and about 28.4% C, 25.58% O, 5.29% H, 4.65% N with 2.66% S (dry basis wt. %, ultimate analysis) [8]. It was also suggested that SS could be effectively converted into usable liquid or gaseous fuel through thermochemical conversion routes, like pyrolysis or gasification [4]. Recently, the gasification of sewage sludge has drawn much attention due to its substantial advantages like, comprehensive destruction of pathogens and microorganisms, swift volumetric reductions, and direct industrial-scale applications like heating and electricity generation [9]. Through

gasification technology, solid wastes could be converted into useful gases and chemicals through thermo-chemical reactions using oxidizing agents like air, steam, N₂, CO₂, and O₂.

Decentralized power generation through a gasifier-engine system is an attractive alternative for achieving the power grid dependency while reducing the environmental impact. For effective sewage sludge-waste to end-use electricity generation by engine integration, this work aims to simulate and investigate the thermal efficiency and performance enhancement of SI engine by employing the various strategies to a high-Geometrical compression ratio (12.0:1) unmodified SI engine model.

1.2. Present Scenario

1.2.1. Sewage management and gasification

Sewage sludge is a component that is generated at municipal, industrial, or domestic sources [10]. It is separated from the wastewater at the sewage treatment facilities [11, 12]. Through the sewage sludge treatment facilities, not only could the wastewater be reused as potable-quality water, but also could an extensive amount of energy be extracted from the separated sludge residuals through various physical, chemical, and biological treatments[11]. Sewage wastes broadly comprise a diverse mix of substances like larger particles such as grit or sand, organic and inorganic compounds, pathogenic bacteria, heavy metals, and toxic/nontoxic pollutants [11]. Overall, these contents possess a higher calorific value and nutrient contents, thus leaving these wastes untreated surmounts to a significant loss [13]. Sewage sludge reuse is a potential solution especially in regions with limited water and fertilizer supplies [14]. In low-income nations with inadequate attention to wastewater collection and treatment, wastewater and sewage sludge are frequently utilized directly and informally [14]. For instance, untreated sewage sludge is considered a useful nutritional resource and is applied as fertilizer directly after drying [15]. In high-income states, wastewater and sewage sludge are

often processed and used in a regulated manner [16]. Most EU member nations restrict the disposal of sewage sludge in landfills. Processing sewage sludge for reuse is gradually adhering the shared attention [17]. The quality and characteristics of the generated sludge is a significant factor towards selecting the processing methodology [11].

The contents and quantity of sewage sludge produced during the treatment greatly depend upon the treatment stage, pollutants, cleaning technologies, stabilization method, mass and volume reduction, and reagents used in wastewater treatment [18]. To effectively treat the sewage sludge, a combination of mechanical, biological, physical, and chemical procedures is required due to its heterogeneous composition [11]. In general, at the municipal sewage sludge treatment facilities, initially undergoes a screening process to separate out the non-homogeneous and isotropous solid elements from the sludge, like plastic wastes. Thickening is generally the next step in the therapy [19], which is applicable for sludge with a water content of 70-95%. Thickening and dewatering both raise sludge concentration and enhance the solid qualities of residual primary sludge. Mechanical dewatering yields 20%-45% solids by weight [20]. Inclusive techniques include techniques such as applying sludge drying beds, pressure filtration, vacuum filtration, reservoir filtration, and centrifugal gravitational separation in hydro-cyclones [11, 21]. After dewatering, the residual sludge gets reduced with 50-75% water content [20]. Sludge then gets aggregated via rapid microbial development at the Clarifiers and aeration channels. A major fraction of the activated sludge is separated at the bottom of primary and secondary clarifiers, attributing to the sedimentation phenomenon. Clarifiers and aeration channels provide sufficient duration for microbial growth inside the sludge which allows a healthy and effective decomposition of the organic components [20]. A 140-Million Liters-per-Day (MLD) -rated Sewage Treatment Plant (STP) facility at Dinapur, in Varanasi, India, provided the operational statistics of a regular STP facility. The STP treated raw sewage of 85,000~115,000 m³/day, during the March 2024. With the extent of sewage treatment, the plant

was capable of producing around 5800~7000 kWh of power using 2300~2800 (Normal-m³) of biogas. Further operational aspects with regard to the 140 MLD STP have been briefed about at the appendix section of the thesis.

At 140 MLD STP, the processed and separated sludge is proceeded to stabilization and energy extraction via the action of anaerobic digestion and biogas production at the digester unit. Samples of undigested samples from the STP, both wet and dried, are presented in Figure 1.2.1-A and B, respectively. Figure 1.2.1-C presents the dried coarse residual sludge (almost for 12 days), which could also be applied for agricultural purposes as it is free of toxic constituents after stabilization [22].

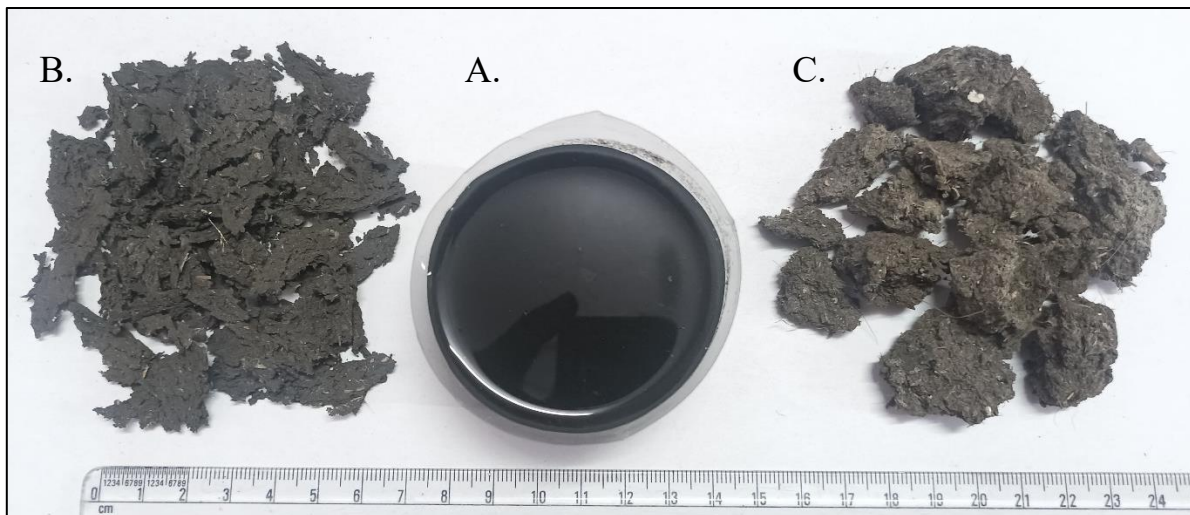


Figure 1.2.1. Dried SS-residual samples pre and post digestion

Among the various modes, methane-extraction means has been a common practice in the STP for implementing waste-to-energy conversion [11, 19]. The anaerobic digesting method is generally employed in large wastewater treatment facilities. Anaerobic digestion relies on enzyme release by microorganisms to produce dissolved organic materials, which are crucial for methanogenic bacteria to produce CO₂ and valuable methane [23]. The methane could be further treated as thermal fuel [11]. This technique also minimizes odour, eradicates infections, and detoxifies substrate. Besides this, after methane extraction via a digester, the nutrient-rich

residual is utilized for agricultural usage [20, 22]. However, the digestion process has the limitation that it cannot sufficiently extract the energy in sewage sludge.

The STP-digestate still contains considerable organic content, that has energy potential, and is also poor in biodegradability [24]. A comprehensive comparison of anaerobic strategy with the other common thermal modes of energy harvesting strategies, like incineration, pyrolysis, and the gasification have been clearly depicted in the references-[24-26]. These studies convey that the incineration is prone to release of harmful emissions, whereas the gasification could still be explored for potential energy extraction opportunities. Reviewing for the effective waste-to-energy extraction, F. Ardolino et al. [27] suggested the “syngas road” facilitates an enhanced techno-economic energy extraction capability rather than the “biogas road”. The “syngas road” applies gasification of dry or semi-dry substrate for energy extraction. The route achieves a higher carbon utilisation potential and enhanced environmental performance than the conventional “biogas road”. Biogas road of energy-extraction involves anaerobic digestion of wet substrate. Their analysis presented a significantly higher contents of H_2 , and CO , and lower CO_2 and H_2S with moderate H_2O contents in the “syngas” relative to utilization of the “biogas” road. This remains advantageous to performance improvement, emission reductions and lower knocking aspects, when used as an alternative fuel in the IC Engine application. On the other hand, they further suggested that the “syngas road” would have an economic viability alongwith a higher plant capacity (greater than 200 MW). While their investigation was based on bio-methane extraction, the scope for SSPG-based techno-economic analysis still requires future investigations. Moreover, it has also been suggested in A.H. Alaedini et al.[28] that the residual digestate after digestion is correspondingly also fit for further energy extraction via thermochemical processes like gasification, to form the producer gas. Sewage sludge digester residue might also be utilized for gasification procedures after drying the secondary sludge following biological-chemical wastewater treatments [29]. While sewage sludge gasification

can accumulate heavy metal concentrations [30], it also has the potential to generate heat or power [31].

Gasification is the partial oxidation of biodegradable material in an air-restricted environment, producing a mixture of combustible gases such as H_2 , CO , and CH_4 (known as producer gas or gasification gas) and a solid component of carbonaceous, ash-rich char [29, 32]. Gasification offers many advantages over the alternative thermochemical methods, like pyrolysis and incineration-based in terms of CO emissions and net-energy extraction potential [28]. Reviewed literature works have reported that the minimum calorific value (C.V.) requirement of any substrate to enable effective thermochemical-based treatments is 1200 kcal/kg [33, 34] (and a minimum of 7 MJ/kg for incineration [28]). Whereas, at the range of 1200~1500 kcal/kg C.V., the treatment through incineration would require additional blending with auxiliary fuel and thus becomes unfavourable [34, 35]. The C.V. of the Sewage sludge, as reviewed in many literature works, is in the range of 10~19 MJ/kg [4, 36]. Further, the undigested residual, as taken from the visited 140 MLD STP, was found to possess a minimum of 2037 kcal/kg. This magnitude of C.V. is very fitting for carrying out the more advantageous gasification technique rather than the other thermochemical methods of incineration and pyrolysis [34]. Therefore, this finding drives the motivation for this research work. This research work thus orients at analysing the waste-to-energy conversion potential by adopting undigested-SS gasification-based producer gas and utilizing it with the already established IC engines application as fuelling agent. The investigation is majorly based on numerical modelling, which is significantly a resource-extensive and economically advantageous analysis method. This approach further enables extending the novelty towards further inspecting the strategies, that could be experimentally resource-intensive, towards performance improvement, emissions reduction and enhanced energy-extraction.

1.2.2. Producer gas fuelled IC engine

Raman and Ram [37] examined the efficiency of PG and natural gas-fueled engines and found that the PG-fueled engine efficiency was lower by 12.5%, which they attributed to the lower quality of PG as a fuel material rendering to its low flame speed and CV. The flame speed in PG is very low compared to conventional fuels, like gasoline and propane [38]. Low CV and flame speed also result in lower heat release and energy density, which are prime factors for engine power derating and unstable combustion, respectively[39]. The calorific value in the generated producer gas is strongly dependent on the feed agents, reaction type, and gasification type [40]. S. Tsiakmakis et al. [39] conducted a comparative experimental investigation and found that both pressure and heat rate increment are lesser for the olive, peach, and grape-kernel biomasses-based PG. Similarly, PG-fuelled experiments were conducted by Singh. et.al [41] showed a 45.71% reduction in fuel usage and, a 69.5% decrease in NO_x emissions, with a decline in brake power (BP) and brake thermal efficiency (BTE). Homdoug et al.[42] also found that the lower energy density in the air/fuel mix-operated DF engine decreases efficiency, torque, and power. Various other investigations [43-46] also confirm that torque and power decrease, attributing to lower energy density and volumetric efficiency in PG-operated DF engines. However, Gobbato et al.[47] found that fuelling the producer gas in IC engines also reduces the CO and NO_x emissions with respect to any operating conditions.

1.2.3. Sewage sludge PG-fuelled engine

Sewage sludge management in an economically and environmentally responsible manner is a crucial issue in many cultures. Wastewater treatment plants in both developed and developing nations are producing significantly more sludge. Compared to other materials, sewage sludge has a large proportion of inorganic ash and a low carbon content. Examples include agricultural wood or lignocellulosic char. As a result, sewage sludge has a low energy value but is adequate to make numerous waste-to-energy processes practical. Furthermore, each wastewater

treatment facility produces a significant volume of sewage sludge. As previously stated, acceptable disposal techniques must be selected [13].

As per the previous discussions, the efficacy of PG-fuelled engine performance is found closely related to the quality of considered PG. This statement has also been apprehended by evaluation works in ref.- [48], where they suggested that moisture content in the gasification substrate, calorific value (CV), and the particular PG volatility and flame speed are prime factors that affect the quality of a PG and correspondingly impact the IC engine performances. Thus, to increase power and efficiency, blending a high CV PG, like the SSPG, with a component of higher flame speed and calorific value, like methane, is significant to improve SI engine performance. Szwaja et al. [49] reported that only a single work is found reporting a few of these critical entities for SSPG application to the SI engine. They reported that the peak pressure and engine power increase with an increase in methane fraction until around 40% methane blends with 60% PG. A rise in PG content is found to hamper satisfactory engine run. They also revealed, that along with SSPG blend fractions, the relative equivalence ratio ($\lambda \approx 0.6-1.6$) also significantly controls the power (maximum at $0.9-1 \lambda$) and exhaust emission of the engine. Methane application is beneficial as it is a renewable form of energy and can be obtained from biogas. It has a greater H/C ratio that results in low CO₂ emission and has a high octane number (120-130), which enhances the possibility of achieving improved efficiency through greater Compression ratio (CR) [50-52]. Therefore, the authors opted for SSPG blending with methane in different proportions for investigating and predicting the optimal engine performance via the modelling approach.

1.2.4. Modelling of SI engine

As per the previous discussions, the efficacy of PG-fuelled engine performance is found closely related to the quality of considered PG. The flexibility of the PG-fuelled IC engines has also been studied and compared. In the works of A. Paykani et al. [48], it is suggested that moisture

content in the gasification substrate, calorific value (CV), and the PG-specific volatility and flame speed are prime factors that affect the quality of a PG and correspondingly impact the IC engine performances. As producer gas has poorer fuel quality than petrol and natural gas, engine design adjustments are required to attain comparable optimal power. However, Spark Ignition (SI) engines require relatively finer modifications for running on PG [53].

Intending to assess the performance proofing before experimentation and saving substantial resources, cost, and time investment, an engine modeling and simulation tool could offer a more anticipated platform [54-57]. It enables parametric engine performance predictions particularly in the early phases of engine design [58]. Literature works present the available engine simulation methodologies as zero/one-dimensional (0D/1D) [55, 59], multi-zone-capable three-dimensional (like, CFD) and quasi-dimensional modelling techniques [55, 60], and Computational Fluid Dynamics (CFD) modelling [61, 62]. And, the literature review section depicts an in-depth study and advantages related to the indicated engine-performance modelling techniques. The QD model circumvents the limitations of 0D and 1D models as it is a more accurate simulation technique [54]. Besides this, the 3D-CFD simulation depends on the size of the computational mesh, which decides a higher requirement of computational resources with finer mesh size to acquire enhanced accuracy. Therefore, the QD combustion modelling is substantially practiced to predict and investigate the SI turbulent combustion without penalizing the prediction accuracy, or the excessive processing/ computational requirements [63].

Table 1.1 summarizes the advantages associated with the widely applied modelling techniques that adeptly simulate the SI engine performance predictions. These techniques include the single zone-based zero (or. one) dimensional technique [55, 59], and the multi-zone-capable three-dimensional (like, CFD) and quasi-dimensional (QD) modelling techniques [55, 60].

Since QD thermodynamic modelling is a quicker approach for simulation and circumvents zero and three-dimensional modelling limitations, it is a quicker simulation method [64].

Table 1.1: Advantages and Limitations of the modelling techniques

1-D	3-D	QDTM
1. Less computational and time required [60]	It is complicated [65] and demands most computational resources and time [60].	Computation required is lesser than 3D models and more than 0D model [60]. Computational time is less as well [66].
2. It treats combustion as only a heat-addition process, and neglects spatial distribution[65].	It enables a more precise species concentration computation. [65]	It is more efficient as compared to multi-dimensional models [65]
3. It is unable to simulate flame-propagation [65].	The rate of burn and combustion is modelled [65].	Rate of burn and combustion is modelled [59, 65].
4. Burn rate profile, using empirical formulas, needs extensive experimental calibration work. [65]	Robust, as it couples combustion chemistry and species transport through 3D-CFD modelling [65]	Ability of wider burn-velocity models to capture the actual engine performance and emissions patterns [65] makes the model more flexible.

Many reviewed pieces of literature ([67-71]) also generated regression modelling and executed optimization with respect to PG-fuelled IC engine performances for the objective of enhancing

engine performance and reducing emissions. These reports provide further information on the statistical-based regression modelling of various engine performance parameters concerning variations in some considered independent parameters and analyzing the responses. Thus this approach could be beneficial in verifying the simulation outcomes with respect to conventional results.

1.3. Identified research gap

- I. Intending towards enhancing the engine output power and efficiency, blending a high CV PG, like the SSPG, with a component of higher flame speed and calorific value, like methane, is significant to improve SI engine performance and requires a diverse amount of analysis work.
- II. SI engines require fewer modification requirements for operating on PG fuel, whereas numerical modelling has not yet been extended towards validating for a high GCR SI engine regarding the PG-blended dual-fuel intake.
- III. Intending to assess the performance proofing before experimentation and saving substantial resource, cost, and time investment, a QDTM-based engine modelling and simulation tool considering PG-based dual fuelled SI engine operation still seeks investigation.
- IV. Further, it could be accessed from the many recent and reviewed pieces of literature-[67-73] that despite the rising attention on biomass and gasification-based alternate fuel sources for IC engines, very few publications report on QDTM and further integration of generated responses to the regression modelling and optimization to declare the optimal settings that best enhance the engine performance and reduce emissions. Integrating the multi-objective optimization and regression modelling to the DF SI engine performance responses via Response surface methodology (RSM) is a potential research gap and offers further novelty to the literature.

- V. Studying the LIVC-based Miller cycle benefits towards enhancing the brake-thermal efficiency improvement with the DF SI engine simulation model at stoichiometric intake.
- VI. Inspecting improvements in power and efficiency responses with respect to boosting up of the SSPG and methane blend fuel-air charge at the intake.
- VII. Studying effects of variations in the equivalence ratios with the DF SI engine simulation model
- VIII. Studying the lean burn effects with the DF SI engine simulation model
- IX. Besides consideration of SSPG and CH₄ blending, inspection of the SI engine performance and emissions fueled with potential blends of N₂-rich grape-based PG and Propane of high CV in different blend proportions, equivalence ratios and CR also remains a potential research gap.

1.4. Research aims and objectives

It is obvious to bridge the research gaps for enabling better prediction of engine response with respect to the engine variables. Keeping this in view, this research work aims to promote enhancement in waste-to-energy conversion by aiming to achieve the following objectives:

- To study the compatibility of dual fuel mode engine operation using QDTM-simulation approach to assist better engine operating prediction.
- To interpret the variation of engine performance and emission responses with regard to variations in the three or four decision/input parameters.
- To demonstrate the specific response sensitivities towards various factor parameters through an RSM-based ANOVA analysis strategy.
- To carry out a detailed assessment of the input variables in the cumulative performance of SI Engine, and optimization for maximizing efficiency and power, and minimizing fuel consumption, along with the emissions, using RSM.

The energy transition necessitates the adoption of new energy sources and sustainable technologies. Optimizing operating variables can significantly improve the performance of the engine for decentralized electricity generation. Further, this article will guide engine researchers on modelling and optimization techniques for improving the performance of dual-fuel SI engines using PG fuels with blends.

1.5. Outline of the thesis

The engine simulation is modelled to operate with a variety of sewage sludge-based producer gas (SSPG) blend proportions with methane. After validating the thermodynamic simulation model using experimental references, it is simulated to explore the dual-fuelled SI engine performance for different operational cases and differing objectives. Effects of independent operating parameters like, blending SSPG to methane, LIVC, and spark timing variations were analyzed using the statistical means of RSM. For the analysis, diverse engine response variables were modelled and later analyzed with the aid of the statistical method of RSM. The diverse set of response parameters, considered in this analysis work, are associated with either of the following categories: engine combustion-affiliated parameters, and performance or emissions-associated parameters. Individual parametric variation trends showed a higher degree of trade-off nature with respect to engine efficiency and power, and CO and NO emissions. Furthermore, the RSM-based optimization was also applied to find the best operating conditions for enhancing performance and diminishing the modelled emissions from the modelling results of the blended fuel-intake SI engine simulation model. The investigation is oriented such that the SS-based renewable energy could be promoted, harvested and subsequently problems of fuel oil scarcity and environment degradation could be squarely met. The presentation of the investigation have been divided into following distinct thesis chapters, details of which are described as follows:

- **Chapter 1**, presents the background and motivation for devising the numerical-based computational model to simulate the engine performance and investigate the corresponding performance enhancement. The regression-based statistical modelling, utilized for studying the simultaneous impacts of various independent input parameters over the diverse output responses, has also been introduced along with the aspects of multi-objective optimization competence. The application purpose of the Response Surface Methodology (RSM), to pursue the optimization operation, is also rationalized as carrying out the multi-objective operation utilizing the RSM allowed confirming the best operational range of the factor parameters regarding the internal combustion engine configuration settings, and fuel blend composition feed, as the independent parameters. Briefs regarding the need for the study, research gaps, and accomplishments of the thesis have been established. Following the mentions of broader research gaps and primary addressing strategies, the implementation and analysis of the innovative techniques carried out through the presented modelling-based investigative approach of this thesis have been highlighted. This chapter also puts forward the aims and objectives of the study. And finally, the outline of the thesis is presented.
- **Chapter 2**, presents a thorough Literature review regarding the PG production and application to this date and the future perspectives. The section illustrates the significance of PG as a renewable source of energy, the application of gasification with various substrate materials for the production of PGs of differing qualities, followed by a review of the application in the SI engine, and finally, the associated advantages and limitations are depicted. The section also reviews the scope for waste-to-energy conversion, and the scope for methane and propane blending towards boosting engine performance. The section covers the necessity for numerical modelling to simulate the IC engine operating with PG or Dual fuel blends, and the significance of progressive strategies to overcome performance

limitations. Through these discussions, the chapter finally signifies the objective works for the research work.

- **Chapter 3**, discusses the particular approaches and sub-models considered for developing the mathematical simulation to mimic the SI Engine performance while signifying the development of the novel innovated strategies of this investigation. It also describes the procedures for extending the modelling principles towards depicting the engine performance, efficiency, and power output responses while keeping the nascent emissions examined. It has been categorized into various subsections, to illustrate the corresponding advantages of adoption of the QDTM technique for modelling. Derivations regarding the in-cylinder pressure development have been presented and discussed in correlation to the defined in-cylinder chamber geometry, specifications, fuel and fuel blend's thermophysical properties, and the nature of flame-front-cum-propagation velocities. Utilizing the defined inputs the in-cylinder thermodynamic states are accessed with the help of various sub-models. These sub-models are specific with respect to the burn entrainment rate, flame speed modelling, heat exchange sub-model, integration of the combustion kinetics and species formations, and assessment of the outcomes through performance formulations. The manner and advantages of inspecting the simulation results to detect and declare the fruitful outcomes by utilizing the statistical RSM approach-based analysis tool is also given insights of . The inclusive operations could be depicted in the following two bullets.

- **Numerical simulation methodology**

In this study, the engine performance simulation has been performed by quasi-dimensional (two-zone combustion) thermodynamic computational modeling. This deals with ordinary differential equations to simulate dynamic behavior during compression, combustion, and expansion stroke of closed power cycle SI engines.

Simulation proceeds with compression stroke from the inlet valve closed, spark at the end of compression and sphere-like shape flame nucleus generation, then propagation of turbulent flame with two zones (burned and unburned) till the end of combustion, and to the expansion up to exhaust valve open. During the combustion phase, the flame front area and corresponding burned volume with the crank angle were calculated by flame front geometry till the end of combustion, and two-zone heat transfer from gas to the wall was computed using Annad's correlation. The termination of burning inside the cylinder was hypothetically assumed when the volume of fresh charge became zero. During combustion, the formation of 12 product species (H_2O , H_2 , OH , H , N_2 , NO , N , CO_2 , CO , O_2 , O , and Ar) have been studied, and their equilibrium molar fractions are determined by the Newton-Raphson approach. Whereas CO and NO concentration for temperature and crank angle have been computed by applying a rate kinetics non-equilibrium model. The molar-specific heat and enthalpy of each mixture species have been found through polynomial interpolations with reference to temperature variation. The differential equation variables were determined using the fourth-order Runge-Kutta approach.

- **Optimization methodology**

Response surface methodology (RSM) is considered the best design of experiment (DOE) methods. It has multiple applications in different segments of the engineering field. The main work of this technique is the simultaneous optimization of the variable objective. Thus, the multi-objective optimization approach using RSM has been incorporated for this present investigation.

➤ **Chapter 4**, section presents the results and discussion. This chapter is categorized into two units. First, it deals with the results and discussion acquired from the different innovative

strategies utilized in this investigation. These approaches are oriented towards inspecting the improvements in engine performance and emission responses for the SSPG-methane-fuelled engine model. Next, it also describes the regression models that can effectively imitate the model formulations and then be used for generating the optimal results.

➤ **Chapter 5**, conclusions and scope of the future work have been presented in this section.

Conclusively, it has been found that effective waste-to-energy conversion capability is possible through the use of SSPG in SI engines as a fuelling agent.

The investigation has always been supported by the blending of SSPG with a higher CV agent-methane. The investigation favours the fuel-blend application and further refinement of engine performance through the application of the strategies such as the LIVC Miller cycle approach, boosting the intake charge, optimizing the spark and ignition timing, and the operational equivalence ratio. Although the mentioned strategies evolved particular modelling challenges as well as response-trade off demerits, consecutive investigative innovations and strategies were incorporated to address the challenges and demerits. And finally, through the various strategies-based investigations, the enhanced energy conversion potential could be established while considering sewage-based producer gas as an alternative SI Engine fuel. Further, this study is expected to provide a base for the end-users and researchers towards the application of integrated gasifier-SI engine systems to improve the energy-crisis scenario, especially in the energy-intensive industrial-prone regions.

