EXPERIMENTAL INVESTIGATION ON PERFORMANCE AND EMISSION CHARACTERISTICS OF DIESEL ENGINE FUELLED WITH BIOGAS AND OXYGENATED FUELS

A
Thesis
Submitted to

For the award of

DOCTOR OF PHILOSOPHY (Ph.D)
in
(Mechanical Engineering)
By
Geetesh Goga
(41400134)

Supervised By
Dr. S.K. Mahla

Co-Supervised by
Dr. Bhupendra Singh Chauhan

LOVELY FACULTY OF SCIENCE AND TECHNOLOGY
LOVELY PROFESSIONAL UNIVERSITY
PUNJAB
2019

Declaration

I hereby certify that the work compiled in this dissertation is the outcome of research work, performed by myself, else stated, under the kind guidance of Dr. S.K. Mahla and Dr. Bhupendra Singh Chauhan.

Any part of this work has not been submitted for the award of any degree, diploma, associate-ship, fellowship or its equivalent to any University or Institution.

Geetesh Goga

Registration No. 41400134

Department of Mechanical Engineering

Lovely Professional University, Punjab

Certificate

It is certified that work contained in this thesis entitled Experimental Investigation on performance and emission characteristics of diesel engine fuelled with biogas and oxygenated fuels, by Geetesh Goga, Registration No. 41400134, a student of Department of Mechanical Engineering, Lovely Professional University, Punjab, for the award of degree of Doctor of Philosophy has been carried out under our supervision and this work has not been submitted elsewhere.

Dr. S.K. Mahla	Dr. Bhupendra Singh Chauhan
Assistant Professor	Professor
Department of Mechanical Engineering	Department of Mechanical Engineering
IKG Punjab Technical University Campus, Hoshiarpur	Lovely Professional University, Punjab

Abstract

Currently, world is totally reliable on fossil fuels from decades for fetching day to day energy needs. Sustainable properties and eco-accommodating nature of biodiesel has made it most well-known among different other options to petroleum products. Presently, researchers and experts have come to the conclusion that biodiesel along with higher alcohols can be an appropriate substitute for this situation. Biodiesel, higher alcohol, and, gaseous fuels are considered to be best and suitable replacement for dwindling natural resources. These substitute fuels not only aid in dealing with enhanced engine performance, but also cooperates in contracting the injurious tailpipe emissions. Former investigations have presented that biodiesel, higher alcohol, and gaseous fuels can help in improving the performance and depreciating harmful exhaust gases in a diesel engine. Nevertheless, attributable to higher amount of oxygen content in biodiesel, it is inadequate in reducing the catastrophic emissions of nitrogen oxides. Likewise higher alcohols are incompetent in trimming down lethal hydrocarbon emissions because of lower cetane number, and gaseous fuels do not have the scope to curtail destructive carbon monoxide emissions owing to inferior amount of oxygen. To overcome this obstacle in decreasing the noxious exhaust emissions from the diesel engine, an effort is made in the present investigating by fuelling a diesel engine with Rice bran methyl esters (biodiesel), n-butanol (higher alcohol), and biogas (gaseous fuel).

Transesterficiation process is observed to be most reasonable for creation of biodiesel. This procedure basically relies upon temperature, molar ratio, type of catalyst used, speed of stirring the oil and time. It was uncovered from the previous researches that for production of biodiesel with alluring characteristics it should have molar proportion of 1:6 with KOH as catalyst and should be mixed at a speed of 700 rpm for an hour at a temperature of 65°C. Fuel properties like flash point, fire point, calorific value, viscosity, density and cetane number are very much similar to diesel.

In the current investigation four different fuels specifically diesel, biodiesel, n-butanol and biogas were taken into consideration for studying their effects on performance and emission characteristics. Blends of diesel-biodiesel and diesel-biodiesel-n-butanol were prepared as D90/B10, D80/B20, D90/nb10, D80/nb20, D80/B10/nb10, D60/B20/nb20, D70/B10/nb20, and D70/B20/nb10. Then these blends were tested in a single cylinder, small utility diesel engine. Subsequently, along with above mentioned fuel blends, biogas is introduced in the engine cylinder by varying its mass flow rate (0.5 kg/h, 1.2 kg/h and 2 kg/h). All the investigation was performed at an invariable engine speed by changing the load conditions of the engine. The load of the engine was changed from no load to full load in intervals of 20% load variation throughout the experimentation. With all the fuels and combinations performance characteristics as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) were taken as parameters. Emission parameters like Carbon monoxide (CO), Hydrocarbons (HC), Oxides of nitrogen (NOx) and smoke opacity in different permutation and combination were tested on a dual fuel engine. Experimental investigation demonstrates that blends of rice bran biodiesel and n-butanol can be used as a fuel in a diesel engine without any change in the engine. The Performance characteristics measured are brake specific fuel consumption and brake thermal efficiency. Exhalations of carbon monoxide, hydrocarbons, nitrogen oxide, and smoke were calculated to find out emission characteristics. All these parameters were related to baseline diesel. It is established from the experimentation that biodiesel, n-butanol, and biogas can aid in improving the BSFC of the engine by about 21% for all fuel blends and BTE by about 15% for combination of diesel, biogas and n-butanol and diminishing the fetid exhaust emissions anticipated by the diesel engine. CO emissions were found to be decreased for fuel blends having biodiesel and n-butanol by about 13% and increased with dual fuel mode by about 15%. HC exhalations were on higher side with n-butanol and biogas by about 12% and diminished with biodiesel fuel blends by about 16%. NOx emissions decreased with biogas and increased with biodiesel and n-butanol by about 18% and 15% respectively. For all combination of fuels smoke emanations were reported to be lower by about 38%.

Keywords: Rice bran biodiesel, n-butanol, biogas, performance, emission, mass flow rate, dual fuel mode, diesel engine.

Acknowledgements

Ph.D is a minute portion of life; nevertheless it trains us the vigorous way of living our life. It is fairly a glorious and colossal guidance. All along the span of this course, apart from getting profound awareness of a microscopic part of scientific guild, Ph.D also educated me how to talk and write productively and perform in groups. I use to come in contact with a variety of astonishing people, during this time, without backing of whom; I may not have completed this task.

Firstly, I would take this opportunity to express my gratitude towards my supervisor Dr. S.K. Mahla, Assistant Professor, Department of Mechanical Engineering, Punjab Technical University Campus, Hoshiarpur for his guidance and constant encouragement throughout the course of thesis. Without his continuous consolation, patience and generous input, the successful completion of this research would have been a distant dream.

I owe my most sincere thanks to my co-supervisor Dr. Bhupendra Singh Chauhan, Professor, Department of Mechanical Engineering, Lovely Professional University, Punjab for his valuable guidance and advice during each and every step of my thesis. In spite of his busy schedule, he could find time to provide me precious guidance. His experience aided me to publish research papers in highly reputed journals. Without his allegiance and appropriate directions it would not have been achievable for me to accomplish this assignment.

The research work reported here is the part of DST-SERB sponsored project entitled “Studies on combustion, performance and emission characteristics of diesel engine fuelled with Biodiesel and Biogas” (SB/FTP/ETA-306/2013). The financial support extended in the project is gratefully acknowledged.

Last but not the least I am very grateful to my parents and my wife, who supported me during this long span of Ph.D work. All my family members provided complete efforts to fulfill all my needs, given me strength and stood with me in my hard times. I thank them for their sacrifices and facilitating me in executing my work.

Date: July 2019 Geetesh Goga

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Nomenclature

List of Abbreviations and Symbols

IC	Internal Combustion
NOx	Oxides of nitrogen
MTOE	Million tons of oil equivalent
MT	Million tons
ORS	Others
CO	Carbon Monoxide
HC	Hydrocarbons
CO_2	Carbon Dioxide
O_2	Oxygen
OBD	On-Board Diagnostics
H	Hydrogen
N_2	Nitrogen
H_2S	Hydrogen Sulphide
kg/m^3	Kilogram per meter cube
m^2/s	Meter square per second
^oC	Degree celsius
kJ/kg	Kilojoule per kilogram
R.P.M/rpm	Revolutions per minute
min.	Minute
Ref.no.	Reference number
wt.	Weight
%	Percentage
MJ/kg	Mega joule per kilogram
kg/L	Kilogram per litre
g/kWh	Gram per kilowatt hour
kW	Kilowatt
VCR	Variable compression ratio
HP	Horse power
CI	Compression ignition
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
BSEC	Brake specific energy consumption
BP	Brake power
PPM	Parts per million
THC	Total hydrocarbons
PM	Particulate matter
DPU	Drawbar pull
BMEP	Brake mean effective pressure
CRDI	Common rail direct injection
MPa	Mega Pascal
BTDC	Before top dead centre
UBHC	Unburned hydrocarbons

Nm	Newton meter
DI	Direct injection
kg	Kilogram
kg/hr	Kilogram per hour
gm	Gram
ml	Millilitre
NaOH	Sodium hydroxide
FFA	Free factty acid
S.No.	Serial number
cst	Centistokes
cm	Centimeter
Cal	Calorie
ASTM	American society for testing and materials
m^3/hr.	Meter cube per hour
EGR	Exhaust gas recirculation

Chapter- 1

INTRODUCTION

1.1 Overview

Petroleum products are essentially utilized by internal combustion engines, and with combustion of fuel, poisonous gases are emitted from exhaust of engine. Majority of these gases results in greenhouse gas emissions. Dwindling fossil fuels, and exhaust gases emissions have compelled the diesel engine experts to search for a substitute of natural diesel which can be procured from non-conventional energy resources and can also help in curtailing the tailpipe emissions. Oxygenated fuels are discovered to be one of the better alternatives for conventional fuel, as it can be produced from vegetable and animal fats and also help in complete combustion of fuel. Oxygenated fuels include biodiesel and higher alcohols. Biodiesel aids in reducing the carbonized exhalations but also emits increased NOx emissions because of the fact that it has increased amount of oxygen. Lower cetane number of higher alcohols is not suitable for the diesel engines and consequently is not appropriate to be used without blending in these engines. Higher alcohols have low viscosity and can be mixed with diesel and biodiesel very easily. So, most of the researchers have blended higher alcohols with diesel and biodiesel to use the fuel blends directly on diesel engines. Gaseous fuels can also be produced from human and animal wastes and supports in reducing the exhaust emissions, but gaseous fuels cannot be used without pilot fuel in IC engines because of high self-ignition temperature, therefore these are used along with liquid fuels in dual fuel mode. Owing to insufficient quantity of oxygen in gaseous fuels it helps in lowering NOx emissions which is contrary to biodiesel and higher alcohols. Based on this concept, the current study focuses on use of blends of diesel rice bran biodiesel and n-butanol as pilot fuel and biogas as a primary fuel. The dual fuel engine was tested by changing the parameters of the engine. The performance and emanation parameters of the diesel engine fuelled with various fuels were related to neat diesel. In this chapter a concise background of diesel engines and dual fuel engines along with oxygenated fuels and biogas is presented. At the end of this chapter framework of ongoing thesis is also discussed.

1.2 Energy crisis

Energy has consistently performed a critical part in evolution of a nation. It is treated as an indicator of fiscal advancement and social development. The hike in utilization of energy is enhancing constantly throughout the globe. The planet has endorsed industrial innovation in the former century, and encountered severe issues related to aimless application of the energy assets. This creed was associated with higher utilization of energy to achieve enhanced industrial advancement but it does not contemplate improved and adequate adoption of energy. The oil restraint in US and successive Gulf War were very atrocious for both advanced and progressive countries. It was then beginning of the negotiation for crude petroleum by the exporting, which shocked the importing nations and consequently resulted in effective utilization of energy throughout the globe. In the previous few decades, the utilization of energy has augmented indeed owing to the transformation in the living standards and the drastic expansion of population. This need of energy resources has been compensated by exhausting fossil assets and therefore resulted in abating fossil fuels, hiking fuel prices and detrimental habitat [1].

1.3 Energy scenario

Energy has sustained a considerable changeover from an accepted field of study of technologies to a valuable topic in financial planning and worldwide connection. Energy is the backbone for socio-economic progress of any nation. Energy raised by 1% in 2016, compared to last decade it is nearly half the average rate. Energy consumption growth has led by the progressive countries and India ranks top among all the nations as shown in Figure 1.1 [2].

A prediction in the Twenty Fifth Plan manuscript of the Organization Commission specifies that entire production of native energy of 669.6 MTOE was in 2016-17 and it will be reached 844 MTOE by 2021-22. About 71 % and 69 % of predictable utilization of energy will be met with this, and the remaining to be encountered from other nations, is about 267.8 MTOE in 2016-17 and 375.6 MTOE by 2021-22. In last decade of the cost and amount of import of crude oil has increased gradually. Since the Indian economy is growing at the rate of 6% or more and the energy demand is therefore, expected to rise to 199 MT by 2021 and 622 MT by 2047. As illustrated in

Figure 1.2 most consumed fossil fuel in 2016-17 was coal, followed by crude petroleum, electric energy generated from hydro nuclear and ORS, Natural Gas, and Lignite [3].

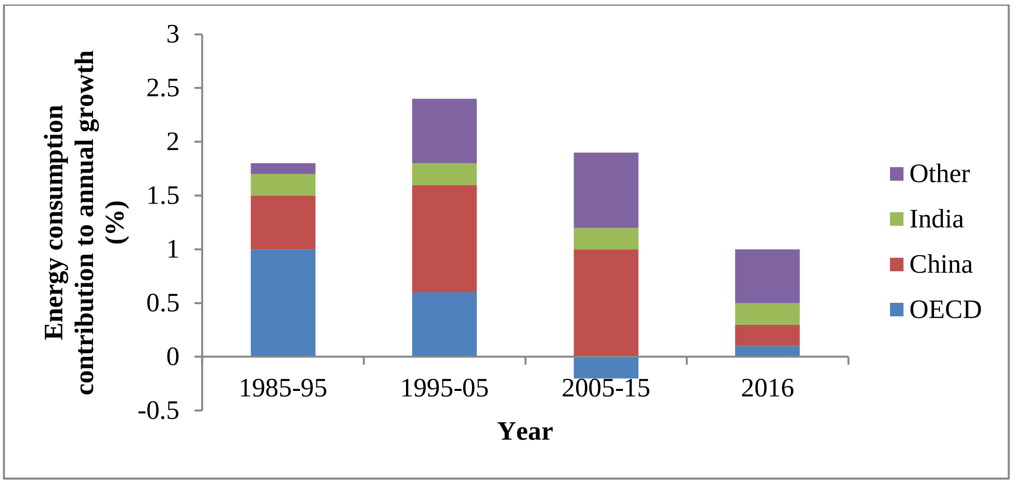


Figure 1.1 Annual growth in contribution of world's energy consumption [2]

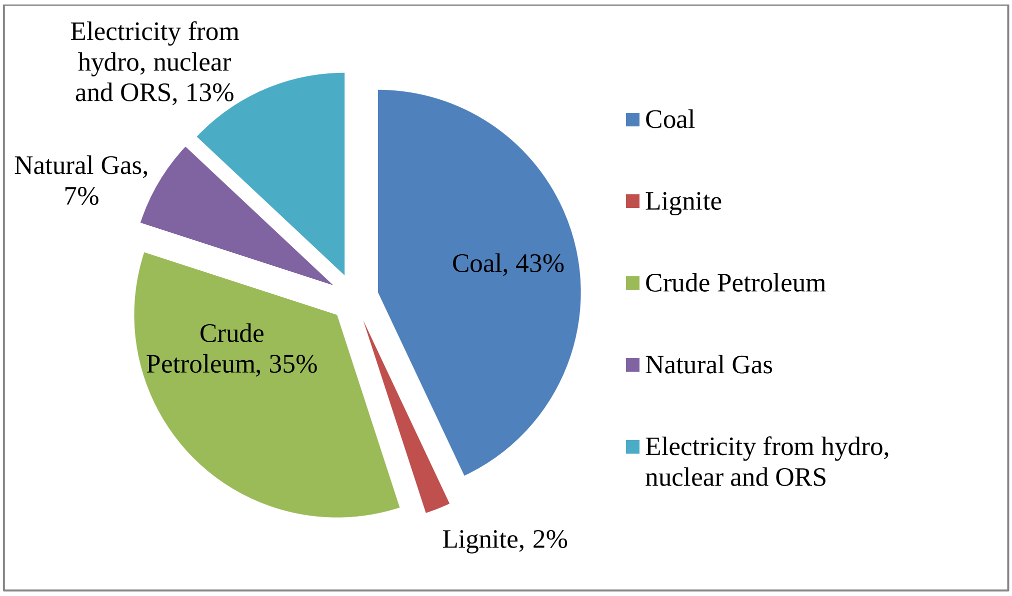


Figure 1.2 Sourcewise consumption of energy in India [3]

1.4 Need of alternative fuels

Requirement for energy boosts up by 6.5 percent annually and more than three fourth petroleum products are imported from other countries to satisfy the demand in India, due to which the country is facing energy crisis and it has become mandatory to minimize the use of conventional resources of energy or to opt for alternative sources [4-5]. One of the major reasons of depletion of fossil fuels is its high demand in industry. On account of the detail that these fuels are usually exhaustible, a day would come when the demand for these fuels would be more than the supply, which would result in a possible world crisis. Moreover, tailpipe exhalations from these engines are very badly affecting the mankind and habitat from so many decades. The exhaust emanations like carbon monoxide (CO), nitrogen oxide (NOx), hydrocarbons (HC), smoke etc. emitted by petroleum products are attributing a huge loss to environment and society [6]. The exhaust emission of harmful pollutants is polluting the environment in a very rapid manner. CO_2 is also a part of exhaust emissions which has been considered as one of the major reasons for global warming [7].In transportation industry energy supply chain needs innovation due to global warming and reduction in petroleum storage.

Diesel engines are one of the dominant prerequisite now a days in so many sectors owing to the fact that it has better fuel economy, higher efficiency, more reliability, lower fuel cost and long lasting capacity. Demand of diesel engines is too much, both on road and off road. They provide globally accepted power solutions due to its durability, ability to produce high torque, unparalleled fuel conversion efficiency. Their applications involve public transport, electricity generation, agricultural implementation, construction equipment, industrial applications and marine propulsion. Exhaust exhalations of diesel engines are also needed to be minimized owing to stringent emission standards in India, and all over the globe. In 1989 the ideal exhalation limits came into existence in India which was replaced by mass emission limits in 1991 and 1992 for petrol and diesel engine respectively. National auto fuel policy was declared in October 2003 and in May 2014, Auto fuel vision and policy was written. Summary of euro exhalation criterions in the country is presented in Table 1.1. As announced in 2016, entire range of freshly manufactured vehicles should adapt according to diesel or blend of diesel and biodiesel (B100) and fit as per emission requirements of diesel and biodiesel. Vehicles having CI engines suitable for biodiesel blends upto B20 needs to meet requirements of diesel fuel only. For test requirement for type approval of biodiesel vehicles is depicted in Table 1.2.

Table 1.1 Indian emission standards (4 wheel vehicles) [8]

Standard	Reference	Date	Region
India 2000	Euro 1	2000	Nationwide
Bharat Stage II	Euro 2	2001	NCR*, Mumbai, Kolkata, Chennai
		2003.4	NCR*, 11 cities †
		2005.4	Nationwide
Bharat Stage III	Euro 3	2005.4	NCR*, 11 cities †
		2010.4	Nationwide
Bharat Stage IV	Euro 4	2010.4	NCR*, 13 cities ‡
		2015.7	Above plus 29 cities mainly in the states of Haryana, Uttar Pradesh, Rajasthan and Maharashtra
		2015.10	North India plus bordering districts of Rajasthan (9 States)
		2016.4	Western India plus parts of South and East India (10 States and Territories)
		2017.4	Nationwide
Bharat Stage V	Euro 5	n/a[a]	
Bharat Stage VI	Euro 6	2020.04	Nationwide

* National Capital Region (Delhi)

† Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, Secunderabad, Ahmedabad, Pune, Surat, Kanpur and Agra

‡ Above cities plus Solapur and Lucknow. The program was lated expanded with the aim of including 50 additional cities by March 2015

[a] Initially proposed in 2015.11 but removed from a 2016.02 proposal and final BS VI regulations

Table 1.2 Test requirements for type approval for flex-fuel biodiesel vehicles [8]

Test	**4 wheeled vehicles with GVW 3,500 kg**	**3 wheeled vehicles**	**4 wheeled vehicles with GVW 3,500 kg**
Gaseous pollutants	Both diesel and B100	Both diesel and B100	Both diesel and B100
Free acceleration smoke	Both diesel and B100	Both diesel and B100	Both diesel and B100
Durability, if opted for instead of fixed Deterioration Factor	Diesel fuel only	Diesel fuel only	Diesel fuel only
OBD	Both diesel and B100	Both diesel and B100	Both diesel and B100

Enhancing rate of population and prospering level of affluence of the common man have engendered a deluge of automobiles on road. Figure 1.3 depicts the statistics for cars sold from 1990 to 2018. It can be apparently examined that the rate of sold cars is increasing with the passing years. From 1990-1999 only 39.2 million cars were sold whereas in 2018 (till July) 81.5 million cars are already sold [9]. Due to hike in automobiles on roads the fossil fuels are depleting at an alarming rate which may result in its permanent deterioration in few decades and will also result in polluting the environment by the detrimental gases coming out of the exhaust of these engines.

These augmenting numbers are an alarm for the mankind to take some initiative to check squandering non-renewable fuel sources and non-ecological exhaust emissions that have forced the researchers to explore a substitute fuel which can be produced from bio-based product and can also help to cut down the detrimental gases coming out from tailpipe of the engine. Additionally, abating fossil fuels and blistering acceleration in demand of energy throughout the world can result in financial crisis all over the world. To overcome this, diesel engine specialists, researchers, and combustion analysts are trying to find a substitute fuel which can upgrade the performance characteristics of the engine and cut down exhaust emissions [10-11].

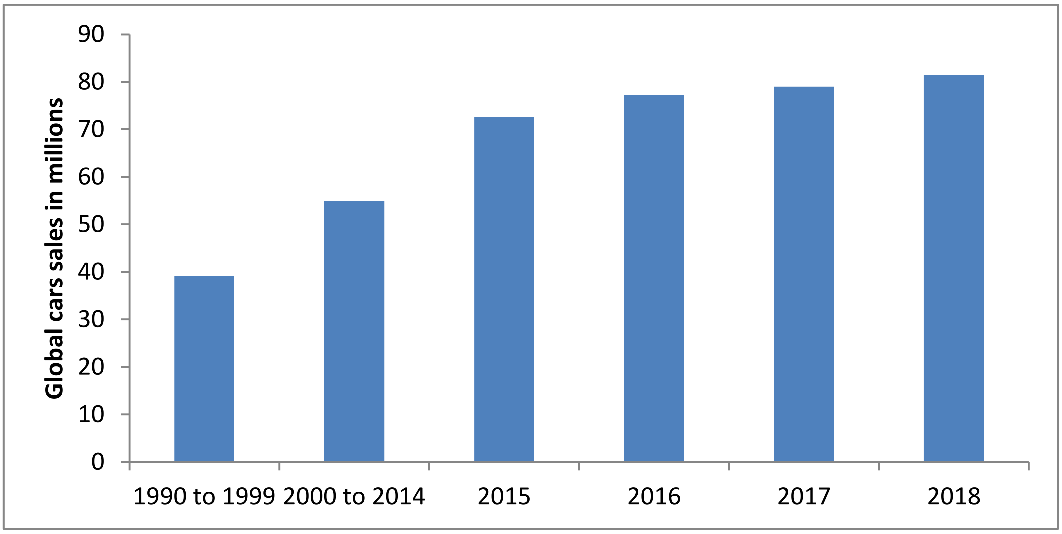
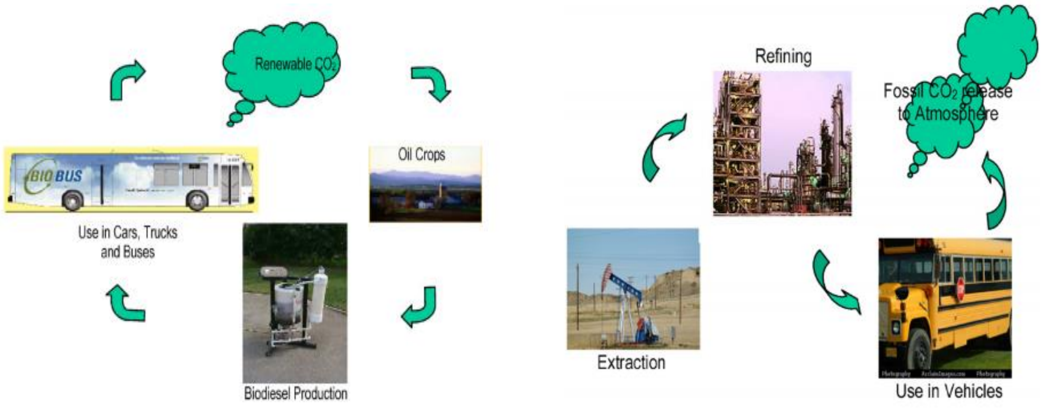


Figure 1.3 Number of cars sold worldwide from 1990 to 2018 (in million units) [9]

1.5 Alternative fuels

The disaster caused to atmosphere owing to excessive adoption of petroleum products can be compensated by use of alternative fuels, based on biomass. It can also help in providing new jobs in the market. The plurality of scientists and diesel engine experts have noted that methyl esters from vegetable and animal fat oil are the leading substitute fuel for conventional diesel which can be utilized in a diesel engine deprived of any transformation in basic engine design. Biofuels is the primary choice of the researchers amidst all alternative fuels due to its properties which helps in producing less greenhouse gases and soot emissions. Moreover these are sustainable in nature and economical than conventional fuels [12]. However, success of sustainable energy process is still limited because of its low production and intricacy in procedure of eradication. Nevertheless it has achieved recognition of global researchers as a result of habitat favorable quality. Properties of the fuel must be improved if it is desired to use biofuels or biodiesel blends in Diesel Engines. It has been found that oxygenated fuels have good ignition ability as they have high cetane number than diesel [13-15].Study of researchers has also been focused on generating fuels that produce less emission and burns cleanly. Moreover it has also been found by researchers that emanations coming out of tailpipe of the engine such as nitrogen oxides, carbon monoxide, hydrocarbons, and smoke etc. can be reduced by using substitute fuels. Biofuels, offer up-to-date and new significance to the ancient acceptance that ‘Trash for one person is a treasure for another’ by way of the fact that it can be procured from the leftovers [16-18].

Biofuels can be categorized in two types: primary and secondary biofuels. First kind of biofuels can be originated from buildups of harvests and animals, timberland and trees. Secondary biofuels are precisely developed from bushes and microorganisms. These can be re-ordered into three kinds of fuels. Ethanol which can be created from starch rich sustenance crops, bioethanol from plants and biodiesel from organisms [19]. At least 25 percent of energy derived from biomass (mixture of biogas, biodiesel and higher alcohol) is expected to be taken as per European Union as it may be helpful in reducing green house effect [20]. Various researchers have utilized diverse feedstock for generation of biodiesel. Scientists have utilized Mahua oil, Rice Bran oil, Waste cooking oil, Jatropha oil, Eucalyptus oil, Pine oil, Karanja oil, Mustard oil, Neem oil, Cottonseed oil, Turpentine oil, Palm oil, Rapeseed oil, Linseed oil, Hazelnut oil, Sunflower oil, Olive oil, Castor oil and Avocado oil for creation of biofuels. In this paper properties and characteristics of different materials which are utilized as biofuels will be checked on. The requirement for production of biodiesel is clearly shown in Figure 1.4 (a) and (b) [21].



(a) **(b)**

Figure 1.4 CO_2 cycle (a) For biodiesel; (b) For diesel [21]

There are different strategies for creation of biodiesel from various feedstock which incorporates transesterification, micro-emulsions, direct blending and catalytic cracking [22]. It has been found by the greater part of the researchers that transesterification has ended up being best and solid strategy for creation of biodiesel as it has given outcomes like diesel when utilized in diesel engines [23-31].

In automobiles inexhaustible liquid and gaseous fuels can also be an attractive substitute to petroleum products. Nowadays experiments are being carried out on dual fuel combustion which has concluded that reduced emission levels, decreased NOx emissions, higher overall equivalence ratios and increased cylinder peak pressure have been achieved as compared to conventional diesel engine mode [32]. Gaseous fuels are an exceptional option as compared to liquid fuels as they conveniently associate with intake air to form homogeneous air-fuel mixture [33]. Consistent ratio of primary fuel and air enters the cylinder in a dual fuel engine, during suction stroke and then liquid fuel is injected which self-ignites and later turns into cause of ignition for gaseous fuel. Ample range of gaseous fuels can be utilized in a dual fuel engine without major alterations in engine [34]. Increased thermal efficiency can be achieved in dual fuel engines because of its higher compression ratio and auto ignition temperature. Conservancy of environment can also be initiated by adoption of biomass based pilot and primary fuels in diesel engines using dual fuel technology [35]. Enhancement of combustion duration and prolonged combustion can be achieved by addition of gaseous fuel in the engine [36].

1.6 Dual Fuel Mode

Dual fuel engines are also known as bi-fuel engines capable of running on two fuels. Out of which one fuel is liquid fuel such as diesel or biodiesel and another is a gaseous fuel such as natural gas or biogas. Owing to high auto-ignition temperature of gaseous fuels, a source of ignition; in form of liquid fuel must be delivered to a dual fuel engine. Dual fuel engines can help in minimizing the use of pilot fuel and replace the traditional diesel up to a great extent. A large number of researchers have shown interest pertaining to dual fuel mode in past decade. Various dual fuel engines were used by researchers such as diesel-biogas [37-38], biodiesel-natural gas [13], diesel-natural gas [39-40]. It has been proved by most of the researchers working on dual fuel mode that if biodiesel is used in dual fuel mode it enhances stability of combustion at high loads and provides higher pressure peak irrespective of load range [41]. It also helps in shortening the postponement in ignition. The pressure rise amount also detected to be advanced in dual fuel mode vis-a-vis the traditional diesel at 100% load [42]. Dual fuel mode reduces brake specific energy consumption and enhances brake thermal efficiency when engine operates under high load [43]. Exhaust gas temperature has similarly been found to be advanced in dual fuel mode in relation with diesel fuel [44]. Dual fuel engines also have the tendency to reduce NOx emissions which is almost impossible while using traditional engines.

1.7 Biodiesel as a fuel

Biodiesel is commonly a vegetable oil (m)ethyl ester, which is obtained by reaction of various oils with alcohol [45]. It is an oxygenated fuel which is produced by various procedures among which transesterification process is considered as one of the best method owing to its efficient and simple procedure [46-47]. Biodiesel can be produced by various processes that are enlisted below:

1.7.1 Transesterification

It is a procedure in which alkoxy gathering of an ester is exchanged by another alcohol. A catalyst is utilized to accelerate the reaction using an acid or a base. It is a process in which methyl or ethyl esters are obtained by reacting fat or oil with an alcohol. It helps in changing the viscosity of the vegetable oil. Primarily, this process was initiated by scientist E. Duffy and J. Patrick in 1853. Rudolf Diesel proposed the idea of replacing gasoline with peanut oil almost 100 years ago. Main constituents of biodiesel are methyl palmitate ($C_{17}H_{34}O_2$), methyl stearate ($C_{19}H_{38}O_2$), methyl oleate ($C_{19}H_{36}O_2$, one double bond), methyl linoleate ($C_{19}H_{34}O_2$, two double bonds), and methyl linoleate ($C_{19}H_{32}O_2$, three double bonds). Separate infrastructure is not required to store biodiesel. Any percentage of biodiesel can be mixed with diesel [49]. It is an oxygenated fuel containing approximately 11% of O_2 in its molecular structure having capacity to reduce Greenhouse effect. It is non-toxic, possesses better lubricity and biodegradable and may be derived from various sources like waste cooking oil, vegetable oil, jatropha oil, palm oil, animal fats; rapeseed oil and soyabean oil [50].

Biodiesel has 12 percent lower energy content in comparison with fossil diesel [51]. Biodiesel has some shortcomings which incorporate higher viscosity and lower volatility in comparison with diesel fuel [52]. It has also been found that nitrogen oxide (NOx) exhalations increase owing to more percentage of oxygen content in methyl esters while Carbon monoxide (CO), hydrocarbons (HC), and smoke reduces when related to diesel [53]. So many investigators have fuelled diesel engine with biodiesel extracted from different feedstocks. They are considered as a clean fuel for IC engines due to the ascription that they can be renewed and decrement of CO_2 discharge. Characteristics of methyl esters are almost alike pure diesel that is why it can be considered as one of the important alternative fuel. Fatty acids can also be used for preparation of biodiesel. The benefits of biodiesel over diesel are; less sulfur contents and aromatic contents [54]. Many researchers have found that if biodiesel is used in pure form it can lead to problems such as cold starting, engine knocking and crank case oil dilution [55-56] that is why transesterification process is used for preparation of biodiesel to decrease the viscosity and oxygen content of the plant oil. Biodiesel having high cetane number and oxygen contents have been found to be the first choice as an alternative fuels in diesel engines among all other alternative fuels as small or no changes are required in original design of engine. Many investigators and researchers have proved that biodiesel helps in improving the performance characteristics and reducing exhaust emission gases in diesel engine [56]. For producing biodiesel from biolipids transesterification process is essential. [21]. Reaction during a transesterification process is shown in Figure 1.5 [48].

1.7.2 Micro emulsions

Microemulsions are isotropic, and thermodynamically stable mixtures of a polar phase with a nonpolar phase obtained spontaneously with the aid of a surfactant and, sometimes, a co-surfactant. In this process oils are blended with emulsifying agents, for example, alcohols. Distilled water may be used as aqueous phase. It is a colloidal balance scattering of optically isotropic fluid microstructures, formed suddenly from two ordinarily immiscible liquids. The significant downside of fuel delivered from this procedure is deficient ignition [21].

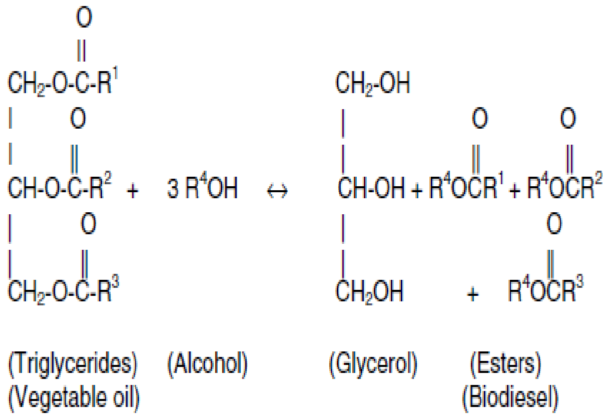


Figure 1.5 Transesterification reaction [24]

1.7.3 Direct blending

This procedure incorporates blending of different oils with diesel specifically, yet because of high consistency of these oils the fuel arranged from this procedure has not been discovered reasonable for use in diesel engines [21].

1.7.4 Catalytic cracking

Catalytic cracking is process in which heat is utilized to change over one substance into another in presence of a catalyst. The pyrolysed substance may incorporate significant measures of foreign materials [21].

1.8 Biogas as a fuel

Biogas is a combination of different gases formed by the anaerobic fermentation of biological material in the lack of oxygen. It is likewise recognized as gobar gas, swamp gas, fuel gas, wet gas, sewer gas and marsh gas [57]. Biogas can be procures from resources such as human and animal leftovers along with agriculture yields or residues and municipal wastes. It usually comprises CH_4; 55-70%, CO_2; 25-50%, H; 1-5% $_2$, N_2; 0.3-3% and tiny amount of of H_2S [58]. Biogas is a gaseous fuel processed from biomass so it may be endless in nature. It is a gas having no color and flavor. Trash and waste material is used to produce biogas rather than crops and digestate left after the anaerobic ingestion of decomposable feedstock is also used as fertilizer.

Once corrosive components like H_2S, CO_2 are removed biogas can be easily transported via pipelines.

Researchers have found biogas to be most considerable as a chief source of energy [59]. It is a non-conventional energy cradle and exerts very small carbon content. It is considered as one of the most promising gaseous fuel referring to reduction in global warming and resource utilization [60]. It can also be utilized in internal combustion engines as a fuel by altering the engine as it has a high octane number and higher compression ratio which helps in maximizing the thermal efficiency. Biogas is a fuel that emits lesser carbon contents during its burning [61]. It has been considered as an important alternative fuel in coming future due to its ease of production, low cost, ability to decrease CO_2 emissions; moreover it is free from carbon which results in improving combustion characteristics and minimizing exhaust emission gases [62]. As a fuel biogas must contain at least 50% of methane to get good combustion [63]. It burns quicker and does not leave any residue behind like solid fuels such as coal. CO_2 also helps in decreasing the heating value and energy density of biogas on volume basis as it is non- combustible [64]. Researchers have concluded that biogas can increase BTE; at high biogas flow rate use of liquid fuel can be minimized but volumetric and thermal efficiency is decreased [65]. It was also noticed that exhaust emissions including NOx and smoke are reduced by means of biogas as a primary fuel [65-66].

1.9 n-butanol as fuel additive

n-butanol can be procured by inebriating fermentation of biomass feedstock used for fermentation of ethanol like sugarcane, beet, corn and sugar beet. It is made from five and six carbon sugars without organism modification. Current units and pipelines can be used for production and transportation of n-butanol. It can be kept in available reservoirs, is less corrosive, and wearing of engine parts is reduced due to its high viscosity [67-69]. It is also known as n-butyl alcohol or normal butanol. It is the main alcohol with a 4-carbon structure and the chemical formula C_4H_9OH. Alcohols cannot be utilized directly in diesel engine owing to its negative properties like low cetane number and high enthalapy of vaporization; but due to good solvent properties they can be mixed with biodiesel easily. n-butanol can be used as higher alcohol blend with biodiesel without any engine modification [68-69]. Due to ample amount of oxygen in bio-alcohol fuel blends, researchers have a desire to use them as an alternative fuel. n-butanol has been found to have properties that are desirable for diesel engine. Better fuel properties like no corrosion to existing pipelines, almost perfect miscibility, higher heating value, less hydrophilic tendency, low vapor pressure, good inter solubility and higher viscosity of n-butanol makes it more preferred to ethanol. Various scientists have researched that addition of n-butanol resulted in reduction of soot emissions in diesel engine [67-69]. With increase in n-butanol concentration NOx and HC emissions have been found to be increase at low EGR rates and highest heat release rate and highest cylinder pressure also rise whereas the combustion durations have been reduced. Brake thermal efficiency and carbon dioxide emissions have also reported to reduce with addition of n-butanol content [69].

In current experimental study, biogas was utilized as a primary fuel and blends of n-butanol and diesel as a secondary fuel in a compression ignition engine which was altered to run on a dual fuel mode.

1.10 Organization of thesis

The thesis has been systematized by intensifying on performance and exhalation parameters of a diesel engine using oxygenated fuels and biogas. Introduction and backdrop of oxygenated fuels and dual fuel concept is discussed in first chapter. Excerpt of substitute fuel among distinct categories and their significance of utilization in dual fuel engines are accentuated in this chapter. Second chapter incorporates survey of literature when diesel engine was fuelled with biodiesel, n-butanol and biogas, recent and previously published high quality research papers are reviewed to gain insights of performance and emission parameters of these fuels in this section. Methodology and objectives of the research work is presented in chapter three. Details of engine test rig. and various type of apparatus used in experimentation along with the uncertainty analysis is mentioned in this section. In chapter four results for all test fuels is discussed along with reasons for the results obtained. Dual fuel operations are represented for biodiesel, n-butanol and biogas as fuels. Summary of whole thesis and future aspects is mentioned in last section of this work.

Chapter-2

Literature Review

2.1 Overview

Pollution is immense hazardous heinous for the planet today which is dominating not only in metro cities but it is augmenting its limits in rural area also. Expanding rate of diesel engines on road is the primary reason for the pollution owing to which decrepit automobiles are outlawed in New Delhi, India. Combustion of petroleum products in CI engines results in polluting the surroundings, as well as diminishing the fossil fuels at an alarming rate. This evidence has captivated bulk of diesel engine experts to explore for substitute fuel which can reinstate the existing diesel fuel. Biodiesel procured from vegetable oil and animal fat oil, higher alcohols like propanol, pentanol, butanol etc. and gaseous fuels like liquefied petroleum gas, biogas, natural gas, compressed natural gas etc. have attained attention by the investigators in last few lustrums. Biodiesel and higher alcohols are oxygenated fuels which aids in complete combustion of fuel and reducing the lethal gases coming out of tailpipe of the diesel engine whereas gaseous fuels is a preference as alternative fuel due to its unmatched properties like higher auto ignition temperature, homogeneous air-fuel mixture etc. In current chapter, a literature survey was done from highly rated journals and also from technical international conference papers to explore the independent outcome of biodiesel, n-butanol and biogas on a diesel engine. This part includes the literature review containing the effects of various parameters on production of biodiesel and work done with biodiesel, n-butanol, and biogas as fuel in the diesel engine. Detailed review of oxygenated fuels and biogas is provided by giving special focus on performance and emission characteristics. The finding from various researchers is summarized in form of tables.

2.2 Effect of various parameters on biodiesel production

Biodiesel is a fuel that can be obtained from vegetable and animal fats by consuming their fatty acids. It has been one of the most desired fuels as an alternative to diesel owing to its properties which are very much comparable to diesel fuel as claimed by numerous researchers which makes biodiesel, an appropriate substitute fuel to be used in diesel engines with inconsequential or no alteration in the engine. Biodiesel contains 10-12% oxygen by weight, has no sulphur, no aromatics, and have high cetane number which assists in minimizing the noxious emanations like CO and HC in relation with conventional diesel. Table 2.1 indicates fuel properties for biodiesel derived from different vegetable oils. It demonstrates that density, viscosity, flash point, cetane number, calorific value, cloud point, pour point and fire point of the biodiesel delivered from the greater part of the oils is significantly more like diesel and can be utilized in diesel engines. It can also be examined from the table that density of almost all the vegetable oils is very much similar to the diesel oil. Except few vegetable oils viscosity is also in range of diesel oil for majority of vegetable oils. Leaving out few vegetable oils all possesses a higher value of flash point than diesel oil. Cetane number is also within permissible limits. Calorific value of few vegetable oils again matches with the diesel oil. Cloud point for Turpentine oil, Hazelnut oil and Sunflower oil is very near to diesel oil. Pour point of Mustard oil, Turpentine oil, Linseed oil, Hazelnut oil and Sunflower oil seems to identical with diesel. Analysis of Fire point is not mentioned by most of the researchers so it is not possible to analyze the same.Various parameters that effect the production of biodiesel are mole ratio, catalyst, reaction temperature, and stirring rate. Table 2.2 shows values of these parameters for biodiesel produced from various oils.

2.2.1 Effect of molar ratio

Yield of alcohol ester to vegetable oil is fundamentally influenced by molar ratio. It has been found by different analysts that separation of methyl esters from glycerin is more difficult due to mixing of excess methanol in glycerin and rise in rate of transesterification with increasing molar ratio of methanol to oil [70-71]. Absorption of free fatty acids shows increase in reaction product with an introductory boost in molar ratio of alcohol to oil [72]. The yield of biodiesel increases from 48.12% to 99.75% when the molar ratio increases from 6:1 to 18:1. Considering that the abundance of methanol would bring about more monetary cost, 18:1 was picked by a few analysts as the generally reasonable molar ratio [73-74]. While some discovered inadequate response for molar proportions over 12:1 on the grounds that the separation of glycerol was muddled and the obvious yield of biodiesel was diminished in light of the fact that a small amount of the glycerol stayed in the biodiesel stage [75-77].

2.2.2 Effect of catalyst amount/type

It was found by the majority of the researchers that with increment in amount of catalyst more viscous fuel is recouped. Subsequently, ideal catalyst amount is 6.0% by weight of oil [70]. It was additionally found that relative substance of unsaturated fat esters in the reaction products owing to utilization of various suggested catalyst [72]. Transformation rate additionally observed to be expanded with an augmentation in catalyst concentration from 2% to 12%. With further increment in catalyst amount, there was little abatement in the conversion efficiency [75].

2.2.3 Effect of reaction temperature

Temperature of the reaction likewise assumes an essential part in choosing the yield level of biodiesel. When compared with low temperature the response rate is discovered quicker at high temperature and ideal temperature of response for the transesterification to create biodiesel is 65°C [70]. An expansion of the process temperature prompts a reduction in the concentration of the basic product [72]. Rising the process temperature additionally enhances the biodiesel yield by more than three times. Higher reaction temperature not only results in more energy consumption, but also requires higher operation pressure to avoid the evaporation of methanol [77-79]. A few analysts found that that ester yield diminishes as the response temperature increments over 55°C [23].

2.2.4. Effect of stirring rate

A few researchers have uncovered that at stirring rate of 60 rpm for a given time the transesterification response is inadequate. Yield of biodiesel at 270 rpm achieves 90% following 3 hour response, if mixing rate is upgraded to 360 rpm it doesn't have any change in biodiesel yield and suggested that mixing pace of 270 rpm is ideal for transesterification reaction [80]. While the majority of the analysts found that with increment in agitation speed the yield of methyl esters increases and at a speed of 700 rpm most extreme yield was obtained [81].

Table 2.1 Properties of various materials used for production of Biodiesel

Oil used	Density (kg/m^3)	Viscosity (m^2/s)	Flash Point (^OC)	Cetane Number	Higher Calorific Value kJ/kg	Cloud Point (^OC)	Pour Point (^OC)	Fire Point (^OC)	Ref. No.
Mahua oil	899	37.18	238	NM	36372	14	15	243	22
Rice Bran Oil	896.4	8.05	173	NM	39030	NM	NM	NM	92
Waste Cooking oil	883	4.94	161	57.1	40111	NM	1	NM	81
Jatropha Oil	870	4.1	180	NM	39900	NM	NM	NM	84
Pine Oil	875	1.3	52	11	42800	NM	NM	NM	93
Mustard Oil	938	6.5	105	NM	NM	6	-13	NM	86
Neem Oil	871	4.63	NM	53.5	41000	NM	NM	NM	87
Cottonseed Oil	864	4.14	NM	52	36800	NM	NM	NM	87
Turpentene Oil	920	2.5	38	38	44400	-15	-23	NM	94

Palm Oil	851	8	270	NM	NM	18	6.7	NM	95
Rapeseed Oil	884	5.5	138.5	51	38200	NM	NM	NM	96
Linseed Oil	852	3.95	151	NM	NM	3.17	-6.25	NM	89
Hazelnut oil	872	4.51	168	53.35	NM	-11	-17	NM	90
Sunflower Oil	882	4.04	179	51.25	NM	-14	-16	NM	90
Castor Oil	896	12.59	124	NM	37931	NM	NM	NM	91
Diesel Oil	820-860	3.5-5	60-80	40-45	42000	-15 to -5	-33 to -15	52 to 96	98

NM –Not mentioned by researcher

Table 2.2 Parameters for Biodiesel Production

Oil Used	Temp. (^{O}C)	Molar Ratio	Catalyst Type	Stirring Speed(R.P.M)	Time (min)	Ref. No.
Mahua Raw oil	60	NM	KOH	500	60	22
Rice Bran Oil	65	6:1	CH3OK	NM	60	79
Waste Cooking oil	100	NM	NM	NM	30	81
Jatropha Oil	60-65	6:1	NaOH	NM	NM	71
Euclyptus Oil	65	NM	CH3OK	NM	60	85
Karanja Oil	60-80	10:1	KOH	NM	NM	77
Mustard Oil	55	NM	NaOH	600	90	86
Neem Oil	55	NM	NaOH	NM	60	87
Cottonseed Oil	55	NM	NaOH	NM	60	87
Palm Oil	65	NM	KOH	700	120	88
Rape Seed Oil	80	NM	$Ca(OH)_2$	60-360	180	80
Linseed Oil	40-60	6:1 to 9:1	NaOH	750	15-180	89
Hazelnut oil	60	6:1	KOH	NM	120	90
Sunflower Oil	60	6:1	NaOH	600	90	90
Castor Oil	80	NM	NaOH	500-600	120	91

NM –Not mentioned by researcher

2.2.5 Free Fatty Acids percentage

Free fatty acids impact fuel properties, yield rate and quality of the fuel. The free unsaturated fats content for Jatropha and Karanja oil is 2.7% and 1.7% respectively [77]. Accordingly, the methyl ester product of the response should likewise incorporate methyl oleate, methyl stearate, methyl a-linolenate, methyl palmitate, methyl linoleate. Methyl oleate originates from two sources, first is the esterification of free unsaturated fat and the second is the transesterification of triglyceride [82]. Table 2.3 shows Chemical structure of various fatty acids.

Table 2.3 Chemical structure of fatty acids [97]

Fatty Acid	Systematic Name	Structure	Formula
Lauric	Dodecanoic	$C_{12}H_{24}O_2$	$C_{12}H_{24}O_2$
Myristic	Tetradecanoic	$C_{14}H_{28}O_2$	$C_{14}H_{28}O_2$
Palmitic	Hexadecanoic	$C_{16}H_{32}O_2$	$C_{16}H_{32}O_2$
Stearic	Octadecanoic	$C_{18}H_{36}O_2$	$C_{18}H_{36}O_2$
Arachidic	Eicosanoic	$C_{20}H_{40}O_2$	$C_{20}H_{40}O_2$
Behenic	Docosanoic	$C_{22}H_{44}O_2$	$C_{22}H_{44}O_2$
Lignoceric	Tetracosanoic	$C_{24}H_{48}O_2$	$C_{24}H_{48}O_2$
Oleic	cis-9-Octadecenoic	$C_{18}H_{34}O_2$	$C_{18}H_{34}O_2$
Linoleic	cis-9,cis-12-Octadecadienoic	$C_{18}H_{32}O_2$	$C_{18}H_{32}O_2$
Linolenic	cis-9,cis-12,cis-15-Octadecatrienoic	$C_{18}H_{30}O_2$	$C_{18}H_{30}O_2$
Erucic	cis-13-Docosenoic	$C_{22}H_{42}O_2$	$C_{22}H_{42}O_2$

Researchers have discovered that free unsaturated fats of crude oil and methyl esters acquired from them are relatively comparative [83]. Table 2.4 shows Chemical composition of vegetable oils.

Table 2.4 Chemical composition of vegetable oil [97]

Vegetable oil	**Fatty acid composition (wt. %)**									
	14:0	**16:0**	**18:0**	**20:0**	**22:0**	**24:0**	**18:1**	**22:1**	**18:2**	**18:3**
Mahua Raw oil	—	16.0–28.2	20.0–25.1	0.0–3.3	—	—	41.0–51.0	—	8.9–13.7	—
Rice Bran Oil	0.4–0.6	11.7–16.5	1.7–2.5	0.4–0.6	—	0.4–0.9	39.2–43.7	—	26.4–35.1	—
Karanja Oil	—	3.7–7.9	2.4–8.9	—	—	1.1–3.5	44.5–71.3	—	10.8–18.3	—
Neem Oil	0.2–0.26	13.6–16.2	14.4–24.1	0.8–3.4	—	—	49.1–61.9	—	2.3–15.8	—
Cottonseed Oil	0	28	1	0	0	0	13	0	58	0
Rape Seed Oil	0	3	1	0	0	0	64	0	22	8
Linseed Oil	0	5	2	0	0	0	20	0	18	55
Sunflower Oil	0	6	3	0	0	0	17	0	74	0

Table 2.5 shows Physical and thermal properties of vegetable oils. It can be seen that Rapeseed Oil has maximum Kinematic viscosity, heating value, carbon residue and ash contents and minimum Cloud point, Density and Sulphur content. Linseed oil has highest density but contains least amount of Kinematic viscosity, Cetane number and heating value. Cottonseed oil acquire best Cetane number though lowest Flash point. Sunflower oil carries top heating value and Flash point in the table.

2.3 Performance and emissions characteristics of biodiesel

Biodiesel may be construed as methyl esters acquired from animal or vegetable oil through transesterification with the addition of methanol [99]. Amidst distinct substitute fuels, biodiesel is treated as most agreeable fuel for the diesel engine [100-101] due to its incomparable properties which include effortless mixing with diesel fuel, enhanced lubricity, biodegradability, uncomplicated storage and transportation, and adaptability with available diesel engines [102].The researchers have employed various vegetable oils for procuring biodiesel such as Jatropha oil [103-106], Neem oil [107-108], Linseed oil[109-112], Soybean oil [113-115], Karanja Oil [116-119], Rapeseed oil [120-122], Waste cooking oil [123-127], Sunflower oil [128-129], Cottonseed oil [130-131], Mahua Oil [132-134], Coconut oil [135-137].

2.3.1 Performance characteristics of biodiesel

Numerous researchers have studied the diesel engine powered with methyl esters to incorporate the performance characteristics like brake power, brake specific fuel consumption, brake thermal efficiency, brake specific energy consumption etc. of the engine relative to natural diesel. Performance characteristics of diesel engines examined by these researchers are presented in this part of the chapter. Table 2.6 presents the analysis of performance characteristics when blends of methyl esters were used in the diesel engine by various researchers.

Kaimal et al. [100] initiated performance analysis on a diesel engine generating 3.7 kW by fuelling it with diesel, rice bran methyl esters, and plastic oil. A continual speed of 155 rpm was kept all along the experimentation. As depicted in Figure 2.1 it was noticed by the researhers that the BSEC of methyl esters was more in comparison with the other two fuels. The lowest value of BSEC was found with fossil diesel. High viscosity and lower calorific value of rice bran methyl esters was the reason for the same. Because of deprived atomization and high viscosity of biodiesel in comparison with regular diesel, BTE of rice bran biodiesel was lowest as compared to remaining fuels. Baseline diesel was found to achieve the highest BTE at all engine loads.

Serin et al. [163] accomplished an experimental investigation utilizing tea seed oil biodiesel blended with conventional diesel and enriched with hydrogen on an unchanged diesel engine at full load conditions and revealed that tea seed oil can be mixed with diesel easily and used on a traditional compression ignition engine. Addition of tea seed oil in the diesel fuel, bring about a growth in the performance characteristics of the engine. An aggravation of 15.03 % as compared to pure diesel was noted in the value of BSFC when 20% tea seed oil biodiesel was blended with diesel. Higher viscidity and density of biodiesel leads to impoverished atomization and lower heating value which consequently increases BSFC.

Table 2.5 Physical and thermal properties of vegetable oils [97]

Vegetable Oil	**Kinematic Viscosity**	**Cetane Number**	**Heating Value (MJ/kg)**	**Cloud point (^{o}C)**	**Pour point (^{o}C)**	**Flash point (^{o}C)**	**Density (kg/L)**	**Carbon residue (wt%)**	**Ash (wt%)**	**Sulphur (wt%)**
Cottonseed Oil	33.5	41.8	39.5	1.7	-15.0	234	0.9148	0.24	0.010	0.01
Rapeseed Oil	37.0	37.6	39.7	-3.9	-31.7	246	0.9115	0.30	0.054	0.0
Linseed Oil	22.2	34.6 3	9.3	1.7	-15.0	241	0.9236	0.22	<0.01	0.01
Sunflower Oil	33.9	37.1	39.6	7.2	-15.0	274	0.9161	0.23	<0.01	0.01

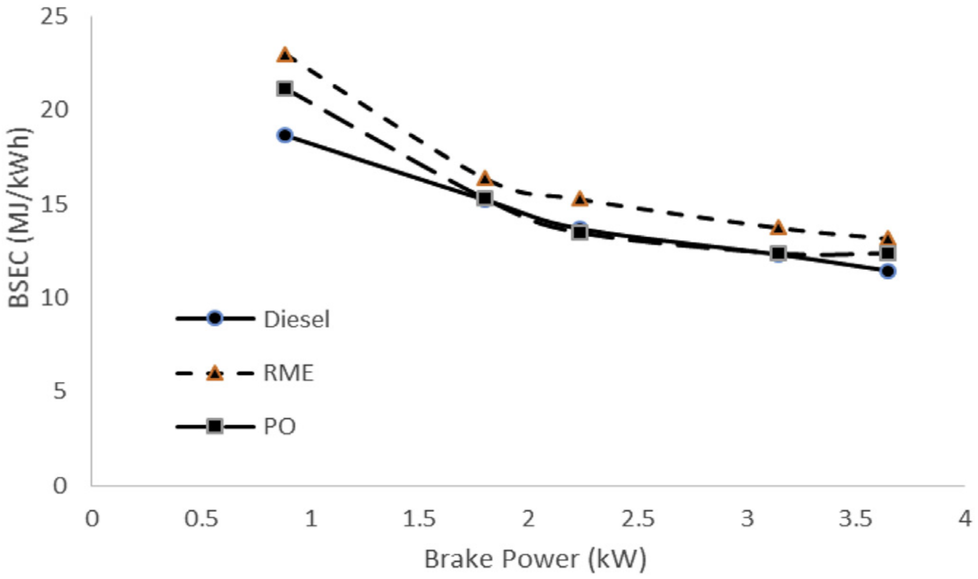


Figure 2.1 Variation of BSEC with Brake Power [100]

Nabi et al. [125] carried out experimental studies on a 4-cylinder, 4-stroke naturally aspirated engine with waste cooking and macadamia biodiesels and diesel blends to investigate the performance characteristics. They distinguished three dissimilar fuel blends with diesel which includes waste cooking oil methyl esters mixed with traditional diesel, macadamia methyl esters mixed with conventional diesel and combinations of waste cooking oil methyl esters, macadamia biodiesel, and diesel fuel. BSEC of the engine was detected to be marginally improved for entire biodiesel fuel blends in relation with baseline diesel. It was reported by the writers that inferior energy content of biodiesel was the culprit for increased BSEC.

Rajak et al. [164] utilized a single cylinder, four-stroke diesel engine to conduct performance test non-edible spirulina microalgae biodiesel blended with baseline diesel fuel with blends constituting 20%, 40%, 60%, 80% and100% biodiesel. BSFC of the engine was noted to be higher for all the blended fuels in relation with ordinary diesel owing to higher energy content and density of the methyl esters. When compared with traditional diesel BTE of all fuel blends were observed to be decreased. They found that BTE was 33.51%, 33.3%, 33.18%, 33.0%, 32.5 % and 32.1% for B0%, B20%, B40%, B60, B80% and B100% respectively at full load condition of engine. Tinier combustion processes owing to high density and viscidity, and inferior enrgy content and volatility of methyl esters lead to decreased BTE.

Table 2.6 Succinct of various performance characteristics of CI engines fuelled with biodiesel blends

S.No.	Reference No.	Biodiesel and its blends	BSFC (g/kWh)	BP (kW)	BTE (%)	BSEC (g/kWh)	Optimized fuel
1	138	B10,B20,B30 B50(Waste cooking oil)	↑	↓	NM	NM	B30
2	139	B10, B20, B30 (Waste cooking oil biodiesel) NM	↑	NM	↓	NM	B30
3	140	B5,B10,B15,B20(Pre-heated palmoil)	NM	↑	NM	NM	B20
4	85	B10, B30, B50, B100 (Eucalyptus oil biodiesel)	↑	NM	↓	NM	B10
5	141	B20, B40,B60,B80 (Waste cooking methyl ester oil)	↓	↓	↑	NM	B40
6	142	B25, B50 (Rice bran oil)	↑	NM	↑	NM	B25
7	143	B10,B20, B30, B100 (Pongamia and waste cooking oil)	↑	NM	↓	NM	B10
8	144	D100,B10,B20(mustard oil methyl ester)	NM	NM	↑	NM	B20
9	108	B10, B20, B30 (Neem oil)	↑	NM	↑	NM	B10
10	145	B20, B40,B60,B80 (Waste cooking methyl ester oil)	↓	↓	↑	NM	B40
11	146	B100 (Waste cooking oil)	↑	NM	↑	NM	B100
12	147	B100 (Jatropha methyl ester and diesel blends)	↑	NM	↑	NM	B100
13	148	AB100, AB90EU10, AB80EU20, AB70EU30, AB60EU40, AB50 EU50 (Aamla and Eucalyptus oil)	↑	NM	↓	NM	AB70EU30
14	149	B100 (Tamanu methyl ester)	↓	NM	↓	NM	B100

15	150	100SME, 20 SME, 100YGME, 20YGME(soyabean oil)	↑	NM	↑	NM	20YGME
16	151	B5,B10,B15,B20(Methyl ester of cottonseed oil)	↓	NM	↓	NM	B20
17	152	B10, B20, B30, B40, B50, B100 (Pongamia oil)	↑	NM	↓	NM	B10
18	153	80% of biodiesel and 20% of pyrolysis of waste tyres	↓	NM	↑	NM	B80
19	154	B20, B40, B60, B80, B100 (Castor biodiesel)	↑	NM	↓	↑	B20
20	155	B50,B70 (waste fried oil methyl ester)	↑	NM	↓	NM	B50
21	12	AB10, AB20, AB30, AB40 (Argemone biodiesel)	↓	NM	↑	NM	AB30
22	156	SME10, SME20, SME30 and SME40(Sal Methyl Ester)	↑	NM	↓	NM	SME 40
23	157	B20, B30, B40, B100(Rice bran biodiesel)	↑	NM	↑	NM	B20
24	158	B10,B30,B50,B80,B100 (Jatropha oil)	NM	NM	↓	NM	B10
25	159	B20,B40,B60,B80 and B100 (Calophyllum Inophyllum linn oil)	↓	NM	↓	NM	B100
26	160	TRFB10, TRFB20, TRFB30 (turkey fat biodiesel)	↑	NM	↓	NM	TRFB20
27	161	JME, Z2JOE15, ATJOE15 (Wood Pyrolysis oil and Jatropha methyl esters)	↑	NM	↑	NM	JME
28	162	B10, B20 (Karanja oil biodiesel)	↑	NM	↓	NM	B10

NM- not mentioned by researcher

Ansari et al. [165] used a direct injection single cylinder four stroke diesel engine to perform an experimental investigation of Polanaga biodiesel at full load conditions. Polanaga biodiesel was mixed with natural diesel and B10, B20, B30, and B40 blends were tested on the engine. BTE of the engine was detected to be reduced as compared to reference diesel when biodiesel was tested. Reduced BTE with biodiesel blends was not validated with any valid reason by the researchers. Fuel blend B30 was reported to have maximum BTE as compared to all other blended fuels.

Akar et al. [166] investigated the performance analysis using an unsurprisingly aspirated, water cooled, four stroke and single cylinder Kirloskar Oil Engine (CI Engine) powered with leftover cooking oil biodiesel and enriched with hydrogen. BTE and BSFC of B10 and B20 mixtures of methyl esters were related with fossil diesel. It was evaluated that BTE was cut off by 0.7% and 1.7% for B10 and B20 fuel blends as related to regular diesel. It was attributed to the fact that biodiesel has more density and viscidity than fossil diesel which results in deprived atomization and partial combustion. Results of BSFC were improved for B10 and B20 blends by 3.8% and 4.9% respectively when compared with regular diesel. Authors addressed that with a decrease in BTE of the engine BSFC will be on the higher side.

Ogunkunle et al. [167] performed experimental tests by fuelling a single cylinder, 5HP diesel engine made by Kipor Machinery Company with mixtures of diesel and sand apple oil methyl esters. B5, B10, B15, and B20 sand apple oil biodiesel and diesel fuel blends were compared with conventional diesel during the experimental process and it was calculated that higher BSFC was attained by using sand apple oil methyl esters blends in relation with traditional diesel. Lower viscosity and the higher energy content were held responsible for decreased BSFC of diesel in comparison with biodiesel blends. It was also concluded that with a rise in the amount of methyl esters in the fuel mixtures BSFC further increased. Highest and lowest BTE was 17.40% for B5 fuel blend at 75% load and 9.60% for B20 at 0% load respectively. BTE for biodiesel fuel blends were observed to be lower in comparison with pure diesel. The researchers mentioned that BTE of the engine can improve due to the high quantity of oxygen and high cetane number of biodiesel and cited examples of other researchers, but were unable to provide the reason for lower BSFC by fuelling the engine with biodiesel blends during their experimentation.

Nair et al. [144] carried out tests on a single cylinder, four stroke, water cooled, constant speed compression ignition engine using conventional diesel and B10, B20, and B30 blends of Neem oil biodiesel. They evaluated performance analysis of the diesel engine and concluded that BSFC was advanced for all tested fuel blends in relation with baseline diesel as illustated in Figure 2.2. BSFC further increased with the addition of neem oil methyl esters in the fuel blends which was because of the inferior calorific value of neem oil methyl esters. Combustion efficiency improves owing to the advanced amount of oxygen in the neem oil methyl esters which was the main reason for increased BTE for B10, B20 and B30 fuel blends at all varying load conditions in comparison with ordinary diesel.

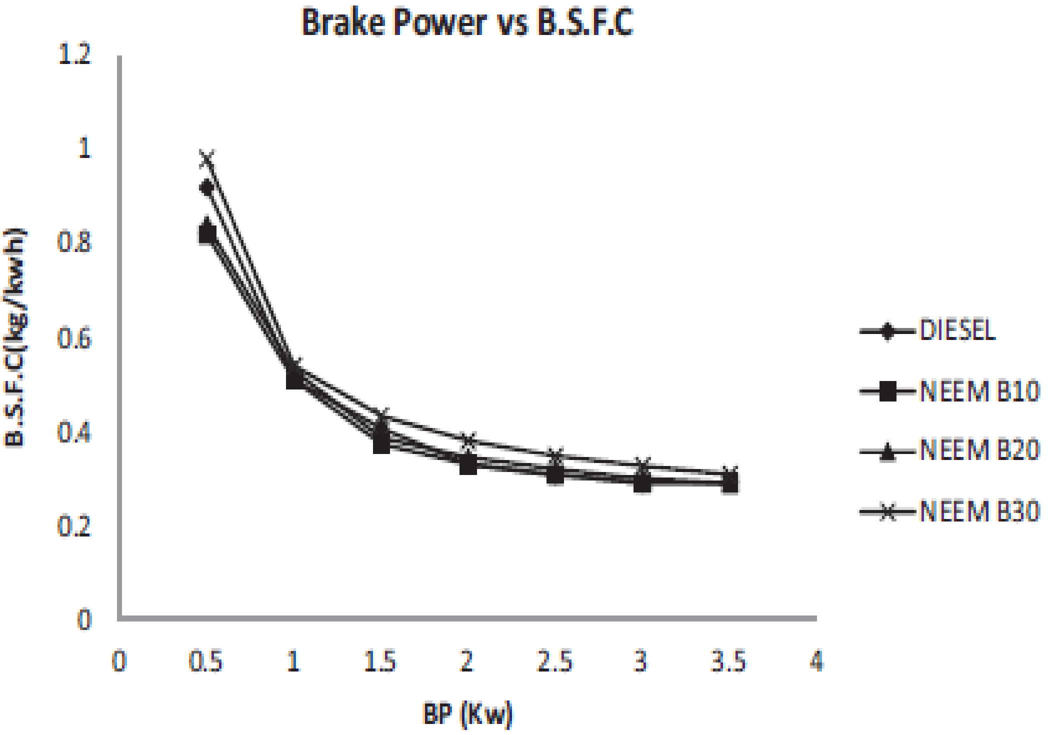


Figure 2.2 Deviation of BSFC with BP [144]

Soto et al. [168] tested diesel and soybean biodiesel fuel blends B20, B50, and Biodiesel on a diesel engine and noted that BSFC of the engine was higher for all other fuel blends owing to more density and viscosity of biodiesel fuel blends. Value of BTE was observed to be reduced with increase in the application of methyl esters in the fuel blends at most of the engine speeds vis-a-vis pure diesel. For a few engine speeds, fuel blend B20 was noted to have more BTE than reference diesel as depicted in Figure 2.3.

Simkic et al. [169] discovered the performance characteristics of a Six-cylinder Power Tech 4VCR, Stage II generation, John Deere 6820 farm tractor by fuelling the engine with diesel and sunflower oil biodiesel fuel blends. As shown in Figure 2.4 BP initially increase up to the engine speed of 2000 min-1 and after that, it subsequently decreased. Torque, BP and BTE reduced with growing methyl esters concentration in the fuel combinations for most of the engine speeds in comparison with baseline diesel. They also reported about BSFC of the engine, in relation with traditional diesel BSFC of the all the combinations of fuels was more at engine speeds ranging from 800 revolutions per minute to 2400 revolutions per minute. The reason for reduced torque, BP and BTE and increased BSFC for blends containing biodiesel were inferior energy content and increased values of density, oxygen content and viscidity of biodiesel.

Yatish et al. [170] conducted a performance test at various loading conditions and consistent engine speed of 1500 RPM on a four-stroke, direct injection diesel engine powered with diesel and bauhinia variegata biodiesel fuel blends. Various biodiesel fuel blends used for experimentation were B10, B20, B30, B40, and B100. BSFC was observed to be inversely proportional to engine loads. Till 25% engine load approximately 65% decrease in BSFC was found for blended diesel fuel as compared to baseline diesel, which decreased a bit after 25% engine load. This was due to the inferior energy content of biodiesel than regular diesel. BTE was observed to decrease with a rise of biodiesel concentration in the fuel mixtures for most of the engine loads. At jam-packed load BTE was noticed to be decreased by 7.8%, 5.8%, 3%, 9.2%, and 17.1% for B10, B20, B30, B40, and B100 respectively. The low calorific value of biodiesel in comparison with fossil diesel was the reason for decreased BTE.

Attia et al. [171] performed experiments by fuelling diesel and castor oil biodiesel blends in a single cylinder, four-stroke, air-cooled, direct injection, naturally aspirated diesel engine to check its performance analysis. B10, B20, B30, and B40 fuel blends were used during the experimentation. At part loads, BSFC was noted to be increased whereas at full loads it shows a decreasing trend. Quality of fuel atomization and mixing of air and fuel was the main reason for this. Values of BSEC of the engine were also very much similar to BSFC values. A rise in BTE was noted with increasing engine loads which was because of better fuel combustion quality at high loading conditions. At low loading conditions, BTE of biodiesel fuel blends were similar to baseline diesel but at full load B30 and B40 were having inferior BTE, B10 was having almost similar BTE, and B20 was having slightly higher BTE in comparison with pure diesel.

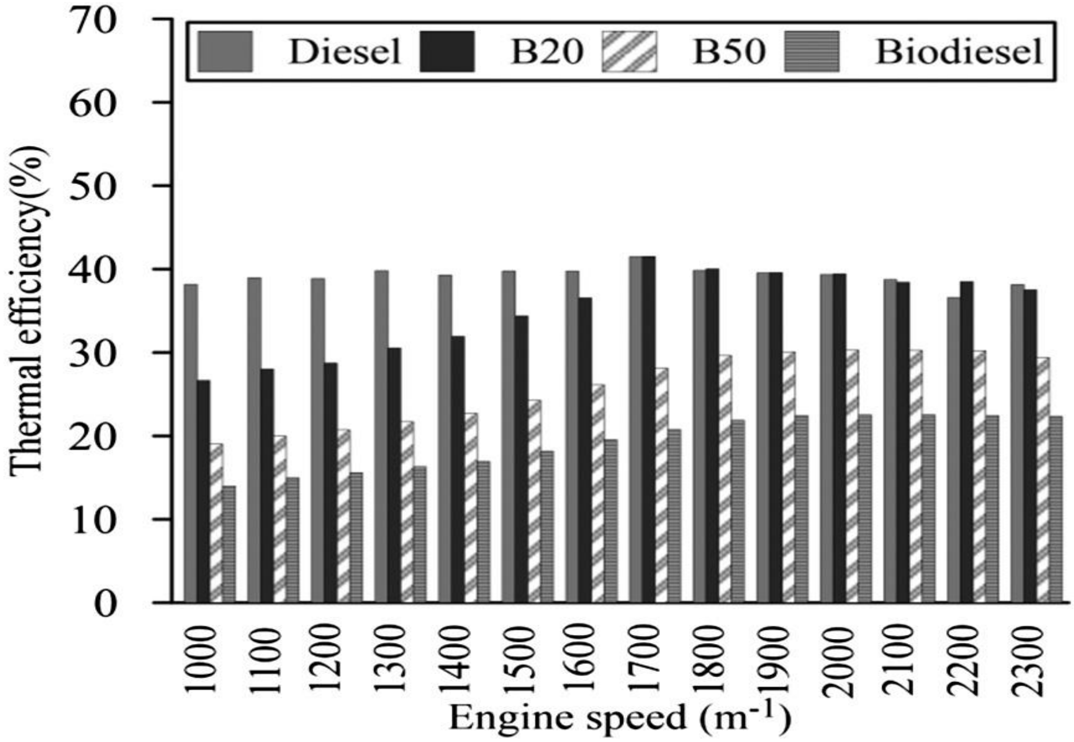


Figure 2.3 Deviation of Brake thermal efficiency with engine speed [168]

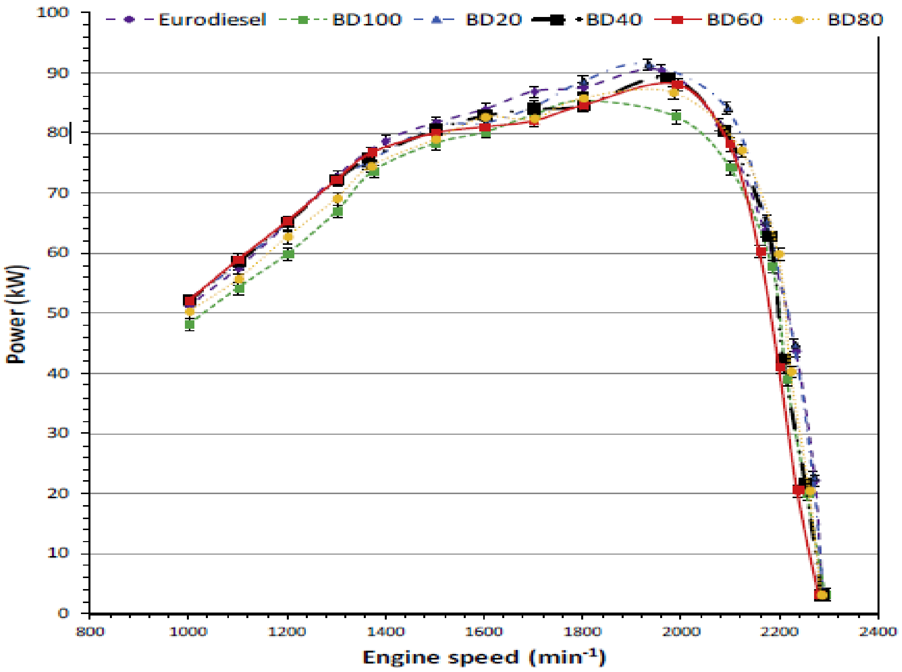


Figure 2.4 Variation of Brake power with engine speed [169]

2.3.2 Emission characteristics of biodiesel

Exhalation parameters of a diesel engine are the main culprits for the effect of pollution on the environment. These include CO, HC, NOx, CO_2, Smoke etc. Various diesel engine experts have performed experimental analysis using biodiesel to study its effect on emanation parameters of the diesel engine. Some of them are presented in this section of the chapter. Investigation of exhalation characteristics of a diesel engine fuelled with biodiesel fuel blends by various scientists is depicted in Table.2.7.

Damodharan et al. [102] fuelled a four-stroke single-cylinder naturally aspirated direct-injection stationary CI engine with fuel combinations comprising diesel, methyl esters of rice bran oil, cottonseed oil and neem to evaluate the performance characteristics relative to conventional diesel. All tests were conducted at an invariable speed of 1500 rpm. HC emissions for all three biodiesel blends were recorded to have decreased in comparison with natural diesel owing to high cetane number of methyl esters which results in less ignition lag and proper combustion of fuel. Conventional diesel was observed to have highest values of CO vis-a-vis biodiesel blends because of the higher quantity of oxygen in methyl esters (Figure 2.5). Relative to all other fuel blends, rice bran methyl esters fuelled engine emitted least CO emissions. The higher quantity of HC radicals and double bonds in methyl esters were held responsible for increased NOx emanations with methyl esters blended fuels in relation with pure diesel. Cottonseed biodiesel blends depicted the least values of NOx emissions amidst all fuels containing biodiesel. Related to diesel, smoke emissions for remaining fuel blends were low because of inferior aromatic HC content of methyl esters than natural diesel.

Serin et al. [163] used blends of diesel and tea seed oil methyl esters to carry out an experimental investigation on a four-stroke diesel engine at varying engine hustles varying from 1000 RPM to 3000 RPM. They studied the effect of biodiesel blends on CO, CO_2 and NOx exhalations of the engine. Owing to the fact that methyl esters are oxygenated fuel it was observed that with the utilization of tea seed oil biodiesel in the fuel blends CO emissions decreased by 23.11% whereas CO_2 increased in comparison with pure diesel. NOx emissions were noted to increase for entire range of fuel combinations containing biodiesel vis-a-vis regular diesel. As reported by authors, the reason for same was higher combustion temperature of biodiesel.

Nabi et al. [125] investigated the effect of using blends of diesel, waste cooking oil biodiesel, and macadamia methyl esters on a 4-cylinder, 4-stroke naturally aspirated diesel engine find out the exhalation parameters of the engine. In comparison with baseline diesel, 27% more NOx exhalations were reported relative to pure diesel. A decrement in of 87%, 53%, and 38% for CO, THC (Figure 2.6), and PM emissions respectively were also noted by the researchers when biodiesel blends were used in comparison with baseline diesel. For the growth in NOx emissions and the reduction in CO, THC and PM emanations, higher amount of oxygen in the biodiesel fuel was held responsible.

Rajak et al. [164] tested B20, B40, B60, B80, and B100 fuel blends using diesel and non-edible spirulina microalgae biodiesel fuel blends and related it with regular diesel. A single cylinder, four-stroke diesel engine was used to conduct the emission analysis and invariable speed of 1500 rpm was maintained during the experimentation. CO_2 emissions were noted to be augmented with rise in biodiesel concentration in fuel blends which was because of the fact that methyl estres are oxygenated fuel. When pure biodiesel was fuelled in the engine CO_2 was noted as 869.07 g/kWh in comparison with diesel having a value of CO_2 as 814.33 g/kWh. In spite of the higher amount of oxygen in the methyl esters, relative to diesel, NOx exhalations were surprisingly reported to be decreased by the authors. HC, CO, and smoke emissions were also found lower for biodiesel blends vis-a-vis pure diesel. The higher quantity of oxygen in biodiesel was the main reason for this.

Ansari et al. [165] performed emission analysis on a direct injection single cylinder four stroke diesel engine using Polanaga biodiesel at various injection timings and pressures. They inspected a small increase in NOx exhalations by using biodiesel compared to pure diesel. B40 fuel blend reported producing the highest NOx emissions with a value of 902 ppm. HC and smoke emissions were observed to be decreased for diesel blended with methyl esters, relative to regular diesel. The higher amount of oxygen and the lower quantity of carbon in biodiesel was the main reason for increased NOx emissions and decreased HC and smoke exhalations.

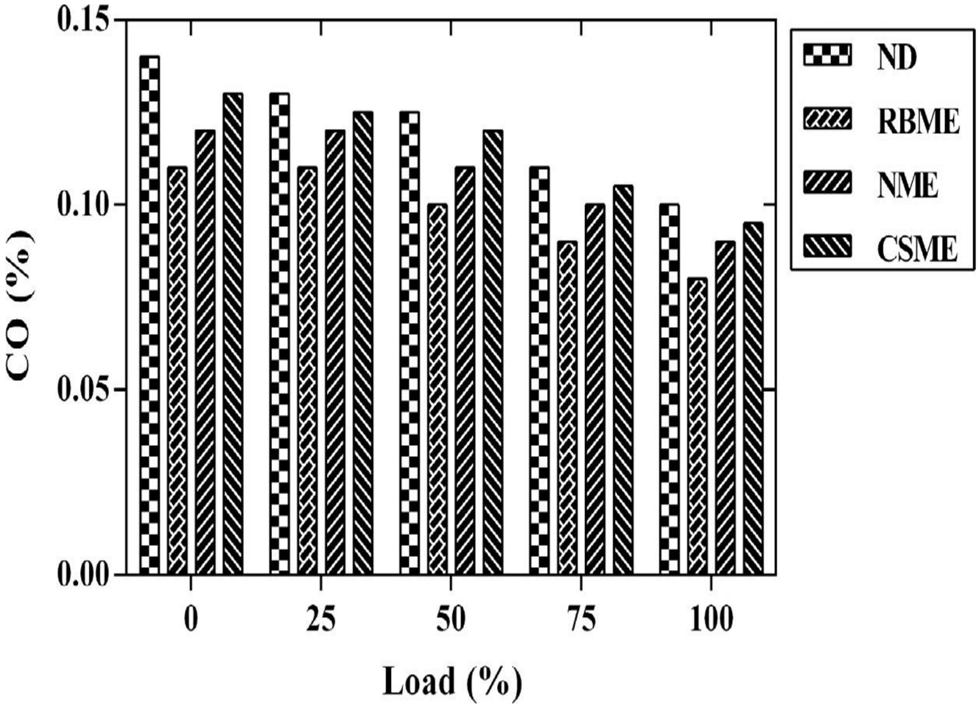


Figure 2.5 Variation of CO emissions with load [102]

Table 2.7 Succinct of various emission characteristics of CI engines fuelled with biodiesel blends

S.No.	Reference no.	Biodiesel and its blends	NOx (g/kWh/%/ppm)	CO_2 (%)	CO (%)	HC (g/kWh)	Smoke (%)	Optimized fuel
1	172	CB10, CB20, CB40 (Rice bran biodiesel)	↑	↓	↑	↑	NM	CB10 and CB20
2	145	D100,B20, B40,B60,B80 (Waste cooking methyl ester oil)	↓	↓	↑	↑	NM	B40
3	138	B10, B20, B30 (Waste cooking oil biodiesel)	↑	↑	↓	↓	↓	B30
4	173	B15(85% palm kernel oil+15% eucalyptus oil)	↑	NM	↓	↓	↓	B15
5	85	B10, B30, B50, B100 (Eucalyptus oil biodiesel)	NM	NM	NM	NM	↓	B10
6	158	B10,B30,B50,B80,B100 (Jatropha oil)	↓	NM	NM	NM	NM	B100
7	143	B10,B20, B30, B100 (Pongamia and waste cooking oil)	↑	NM	↓	↓	NM	B10
8	173	B40	↑	↑	↓	↓	NM	B40
9	108	B10, B20, B30 (Neem oil)	↓	NM	↓	↓	↑	B10
10	159	B20,B40,B60,B80 and B100(Calophyllum Inophyllum linn oil)	↓	↓	↑	NM	↓	B100

11	146	B100 (Waste cooking oil)	↑	NM	NM	NM	NM	B100
12	164	SME10, SME20, SME30 and SME40(Sal Methyl Ester)	↑	NM	↓	↓	↓	SME 40
13	148	AB100, AB90EU10, AB80EU20, AB70EU30, AB60EU40, AB50 EU50 (Aamla and Eucalyptus oil)	↓	NM	↓	↓	↓	AB70EU30
14	149	B100-Tamanu methyl ester and diesel blends.	↑	↑	↓	↓	NM	B100
15	151	B5,B10,B15,B20 (Methyl ester of cottonseed oil)	↑	NM	↓	↓	↓	B20
16	152	B10, B20, B30, B40, B50, B100 (Pongomia oil)	↑	NM	↓	↓	NM	B10
17	153	80% of biodiesel and 20% of pyrolysis of waste tyres	↑	NM	↓	↓	↓	B80
18	154	B20, B40, B60, B80, B100 (Castor biodiesel)	↑	NM	↓	↓	↑	B20
19	141	B20, B40,B60,B80 (Waste cooking methyl ester oil)	↑	↓	↑	↑	NM	B40
20	12	AB10, AB20, AB30, AB40 (Argemone biodiesel)	↑	↑	↓	↓	↓	AB30
21	147	B100(Jatropha methyl ester and diesel blends)	↓	↑	↑	↓	↓	B100

22	157	B20, B40 (Emulsifiers Sorbitan Monoleate and Polyoxyethylene Sorbitan Monoleate)	↑	NM	↓	↓	↑	B20
23	144	D100,B10,B20(mustard oil methyl ester)	↓	NM	↓	↓	NM	B20
24	160	TRFB10, TRFB20, TRFB30 (turkey fat biodiesel)	↑	NM	NM	NM	↓	TRFB20
25	140	B5,B10,B15,B20 (Pre-heated palm oil)	NM	NM	↓	↓	NM	B20
26	161	JME, Z2JOE15, ATJOE15 (Wood Pyrolysis oil and Jatropha methyl esters)	↑	NM	↑	↓	↓	JME
27	138	B10,B20,B30 B50(Waste cooking oil)	↑	↑	↓	↓	NM	B20
28	173	FAME, TBK (Fatty Acid Methyl Ester and Thesz-Boros-Kiraly)	↑	↓	NM	NM	↓	TBK
29	162	B10, B20 (Karanje oil biodiesel)	↑	↑	↓	↓	↓	B10

NM- not mentioned by researcher

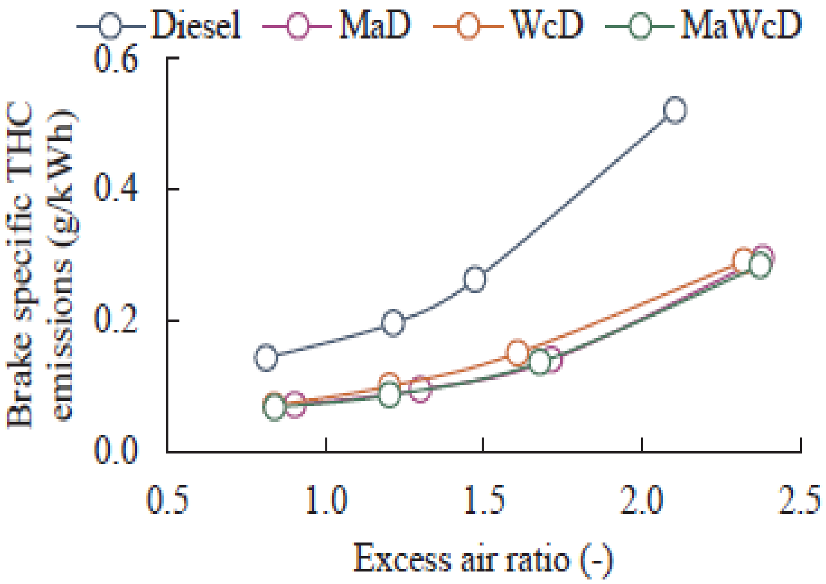


Figure 2.6 Variation of Total Hydrocarbons with excess air ratio [125]

Akar et al. [166] fuelled naturally aspirated, water cooled, four stroke and single cylinder Kirloskar Oil Engine (CI Engine) with diesel, B10 and B20 fuel blends of waste cooking oil methyl esters. While carrying out emission analysis the authors found a noticeable decrease in CO exhalations with methyl esters fuel mixtures relative to fossil diesel. B20 fuel blend was observed to have minimum CO exhalations. CO_2 emissions were found to be increased with biodiesel fuel blends as compared to baseline diesel. Lower oxygen content in diesel fuel was held responsible for decreased CO and increased CO_2 emissions for fuel comprising biodiesel. Relative to diesel fuel NOx emissions also increased when biodiesel was blended with diesel owing to the advanced combustion heat of biodiesel.

Nair et al. [108] also assessed the exhalation characteristics of a compression ignition engine. The authors reported a decrease in CO emissions by mixing neem methyl esters with diesel. It was credited to the statistic that methyl esters are oxygenated fuel. They also noticed decrement in HC exhalations with the concentration of neem oil methyl esters in diesel fuel, owing to impartial combustion of fuel. A decrease in NOx exhalations with the use of biodiesel blends in a diesel engine is not a usual trend, but the authors reported the same as shown in Figure 2.7. Poor mixing of air and fuel blends which give rise to inferior heat generation amount and inferior combustion temperature and consequently inferior NOx formation. Smoke opacity was likewise observed to be increased with biodiesel fuel mixtures in comparison with regular diesel because of the more viscidity of biodiesel leading and lesser atomization and hence slow combustion.

Soto et al. [168] used a turbocharged four-cylinder four-stroke stationary agricultural diesel engine powered with diesel and soybean methyl esters combinations at varying speeds from 1000 rpm to 2300 rpm and full load conditions. Among various emission characteristics, they choose to evaluate only smoke opacity and concluded that smoke emissions decreased with increase in engine speed. As depicted in Figure 2.8 exhalations of smoke were found to be decreased by using soybean methyl esters. This was credited to the statistic that biodiesel has a lower boiling point and the excess amount of oxygen vis-a-vis diesel.

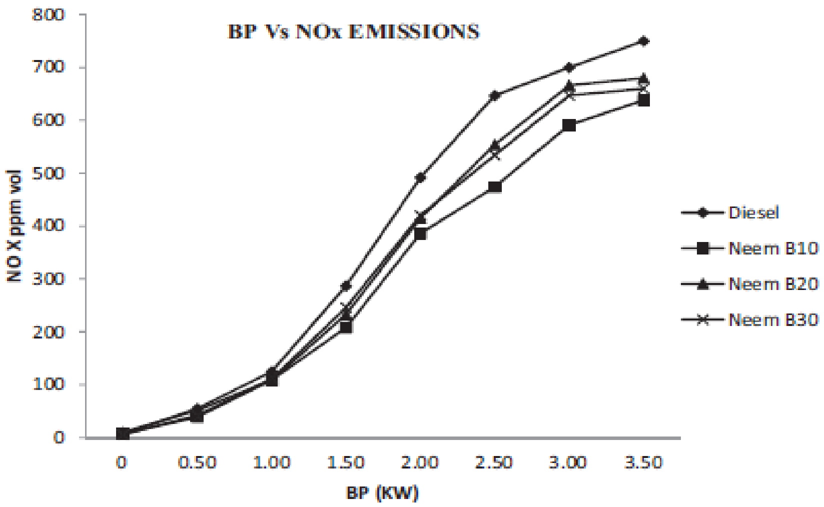


Figure 2.7 Variation of NOx emissions with brake power [108]

Simkic et al. [169] verified the emissions characteristics of a diesel engine of farm tractor in stationary and non-stationary conditions by fuelling the engine with mixtures of sunflower methyl esters and fossil diesel. They tested fuel blends Euro diesel, B20, B40, B60, B80, B100 and concluded that CO emissions increased at lower DPU but decreased at higher DPU with aid of biodiesel vis-a-vis baseline diesel. For all the methyl ester blended fuels NOx emissions increased at all values of DPU in relation with regular diesel. CO_2 exhalations of biodiesel blended fuels were almost similar to diesel at low DPU but at high DPU it increased.

Yatish et al. [170] used B10, B20, B30, B40 and B100 fuel blends to find out emission charaterstics of a diesel engine. CO_2 exhalations for methyl esters blended fuels were observed to be increased as related to fossil diesel for all fuel blends except for B10 at 75% and 100% engine load. B100 fuel blend considerably had the highest value of CO and HC as compared to all other tested fuels. Pure diesel ranks second and noted more CO an HC emissions than B10, B20, B30, and B40. Reason for decreased emissions of B10, B20, B30, and B40 was abundant oxygen in biodiesel. NOx emissions were on the higher side for all fuel blends containing methyl esters in comparison with baseline diesel. Maximum NOx exhalations were reported for B30 at full load conditions. Higher combustion temperature of biodiesel was justification for the same.

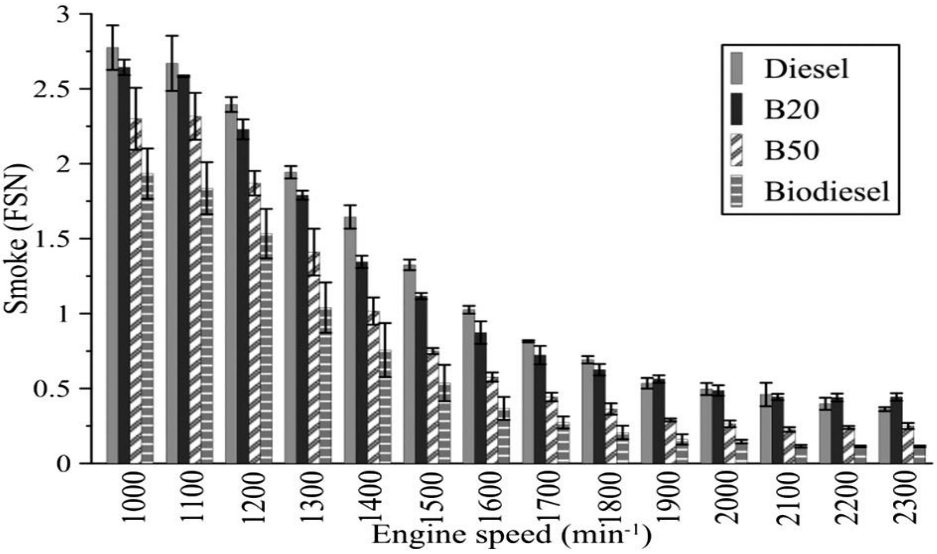


Figure 2.8 Deviation of smoke opacity with engine load [168]

Attia et al. [171] tested the diesel engine to find out the parameters of the emissions coming out of the tailpipe of the diesel engine in variation with brake power of the engine ranging from 0 kW to 6 kW with hiatus of 1 kW. CO emissions were reported to be decreased at low and high engine loads for fuel having biodiesel as a constituent in comparison with pure diesel, whereas at intermediate loads it depicted an increase. Almost same trend was also found for HC emissions. Minimum HC and CO emissions were noted for B10 and maximum for B30 fuel blend. NOx emanations were observed to be more at all engine loads by fuelling the engine with biodiesel fuel blends in comparison with fossil diesel other than B10 at intermediate and high engine loads. Acceleration effect of oxygenated biodiesel was held responsible for this. Smoke opacity was reported to be directly proportional to engine load. The smoke opacity increased again after attaining its minimum value of 30% with an accumulative attentiveness of methyl esters in the fuel blends. B30 fuel blend was selected as optimized fuel for smoke opacity. It was also noticed that CO_2 emissions decreased (Figure 2.9) whereas O_2 exhalations increased (Figure 2.10) with biodiesel blended fuels than fossil diesel. The high amount of oxygen content was ascribed for the same.

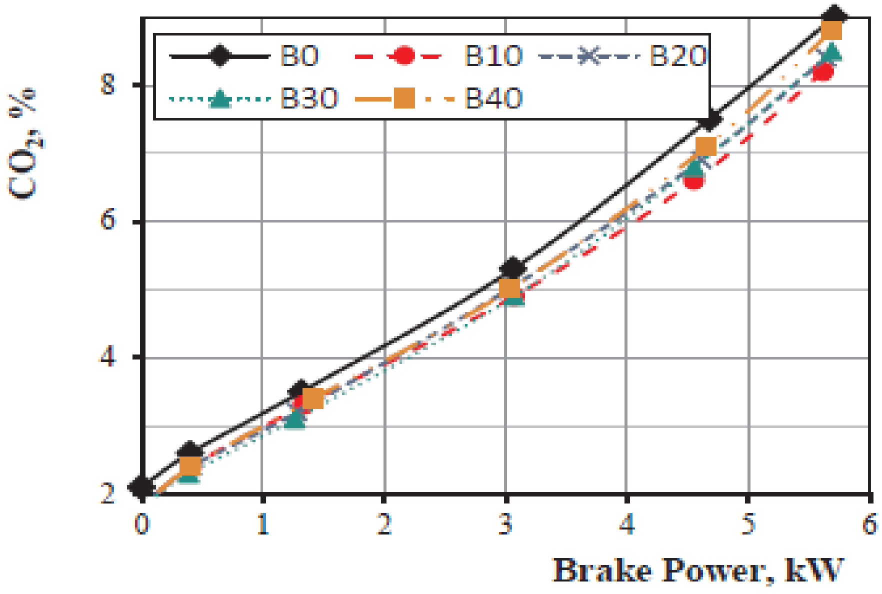


Figure 2.9 Variation of CO2 with brake power [171]

2.3.3 Summary of performance and emission characteristics of biodiesel

It can be established from the literature that methyl esters can be mixed with pure diesel to be utilized in diesel engines and may also be used as neat, but while using neat biodiesel the engine may be damaged owing to the greater viscidity of the methyl esters. The consequences of the referenced papers, when merged together depict that when mmethyl esters are mixed with traditional diesel it results in the underneath impacts on the performance and exhalation parameters of the engine:

- An incement in BSFC and BSEC is found by a majority of researchers by using biodiesel blends vis-a-vis traditional diesel. Higher viscidity and density, and inferior calorific value of methyl esters results in impoverished atomization and lower heating value which consequently increases BSFC and BSEC.

- By fuelling the diesel engine with biodiesel BTE and BP is noticed to be on the lower side relative to natural diesel by the major part of diesel engine experts which is attributed to the tinier combustion processes owing to high density and viscidity, and inferior heating value and volatility of methyl esters lead to decreased BTE.
- NOx exhalations are reported to enhance by the bulk of researchers. The higher quantity of HC radicals and double bonds in methyl esters, higher combustion temperature and amount of oxygen was held responsible for this.
- It is established by most of the researchers that emissions of CO_2 and O_2 increases whilst CO exhalations decrease with fuel blends incorporating biodiesel owing to the higher content of oxygen in the biodiesel.
- HC emissions of biodiesel fuel blends are lower owing to high cetane number and more oxygen content of biodiesel which results in less ignition delay and proper combustion of fuel.
- Lower aromatic HC content and higher oxygen amount of methyl esters than natural diesel is the reason for lower smoke opacity for biodiesel blends relative to pure diesel as evaluated by maximum scholars.

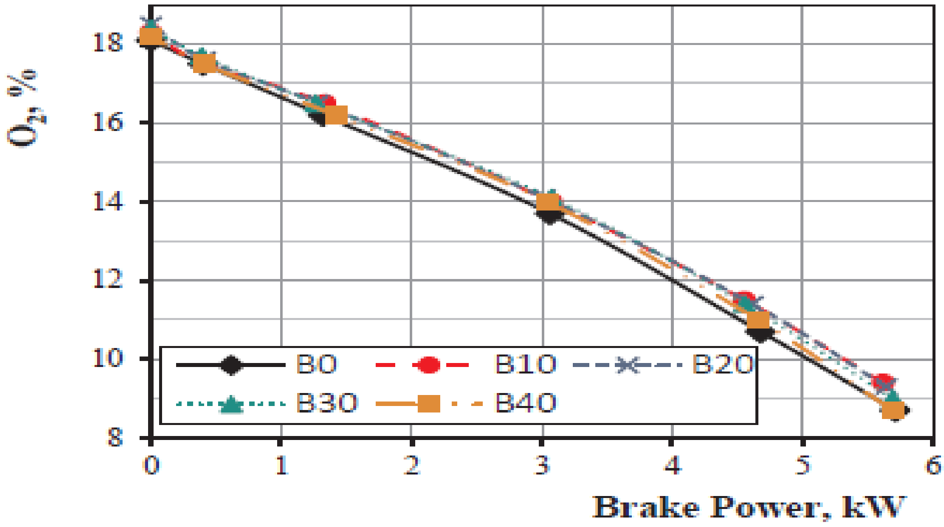


Fig. 2.10 Deviation of O2 with brake power [171]

2.4 Performance and emission characteristics of n-butanol

Alcohols have the tendency to mix with natural diesel as well as other substitute fuels which can improve the performance and emanation characteristics of the engine [174]. n-butanol has been considered as one of the dominating fuel additives to control air pollution and increase the efficiency of the diesel engine by numerous scientists [175-176]. It can be procured from non-conventional resources and is venomous alcohol [177-178]. Properties of n-butanol include high volatility, low cetane number, and viscosity, sufficient amount of oxygen and it can be easily blended with regular diesel [179-181]. Higher alcohols like propanol [182-186], butanol [187-192], pentanol [193-195], Hexanol [196-197], Octanol [198-199].

2.4.1 Performance characteristics of n-butanol

Various performance parameters of n-butanol are discussed in this section of the paper. n-butanol has been used as fuel additives by so many researchers to check its numerous performance characteristics. Summary of performance parameters of the diesel engine fuelled with mixtures of n-butanol by numerous diesel engine experts is presented in table 2.8.

Wakale et al. [219] distinguished B5, B10 and B20 fuel blends of n-butanol with pure diesel in a modified single cylinder CRDI engine. The injection pressure of 800 bars and BMEP of 3.48 was kept during experimentation. Authors reported that BSFC of the engine was almost identical for B10 and B20 fuel blends of n-butanol. A decrement in BSFC was noticed when the engine was fuelled with fuel blend consisting 5% n-butanol in analogy with fossil diesel as depicted in Figure 2.11 BTE also illustrated the same conclusions for B10 and B20 fuel blends. Maximum BTE was found for B5 fuel blend. This was associated with the fact that the equivalence ratio of B5 fuel blend was less as compared to all other fuels.

Table 2.8 Succinct of various performance characteristics of CI engines fuelled with n-butanol blends

S.No.	Reference No.	Fuel used	BSFC (g/kWh)	BP (kW)	BTE (%)	BSEC (g/kWh)	Optimized parameter
1	200	D85B10 P5, D80B10P10, D75B10P15 (papaya seed oil methyl ester)	NM	NM	↑	NM	D80B10P10
2	201	D60B10nBu30, D50B30nBu20, D30B30nBu40, D30B10nBu60, D20B20nBu60 (cotton oil methyl esters)	↑	↓	↓	NM	D60B10nBu 30
3	202	D60B30E5nb5, D40B50E5nb5 (Trap grease biodiesel, ethanol)	↑	NM	NM	NM	D60B30E5n b5
4	188	nb5, nb10, nb15 nb20 (Diesel)	↑	NM	↑	NM	nb10
5	203	D85 nb15, D70 nb30 (Diesel)	↑	NM	NM	NM	D85 nb15
6	204	JEE5Bu15D80 JEE10Bu10D80 JME5Bu15D80 JME10Bu10D80 (Jatropha methyl esters)	↑	↓	↑	NM	JME10Bu10 D80
7	205	D70B15nBu15, D60B20nBu20, (vegetable oil methyl esters)	NM	↑	NM	NM	D70B15nBu 15
8	206	nbu10B10, nbu20B20	↑	↓	↑	NM	nbu10B10
9	207	DnB40 (Diesel)	NM	NM	↑	NM	DnB40
10	208	DnB5, DnB25, DnB35 (Diesel)	↑	NM	↓	NM	DnB25

11	127	D50B45nBu5, D45B45nBu10 D40B40nBu20 (Waste cooking oil methyl esters)	↑	NM	NM	NM	D40B40nBu20
12	209	Nb10	↑	NM	↑	NM	Nb10
13	210	D95nB5, D90nB10, D85nB15, D80nB20 (Diesel)	↑	NM	↓	NM	D90nB10
14	211	D92nB8, D84nB16 (Diesel)	↑	NM	↑	NM	D84nB16
15	212	D80nB20 (Diesel)	↓	NM	NM	NM	D80nB20
16	213	D80nB20, D60nB40 (Diesel)	↑	NM	NM	NM	D80nB20
17	214	D80nB20, D70nB30, D60nB40 (Diesel)	↑	NM	↑	NM	D80nB20
18	215	D92nB8, D84nB16, D76nB24 (Diesel)	↑	NM	↑	NM	D84nB16
19	216	Nb20	↑	NM	↑	NM	Nb20
20	217	D90nB10, D80nB20, D70nB30, D60nB40 (Diesel)	↑	↓	↓	NM	D70nB30
21	218	B10 nb10, B20 nb20 (Rice bran biodiesel)	↑	NM	↓	NM	B10 nb10

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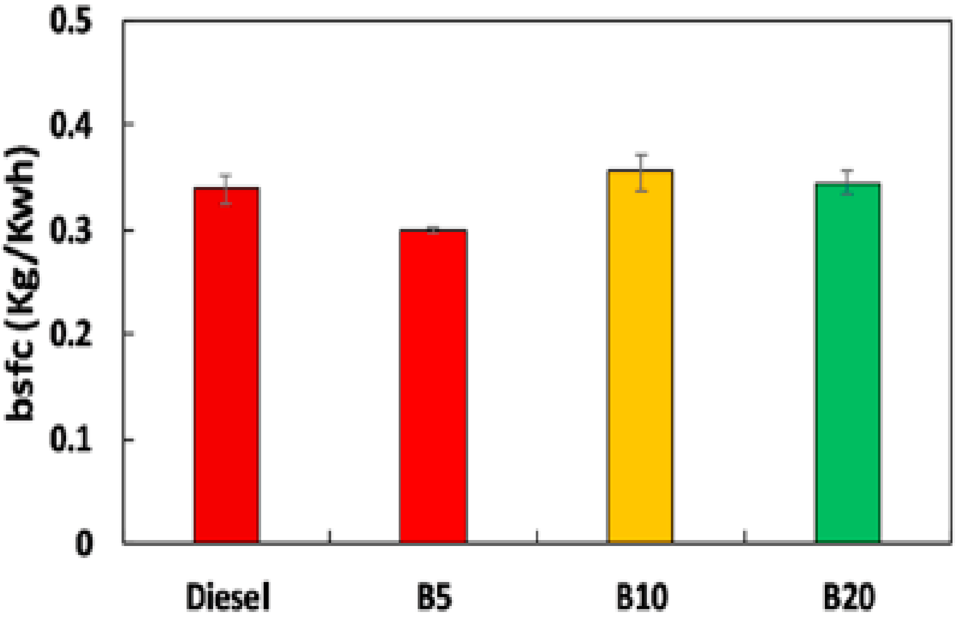

Figure 2.11 BSFC of the neat diesel, 5%, 10% and 20% n-butanol respectively at 3.48 BMEP [219]

Sahin et al. [220] performed a series of experiments using a 4 cylinder, 4-stroke, water-cooled, turbocharged, common-rail injection diesel engine fed with blends of n-butanol and natural diesel comprising 2%, 4% and 6% n-butanol by volume. Value of BSFC was observed to be reduced a bit in comparison with regular diesel when nB2 fuel blend was considered. At specific loading conditions and engine speeds, BSFC increased for nB4 and nB6 in relation with traditional diesel.

Algayyim et al. [221] considered performance characteristics of a diesel engine on engine speeds of 1400 rpm, 2000 rpm, and 2600 rpm. Figure 2.12 illustrates that torque of the engine was observed to be decreased for n-butanol fuel combinations when related with diesel. Same results were obtained for BP. The chief reason for this was the lower calorific value of n-butanol in comparison with fossil diesel. 20nB was found to have the highest BTE as compared to all other fuel blends, whereas natural diesel obtained the lowest value at all ranges of engine speeds. Increased combustion efficiency and rapid energy release due to improved air-fuel mixing and lower cetane number of n-butanol was justification for the same. BSFC also had an increasing trend for all n-butanol fuel combinations in relation with natural diesel owing to the lower calorific value of higher alcohols.

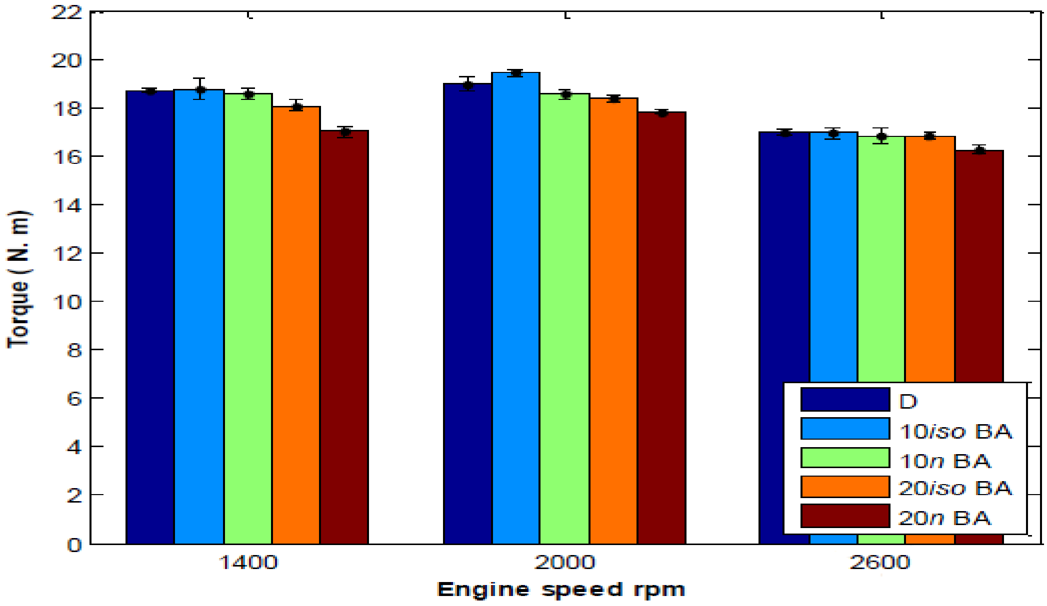

Figure 2.12 Variation of torque with engine speed [221]

Ors et al. [222] assessed the performance parameters of a diesel engine at 100% engine load within engine speed varying from 1000 rpm to 3000 rpm with 200 rpm break. They fuelled the engine with waste cooking oil methyl esters, n-butanol, and Ti nanoparticles. It was observed by the authors that engine power and engine torque for the blend containing biodiesel and n-butanol was inferior as compared to natural diesel for all engine speeds because ofthe inferior heating value of n-butanol vis-a-vis pure diesel. Increased BSFC was recorded for fuel blend comprising methyl esters and n-butanol in comparison with traditional diesel. It was credited to the statistic that n-butanol is an oxygenated fuel and have lower calorific value.

Huang et al. [223] compared blends of n-butanol with pure diesel to test the performance characteristics of a diesel engine. The experimental study was accompanied at BMEP ranging from 0.4 MPa to 1.6 MPa with an interval of 0.4 MPa. n-butanol fuel blend comprising 20% n-butanol and 80% diesel was inflamed in the engine and BSFC was figured by mathematical calculations. The consequences interpret that BSFC of the engine was more for BD20 fuel blend in comparison with natural diesel at all BMEPs of the engine. Minimum BSFC was recorded by pure diesel at BMEP of 1.6 MPa.

Mohebbi et al. [224] fuelled a diesel engine with n-butanol blends comprising B0, B20, and B40 and tested the engine for examining its performance parameters at an invariable speed of 1800 rpm. The thermal efficiency of the engine was noted to be decreased for n-butanol fuel blends as compared to B0 as a result of diffusion combustion features that dominated over other parameters as shown in Figure 2.13.

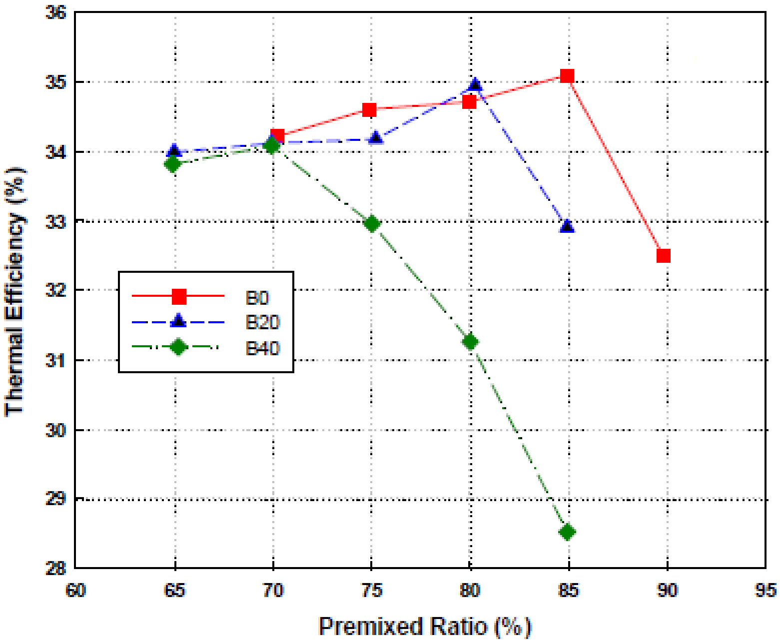

Figure 2.13 Deviation of thermal efficiency with premixed ratio [224]

Celibi et al. [225] selected a 4-cylinder, 4-stroke, water cooled diesel engine with 17 kW maximum brake power and tested n-butanol fuel combinations comprising 10% and 20% n-butanol. The authors reported an increase in the value of BSFC for all fuel blends comprising n-butanol vis-a-vis pure diesel. The increment in BSFC was due to the fact that n-butanol increases efficiency and combustion of the engine. A decrease in BTE was observed by using n-butanol fuel blends in the engine related to natural diesel owing to low cetane number and heating value of n-butanol.

Yesilyurt et al. [226] carried out performance tests by fuelling biodiesel and n-butanol fuel blends in a diesel engine. The speed of the engine was kept between 1000 rpm to

3200 rpm during the experimentation. It was reported by the researchers that there was a decrease in BP of the engine with an increasing concentration of n-butanol in fuel blend when compared with diesel fuel (Figure 2.14). Low energy content and cetane number of n-butanol were accountable for that. Leakage also occurs in the fuel pump and injector owing to low viscosity and density of fuel blends comprising n-butanol. With the addition of n-butanol in fuel blends BSFC was detected to be increased in comparison with baseline diesel. This was referred to the evidence that the heating value of n-butanol is less than pure diesel. Highest BSFC was noted at the engine speed of 3200 rpm. Due to the fact that n-butanol is an oxygenated fuel an increment was noticed in values of BTE for n-butanol fuel combinations in relation with fossil diesel.

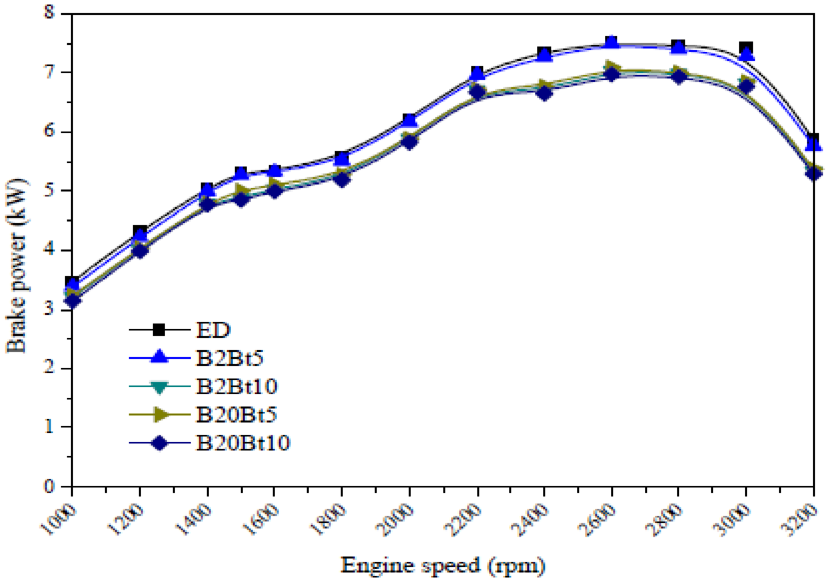

Figure 2.14 Variation of brake power with engine speed [226]

Huang et al. [227] carried out experiments on a four-cylinder, turbocharged diesel engine equipped with a common rail fuel injection system to evaluate performance characteristics of the engine. Fuel blend comprising 20% n-butanol was compared with natural diesel during the experimentation. The lower heating value of n-butanol resulted in more fuel consumption by n-butanol blend to obtain alike power. This was the considerable logic for increased values of BSFC for B20 as distinguished with reference diesel for all values of injection pressure.

Jeevahan et al. [228] conducted a performance evaluation of a single cylinder four stroke diesel engine with a maximum speed of 2000 rpm by fuelling it with diesel and n-butanol. Value of BTE was reduced with improving concentration of n-butanol in the fuel combinations. More heat was consumed as a consequence of high vaporizing heat of n-butanol and hence aids in lowering BTE. The combustion efficiency of the engine also decreases with n-butanol due to its low cetane number; this was the secondary reason for low BTE. The high heat of vaporization of n-butanol also resulted in improved BSFC for n-butanol combinations vis-a-vis fossil diesel by absorbing more amount of heat during the combustion process. Lower viscosity of n-butanol leads to complete consumption and hence increased BSFC.

2.4.2 Emission characteristics of n-butanol

n-butanol has been proved as an alternative fuel that can assist in reducing the catastrophic pollution generating gases by immense scientists. The exhalation parameters of n-butanol evaluated by various researchers are presented here. Table 11.shows numerous performance parameters of the diesel engine when n-butanol blends were used as fuel.

Wakale et al. [219] performed an investigational examination to study the exhaust exhalations of a diesel engine corresponding to split injection, fuel injection pressure and the start of injection. They were successful in reducing NOx emissions of the engine relative to baseline diesel. Among fuel blends containing n-butanol, maximum NOx emissions were noted for B10. The minimum value for NOx exhalations was found at 4^{o} BTDC for B5 fuel blend.

Nabi et al. [125] used fuel blends containing 4% and 6% n-butanol and compared both fuels with regular diesel. As shown in Figure 2.15 they found a decrement in UBHC emissions by utilizing Bu4 and Bu6 fuel blends in comparison with diesel. Reduction of 34% and 36% HC emissions were discovered with Bu4 and Bu6 respectively when compared to regular diesel. Highest NOx emissions were noticed for Bu6 amidst all fuels used during the experimentation. Minimum NOx exhalations of 0.28 g/kWh were recorded for pure diesel.

Table 2.9 Succinct of various performance characteristics of CI engines fuelled with n-butanol blends

S.No.	Reference No.	Fuel used	NOx (g/kWh/%/ppm)	CO(%)	CO_2 (%)	HC (g/kWh)	Smoke (%)	Optimized parameter
1	226	nb 5, nb10, nb20 (Diesel)	↑	↓	↑	↓	↑	nb10
2	200	D85B10 P5, D80B10P10, D75B10P15 (papaya seed oil methyl ester)	↑	↓	NM	↓	↓	D80B10P10
3	201	D60B10nBu30, D50B30nBu20, D30B30nBu40, D30B10nBu60, D20B20nBu60 (cotton oil methyl esters)	NM	↓	NM	↓	NM	D50B30nBu20
4	202	D60B30E5nb5, D40B50E5nb5 (Trap grease biodiesel, ethanol)	↑	↓	NM	↓	NM	D60B30E5nb5
5	188	nb 5, nb10, nb15 nb20 (Diesel)	↓	↓	NM	↑	↓	nb10
6	230	nb30, nb40, nb50 (Diesel)	↑	NM	NM	NM	↓	nb30
7	203	D85 nb15, D70 nb30 (Diesel)	↓	↑	NM	NM	NM	D85 nb15
8	231	Nb5, nb10	↓	NM	NM	NM	↓	Nb10
9	232	Nb2.5, nb5, nb10	↓	NM	NM	NM	NM	Nb5
10	206	nbu10B10, nbu20B20	↑	↓	NM	↑	NM	nbu10B10

11	204	JEE5Bu15D80 JEE10Bu10D80 JME5Bu15D80 JME10Bu10D80 (Jatropha methyl esters)	NM	↓	↑	↓	NM	JME10Bu10D80
12	216	Nb20	↑	NM	NM	NM	NM	Nb20
13	191	D80nb20	↓	↑	NM	↑	NM	D80nb20
14	208	DnB5, DnB25, DnB35 (Diesel)	↓	↓	↓	↑	↓	DnB25
15	229	Nb5, nb10, nb20	↑	NM	NM	NM	↓	Nb20
16	127	D50B45nBu5, D45B45nBu10 D40B40nBu20 (Waste cooking oil methyl esters)	↑	↑	NM	↑	NM	D40B40nBu20
17	233	D80nB20, D60nB40 (Diesel)	NM	↓	NM	↓	NM	D80nB20
18	210	D95nB5, D90nB10, D85nB15, D80nB20 (Diesel)	↓	↓	NM	↑	↓	D90nB10
19	211	D92nB8, D84nB16 (Diesel)	↓	NM	NM	NM	NM	D84nB16
20	234	Nb10, nb20, nb30, nb40, nb50	↓	NM	NM	NM	↓	Nb20
21	213	D80nB20, D60nB40 (Diesel)	↑	↑	NM	↑	NM	D80nB20
22	215	D92nB8, D84nB16, D76nB24(Diesel)	↓	NM	↑	↓	↓	D84nB16

23	214	D80nB20, D70nB30, D60nB40 (Diesel)	NM	↓	NM	↑	↓	D80nB20
24	235	D80nB20	↓	NM	NM	NM	↓	D80nB20
25	209	Nb10	↓	↓	NM	NM	NM	Nb10
26	236	D70nB30	↓	↓	NM	↓	↓	D70nB30
27	187	D60nB40	↑	↑	NM	↑	↓	D60nB40

NM- not mentioned by researcher

Properties of n-butanol, the quantity of oxygen in fuels and in-cylinder gas temperature were held responsible for higher NOx emissions for blends containing n-butanol relative to fossil diesel.

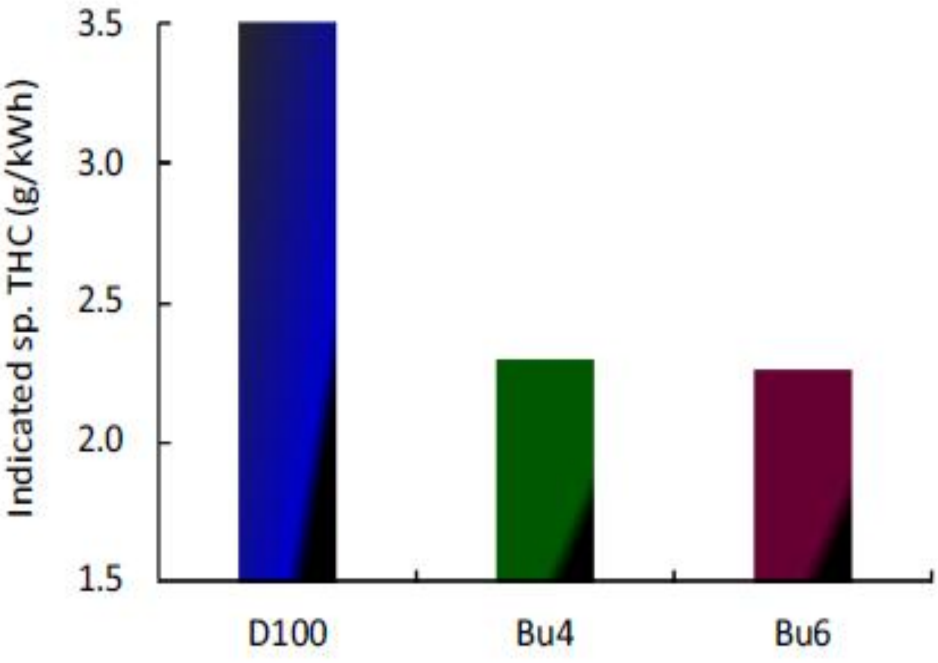

Figure 2.15 Indicated specific UBHC emissions with reference diesel and n-butanol blends under the ESC test [125]

Sahin et al. [220] utilized a diesel engine and conducted experiments at engine speeds of 2000 rpm (engine load 145 and 132 Nm) and 4000 rpm (engine load 100 and 96 Nm) to evaluate emanation characteristics of the engine using n-butanol fuel combinations. At specific loading conditions and engine speeds NOx emissions were recorded to be least with nB2 blends among all other fuels used. Increasing of excess air coefficients inside the engine cylinder was less adequate over the reducing combustion temperature which was the major reason for lower NOx exhalations for nB2. Whereas its opposite was observed for nB4 and nB6 blends which resulted in increased NOx emissions for these fuel blends than traditional diesel. Fuel blends containing n-butanol have a lower viscosity than regular diesel which resulted in smaller fuel droplet size and hence NOx emissions increases. The same reason was given by the authors for higher HC exhalations by using n-butanol blends in comparison with diesel. CO_2 emissions were concluded to be enhanced with n-butanol relative to natural diesel because of the higher quantity of oxygen in n-butanol which resulted in impartial combustion. Because of the low cetane number of n-butanol smoke opacity for blends comprising n-butanol were having decreased smoke opacity as compared to neat diesel (Figure 2.16).

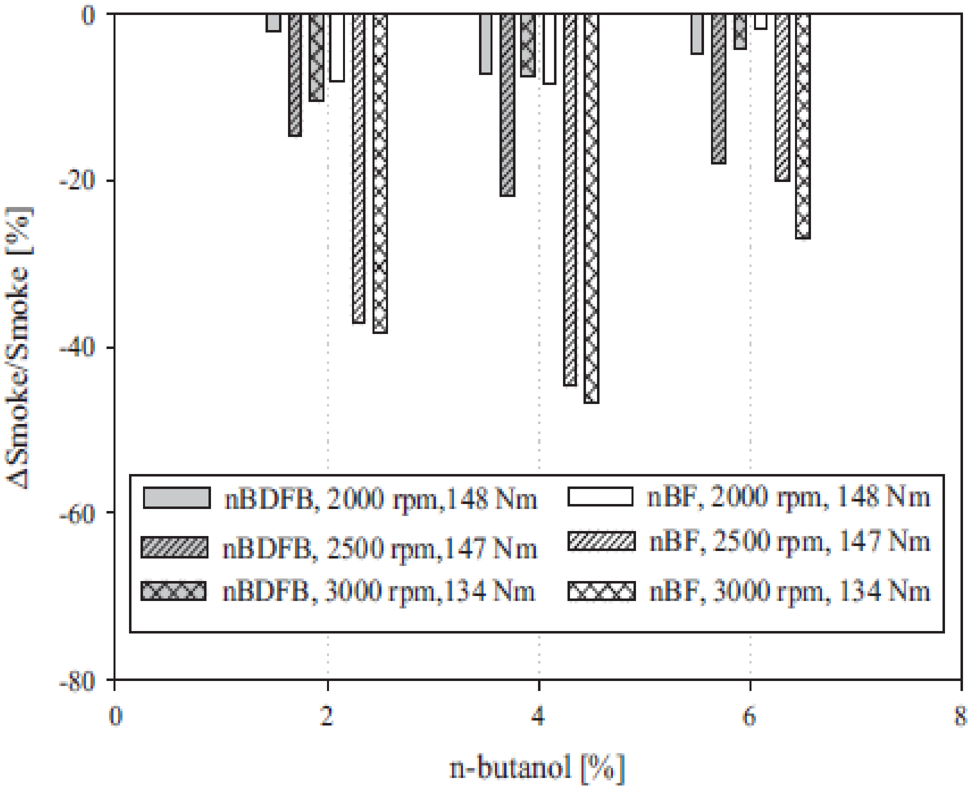

Figure 2.16 Deviations of the variation ratios of smoke at different engine speeds for different n-butanol ratios [220]

Algayyim et al. [221] fed a direct injection diesel engine with fuel combinations containing 10% and 20% n-butanol and performed emission tests at full loading conditions. HC emissions recorded a decrement by using both n-butanol fuel blends relative to reference diesel. Minimum HC exhalations were found for nB20 at 1400 rpm. The higher amount of heat of vaporization of n-butanol was reported to aid in a decrease in HC emissions. NOx exhalations were also observed to decrease slightly with the blending of n-butanol in fuel combinations vis-a-vis baseline diesel. Least value of NOx emissions was found for nB20 at 2600 rpm. The higher amount of oxygen and a lower combustion temperature in n-butanol was accountable for this. CO_2 emissions were also having a decreasing trend with all n-butanol comprising fuel blends in comparison with natural diesel at low engine speed (Figure 2.17). Reason for this was that at low engine speed lean mixture was formed. At high speeds increased CO_2 emissions were noted for butanol blends owing to the higher amount of oxygen in-butanol fuel blends.

Zhu et al. [237] compared a fuel blend of n-butanol having 30% n-butanol with fossil diesel on a four-cylinder direct injection diesel engine at different intake oxygen concentrations and revealed that CO exhalations were on higher side for B30 in relation with natural diesel at all intake oxygen concentrations. Figure 2.18 depicts that NOx exhalations were slightly less for B30 fuel blends in comparison with D100 as a result of decreased in-cylinder temperature by using n-butanol. Smoke emissions were also recorded lower for n-butanol fuel blend than pure diesel. The researchers were not able to provide an appropriate explanation for this.

Ors et al. [222] utilized four-stroke single cylinder water cooled DI diesel engine and an emission analyzer to find emission characteristics of various fuel blends. The blend containing n-butanol and biodiesel was named as B20But10 by them. It was concluded by the researchers that lower amount of CO exhalations were recorded for B20But10 blend vis-a-vis diesel fuel because of the achievement of complete combustion with n-butanol due to the statistic that n-butanol has more oxygen than reference diesel. The same reason was presented by the authors for the higher amount of CO_2 and HC exhalations emitted by B20But10 fuel blend than diesel. Minimum NO emanations were recorded for B20But10 fuel combinations in relation with all other fuels used during the experimentation due to the fact that nitrogen and oxygen do not react at low in-cylinder temperature owing to low heat of vaporization of n-butanol. Pure diesel was found to have maximum NO emissions. Smoke opacity was also low for B20But10 fuel blend relative to natural diesel. Carbon atoms and a high amount of oxygen atoms available in n-butanol reacts easily and hence results in low smoke formation for blends containing n-butanol.

Huang et al. [223] fuelled a four-cylinder diesel engine with BD 20 and D100 fuel blends. The exhaust emissions of the engine were evaluated by performing experiments at a constant speed of 1600 rpm. Soot emissions for pure diesel were reported to be more in comparison with BD20 fuel blend due to high volatility, more amount of oxygen and low content of aromatic hydrocarbon in n-butanol. Increased air-fuel ratio owing to high oxygen content in n-butanol resulted in increased NOx exhalations in BD20 in relation with reference diesel. Figure 2.19 depicts that CO emissions were also on the higher side for n-butanol blend in comparison with natural diesel. Reason reported for this was inferior cetane number and higher latent heat of vaporization of n-butanol. Higher volatility of n-butanol resulted in decreased THC for entire range of engine loads vis-a-vis diesel fuel.

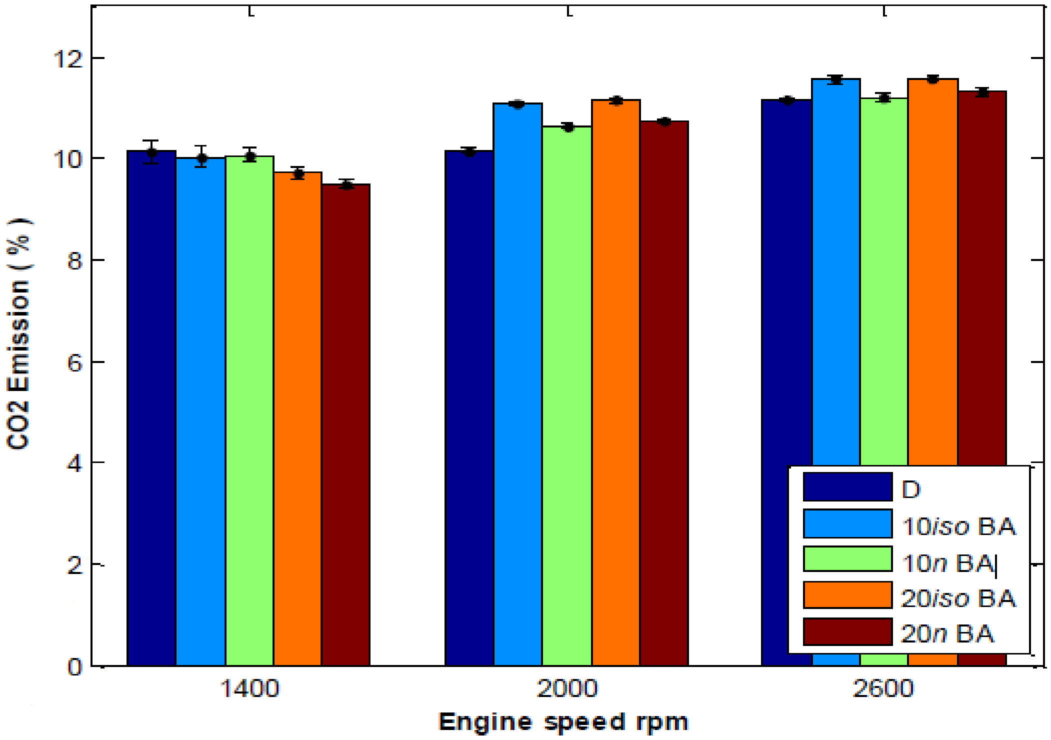

Figure 2.17 Variation of CO_2 emissions with engine speed [221]

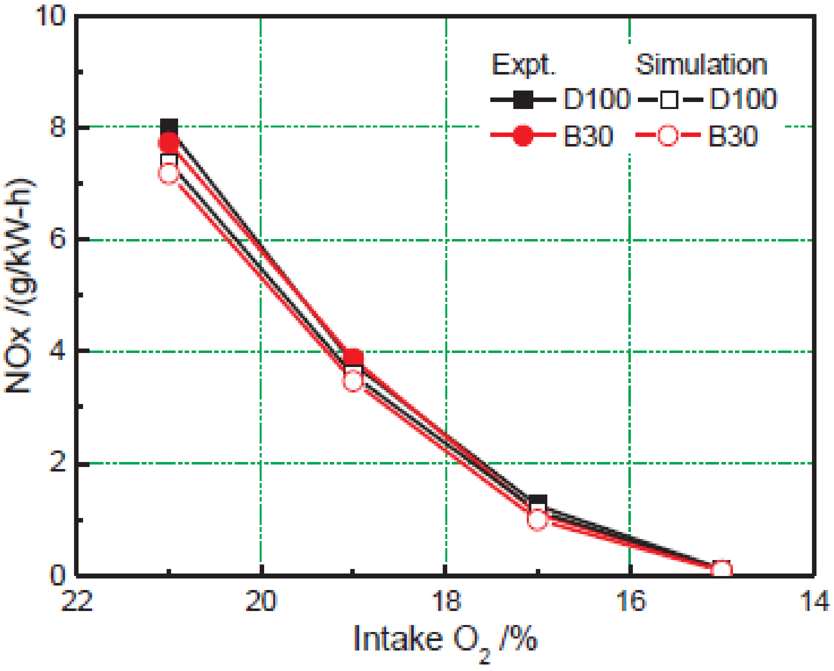

Figure 2.18 Variation of NOx emissions with intake O_2/% [237]

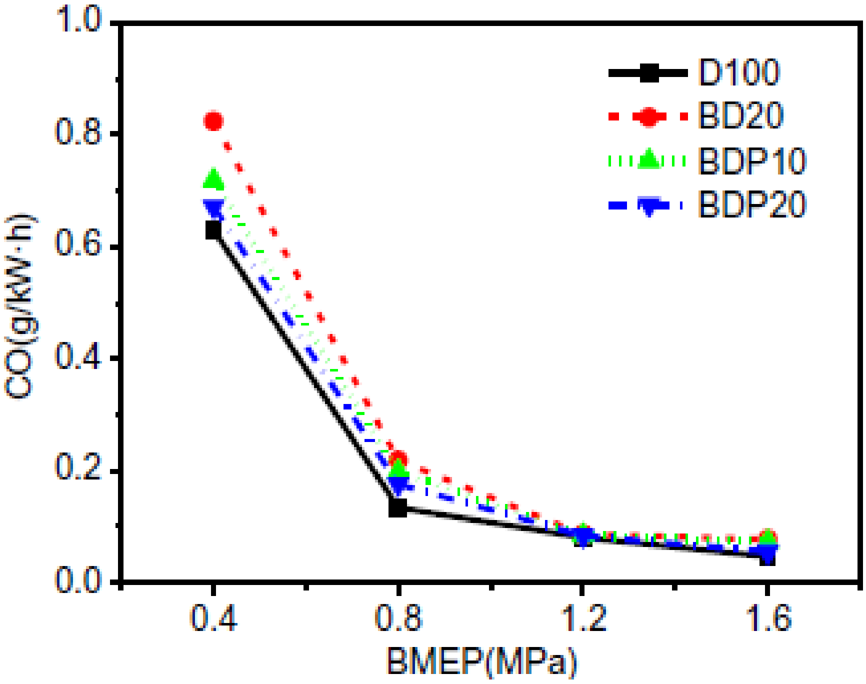

Figure 2.19 Deviation of CO emissions with BMEP [223]

Mohebbi et al. [224] used a modified single-cylinder marine gen-set diesel engine at an injection pressure of 400 bar. The tests were lead at a premixed ratio varying from 60% to 95% with a recess of 5% to test emission parameters of the engine. CO emissions lessens with the addition of n-butanol in the fuel combinations in relation with baseline diesel due to enhanced premixed heat release as n-butanol has the higher amount of oxygen. n-butanol has the higher latent heat which results in decreased combustion temperature inside the engine cylinder. This was considered a major reason for increment in HC exhalations for B20 and B40 in comparison to reference diesel.

Celibi et al. [225] performed experiments at a constant BMEP of 2.78 bar and engine speed of 1500 rpm to find out emission characteristics of n-butanol blended fuels. Inferior CO and enhances CO_2 exhalations were noted for n-butanol fuel combinations which were attributed to the fact that n-butanol has the higher amount of oxygen vis-a-vis diesel. The same reason was given by the researchers for lower HC emissions and higher NOx exhalations obtained by using n-butanol combinations related to pure diesel.

Yesilyurt et al. [226] conducted experiments at Automotive Laboratory, Technical Sciences Vocational School Automotive Program, Aksaray University, Turkey to find emission parameters of a diesel engine. Ambient temperature was 25^oC while conducting the study. Owing to more oxygen content in n-butanol it resulted in impartial combustion of fuel inside the combustion chamber and hence reported by the authors that n-butanol fuel blends emitted less CO emissions and smoke opacity than natural diesel. The same reason was given by researchers for an increased amount of O_2 exhalations and for blends containing n-butanol as compared to natural diesel (Figure 2.20). CO_2 exhalations were found to be decreased by using n-butanol fuel combinations vis-a-vis reference diesel. This surprising result was justified by the authors by attributing that structure of alcohols contained less number of carbon atoms relative to pure diesel. NOx emissions were noticed to decrease by using n-butanol fuel combinations in relation with diesel owing to the cooling effect of alcohols which resulted in decreasing the in-cylinder temperature and hence less amount of nitrogen and oxygen atoms combine with each other.

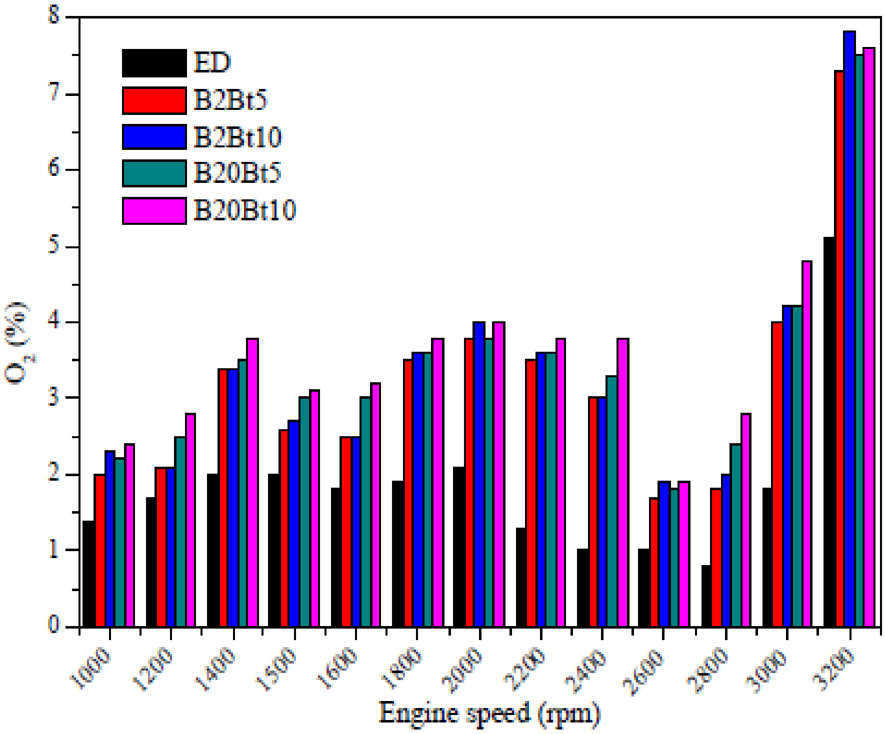

Figure 2.20 Variation of O_2 exhalations with engine speed [226]

Huang et al. [227] tested emission parameters of a diesel engine with injection pressure ranging from 100 MPa to 160 MPa with an interval of 20 MPa. Other than NOx emissions values of all other tested exhaust exhalations decreased with an increase in injection pressure. Relative to fossil diesel, soot emissions decreased with the addition of n-butanol in the fuel combinations; owing to the statistic that n-butanol is an oxygenated fuel. NOx emissions were also noticed to decrease with B20 fuel blend in comparison with pure diesel due to low ignition delay period and low cetane number of n-butanol which lead to low combustion temperature and pressure inside the engine cylinder. The reason for the increased value of HC and CO emissions for n-butanol blends in comparison with baseline diesel was highly volatile nature of n-butanol which results in the injection of more fuel inside boundary layer and crevice of the cylinder wall.

Jeevahan et al. [228] used an AVL digas 444 gas analyzer to measure emission parameters of a diesel engine at engine loads ranging from 0 kg to 20 kg with an interval of 5 kg. NOx emissions were more for regular diesel when compared with fuel blends comprising n-butanol. This was aided with the fact that n-butanol has a high heat of vaporization due to which extra heat is absorbed and combustion temperature reduces. Complete combustion was also achieved owing to lower viscosity of n-butanol as compared to diesel. The low cetane number of n-butanol resulted in ignition lag which caused higher CO emissions for n-butanol blends than fossil diesel. With increasing concentration of n-butanol in fuel blends HC exhalations were noticed to be decreased for all engine loads owing to oxygen content in n-butanol which results in impartial combustion inside the engine cylinder and hence decreasing HC emissions.

2.4.3 Summary of performance and emission characteristics of n-butanol

Literature review reveals that n–butanol has the ability to easily get mixed with diesel and biodiesel. Below mentioned conclusions can be drawn from the referred literature related to the performance and exhalation characteristics of the engine relative to conventional diesel:

- Lower viscosity and calorific value, and high heat of vaporization of n-butanol results in higher BSFC and BSEC when n-butanol is fuelled inside the engine in comparison with natural diesel.
- Value of BTE and BP is found to decrease with n-butanol fuel blends owing to the high heat of vaporization and the low cetane number of n-butanol.
- Generally, NOx emissions were reported less with n-butanol fuel combinations in relation with baseline diesel. Reason for this is lower viscosity and higher heat of vaporization of n-butanol which results in better atomization properties and decreasing the combustion temperature respectively.
- Due to the fact that n-butanol is an oxygenated fuel and helps in complete combustion of fuel CO emissions and smoke opacity are found to decrease and CO_2 and O_2 exhalations are on higher side by maximum researchers.
- HC emissions increase owing to high volatility and low cetane number of n-butanol.

2.5 Biogas as an alternative fuel

Gaseous fuel such as Hydrogen [242-246], Biogas [247-250], Syngas [251-252], natural gas [253-256] and CNG [257-259] has been utilized by so many diesel engine experts in dual fuel mode. Biogas emits a lower quantity of greenhouse gases in comparison with natural diesel [238].Methane (CH_4) and Carbon dioxide (CO_2) are the major components of biogas. Process parameters and raw material contents are dominant factors for the composition of biogas [239]

Usually biogas consists of methane, carbon dioxide, nitrogen, hydrogen, hydrogen sulphide and oxygen, containing (50-75%), (25-45%), (0-10%), (1-2%), (0-0.5%), (0-0.2%) respectively [240]. Biogas is a non-conventional gaseous fuel produced by anaerobic fermentation of biological matter such as kitchen waste, cow dungs, sewage mud, municipal and agriculture waste etc. It is considered to be a cleaner and cheaper fuel [241].

2.5.1 Performance characteristics of biogas

Performance characteristics like brake specific fuel consumption, brake thermal efficiency, brake power, brake specific energy consumption etc. of the dual fuel engine vis-à-vis diesel fuel mode have been evaluated by a number of researchers. This section of the chapter incorporates the performance characteristics of dual fuel engines inspected by these scientists. Table 2.10 shows a comparison of performance characteristics when the diesel engine was fuelled by biogas relative to the single fuel mode.

Makareviciene et al. [267] performed experimental investigations on an automated engine test stand KI-5543 at various indicated mean effective pressures ranging from 0.3 MPa to 0.9 MPa with a regular interval of 0.1 MPa. BSFC of the engine increased whilst BTE decreased by fuelling the engine with gaseous fuel relative to natural diesel. The results were not justified by the researchers by giving any relevant reason.

Table 2.10 Succinct of various performance characteristics of dual fuel engines fuelled with biogas

S.No.	Author(s)	Liquid Fuel used	Gaseous Fuel used	BSFC (g/kWh)	BP (kW)	BTE (%)	BSEC (g/kWh)	Optimized mode
1	65	Diesel and Biodiesel	Biogas	NM	NM	↓	NM	Dual fuel
2	260	Diesel	Biogas	NM	NM	↓	↑	Dual fuel
3	261	Diesel	Biogas	NM	↑	↑	NM	Dual fuel
4	35	Diesel	Biogas	↑	NM	↓	↑	Dual fuel
5	262	Emulsified Biodiesel	Biogas	NM	NM	↑	NM	Dual fuel
6	263	Diesel	Biogas	NM	NM	NM	↑	Dual fuel
7	264	Diesel	Biogas	NM	NM	↑	NM	Dual fuel
8	34	Diesel	Biogas	↑	NM	↑	NM	Dual fuel
9	265	Biodiesel	Biogas	NM	NM	↓	NM	Dual fuel
10	266	Diesel	Biogas	↑	NM	↑	NM	Dual fuel
11	267	Diesel	Biogas	↑	NM	NM	NM	Dual fuel
12	268	Biodiesel	Biogas	↑	NM	↓	NM	Dual fuel
13	269	Diesel	Biogas	NM	NM	NM	↑	Dual fuel
14	270	Diesel	Biogas	↑	NM	NM	↑	Dual fuel

15	271	Diesel	Biogas	NM	NM	↑	NM	Dual fuel
16	272	Biodiesel	Biogas	NM	NM	NM	↑	Dual fuel
17	273	Biodiesel	Biogas	↓	NM	↑	NM	Dual fuel
18	249	Diesel	Biogas	NM	NM	↓	NM	Dual fuel
19	274	Diesel	Biogas	↑	NM	↑	NM	Dual fuel
20	275	Diesel	Biogas	NM	NM	↑	NM	Dual fuel
21	276	Biodiesel	Biogas	↓	NM	↑	NM	Dual fuel
22	277	Diesel	Biogas	↓	NM	↑	NM	Dual fuel
23	278	Diesel	Biogas	↑	NM	↓	NM	Dual fuel
24	279	Biodiesel	Biogas	↑	NM	↓	NM	Dual fuel
25	247	Biodiesel	Biogas	↑	NM	↓	NM	Dual fuel
26	250	Biodiesel	Biogas	↑	NM	↓	NM	Dual fuel

NM- not mentioned by researcher

Bari [280] utilized a four-stroke twin cylinder diesel engine with a rated power of 16.5 kW to assess the performance parameters of a diesel engine by fuelling it with biogas and varying the percentage of CO_2 in biogas as shown in Figure 2.21. He found an enhancement in values of BSFC with biogas having 30% CO_2 which was owing to the decreased gas temperature privileged the combustion chamber because of the fact that diluents like CO_2 absorbs the heat and lowers the speed of burning of fuel-air charge.

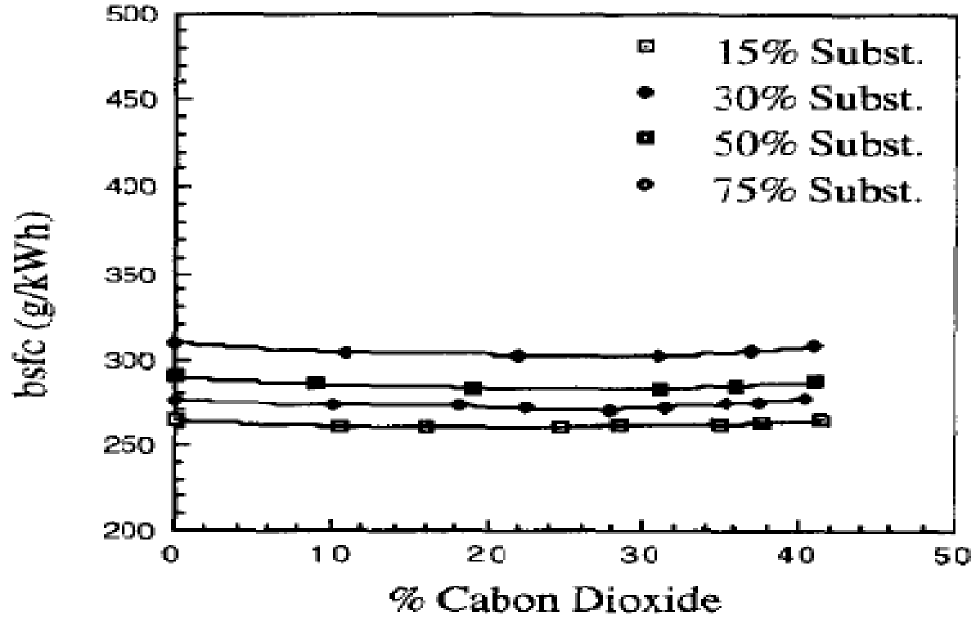

Figure 2.21 Variation of BSFC with Carbon dioxide percentage [280]

Barik et al. [278] carried out experimentation by varying the mass flow rate of biogas ranging from 0.3 kg/h to 1.2 kg/h with an interval of 0.3 kg/h. It was noticed by the researchers that value of BSFC was advanced for dual fuel mode vis-a-vis normal diesel mode at low loads and it keeps on increasing with enhancement in the mass flow rate of biogas. Speedy burning of fuel was prevented owing to the presence of CO_2 in biogas and inferior temperature of the cylinder because of the inferior energy content of biogas was quoted to be the main reason for less BSFC at part loads. It was also reported that BSFC of the engine was nearly comparable to natural diesel for dual fuel operation at full loading conditions because at high loads cylinder temperature increases as a result of the fact that energy needed from fuel is less at full loads than at part loads. BTE of the engine for dual fuel mode was lesser than diesel fuel mode for all loading conditions due to the fact that with the introduction of biogas inside the combustion chamber insufficient supply of oxygen results in unfinished combustion and consequently lower BTE.

An investigational study on performance parameters of a naturally aspirated, four stroke, single cylinder diesel engine was conducted by Mahla et al. [35]. It was reported by the scientists that there was a decrement in BSEC of the engine by fuelling it with biogas in comparison with diesel fuel. Enhancement in the mass flow rate of biogas further aids in increasing the BSEC at part loads due to the fact that decreased temperature inside the combustion chamber is achieved and biogas is not used adequately while engine performs under dual fuel mode. Poor application of gaseous fuel inside the combustion chamber was also responsible for reduced BTE for biogas enabled fuel relative to natural diesel (Figure 2.22). Lower combustion temperature and thin fuel-air mixture are the consequences of poor gaseous fuel utilization.

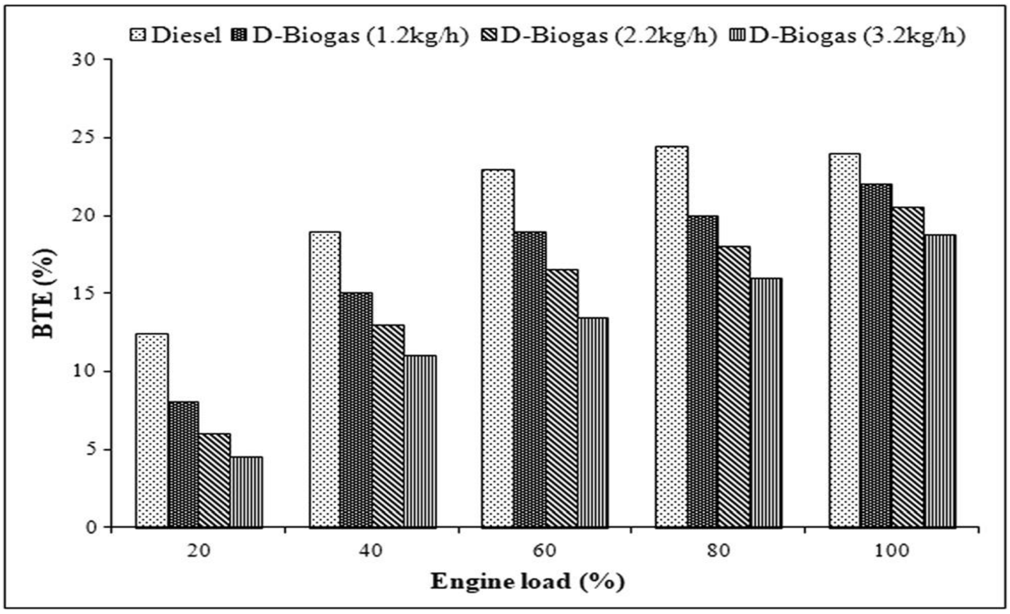

Figure 2.22 Deviation of BTE with engine load [35]

Verma et al. [263] utilized a single cylinder; air cooled four stroke engine to observe the performance characteristics of a diesel engine fed with biogas and diesel. At all engine loading conditions, BSEC of dual fuel mode were more in relation with diesel mode as depicted in Figure 2.23. At high engine load difference in BSEC of dual fuel mode and diesel mode was more in comparison to part loads. This was due to constituents and amount of biogas fuelled into the cylinder at high loads. At part loads, the excess quantity of gaseous fuel introduction results in an insufficient quantity of pilot fuel and hence leads to incomplete combustion.

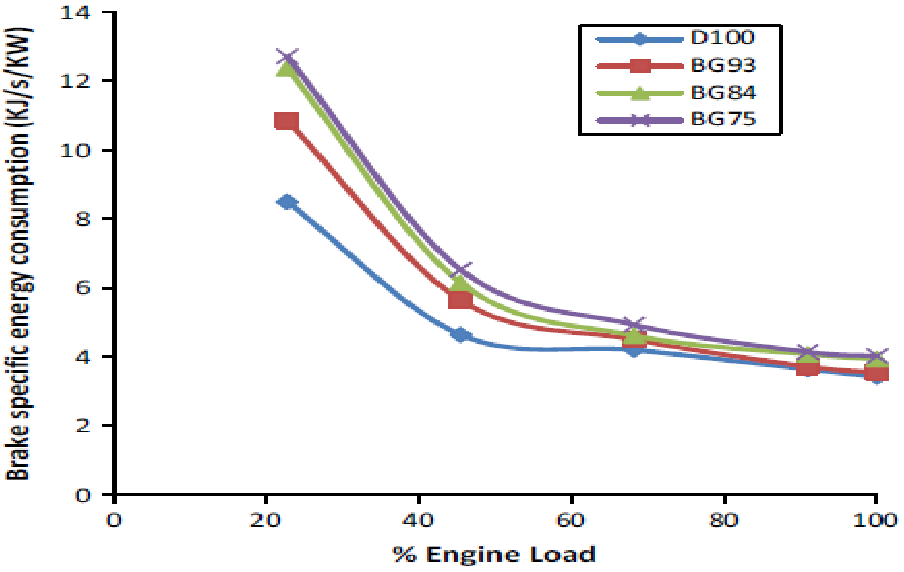

Figure 2.23 Variation of BSEC with engine load [263]

Yoon et al. [247] utilized a turbocharged four-cylinder engine to test the performance analysis by comparing the results of dual fuel mode with single fuel mode. The authors reported that BSFC for dual fuel mode was higher in comparison with the single fuel mode. This result was credited to the fact that in dual fuel mode air-fuel ratio is lesser as compared to only pilot fuel mode, which resulted in lower combustion temperature and hence decreased transformation of biogas to work. At high engine loads, the BSFC for the single fuel mode and dual fuel mode was almost similar owing to a rise in cylinder temperature at higher engine loads.

Ramesha et al. [265] worked out the numerous performance parameters of a diesel engine at an invariable speed of 1500 rpm and loading conditions ranging from 25% to 100% with an interval of 25%. It was noticed by the researchers that BTE for dual fuel mode was inferior vis-a-vis diesel only mode owing to insufficiency of fresh air inside the combustion chamber due to induction of biogas as primary fuel and consequently decreasing the efficiency of the engine. The inferior temperature of combustion and leftovers of biogas also results in decreased BTE.

2.5.2 Emission characteristics of biogas

It has been verified by most of the renowned researchers that biogas is a gaseous fuel that aids in minimizing the detrimental gases that pollute the habitat, especially NOx emissions. Emission characteristics of biogas are mentioned in this section of the chapter. Table 2.11 depicts various performance characteristics of the diesel engine when biogas was used as a primary fuel.

Makareviciene et al. [267] fuelled a dual fuel engine with biogas and diesel and tried to assess the emanation parameters of the engine using an AVL DiCom 4000 exhaust gas analyzer but were unable to provide valid reasons for the outcomes. Smoke opacity and CO_2 emissions of the engine were noticed to be increased with biogas fuelled engine in comparison with baseline diesel. It was also found that with increasing biogas mass flow rate smoke opacity and CO_2 further increased. Same results were also reported by the authors for CO and HC exhalations. NOx emissions were on the lower side with gaseous fuel addition inside the cylinder. NOx exhalations were observed to be inversely proportional with enhancing biogas mass flow rate.

Barik et al. [278] performed emission evaluation on a stationary, single cylinder, four-stroke diesel engine. The whole research was completed at a invariable speed of 1500 rpm. Exhalations of CO were reported to be more for dual fuel mode related to diesel only mode. CO emissions keep on enhancing with fluctuating mass flow rate of biogas. It was attributed to the fact that biogas contains a higher amount of CO_2 and insufficient oxygen which may have resulted in incomplete combustion. Deficient mixing of liquid and gaseous fuel also increases CO emissions. The same reason was also applicable for increasing amount of HC emissions for dual fuel mode relative to diesel mode. NO exhalations for biogas fuelled mode was considerably lower than diesel mode due to ample quantity of CO_2 present in biogas which lessens the absorption of oxygen and in turn provide fewer oxygen atoms to react with nitrogen inside the cylinder and hence producing lower NO emissions. Deficiency of oxygen in biogas did not provide enough oxygen to react with carbon which is the reason for incomplete combustion and consequently emitting higher CO_2 emissions. Non-availability of savory compounds in biogas was the reason for less smoke opacity of biogas fuelled engine.

Mahla et al. [35] fuelled a diesel engine with diesel and biogas and performed emission tests at a constant speed of 1500 rpm by varying the mass flow rate of biogas from 1.2 kg/h to 3.2 kg/h with an interval of 1 kg/h. Introducing biogas inside the engine resulted in less amount of NOx emissions with increasing mass flow rate of gaseous fuel as compared to traditional diesel as shown in Figure 2. 24. CO_2 is one of the main constituents of biogas, higher specific heat of CO_2 results in diluting the charge and hence reducing in-cylinder temperature and availability of oxygen which consequently resulted in lower NOx emissions for gaseous fuel. Smoke opacity was also on the lower side for the dual fuel mode in comparison with diesel mode. It was attributed to the fact that a homogeneous combination is made by biogas along with air which leads to increased oxygen reactions and consequently decreased soot emissions. Due to the higher amount of unburned fuel during dual fuel mode, HC emissions were recorded more in relation to pure diesel. Reason for unburned fuel was the introduction of biogas which leads to lean air-fuel mixture and hence insufficient amount of oxygen for combustion. Same justification is also feasible for increased CO exhalations for dual fuel engines in comparison with diesel mode.

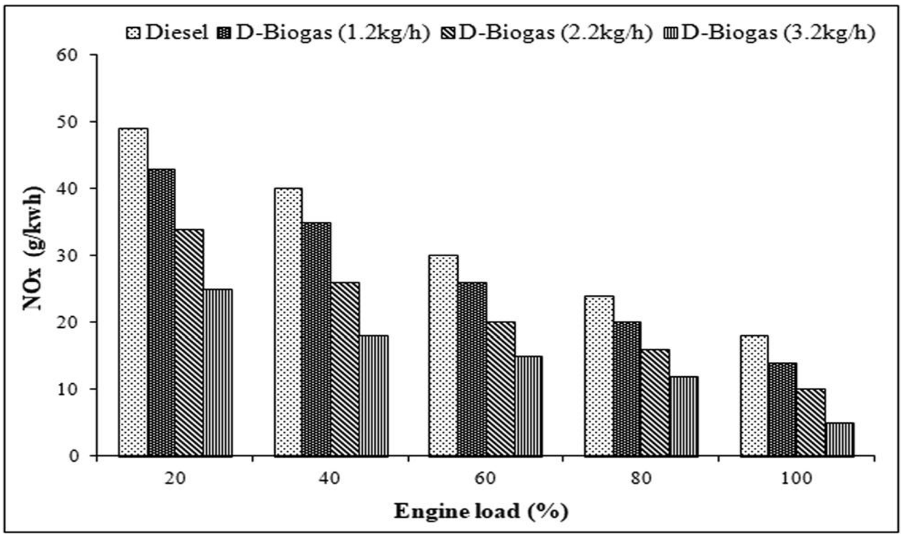

Figure 2.24 Variation of NOx with engine load [35]

Table 2.11 Succinct of various performance characteristics of dual fuel engines fuelled with biogas

S.No.	Reference No.	Liquid Fuel used	Gaseous Fuel used	NOx (g/kWh/%/ppm)	CO_2 (%)	CO (%)	HC (g/kWh)	Smoke (%)	Optimized mode
1	65	Diesel and Biodiesel	Biogas	↓	↑	↑	↑	NM	Dual fuel
2	261	Diesel	Biogas	NM	NM	NM	↑	↓	Dual fuel
3	35	Diesel	Biogas	↓	NM	↑	↑	↓	Dual fuel
4	262	Emulsified Biodiesel	Biogas	↑	NM	↓	↓	NM	Dual fuel
5	281	Diesel	Biogas	↓	NM	↑	↑	↓	Dual fuel
6	264	Diesel	Biogas	NM	NM	NM	↑	↓	Dual fuel
7	263	Diesel	Biogas	↓	NM	↑	↑	↓	Dual fuel
8	265	Biodiesel	Biogas	↓	NM	↑	↑	↓	Dual fuel
9	34	Diesel	Biogas	↓	NM	↑	↑	↓	Dual fuel
10	267	Diesel	Biogas	↑	↑	↓	↓	NM	Dual fuel
11	266	Diesel	Biogas	↓	↑	↑	↑	↓	Dual fuel
12	269	Diesel	Biogas	↑	↑	↓	↓	NM	Dual fuel
13	268	Biodiesel	Biogas	↑	↑	↑	↑	↑	Dual fuel
14	271	Diesel	Biogas	NM	NM	↓	NM	NM	Dual fuel

15	270	Diesel	Biogas	↓	NM	↑	↑	NM	Dual fuel
16	273	Biodiesel	Biogas	↑	NM	↓	↓	↓	Dual fuel
17	127	Diesel	Biogas	↑	NM	NM	↑	↓	Dual fuel
18	249	Diesel	Biogas	↓	NM	↑	↑	NM	Dual fuel
19	272	Biodiesel	Biogas	↓	↓	↑	↑	↓	Dual fuel
20	274	Diesel	Biogas	↑	NM	↓	↓	↓	Dual fuel
21	276	Biodiesel	Biogas	↑	↑	↓	↓	NM	Dual fuel
22	277	Diesel	Biogas	↑	↑	↓	↓	NM	Dual fuel
23	278	Diesel	Biogas	↑	NM	↑	↓	↓	Dual fuel
24	279	Biodiesel	Biogas	↓	NM	↑	↑	NM	Dual fuel
25	247	Biodiesel	Biogas	↓	NM	↑	↑	↓	Dual fuel
26	250	Biodiesel	Biogas	↓	NM	↑	↑	↓	Dual fuel

NM- not mentioned by researcher

Verma et al. [263] performed emission analysis of a diesel engine on steady-state engine operating conditions. The load was varied during the experimentation and an invariable speed of 1500 rpm was set. Higher equivalence ratio at higher loading conditions resulted in increased NOx emissions with increasing engine load. NOx emissions were noticed to be decreased with increasing mass flow rate of biogas. Presence of CO_2 as one of the main constituents of biogas was reported to be responsible for this. CO_2 has more specific heat and results in reduced cylinder temperature. Incomplete combustion due to the high quantity of CO_2 and low amount of oxygen in biogas was held culprit by the authors for enhancement in HC exhalations for dual fuel mode. The same reason was presented for the increased amount of CO exhalations with dual fuel mode in comparison to diesel only mode. Smoke emissions with biogas and diesel fuelled engine were on the lower side relative to diesel mode as depicted in Figure 25. This was due to the fact that in dual fuel mode the high amount of conventional diesel is substituted by the gaseous fuel and hence results in less soot formation.

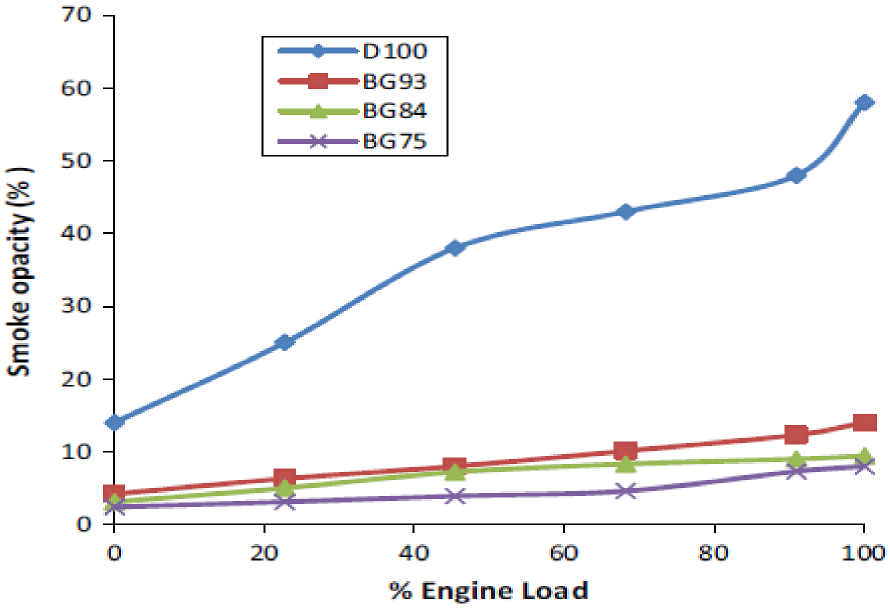

Figure 2.25 Deviation of smoke opacity with engine load [263]

Yilmaz et al. [282] carried out experiments to evaluate the emission parameters of a multi-cylinder test rig. turbocharged engine which was connected to a dynamometer.

The authors investigated that, HC exhalations for dual fuel mode was higher in comparison with single fuel mode as shown in Figure 2. 26 due to the impact of the inert gas CO_2 which is the main constituent of biogas, inadequate use of biogas, and low peak cylinder temperature. NOx emissions for dual fuel mode were lower at part loads owing to lower premixed controlled combustion of gaseous fuel. At high and intermediate engine loads NOx exhalations were found to be increased for dual fuel mode than diesel mode. With an increase in the load of the engine peak cylinder temperature also increases and allows more rapid reaction between Nitrogen and Oxygen which in turn results in higher NOx emissions. Reduced amount of smoke opacity was encountered for dual fuel mode in comparison with single fuel mode owing to unavailability of sulfur and availability of Methane in biogas.

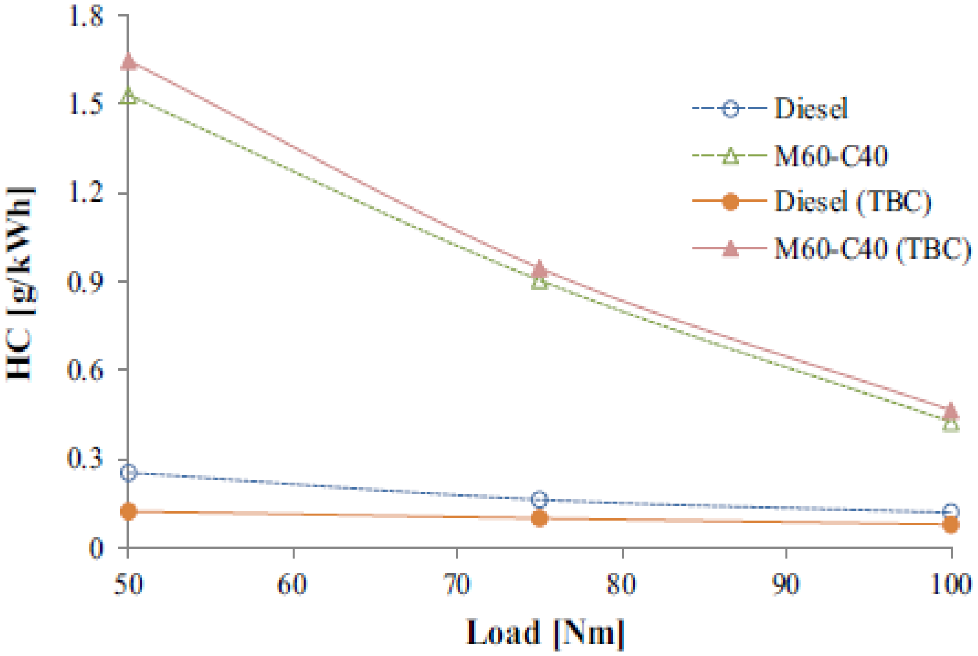

Figure 2.26 Variation of NOx with engine load [282]

Shan et al. [283] compared two compositions of biogas in a dual fuel engine. 5% Hydrogen and 40% CO by volume were used in Biogas 1# and 15% Hydrogen and 30% CO by volume were used in Biogas 2#. The emission characteristics revealed that CO exhalations were on the higher side for Biogas 1# as compared to Biogas2 #. Reason for this was the lower quantity of hydrogen and higher amount of CO contained in Biogas1 # which enables the excess amount of CO to be bound inside the cylinder. It was also revealed that NOx emissions of Biogas2 # were more in comparison with Biogas1#. Increased peak cylinder pressure due to the higher burning rate of Biogas2 # was responsible for the same.

Yoon et al. [280] performed experiments on a dual fuel engine by keeping the speed of the engine constant at 2000 rpm to reveal the exhaust emission characteristics of the engine. NOx exhalations for dual fuel mode were lower for dual fuel mode relative to the single fuel mode as a result of combined impact of presence of CO_2 in the biogas which decreases the rate of combustion of biogas by diluting the concentration of oxygen of the fuel, and low flame formation due to increased specific heat capacity of fuel by induction of gaseous fuel. Unavailability of the amount of sulfur in biogas resulted in decreased soot emissions for dual fuel mode in comparison with single fuel mode. CO emissions were found to be higher for dual fuel mode than single mode owing to insufficient oxygen content inside the combustion chamber due to the availability of CO_2 in the biogas which leads to incomplete combustion and hence enhances CO exhalations (Figure 2.27). Same justification was also given for increased HC emissions.

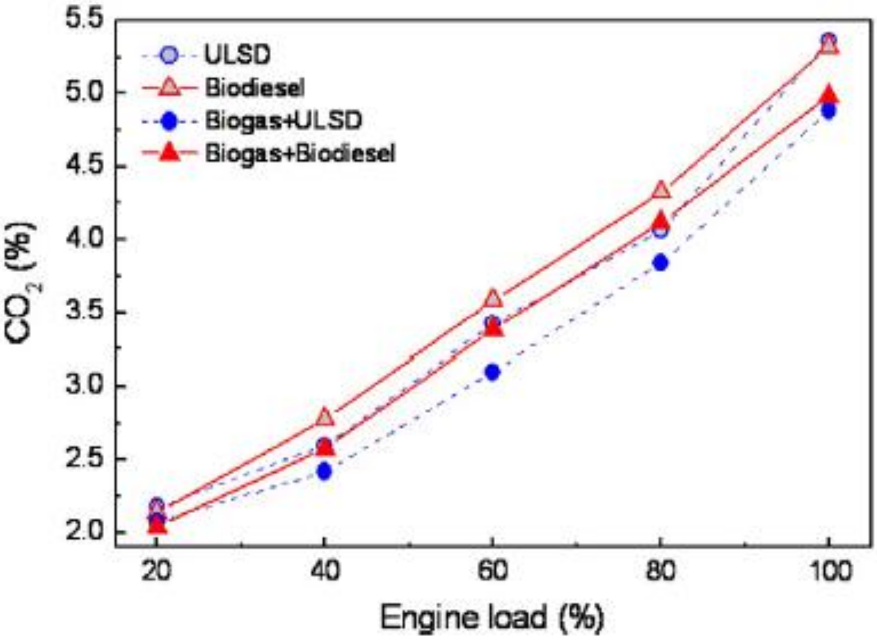

Fig. 2.27 Deviation of CO2 emissions with engine load [280]

Ramesha et al. [265] carried out experimental investigations on single cylinder water cooled diesel engine to evaluate emission parameters of the engine by comparing dual fuel mode with single fuel mode. As usual exhalations of NOx were found to be decreased for the dual fuel mode in relation to the single fuel mode. Authors justified this result by attributing to the low cylinder temperature owing to low flame propagation due to the increased specific heat of the charge by the introduction of biogas inside the combustion chamber. Reason for increment in HC emissions and CO exhalations (Figure 2.28) for dual fuel mode in comparison with single fuel mode was exactly same as justification given by Yoon et al. Presence of Methane in biogas was given credit for lesser amount of soot exhalations for dual fuel mode as methane helps in decreasing the soot emissions.

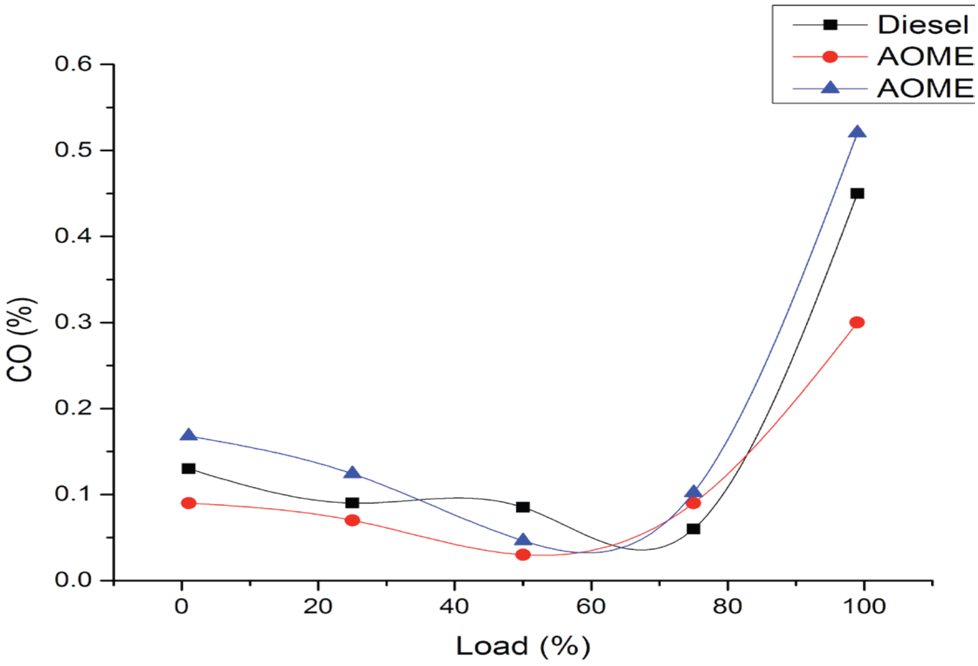

Figure 2.28 Variation of CO with engine load [265]

2.5.3 Summary of performance and emission characteristics of biogas

Biogas can be used a primary fuel in dual fuel engines as clearly depicted through reviewed papers. Following are the conclusions of performance and emission characteristics of the engine when the literature is reviewed for dual fuel engines in comparison with fossil diesel:

- BSFC and BSEC were higher, this result was attributed to the fact that in dual fuel mode air-fuel ratio is lesser as compared to only pilot fuel mode, which resulted in lower combustion temperature and hence decreased transformation of biogas to work.
- BTE and BP for dual fuel mode were lower in comparison with diesel only mode owing to insufficiency of fresh air inside the combustion chamber due to induction of biogas as primary fuel and consequently decreasing the efficiency of the engine.
- NOx exhalations for biogas fuelled mode was considerably lower than diesel mode due to ample quantity of CO_2 present in biogas which lessens the absorption of oxygen and in turn, provide fewer oxygen atoms to react with nitrogen inside the cylinder and hence producing lower NOx emissions, and low cylinder temperature owing to low flame propagation due to increased specific heat of the charge by introduction of biogas inside the combustion chamber.
- Exhalations of CO and HC were reported to be more for dual fuel mode in comparison to diesel only mode. CO emissions keep on enhancing with fluctuating mass flow rate of biogas. It was attributed to the fact that biogas contains a higher amount of CO_2 and insufficient oxygen which may have resulted in incomplete combustion. Deficient mixing of liquid and gaseous fuel also increases CO emissions.
- Lower smoke and CO_2 emissions were reported for dual fuel engine in comparison with single fuel mode. It was attributed to the fact that a homogeneous combination is made by biogas along with air which leads to increased oxygen reactions and consequently decreased soot emissions.

2.6 Summary of conclusions

- BSFC and BSEC were found to be higher for biodiesel, n-butanol, and biogas as compared to diesel fuel.
- BTE and BP were lower in relation with conventional diesel for all other fuels.
- NOx emissions were on the higher side for biodiesel fuel blends whereas for

n-butanol and biogas it depicts a decreasing trend in comparison with pure diesel.

- CO_2 and O_2 exhalations were reported to increase for biodiesel and n-butanol fuel blends whilst it shows a decrease with biogas fuelled engine in relation with conventional diesel. CO emissions were exactly opposite to CO_2 and O_2 emissions.
- Smoke opacity was superior for fossil diesel than remaining fuels.
- HC emissions were noted to be on lesser for biodiesel whereas it was higher for n-butanol and biogas fuelled engines as compared to natural diesel.

2.7 Identified research gap

It has been found by the literature review that with use of biogas as a primary fuel the exhaust exhalations like CO and HC increases when related with conventional diesel. To overcome this problem a fuel having higher oxygen content is required along with biogas. So, biodiesel owing to its higher oxygen content and high cetane number along with n-butanol which can be easily mixed with biodiesel to reduce it viscosity and also having ample quantity of oxygen were blended with diesel fuel and tested as a pilot fuel to check the performance and emission characteristics of the engine in the present study.

2.8 Novelty in research

The review of literature has concentrated largely on performance and emission characteristics of diesel engines fuelled with biodiesel, n-butanol and biogas. It can be seen that oxygenated fuels and biogas can increase efficiency of engine and can also help in reducing the harmful gases emitted from exhaust. Most of the researchers have used biodiesel as fuel, some have tried to find investigations of dual fuel engines and some have used higher alcohols in the fuel to increase its efficiency. This has been the latest area of research for many researchers. However according to open literature, little research work has been done on dual fuel engine mode containing biogas and oxygenated fuel blends. It has been found that most of the experimentation done by the researchers to find out the performance and emission characteristics of the engine was carried out using following methods:

- Using Diesel-biodiesel blends
- Using Diesel with a gaseous fuel
- Using Diesel-biodiesel blends with gaseous fuel
- Using Diesel-biodiesel blends with higher alcohol
- Using Diesel with higher alcohol
- Using Diesel-biodiesel blends with gaseous fuel and higher alcohol

But no study has yet been initiated by any researcher to find out the combined effect of Diesel-biodiesel and n-butanol blends with biogas as primary fuel.

Chapter-3

Problem Formulation and objectives

3.1 Overview

After reviewing the literature it has been found that oxygenated fuels can be used as an alternative fuel because according to an estimate our sources for traditional fuels including diesel would be depleted in next few decades. Owing to the fact that these fuels are typically not renewable, a day would come when the demand for these fuels would be more than the supply, which would result in a possible world crisis. Moreover it has also been found by researchers that the use of alternative fuels considerably decreases harmful exhaust emissions (such as carbon dioxide, carbon monoxide, particulate matter and sulfur dioxide) as well as ozone-producing emissions. Biofuels, provide modern and fresh relevance to the old belief that 'Trash for one person is a treasure for another' as it can be produced from waste. So it has been decided that testing of diesel engine will be done to find out its performance and emission characteristics using Diesel-biodiesel blend, Biogas and n-butanol.

3.2 Need and significance of proposed research work

Due to population explosion, globalization, competition in automobile industries and prospering financial status of common man in India and all over the world there is a heap of automobiles on roads, which is giving rise to depletion of petroleum products at an alarming rate. Moreover it is also helping in environmental pollution, Global warming and Green house effect due to exhaust emissions coming out of automobiles. Comparison of various combinations of fuels and additives will be done and best optimum alternative fuel will be found.

3.3 Research Problem

It is a fact that automobiles are polluting the environment and are accelerating the depletion of fossil fuels but at the same time we cannot even think our present and future without automobiles. So at the same time we have to use automobiles as well as find an alternative fuel which can replace conventional fuel, reduce exhaust emission gases and can be a renewable fuel. This research problem has been undertaken to make a research so that exhaust emissions of the engine can be reduced and efficiency can be increased.

3.4 Research Methodology

The present work will be undertaken to find out the performance, combustion and emission characteristics of a dual fuel diesel engine using n-butanol as higher alcohol under varying load conditions. Biogas will be used as primary fuel and biodiesel blends will be used as pilot fuel. During the whole process all the fuels and additives will be tested by changing their composition and proportion at various engine loads. During the process Brake Power, Brake thermal efficiency, Brake specific fuel consumption and various exhaust emissions like carbon dioxide, carbon monoxide and hydrocarbon emissions of the engine will be evaluated.

3.5 Scope

As it is evident from the diversity of application areas, the study of oxygenated fuels are very important for the technology of today and the near future, as fossils fuels are depleting at a very fast rate due to increasing number of automobiles on road. Biodiesel and higher alcohols have been found helpful in increasing engine efficiency and reducing pollution. There is futuristic scope of dual fuel mode engines with higher alcohol from technological as well as application point of view.

3.6 Objectives

Following are the main objectives of proposed research work:

1. Production of biodiesel from Rice bran oil through transesterification process.
2. To modify the intake manifold of the diesel engine to use it on dual fuel mode, so that it can run on biogas and biodiesel simultaneously.
3. To conduct a series of experimental investigations for studying the effect of higher alcohols on diesel biodiesel blend on performance and emission characteristics of the engine.
4. To analyze the engine performance and exhaust emission characteristics at various biogas flow rate and varying load conditions.

5. To compare performance and emission characteristics of various combinations of diesel-biodiesel blends, biogas and n-butanol.

Chapter-4

Materials and Methods

4.1 Overview

Oxygenated fuels owing to a possible substitute to natural diesel are fetching attention by researchers and diesel engine experts gradually. These fuels consist of biodiesel and n-butanol owing to higher amount of oxygen content incorporated in them. Gaseous fuels are also one of the potential selections of scientists and diesel engine specialists as they support in dropping the detrimental NOx emissions. In this division, the preparation of biodiesel fuel and its blends are conferred elaborately. Approaches to find the numerous properties of fuel blends and fuel matrix is similarly been discussed. Thereafter, the experimental set up is particularized in three sub-sections.

4.2 Biodiesel Production

Biodiesel was procured in the chemistry lab by using transesterification process. 500 ml Rice Bran oil sample was taken in beaker and heated upto 30°C to reduce viscosity of oil and filter it. 135 ml methanol was taken in a flask and 2.5 gm of NaOH was added into it. Flask was covered and constant stirring till proper mixing of methanol and sodium hydroxide solution on magnetic stirrer was done. An electrically operator stirrer (biodiesel reactor) was used for the reaction of Methanol and sodium hydroxide solution with Rice Bran oil at constant temperature of 55°C at constant speed of 700 rpm for one hour as shown in Figure 4.1.

The product was then permitted to settle overnight as depicted in Figure 4.2, so that ester phase (biodiesel) and glycerol phase can separate. After that ester phase was formed at the top and glycerol phase at the bottom as shown in Figure 4.3. Then glycerol was separated using separating funnel. Gravity separator was used for separation of biodiesel and glycerol. The oil obtained from reaction was poured into gravity separator for 24hours. Purification of biodiesel was done with the water washing method. In water washing the water was heated upto 70°C and then added to biodiesel in gravity separator. The crude biodiesel and water mixture was shaken thoroughly for 1 min and placed on stand in separating funnel to allow separation of biodiesel and water layers. 24 hour time was given between next washing. Water washing of the biodiesel thus produced is essential for removal of the impurities and the residual catalyst, which may be harmful for combustion engines. It was purified by washing with distilled water to remove all the residual by-products. Water washing was done for 3-4 times to remove the glycerol from biodiesel.

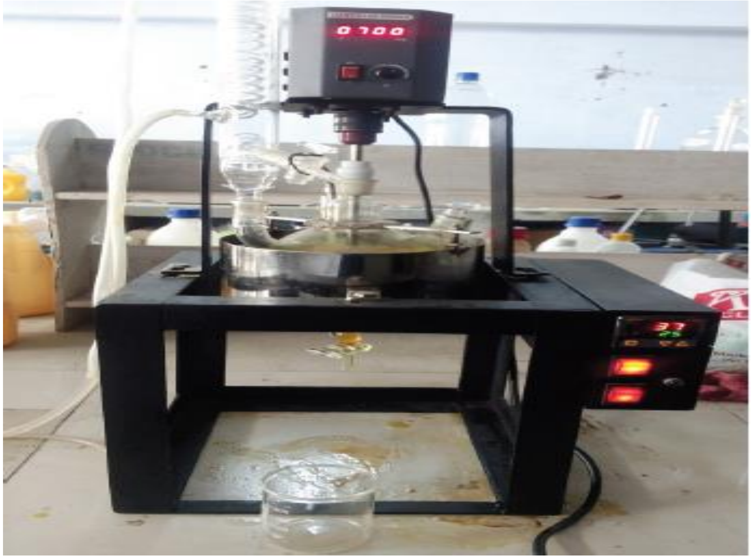

Figure 4.1 Biodiesel reactor

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Figure 4.2 Product allowed to settle down

Figure 4.3 Formation of ester phase and glycerol

Biodiesel was heated above 100° C for the removal of water contents and methanol after washing process as shown in Figure 4.4. The water contents present in the biodiesel may affect the performance of the engine, so it is necessary to remove these water contents. At the end 320 ml biodiesel was produced. The whole process was repeated for producing more biodiesel.

Figure 4.4 Heating of biodiesel

4.3 Fuel blending

Blends of Diesel, Biodiesel and n-butanol were prepared in various proportions. Blends of diesel, biodiesel, and n-butanol were designated as shown in Table 4.1. The percentage of biodiesel and n-butanol was choosen randomly [295]. Some of the fuel blends are shown in Figure 4.5.

Figure 4.5 Blend formation

Table 4.1 Designation of fuel blends

S.No.	Name	Percentage of diesel in liquid fuel	Percentage of biodiesel in liquid fuel	Percentage of n-butanol in liquid fuel
1.	D90/B10	90	10	_
2.	D80/B20	80	20	_
3.	D90/nb10	90	_	10
4.	D80/nb20	80	_	20
5.	D80/B10/nb10	80	10	10
6.	D80/B20/nb20	60	20	20
7.	D70/B10/nb20	70	10	20
8.	D70/B20/nb10	70	20	10

4.4 Yield of Oil

It is defined as the amount of biodiesel that can be procured from the base oil (Rice bran). To obtain the best results yielding of oil should be maximum in view of quantity of methyl esters extracted from base oil.

4.4.1 Calculation of Yield of Rice Bran Biodiesel before washing process

Raw rice bran oil used=500ml

Biodiesel obtained after transesterification = 480ml (before washing)

Yield = 480/500

= 96% (before washing)

4.4.2 Calculation of Yield of Rice Bran Biodiesel after washing process

Raw rice bran oil used=500ml

Biodiesel obtained after transesterification= 458ml (after washing)

Yield= 458/500

= 91.6% (after washing)

4.5 Properties of biodiesel and n-butanol blends

Numerous apparatus were used to calculate the properties of procured biodiesel. Various properties and equipment used in this process are depicted in Table 4.2

Table 4.2 Various properties of biodiesel and n-butanol blends and apparatus used for calculation

S.No.	Property	Apparatus used
1	Free Fatty Acids (FFA)	--------------
2	Density	Weighing balance
3	Kinematic Viscosity	Redwood viscometer
4	Carbon residue content	Ram’s bottom apparatus
5	Ash content	Muffle furnace
6	Cloud point	Cloud and pour point apparatus
7	Pour point	Cloud and pour point apparatus
8	Flash point	Flash and fire point apparatus
9	Fire point	Flash and fire point apparatus
10	Calorific value	Bomb calorimeter

4.5.1 Free Fatty Acid (FFA) Content

It is very difficult to separate the glycerol from methyl esters at the end of reaction if FFA or water content will be high due to saponification (reaction of an ester with metallic base and water). The FFA content is inversely proportional to the yield of oil.

Maximum oil yield can be achieved by very low FFA content of <0.2. As the high value of FFA results in saponification instead of biodiesel production, it is necessary to find out the FFA content in fuel blends. 50 ml spirit was taken in a conical flask and indicator phenolphthalein was added in it. After that 10 ml of base oil was added to the mixture and the mixture was heated till bubbles start to appear (approximately 70°C). Phenolphthalein indicates the end of the reaction as red/pink color; when NaOH is used as titrate. When quantities are known the FFA content can be calculated.

Weight of sample = Volume × density

FFA Value = (28.2×V×N) / (weight of sample)

Where,

V= Volume of NaOH consumed in the titration

N= Normality of NaOH

Table 4.3 illustrates value of free fatty acid of different fuel blends.

Table 4.3 Free fatty acid value of different blends

S. No.	Blended fuel	Free fatty acid value
1	D90/B10	0.0102
2	D80/B20	0.0105
3	D90/nb10	0.0106
4	D80/nb20	0.0107
5	D80/B10/nb10	0.0109
6	D60/B20/nb20	0.0114
7.	D70/B10/nb20	0.0107
8.	D70/B20/nb10	0.0108

4.5.2 Density

Density of a fuel is the mass of the fuel per unit volume and is measured in kg/m^3. First of all, an empty cylindrical flask of 100 ml volume was weighed. 100 ml of respective fuel blend was poured into the flask and the cylindrical flask was again weighed. The weight of fuel blend alone was calculated by subtracting the weight of empty cylindrical flask from the weight of filled cylindrical flask. Density was calculated by dividing the mass of the fuel blend with the volume of the flask. Density of different fuel blends is presented in table 4.4.

Table 4.4 Density of different blends

S. No.	Blended fuel	Density (kg/m^3)
1	D90/B10	834.2
2	D80/B20	841.4
3	D90/nb10	789.1
4	D80/nb20	782.9
5	D80/B10/nb10	818.5
6	D60/B20/nb20	805.1
7.	D70/B10/nb20	817.2
8.	D70/B20/nb10	828.6

4.5.3 KinematicViscosity

Viscosity can be defined as the resistance to flow of liquid due to the internal friction between the liquid and surface. It plays an important role in the performance of an engine fuel system operating through a wide range of temperature. Kinematic viscosity affects the injection system. Low viscosity can result in an excessive wear in injection pumps and power loss due to pump leakage whereas high viscosity may result in excessive pump resistance, filter blockage, high pressure and coarse atomization and fuel delivery rates. A Redwood viscometer as shown in Figure 4.6 is used for measurement of kinematic viscosity of fuel samples.

The instrument measures the time of gravity flow in seconds, of a fixed volume of the fluid (50ml) through specified orifice made in a piece. The apparatus could be used for flow time between 30 to 2000 seconds. The fuel was filled in a cup fitted with a gate jet at the bottom upto a specified level indicated in a cup. The cup was surrounded by water jacket having an immersion heater. The heater was heated to 38°C by regulating the rate of heating using a Voltage regulator of the instrument. A simple metallic ball was used to open and close the gate jet. A standard 50 ml volumetric glass was kept below the gate jet to collect a falling fuel samples. Each test was replicated thrice. Kinematic viscosity in centistokes was then calculated from time units by using the relationships:

$Vk = 0.26\ t-179 / t$ (i)

When $34 < t < 100$ and

$Vk= 0.24\ t - 50 / t$ (ii)

When $t > 100$

Vk= Kinematic viscosity in centistokes, cSt

t=Time for flow of 50 ml sample,

Table 4.5 depicts kinematic viscosity of different fuel blends

Table 4.5 Kinematic viscosity of different blends

S. No.	Blended fuel	Kinematic viscosity (cSt)
1	D90/B10	2.508
2	D80/B20	2.754
3	D90/nb10	2.001
4	D80/nb20	1.915
5	D80/B10/nb10	2.293
6	D60/B20/nb20	2.347
7	D70/B10/nb20	2.192
8	D70/B20/nb10	2.239

4.5.4 Carbon Residue Content

The carbon residue is the amount of carbon residue that is considered as byproducts of fuel. After fuel is burned, they are leftover on the piston surface which is not desirable. Carbon Residue Content should be small for the biodiesels. These are measured in weight% with help of carbon residue content apparatus as shown in Figure 4.7.

Figure 4.6 Redwood viscometer

Figure 4.7 Carbon residue content apparatus

Firstly, the bulb was weighed empty and then with the fuel sample. 4-5 gm fuel was added in a bulb and weighed again. The sample weight was obtained from the difference between the initial and final weight of the bulb then placed in the carbon residue measurement content and heated at 500° C for 20 minutes. The carbon residue content was obtained using the equation given below:-

Cr = Wc / Ws × 100

Where,

Cr = Carbon residue content, %

Wc = Weight of carbon residue, gm

Ws = Weight of the sample, gm

Carbon residue content of different blends is illustrated in Table 4.6

Table 4.6 Carbon residue content of different blends

S. No.	**Blended fuel**	**Carbon residue content (%)**
1	D90/B10	0.0176
2	D80/B20	0.0180
3	D90/nb10	0.0186
4	D80/nb20	0.0189
5	D80/B10/nb10	0.0205
6	D60/B20/nb20	0.0198
7	D70/B10/nb20	0.0192
8	D70/B20/nb10	0.0191

4.5.5 Ash Content

Ash in a fuel can result from oil, water soluble material compounds or extraneous solids, such as dirt and rust. First of all, sample was taken in a silica dish. The dish was first weighed empty and then with the fuel sample (14-15gm).

The sample weight was obtained from the difference between the initial and final weight of the dish and placed in the muffle furnace as depicted in Figure 4.8 and heated at 500°C for 20 minutes. The ash content was obtained using the equation given below:

AC = (Weight of dish after experiment -Weight of dish) / (Weight of sample) × 100

Where, AC= Ash content (%)

Ash content of various fuel blends is shown in table 4.7

4.5.6 Cloud and Pour Point

The Cloud and Pour point is the measure which indicates that the fuel is sufficiently fluid to be pumped or transferred. Hence it holds significance to engines operating in cold climate.

Figure 4.8 Muffle furnace

The cloud point is defined as the temperature at which a cloud or haze of wax crystal appears at the bottom of a test jar when chilled under prescribed conditions. The pour point is defined as the temperature at which the fuel ceases to flow. Both properties may indicate the tendency towards filter plugging and flow problems in the fuel line. Cloud point and pour point is measured with help of cloud and pour point apparatus as depicted in Figure 4.9. The apparatus mainly consists of 12 cm high glass tubes of 3cm diameter. These tubes are enclosed in an air jacket, which is filled with a freezing mixture of crush and sodium chloride crystals. The glass tube containing fuel sample is taken out from the jacket at every 1°C intervals the temperature falls, and is inspected for cloud formation. The point at which a haze was first seen at the bottom of the sample was taken as the cloud point.

Table 4.7 Ash content of different blends

S. No.	Blended fuel	Ash content (%)
1	D90/B10	0.0089
2	D80/B20	0.0094
3	D90/nb10	0.0099
4	D80/nb20	0.0102
5	D80/B10/nb10	0.0105
6	D60/B20/nb20	0.0110
7	D70/B10/nb20	0.0093
8	D70/B20/nb10	0.0090

Figure 4.9 Cloud and pour point apparatus

The apparatus and the procedure for the pour point was same as for cloud point only the sample was pre-heated to 48°C and then cooled to 35°C in the air before it was filled in the glass tube. Thereafter, the cooled samples were placed in the apparatus and withdrawn from the cooling bath at 1°C interval for checking its flowability. The pour point was taken to be the temperature 1°C above the temperature at which no motion of fuel was observed for five seconds on tilting the tube to a horizontal position. Cloud and pour points of various blends of biodiesel and n-butanol are illustrated in Table 4.8.

Table 4.8 Cloud point and pour point of different blends

S. No.	Blended fuel	Cloud point (°C)	Pour point (°C)
1	D90/B10	3.5	-1.1
2	D80/B20	3.8	-0.8
3	D90/nb10	4.0	-0.6
4	D80/nb20	4.7	-0.3
5	D80/B10/nb10	5.1	0.1
6	D60/B20/nb20	5.5	0.5
7	D70/B10/nb20	4.9	0.2
8	D70/B20/nb10	4.6	-0.1

4.5.7 Flash and Fire Point

The Flash point is defined as the lowest temperature at which the fuel gives off sufficient vapors and ignites for a moment. The fire point is an extension of flash point in a way that it reflects the condition at which vapor burns continuously for five seconds. The fire point is always higher than flash point by 5 to 8°C. Flash point and fire point apparatus as shown in Figure 4.10 is used to calculate the value of flash point and fire point. The sample was filled in the test cup up to the specified level and heated by heating the air bath with the help of a heater. The fuel sample was stirred at a slow constant rate. The sample was heated in such a way that the rate of temperature rise was approximately 5°C per minute. The temperature was measured with the help of a thermometer of -10 to 400°C range.

At every 1°C temperature rise, the flame was introduced for a moment with the help of a shutter. The temperature at which a flash appeared in the form of sound and light was recorded as the flash point. The fire point was recorded as the temperature at which fuel vapor catches fire and stays for a minimum of five seconds. Table 4.9 illustrates the values of flash point and fire point of various fuel blends.

4.5.8 Calorific Value

The heat of combustion or calorific value of a fuel is an important measure since it is the heat produced by the fuel within the engine that enables the engine to do the useful work. The heat of combustion of fuel samples was determined with the help of a Bomb Calorimeter (Figure 4.11).

Table 4.9 Flash point and Fire point of different blends

S. No.	Blended fuel	Flash point (^oC)	Fire point (^oC)
1	D90/B10	63	70
2	D80/B20	66	75
3	D90/nb10	74	79
4	D80/nb20	71	83
5	D80/B10/nb10	79	86
6	D60/B20/nb20	90	95
7	D70/B10/nb20	88	89
8	D70/B20/nb10	83	87

Figure 4.10 Flash point and fire point apparatus

Figure 4.11 Bomb calorimeter

A fuel sample of 1ml was burnt in the bomb of the calorimeter in the presence of pure oxygen. The sample was ignited electrically. As the heat was produced, the rise in temperature of the water was measured. The water equivalent (effective heat capacity of the calorimeter) was also determined using pure and dry benzoic acid as a test fuel. The gross heat of combustion of the fuel samples was calculated using the equation given below:

$Hc = Wc \times \Delta T / Ms$

Where,

Hc =Heat of combustion of the fuel sample, Cal/g

Wc= Water equivalent of the calorimeter, Cal/^{o}C

ΔT=Rise in Temperature, ^{o}C

Ms= Mass of sample burnt, gm

Table 4.10 shows the calorific value of various fuel blends.

Table 4.10 Calorific Value of different blends

S. No.	Blended fuel	Calorific value
1	D90/B10	42376
2	D80/B20	41966
3	D90/nb10	42187
4	D80/nb20	42107
5	D80/B10/nb10	41470
6	D60/B20/nb20	40090
7	D70/B10/nb20	41230
8	D70/B20/nb10	41387

4.6 Comparative properties of diesel and blended fuel

Various calculated properties of the blended fuels were related with diesel fuel as illustrated in table 4.11 and it was found that most of the intended properties were very much alike to natural diesel and were meeting the requirements of ASTM limits.

4.7 Biogas production

Biogas was produced in the biogas generator using cow dung and kitchen waste. A fixed dome type biogas digester as shown in Figure 4.12 was used for producing biogas. A fixed-dome type biogas digester consists of a digester with a stable, non-movable gas container, which be seated on upper part of the digester. Slurry was set by fraternization of water in cattle dung in equivalent fraction, and partial quantity of kitchen waste in mixing reservoir. The slurry was then guided into the digester container with the aid of inlet compartment, where the composite carbon combinations existing in the cattle dung and kitchen waste breaks into simpler matters by the act of anaerobic microbes in the company of water. This anaerobic disintegration of composite carbon combinations available in cattle dung and kitchen waste procures biogas and a cycle is accomplished in approximately 2 months. The biogas so formed collects in dome designed top of biogas generator and is supplied to the engine with help of pipes. The consumed slurry is substituted from time to time with new slurry to carry on the fabrication of biogas. Three different mass flow rates of biogas at 0.5 kg/h, 1.2 kg/h, and 2kg/h were selected arbitrarily [295]. Fuel blends designated in table 4.1 were further designated as illustrated in table 4.12. A Junkers gas calorimeter as depicted in Figure 4.13 was used to measure the calorific value of biogas. Calorific value of biogas was found to be 2067 kJ/kg.

Figure 4.12 Biogas digester

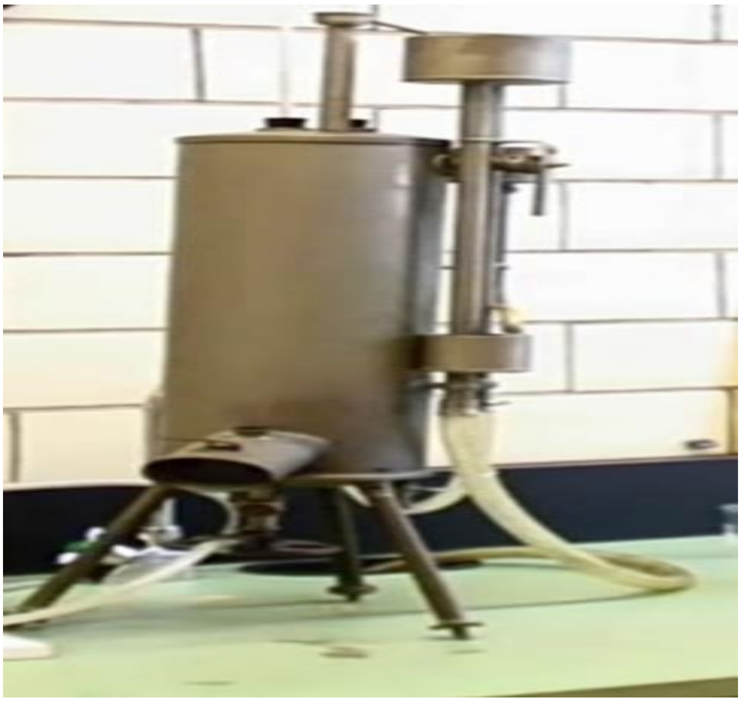

Figure 4.13 Junkers gas calorimeter

Table 4.11 Comparative properties of diesel and blended fuels

S. N.	**Properties**	**Units**	**ASTM limits**	**ASTM D6751 Test**	**Diesel**	**D90/ B10**	**D80/ B20**	**D90/ nb10**	**D80/ nb20**	**D80/ B10/ nb10**	**D60/ B20/ nb20**	**D70/ B10/ nb10**	**D70/ B10/ nb20**
1	Density	Kg/m^3	840-860	D4052	832	834.2	841.4	789.1	782.9	818.5	805.1	817.2	828.6
2	FFA value	%	<0.2	---	---	0.0102	0.0105	0.0106	0.0107	0.0109	0.0114	0.0107	0.0108
3	Viscosity	cSt	1.9-6.0	D445	2.023	2.508	2.754	2.001	1.915	2.293	2.347	2.192	2.239
4	Flash point	^{o}C	<130	D93	69	63	66	74	71	79	90	88	83
5	Fire point	^{o}C	>53	D93	74	70	75	79	83	86	95	89	87
6	Cloud point	^{o}C	-3 to 12	D2500	3	3.5	3.8	4.0	4.7	5.1	5.5	4.9	4.6
7	Pour point	^{o}C	-15 to 10	D97	-2	-1.1	-0.8	-0.6	-0.3	0.1	0.5	0.2	-0.1
8	Calorific value	kJ/kg	>33000	D4809	42850	42376	41966	42187	42017	41470	40090	41230	41387

Table 4.12 Designation of fuel matrix

S. N.	**Name of designated fuel**	**Percentage of diesel in liquid fuel**	**Percentage of biodiesel in liquid fuel**	**Percentage of n-butanol in liquid fuel**	**Mass flow rate of biogas**
					kg/h
1.	D100+BG(0.5 kg/h)	100	_	_	0.5
2.	D100+BG(1.2 kg/h)	100	_	_	1.2
3.	D100+BG(2 kg/h)	100	_	_	2
4.	D90/nb10+BG(0.5 kg/h)	90	_	10	0.5
5.	D90/nb10+BG(1.2 kg/h)	90	_	10	1.2
6.	D90/nb10+BG(2 kg/h)	90	_	10	2
7.	D80/nb20+BG(0.5 kg/h)	80	_	20	0.5
8.	D80/nb20+BG(1.2 kg/h)	80	_	20	1.2
9.	D80/nb20+BG(2 kg/h)	80	_	20	2
10.	D90/B10+BG(0.5 kg/h)	90	10	_	0.5
11.	D90/B10+BG(1.2 kg/h)	90	10	_	1.2
12.	D90/B10+BG(2 kg/h)	90	10	_	2
13.	D80/B20+BG(0.5 kg/h)	80	20	_	0.5
14.	D80/B20+BG(1.2 kg/h)	80	20	_	1.2
15.	D80/B20+BG(2 kg/h)	80	20	_	2
16.	D80/B10/nb10+BG(0.5 kg/h)	80	10	10	0.5
17.	D80/B10/nb10+BG(1.2 kg/h)	80	10	10	1.2
18.	D80/B10/nb10+BG(2 kg/h)	80	10	10	2
19.	D60/B20/nb20+BG(0.5 kg/h)	60	20	20	0.5
20.	D60/B20/nb20+BG(1.2 kg/h)	60	20	20	1.2
21.	D60/B20/nb20+BG(2 kg/h)	60	20	20	2
22.	D70/B10/nb20 BG(0.5 kg/h)	70	10	20	0.5
23.	D70/B10/nb20 BG(1.2 kg/h)	70	10	20	1.2
24.	D70/B10/nb20 BG(2 kg/h)	70	10	20	2
25.	D70/B20/nb10 BG(0.5 kg/h)	70	20	10	0.5
26.	D70/B20/nb10 BG(1.2 kg/h)	70	20	10	1.2
27.	D70/B20/nb10 BG(2 kg/h)	70	20	10	2

4.8 Experimental set up

A single cylinder, small utility diesel engine with a rated power output of 3.75 kW was employed in this study. It was a direct injection, air cooled engine manufactured by Kirloskar Oil India limited Experimentation was done at a constant speed of 1550 rpm. Technical specification of the experimental test set up is illustrated in table 4.13.

Table 4.13 Engine specification

Parameter	Description
Manufacture	Kirloskar
Engine type	Vertical, 4-stroke
Rated power output (kW)	3.75
Engine cooling	Air cooled
Engine speed (rpm)	1500
No. of cylinder	1
Stroke length, (mm)	110
Bore (mm)	87.5
Compression ratio	16.5 : 1
Displacement volume (cc)	252.9
Injection pressure (kg cm^{-2})	200

Power output of the engine was measured by an eddy current dynamometer coupled with engine shaft and loaded with help of resistive load bank. An AVL DIGAS 444 N gas analyzer was used to measure the concentration of gaseous emissions such as unburned hydrocarbon, carbon monoxide, carbon dioxide and nitrogen oxides. Digital readings of all the gaseous emissions were obtained by placing the probe in exhaust of cylinder. Smoke meter was used to measure the smoke opacity. Layout and Schematic diagram of the engine set up is shown in Figure 4.14. Actual photograph of experimental set up is depicted in Figure 4.15.

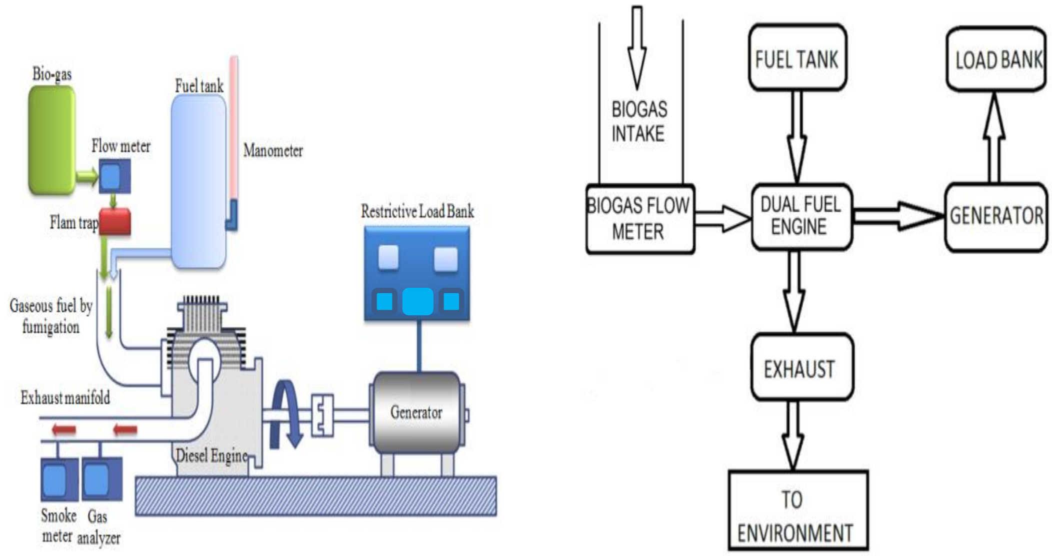

Figure 4.14 Schematic diagram and block diagram of experimental set up

Figure 4.15 Actual experimental set up

Key: 1.Engine. 2. Dynamo. 3. Resistive Load Bank. 4. Electric Control Panel. 5. Air SurgeTank. 6. Biogas Flow Meter. 7. Digital Tachometer. 8. Exhaust Gas Temperature Thermocouple. 9. AVL Exhaust Gas Analyser. 10. Probe. 11. Fuel Measuring Burette. 12. U-Tube Manometer.

Testing of blends at biogas at mass flow rate of 0.5 kg/ hr, 1.2 kg/ hr and 2 kg/ hr was carried out under different load conditions (i.e: 20%, 40%, 60%, 80%, 100%) on dual fuel engine. The performance and emission tests are carried out on the C.I. engine. R.P.M of the engine was calculated using a digital tachometer. The fuel consumption of engine was measured by determining the time required for consumption of 10 ml of fuel using a glass burette. Initial and final readings of biogas flow were taken to calculate flow rate of biogas per minute. Voltage and current readings of electrical panel attached with engine was also tabulated on different load conditions. Readings of concentration of gaseous emissions such as unburned hydrocarbon, carbon monoxide, carbon dioxide and nitrogen oxides were noted using AVL gas analyzer.

A 5 kW load bank with electrical panel was used in set up as shown in Figure 4.16 A load bank is a device which develops an electrical load, applies the load to an Electrical power source and converts or dissipates the resultant power output of the source. The purpose of a load bank is to accurately mimic the operational or “real” load that a power source will see in actual application. The load was applied on the engine into 5 steps. There are 10 switches on the Load bank. Each switch has capacity of 0.5 KW load. Load was applied on these switches one by one. First of all, engine was run on no load condition, then 0.5 kW load was applied on the engine and this process continued till 5 kW load.

Figure 4.16 Load bank with electrical panels

The intake manifold of the engine was suitably modified so that biogas can be introduced into the engine cylinder along with intake air as shown in Figure 4.17.

Figure 4.17 Modification of intake manifold of the engine

A manual biogas flow meter was used to control the flow of biogas as shown in Figure 4.18. Biogas was directed from the pipelines to this manual biogas mass flow meter and the mass flow rate of biogas was set accordingly by hit and trail method before delivering the biogas to the inlet manifold of the engine cylinder.

Figure 4.18 Manual biogas mass flow meter

An AVL DIGAS 444 N gas analyzer as shown in Figure 4.19 was used to measure the concentration of gaseous emissions such as unburned hydrocarbon, carbon monoxide, carbon dioxide and nitrogen oxides. Digital readings of all the gaseous emissions were obtained by placing the probe into exhaust of cylinder. As and when reading on gas analyzer seems to be constant that value is taken as final value.

Figure 4.19 AVL DIGAS 444 N gas analyzer

The intensity of smoke emission was measured with the help of a diesel smoke meter (AVL 437C). The probe of the smoke meter was placed into the exhaust of the cylinder to check the smoke emanations coming out of the engine exhaust. A photographic view of the AVL 437C diesel smoke meter is illustrated in Figure 4.20.

Figure 4.20 Smoke meter

4.9 Uncertainty Analysis

Uncertainty is used to calculate any miscue of a conclusion. Authenticity of the experimental study may be affected due to some uncertainties. To make sure that the obtained results are accurate uncertainty analysis must be performed. Calibration of all the apparatus used for experimentation is also necessary for getting exact value. Most of the familiar investigators advise to perform this analysis. Accordingly, to achieve a valid value all the experimentation was performed in a way that readings were taken more than two times and after that arithmetic mean of entire range of values was calculated. The range and accuracy of the gas analyzer and smoke meter is depicted in Table 4.14.

Table 4.14 Uncertainty, range and accuracy of gas analyzer and smoke meter

Exhaust emissions	Range	Accuracy	Uncertainties
HC	0–19,999	± 10 ppm	± 0.1 (%)
CO	0–4000 ppm	0.015%	± 0.4 (%)
Smoke		0.005%	± 1.0 (%)
NOx	0–4000 ppm	± 10 ppm	± 0.2 (%)

4.10 Performance parameters and biogas energy share calculations

All the performance parameters were calculated as per definitive protocols [35] and are mentioned underneath:

$$\mathrm{B.P.} = \frac{\mathrm{V\ x\ I}}{0.88\ \mathrm{x}\ 1000}\,\mathrm{kW} \qquad \text{(i)}$$

where, B.P. is brake power, V denotes voltage and I denotes current in amperes. The efficiency of engine was 88%.

$$\mathrm{B.T.E} = \frac{\mathrm{B.P.x}\ 3600\ \mathrm{x}100}{(\mathrm{m_{BIO}\ x\ LCV_{BIO}} + \mathrm{m_{Pilot\ fuel}\ x\ LCV_{Pilot\ fuel}})}\ \% \qquad \text{(ii)}$$

where, B.T.E stands for brake thermal efficiency, m_{BIO} and m_{RBD} symbolize mass of biogas (kg/h) and blend of rice bran methyl ester added with diesel respectively. LCV_{BIO} and $LCV_{Pilot\ fuel}$ denote lower calorific value of biogas and rice bran biodiesel blended diesel respectively.

$$\mathrm{B.S.F.C} = \frac{(m_{BIO}+m_{Pilot\ fuel})}{\mathrm{B.P.}} \qquad \text{(iii)}$$

where, B.S.F.C. signifies brake specific fuel consumption.

$$\text{Biogas energy share} = \frac{\text{Energy equivalent of biogas}}{\text{Energy equivalent of (diesel+biogas)}} \text{ x } 100 \qquad \text{(iv)}$$

where,

$$\text{Energy equivalent of biogas} = \frac{m_{Biogas} \text{ x } CV_{Biogas}}{3600} \qquad \text{(v)}$$

and,

$$\text{Energy equivalent of primary fuel} = \frac{m_{Diesel} \text{ x } CV_{Diesel}}{3600} \qquad \text{(vi)}$$

Chapter 5

Results and discussions

5.1 Overview

The main motive of this thesis is to evaluate the conduct of rice bran biodiesel, n-butanol, and biogas in a diesel engine. However, comprehend this evidence; it is crucial to understand the effect of pure diesel at similar engine conditions, which can be treated as baseline conditions. The engine is run at a stable speed of 1500 rpm and its loading conditions are varied from 20% to 100% in intervals of 20% each. The comprehensive experimentation is separated into performance and emission characteristics of the engine. In every portion reasoning is provided based on blends, mass flow rate, and loads. The result of the experimental study is related to pure diesel. The performance of the engine is resolved on the basis of brake specific fuel consumption and brake power, whereas the emission characteristics of carbon monoxide; hydrocarbons, nitrogen oxides, and smoke are recorded by an AVL gas analyzer. The performance and emission parameters of the diesel engine energized with diesel, rice brine methyl esters, n-butanol and biogas are discussed in this segment.

5.2 Combination of diesel and biodiesel

The blends of diesel and biodiesel are tested on the diesel engine in this section to evaluate the performance and emission parameters of the engine. Performance and emission characteristics of the diesel engine for fuel blends D90/B10 and D80/B20 are correlated with natural diesel. Therefore, the graphs including performance and exhalation parameters are merged and composed.

5.2.1 Variation of BSFC with engine load

Brake Specific fuel consumption is a crucial criterion, to examine the efficiency with which the fuel is being consumed in an engine [99]. Figure 5.1 shows variations of BSFC when the engine was fuelled with Rice bran methyl esters compared to baseline diesel. It was observed that with increment in load utilization of fuel decreased for all test fuels. Improved combustion inside the cylinder due to decreased ignition delay, which was a result of high cylinder wall temperature at high engine loads, was the reason for low BSFC at high engine loads [218]. As the quantity of Rice bran biodiesel was increased in fuel blend BSFC was also on the higher side which can be owing to more viscosity, low calorific value and a high index of hydrogen deficiency of biodiesel [85]. BSFC was detected to be maximum for D80/B20 fuel blend at 20% load and minimum for the conventional diesel at 80% load. The highest value for D90/B10 fuel blend was at 40% load and lowest was at 80% load. Fuel blend D80/B20 has 21.8%, 23.7%, 20.48%, 24.5%, and 15.2% more BSFC than pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average increase of 21.1%. It is found that an increment of 8.3%, 15.2%, 13.9%, 13.4%, and 7.1% is achieved in BSFC at the engine loads ranging from 20% to full load in intervals of 20% each respectively in comparison with traditional diesel. An average increment of 11.6% is noticed.

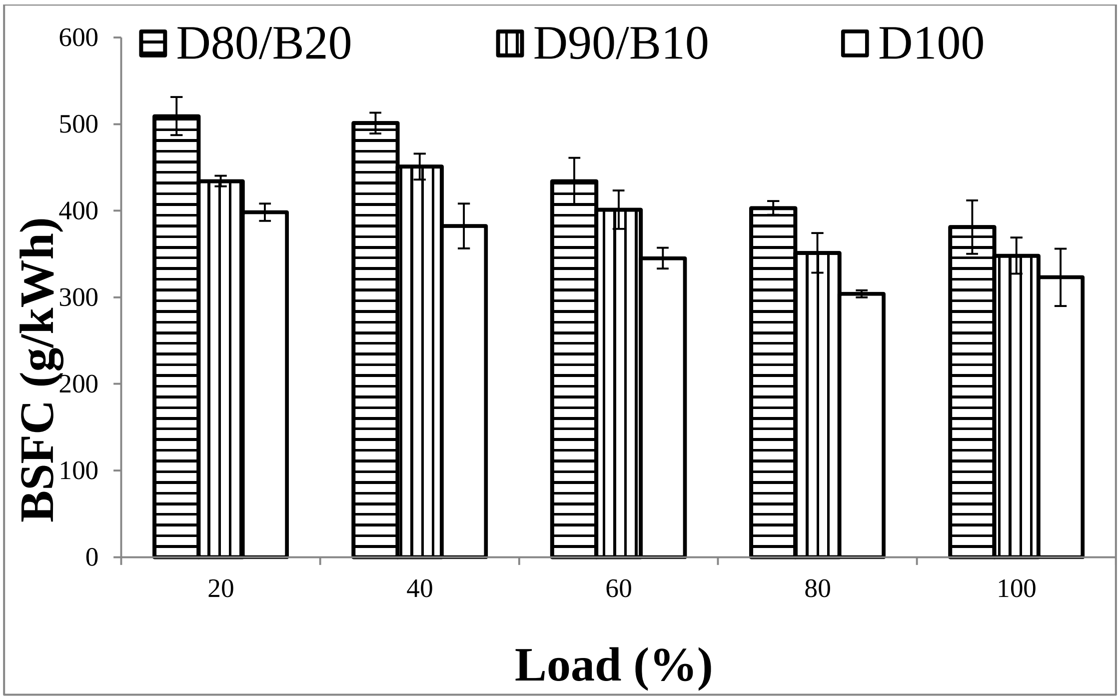

Figure 5.1 Variation of BSFC with load for diesel and biodiesel

5.2.2 Variation of BTE with engine load

Brake thermal efficiency is the ratio of brake power output to the energy of fuel consumed. It speaks for the combustion quality of the engine [35]. From Figure 5.2 it was noticed that BTE was directly proportional to engine load for all fuel blends. Similar trends were also observed by Bora et al. [65] and Dhamodaran et al. [102]. It was also found that BTE decreases with the addition of Rice bran methyl esters in fuel blends as a result of higher viscosity and lower heating value of biodiesel [206]. The highest value of BTE was for fossil diesel at full load and lowest was for D80/B20 fuel blend at 20% load. D90/B10 fuel blend achieved maximum BTE at 100% load and the minimum value at part loads. Reduction of 0.4%, 1.1%, 2.4%, 3.2%, and 0.5% is attained in BTE at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D90/B10 fuel blend when compared with pure diesel. An average decrement of 1.5% is discovered. Fuel blend D80/B20 has 2.2%, 5.4%, 6.3%, 8.1%, and 2.4% reduced BTE than pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 4.9%.

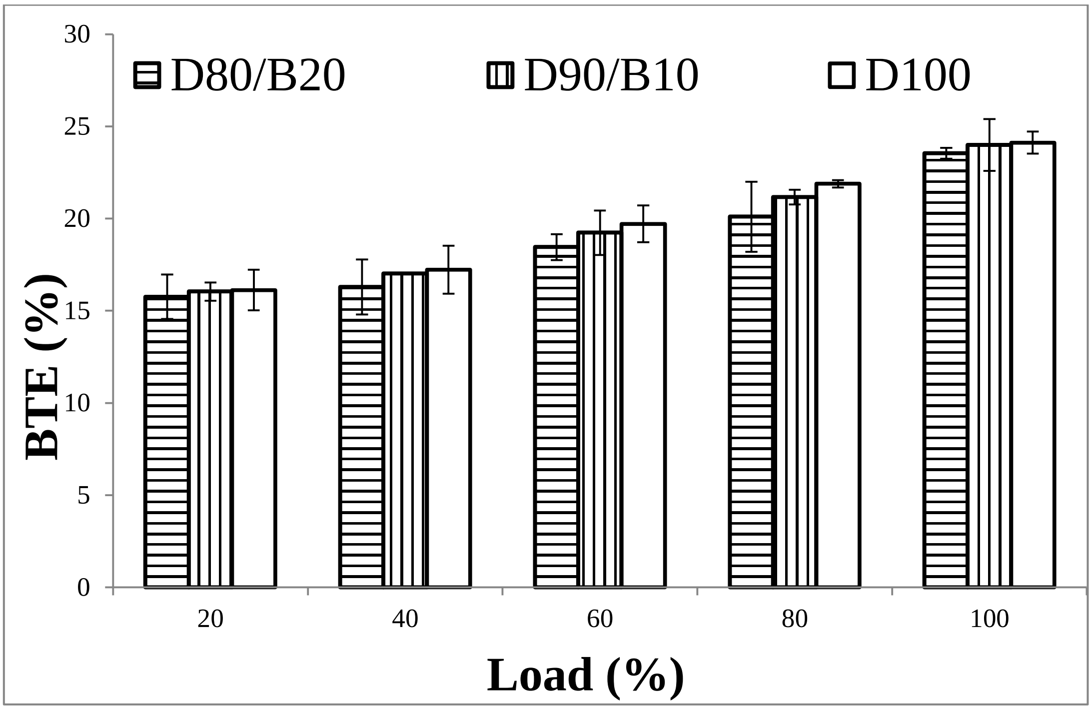

Figure 5.2 Variation of BTE with load for diesel and biodiesel

5.2.3 Variation of CO with engine load

Carbon monoxide emissions are the result of incomplete combustion of hydrocarbons available in the fuel. Figure 5.3 depicts that CO emissions firstly decreases with engine load up to a particular limit and then increase with the increase in load. The same trend was observed by Satsangi et al. [210] and Mahla et al. [35]. It can also be seen that addition of biodiesel in biodiesel-diesel fuel blends is inversely proportional to CO emissions which is very similarly observed by Chauhan et al.[104] and Chauhan et al.[118] It may be due to improved combustion of biodiesel in comparison with diesel as biodiesel contains lower carbon contents and more oxygen particles [139]. Exhalations of CO got the minimum value for D80/B20 fuel blend at 60% load and maximum for natural diesel at full load. The highest value for D90/B10 fuel blend was at 100% load and lowest at 60% load. Fuel blend D80/B20 has 21.4%, 16.6%, 11.3%, 7.4%, and 27.9% less CO exhalations than conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 16.9%. A reduction of 12.6%, 3.5%, 2.3%, 2.3%, and 10.7% is found in emissions of CO at the engine loads ranging from 20% to full load in intervals of 20% each respectively in comparison with diesel. An average decrement of 6.3% is reported.

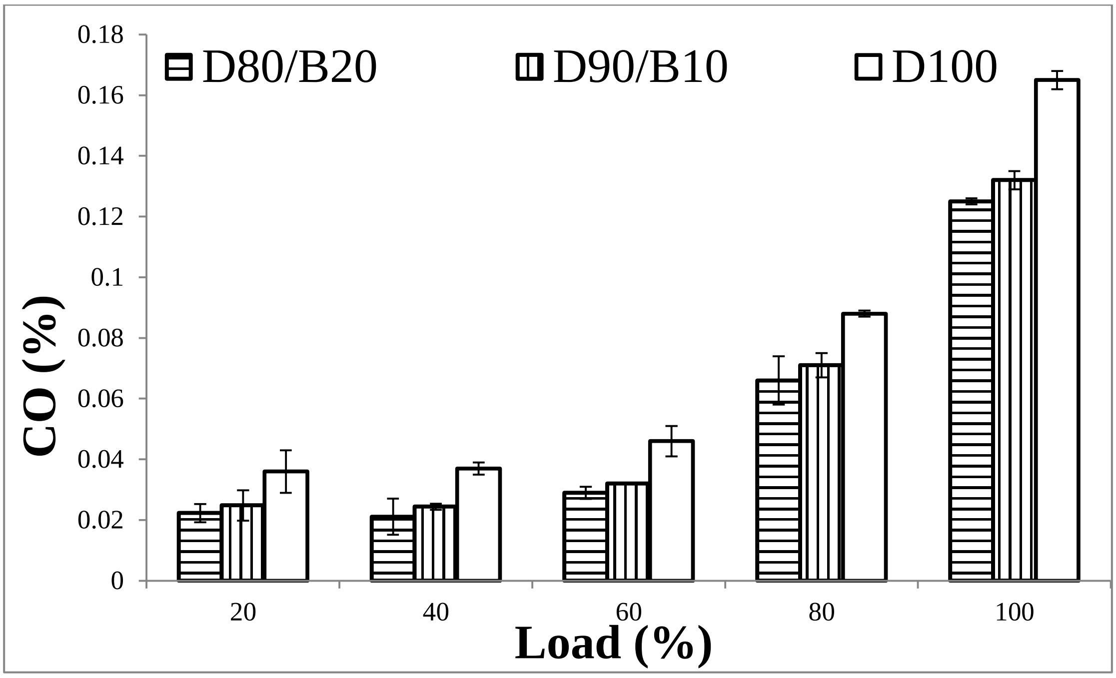

Figure 5.3 Variation of CO with load for diesel and biodiesel

5.2.4 Variation of HC with engine load

Hydrocarbon emissions are the outcome of partial combustion of fuel inside the combustion chamber [284]. Fig. 5.4 shows that for fuel blend D90/B10 HC emissions were found to be lower than baseline diesel whereas the minimum amount of HC emissions was recognized for D80/B20 which may be correlated with short ignition delay due to higher cetane number of biodiesel as compared to diesel [285]. Maximum emissions of HC are found for natural diesel at 100% engine load and the minimum for D80/B20 fuel blend at 20% engine load. D90/B10 fuel blend achieved the highest amount of HC at full load and least value at part loads. A decrement of 3.4%, 2.3%, 3.4%, 3.3%, and 1.6% is achieved in HC exhalations at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D90/B10 fuel blend when compared with conventional diesel. An average reduction of 2.8% is attained. Fuel blend D80/B20 show 10%, 10.1%, 10.6%, 12%, and 9.4% reduced HC emissions than diesel fuel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deduction of 10.4%.

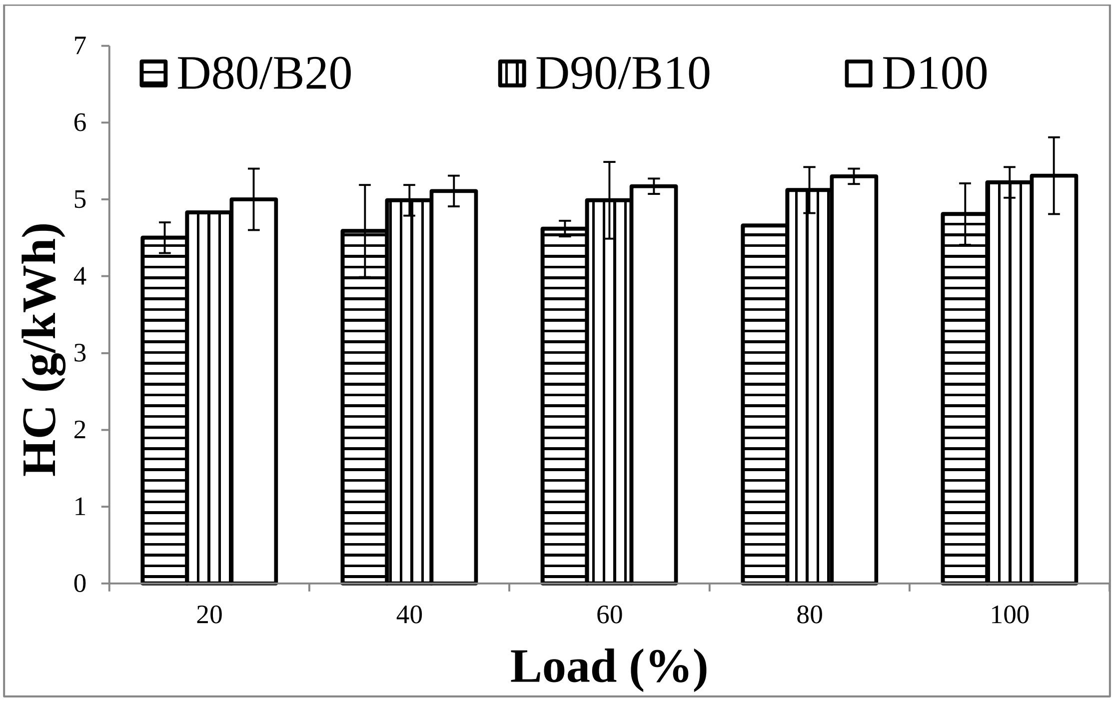

Figure 5.4 Variation of HC with load for diesel and biodiesel

5.2.5 Variation of NOx with engine load

Nitrogen Oxides are the consequences of reaction between oxygen and nitrogen particles present in the air at a high temperature. It was established from Figure 5.5 that NOx emissions were more for biodiesel blends as compared to diesel which banks on higher combustion temperature of biodiesel [163] and higher unsaturation degree [286]. Maximum NOx emissions were found for D80/B20 fuel blend followed by D90/B10 fuel blend and conventional diesel at all engine loads. With an increase in load NOx emissions were noted to be decreased owing to lean air-fuel mixture at high engine loads which does not allow complete combustion of fuel and hence does not allow reacting nitrogen and oxygen atoms properly. Highest NOx exhalations were recorded for D80/B20 fuel blend at 20% load and lowest for natural diesel at full load. The maximum and minimum value of NOx for D90/B10 fuel blend was found at 20% and 100% loads respectively. D80/B20 fuel blend has 10.7%, 13.6%, 18.8%, 27.1%, and 22.2% more NOx exhalations than fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average increment of 18.5%. An increase of 7.7%, 9.6%, 10.4%, 16.2%, and 15.4% is noted in exhalations of NOx at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D90/B10 fuel blends in comparison with natural diesel. An average enhancement of 11.9% is reported.

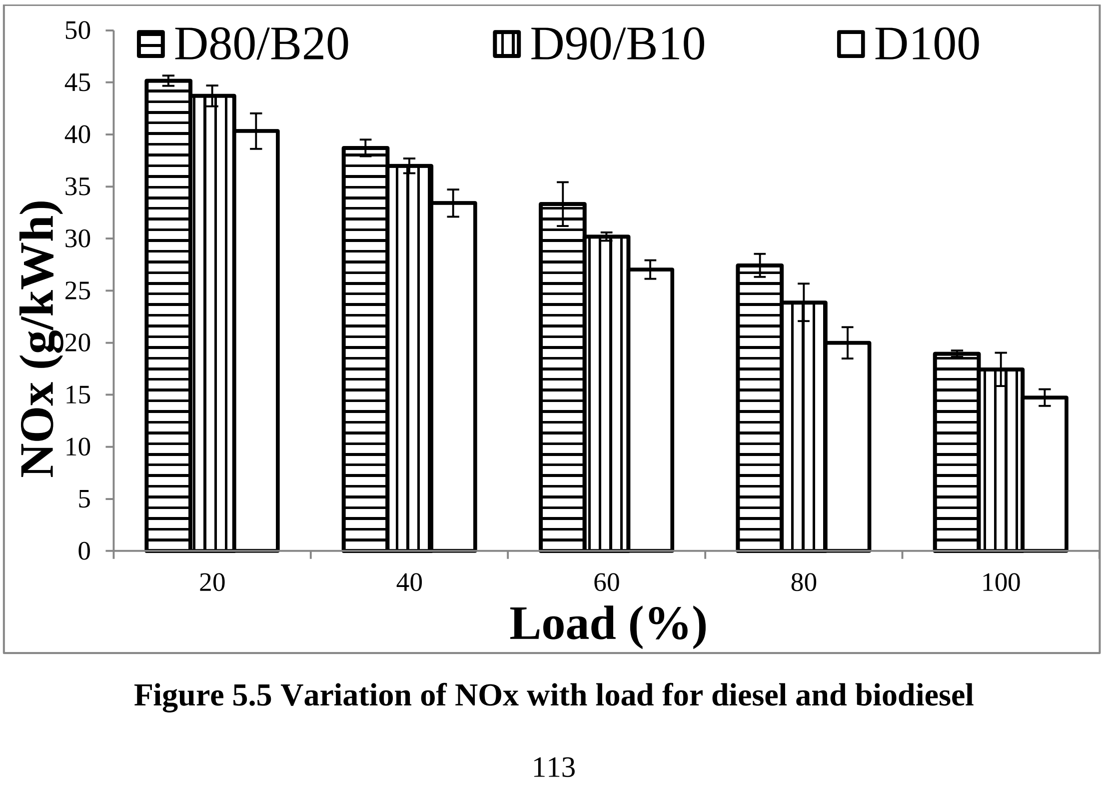

Figure 5.5 Variation of NOx with load for diesel and biodiesel

5.2.6 Variation of Smoke with engine load

Incomplete combustion of fuel aids in producing smoke which helps in originating smoke opacity [287]. Figure 5.6 presents an increased trend of smoke emissions with an increase in load which is due to high utilization of fuel at higher loads. Fuel blends with biodiesel were having decreased level of smoke emissions than pure diesel owing to the higher amount of oxygen in biodiesel which helps in complete combustion of fuel [139]. Least amount of smoke opacity was recorded for D80/B20 fuel blend, whereas fossil diesel depicts the highest smoke emissions. Smoke opacity for D80/B20 fuel blend at 20% load was found to be minimum and its maximum value was noted for pure diesel at 100% load. D90/B10 fuel blend shows the highest value of smoke at full loading conditions and lowest at 20% load. A decrease of 33.3%, 12.5%, 13.3%, 7.6%, and 5.1% is attained in smoke opacity at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D90/B10 fuel blend when compared with raw diesel. An average reduction of 14.3% is recorded. Fuel blend D80/B20 has 33.3%, 25%, 20%, 23%, and 12.8% less smoke exhalations than conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 22.8%.

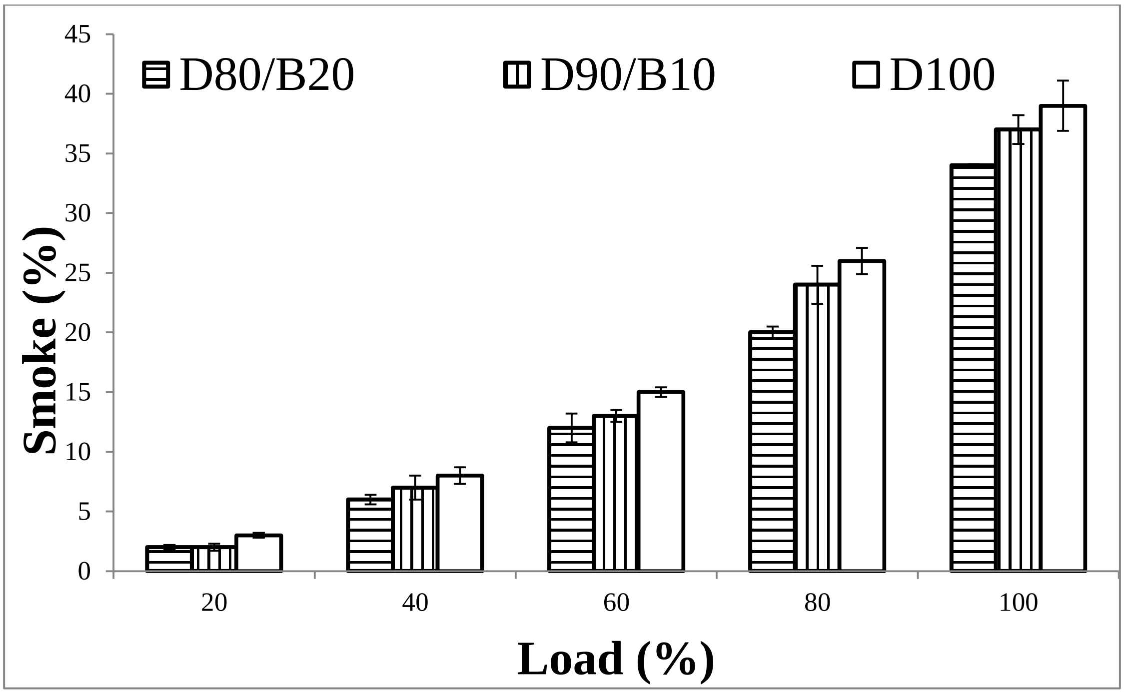

Figure 5.6 Variation of smoke with load for diesel and biodiesel

5.3 Combination of Diesel and n-butanol

The blends of diesel and n-butanol are tested on the diesel engine in this segment of the chapter to check the performance and emission characteristics of the engine. Performance and emission parameter of the diesel engine for fuel blends D90/nb10 and D80/nb20 are compared with fossil diesel. Accordingly, the plots comprising performance and exhalation characteristics are clubbed together.

5.3.1 Variation of BSFC with engine load

Deviation of BSFC with engine load is depicted in Figure 5.7 when the engine was fuelled with blends of diesel and n-butanol relative to traditional diesel. BSFC is noticed to be decreased with increasing engine load for all loading conditions. As a result of the lower calorific value of n-butanol, increased value of BSFC is observed for all n-butanol fuel blends compared to pure diesel [125]. The maximum value of BSFC was recorded for D80/nb20 fuel blend followed by D90/nb10 fuel blend and conventional diesel respectively. At 80% engine load for natural diesel, amount of BSFC is noted to be lowest, whereas its highest value was at 20% load for D80/nb20 fuel blend. For D90/nb10 fuel blend BSFC was maximum at 20% load and minimum at full load. BSFC is detected to be extreme for D80/nb20 fuel blend at 20% load and least for the conventional diesel at 80% load. The highest value for D90/nb10 fuel blend was at 40% load and lowest was at 80% load. D80/nb20 fuel blend is having 23.3%, 23.6%, 29.7%, 27.5%, and 19.2% increased BSFC than natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increase of 24.7%. It is noted that enhancement of 18.4%, 17.3%, 19.8%, 27.1%, and 8.5% is attained in BSFC at the engine loads ranging from 20% to full load in intervals of 20% each respectively in comparison with fossil diesel for D90/nb10. An average increment of 18.2% is recorded.

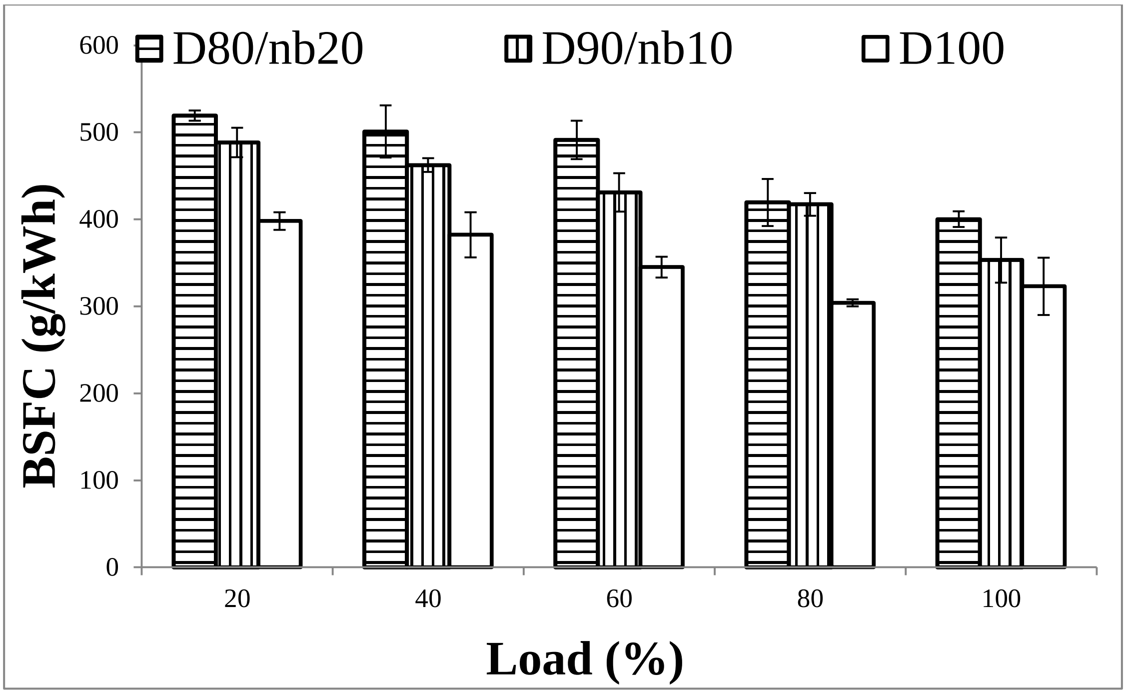

Figure 5.7 Variation of BSFC with engine load for diesel and n-butanol

5.3.2 Variation of BTE with engine load

Deviation of BTE with engine load is shown in Figure 5.8. It was recorded that BTE for all test fuels increases with enhancement in load, the identical trends obtained by various scientists already mentioned in the previous section. Fuel blends containing n-butanol was having lower values of BTE in comparison with diesel fuel. Lower cetane number and energy content and high heat of vaporization of n-butanol was the main reason for this [160]. The maximum value of BTE in percentage was obtained for traditional diesel followed by D80/nb20 and D90/nb10. Values of BTE for D90/nb10 and D80/nb20 fuel blends were almost similar, especially at part loads. Fossil diesel was found to have achieved maximum value of BTE at full load, whereas D80/nb20 depicts the minimum amount of BTE at 20% load. Value of BTE for D90/nb10 fuel blend was recorded to be more than D80/nb20 fuel blend at 20% engine load, whereas it was lesser at full loading conditions. The decrement of 6.8%, 10.9%, 13.8%, 20.2%, and 19.6% is attained in BTE at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D90/nb10 fuel blend relative to conventional diesel. An average decrement of 14.3% is noticed. Fuel blend D80/nb20 has 11.4%, 10.2%, 12.5%, 15.4%, and 16.2% less BTE in comparison with natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 13.2%.

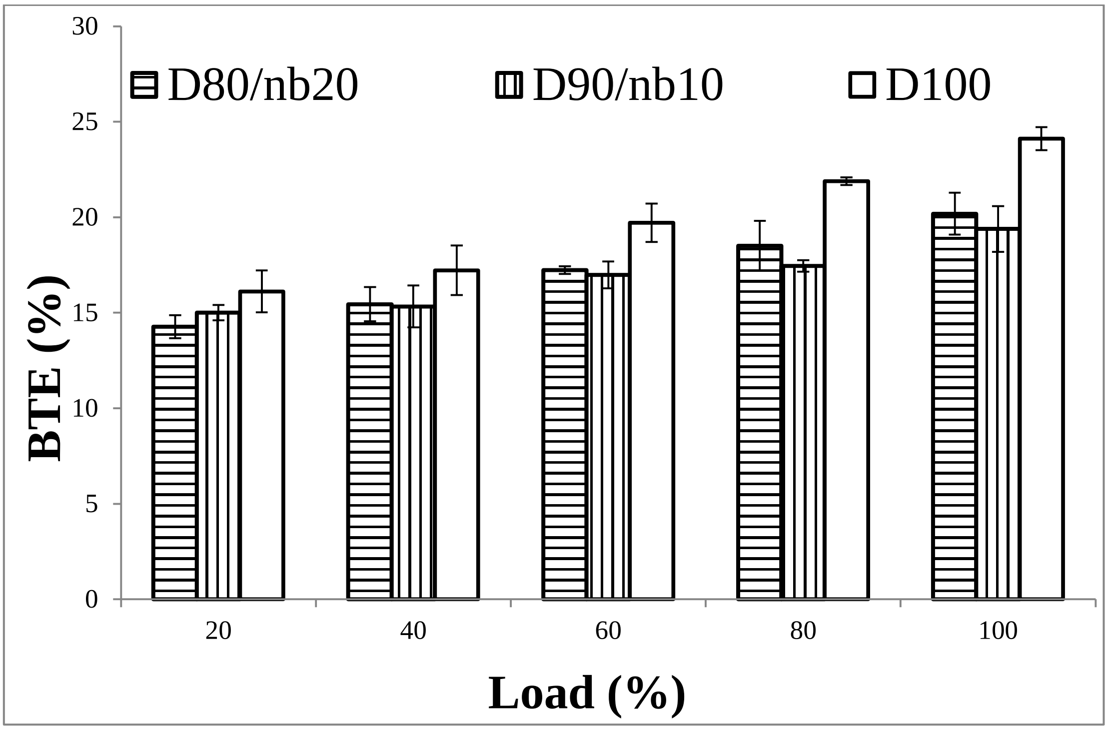

Figure 5.8 Variation of BTE with engine load for diesel and n-butanol

5.3.3 Variation of CO with engine load

As it can be clearly seen, that emissions of CO decreased initially and after that increased rapidly with increment in engine load. Deviation of CO exhalations with engine load is depicted in Figure 5.9. Adding n-butanol in fuel blend aided in lowering CO emissions relative to reference diesel owing to the fact that n-butanol is an oxygenated fuel which helped in better combustion of fuel inside the combustion chamber and hence decreasing CO exhalations [225]. Values of CO emissions were almost similar for conventional diesel and D80/nb20 fuel blend at 80% engine load. Maximum CO exhalations were recorded for natural diesel at full load and minimum for D90/nb10 fuel blend at 60% load. D80/nb20 fuel blend achieved highest CO emissions at 100% load and lowest at 60% engine load. 18.6%, 18.1%, 9%, 1.8%, and 27.9% less CO exhalations is found for D80/nb20 fuel blend in relation with conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 15.1%. A decrement of 26%, 21.3%, 14.2%, 8.8%, and 31.1% is noted in exhalations of CO for D90/nb10 fuel blend at the engine loads ranging from 20% to full load in intervals of 20% each respectively when compared with diesel. An average reduction of 20.3% is attained.

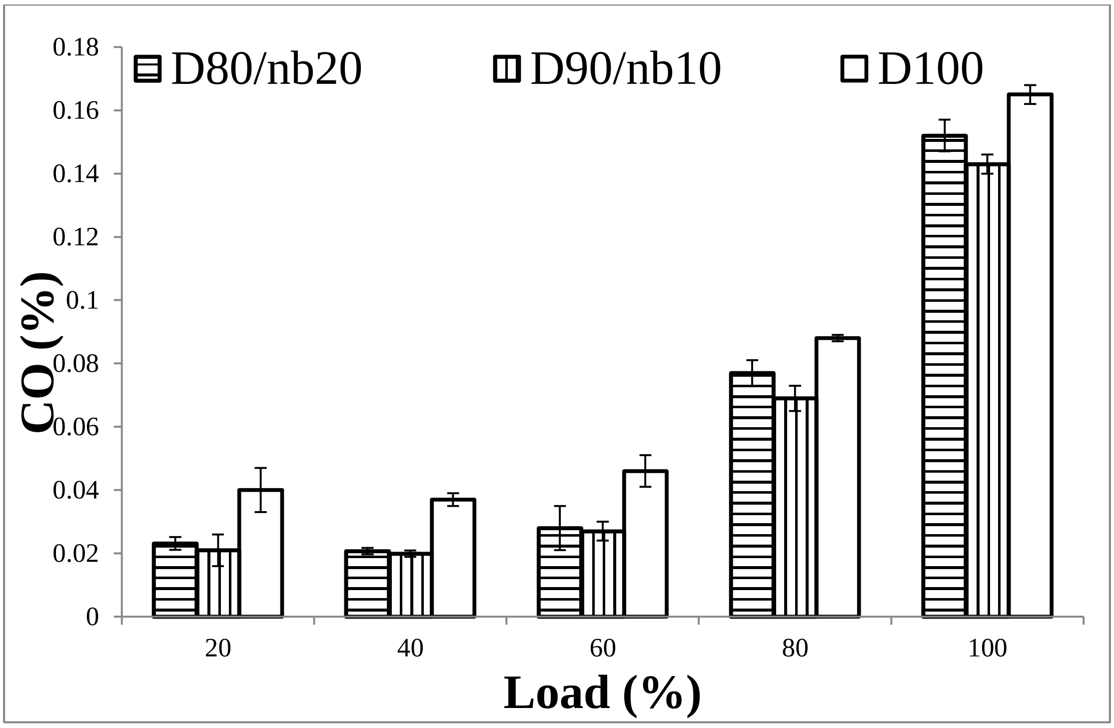

Figure 5.9 Variation of CO with engine load for diesel and n-butanol

5.3.4 Variation of HC with engine load

Figure 5.10 depicts that a higher amount of HC exhalations are found for fuel blends containing n-butanol when compared with natural diesel. The maximum value of HC emissions is noted for D80/nb20 fuel blend followed by D90/nb10 fuel blend and conventional diesel which can be attributed to the fact that due to low cetane number of n-butanol longer ignition delay is attained which consequently results in partial combustion of fuel and consequently higher HC exhalations [7]. The highest value of HC exhalations is reported for D80/nb20 fuel blend at full loading conditions and lowest value at 20% load for diesel fuel. Fuel blend D90/nb10 has a maximum value at 100% load and minimum at 20% engine load. An increase of 1.9%, 3.7%, 3%, 2%, and 2.9% is attained in HC emissions at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D90/nb10 fuel blend than traditional diesel. An average increment of 2.7% is found. Fuel blend D80/nb20 depicts 4.3%, 4.8%, 4%, 3.6%, and 4.3% decreased HC emissions in comparison with diesel fuel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average increase of 4.2%.

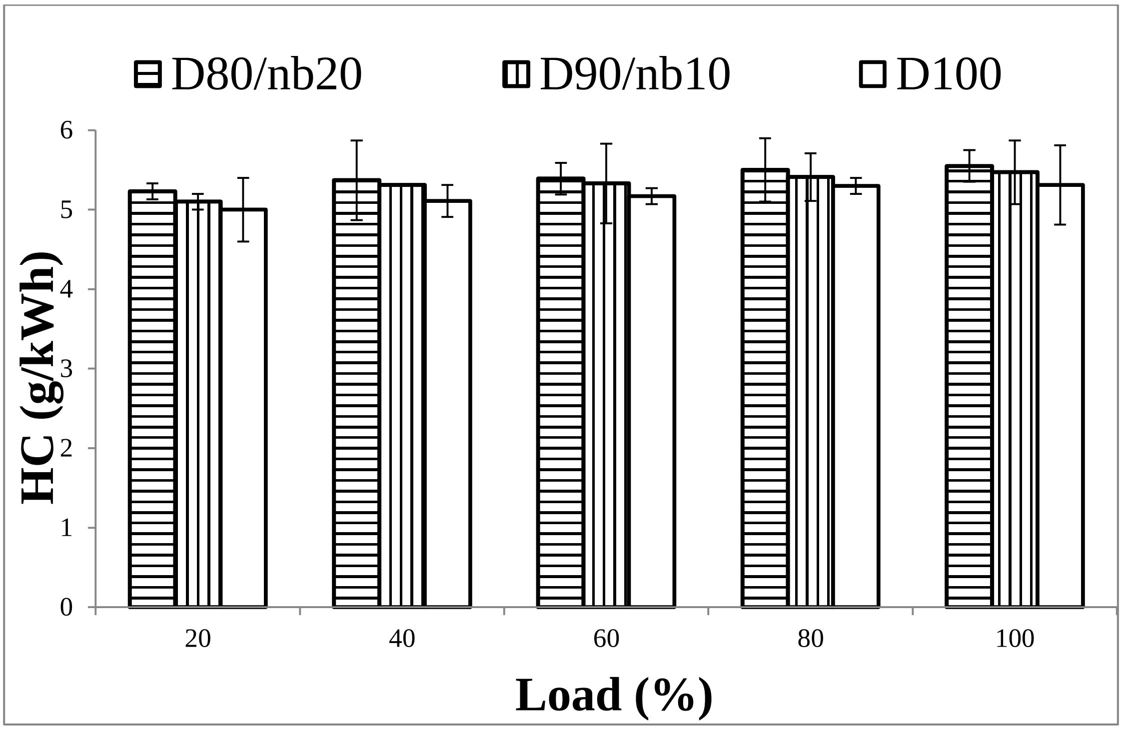

Figure 5.10 Variation of HC with engine load for diesel and n-butanol

5.3.5 Variation of NOx with engine load

Ordinary diesel was observed to emit maximum NOx during testing as compared to fuel blends containing n-butanol as illustrated in Figure 5.11. This was attributed to the fact that n-butanol has higher heat of vaporization which produces cooling effect and does not provide enough temperature inside the combustion chamber to allow the chemical reaction between Nitrogen and Oxygen and consequently emitting a low quantity of NOx for fuel blends incorporating n-butanol [160]. Increasing engine load resulted in less formation of NOx exhalations which can be clearly seen in variation graph of NOx emissions and engine load. It can also be seen that NOx emissions were highest for traditional diesel followed by D90/nb10 fuel blend and D80/nb20 fuel blend. Maximum NOx exhalations were recorded for pure diesel at 20% engine load and minimum for D80/nb20 fuel blend at highest load. D80/nb20 fuel blend shows

16%, 13.2%, 23.7%, 23.3%, and 26% decreased NOx emissions in relation with baseline diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 20.4%. A decrement of 11.3%, 7.9%, 8.3%, 10.9%, and 12.6% is reported in NOx emissions at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D90/nb10 fuel blends in comparison with natural diesel. An average reduction of 10.2% is noticed.

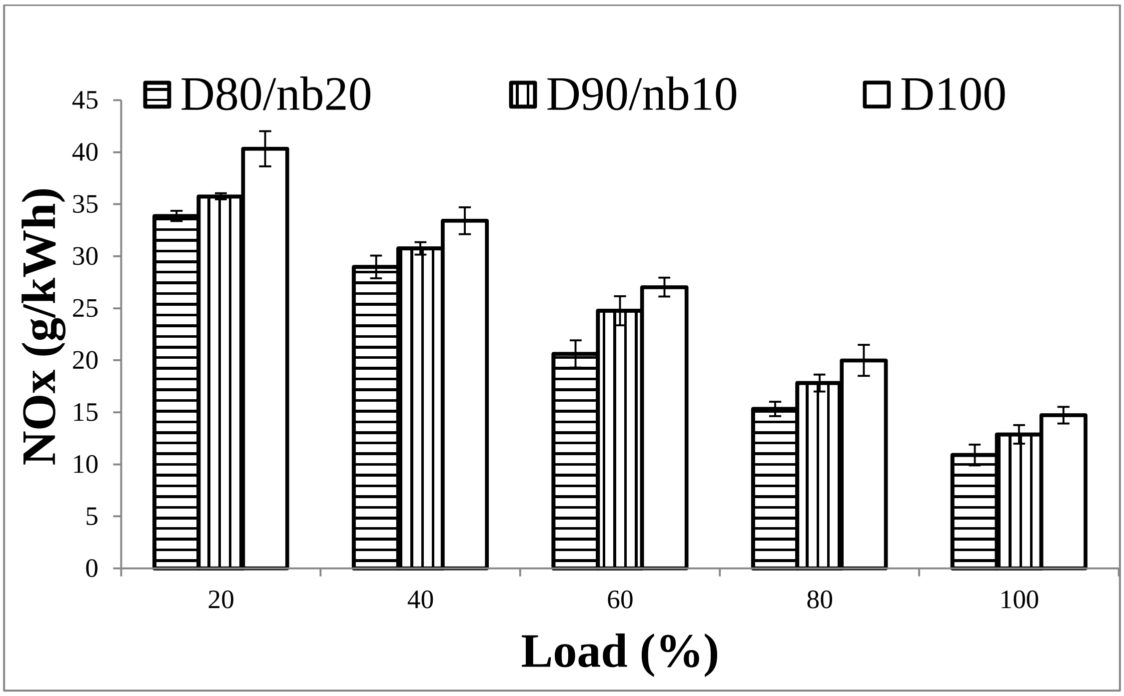

Figure 5.11 Variation of NOx with engine load for diesel and n-butanol

5.3.6 Variation of Smoke with engine load

Smoke emissions were on higher side with enhancing load on the engine which is depicted in Figure 5.12. n-butanol fuel blends can help in lowering the smoke opacity which was concluded from the experimentation with D90/nb10 and D80/nb20 fuel blends in comparison with fossil diesel. Due to the fact that n-butanol is an oxygenated fuel, carbon atoms were able to find ample amount of oxygen atoms to react with which resulted in more complete combustion and consequently producing a lesser quantity of smoke exhalations [222]. At part engine loads the value of smoke opacity was very much similar for all three fuel blends tested in this segment, and with an increase in the engine load the difference among this value increases subsequently. Maximum smoke emissions were recorded for natural diesel followed by D90/nb10 fuel blend and D80/nb20 fuel blend. The highest and lowest amount of smoke opacity was noted for pure diesel at full loading conditions and D80/nb20 fuel blend at 20% load respectively. Reduction of 33.3%, 12.5%, 6.6%, 11.5%, and 10.2% is achieved in smoke exhalations at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D90/nb10 fuel blend in relation with diesel. An average decrement of 14.8% is recorded. Fuel blend D80/nb20 depicts 66.6%, 37.5%, 26.6%, 23%, and 23% reduced smoke opacity in comparison with natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 35.3%.

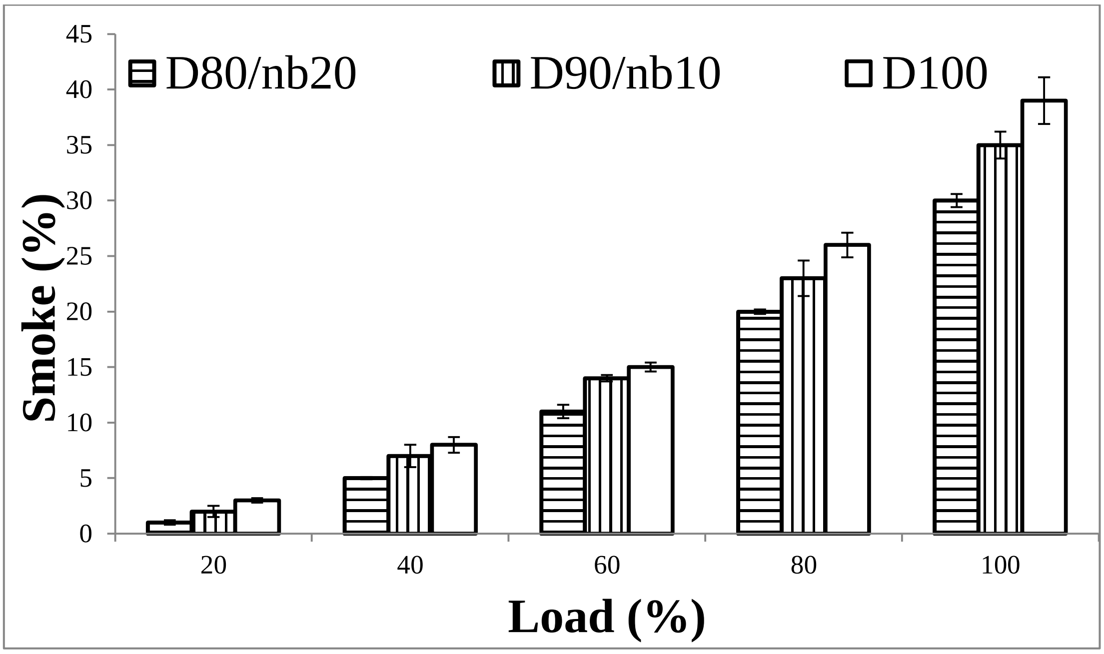

Figure 5.12 Variation of smoke with engine load for diesel and n-butanol

5.4 Combination of Diesel and Biogas

The combination of diesel and Biogas are tested on the dual fuel engine in this part to check the performance and emanation features of the engine. Performance and exhalation consideration of the diesel engine for fuel blends D100+BG(2 kg/h), D100+BG(1.2 kg/h), and D100+BG(0.5 kg/h) are associated with baseline diesel. Consequently, the charts containing performance and emission features are merged together.

5.4.1 Variation of BSFC with engine load

BSFC variation with the engine load is shown in Figure 5.13 for D100+BG(2 kg/h), D100+BG(1.2 kg/h), D100+BG(0.5 kg/h) and diesel. A decrement in BSFC is noticed with increasing engine load. BSFC for diesel engine is found minimum, in comparison with all other fuel blends that contain gaseous fuel. Furthermore with increasing biogas mass flow rate of biogas BSFC goes on increasing because of slow ignition of fuel inside the combustion chamber owing to the availability of CO_2 in Biogas and lower calorific value of Biogas [278]. Maximum BSFC is recorded for D100+BG(2 kg/h) followed by D100+BG(1.2 kg/h), D100+BG(0.5 kg/h) and diesel. The highest amount of BSFC is noted for D100+BG(2 kg/h) at 20% load and lowest for pure diesel at 80% engine load. D100+BG(2 kg/h) fuel blend is having 25%, 27%, 32.6%, 39.2%, and 32.3% increased BSFC than natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increase of 31.2%. It is noted that a hike of 21.3%, 22.1%, 27.6%, 31.5%, and 25% is attained in BSFC for D100+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively in comparison with fossil diesel. An average enhancement of 25.5% is noted. Relative to traditional diesel fuel blend D100+BG(0.5 kg/h) is reported to have an increase of 17.3%, 16.1%, 13.9%, 16.7%, and 8.9% BSFC at engine loads varying in intervals of 20% each from 20% to 100% load respectively and noticed to have average enhancement of 14.6%.

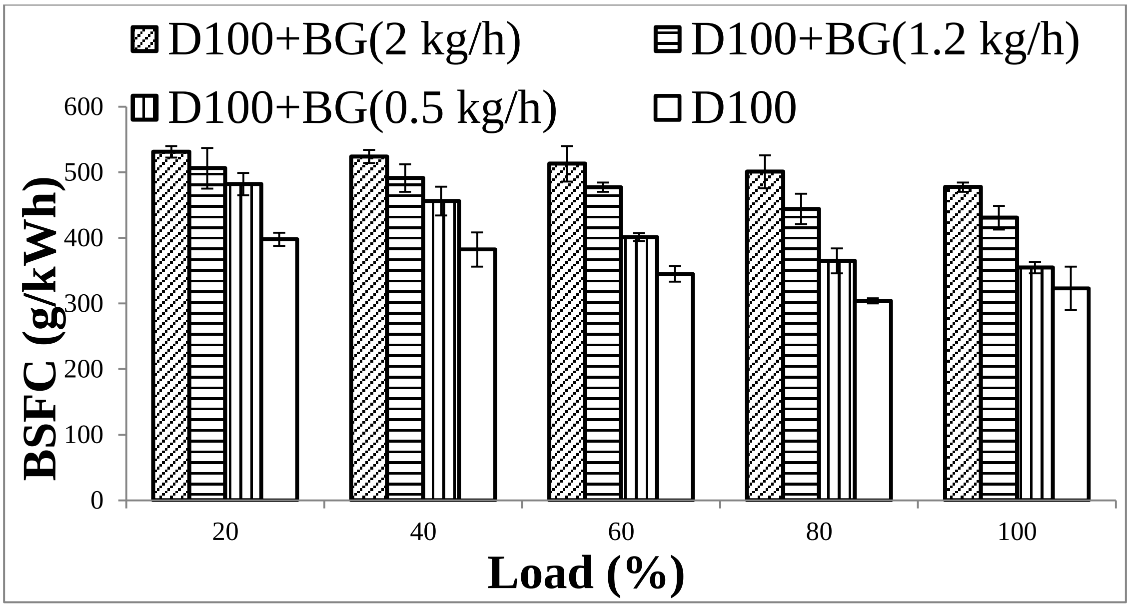

Figure 5.13 Variation of BSFC with engine load for diesel and Biogas

5.4.2 Variation of BTE with engine load

BTE for D100+BG(2 kg/h), D100+BG(1.2 kg/h) and D100+BG(0.5 kg/h) is noted to be on the lower side relative to pure diesel at all engine loads as depicted in Figure 5.14. This is owing to the fact that at part loads combustion temperature is less as a result of the leaner fuel-air mixture due to poor utilization of biogas which leads to decreased BTE [35]. The variation of BTE with engine load also shows that BTE keeps on decreasing with increasing mass flow rate of gaseous fuel. BTE is found directly proportional to the engine load. The maximum value of BTE was noted for natural diesel and minimum for D100+BG(2 kg/h) fuel blend. Value of BTE for D100+BG(1.2 kg/h) and D100+BG(0.5 kg/h) fuel blend at 60% engine load was almost the same. Reduction of 55.2%, 42.1%, 31.5%, 34.5%, and 44.8% is noticed in BTE at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D100+BG(2 kg/h) fuel blend relative to conventional diesel. An average decrement of 41.6% is attained. Fuel blend D100+BG(1.2 kg/h) has 43.6%, 25.8%, 18.9%, 25.6%, and 31% less BTE in comparison with natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 29%. In relation with fossil diesel fuel D100+BG(0.5 kg/h) has 29%, 11.5%, 18.1%, 17.6%, and 14.6% decreased BTE for engine load varying from 20% to 100% in intervals of 20% each respectively.

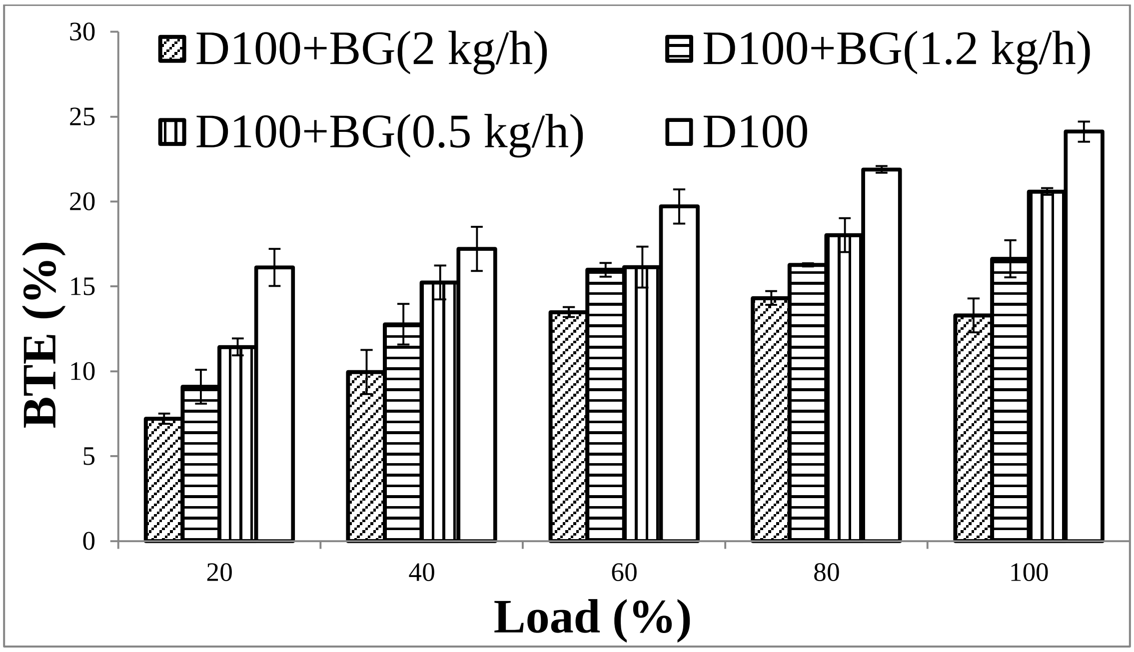

Figure 5.14 Variation of BTE with engine load for diesel and Biogas

5.4.3 Variation of CO with engine load

With Biogas induction, emissions of CO for all engine loads are found to be enhanced in comparison with ordinary diesel as depicted in Figure 5.15. Increasing mass flow rate of biogas resulted in further increasing CO exhalations. This can be attributed to the fact that biogas incorporates CO_2 which results in higher amount of CO emissions for dual fuel mode in relation to diesel fuel. Another reason may be higher fuel-air equivalence ratio of the gaseous fuel [60]. CO exhalations were found to be maximum for D100+BG(2 kg/h) fuel blend and minimum for pure diesel. Amount of CO emissions for fuel blend D100+BG(2 kg/h) and D100+BG(1.2 kg/h) were almost the same at 80% engine load. At full loading conditions, CO exhalations were recorded to be very much similar for all the fuel blends and fossil diesel. 18.3%, 15.9%, 22.4%, 20.3%, and 3.8% enhanced CO emissions is found for D100+BG(2 kg/h) fuel blend relative to conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average increment of 16.1%. An increase of 16.2%, 12.4%, 16.6%, 19.4%, and 2.6% is noted in exhalations of CO for D100+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively when compared with diesel. An average enhancement of 13.4% is noticed. For D100+BG(0.5 kg/h) hike of 8.9%, 4.8%, 10.9%, 13.6%, and 1.7% is recorded for at 20%, 40%, 60%, 80%, and 100% engine load respectively when compared with pure diesel.

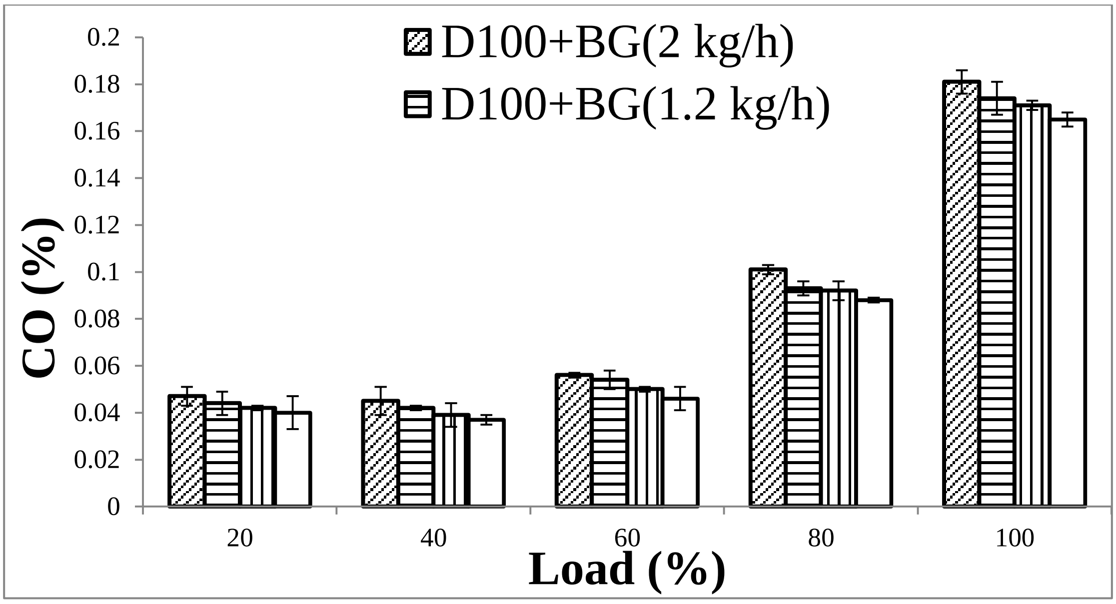

Figure 5.15 Variation of CO with engine load for diesel and Biogas

5.4.4 Variation of HC with engine load

Variation of HC emissions with respect to engine load is illustrated in Figure 5.16. It can be seen very clearly that with the introduction of biogas as a fuel, HC emissions increases. Reduced amount of oxygen inside the combustion chamber due to the introduction of gaseous fuel in the combustion chamber and lower flame velocity of biogas are the culprits for enhanced value of HC emissions for all the fuel blends incorporating biogas relative to conventional diesel [276]. HC emissions are found to directly proportional to the mass flow rate of Biogas. Maximum HC emissions are recorded for D100+BG(2 kg/h) fuel blend, followed by D100+BG(1.2 kg/h) and D100+BG(0.5 kg/h) fuel blends. Least value of HC exhalations is noted for pure diesel. It is also noticed that emissions of HC increase with an increase in engine load. Fuel blends D100+BG(2 kg/h) and D100+BG(1.2 kg/h) has almost the same value from 60% engine load to full load. An increase of 25.4%, 27.2%, 29.3%, 28.4%, and 29% is recorded in HC exhalations at the engine loads ranging from 20% to full load conditions in spells of 20% each respectively for D100+BG(1.2 kg/h) fuel blends relative to conventional diesel. An average enhancement of 27.9% is noted. For D100+BG(0.5 kg/h) fuel blend, an increment of 16.1%, 15.1%, 17%, 15.8%, and 15.1% is recorded at engine loads varying from 20% to 100% at regular intervals of 20% each respectively compared to with fossil diesel.

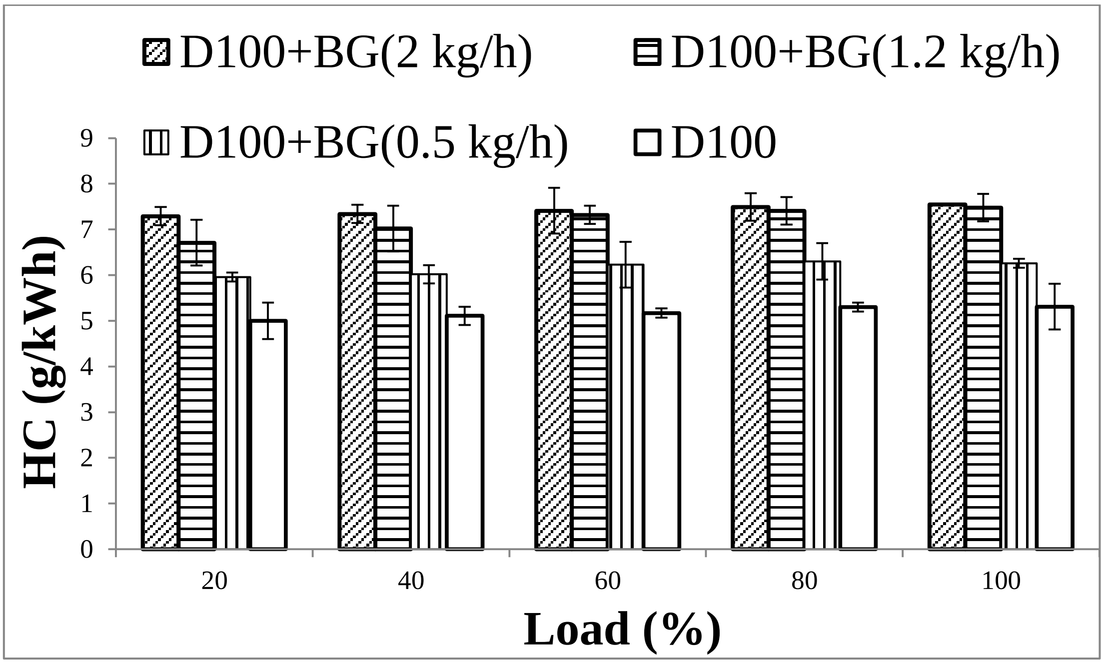

Figure 5.16 Variation of HC with engine load for diesel and Biogas

5.4.5 Variation of NOx with engine load

Figure 5.17 shows the deviation of NOx emissions with the engine load for D100+BG(2 kg/h), D100+BG(1.2 kg/h), D100+BG(0.5 kg/h) and diesel. NOx exhalations are noticed to be decreased for dual fuel mode in comparison with pure diesel. Increasing mass flow rate of Biogas resulted in decreasing NOx emissions. The reason for same is ample availability of CO_2 in Biogas which helps in minimizing oxygen availability and peak combustion temperature inside the cylinder which allow fewer amounts of nitrogen and oxygen to react [293]. Increasing engine load results in decreased NOx exhalations. NOx emissions are noted highest for conventional diesel and lowest for the maximum mass flow rate of Biogas. loading conditions. D100+BG(2 kg/h) fuel blend depicts 40.2%, 31.6%, 26.2%, 30.3%, and 37.4% reduced NOx exhalations relative to fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 33.1%. Deterioration of 24.2%, 22.1%, 17.1%, 22.2%, and 19.6% is noticed in NOx emissions at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D100+BG(1.2 kg/h) fuel blends in comparison with natural diesel. An average reduction of 21% is recorded. For D100+BG(0.5 kg/h) fuel blend a reduction of 10.2%, 12.2%, 10.7%, 7.2%, and 14.1% is noted at engine loads varying from 20% to 100% at regular intervals of 20% each respectively in comparison with diesel fuel.

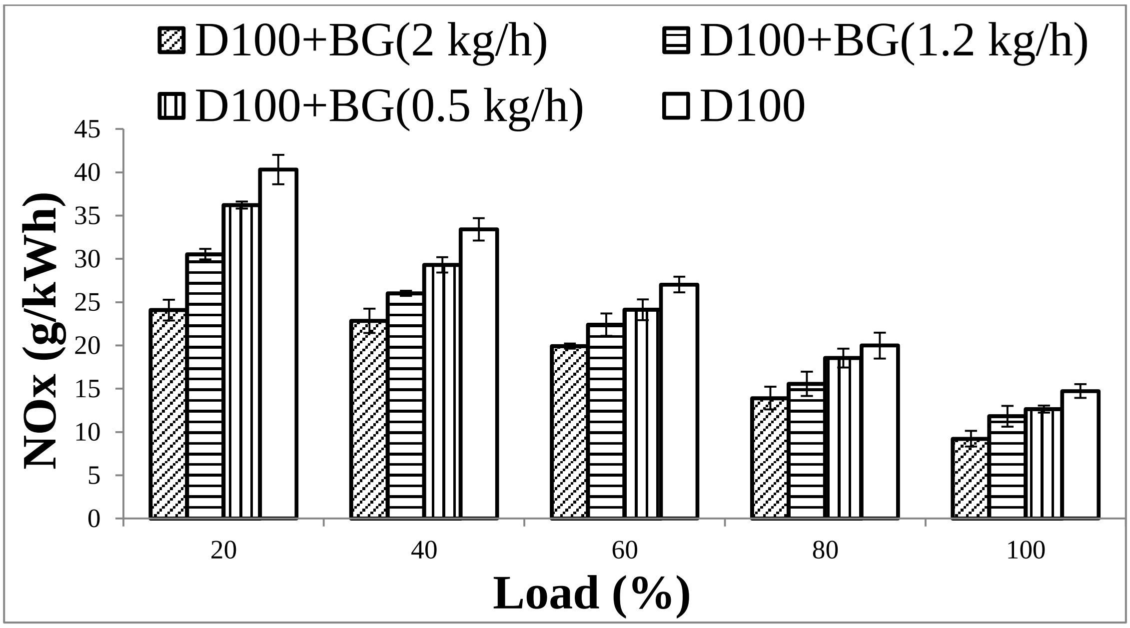

Figure 5.17 Variation of NOx with engine load for diesel and Biogas

5.4.6 Variation of Smoke with engine load

Figure 5.18 depicts the variation of smoke opacity with the engine load. It is noticed that smoke opacity is directly in proportion with engine load. During the dual fuel operation, smoke emissions are decreased in comparison with baseline diesel and it further decrease with the increase in mass flow rate of Biogas. This can be owing to the presence of Methane in biogas which aids in procuring less amount of smoke [294]. Minimum smoke opacity is recorded for fuel blend D100+BG(2 kg/h) and maximum for fossil diesel. The highest amount of smoke exhalations is noted for diesel fuel at 100% load and lowest for D100+BG(0.5 kg/h) at 20% engine load. The decrement of 58.3%, 56.8%, 61.6%, 57.2%, and 50.4% is achieved in smoke exhalations at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D100+BG(2 kg/h) fuel blend in relation with diesel. An average reduction of 56.9% is recorded. Fuel blend D100+BG(1.2 kg/h) shows 44.4%, 47.5%, 51.9%, 43.4%, and 39.7% reduced smoke opacity in comparison with natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 45.4%. For D100+BG(0.5 kg/h) fuel blend deterioration of 31.2%, 31.8%, 27.8%, 26.5%, and 31.5% is noticed relative to baseline diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 29.7%.

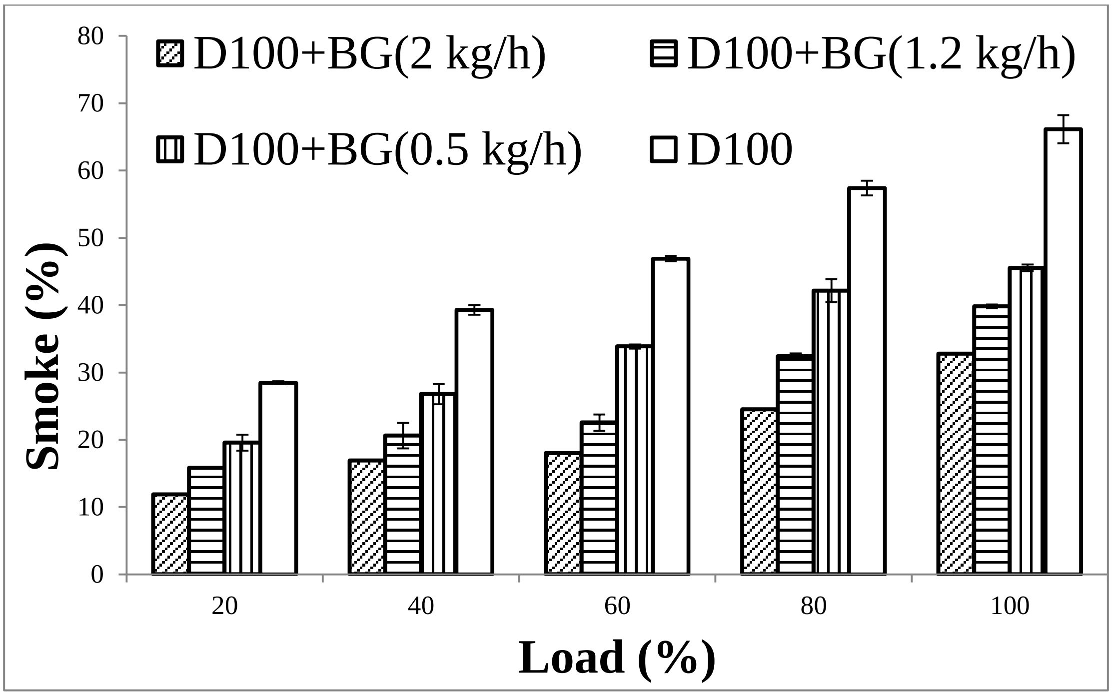

Figure 5.18 Variation of Smoke with engine load for diesel and biogas

5.5 Combination of Diesel, Biodiesel, and n-butanol

The combination of diesel, biodiesel, and n-butanol are checked on the diesel engine in this subdivision of the thesis to assess the performance and exhalation parameters of the engine. Performance and emanation characteristics of the diesel engine for fuel mixtures D80/B10/nb10 and D60/B20/nb20 are interrelated with ordinary diesel. Hence, the grids with performance and exhalation parameters are amalgamated.

5.5.1 Variation of BSFC with engine load

Figure 5.19 shows variations of BSFC when the engine was fuelled with Rice bran methyl esters and n-butanol compared to baseline diesel. It is observed that with increment in load utilization of fuel decreased for all test fuels. It may be owing to the fact that at part loads the temperature of the cylinder is inferior as compared to high engine loads which bring about partial combustion of fuel and consequently contributes to higher BSFC. When combustion of fuel is not complete, it results in an excess amount of fuel required to get the same amount of energy and hence results in higher BSFC [284]. Maximum BSFC is noted for D60/B20/nb20 fuel blend at 20% engine load and minimum BSFC is recorded for pure diesel at 80% engine load. As the quantity of Rice bran biodiesel is increased in fuel blend BSFC is also on the higher side which can be owing to more viscosity, low calorific value and the high index of hydrogen deficiency of biodiesel [85]. Lower energy content and higher viscosity of fuel leads to partial combustion and hence results in improved BSFC. BSFC also found to be increased with increase in the amount of n-butanol in fuel blends. It is correlated with the fact that the calorific value of n-butanol is less than that of baseline diesel and n-butanol ignites with lesser efficiency as compared to diesel [209]. Lesser efficiency of ignition of fuel leads to partial combustion of fuel and consequently higher BSFC. The maximum value of BSFC is recorded for D60/B20/nb20 fuel blend followed by D80/B10/nb10 fuel blend and conventional diesel. At 80% engine load for natural diesel, amount of BSFC is noted to be minimum, whilst its maximum value is at 20% load for D60/B20/nb20 fuel blend. For D80/B10/nb10 fuel blend, BSFC is highest at 20% load and lowest at full load. BSFC is noted to be highest for D60/B20/nb20 fuel blend at 20% load and minimum for the conventional diesel at 80% load. The maximum value for D80/B10/nb10 fuel blend is at 40% load and lowest is at 80% load. D60/B20/nb20 fuel blend is having 27.4%, 28.4%, 33.8%, 35.7%, and 29.8% increased BSFC than natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increment of 31%. It is noted that an increment of 25.1%, 27%, 30.8%, 31.9%, and 25.2% is attained in BSFC at the engine loads ranging from 20% to full load in intervals of 20% each respectively in comparison with fossil diesel for D80/B10/nb10. An average increment of 28% is noticed.

5.5.2 Variation of BTE with load

From Figure 5.20 it is noticed that BTE was directly proportional to engine load for all fuel blends. Similar trends are also observed by Bora et al. [65] and Dhamodaran et al. [102]. It may be due to the fact that at higher engine loads the cylinder temperature enhances and hence complete combustion is attained which consequently results in higher BTE. Impartial combustion of fuel aids in burning of more fuel and increasing the output of the engine and improving the BTE [284]. Improved content of oxygen in fuel contributes to providing more oxygen for proper burning of fuel and bring about an increase in BTE. Due to higher viscosity and lower calorific value of fuel, the combustion of fuel inside the cylinder is not achieved completely which serves in resulting lower BTE [206]. Highest BTE is noticed for D60/B20/nb20 fuel blend at full load whereas for conventional diesel lowest BTE was observed at 20% load. BTE is also found to be lower than baseline diesel with the inclusion of n-butanol in all test fuels. It can be attributed to the fact that the cooling effect is generated by n-butanol which leads to decreased BTE [160]. Decreased cylinder temperature owing to the cooling effect of n-butanol contributes to impartial combustion of fuel and consequently lower BTE. The maximum value of BTE in percentage was obtained for natural diesel followed by D80/B10/nb10 and D60/B20/nb20. Values of BTE for D80/B10/nb10 and D60/B20/nb20 fuel blends are almost similar especially from 20% to 40% engine load. Conventional diesel is found to have attained the highest value of BTE at full load, whereas D60/B20/nb20 shows the lowest amount of BTE at 20% load. Value of BTE for D80/B10/nb10 fuel blend is noticed to be more than D60/B20/nb20 fuel blend at 20% engine load, whilst it is lower at 100% load. Reduction of 11.7%, 12.7%, 11.5%, 13.3%, and 8.4% is noted in

BTE at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D80/B10/nb10 fuel blend in relation with traditional diesel. An average reduction of 11.5% is noticed. Fuel blend D60/B20/nb20 has 18%, 14.2%, 14.2%, 16.8%, and 12.4% reduced BTE in comparison with fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 11.5%.

5.5.3 Variation of CO with engine load

Exhalations of CO mainly banks upon air-fuel mixture. When carbon present in the fuel reacts with oxygen inside the combustion chamber, CO is the outcome of the partial combustion. If complete combustion is achieved, carbon and oxygen react to form $CO_{2.}$ Exhalations of CO are mainly relying on the air-fuel mixture. Lack of ample air does not allow all the carbon to convert into CO_2 and results in the formation of CO emissions. Figure 5.21 depicts that CO emissions firstly decreases with engine load up to a particular limit and then increase with the increase in load. CO emissions decreased owing to low cylinder temperature at intermediate loads which restricts the combustion of hydrocarbons and hence leads to lower CO emissions. The lean air-fuel mixture at higher engine loads bring about partial combustion and hence contributes to increased CO emissions. Owing to rich fuel-air mixture lesser content of oxygen is provided to the fuel for complete combustion and hence partial combustion is attained [284]. The same trend was observed by Satsangi et al. [210] and Mahla et al. [35]. It can also be seen that addition of biodiesel in biodiesel-diesel fuel blends is inversely proportional to CO emissions which is very similarly observed by Chauhan et al.[104] and Chauhan et al.[118] It may be due to improved combustion of biodiesel in comparison with diesel as biodiesel contains lower carbon contents and more oxygen particles [139]. Increased quantity of oxygen and decreased amount of carbon in the fuel aids in providing sufficient oxygen to the combustion products and hence leads to impartial combustion of fuel. As a result of complete combustion owing to the high amount of oxygen in n-butanol, lower CO emissions were detected for fuel blends containing n-butanol [225]. Highest CO emissions were noticed for baseline diesel at 100% load and lowest for D80/B10/nb10 fuel blend at 60% load. D60/B20/nb20 fuel blend attained maximum CO exhalations at full loading conditions and lowest at 60% engine load. 33%, 26.8%, 29.3%, 29.7%, and 45.3% reduced CO emissions is recorded for D60/B20/nb20 fuel blend when compared with natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 32.9%. A reduction of 32.3%, 25.2%, 28.9%, 24.6%, and 44.3% is attained in emissions of CO for D80/B10/nb10 fuel blend at the engine loads ranging from 20% to full load in intervals of 20% each respectively in relation with fossil diesel. An average decrement of 31.1% is achieved.

5.5.4 Variation of HC with engine load

Hydrogen and carbon are the main constituents of the diesel fuel. Hydrocarbon emissions are the outcome of partial combustion of fuel inside the combustion chamber. A lean mixture of air and fuel leads to low flame speeds which results in incomplete combustion, is the primary cause of emissions of hydrocarbons. The deposits of carbon inside the combustion chamber are porous. When the mixture of air and fuel is compressed, some hydrocarbons struck in these pores and do not burn during the power stroke, and are emitted by the cylinder during the exhaust stroke [284]. Figure 5.22 shows that for fuel blend D80/B10/nb10, HC emissions are found to be lower than baseline diesel whereas the minimum amount of HC emissions were recognized for D80/B10/nb10 which may be correlated with short ignition delay due to higher cetane number of biodiesel as compared to diesel. Shorter ignition delay period brings about more complete combustion of fuel and consequently, lower hydrocarbon exhalations are emitted [285]. Addition of n-butanol in fuel blends attributed in increased HC emissions which may be due to longer ignition delay owing to low cetane number of higher alcohols [7]. Partial combustion of fuel is achieved as a consequence of longer ignition delay period. The minimum value of HC exhalations is noted for B20 fuel blend at 20% engine load and maximum HC emissions are recorded for D60/B20/nb20 fuel blend at 100% load. For pure diesel highest value of HC emissions is found to be 5.31 g/kWh at 20% load and lowest value of 5.01 g/kWh are observed at full load conditions. The maximum amount of HC exhalations are recorded for D60/B20/nb20 fuel blend at full loading conditions and lowest value at 20% load for fossil diesel. Fuel blend D80/B10/nb10 has the highest value at full load and least at 20% engine load. Enhancement of 6.4%, 8.4%, 8.3%, 9%, and 12.8% is attained in HC emissions at the engine loads ranging from

20% to full load in intervals of 20% each respectively for D60/B20/nb20 fuel blend than traditional diesel. An average increment of 8.9% is found. Fuel blend D80/B10/nb10 depicts 0.4%, 0.7%,1.9%, 3.3%, and 3% reduced HC emissions in comparison with diesel fuel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average increment of 1.9%.

5.5.5 Variation of NOx with engine load

Nitrogen Oxides are the consequences of reaction between oxygen and nitrogen particles inside the engine cylinder especially at high temperature [163]. As reported by Zeldovich mechanism, the phenomenon of NOx formation in a compression ignition engine is exhibited as following:

N_2 / [O] → NO / [N]

[N] / O2 → NO / [O]

[N] / [OH] → NO / [H]

It is established from Figure 5.23 that NOx emissions were more for biodiesel blends as compared to diesel which banks on higher combustion temperature of biodiesel [165] and higher unsaturation degree [286]. Increased temperature of combustion leads to the reaction of oxygen and nitrogen atoms at a higher rate. Minimum and maximum values of NOx emissions are recorded for D60/B20/nb20 and diesel at 20% and 100% load respectively. NOx emissions are found to be on higher side with the increase in engine load whereas inclusion of n-butanol helps in trimming down NOx emissions. Reason for later can be lower viscosity and higher heat of vaporization of n-butanol which results in better atomization properties and decreasing the combustion temperature respectively [228]. Superior atomization properties result in improved combustion and, inferior combustion temperature aids in minimizing the reaction between nitrogen and oxygen [284]. It can also be seen that NOx exhalations were maximum for conventional diesel followed by D80/B10/nb10 fuel blend and D60/B20/nb20 fuel blend. Highest NOx emissions are noted for baseline diesel at 20% engine load and lowest for D60/B20/nb20 fuel blend at full load. D60/B20/nb20 fuel blend depicts 8.5%, 9.8%, 6.3%, 25.6%, and 31.9% reduced NOx emissions in comparison with fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 16.4%. Reduction of 5.2%, 6.4%, 4.2%, 14%, and 13.3% is noticed in NOx exhalations at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D80/B10/nb10 fuel blends in relation with diesel. An average decrement of 8.6% is recorded.

5.5.6 Variation of Smoke with engine load

Incomplete combustion of fuel aids in producing smoke which helps in originating smoke opacity [287]. It is an unintended measure of existence of soot particles in the exhaust. Figure 5.24 presents an increased trend of smoke emissions with the increase in load which is due to the high utilization of fuel at higher loads. When excess fuel enters inside the combustion chamber at high engine loads it results in partial combustion of fuel and consequently more smoke emissions [284]. Fossil diesel was found to have the maximum value of smoke opacity at full load whereas the minimum value of smoke emissions was noted for D60/B20/nb20 fuel blend at 20% engine load. Fuel blends with biodiesel were having decreased level of smoke emissions than pure diesel owing to a higher amount of oxygen in biodiesel which helps to achieve complete combustion of fuel [139]. There was a further decrease in smoke opacity with the inclusion of n-butanol in the fuel blends which may be the result of the higher oxygen content of n-butanol [288-289]. More quantity of oxygen in fuel aids in supplying ample amount of oxygen atoms to the combustion products and consequently results in complete combustion of fuel. Highest smoke exhalations were noticed for conventional diesel followed by D80/B10/nb10 fuel blend and D60/B20/nb20 fuel blend. The maximum and minimum value of smoke opacity was recorded for fossil diesel at 100% load and D60/B20/nb20 fuel blend at 20% load respectively. The decrement of 66.6%, 50%, 40 %, 42.3%, and 25.6% is attained in smoke emissions at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D80/B10/nb10 fuel blend in comparison with conventional diesel. An average reduction of 44.9% is noticed. Fuel blend D60/B20/nb20 shows 66.6%, 37.5%, 26.6%, 34.6%, and 17.9% lesser smoke exhalations in relation with pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 36.6%.

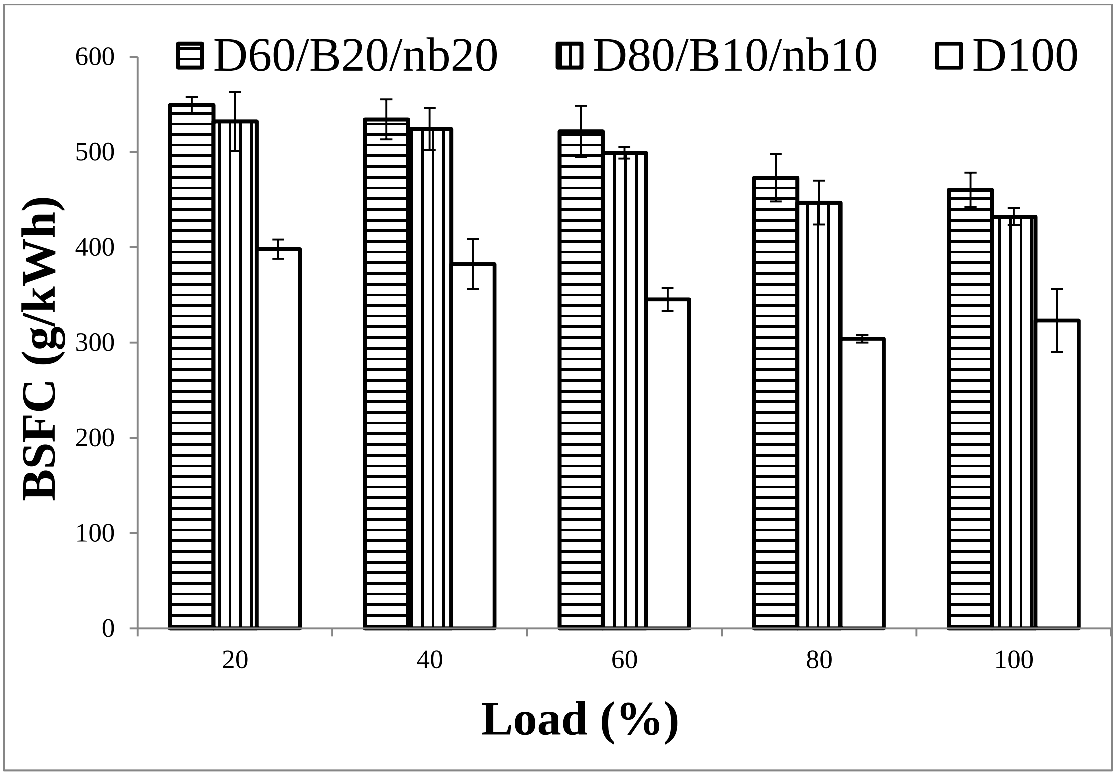

Figure 5.19 Variation of BSFC with engine load for diesel, biodiesel, and n-butanol

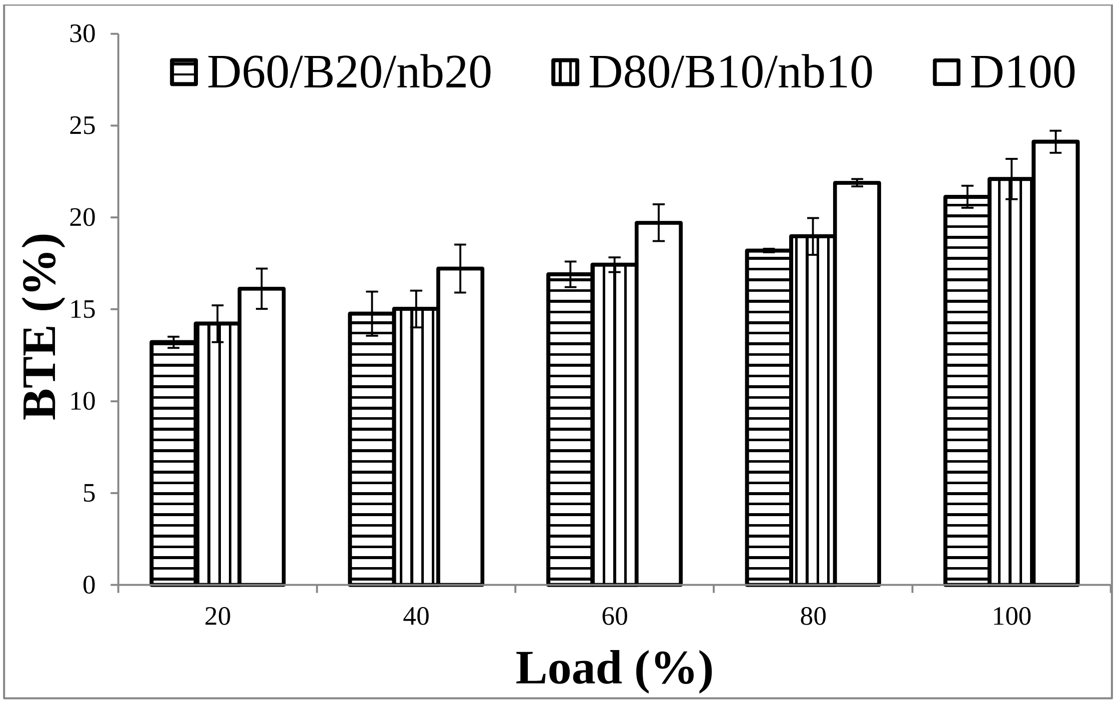

Figure 5.20 Variation of BTE with engine load for diesel, biodiesel, and n-butanol

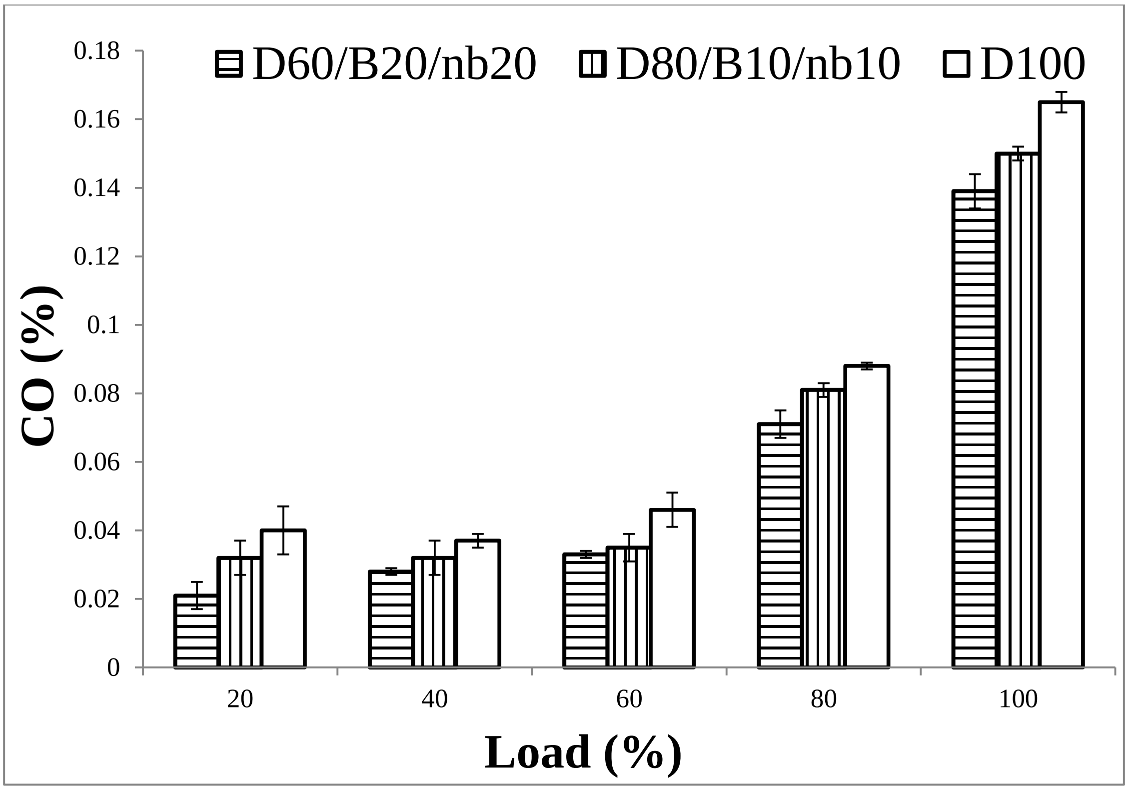

Figure 5.21 Variation of CO with engine load for diesel, biodiesel, and n-butanol

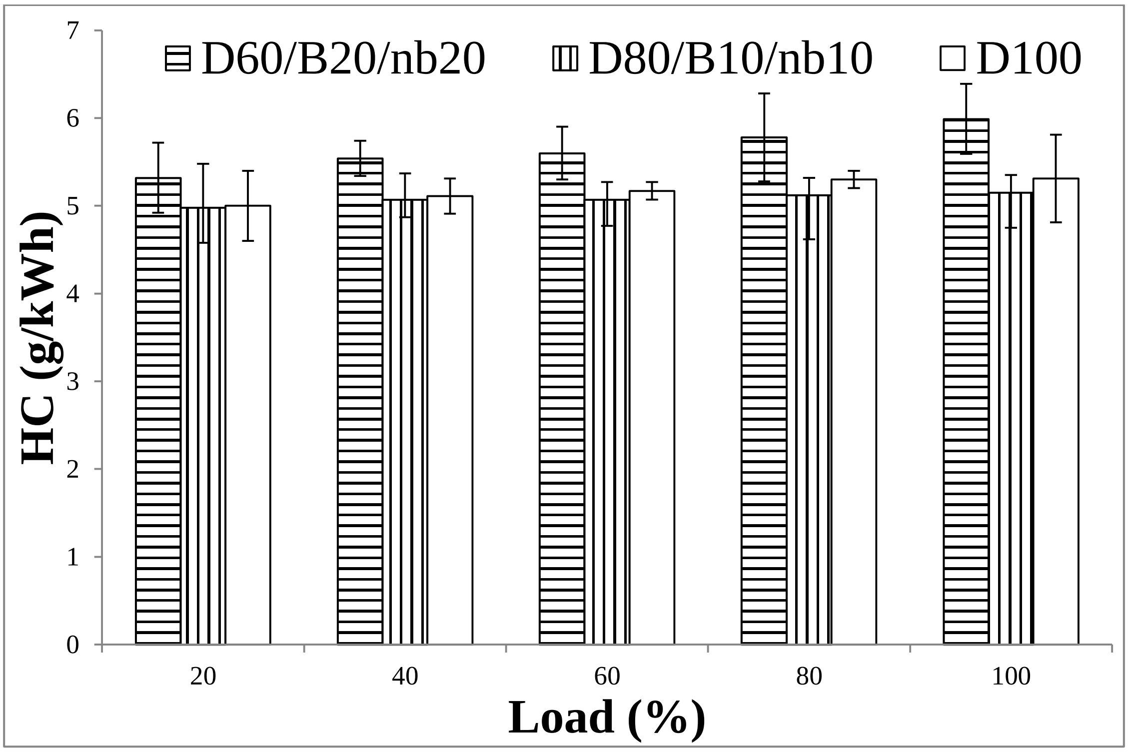

Figure 5.22 Variation of HC with engine load for diesel, biodiesel, and n-butanol

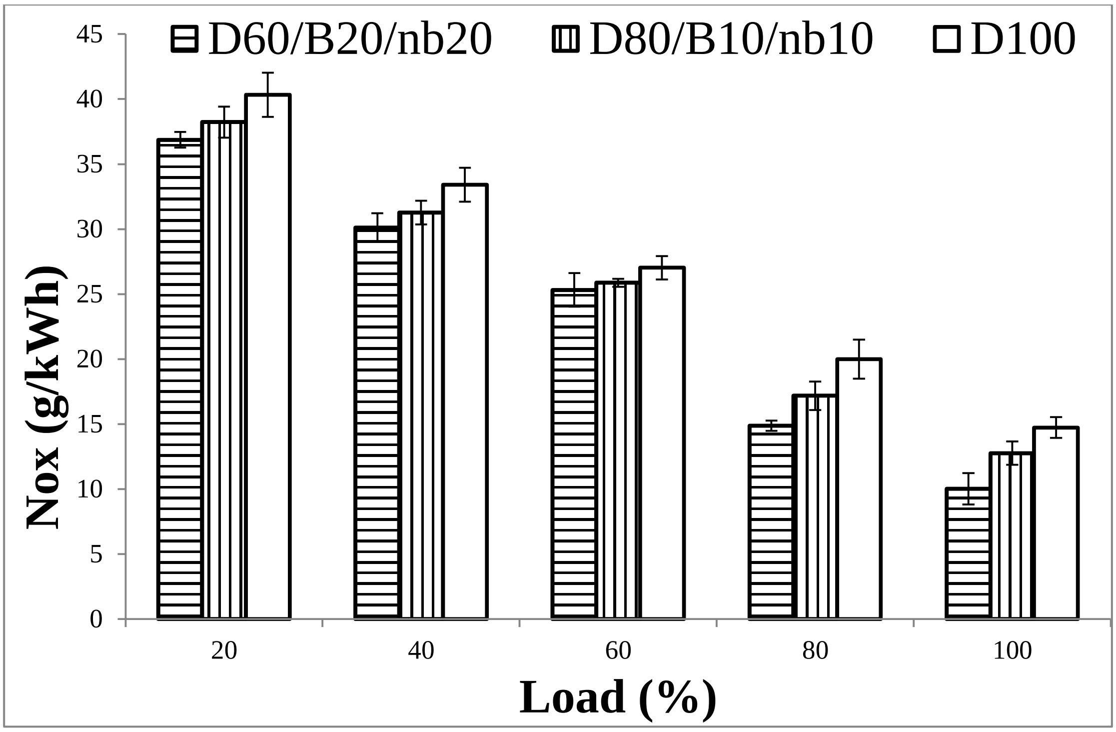

Figure 5.23 Variation of NOx with engine load for diesel, biodiesel, and n-butanol

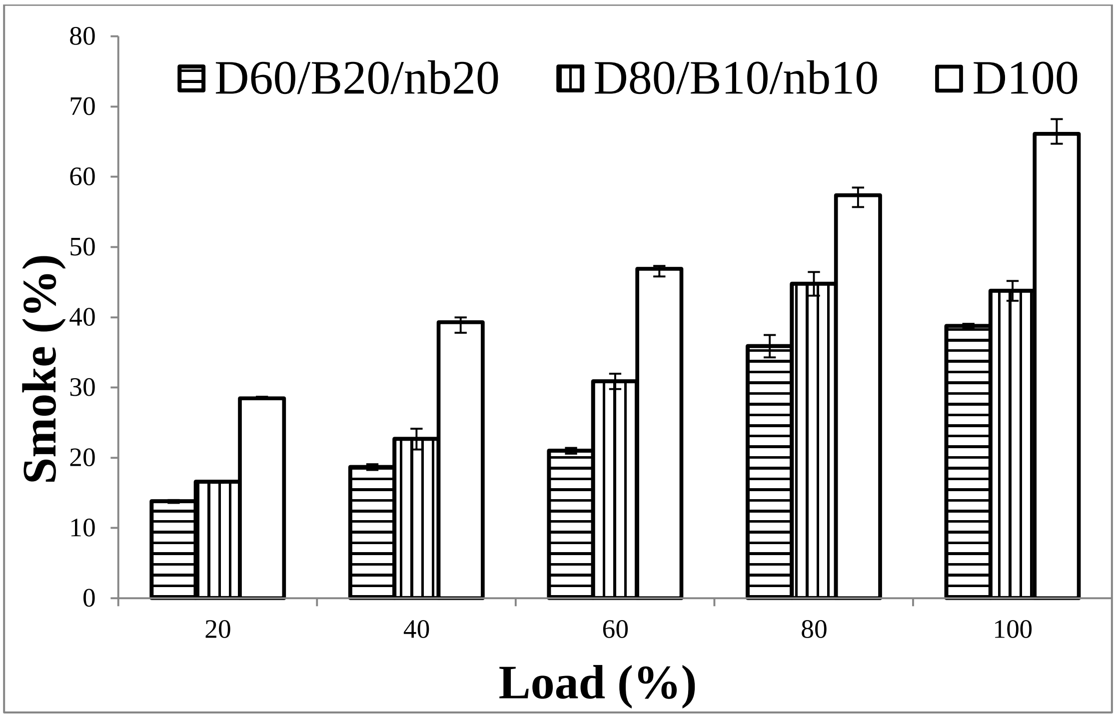

Figure 5.24 Variation of Smoke with engine load for diesel, biodiesel, and n-butanol

5.6 Combination of Diesel, Biodiesel, and Biogas

The permutation of diesel, biodiesel, and biogas are tested on the diesel engine in this division of the episode to judge the performance and emanation factors of the engine. Performance and emission characteristics of the diesel engine for fuel combinations D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h) and, D80/B20+BG(2 kg/h) are related with regular diesel. Afterwards, the plots with performance and exhalation parameters are integrated.

5.6.1 Variation of BSFC with engine load

BSFC is a critical criterion, to evaluate how adroitly the fuel is being utilized in an engine [12]. It can be examined from Figure 5.25 that with an increase in the load of the engine BSFC depreciates due to the fact that with increment in the engine load, combustion character and fuel atomization increases [33]. RBME blended diesel aided in an increase of BSFC as compared to baseline diesel throughout the load spectrum which may be owing to high viscidity and low energy content in biodiesel [85,152]. BSFC is found to be increased with increasing proportion of biodiesel in the fuel blends. It is also determined that BSFC is further increased when biogas is introduced as primary fuel and its mass flow rate was raised, which may be due to the evidence that a lower transformation of gaseous fuel to work is achieved because of establishment of a lean mixture and a low combustion temperature in the combustion chamber [290]. Highest BSFC is recorded for D80/B20+BG(2 kg/h) and lowest for natural diesel. The maximum value of BSFC is noted for D80/B20+BG(2 kg/h) at 20% load and minimum for fossil diesel at 80% engine load. D80/B20+BG(0.5 kg/h) fuel blend is having 22.6%, 23.4%, 19%, 25.9%, and 17.9% enhanced BSFC than conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increment of 21.8%. It is recorded that an increment of 24.9%, 27.3%, 30.9%, 32.6%, and 23.3% is attained in BSFC for D80/B20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively when compared with natural diesel. An average increment of 27.8% is recorded. In relation with conventional diesel, fuel blend D80/B20+BG(2 kg/h) is noticed to have enhancement of 26.5%, 28.2%, 34.4%, 34.3%, and 28.5% BSFC at engine loads varying in intervals of 20% each from 20% to 100% load respectively and noted to have an average increment of 30.4%. D90/B10+BG(0.5 kg/h) fuel blend have 2.8%, 4.8%, 10.7%, 10%, and 0.3% more BSFC than fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average enhancement of 5.7%. It is recorded that a hike of 12.2%, 12.2%, 20.3%, 27.5%, and 19.2% is achieved in BSFC for D90/B10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively in relation with traditional diesel. An average gain of 18.3% is noticed.

5.6.2 Variation of BTE with engine load

Combustion quality of an engine can be recognized with help of BTE. It is the product of mechanical efficiency and indicated thermal efficiency [291]. Variation of BTE with load is shown in Figure 5.26. BTE was observed to be directly proportional to the engine load for the entire range of test fuels. Pure diesel was found to have maximum BTE as compared to all other fuels irrespective of engine load. As compared to pure diesel BTE was on lower side for RBO, the decline in heating values of biodiesel blends have more impact on BTE possibly will be recognized for the same [160]. Under dual fuel mode, the value of BTE was noticed to be lesser than diesel fuel and with increasing mass flow rate of biogas, BTE was observed to decrease further. Poor utilization of gaseous fuel may be blamed for lower BTE under dual fuel mode [35]. The highest value of BTE was recorded for baseline diesel and lowest for D90/B10+BG(2 kg/h) fuel blend. Value of BTE for diesel fuel and D80/B20+BG(0.5 kg/h) fuel blend is very much alike for all engine loads. Decrement of 1.1%, 1.2%, 2.5%, 0.4%, and 3.6% is recorded in BTE at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D80/B20+BG(2 kg/h) fuel blend in relation with conventional diesel. An average downfall of 1.8% is noted. Fuel blend D80/B20+BG(1.2 kg/h) has 16.8%, 10.6%, 11.5%, 11.2%, and 10.2% reduced BTE than fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 12.1%. In comparison with traditional diesel fuel blend D80/B20+BG(0.5 kg/h) has 30.3%, 27.7%, 20.5%, 26.1%, and 25.8% reduced BTE for engine load varying from 20% to 100% in intervals of 20% each respectively. 7.5%, 3.5%, 7.7%, 12.5%, and 7.6% lower BTE is noticed at the engine loads ranging from 20% to 100% load in intervals of 20% each respectively for D90/B10+BG(2 kg/h) fuel blend when compared with baseline diesel. An average reduction of 7.8% is noticed. Fuel blend D90/B10+BG(1.2 kg/h) has 20.4%, 15.8%, 16.2%, 19.1%, and 19.1% lower BTE relative to conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 18.1%. In comparison with fossil diesel fuel blend D90/B10+BG(0.5 kg/h) has 36.9%, 23.3%, 27.1%, 27.2%, and 29.8% lower BTE for engine load varying from 20% to 100% in intervals of 20% each respectively.

5.6.3 Variation of CO with engine load

CO is eminently pernicious gas produced due to incomplete combustion of fuel [291]. Figure 5.27 portrays that with increment in the engine load CO exhalations decreases up to intermediate loads. This can be attributed to the existence of biogas leftover inside the engine cylinder. At high engine loads, CO emissions increased with the rise in engine load which may be due to high cylinder gas temperature leading to complete combustion of fuel [35]. Blends of biodiesel and diesel helped a decline in CO emissions. The higher quantity of oxygen in biodiesel which results in complete combustion is the main reason for this [139]. CO emissions were noted highest with increasing amount of biogas mass flow rate in the engine due to rich air-fuel mixture employed with the introduction of gaseous fuel leading to an insufficient supply of oxygen [60]. CO emissions are reported to be highest for D90/B10+BG(2 kg/h) fuel blend and lowest for natural diesel. Values of CO exhalations for fuel blend D80/B20+BG(0.5 kg/h) and baseline diesel are almost similar at full engine load. 38.9%, 35%, 4.1%, 5.3%, and 2.9% increased CO exhalations are noticed for D80/B20+BG(2 kg/h) fuel blend in relation with conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average enhancement of 17.3%. The increment of 71.2%, 64.4%, 49.4%, 12%, and 26% is noted in emissions of CO for D80/B20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively in relation with fossil diesel. An average increment of 44.68% is recorded. For D80/B20+BG(0.5 kg/h) increase of 80.2%, 76.74.8%, 64.8%, 41.3%, and 29.7% is noted for at 20%, 40%, 60%, 80%, and 100% engine load respectively in comparison with traditional diesel. 40.9%, 42.1%, 29.2%, 2.2%, and 12.2% more CO emissions is found for D90/B10+BG(2 kg/h) fuel blend than pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average hike of 25.3%. Enhancement of 76.4%, 70.1%, 54.9%, 38.4%, and 29.1% is noticed in emissions of CO for D90/B10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively relative to diesel fuel. An average increment of 53.8% is noted. For D90/B10+BG(0.5 kg/h) hike of 82%, 79.5%, 72.2%, 59%, and 32% is noticed for at 20%, 40%, 60%, 80%, and 100% engine load respectively in relation with natural diesel. CO emissions are reported to be highest for D90/B10+BG(2 kg/h) fuel blend and lowest for natural diesel. Values of CO exhalations for fuel blend D80/B20+BG(0.5 kg/h) and baseline diesel are almost similar at full engine load. 38.9%, 35%, 4.1%, 5.3%, and 2.9% increased CO exhalations are noticed for D80/B20+BG(2 kg/h) fuel blend in relation with conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average enhancement of 17.3%. The increment of 71.2%, 64.4%, 49.4%, 12%, and 26% is noted in emissions of CO for D80/B20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively in relation with fossil diesel. An average increment of 44.68% is recorded. For D80/B20+BG(0.5 kg/h) increase of 80.2%, 76.74.8%, 64.8%, 41.3%, and 29.7% is noted for at 20%, 40%, 60%, 80%, and 100% engine load respectively in comparison with traditional diesel. 40.9%, 42.1%, 29.2%, 2.2%, and 12.2% more CO emissions is found for D90/B10+BG(2 kg/h) fuel blend than pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average hike of 25.3%. Enhancement of 76.4%, 70.1%, 54.9%, 38.4%, and 29.1% is noticed in emissions of CO for D90/B10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively relative to diesel fuel. An average increment of 53.8% is noted.

5.6.4 Variation of HC with engine load

HC exhalations are produced due to partial combustion of fuel inside the combustion chamber [284]. Figure 5.28 depicts the variation of HC emissions with the load. HC emissions for dual fuel engine enhances as compared to diesel engine mode irrespective of the fuels used due to the lower amount of oxygen inside the engine cylinder owing to the introduction of biogas. It is observed that the introduction of biogas in the inlet manifold of the engine promotes higher HC emissions due to the lower flame velocity of biogas [276], however RBME blended with diesel are found to emit a decreased amount of HC as compared to diesel because of the greater percentage of oxygen in biodiesel [292]. More oxygen contained in all B20 blends as compared to all B10 blends helped decreased HC emissions for all B20 blends when compared to all B10 blends. Maximum HC exhalations are recorded for D90/B10+BG(2 kg/h) and minimum for pure diesel. The highest value of HC emissions is recorded for D90/B10+BG(2 kg/h) at 20% load and least for natural diesel at full engine load. D80/B20+BG(0.5 kg/h) fuel blend is having 6%, 4.3%, 6%, 5.5%, and 6.1% more HC exhalations relative to fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average enhancement of 5.6%. It is noted that enhancement of 16.6%, 17.5%, 18.4%, 17.7%, and 21.6% is achieved in HC emissions for D80/B20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in spells of 20% each respectively when compared with pure diesel. An average increment of 18.4% is noticed. In comparison with baseline diesel fuel blend D80/B20+BG(2 kg/h) is noted to have an increment of 22.2%, 21.9%, 24.8%, 23.7%, and 25.9% HC at engine loads varying in intervals of 20% each from 20% to 100% load respectively and reported to have an average increase of 23.7%. D90/B10+BG(0.5 kg/h) fuel blend have 9.5%, 9.3%, 10%, 8.1%, and 8.9% extra HC emissions than pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increment of 9.2%. It is noted that a gain of 21.1%, 24.2%, 24%, 24.2%, and 25.4% is attained in HC emissions for D90/B10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively than conventional diesel. An average hike of 23.8% is recorded. In relation with fossil diesel, fuel blend D90/B10+BG(2 kg/h) is noticed to have an increment of 27.2%, 26.1%, 27.3%, 26.2%, and 27.4% HC exhalations at engine loads varying in intervals of 20% each from 20% to 100% load respectively and have an average increment of 26.9%.

5.6.5 Variation of NOx with engine load

Figure 5.29 presents the variation of NOx with the engine load. NOx exhalations are found to be decreased for D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), and D90/B10+BG(2 kg/h) as compared to diesel throughout the load spectrum. It is extensively acknowledged that the high level of the amount of oxygen in any fuel develops more NOx emissions. Addition of RBME in the fuel blends always results in higher NOx emissions owing to higher oxygen content in biodiesel [154], whereas biogas induction inside the combustion chamber assists in abating these fatal emissions because of absence of oxygen in biogas [293]. It is also noticed that NOx emissions further declined with increasing mass flow rate of biogas. Amount of NOx exhalations for diesel fuel and D80/B20+BG(0.5 kg/h) fuel blend are nearly alike at all the engine loading conditions. D80/B20+BG(0.5 kg/h) fuel blend shows 0.1%, 0.3%, 0.2%, 3.2%, and 10.3% lesser NOx emissions compared to fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 2.8%. The decrement of 13.7%, 9.2%, 8.8%, 8.6%, and 13.7% is recorded in NOx exhalations at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D80/B20+BG(1.2 kg/h) fuel blends in relative to pure diesel. An average deterioration of 10.8% is noted. For D80/B20+BG(2 kg/h) fuel blend a decrement of 24.3%, 18.3%, 18.3%, 15.3%, and 24.8% is recorded at engine loads varying from 20% to 100% at regular intervals of 20% each respectively than conventional diesel. D90/B10+BG(0.5 kg/h) fuel blend illustrates 4.9%, 4.5%, 7.1%, 1.9%, and 5% decreased NOx exhalations relative to natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average fall off of 4.7%. The decrement of 16.9%, 15.4%, 11.5%, 13.5%, and 16.6% is noted in NOx emissions at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D90/B10+BG(1.2 kg/h) fuel blends compared to natural diesel. An average deterioration of 14.8% is achieved. For D90/B10+BG(2 kg/h) fuel blend a decrease of 33.8%, 22.9%, 20.7%, 23.5%, and 28.9% NOx emissions is recorded at engine loads varying from 20% to 100% at regular intervals of 20% each respectively relative to diesel fuel.

5.6.6 Variation of smoke with engine load

Smoke is produced due to incomplete combustion of fuel inside the combustion chamber owing to deficient oxygen supply [287]. Variation of smoke with the engine load is illustrated in Figure 5.30 which presents that in dual fuel mode biogas along with biodiesel supports in decreasing smoke opacity. RBME addition in liquid fuel resulted in lower smoke opacity when compared with diesel fuel. The increasing proportion of RBO in the fuel blends aids in decreasing the smoke opacity more due to the enhanced amount of oxygen available in biodiesel results in better combustion and reducing smoke opacity. Biogas also helps in decreasing the smoke. It is also noted that increasing biogas mass flow rate helps in further minimizing the smoke opacity [160]. The reason for the same may be the presence of methane as a main constituent of biogas. Methane as a lower member of the paraffin family, if used as fuel; results in producing lower smoke [294]. Highest smoke opacity was reported for fuel blend D80/B20+BG(2 kg/h) and lowest for fossil diesel. The maximum value of smoke emissions is recorded for diesel fuel at 100% load and minimum for D80/B20+BG(0.5 kg/h) at 20% engine load. Deterioration of 18.2%, 21.2%, 18.8%, 21.3%, and 24% is attained in smoke exhalations at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D80/B20+BG(0.5 kg/h) fuel blend in relation with diesel. An average decrement of 20.7% is achieved. Fuel blend D80/B20+BG(1.2 kg/h) shows 38%, 36.6%, 42.4%, 37.7%, and 37.2% decreased smoke opacity relative to natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 38.4%. For D80/B20+BG(2 kg/h) fuel blend decrement of 57%, 51.1%, 52.6%, 47.5%, 48% is recorded than conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deterioration of 51.2%. Reduction of 13.1%, 17.1%, 19.3%, 17%, and 20.5% is illustrated in smoke exhalations at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D90/B10+BG(0.5 kg/h) fuel blend compared to pure diesel. An average reduction of 17.4% is recorded. Fuel blend D90/B10+BG(1.2 kg/h) depicts 31.4%, 31.5%, 42.6%, 31%, and 33.9% lesser smoke opacity than diesel fuel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deterioration of 34.1%. For D90/B10+BG(2 kg/h) fuel blend reduction of 48.2%, 46.9%, 49.4%, 43%, and 44.3% is noted in comparison with pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 29.7%.

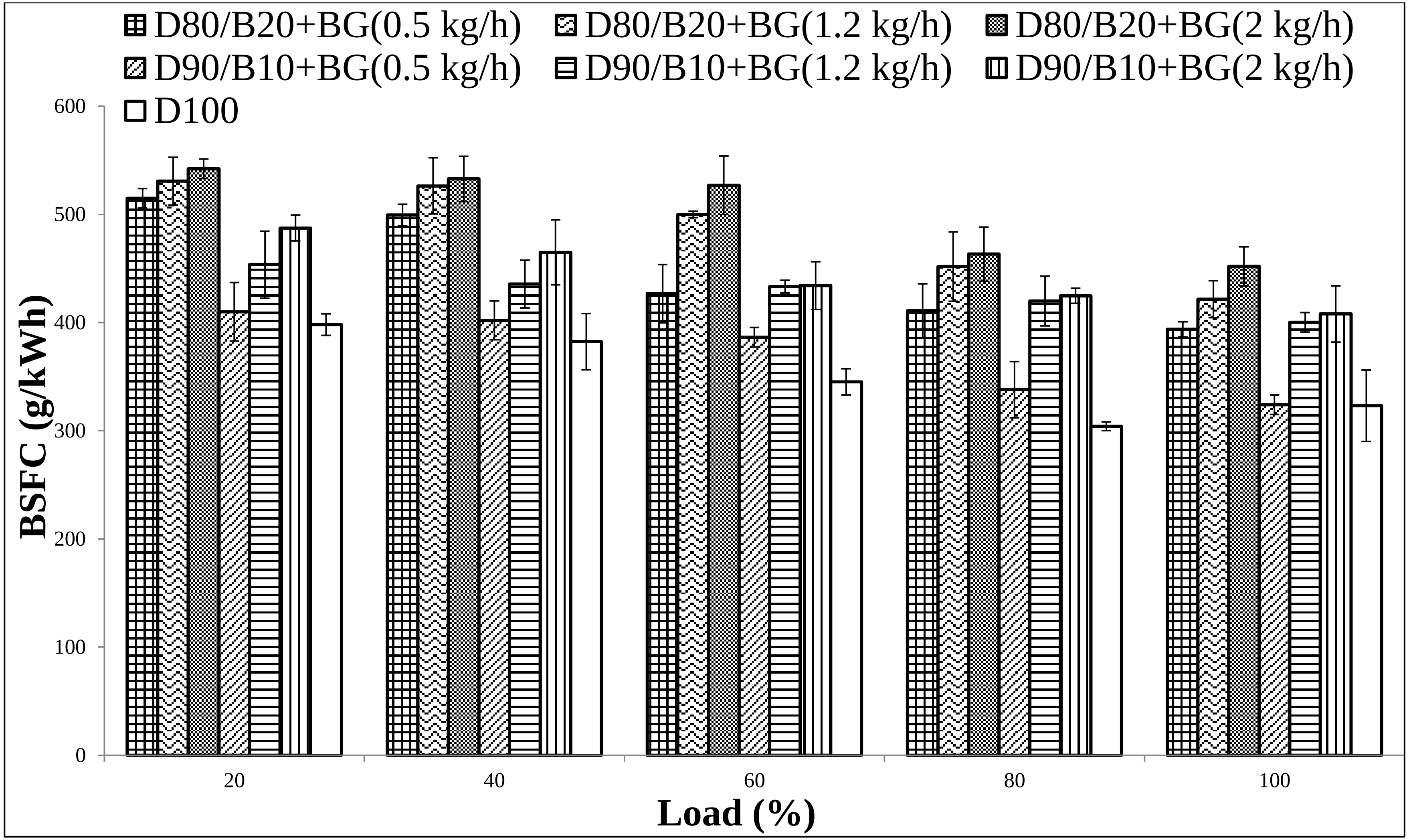

Figure 5.25 Variation of BSFC with engine load for diesel, biodiesel, and, biogas

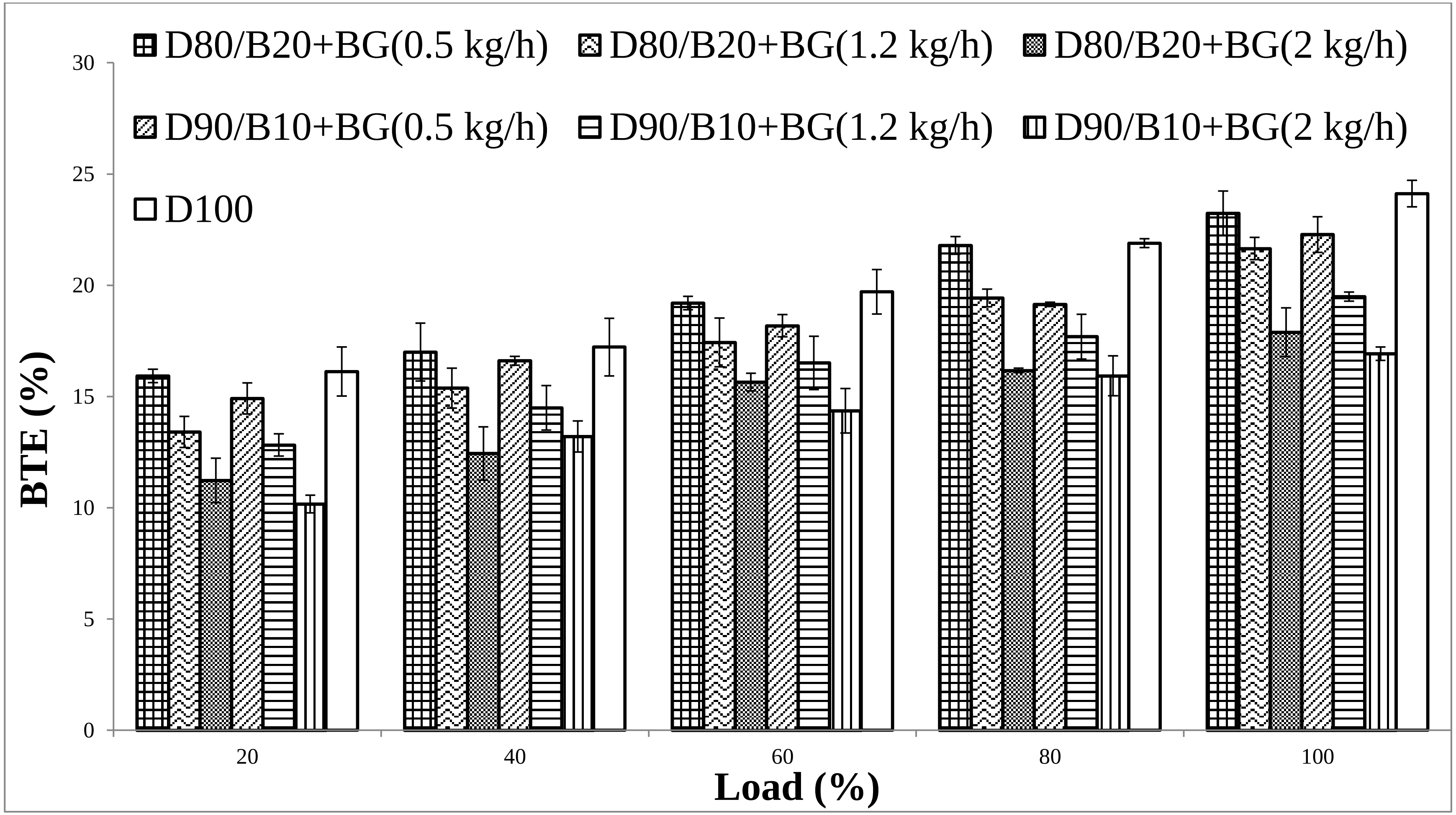

Figure 5.26 Variation of BTE with engine load for diesel, biodiesel, and biogas

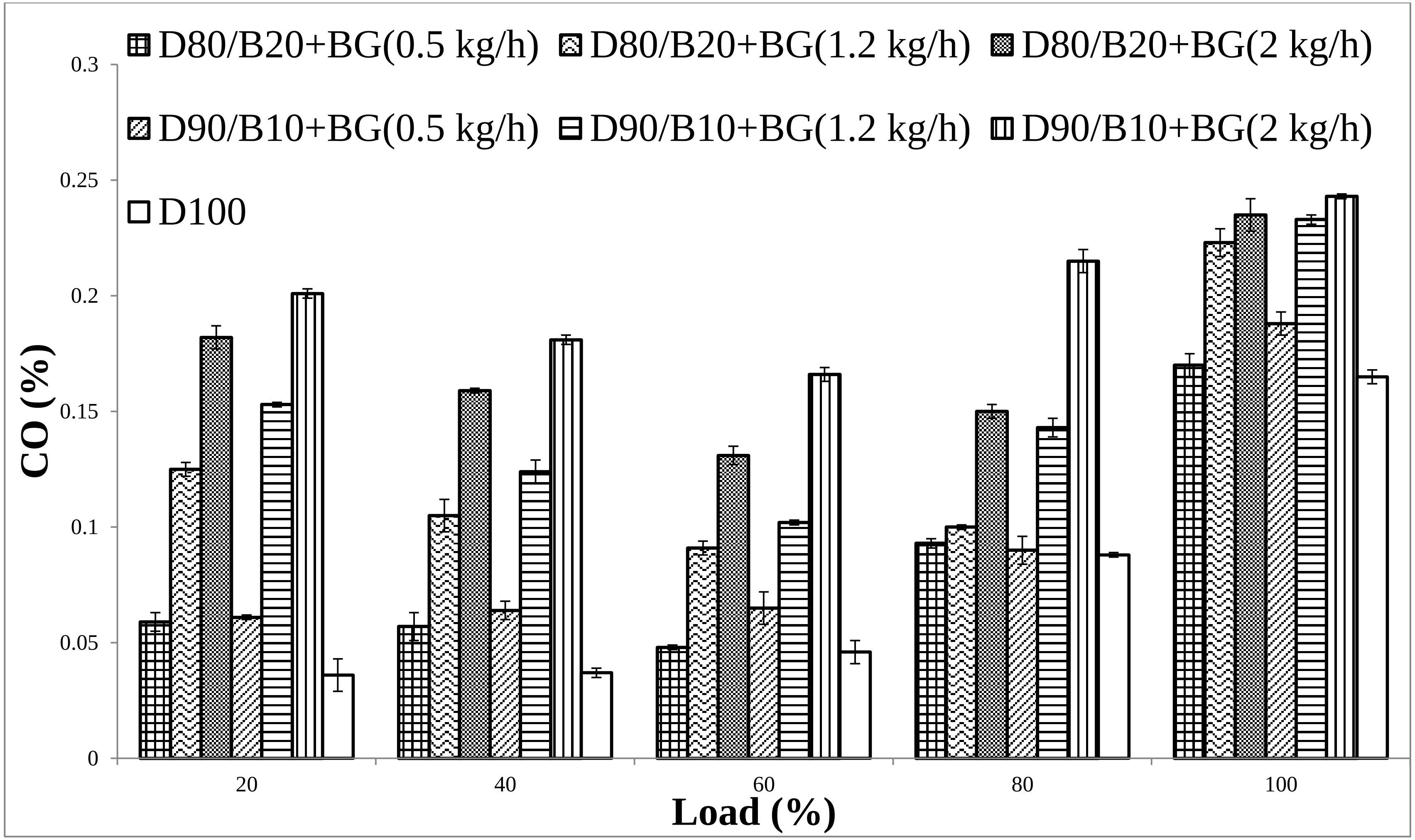

Figure 5.27 Variation of CO with engine load for diesel, biodiesel, and biogas

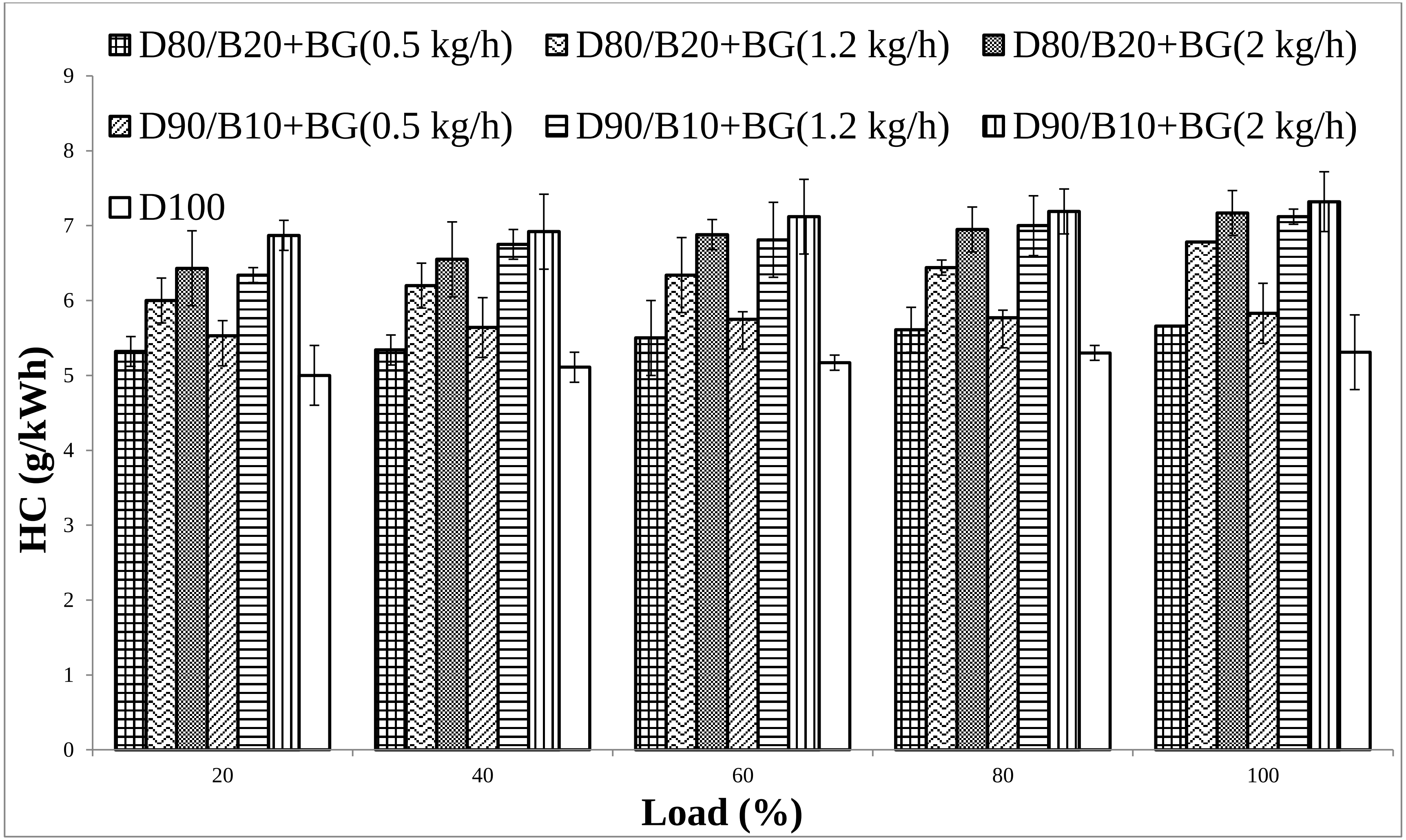

Figure 5.28 Variation of HC with engine load for diesel, biodiesel, and biogas

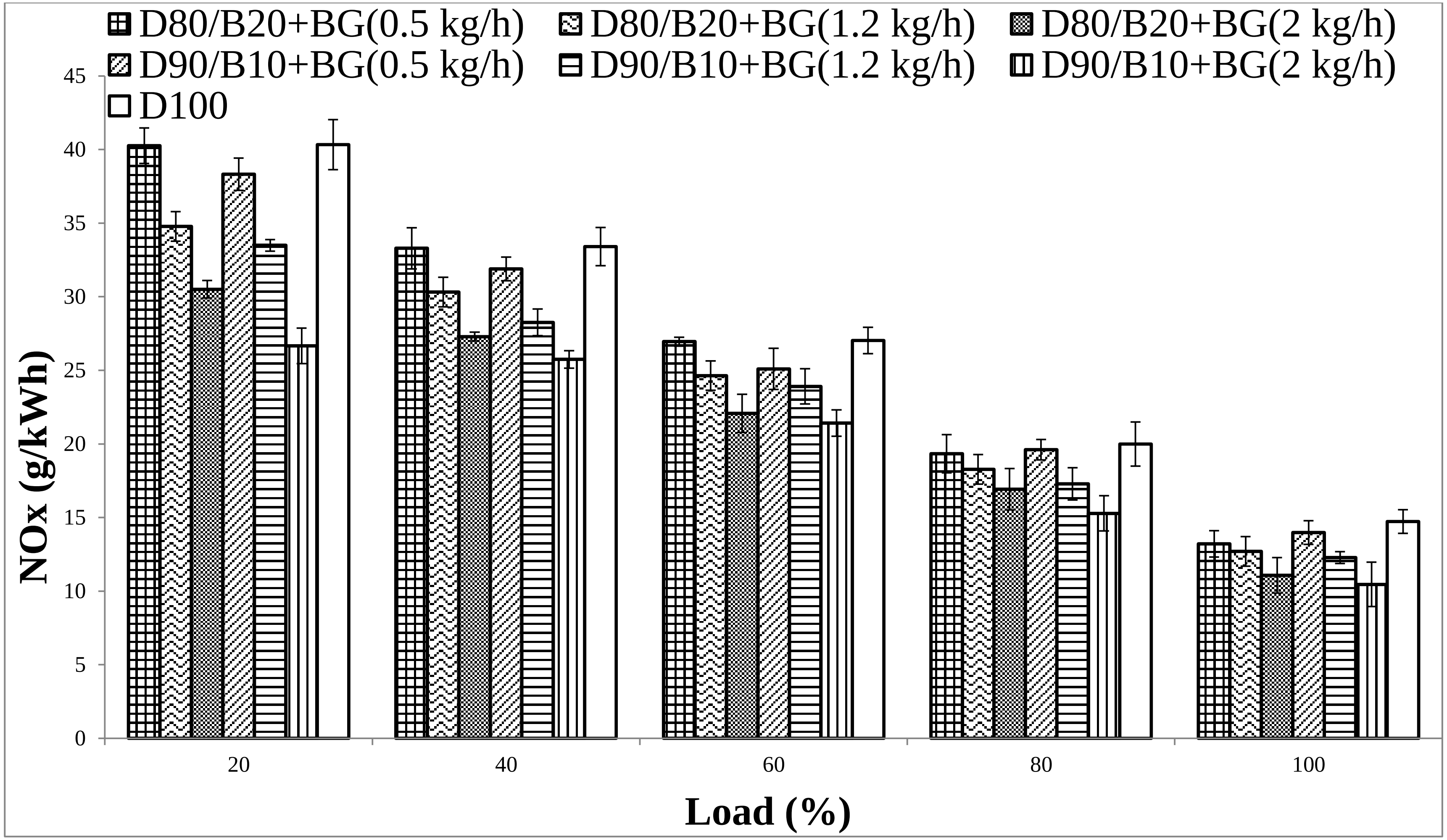

Figure 5.29 Variation of NOx with engine load for diesel, biodiesel, and biogas

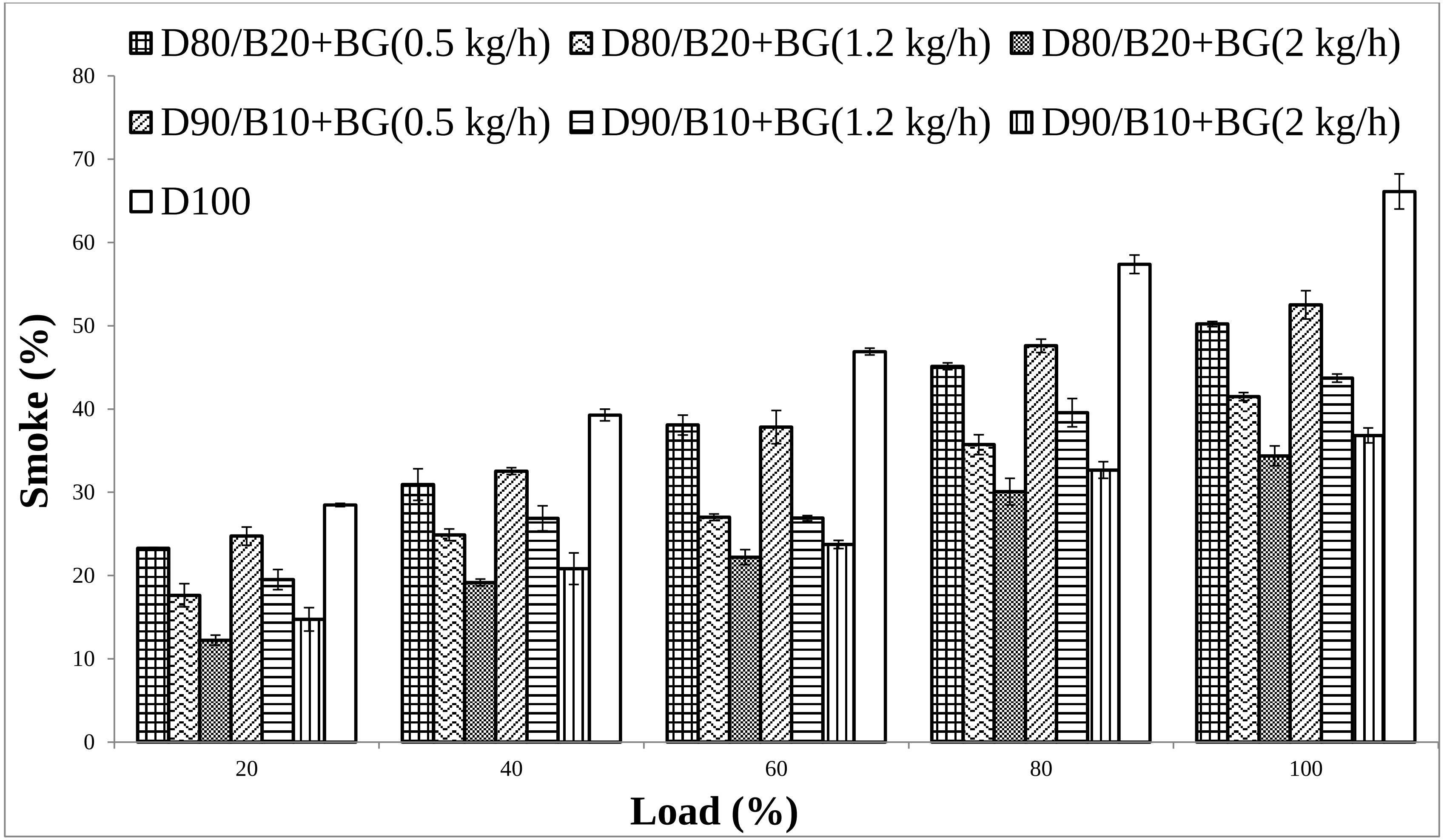

Figure 5.30 Variation of Smoke with engine load for diesel, biodiesel, and biogas

5.7 Combination of Diesel, Biogas, and n-butanol

The arrangement of diesel, biodiesel, and n biogas are tried on the diesel engine in this section of the chapter to evaluate the performance and exhalation features of the engine. Performance and discharge characteristics of the diesel engine for fuel combinations D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), D90/nb10+BG(2 kg/h), D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h) and, D80/nb20+BG(2 kg/h) are linked with regular diesel. Later, the graphs with performance and emission parameters are merged together.

5.7.1 Variation of BSFC with engine load

Variation of BSFC of the engine load for various fuel blends is depicted in Figure 5.31. It is noticed that BSFC is inversely proportional to the engine load. BSFC for all tested fuels is higher than diesel fuel. BSFC is found to be increased with increasing n-butanol in liquid fuel and mass flow rate of gaseous fuel. The lower calorific value of n-butanol [125] and poor conversion of biogas into work [278] can be the reason for lower BSFC using n-butanol and biogas as fuel in comparison with diesel fuel. Maximum BSFC is achieved for D90/nb10+BG(2 kg/h) and minimum for traditional diesel. Best value of BSFC is noted for D80/nb20+BG(2 kg/h) at 20% load and least for fossil diesel at 80% engine load. D80/nb20+BG(0.5 kg/h) fuel blend have 24.9%, 25.3%, 20.9%, 27.9%, and 21.1% augmenting BSFC correlated to natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an mediocre gain of 24%. It is documented that an increment of 26.5%, 28.1%, 32.9%, 35.1%, and 26.6% is obtained in BSFC for D80/nb20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in spells of 20% each respectively when corresponding to fossil diesel. An average increment of 29.8% is noticed. Compared to traditional diesel fuel blend D80/nb20+BG(2 kg/h) is recorded to have a hike of 28%, 29.3%, 35.3%, 36.5%, and 29.6% BSFC at engine loads varying in intervals of 20% each from 20% to 100% load respectively and noted to have an average rise of 31.7%. D90/nb10+BG(0.5 kg/h) fuel blend have 3.9%, 4.4%, 2.5%, 13.5%, and 5.9% increased BSFC than diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increment of 6%. It is noticed that an increment of 14.2%, 15.1%, 22.4%, 30%, and 22.7% is gained in BSFC for D90/nb10+BG(1.2

kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively relative to natural diesel. An average enhancement of 20.9% is recorded.

5.7.2 Variation of BTE with engine load

Figure 5.32 shows that BTE increased for all fuels relative to natural diesel. It is a huge achievement as BTE was on the lower side in comparison with traditional diesel when n-butanol and biogas were separately used with diesel fuel. Reason for increased BTE may be owing to higher amount of oxygen content in n-butanol fuel blends leading to the complete combustion of fuel inside the combustion chamber and consequently higher BTE [200] and the fact that biogas induction into the combustion chamber led to lower consumption of pilot fuel and subsequently higher BTE [34]. Best value of BTE is recorded for D80/nb20+BG(2kg/h) and least for natural diesel. Value of BTE for diesel fuel and D80/nb20+BG(0.5 kg/h) fuel blend is very much alike for all engine loads. The increment of 21.7%, 18.2%, 11.4%, 8.7%, and 9.8% is recorded in BTE at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D80/nb20+BG(0.5 kg/h) fuel blend in relation with conventional diesel. An average downfall of 14% is noted. Fuel blend D80/nb20+BG(1.2 kg/h) has 21.8%, 24.4%, 9.4%, 10.2%, and 12% enhances BTE than fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average enhancement of 15.6%. In comparison with traditional diesel fuel blend D80/nb20+BG(2 kg/h) has 26.2%, 24.2%, 12.7%, 11.4%, and 13.6% increased BTE for engine load varying from 20% to 100% in intervals of 20% each respectively. 6.4%, 9.4%, 2.7%, 3%, and 3.5% lower BTE is noticed at the engine loads ranging from 20% to 100% load in intervals of 20% each respectively for D90/nb10+BG(0.5 kg/h) fuel blend when compared with baseline diesel. An average augmentation of 5% is noticed. Fuel blend D90/nb10+BG(1.2 kg/h) has 12.3%, 15.5%, 6.9%, 5%, and 5.1% higher BTE relative to conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average increment of 9%.

5.7.3 Variation of CO with engine load

Figure 5.33 depicts deviation of CO emissions with the engine load. Emissions of CO are noted to decrease up to a certain limit and then increase with the engine load.

Diesel fuel is observed to emit minimum quantity of CO in comparison with D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), and D80/nb20+BG(2 kg/h). Fuels incorporating n-butanol and biogas are having more amount of CO emissions owing to the fact that insufficient oxygen is present inside the cylinder of the engine, as higher quantity of CO_2 is available in biogas [278]. The higher amount of oxygen content in n-butanol is submissive than the deficient oxygen present in biogas which consequently resulted in higher CO emissions for the combination of n-butanol and biogas fuels. CO emissions are found to be maximum for D80/nb20+BG(2 kg/h) fuel blend and minimum for conventional diesel. Amount of CO emissions for fuel blend D90/nb10+BG(0.5 kg/h) and D80/nb20+BG(0.5 kg/h) are very much alike at 100% engine load. 63.2%, 54.8%, 40.2%, 5.3%, and 8.8% increased CO exhalations are noticed for D80/nb20+BG(0.5 kg/h) fuel blend when compared with natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average increment of 34.5%. Enhancement of 79%, 73.5%, 62.9%, 39.3%, and 34.5% is noted in emissions of CO for D80/nb20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively in relation with fossil diesel. An average hike of 57.8% is noticed. For D80/nb20+BG(2 kg/h) enhancement of 85.1%, 81.7%, 75.5%, 60.5%, and 40.6% is recorded at 20%, 40%, 60%, 80%, and 100% engine load respectively in relation with traditional fossil diesel. 51.3%, 48.6%, 24.5%, 3.2%, and 5.7% more CO exhalations are recorded for D90/nb10+BG(0.5 kg/h) fuel blend compared to natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average increment of 26.7%. A gain of 74.8%, 69.9%, 60.3%, 33.3%, and 33.4% is noted in emissions of CO for D90/nb10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively than traditional diesel. An average enhancement of 54.3% is reported.

5.7.4 Variation of HC with engine load

Variation of HC exhalations with engine load shows that there is a decrement in HC emissions with the increase in engine load. Figure 5.34 depicts that HC emissions increased drastically with fuels containing n-butanol and biogas relative to conventional diesel. The separate effect of n-butanol and biogas on HC emissions also shows similar results. The reason that HC exhalations are on the higher side was that n-butanol has a lower cetane number than diesel fuel [160] and lower flame velocity of biogas in relation with traditional diesel [276]. Highest HC exhalations are noticed for D80/nb20+BG(2 kg/h) and lowest for traditional diesel. The maximum value of HC emissions are recorded for D/B20+BG(2 kg/h) at 20% load and minimum for fossil diesel at100% engine load. D80/nb20+BG(0.5 kg/h) fuel blend shows 19.6%, 14.6%, 15.5%, 11.9%, and 16.2% enhanced HC exhalations in comparison with baseline diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increment of 15.6%. It is reported that an increase of 24.9%, 27%, 26.2%, 25.9%, and 26.5% is achieved in HC exhalations for D80/nb20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in spells of 20% each respectively than conventional diesel. An average increase of 26.1% is noticed. Relative to diesel, fuel blend D80/nb20+BG(2 kg/h) is noted to have enhancement of 31.8%, 29.1%, 28%, 26%, and 29.2% HC at engine loads varying in spells of 20% each from 20% to 100% load respectively and noted to have an average increase of 28.8%. D90/nb10+BG(0.5 kg/h) fuel blend have 16.6%, 11.4%, 11%, 8.3%, and 11.6% more HC emissions correlated to natural diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average enhancement of 11.8%. It is noted that a hike of 23.3%, 25.5%, 25.5%, 24.7%, and 25.7% is reported in HC emissions for D90/nb10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively than diesel. An average hike of 24.9% is noticed.

5.7.5 Variation of NOx with engine load

Deviation of NOx emissions with the engine load is depicted in Figure 5.35 from which it can be understood that NOx emissions are inversely proportional to the engine load. Diesel fuel is noticed to emit maximum NOx exhalations in comparison with all other fuels used. The separate effect of biogas and n-butanol shows a decrease and increase in NOx emissions respectively. In combined case shortage of quantity of oxygen in biogas [278] is may be more than the availability of high oxygen content in n-butanol [225]. Value of NOx emissions for D90/nb10+BG(2 kg/h) fuel blend and D/B20+BG(2 kg/h) fuel blend are nearly alike at 40% engine loading conditions. D80/nb20+BG(0.5 kg/h) fuel blend illustrates 12.5%, 9.2%, 13.7%, 30.8%, and

14.3% reduced NOx exhalations in relation with pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deterioration of 16.1%. Loss of 27.3%, 26.9%, 39.2%, 49.8%, and 39% is noted in NOx emissions at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D80/nb20+BG(1.2 kg/h) fuel blends than baseline diesel. An average reduction of 36.4% is attained. For D80/nb20+BG(2 kg/h) fuel blend a reduction of 39.8%, 39.7%, 52%, 70%, and 64.1% is noticed at engine loads varying from 20% to 100% at regular intervals of 20% each respectively compared to diesel fuel. D90/nb10+BG(0.5 kg/h) fuel blend depicts 18.2%, 19.5%, 20.7%, 37.8%, and 36.7% lesser NOx emissions in comparison with conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deterioration of 26.6%. Reduction of 35.8%, 40.3%, 47%, 55.1%, and 62.7% is reported in NOx exhalations at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D90/nb10+BG(1.2 kg/h) fuel blends than pure diesel. An average reduction of 48.2% is attained.

5.7.6 Variation of Smoke with engine load

Smoke emissions are found to be decreased with n-butanol and biogas containing fuels as shown in Figure 5.36. This result is obvious as separate effects of both these fuels also had the same result. The reason for lesser smoke opacity for fuels incorporating n-butanol and biogas can be attributed to the fact that higher amount of oxygen is available in n-butanol which aids in complete combustion of fuel [225] and the main constituent of biogas is methane which helps in reducing the level of smoke [294]. It is also noticed that smoke opacity decreases with increase in load. Minimum smoke exhalations are noted for fuel blend D80/nb20+BG(2 kg/h) and maximum for traditional diesel. The highest amount of smoke opacity is noticed for diesel fuel at 100% load and lowest for D80/nb20+BG(0.5 kg/h) at 20% engine load. The decrement of 34.8%, 41.5%, 30.7%, 34%, and 31.4% is achieved in smoke emissions at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D80/nb20+BG(0.5 kg/h) fuel blend as compared to fossil diesel. An average reduction of 34.5% is attained. Fuel blend D80/nb20+BG(1.2 kg/h) illustrates 54.4%, 46%, 47.2%, 50.5%, and 44.4% lesser smoke emissions in comparison with pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deterioration of 48.5%. For D80/nb20+BG(2 kg/h) fuel blend decrement of 64.1%, 61.2%, 63.3%, 59.9%, 57.4% is noted relative to diesel fuel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 61.2%. The decrement of 24.5%, 37.5%, 28.2%, 27.9%, and 28.4% is depicted in smoke opacity at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D90/nb10+BG(0.5 kg/h) fuel blend relative to baseline diesel. An average reduction of 29.3% is noted. Fuel blend D90/nb10+BG(1.2 kg/h) shows 43.7%, 42.6%, 45.2%, 41.1%, and 42.6% reduced smoke exhalations relative to pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 43%. For D90/nb10+BG(2 kg/h) fuel blend decrement of 26.3%, 33.8%, 25.9%, 30.2%, and 29.1% is recorded in relation with traditional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 29.1%.

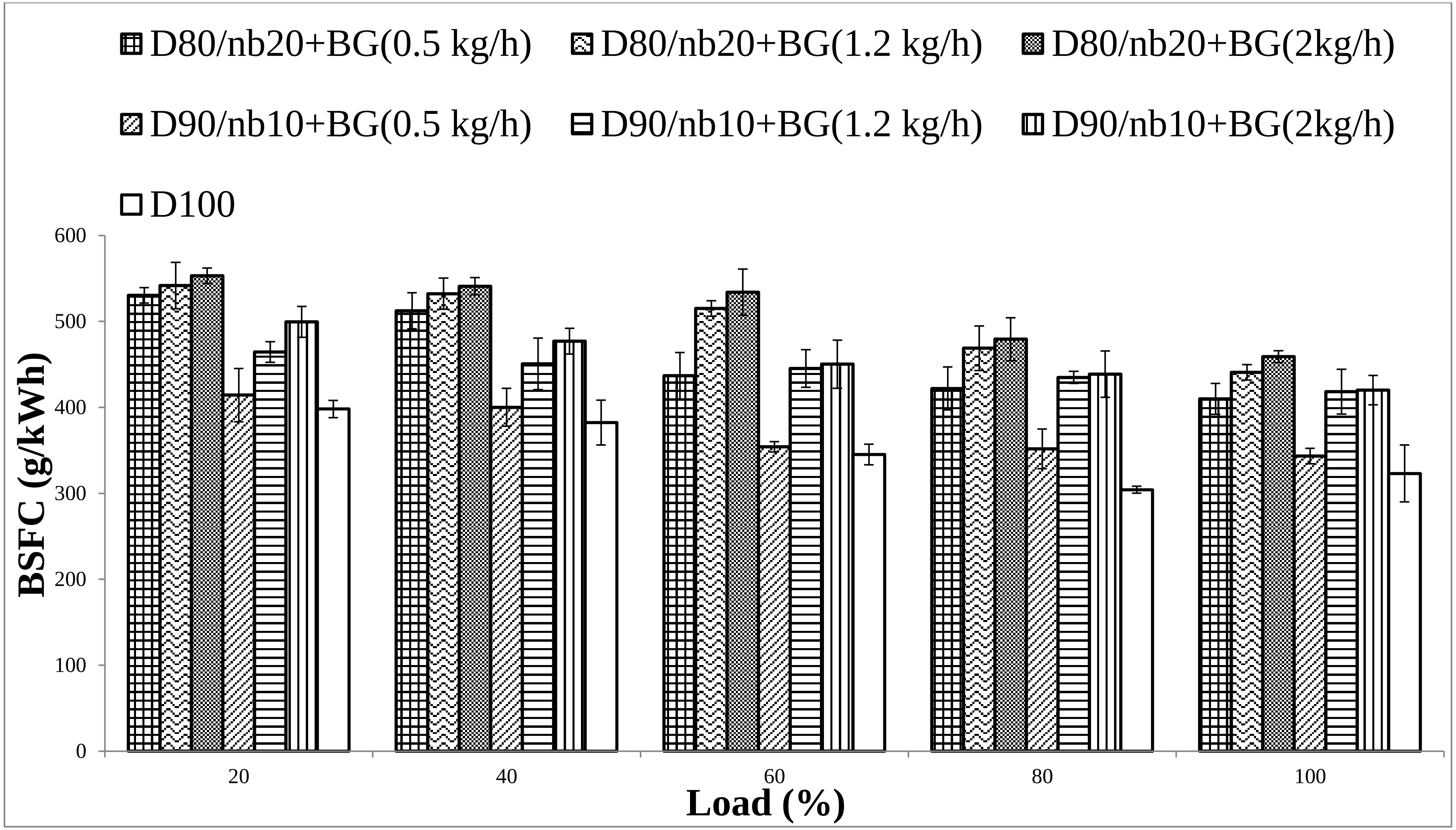

Figure 5.31 Variation of BSFC with engine load for diesel, biogas and n-butanol

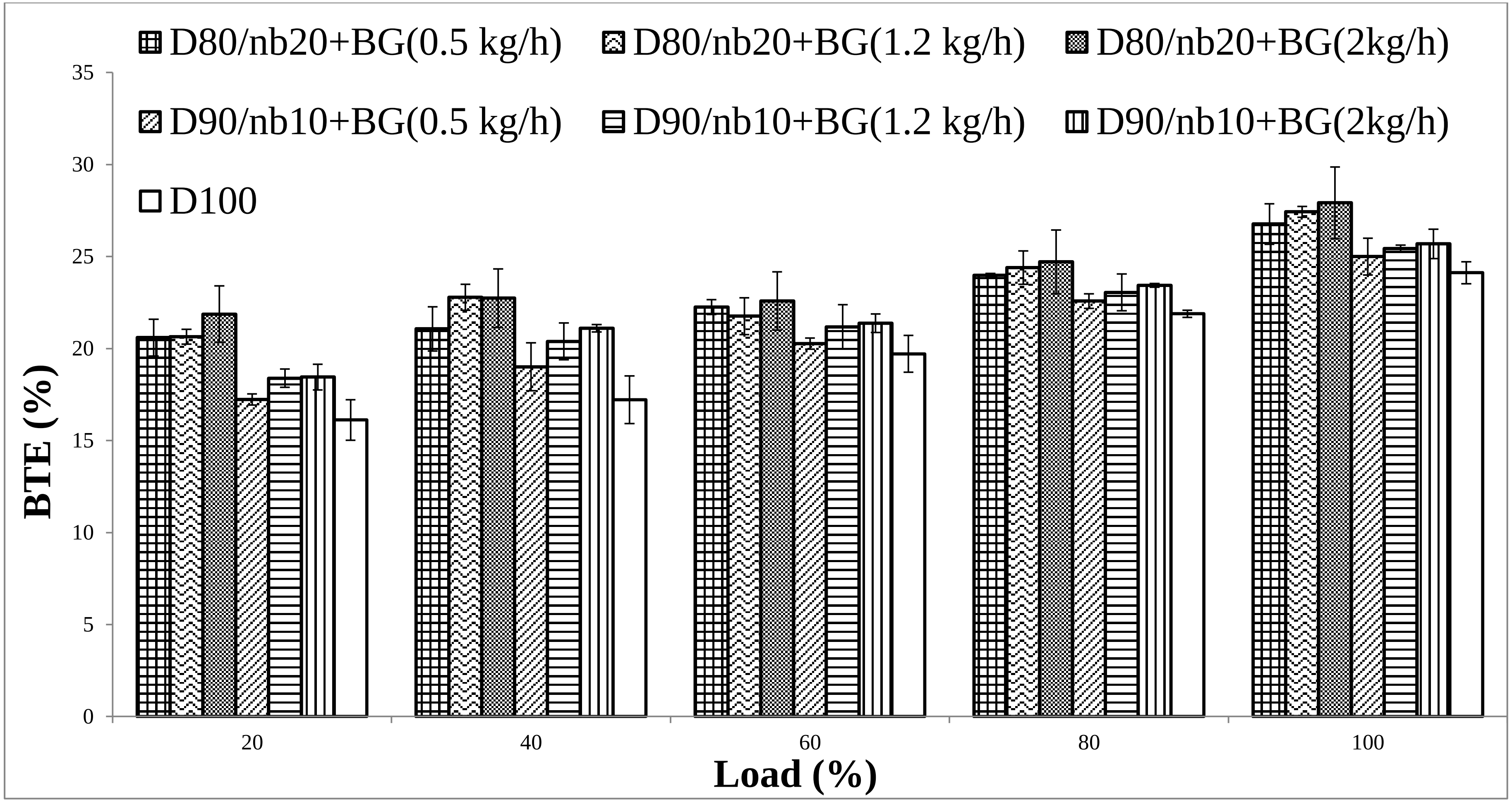

Figure 5.32 Variation of BTE with engine load for diesel, biogas, and n-butanol

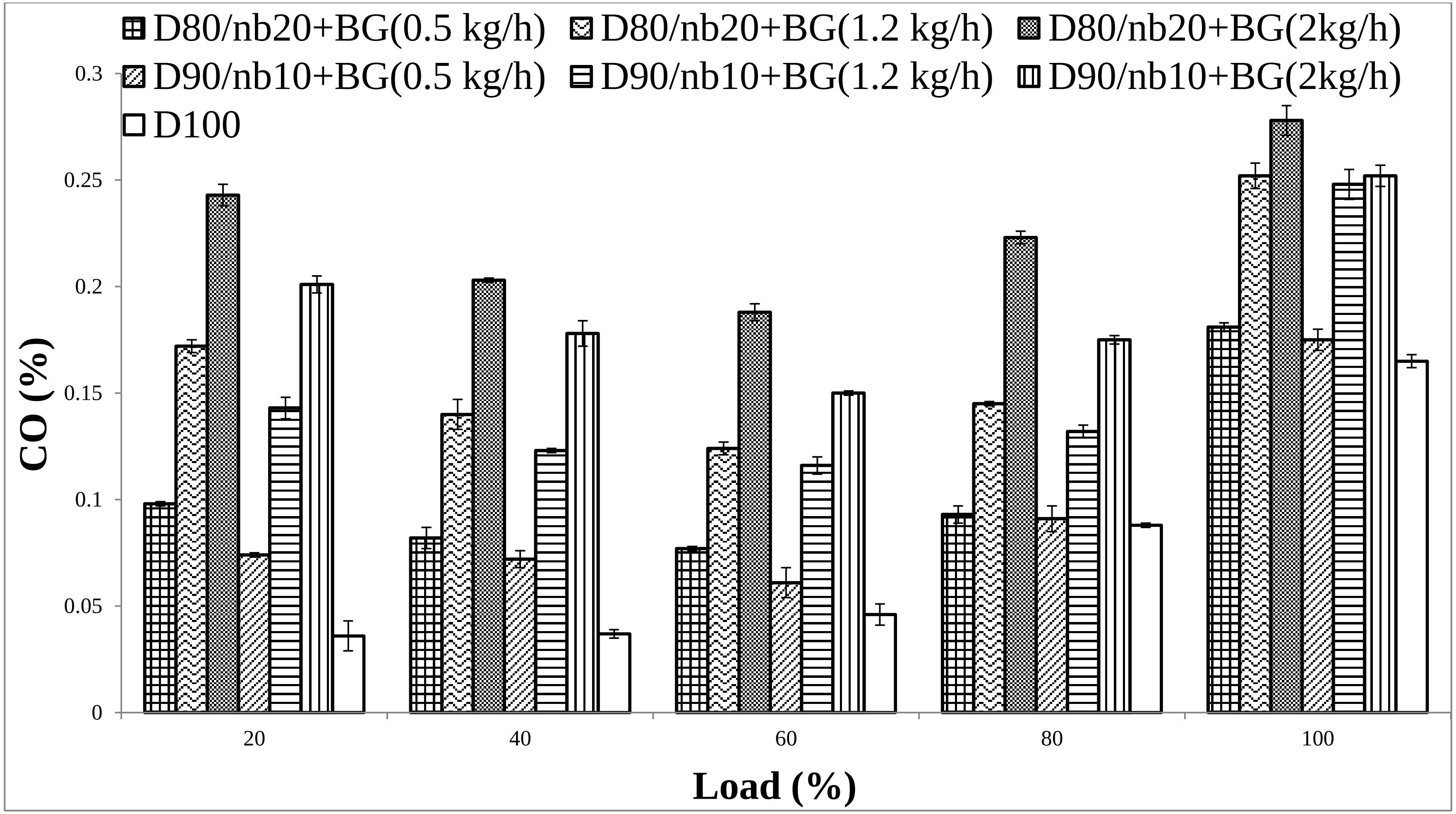

Figure 5.33 Variation of CO with engine load for diesel, biogas, and n-butanol

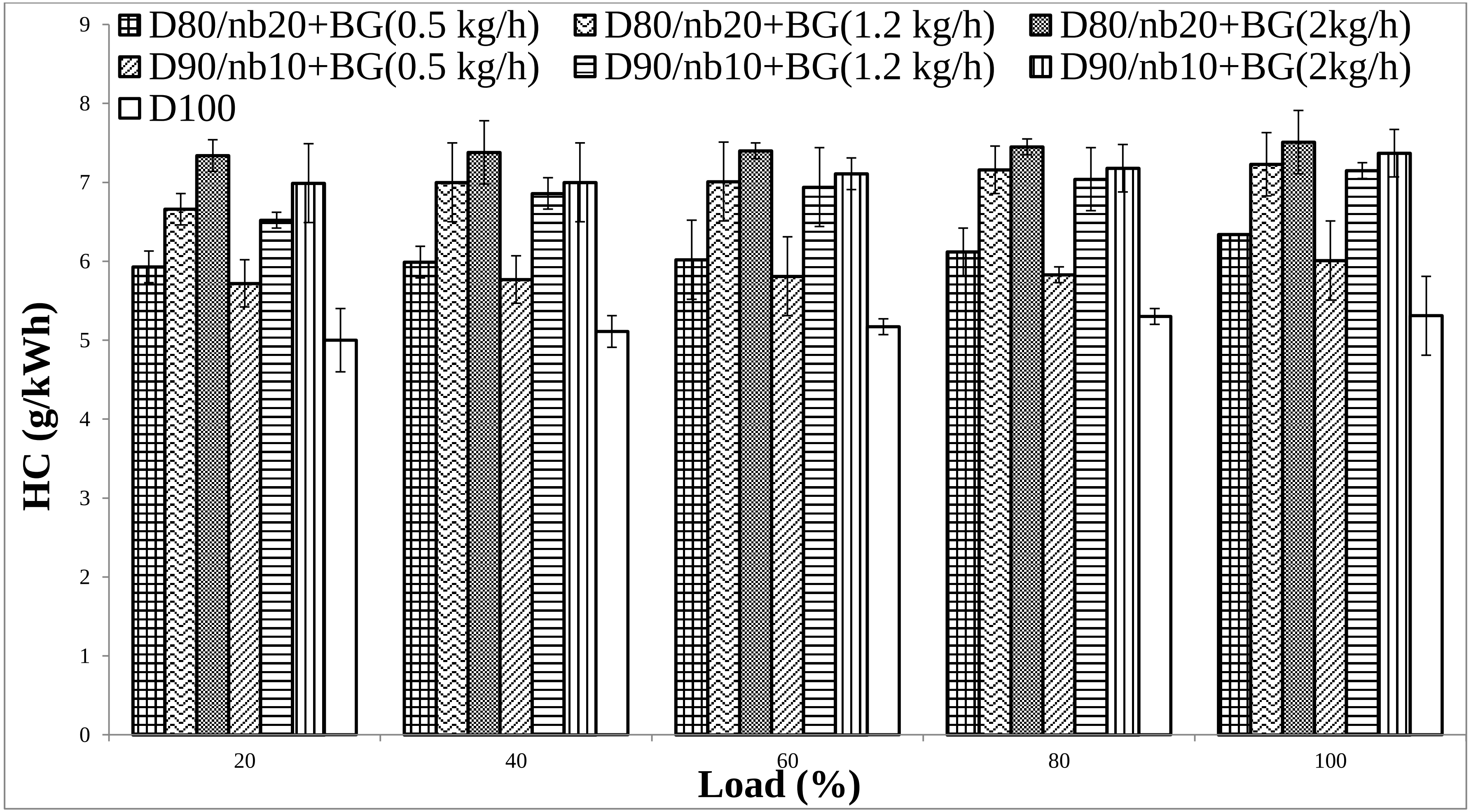

Figure 5.34 Variation of HC with engine load for diesel, biogas, and n-butanol

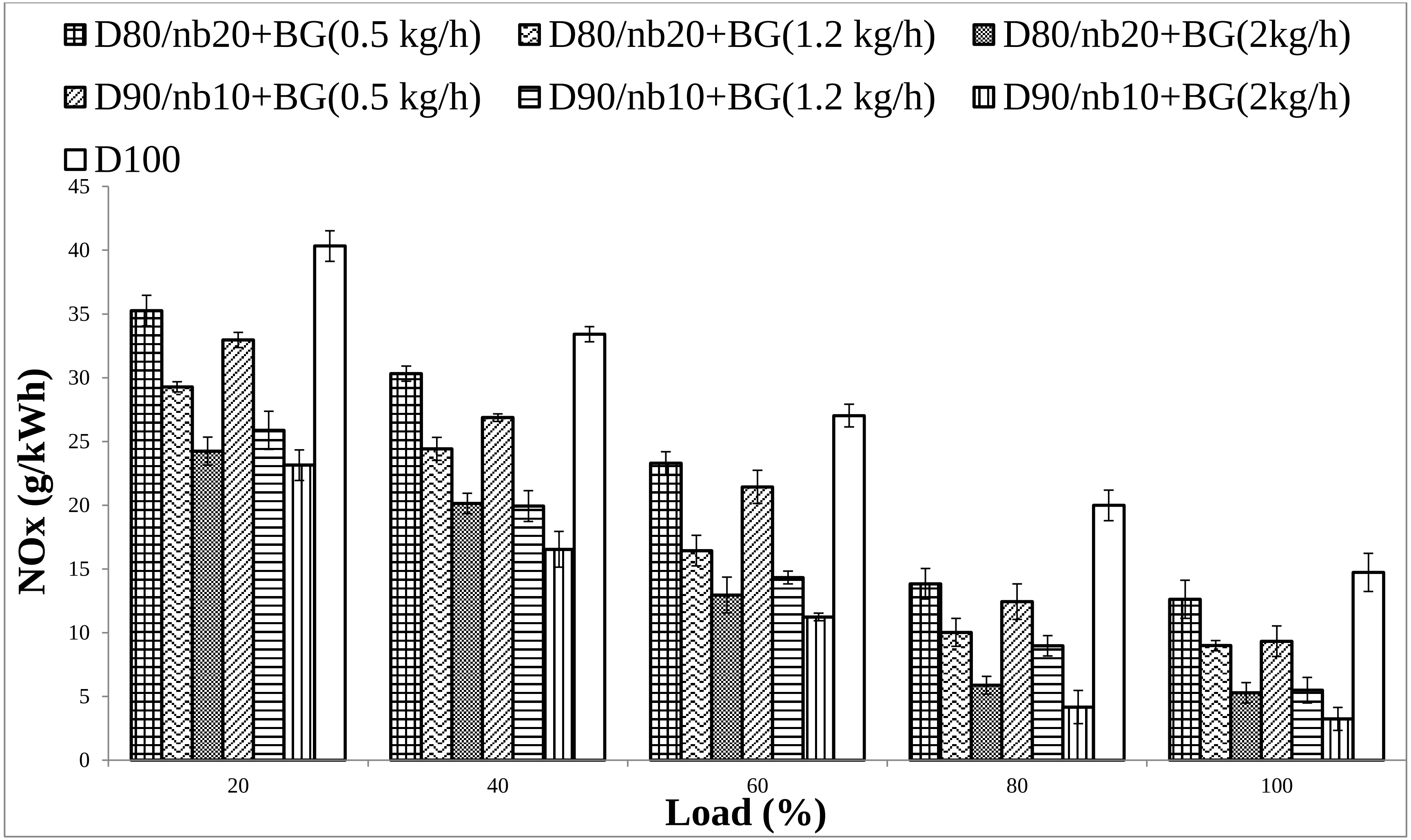

Figure 5.35 Variation of NOx with engine load for diesel, biogas, and n-butanol

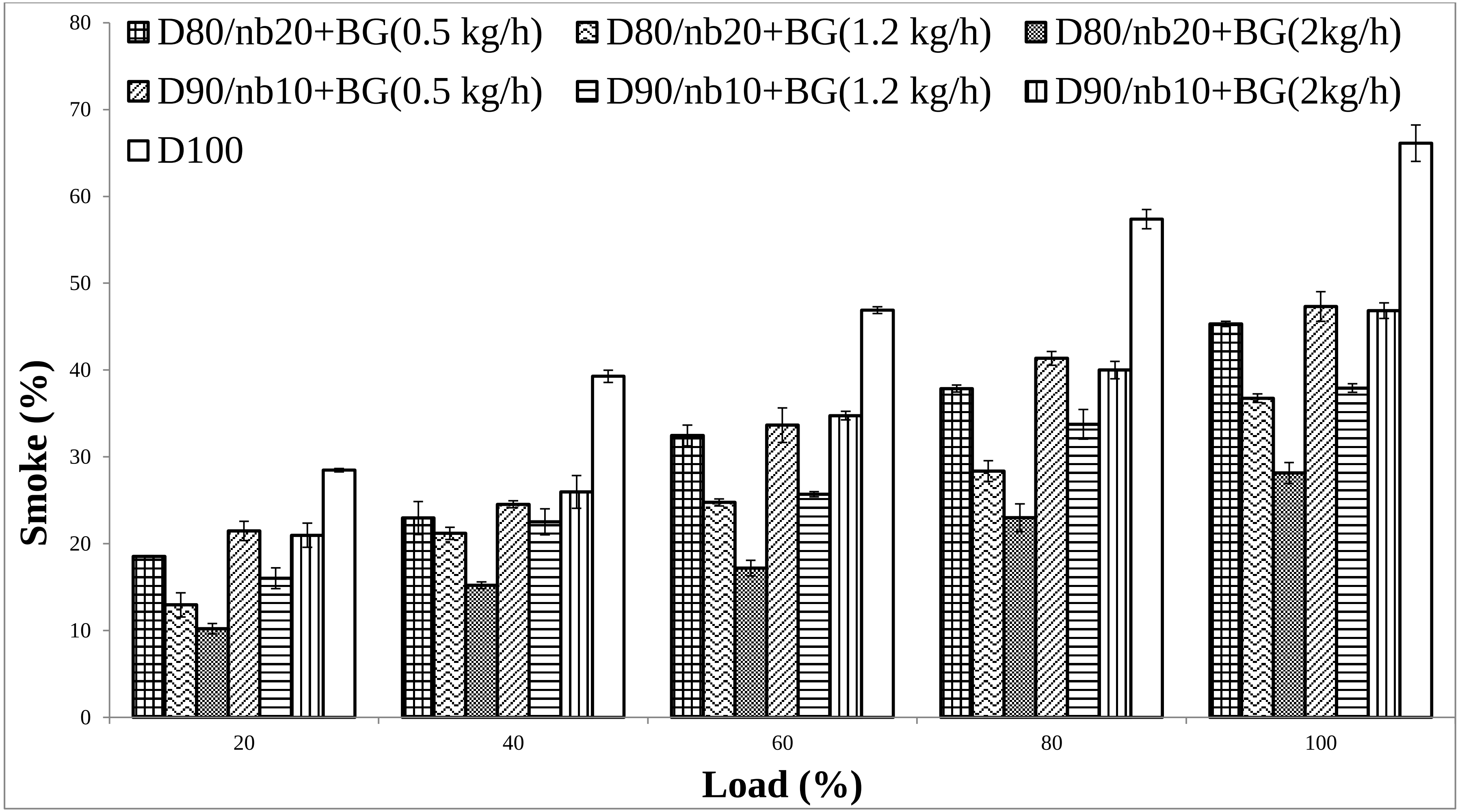

Figure 5.36 Variation of Smoke with engine load for diesel, biogas, and n-butanol

5.8 Combination of Diesel, Biodiesel, Biogas, and n-butanol (D60 and D80)

The combination of diesel, biodiesel, biogas, and n-butanol is used on the diesel engine in this sub division of the chapter to check the performance and emission parameters of the engine. Performance and exhalation characteristics of the diesel engine for fuel combinations D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), D80/B10/nb10+BG(2 kg/h), D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h) and, D60/B20/nb20+BG(2 kg/h) are associated with traditional diesel. Thereafter, the grids with performance and emanation parameters are clubbed together.

5.8.1 Variation of BSFC with engine load

Figure 5.37 depicts deviation of BSFC with engine load for fuel blends containing diesel, biodiesel and n-butanol, and using biogas as a primary fuel. It can be seen that with the increase in the engine load BSFC decreases. BSFC for all fuels used is higher in comparison with natural diesel. The separate impact of biodiesel, n-butanol and biogas also reports the same result. Increased BSFC for other fuels compared to pure diesel may owe to fact that biodiesel is more viscous and has less heating value than conventional diesel [85]. Another reason can be lower energy content and less burning efficiency of n-butanol [125]. It may also be attributed to the lean mixture and low combustion temperature owing to the addition of gaseous fuel in the combustion chamber [278]. Highest BSFC is achieved for D60/B20/nb20+BG(2 kg/h) and lowest for natural diesel. Best value of BSFC is noticed for D60/B20/nb20+BG(2 kg/h) at 20% load and least for raw diesel at 80% engine load. D60/B20/nb20+BG(0.5 kg/h) fuel blend have 25%, 25.5%, 26.2%, 32%, and 24.2% improved BSFC in relation with conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with a mediocre increment of 26.6%. It is reported that an enhancement of 27.9%, 29.4%, 33.5%, 35.1%, and 26.5% is obtained in BSFC for D60/B20/nb20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively correlated with traditional diesel. An average increment of 30.5% is noted. In relation with fossil diesel fuel blend D60/B20/nb20+BG(2 kg/h) is documented to have an increase of 29%, 30.4%, 36.4%, 37.7%, and 31% BSFC at engine loads varying in intervals of 20% each from

20% to 100% load respectively and have an average rise of 32.9%. D80/B10/nb10+BG(0.5 kg/h) fuel blend have 4.5%, 6.3%, 4.7%, 14%, and 7.1% augmenting BSFC than diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increase of 7.3%. It is noticed that an enhancement of 17.3%, 15.2%, 22%, 26.9%, and 19.6% is attained in BSFC for D80/B10/nb10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively compared to diesel fuel. An average increment of 20.2% is documented. In comparison with baseline diesel, fuel blend D80/B10/nb10+BG(2 kg/h) is noticed to have enhanced BSFC of 20.5%, 20.5%, 23.3%, 31%, and 23.6% at engine loads varying in intervals of 20% each from 20% to 100% load respectively and have an average increment of 23.8%.

5.8.2 Variation of BTE with engine load

BTE of diesel is observed to be highest relative to all other fuels tested in this section which can be clearly understood form variation of BTE with the engine load as shown in Figure 5.38. It is very much obvious, if separate effects of biodiesel, n-butanol and biogas on BTE of the engine are taken as reference, because BTE is lower for Diesel and biodiesel, Diesel and n-butanol, and Diesel and biogas. It is because of lower calorific value and high viscosity of biodiesel [206]. Lower heating value and cetane number are also responsible for the same [160]. It can also be attributed to the fact that gaseous fuel is not utilized efficiently in the combustion chamber [35]. The maximum value of BTE is noted for fossil diesel and minimum for D80/B10/nb10+BG(0.5 kg/h) fuel blend. Amount of BTE for D80/B10/nb10+BG(1.2 kg/h) and D80/B10/nb10+BG(2 kg/h) fuel blends is very much similar for 20% engine load. Reduction of 15.2%, 15.3%, 6%, 16.9%, and12.1% is noted in BTE at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D60/B20/nb20+BG(0.5 kg/h) fuel blend in comparison with pure diesel. An average reduction of 13.1% is recorded. Fuel blend D60/B20/nb20+BG(1.2 kg/h) has 12.3%, 13.8%, 6.4%, 10.1%, and 8.1% lesser BTE than fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deterioration of 10.1%. Relative to natural diesel, fuel blends D/B20+BG(0.5 kg/h) has 10.2%, 9.5%, 4.5%, 8.6%, and 7.6% lesser BTE for engine load varying from 20% to 100% in intervals of

20% each respectively. 30.4%, 24.1%, 14.9%, 19.4%, and 17.1% reduced BTE is noted at the engine loads ranging from 20% to 100% load in intervals of 20% each respectively for D80/B10/nb10+BG(0.5 kg/h) fuel blend when related with raw diesel. An average decrement of 21.2% is noticed. Fuel blend D80/B10/nb10+BG(1.2 kg/h) has 27.4%, 16.8%, 6.4%, 12.9%, and 14.6% lower BTE relative to conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 15.6%. Compared to baseline diesel fuel blend D80/B10/nb10+BG(2 kg/h) has 27.4%, 20.3%, 9%, 16%, and 16.1% reduced BTE for engine load varying from 20% to 100% in intervals of 20% each respectively.

5.8.3 Variation of CO with engine load

CO emissions are on the higher side for all fuels tested in this part of the thesis relative to baseline diesel as illustrated in Figure 5.39. Fuels containing biodiesel, n-butanol and biogas are having more amounts of CO emissions in comparison with pure diesel because of lean fuel-air mixture owing to the introduction of biogas which resulted in lower oxygen quantity inside the combustion chamber [225]. This reason may be more dominating over the high amount of oxygen present in biodiesel and n-butanol. CO emissions are found to be maximum for D60/B20/nb20+BG(2 kg/h) fuel blend and minimum for conventional diesel. Amount of CO emissions for fuel blend D60/B20/nb20+BG(0.5 kg/h) and diesel are very much similar at 80% engine load. 51.1%, 41.2%, 33.3%, 2.3%, and 7.8% enhanced CO emissions are recorded for D60/B20/nb20+BG(0.5 kg/h) fuel blend relative to pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average enhancement of 26.9%. The increment of 77.9%, 71.9%, 56.6%, 35.6%, and 33.4% is recorded in exhalations of CO for D60/B20/nb20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively when compared with conventional diesel. An average increase of 55.3% is noted. For D60/B20/nb20+BG(2 kg/h) increment of 83.2%, 78.7%, 73.5%, 57.8%, and 35.5% is noted at 20%, 40%, 60%, 80%, and 100% engine load respectively relative to traditional diesel. 41.9%, 37.2%, 13.2%, 7.3%, and 21.8% more CO emissions are noticed for D80/B10/nb10+BG(0.5 kg/h) fuel blend than pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average enhancement of 21.3%. Hike of 72.3%, 63.3%, 52.5%, 16.9%, and

28.8% is recorded in exhalations of CO for D80/B10/nb10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively than baseline diesel. An average increase of 46.8% is reported. For D80/B10/nb10+BG(2 kg/h) enhancement of 80.6%, 77.8%, 63.7%, 43.2%, and 30.6% is recorded at 20%, 40%, 60%, 80%, and 100% engine load respectively relative to diesel fuel.

5.8.4 Variation of HC with engine load

Deviation of HC emissions with the engine is illustrated in Figure 6.39. It is found that HC emissions enhanced with fuels containing biodiesel, n-butanol and biogas in comparison with natural diesel. The separate effect of n-butanol and biogas on HC emissions also shows similar results. The reason that HC exhalations were on the higher side may be that lower cetane number of n-butanol than diesel fuel [160] and lower flame velocity of biogas [276] was more dominant than extra oxygen content in biodiesel [139]. Maximum HC exhalations are noticed for D80/B10/nb10+BG(2 kg/h) and minimum for fossil diesel. Best value of HC exhalations are noted for D80/B10/nb10+BG(2 kg/h) at 20% load and least for pure diesel at full engine load. D60/B20/nb20+BG(0.5 kg/h) fuel blend depicts 7.9%, 6.7%, 7%, 6.8%, and 7.1% extra HC exhalations than baseline diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average enhancement of 7.1%. An increase of 18.1%, 18.5%, 19.5%, 19.2%, and 22.7% is attained in HC emissions for D60/B20/nb20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively correlated with diesel fuel. An average enhancement of 19.6% is recorded. Compared to pure diesel, fuel blend D60/B20/nb20+BG(2 kg/h) is noted to have enhancement of 27.7%, 26.8%, 27.2%, 26.2%, and 26.5% HC at engine loads varying in spells of 20% each from 20% to 100% load respectively and noted to have an average increment of 26.9%. D80/B10/nb10+BG(0.5 kg/h) fuel blend have 10.7%, 10.1%, 11.1%, 9.7%, and 11.3% enhanced HC emissions than raw diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increase of 10.6%. A gain of 23.6%, 24%, 24.7%, 24.7%, and 16% is noticed in HC emissions for D80/B10/nb10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in spells of 20% each respectively relative to fossil diesel. An average enhancement of 24.6% is recorded. In relation to diesel, fuel blend D80/B10/nb10+BG(2 kg/h) have increment of 28.8%, 28.3%, 27.9%, 27.5%, and 29.2% HC emissions at engine loads varying in intervals of 20% each from 20% to 100% load respectively and have average hike of 28.3%.

5.8.5 Variation of NOx with engine load

Figure 5.41 shows the variation of NOx exhalations with the engine load. Effect of biogas is more dominating over biodiesel and n-butanol and consequently NOx emissions decrease for fuels incorporating biodiesel, n-butanol, and biogas than diesel fuel. It is also observed that NOx emissions are on the lower side with the increase in the engine load. Insufficient supply of oxygen with biogas fuel [278] may have dominated more over the higher amount of oxygen content in biodiesel [154] and n-butanol [225] which resulted in a decrement in NOx exhalations for D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D/B10/nb20+BG(0.5 kg/h), D/B10/nb20+BG(1.2 kg/h) and D/B10/nb20+BG(2 kg/h) in comparison with ordinary diesel. Value of NOx emissions for D60/B20/nb20+BG(2 kg/h) fuel blend and D80/B10/nb10+BG(1.2 kg/h) fuel blend were almost alike at 40% engine loading conditions. D60/B20/nb20+BG(0.5 kg/h) fuel blend depicts 8.4%, 10.1%, 14.5%, 20.5%, and 12.2% lesser NOx emissions compared to fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 13.1%. Loss of 25.5%, 25.2%, 31.9%, 45.6%, and 41.2% is noticed in NOx exhalations at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D60/B20/nb20+BG(1.2 kg/h) fuel blends relative to traditional diesel. An average reduction of 33.9% is achieved. For D60/B20/nb20+BG(2 kg/h) fuel blend a deterioration of 37.9%, 39.8%, 49.2%, 68.4%, and 66.3% is recorded at engine loads varying from 20% to 100% at regular intervals of 20% each respectively than traditional diesel. D80/B10/nb10+BG(0.5 kg/h) fuel blend illustrates 16%, 16.4%, 22%, 35.2%, and 32.7% reduced NOx exhalations in relation with baseline diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 24.51%. The decrement of 34.5%, 37.8%, 39.3%, 55.7%, and 58.5% is noticed in NOx emissions at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D80/B10/nb10+BG(1.2 kg/h) fuel blends compared to natural diesel. An average reduction of 45.21% is found. For D80/B10/nb10+BG(2 kg/h) fuel blend a reduction of 41.9%, 48.7%, 56.2%, 76%, and 79.2% NOx emissions is noted at engine loads varying from 20% to 100% at regular intervals of 20% each respectively relative to pure diesel.

5.8.6 Variation of Smoke with engine load

Smoke opacity decreased drastically for all fuels containing biodiesel, n-butanol and biogas relative to diesel. Figure 5.42 depicts the variation of smoke with the engine load which shows that smoke opacity increases with increase in engine load. Reason for higher smoke exhalations of diesel is due to the higher content of oxygen in biodiesel [154] and n-butanol [225] which resulted in complete combustion of fuel. Methane as a major constituent of biogas [294] also contributed to decreased emissions of smoke for fuels incorporating biodiesel, n-butanol, and biogas compared to natural diesel. Highest smoke emissions are noticed for natural diesel and least for fuel blend D60/B20/nb20+BG(2 kg/h) and least for natural diesel. The maximum value of smoke emissions is recorded for conventional diesel at 100% load and lowest for D60/B20/nb20+BG(2 kg/h) at 20% engine load. Deterioration of 44.6%, 47.4%, 36.6%, 37.4%, and 36.2% is attained in smoke opacity at the engine loads ranging from 20% to full load in spells of 20% each respectively for D60/B20/nb20+BG(0.5 kg/h) fuel blend as compared to fossil diesel. An average reduction of 40.4% is attained. Fuel blend D60/B20/nb20+BG(1.2 kg/h) shows 63.8%, 53.6%, 54.4%, 53.1%, and 49.9% reduced smoke exhalations relative to raw diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 54.9%. For D60/B20/nb20+BG(2 kg/h) fuel blend deterioration of 72.2%, 68.9%, 69.4%, 64.1%, 60.5% is recorded than fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 67%. Reduction of 36%, 43.2%, 33.9%, 32.9%, and 31.1% is illustrated in smoke opacity at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D80/B10/nb10+BG(0.5 kg/h) fuel blend in comparison with pure diesel. An average decrement of 35.4% is noted. Fuel blend D80/B10/nb10+BG(1.2 kg/h) depicts 53.7%, 46.3%, 51.2%, 48.2%, and 46.7% lesser smoke emissions compared to conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deterioration of 49.2%.

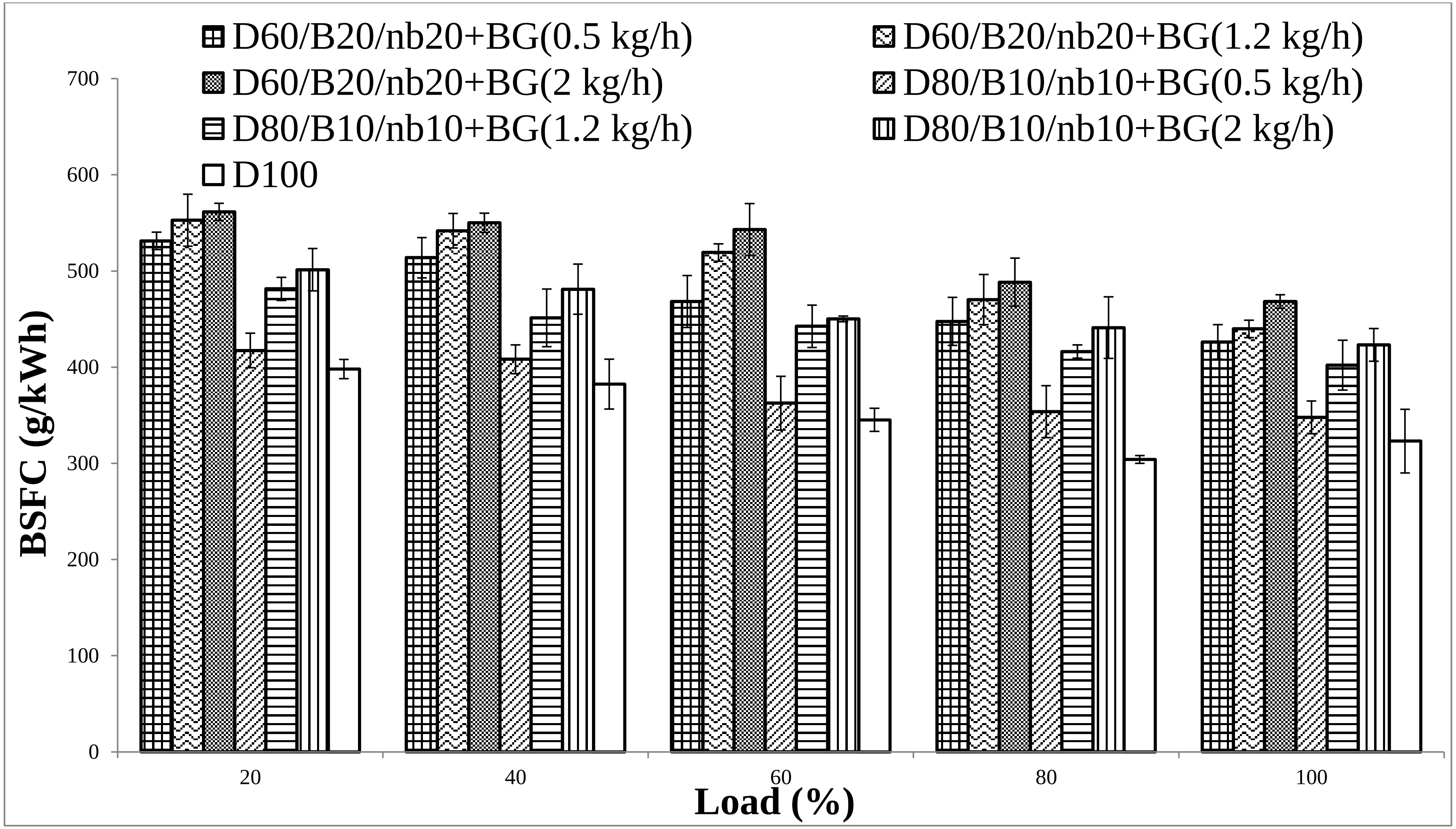

Figure 5.37 Variation of BSFC with engine load for diesel, biodiesel, biogas, and n-butanol (D60 and D80)

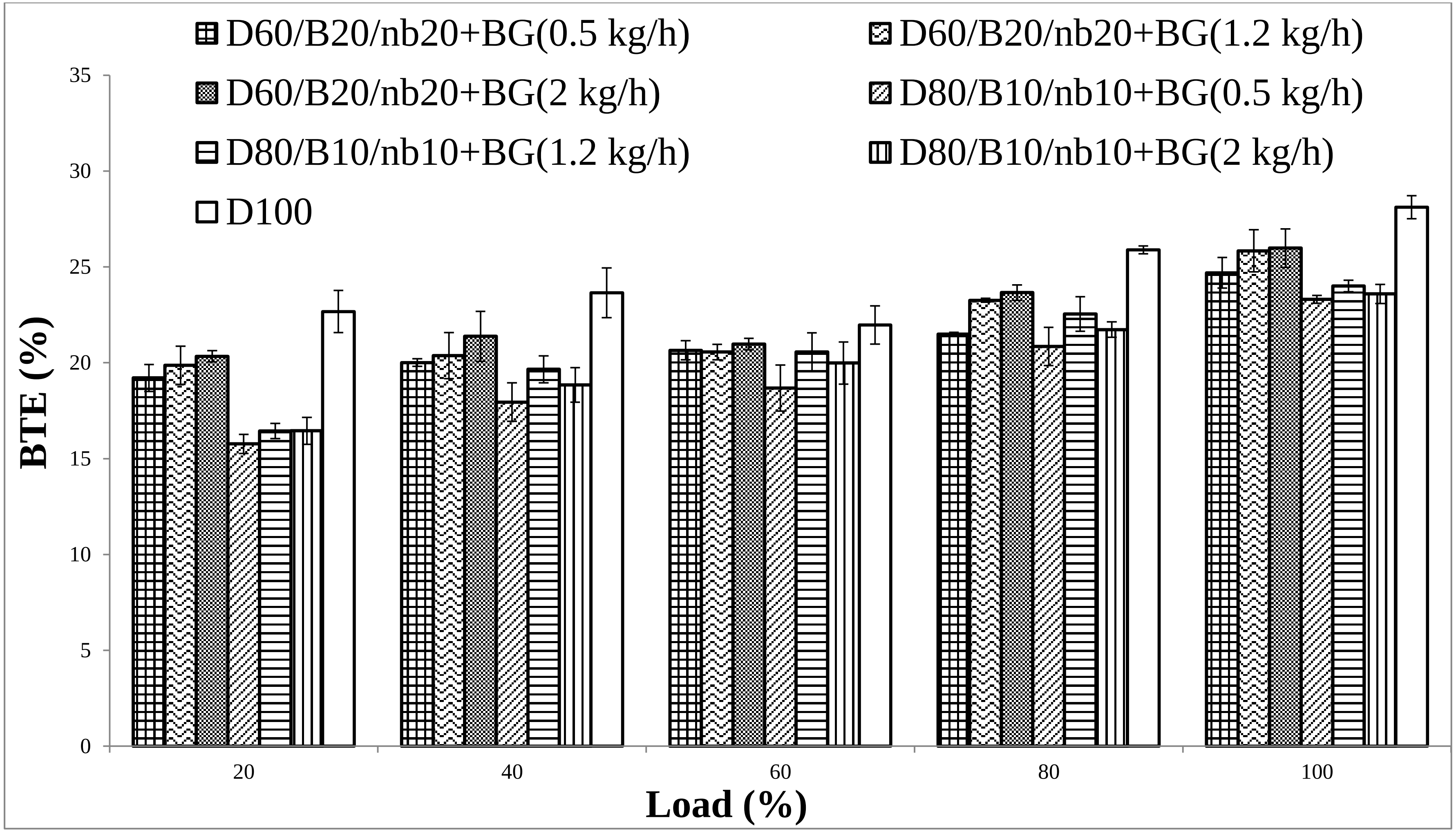

Figure 5.38 Variation of BTE with engine load for diesel, biodiesel, biogas, and n-butanol (D60 and D80)

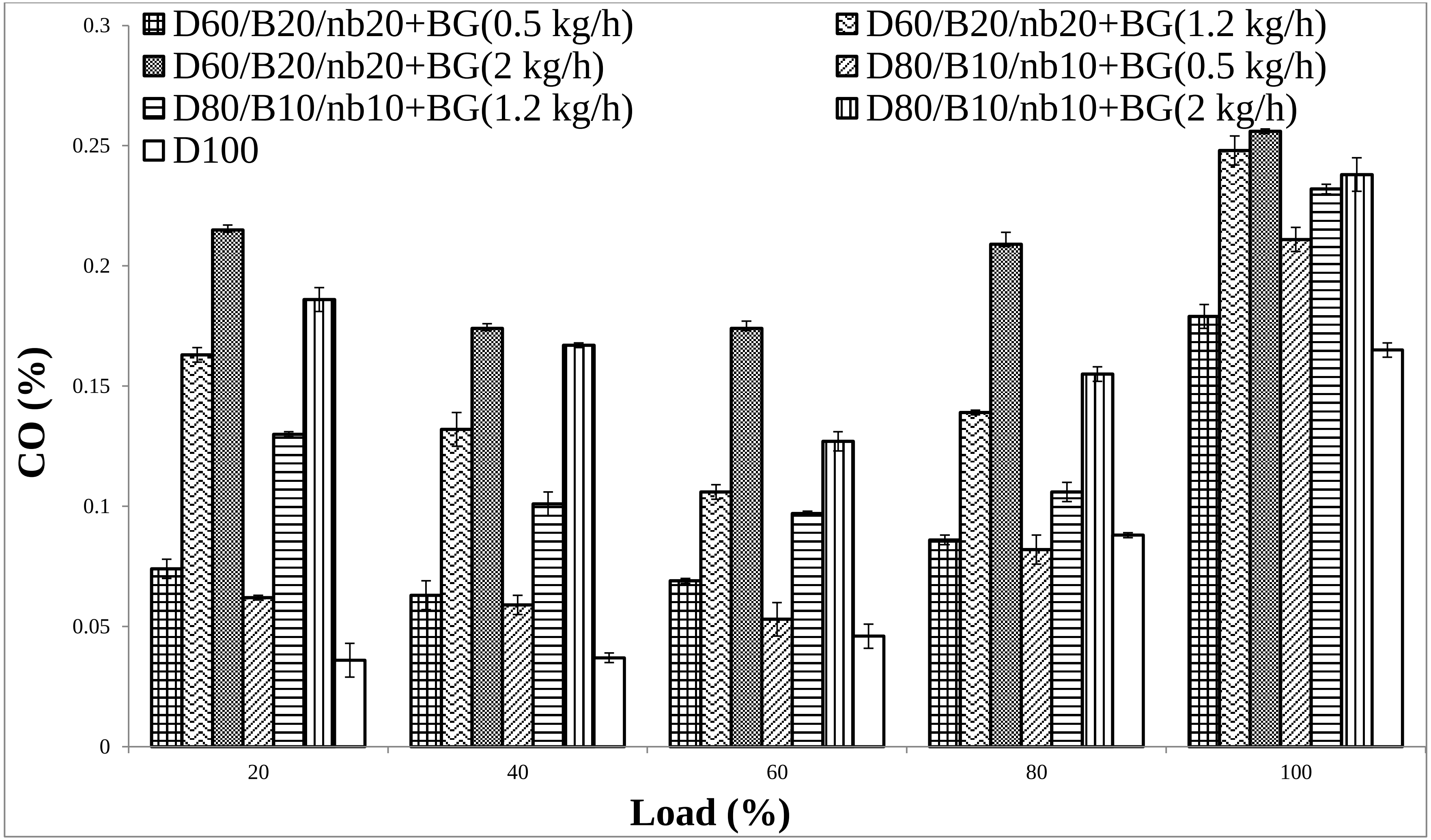

Figure 5.39 Variation of CO with engine load for diesel, biodiesel, biogas, and n-butanol (D60 and D80)

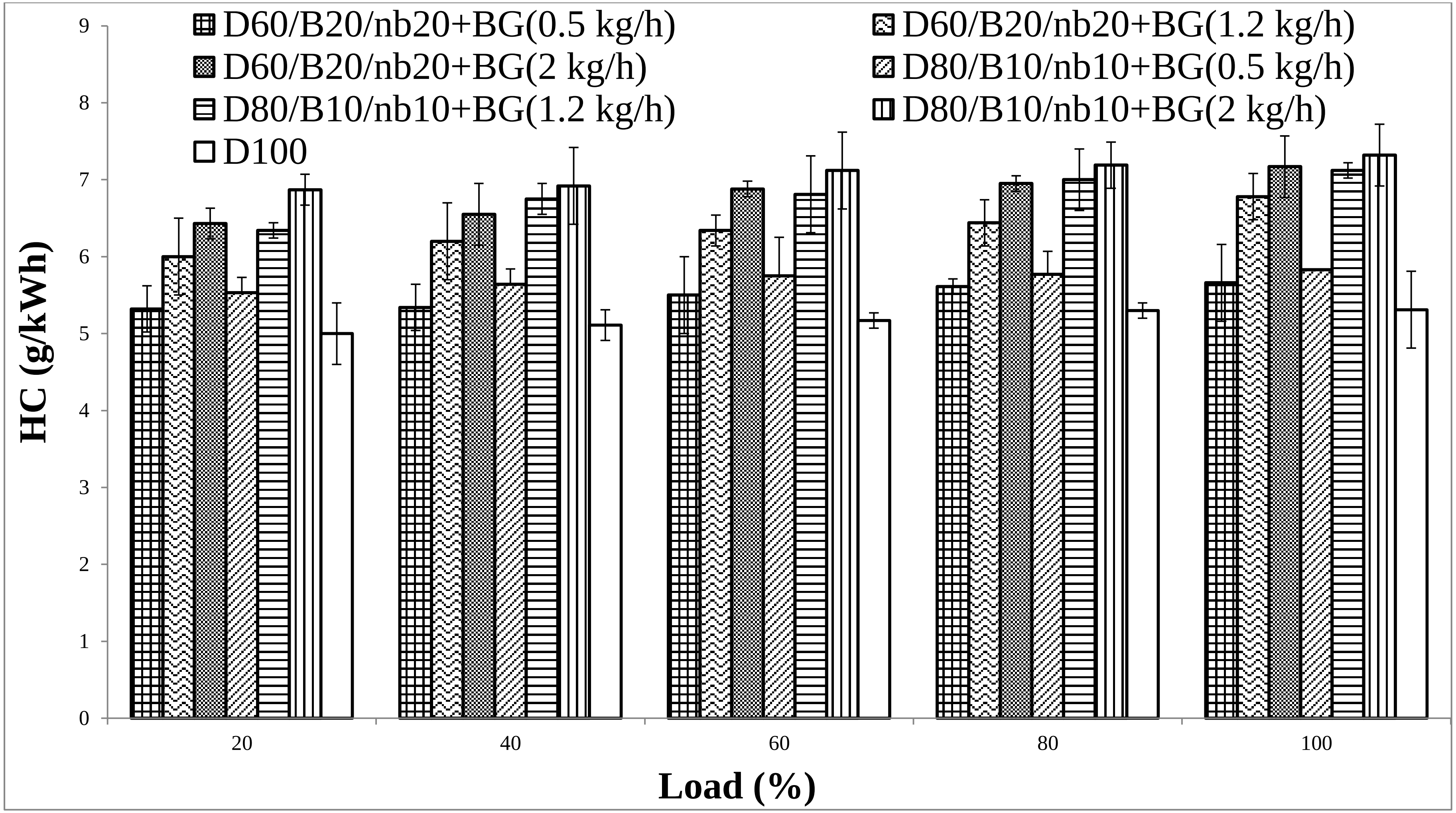

Figure 5.40 Variation of HC with engine load for diesel, biodiesel, biogas, and n-butanol (D60 and D80)

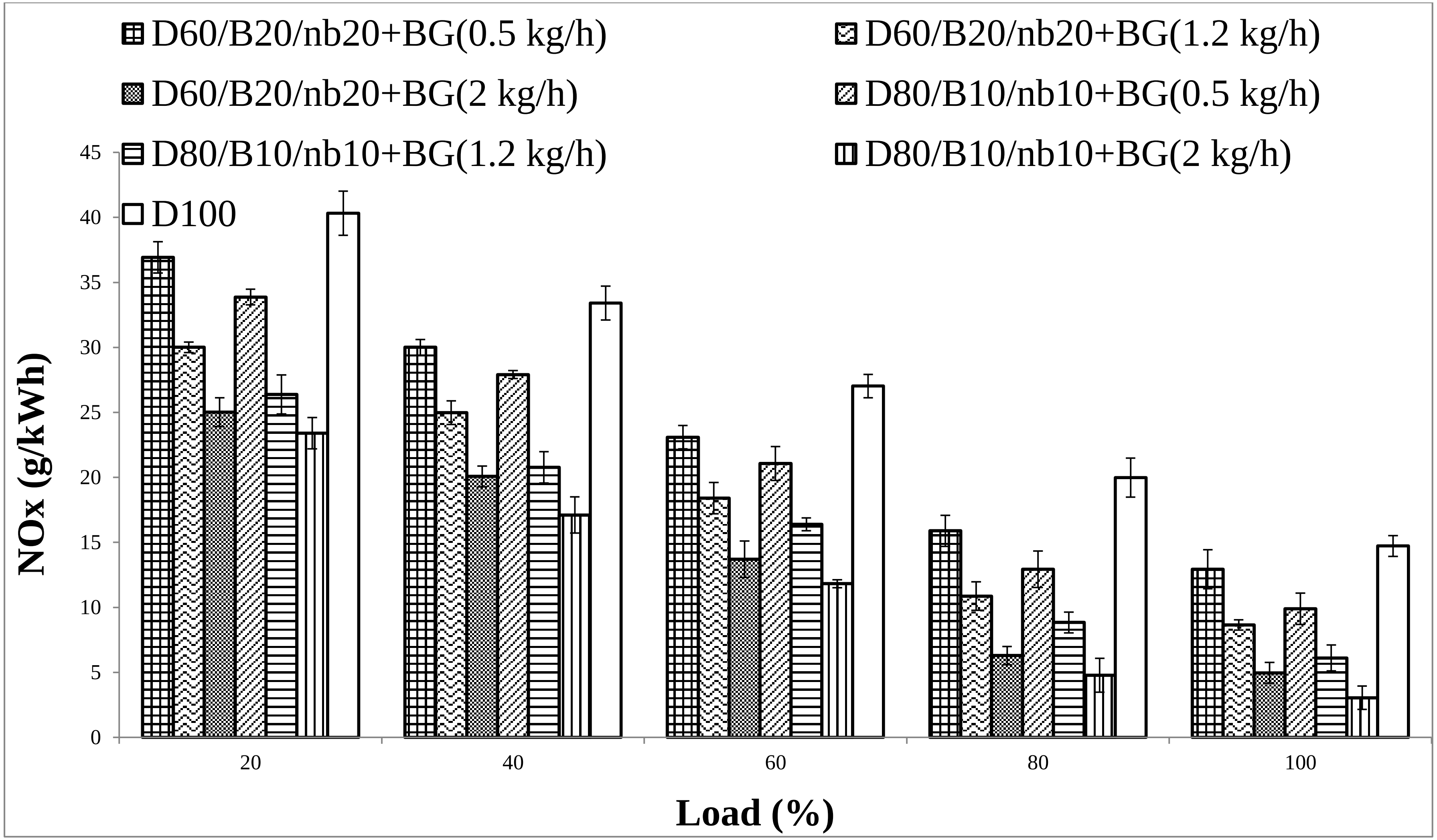

Figure 5.41 Variation of NOx with engine load for diesel, biodiesel, biogas, and n-butanol (D60 and D80)

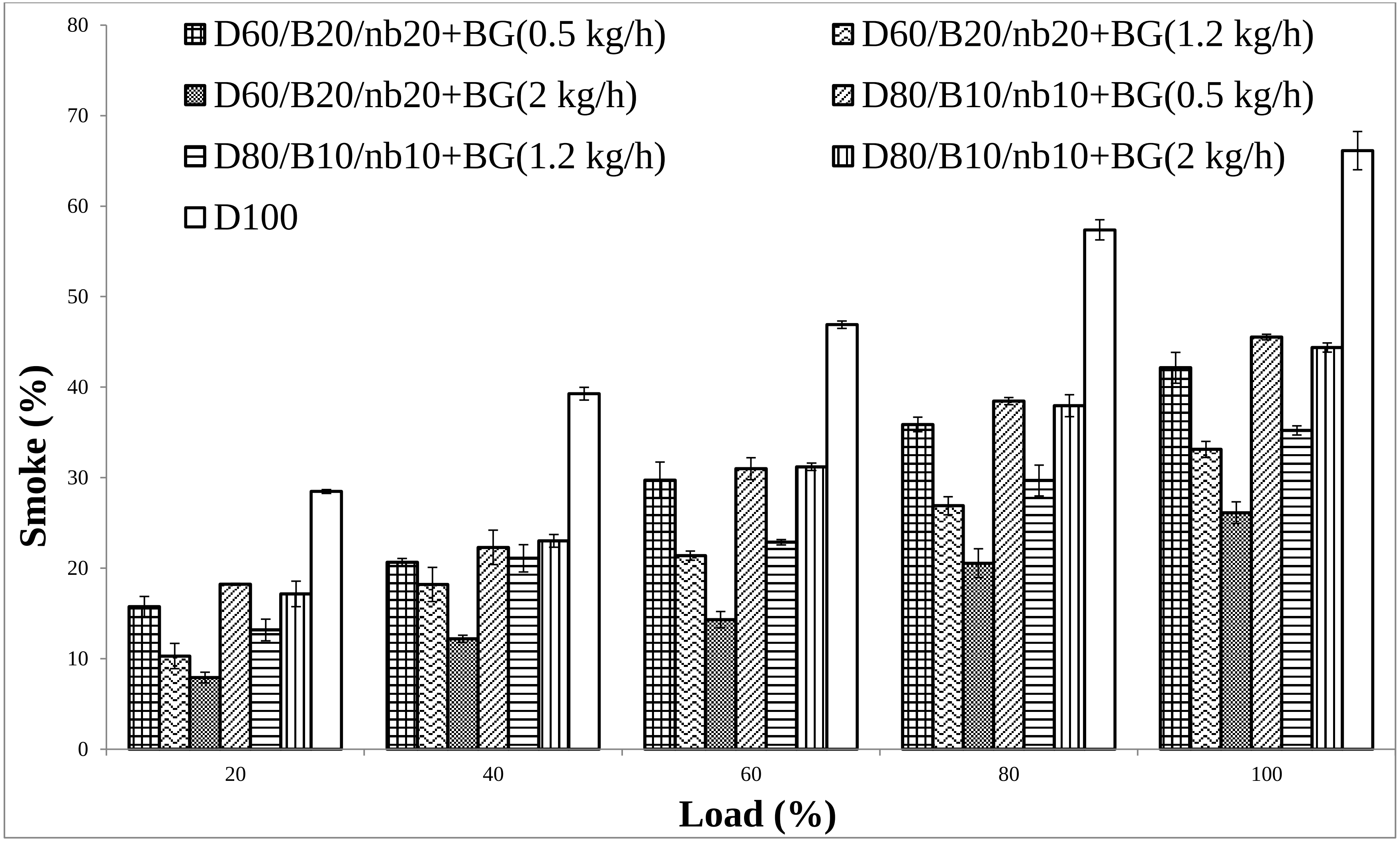

Figure 5.42 Variation of Smoke with engine load for diesel, biodiesel, biogas, and n-butanol ((D60 and D80)

5.9 Combination of Diesel, Biodiesel, Biogas, and n-butanol (D70)

Fuel combinations containing diesel, biodiesel, biogas, and n-butanol are used on the dual fuel engine in this section to find out the performance and emission characteristics of the engine. Performance and emission characteristics of the dual fuel engine for fuel combinations D70/B20/nb10+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D70/B10/nb20+BG(0.5 kg/h), D70/B10/nb20+BG(1.2 kg/h) and, D70/B10/nb20+BG(2 kg/h) are compared with fossil diesel. Afterwards, the bar graphs for performance and exhalation characteristics are plotted.

5.9.1 Variation of BSFC with engine load

Figure 5.43 illustrates variation of BSFC with engine load for fuel blends containing diesel, biodiesel and n-butanol, and using biogas as a primary fuel. It can be seen that with the increase in the engine load BSFC decreases. BSFC for all fuels used is higher in comparison with natural diesel. The separate impact of biodiesel, n-butanol and biogas also reports the same result and the reason for the same has already been discussed in previous section. Highest BSFC is achieved for D70/B20/nb10+BG(2 kg/h) and lowest for natural diesel. Best value of BSFC is noticed for D70/B20/nb10+BG(2 kg/h)at 20% load and least for raw diesel at 80% engine load. D70/B20/nb10+BG(0.5 kg/h) fuel blend have 22.5%, 18.3%, 22.8%, 28.6%, and 22.5% improved BSFC in relation with conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with a mediocre increment of 26.6%. It is reported that an enhancement of 26.5%, 26.3%, 26.5%, 30.8%, and 23.1% is obtained in BSFC for D70/B20/nb10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively correlated with traditional diesel. An average increment of 26.6% is noted. In relation with fossil diesel fuel blend D70/B20/nb10+BG(2 kg/h) is documented to have an increase of 27.6%, 29.5%, 29.3%, 35%, and 28% BSFC at engine loads varying in intervals of 20% each from 20% to 100% load respectively and have an average rise of 30%. D70/B10/nb20+BG(0.5 kg/h) fuel blend have 7.8%, 8.3%, 15.4%, 16.1%, and 8.6% augmenting BSFC than diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increase of 11.2%. It is noticed that an enhancement of

20.3%, 20.5%, 23.5%, 31.2%, and 22.3% is attained in BSFC for D70/B10/nb20+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively compared to diesel fuel. An average increment of 23.6% is documented. In comparison with baseline diesel, fuel blend D70/B10/nb20+BG(2 kg/h) is noticed to have enhanced BSFC of 24.5%, 23.5%, 28.3%, 32%, and 26.6% at engine loads varying in intervals of 20% each from 20% to 100% load respectively and have an average increment of 27.8%.

5.9.2 Variation of BTE with engine load

BTE of natural diesel is noted to be maximum relative to all other fuels tested in this section which can be clearly seen form deviation of BTE with the engine load as shown in Figure 5.44. BTE for separate effects of biodiesel, n-butanol and biogas on BTE of the engine are taken as allusion because BTE is lower for Diesel and biodiesel, Diesel and n-butanol, and Diesel and biogas except one fuel combination. Reason for lower BTE is same as mentioned in section 5.8.2. The maximum value of BTE is noted for D70/B20/nb10+BG(2 kg/h) and minimum for D70/B10/nb20+BG(0.5 kg/h) fuel blend. Amount of BTE for D70/B10/nb20+BG(1.2 kg/h) and D70/B10/nb20+BG(2 kg/h) fuel blends is very much similar for 20% engine load. Reduction of 11.2%, 12.3%, 2%, 4.9%, and 1.1% is noted in BTE at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D70/B20/nb10+BG(0.5 kg/h) fuel blend in comparison with pure diesel. An average reduction of 6.1% is recorded. Fuel blend D70/B20/nb10+BG(1.2 kg/h) has 10.3%, 13.8%, -5.4%, 0.1%, and -2.1% lesser BTE than fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deterioration of 2.1%. Relative to natural diesel, fuel blends D70/B20/nb10+BG(2 kg/h) has 5.2%, 11.5%, -7.5%, -0.6%, and -6.6% lesser BTE for engine load varying from 20% to 100% in intervals of 20% each respectively. 39.4%, 33.1%, 18.9%, 27.4%, and 25.1% reduced BTE is noted at the engine loads ranging from 20% to 100% load in intervals of 20% each respectively for D70/B10/nb20+BG(0.5 kg/h) fuel blend when related with raw diesel. An average decrement of 28.2% is noticed. Fuel blend D70/B10/nb20+BG(1.2 kg/h) has 40.4%, 30.8%, 10.4%, 20.9%, and 19.6% lower BTE relative to conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 24.6%. Compared to baseline diesel fuel blend D70/B10/nb20+BG(2 kg/h) has 40.4%, 30.3%, 14%, 22%, and 22.1% reduced BTE for engine load varying from 20% to 100% in intervals of 20% each respectively.

5.9.3 Variation of CO with engine load

CO exhalations are increased for all fuels tested in this part of the chapter in comparison with traditional diesel as depicted in Figure 5.45. Fuels incorporating biodiesel, n-butanol and biogas are having more value of CO emanations relative to natural diesel. Justification for increase in CO emanations has been conferred in preceding segment. CO emissions are found to be maximum for D70/B20/nb10+BG(2 kg/h) fuel blend and minimum for conventional diesel. Amount of CO emissions for fuel blend D70/B20/nb10+BG(0.5 kg/h) and diesel are very much similar at 100% engine load. 44.1%, 28.2%, 23.3%, -18.3%, and -3.8% enhanced CO emissions are recorded for D70/B20/nb10+BG(0.5 kg/h) fuel blend relative to pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average enhancement of 14.9%. The increment of 76.9%, 68.9%, 69.6%, 29.6%, and 25.4% is recorded in exhalations of CO for D70/B20/nb10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively when compared with conventional diesel. An average increase of 50.3% is noted. For D70/B20/nb10+BG(2 kg/h) increment of 82.2%, 77.7%, 70.5%, 55.8%, and 30.5% is noted at 20%, 40%, 60%, 80%, and 100% engine load respectively relative to traditional diesel. 48.9%, 43.2%, 25.2%, 11.3%, and 26.8% more CO emissions are noticed for D70/B10/nb20+BG(0.5 kg/h) fuel blend than pure diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average enhancement of 31.3%. Hike of 74.3%, 69.3%, 58.5%, 27.9%, and 34.8% is recorded in exhalations of CO for D70/B10/nb20+BG(1.2 kg/h)at the engine loads ranging from 20% to full load in intervals of 20% each respectively than baseline diesel. An average increase of 52.8% is reported. For D70/B10/nb20+BG(2 kg/h)enhancement of 81.6%, 79.8%, 65.7%, 48.2%, and 34.6% is recorded at 20%, 40%, 60%, 80%, and 100% engine load respectively relative to diesel fuel.

5.9.4 Variation of HC with engine load

Variation of HC exhalations with the engine is shown in Figure 5.46. It is found that HC exhalations enhanced with fuels incorporating biodiesel, n-butanol and biogas in relation with diesel. The separate effect of n-butanol and biogas on HC emissions also shows similar results. In section 5.8.4 reason for augmented emanations of HC for fuel matrix incorporating diesel, biodiesel, n-butanol and biogas has been clarified. Maximum HC exhalations are noticed for D70/B10/nb20+BG(2 kg/h) and minimum for fossil diesel. Best value of HC exhalations are noted for D70/B10/nb20+BG(2 kg/h) at 20% load and least for natural diesel at full engine load. D70/B20/nb10+BG(0.5 kg/h) fuel blend depicts 4.9%, 3.7%, 3%, 3.8%, and 5.1% extra HC exhalations than baseline diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average enhancement of 3.1%. An increase of 15.1%, 14.5%, 16.5%, 16.2%, and 17.7% is attained in HC emissions for D70/B20/nb10+BG(1.2 kg/h) at the engine loads ranging from 20% to full load in intervals of 20% each respectively correlated with diesel fuel. An average enhancement of 16.6% is recorded. Compared to pure diesel, fuel blend D70/B20/nb10+BG(2 kg/h) is noted to have enhancement of 20.7%, 20.8%, 21.2%, 22.2%, and 23.5% HC at engine loads varying in spells of 20% each from 20% to 100% load respectively and noted to have an average increment of 21.9%. D70/B10/nb20+BG(0.5 kg/h) fuel blend have 11.7%, 11.1%, 10.1%, 9.7%, and 11.3% enhanced HC emissions than raw diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with an average increase of 10.6%. A gain of 25.6%, 24%, 26.7%, 25.7%, and 25% is noticed in HC emissions for D70/B10/nb20+BG(1.2 kg/h)at the engine loads ranging from 20% to full load in spells of 20% each respectively relative to fossil diesel. An average enhancement of 24.6% is recorded. In relation to diesel, fuel blend D70/B10/nb20+BG(2 kg/h) have increment of 27.8%, 28.3%, 28.9%, 27.5%, and 27.2% HC emissions at engine loads varying in intervals of 20% each from 20% to 100% load respectively and have average hike of 27.3%.

5.9.5 Variation of NOx with engine load

Figure 5.47 depicts the deviation of NOx emanations with the engine load. Effect of biogas is more dominating over biodiesel and n-butanol and consequently NOx emissions decrease for fuels incorporating biodiesel, n-butanol, and biogas than diesel fuel. It is also observed that NOx emissions are on the lower side with the increase in the engine load. Insufficient supply of oxygen with biogas fuel may have dominated more over the higher amount of oxygen content in biodiesel and n-butanol which resulted in a decrement in NOx exhalations for D70/B20/nb10+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D70/B20/nb10+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h) and D70/B20/nb10+BG(2 kg/h) in comparison with ordinary diesel. Value of NOx emissions for D70/B20/nb10+BG(2 kg/h) fuel blend and D70/B10/nb20+BG(1.2 kg/h) fuel blend were almost alike at 100% engine loading conditions. D70/B20/nb10+BG(0.5 kg/h) fuel blend depicts 3.4%, -10.1%, -11.5%, -15.5%, and -7.2% lesser NOx emissions compared to fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of -8.1%. Loss of 20.5%, 10.2%, 7.9%, 7.6%, and 26.2% is noticed in NOx exhalations at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D70/B20/nb10+BG(1.2 kg/h) fuel blends relative to traditional diesel. An average reduction of 14.9% is achieved. For D70/B20/nb10+BG(2 kg/h) fuel blend a deterioration of 33.9%,25.8%, 25.2%, 31.4%, and 57.3% is recorded at engine loads varying from 20% to 100% at regular intervals of 20% each respectively than traditional diesel. D70/B10/nb20+BG(0.5 kg/h) fuel blend illustrates 30%, 36.4%, 52%, 500.2%, and 46.7% reduced NOx exhalations in relation with baseline diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 43.51%. The decrement of 50.5%, 67.8%, 69.3%, 59.7%, and 59.5% is noticed in NOx emissions at the engine loads ranging from 20% to full load conditions in intervals of 20% each respectively for D70/B10/nb20+BG(1.2 kg/h) fuel blends compared to natural diesel.

5.9.6 Variation of Smoke with engine load

Smoke denseness reduced radically for all fuels comprising biodiesel, n-butanol and biogas comparative to fossil diesel. Figure 5.48 depicts the deviation of smoke with the engine load which displays that smoke opacity increases with increase in engine load. Explanation for inferior smoke emissions of fuels comprising biodiesel, biogas, and n-butanol is debated in former division. Highest smoke emissions are noticed for natural diesel and least for fuel blend D70/B20/nb10+BG(2 kg/h) and least for natural diesel. The maximum value of smoke emissions is recorded for conventional diesel at 100% load and lowest for D70/B20/nb10+BG(2 kg/h) at 20% engine load. Deterioration of 27.6%, 24.4%, 23.6%, 36.4%, and 31.2% is attained in smoke opacity at the engine loads ranging from 20% to full load in spells of 20% each respectively for D70/B20/nb10+BG(0.5 kg/h) fuel blend as compared to fossil diesel. An average reduction of 26.4% is attained. Fuel blend D70/B20/nb10+BG(1.2 kg/h) shows 36.8%, 45.6%, 42.4%, 42.1%, and 46.9% reduced smoke exhalations relative to raw diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average reduction of 42.9%. For D70/B20/nb10+BG(2 kg/h) fuel blend deterioration of 57.2%, 63.9%, 56.4%, 54.1%, 55.5% is recorded than fossil diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 57%. Reduction of 46%, 53.2%, 52.9%, 45.9%, and 41.1% is illustrated in smoke opacity at the engine loads ranging from 20% to full load in intervals of 20% each respectively for D70/B10/nb20+BG(0.5 kg/h) fuel blend in comparison with pure diesel. An average decrement of 48.4% is noted. Fuel blend D70/B10/nb20+BG(1.2 kg/h) depicts 57.7%, 66.3%, 55.2%, 60.2%, and 55.7% lesser smoke emissions compared to conventional diesel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average deterioration of 58.2%. For D70/B10/nb20+BG(2 kg/h) fuel blend reduction of 46.7%, 56.4%, 50.4%, 45.8%, and 42.8% is noticed than diesel fuel at 20%, 40%, 60%, 80%, and 100% engine load respectively with average decrement of 48.2%.

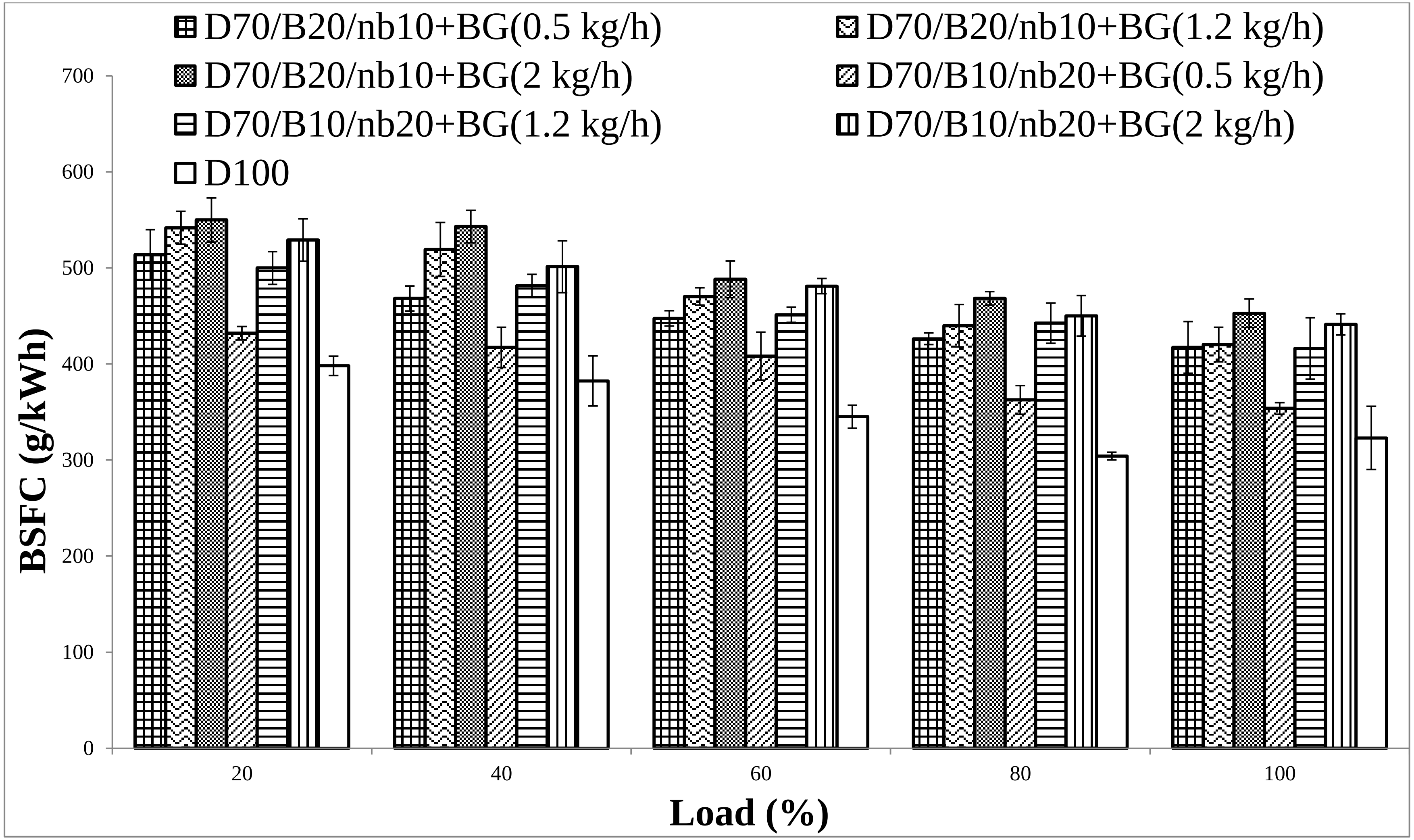

Figure 5.43 Variation of BSFC with engine load for diesel, biodiesel, biogas, and n-butanol (D70)

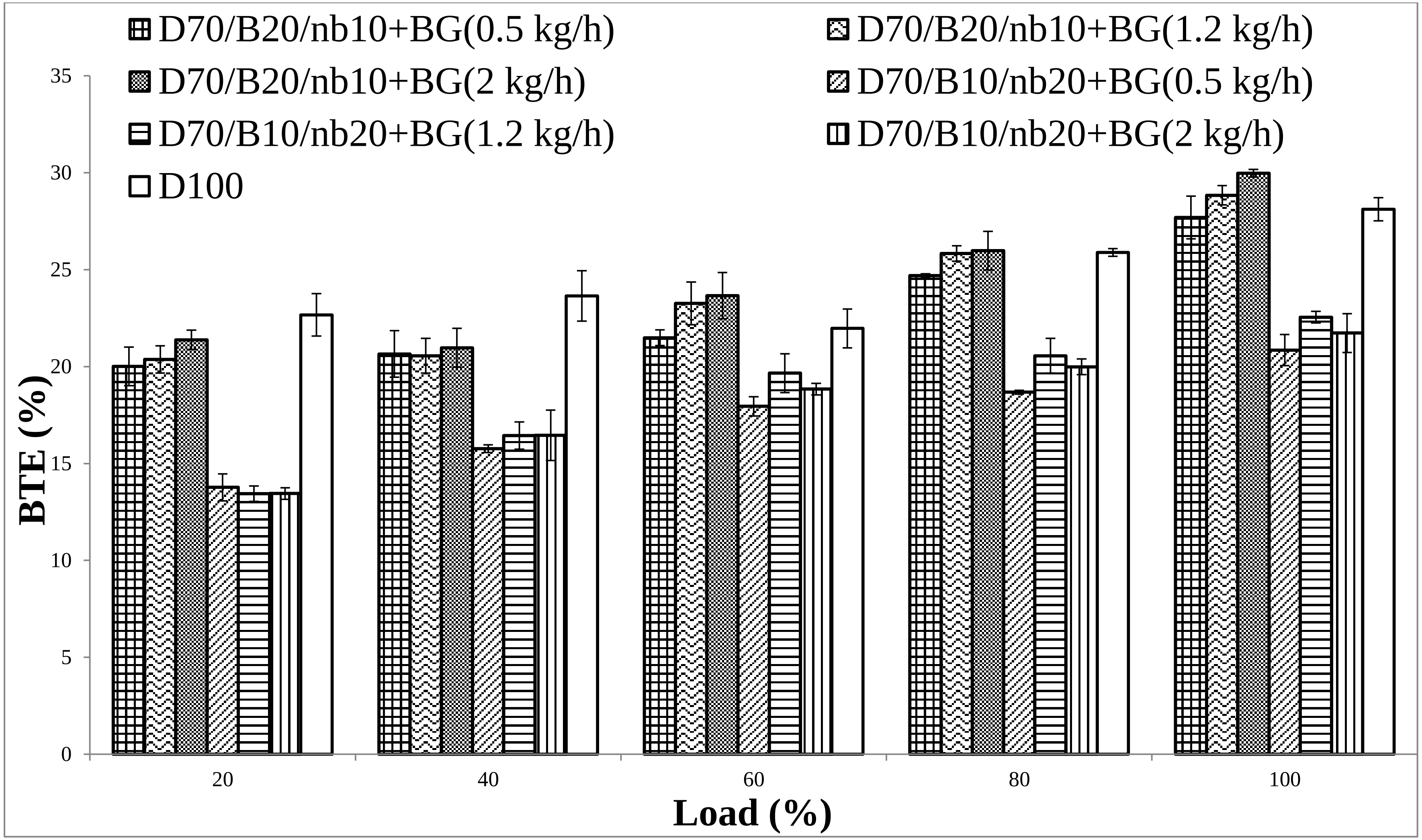

Figure 5.44 Variation of BTE with engine load for diesel, biodiesel, biogas, and n-butanol (D70)

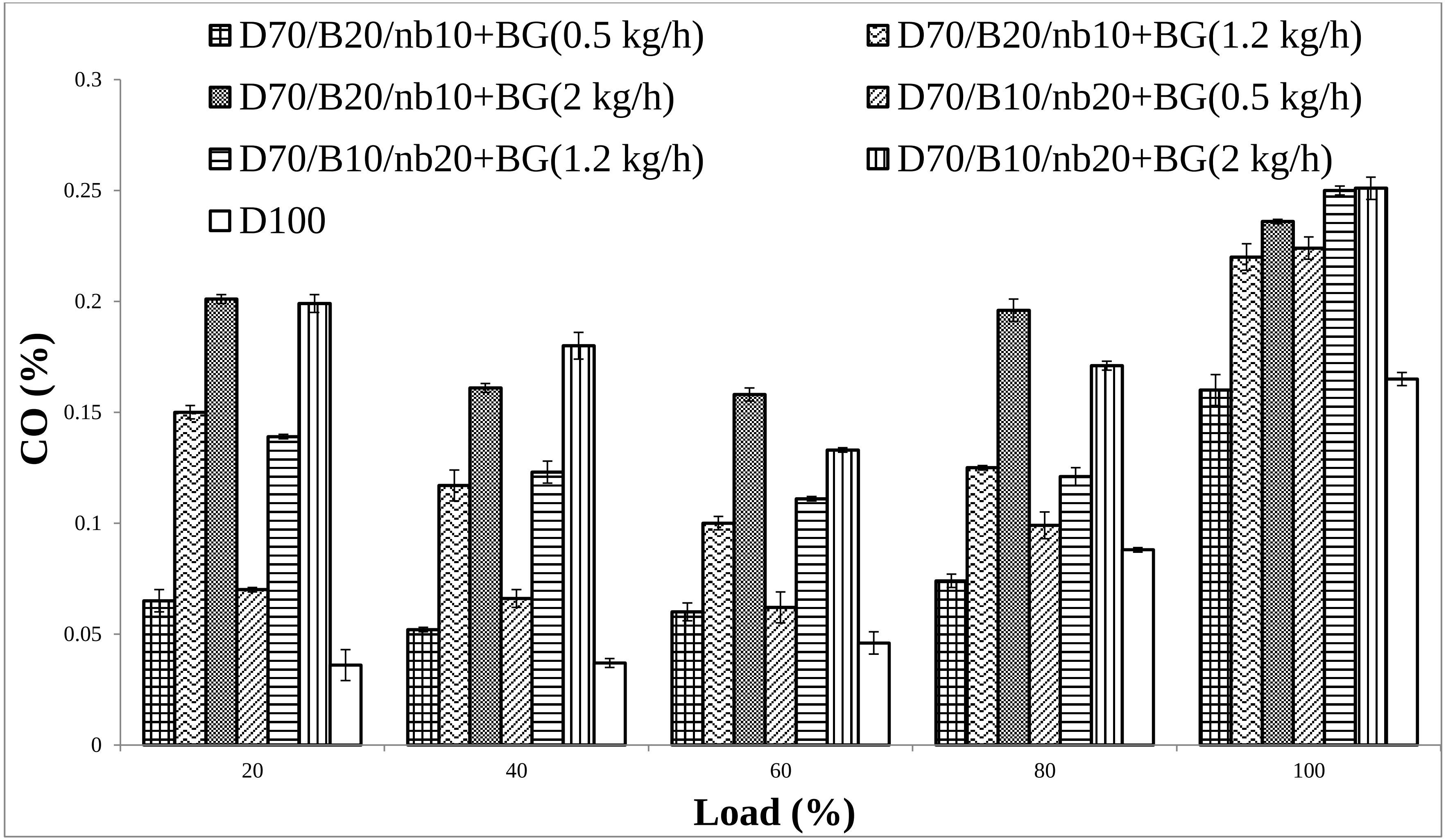

Figure 5.45 Variation of CO with engine load for diesel, biodiesel, biogas, and n-butanol (D70)

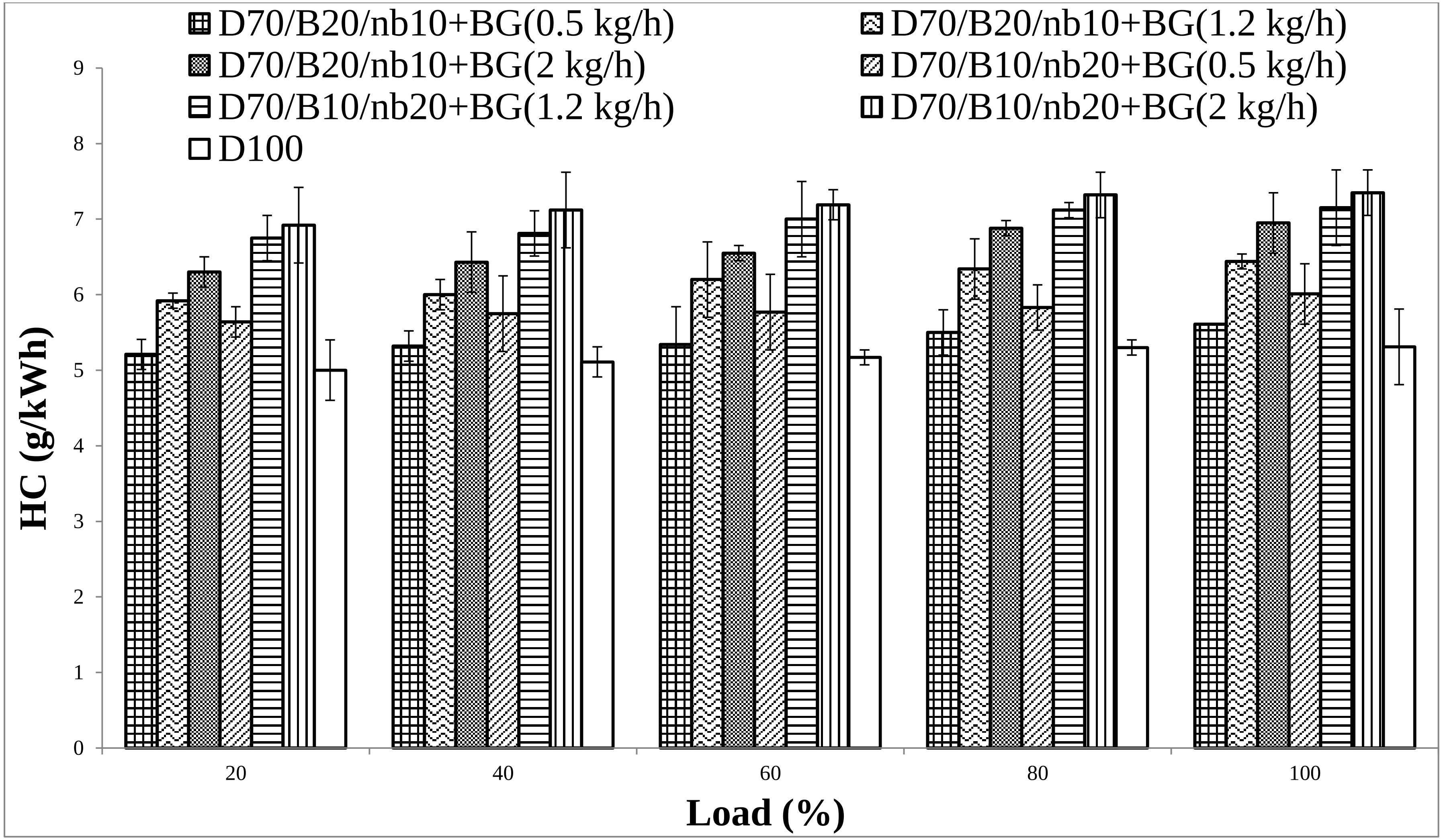

Figure 5.46 Variation of HC with engine load for diesel, biodiesel, biogas, and n-butanol (D70)

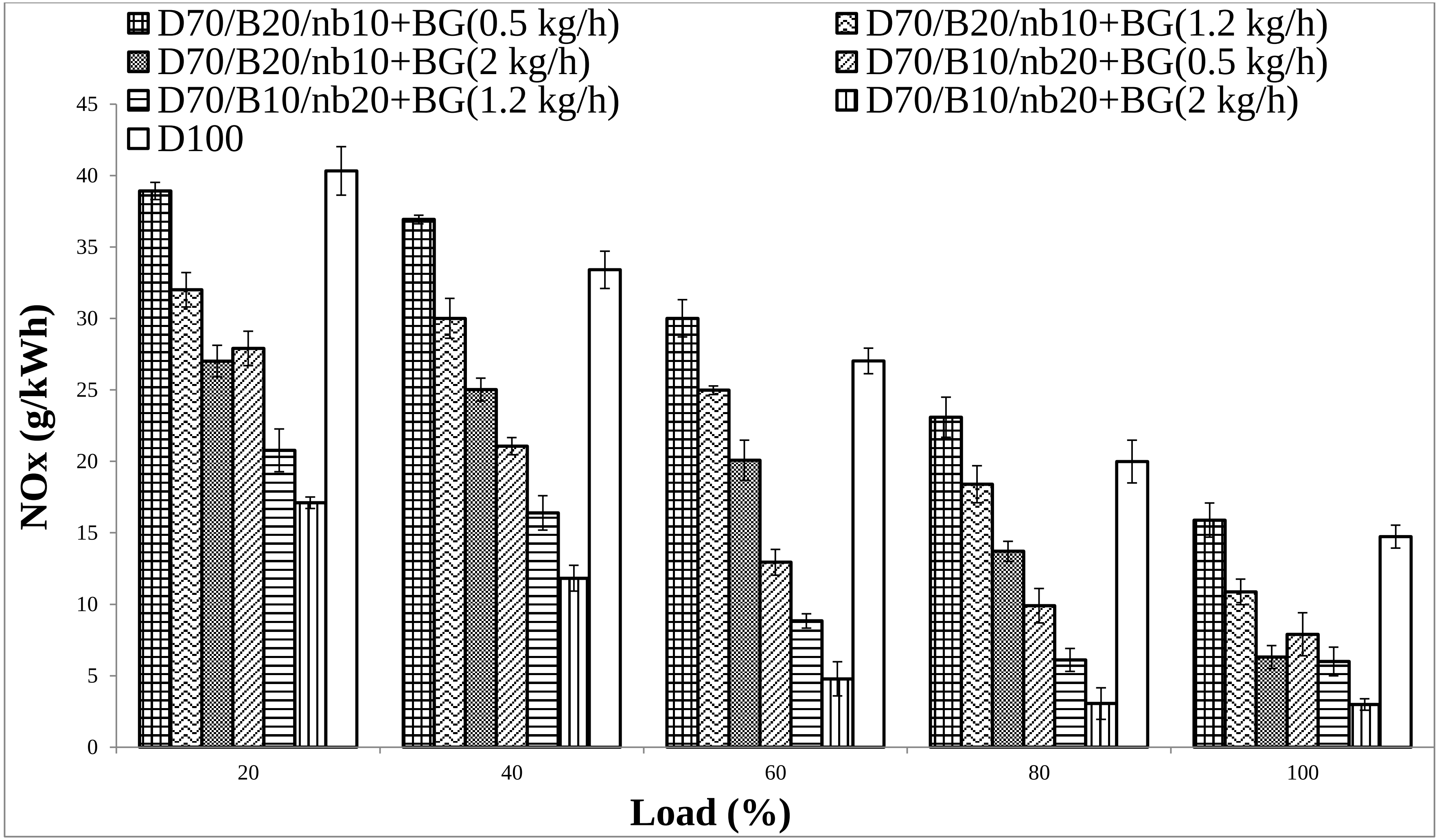

Figure 5.47 Variation of NOx with engine load for diesel, biodiesel, biogas, and n-butanol (D70)

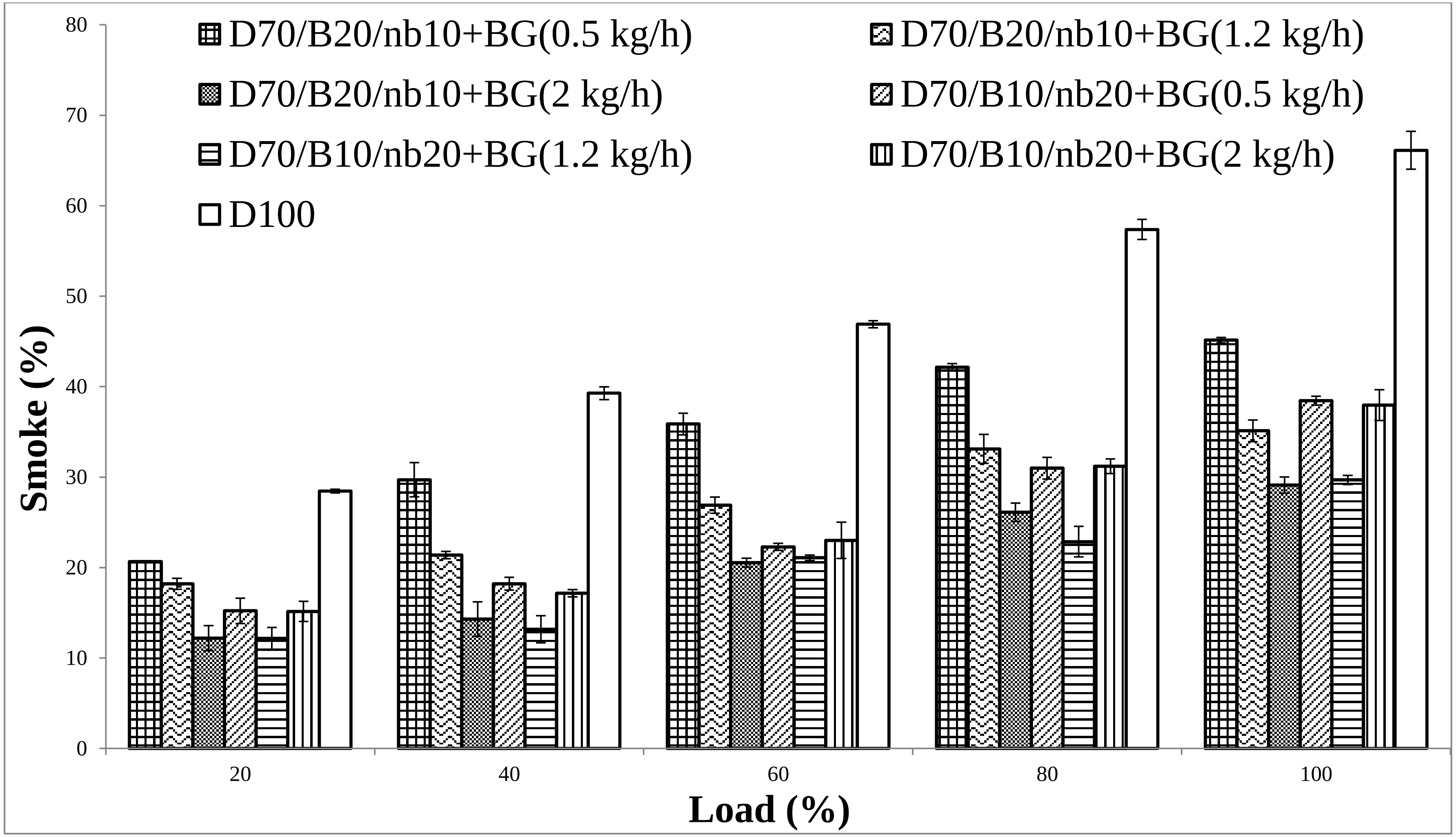

Figure 5.48 Variation of Smoke with engine load for diesel, biodiesel, biogas, and n-butanol (D70)

5.10 Stoichiometric Air-fuel ratio (λ)

Stoichiometric air-fuel ratio denoted by λ, is the ratio of air and fuel when the precise quantity of air is existent in the engine to burn the fuel entirely. This ratio is applied to establish the accurate ratio of air and fuel to be utilized in an engine to achieve improved mileage and a suitable lifespan for engine. A rich air fuel mixture is achieved when stoichiometric air-fuel ratio is lower i.e. more fuel is presented in comparison with air. This type of mixture provides great amount of power and is better for life of the engine but it is not cost-effective owing to the fact that a lot of fuel is burned in this progression. A lean air fuel mixture is attained when stoichiometric air-fuel ratio is higher i.e. less fuel is offered in relation with air. This type of mixture is cheap to run as it burns a smaller amount of fuel but consecutively their efficiency is on the lower side which can result in wear and tear of the engine. Ideally, this ratio will be presented independently for a stoichiometric mixture, which is a perfect mixture and practically this mixture has certainly not been developed for any machine till date. It is nearly impossible to attain the ideal ratio due to the fact that each combustion cycle in a diesel engine is very minute. Nevertheless, air-fuel ratios similar to it can be accomplished by amending the design of the engine and using appropriate admixtures and catalysts to regulate the pressure and temperature of the fuel. The stoichiometric air-fuel ratio of pilot fuel and primary fuel were calculated using AVL DIGAS 444 N gas analyzer. Figure 5.49 depicts the variation of stoichiometric air-fuel ratio at various engine loads. It can be established from the figure that stoichiometric air-fuel ratio was maximum for the diesel fuel in comparison with the dual fuel mode. The reason for this was that when pilot fuel alone was introduced in the combustion chamber more amount of air is achieved in relation with the dual fuel mode. When biogas was introduced inside the combustion chamber along with air, lesser quantity of air was available for the combustion process leading to lower stoichiometric air-fuel ratio as compared to diesel only mode. It was also evaluated that with increase in mass flow rate of biogas inside the combustion chamber along with air, the stoichiometric air-fuel ratio goes on decreasing. It was owing to the fact that ample amount of air was not allowed entering in the combustion chamber when biogas is introduced as pilot fuel. With increase in mass flow rate of biogas lesser amount of air was entering inside the combustion chamber and hence lower stoichiometric air-fuel ratio was achieved. Value of stoichiometric air-fuel ratio was also found to be decreasing with increasing engine load. It was attributed to the fact that at higher engine loads more quantity of pilot fuel enters inside the engine cylinder and hence lesser air is inducted, which leads to lower stoichiometric air-fuel ratio. In case of lower engine loads lesser amount of pilot fuel pass in the engine cylinder and therefore more amount of air is entered, subsequently higher value of stoichiometric air-fuel ratio is achieved. Highest value of stoichiometric air-fuel ratio was 4.7 for pure diesel at 20% engine load and lowest value was 1.93 for D100+BG(2 kg/h) at 100% engine load.

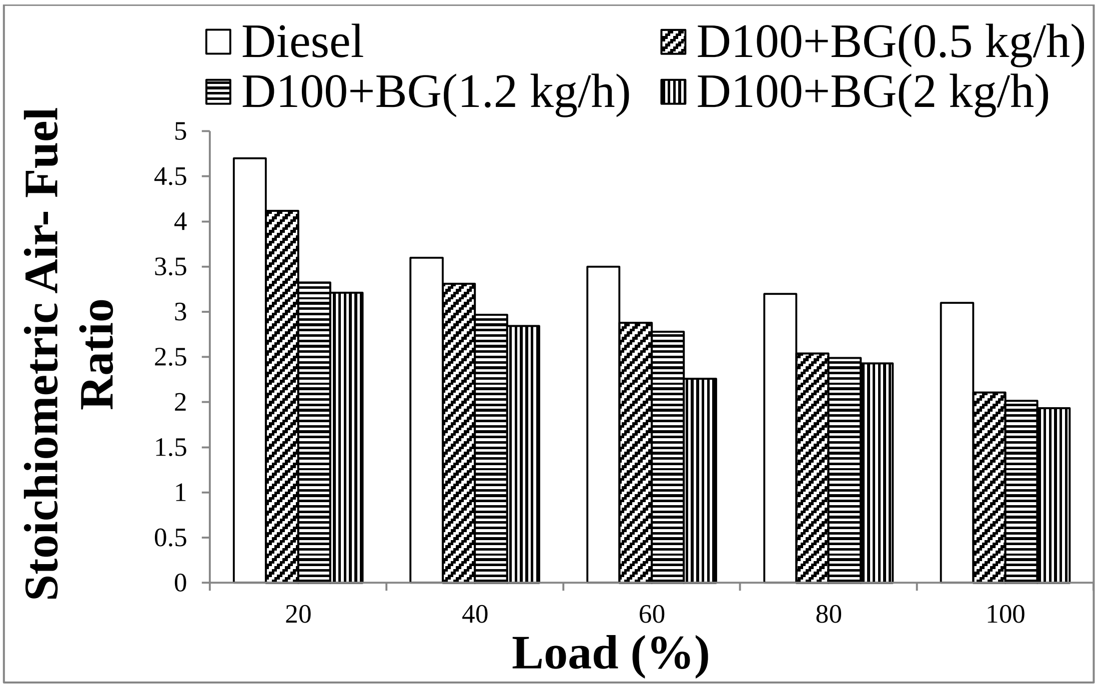

Figure 5.49 Deviation of Stoichiometric Air-fuel ratio share with engine load

5.11 Biogas energy share

The energy share of the pilot fuel and biogas at various flow rates of biogas i.e. 0.5 kg/h, 1.2 kg/h, and 2 kg/h is illustrated in Table 5.1. The energy share of the primary fuel is a vital consideration in dual fuel mode operation. Energy share of the primary fuel may be defined as the ratio of energy equivalent of the primary fuel, to the addition of the energy equivalent of the primary fuel and the pilot fuel. The energy is added by the primary fuel as well as the pilot fuel with the intention of producing a definite extent of power. The energy content and the consumption of fuel have a robust effect on the energy share. With the variation in load of the engine, the utilization of primary fuel does not alter, whereas the consumption of pilot fuel changes for the duration of combustion process.

The deviation of biogas energy share with the engine load is shown in Figure 5.49. For the entire range of biogas flow rates, the energy share of biogas was found to inversely proportional with engine load. It can be attributed to the fact that at high engine loads, more amount of pilot fuel is supplied to the combustion chamber as compared to low engine loads. Maximum amount of biogas energy share was 64.7 % for D100+BG(2 kg/h) at 20% engine load and minimum amount was 11.5% for D100+BG(0.5 kg/h) at full load. Values of 13.5%, 25.6%, and 43.9% was found for fuel combinations D100+BG(0.5 kg/h), D100+BG(1.2 kg/h), and D+100BG(2 kg/h) respectively at 80% engine load.

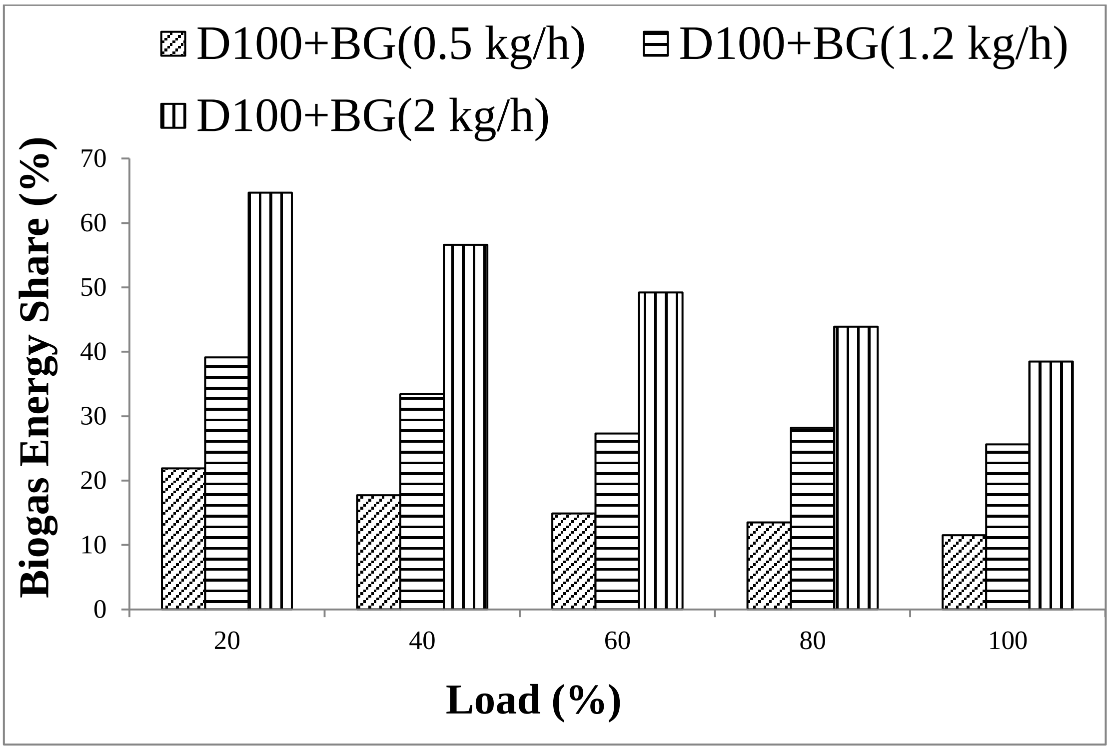

Figure 5.50 Deviation of biogas energy share with engine load

Table 5.1 Energy share of pilot fuel and biogas

Mode of operation	**Load (%)**	**Brake Power (kW)**	**Mass of pilot fuel (kg/h)**	**Mass of biogas (kg/h)**	**Energy equivalent of diesel (kW)**	**Energy equivalent of biogas, (kW)**	**Pilot fuel energy share (%)**	**Biogas energy share (%)**
Diesel	20	1.95	0.88	_	10.71	_	100	_
	40	3.07	1.15	_	13.99	_	100	_
	60	4.00	1.36	_	16.55	_	100	_
	80	4.43	1.49	_	18.13	_	100	_
	100	5.08	1.66	_	20.20	_	100	_
D100/BG (0.5 kg/h)	20	1.95	0.70	0.5	8.48	2.38	78.1	21.9
	40	3.07	0.91	0.5	11.06	2.38	82.3	17.7
	60	4.00	1.11	0.5	13.51	2.38	85.1	14.9
	80	4.43	1.25	0.5	15.20	2.38	86.5	13.5
	100	5.08	1.50	0.5	18.24	2.38	88.5	11.5
D100/BG (1.2 kg/h)	20	1.95	0.73	1.2	8.90	5.73	60.9	39.1
	40	3.07	0.94	1.2	11.40	5.73	66.6	33.4
	60	4.00	1.25	1.2	15.20	5.73	72.7	27.3
	80	4.43	1.20	1.2	14.59	5.73	71.8	28.2
	100	5.08	1.36	1.2	16.58	5.73	74.4	25.6
D100/BG (2 kg/h)	20	1.95	0.43	2	5.21	9.55	35.3	64.7
	40	3.07	0.60	2	7.30	9.55	43.4	56.6
	60	4.00	0.81	2	9.86	9.55	50.8	49.2
	80	4.43	1.00	2	12.16	9.55	56.1	43.9
	100	5.08	1.25	2	15.20	9.55	61.5	38.5

5.12 Comparison of performance and emission characteristics for all test fuels at full load

In this segment of the chapter the performance and emission characteristics of the engine are compared for all the test fuels at 100% engine load. BSFC, BTE, CO emanations, HC emissions, NOx exhalations, and smoke opacity of all the test fuels were compared separately.

5.12.1 Comparison of BSFC for all test fuels at full load

Figure 5.50 illustrates comparison of BSFC for all test fuels at 100% load. Minimum amount of BSFC was found for the conventional diesel relative to all other combination of fuels used in the research work. Value of D90/B10+BG(0.5 kg/h) was very much alike to the traditional diesel. Maximum value of BSFC was calculated for D100+BG(2 kg/h) followed by D60/B20/nb20+BG(2 kg/h), D60/B20/nb20, D80/nb20+BG(2 kg/h), D70/B20/nb10+BG(2 kg/h), D80/nb20+BG(1.2 kg/h), D70/B10/nb20+BG(2 kg/h), D60/B20/nb20+BG(1.2 kg/h), D80/B10/nb10, D+BG(1.2 kg/h), D60/B20/nb20+BG(0.5 kg/h), D80/B10/nb10+BG(2 kg/h), D80/B20+BG(1.2 kg/h), D70/B20/nb10+BG(1.2 kg/h), D90/nb10+BG(2 kg/h), D90/nb10+BG(1.2 kg/h), D70/B20/nb10+BG(0.5 kg/h), D70/B10/nb20+BG(1.2 kg/h), D80/nb20+BG(0.5 kg/h), D90/B10+BG(2 kg/h), D80/B10/nb10+BG(1.2 kg/h), D90/B10+BG(1.2 kg/h), D80/nb20, D80/B20+BG(0.5 kg/h), D80/B20, D100+BG(0.5 kg/h), D90/nb10, D80/B10, D80/B10/nb10+BG(0.5 kg/h), D90/nb10+BG(0.5 kg/h), D70/B10/nb20+BG(0.5 kg/h), D90/B10+BG(0.5 kg/h), and Diesel.

5.12.2 Comparison of BTE for all test fuels at full load

The comparison of BTE among all the utilized test fuels is depicted in Figure 5.51. Majority of test fuels were found to have values of BTE lower than natural diesel whereas few combinations of test fuels were having exceeded value of BTE in relation with fossil diesel. D60/B20/nb20+BG(1.2 kg/h) and D60/B20/nb20+BG(0.5 kg/h) were having values of BTE very near to diesel fuel. D100+BG(2 kg/h) was recognized to have least value of BTE and D70/B20/nb10+BG(2 kg/h) was having highest value. D60/B20/nb20+BG(0.5 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), D90/nb10+BG(2 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/nb20+BG(0.5 kg/h), D80/nb20BIO(1.2), D70/B20/nb10+BG(0.5 kg/h), D80/nb20BIO(2), D70/B20/nb10+BG(1.2 kg/h), and D70/B20/nb10+BG(2 kg/h) test fuels were found to have more value than natural diesel in increasing order. Test fuels D80/B10/nb10+BG(1.2 kg/h), D90/B10, D80/B10/nb10+BG(2 kg/h), D80/B20, D80/B10/nb10+BG(0.5 kg/h), D80/B20+BG(0.5 kg/h), D90/B10+BG(0.5 kg/h), D80/B10/nb10, D/B20+BG(1.2 kg/h), D60/B20/nb20, D100+BG(0.5 kg/h), D80/nb20, D90/B10+BG(1.2 kg/h), D90/nb10, D80/B20+BG(2 kg/h), D90/B10+BG(2 kg/h), D100+BG(1.2 kg/h), and D100+BG(2 kg/h) possessed less value of BTE in comparison with pure diesel in increasing trend.

5.12.3 Comparison of CO for all test fuels at full load

In Figure 5.52 the comparison of CO for all the test fuels is shown at full load conditions. It was found that most of the tested fuels were having lesser value of CO emanations as compared to conventional diesel. Fuel combinations comprising of diesel and biogas were recorded increased amount of CO emanations relative to fossil diesel. Amount of CO exhalations for fuel combination D100+BG(0.5 kg/h) was almost equal to natural diesel. Highest amount of CO emissions were noted for D100+BG(2 kg/h) fuel combination and leaset value was found for D70/B20/nb10+BG(0.5 kg/h). Fuel combinations D90/B10, D80/nb20, D80/B20, D80/nb20+BG(2 kg/h), D90/nb10, D60/B20/nb20+BG(2 kg/h), D80/nb10+BG(2 kg/h), D80/nb20+BG(1.2 kg/h), D70/B10/nb20+BG(2 kg/h), D90/B10+BG(2 kg/h), D80/B10/nb10+BG(2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(1.2 kg/h), D80/B20/nb10+BG(1.2 kg/h), D80/B20+BG(1.2 kg/h), D80/B10/nb10, D70/B20/nb10+BG(1.2 kg/h), D60/B20/nb20, D80/B10/nb10+BG(0.5 kg/h), D90/B10+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D90/nb10+BG(0.5 kg/h), D80/B20+BG(0.5 kg/h), and D70/B20/nb10+BG(0.5 kg/h)were noted to have decreased value of CO exhalations as compared to diesel in decreasing order.

5.12.4 Comparison of HC for all test fuels at full load

Figure 5.53 illustrates the assessment of HC emissions for all the test fuels at full engine load. HC exhalations were reported to be more for all the test fuels in comparison with pure diesel except D80/B20, D80/B10/nb10, and D90/B10. Extreme amount of HC emanations were found to be for D100+BG(2 kg/h) and minutest for D80/B20 fuel blend. D90/nb10, D80/nb20, D70/B20/nb10+BG(0.5 kg/h), D80/B20+BG(0.5 kg/h), D60/B20/nb20BIO(0.5), D90/B10+BG(0.5 kg/h), D80/B10/nb10+BG(0.5 kg/h), D60/B20/nb20, D90/nb10+BG(0.5 kg/h), D70/B10/nb20+BG(0.5 kg/h), D100+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h), D80/B20+BG(1.2 kg/h), D60/B20/nb20+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D90/B10+BG(1.2 kg/h), D80/B10/nb10+BG(1.2 kg/h), D90/nb10+BG(1.2 kg/h), D70/B10/nb20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/nb20+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D80/B10/nb10+BG(2 kg/h), D70/B10/nb20+BG(2 kg/h), D90/nb10+BG(2 kg/h), D100+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), and D100+BG(2 kg/h) were found to have more value of HC exhalations in relation to natural diesel in increasing trend.

5.12.5 Comparison of NOx for all test fuels at full load

Comparison of NOx emissions at full loading conditions for all the test fuels is illustrated in Figure 5.54. D90/B10+BG(0.5 kg/h), D80/B20+BG(0.5 kg/h), D60/B20/nb20+BG(0.5 kg/h), D90/nb10, D80/B10/nb10, D/B20+BG(1.2 kg/h), D100+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), D100+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D80/nb20, D70/B20/nb10+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D60/B20/nb20, D80/B10/nb10+BG(0.5 kg/h), D90/nb10+BG(0.5 kg/h), D100+BG(2 kg/h), D80/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(1.2 kg/h), D70/B10/nb20+BG(0.5 kg/h), D70/B20/nb10+BG(2 kg/h), D80/B10/nb10+BG(1.2 kg/h), D70/B10/nb20+BG(1.2 kg/h), D90/nb10+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D60/B20/nb20+BG(2 kg/h), D90/nb10+BG(2 kg/h), D80/B10/nb10+BG(2 kg/h), and D70/B10/nb20+BG(2 kg/h) test fuels were having lesser NOx emissions than conventional diesel in declining trend.

5.12.6 Comparison of smoke opacity for all test fuels at full load

Figure 5.55 depicts comparison of smoke opacity for all test fuels at full loading conditions in comparison with natural diesel. It can be seen that more than half of the tested fuels were having reduced exhalations of smoke than traditional diesel. Highest amount of smoke opacity was noted for D90/B10+BG(0.5 kg/h) and lowest for

D80/B20nb20BIO(2). In relation with fossil diesel, test fuels D90/B10+BG(0.5 kg/h), D80/B20+BG(0.5 kg/h), D90/nb10+BG(0.5 kg/h), D80/B10nb10+BG(0.5 kg/h), D100+BG(0.5 kg/h), D70/B20/nb10+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D80/B10nb10+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D60/B20/nb20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), and D100+BG(1.2 kg/h) were found to have greater value of smoke opacity in decreasing order. D60/B20/nb20+BG(2 kg/h), D80/nb20+BG(2 kg/h), D60/B20/nb20, D80/nb20, D80/B10/nb10, D100+BG(2 kg/h), D60/B20/nb20+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D70/B10/nb20+BG(1.2 kg/h), D80/B20, D80/B20+BG(2 kg/h), D90/nb10, D70/B20/nb10+BG(1.2 kg/h), D80/B10/nb10+BG(1.2 kg/h), D80/nb20+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D90/B10, D90/nb10+BG(1.2 kg/h), D70/B10/nb20+BG(2 kg/h), and D70/B10/nb20+BG(0.5 kg/h), test fuels were recorded to have reduced smoke emanations than diesel in increasing order.

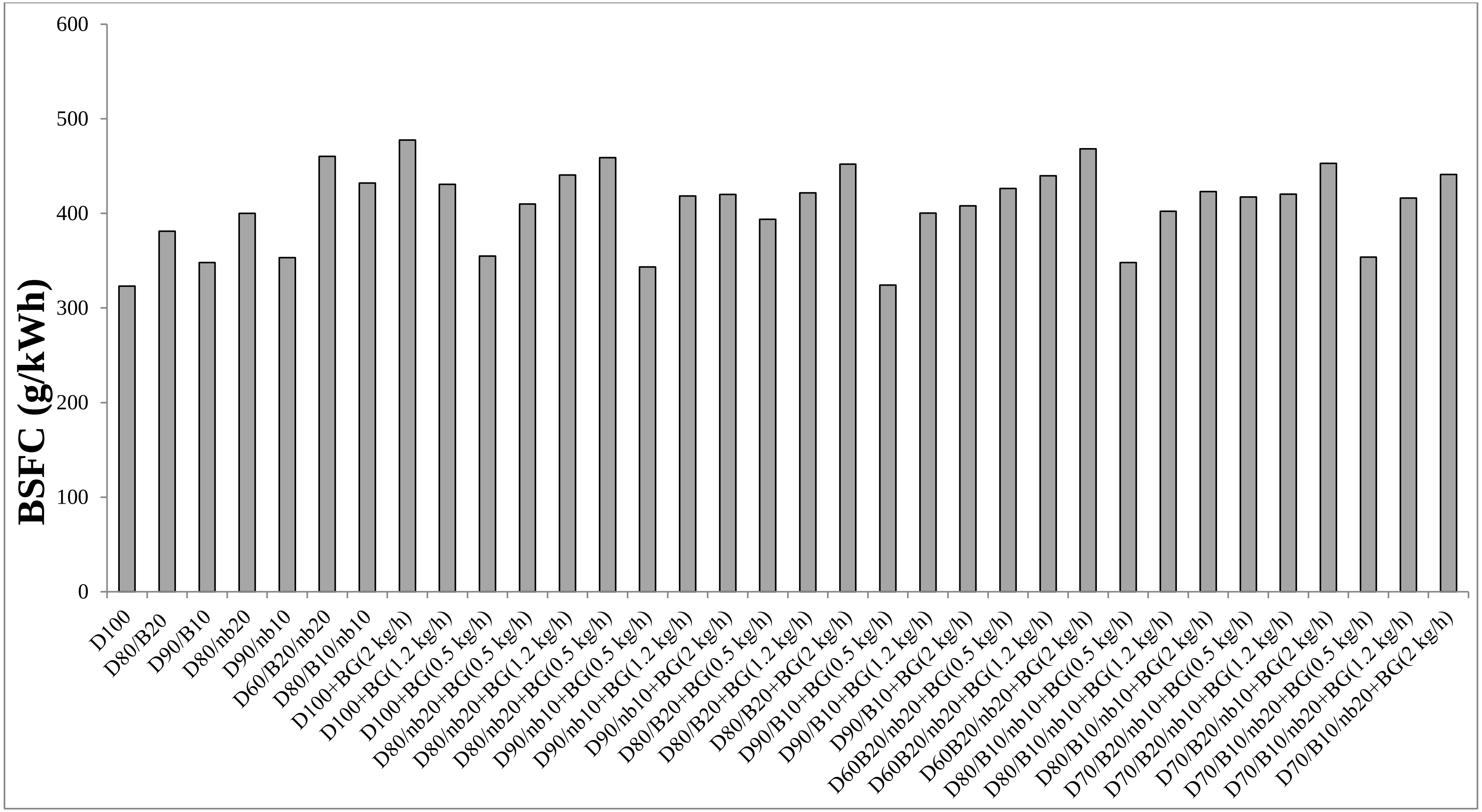

Figure 5.51 Comparison of BSFC for all test fuels at full load

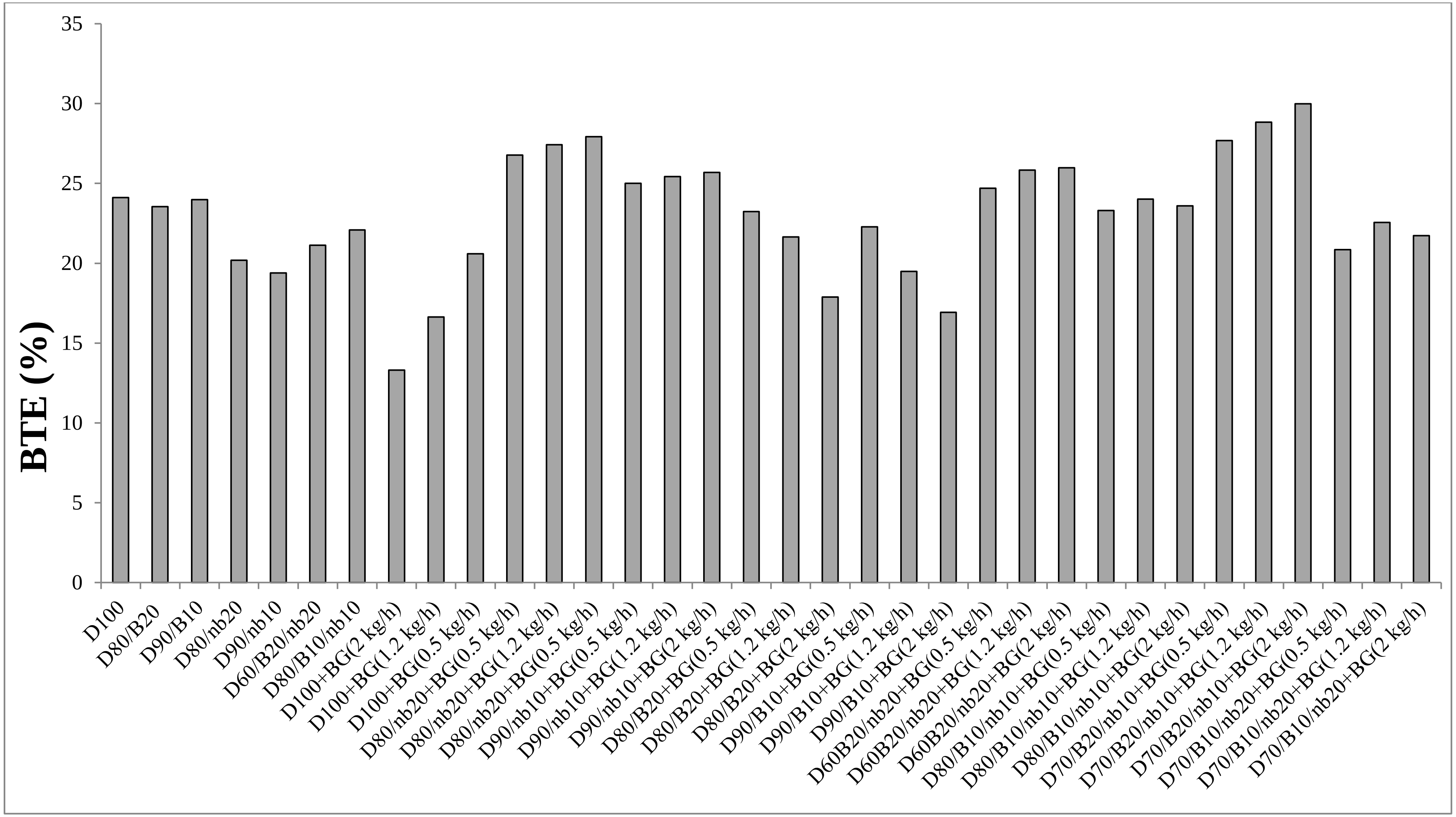

Figure 5.52 Comparison of BTE for all test fuels at full load

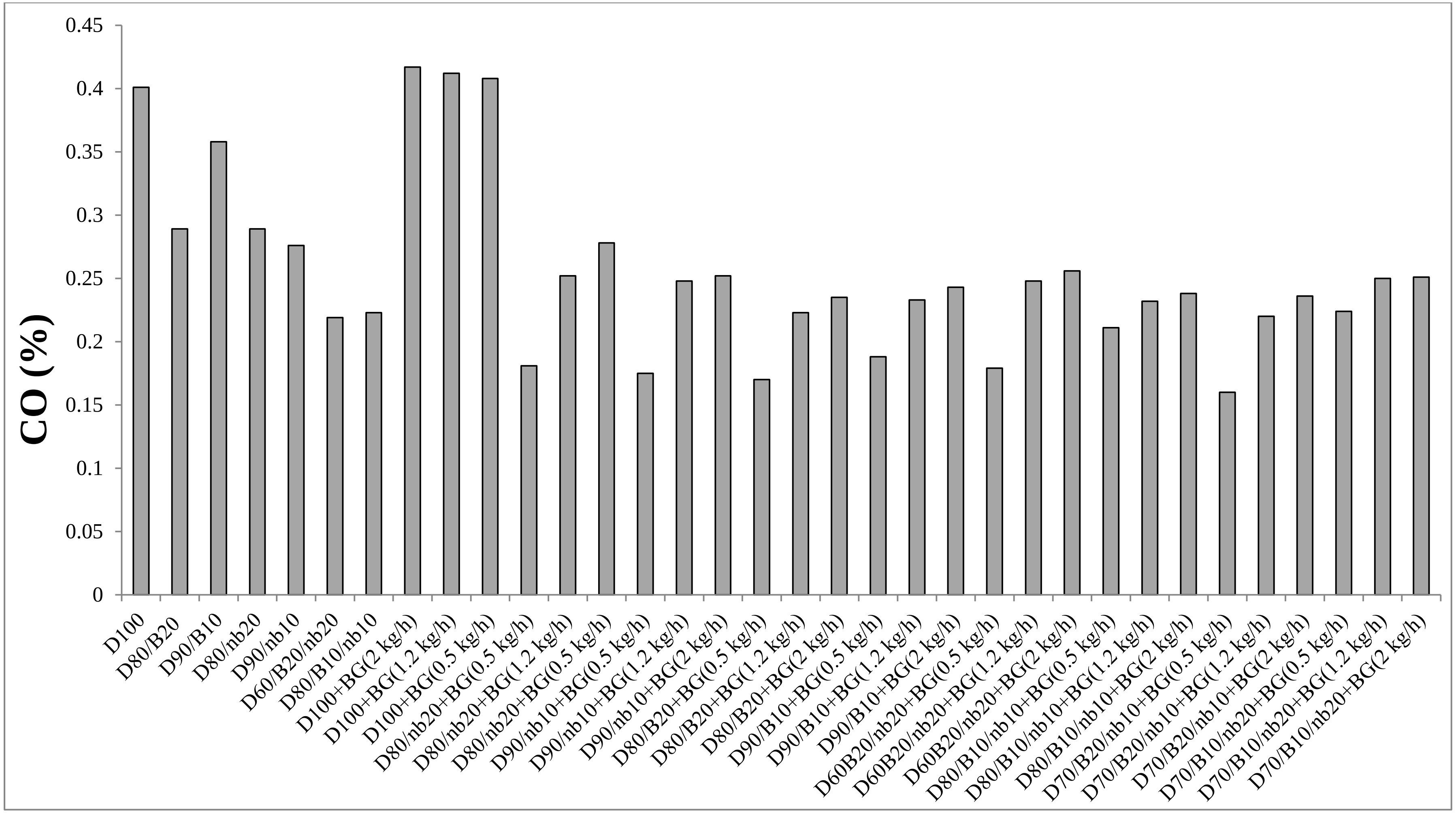

Figure 5.53 Comparison of CO for all test fuels at full load

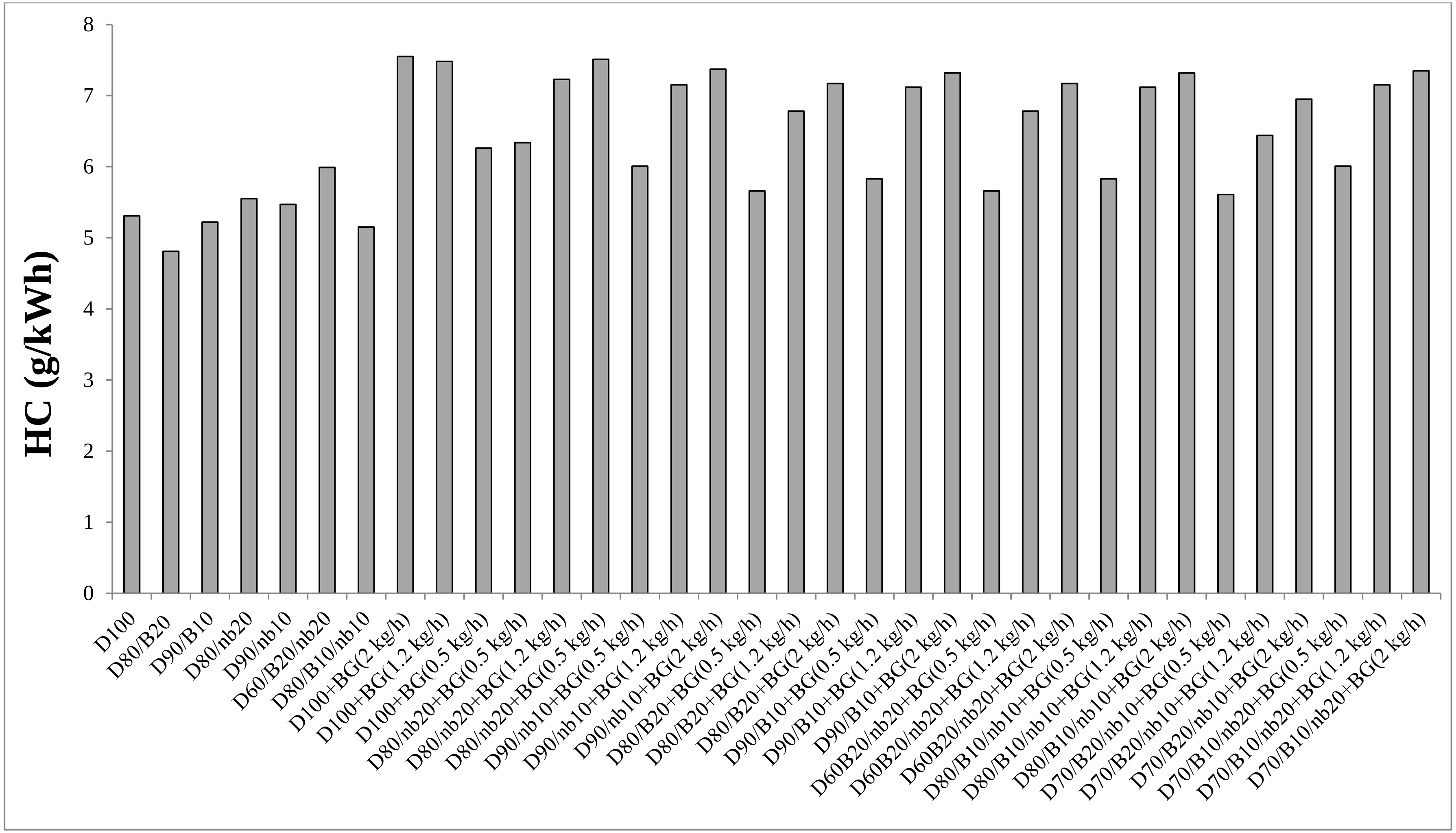

Figure 5.54 Comparison of HC for all test fuels at full load

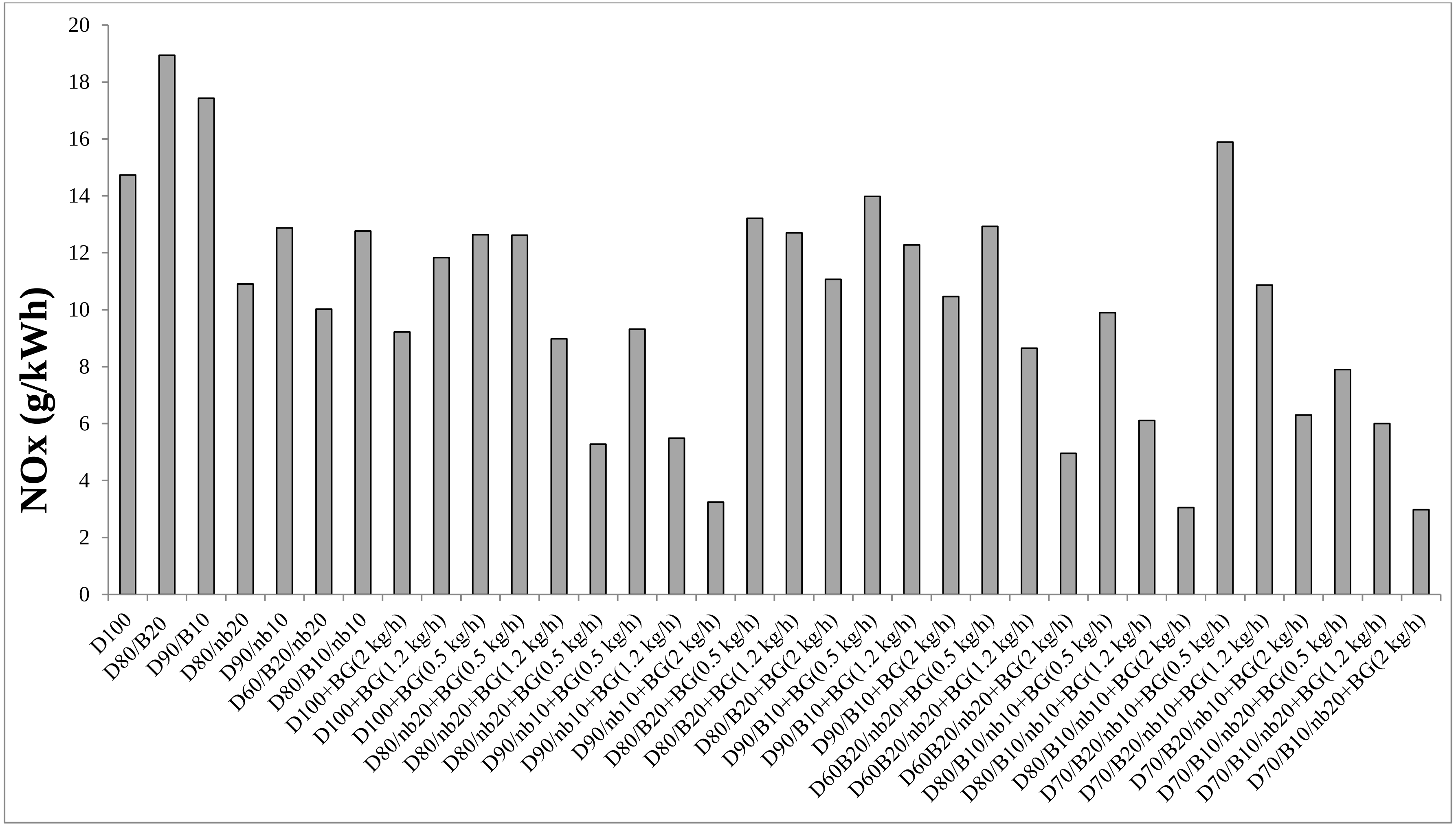

Figure 5.55 Comparison of NOx for all test fuels at full load

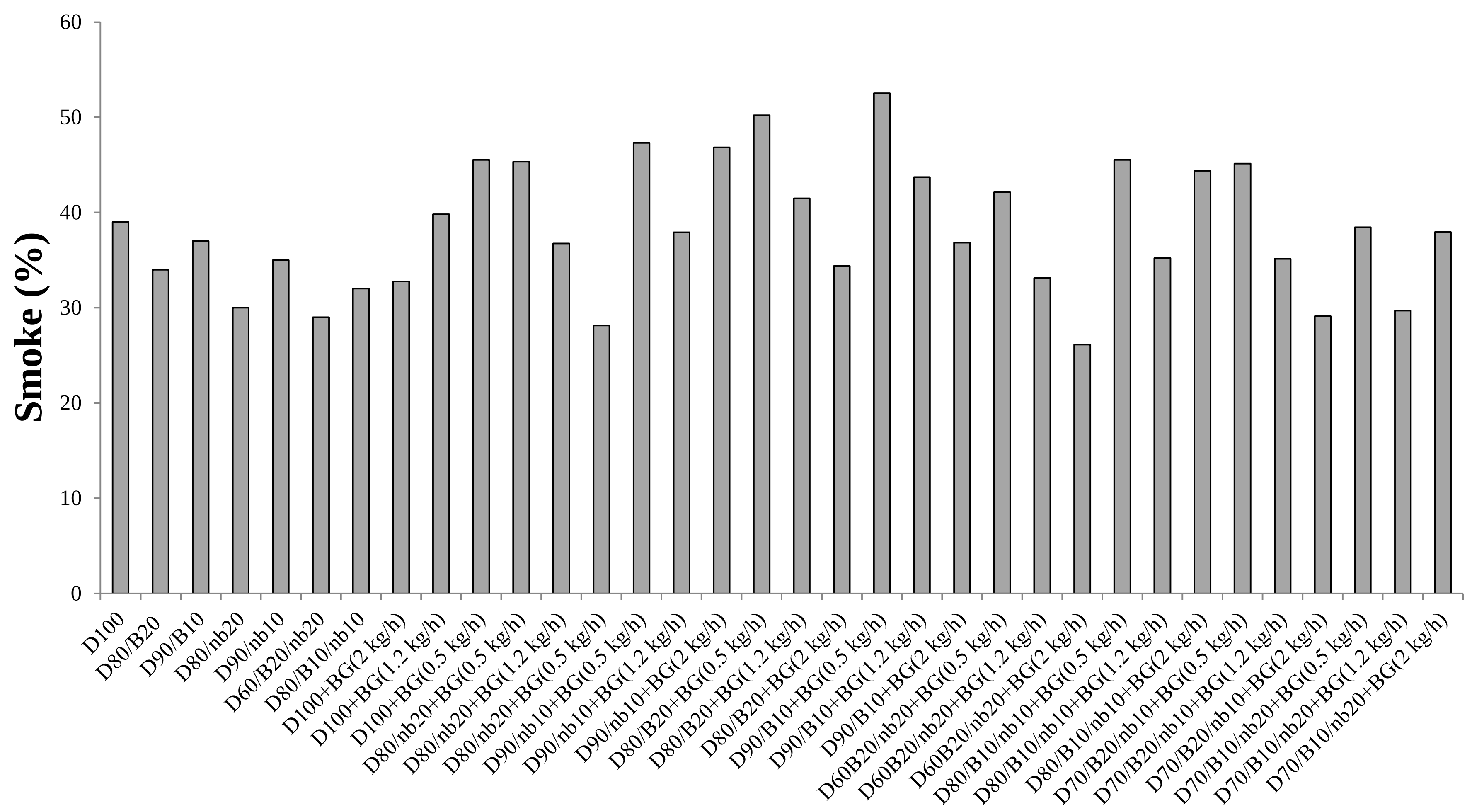

Figure 5.56 Comparison of smoke opacity for all test fuels at full load

5.13 Percentage variation of performance and emission characteristics for all test fuels at full load in comparison with diesel

The deviation of performance and emission characteristics of the engine in percentage is associated for all the test fuels at full engine load in this portion. As compared to pure diesel increment and decrement in percentage of BSFC, BTE, CO exhalations, HC emanations, NOx emissions and smoke opacity are discussed distinctly in the succeeding subsections.

5.13.1 Percentage variation of BSFC for all test fuels at full load

The variation in percentage of BSFC for all the tested fuels at 100% engine load relative to pure diesel is depicted in Figure 5.56. It can be illustrated that D100+BG(2 kg/h) test fuel was having maximum percentage increase of BSFC, whilst D90/B10+BG(0.5 kg/h) was found to have minimum increase in percentage. An increment of 17.95%, 7.75%, 23.84%, 9.32%, 42.48%, 33.75%, 47.77%, 33.35%, 9.80%, 26.84%, 36.38%, 42.08%, 6.29%, 29.46%, 30%, 21.89%, 30.50%, 39.91%, 0.32%, 23.89%, 26.29%, 31.94%, 36.12%, 44.95%, 7.68%, 24.47%, and 30.99% was recorded for D80/B20, D90/B10, D80/nb20, D90/nb10, D60/B20/nb20, D80/B10/nb10, D100+BG(2 kg/h), D100+BG(1.2 kg/h), D100+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), D90/nb10+BG(2 kg/h), D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) respectively in comparison with fossil diesel.

5.13.2 Percentage variation of BTE for all test fuels at full load

Figure 5.57 shows the disparity in percentage of BTE for all the tested fuels at full engine load comparative to natural diesel. Highest percentage of increment and decrement in BTE was calculated for D/nb20+BG(2 kg/h) and D+BG(2 kg/h) respectively, and lowest percentage of augmentation and diminution in BTE was intended for D80/B20/nb20+BG(0.5 kg/h) and D80/B10/nb10+BG(1.2 kg/h) correspondingly. Fuel combinations D80/B20, D90/B10, D80/nb20, D90/nb10, D60/B20/nb20, D80/B10/nb10, D100+BG(2 kg/h), D100+BG(1.2 kg/h), D100+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), D90/nb10+BG(2 kg/h), D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) had -2.40%, -0.54%, -16.29%, -19.61%, -12.44%, -8.42%, -44.86%, -31.05%, -14.64%, 10.99%, 13.72%, 15.75%, 3.65%, 5.43%, 6.51%, -3.65%, -10.24%, -25.83%, -7.63%, -19.20%, -29.85%, 2.36%, 7.13%, 7.71%, -3.36%, -0.46%, and -2.20% more BTE in percentage respectively when related to conventional diesel.

5.13.3 Percentage variation of CO for all test fuels at full load

The percentage variation of CO emanations for all the tested fuels at full loading conditions relative to traditional diesel is illustrated in Figure 5.58. Minimum percentage of increase and decrease in CO was recorded for D100+BG(0.5 kg/h) and D90/B10 respectively, and maximum percentage of growth and reduction in CO emissions was noted for D100+BG(2 kg/h) and D80/B20+BG(0.5 kg/h) respectively. -27.93%, -10.72%, -27.93%, -31.17%, -45.39%, -44.39%, 3.99%, 2.74%, 1.75%, -54.86%, -37.16%, -30.67%, -56.36%, -38.15%, -37.16, -57.61%, -44.39%, -41.40%, -53.12%, -41.90%, -39.40%, -55.36%, -38.15%, -36.16%, -47.38%, -42.14%, and -40.65% variation in percentage of CO was found for D80/B20, D90/B10, D80/nb20, D90/nb10, D60/B20/nb20, D80/B10/nb10, D100+BG(2 kg/h), D100+BG(1.2 kg/h), D100+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), D90/nb10+BG(2 kg/h), D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) fuel combinations respectively.

5.13.4 Percentage variation of HC for all test fuels at full load

Figure 5.59 depicts the deviation of HC exhalations in percentage for all the tested fuels at 100% engine load when related to pure diesel. Maximum percentage of increment and decrement in HC emanations was calculated for D100+BG(2 kg/h) and D80/B20 respectively, and minimum percentage of rise and lessening in HC was noted for D90/nb10 and D90/B10 correspondingly. D80/B20, D90/B10, D80/nb20, D90/nb10, D60/B20/nb20, D80/B10/nb10, D100+BG(2 kg/h), D100+BG(1.2 kg/h), D100+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), D90/nb10+BG(2 kg/h), D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) fuel combinations were found to have -9.42%, -1.69%, 4.52%, 3.01%, 12.81%, -3.01%, 42.18%, 40.87%, 17.89%, 19.40%, 36.16%, 41.43%, 13.18%, %, 34.65%, 38.79%, 6.59%, 27.68%, 35.03%, 9.79%, 34.09%, 37.85%, 6.59%, 27.68%, 35.03%, 9.79%, 34.09%, and 37.85% deviation in percentage respectively for HC emissions than natural diesel.

5.13.5 Percentage variation of NOx for all test fuels at full load

The percentage variation of NOx emanations for all the tested fuels at full loading conditions compared to diesel is shown in Figure 5.60. Least percentage of rise and fall in NOx emissions was found for D90/B10 and D90/B10+BG(0.5 kg/h) respectively, and highest percentage of advancement and drop in NOx was noticed for D80/B20 and D80/B10/nb10+BG(2 kg/h) respectively. 28.58%, 18.33%, -26.00%, -12.63%, -31.98%, -13.37%, -37.41%, -19.69%, -14.19%, -14.32%, -39.04%, -64.15%, -36.73%, -62.73%, -78%, -10.32%, -13.78%, -24.85%, -5.09%, -16.63%, -28.99%, -12.22%, -41.28%, -66.33%, -32.79%, -58.52%, and -79.29% deviation in percentage of NOx emissions was noted for fuel combinations D80/B20, D90/B10, D80/nb20, D90/nb10, D60/B20/nb20, D80/B10/nb10, D100+BG(2 kg/h), D100+BG(1.2 kg/h), D100+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), D90/nb10+BG(2 kg/h), D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) respectively than traditional diesel.

5.13.6 Percentage variation of smoke for all test fuels at full load

Figure 5.61 shows the deviation of smoke opacity in percentage for all the tested fuels at full load in relation with diesel fuel. Highest percentage of increase and decrease in smoke was premeditated for D90/B10+BG(0.5 kg/h) and D60/B20/nb20+BG(2 kg/h) correspondingly, and lowest percentage of escalation and declining in smoke was recorded for D100+BG(1.2 kg/h) and D90/nb10+BG(1.2 kg/h) respectively. D80/B20, D90/B10, D80/nb20, D90/nb10, D60/B20/nb20, D80/B10/nb10, D100+BG(2 kg/h), D100+BG(1.2 kg/h), D100+BG(0.5 kg/h), D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), D90/nb10+BG(2 kg/h), D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), D90/B10+BG(2 kg/h), D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) fuel combinations had -12.82%, -5.13%, -23.08%, -10.26%, -25.64%, -17.95%, -16.00%, 2.10%, 16.74%, 16.21%, -5.74%, -27.85%, 21.33%, %, -2.74%, 20.08%, 28.74%, 6.38%, -11.87%, 34.67%, 12.08%, -5.59%, 8.05%, -15.08%, -33.03%, 16.74%, -9.69%, and 13.79% variation in percentage respectively for smoke emissions associated to fossil diesel.

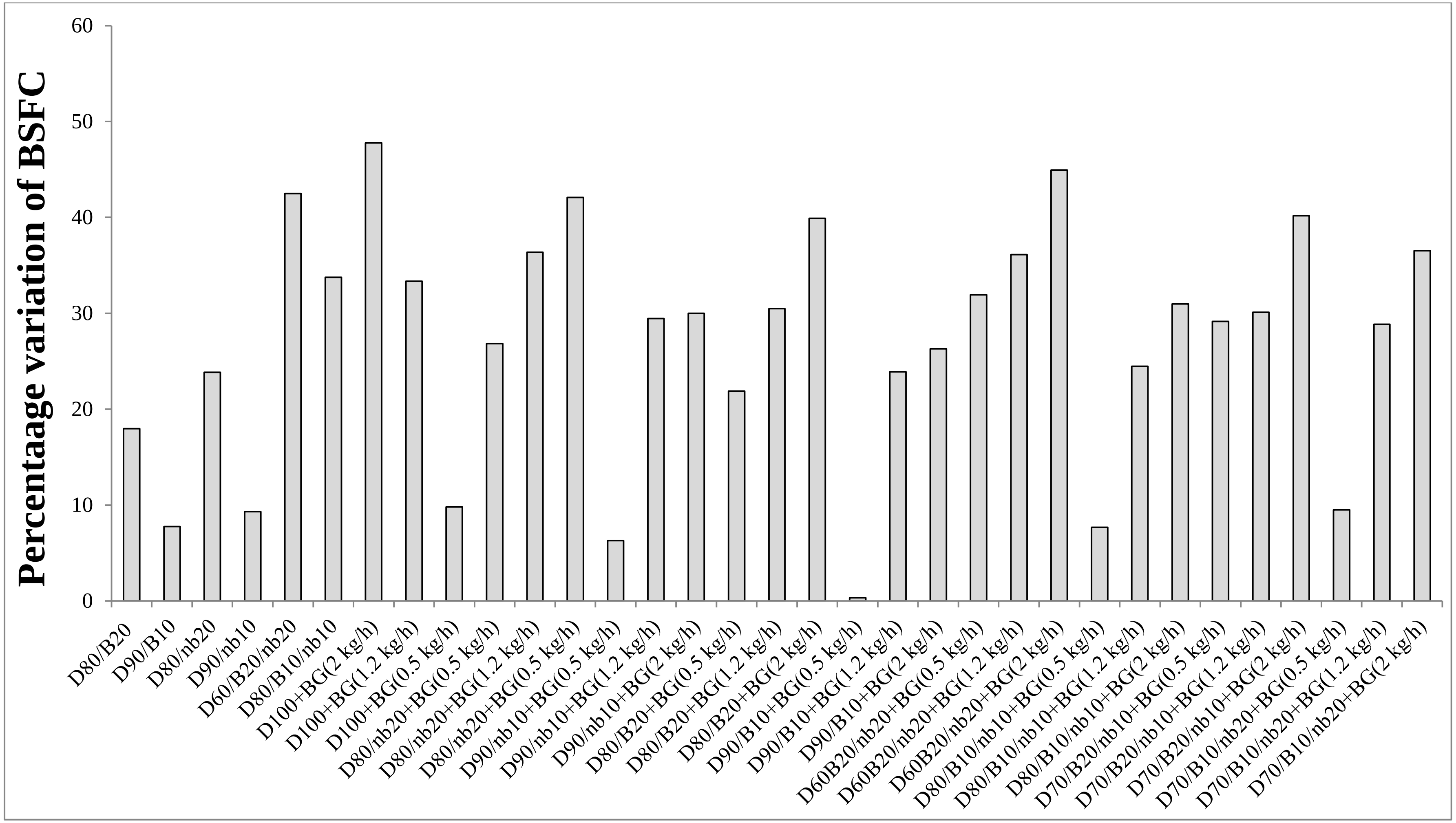

Figure 5.57 Percentage variation of BSFC for all test fuels at full load relative to diesel

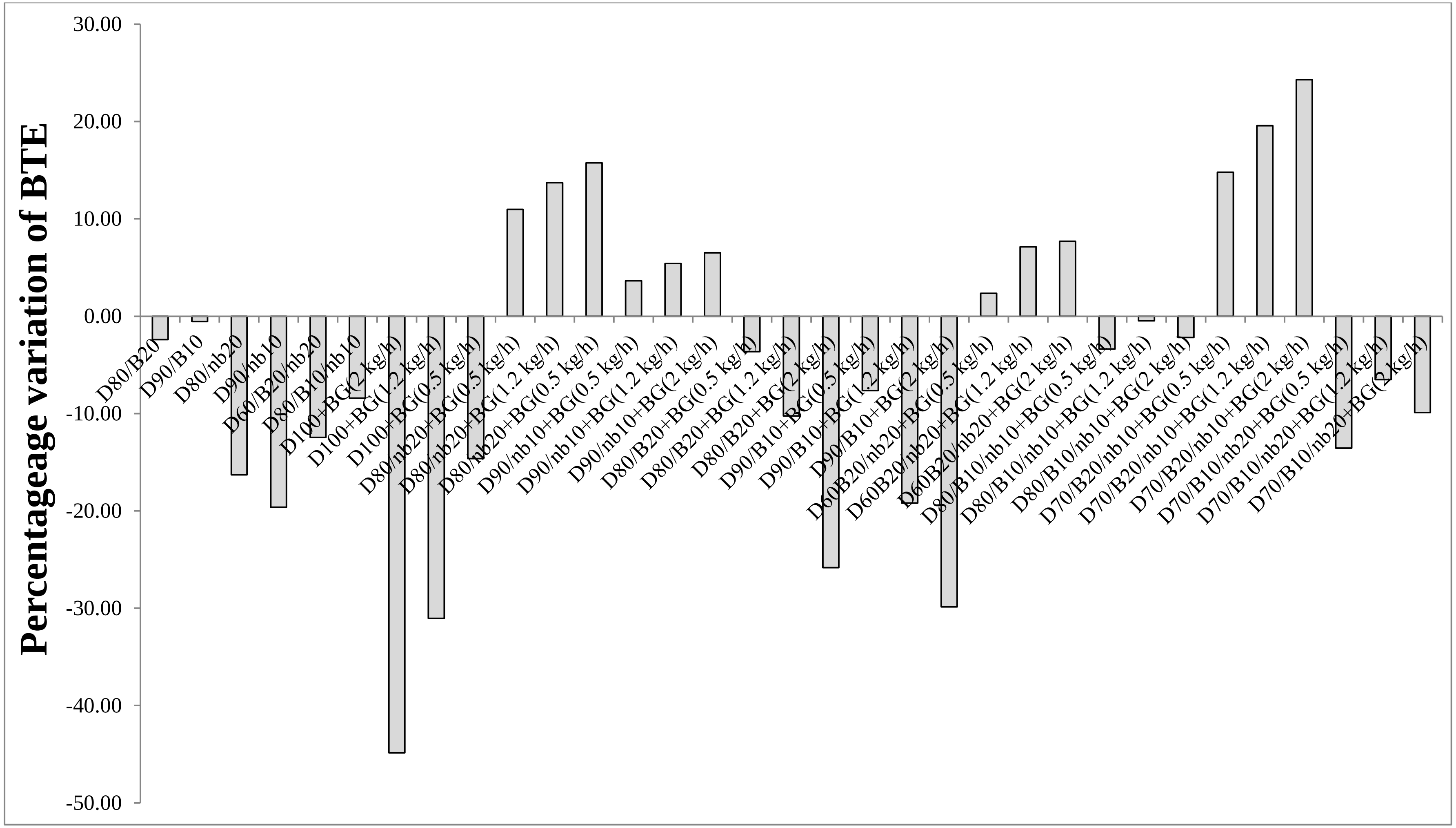

Figure 5.58 Percentage variation of BTE for all test fuels at full load relative to diesel

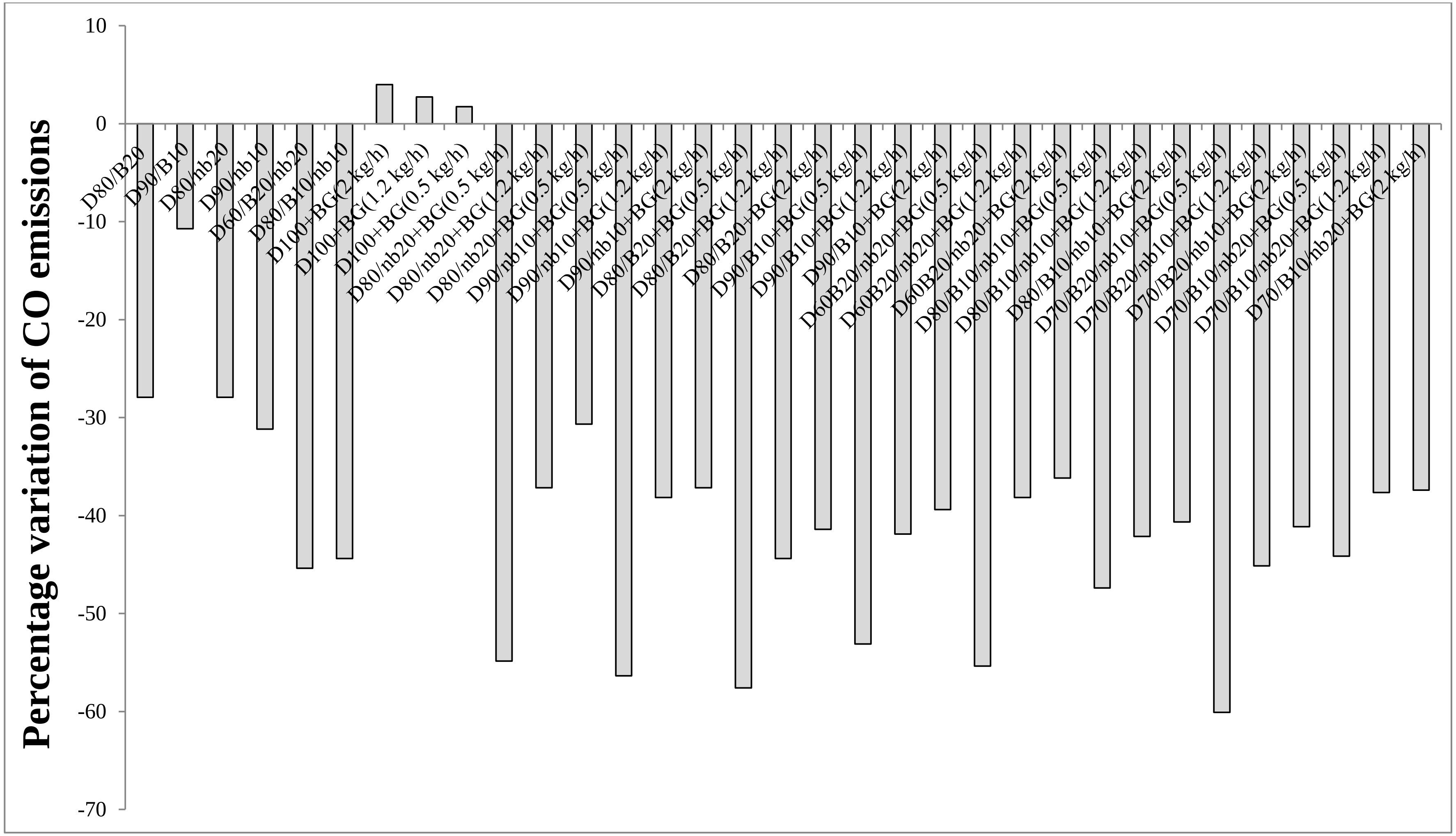

Figure 5.59 Percentage variation of CO for all test fuels at full load relative to diesel

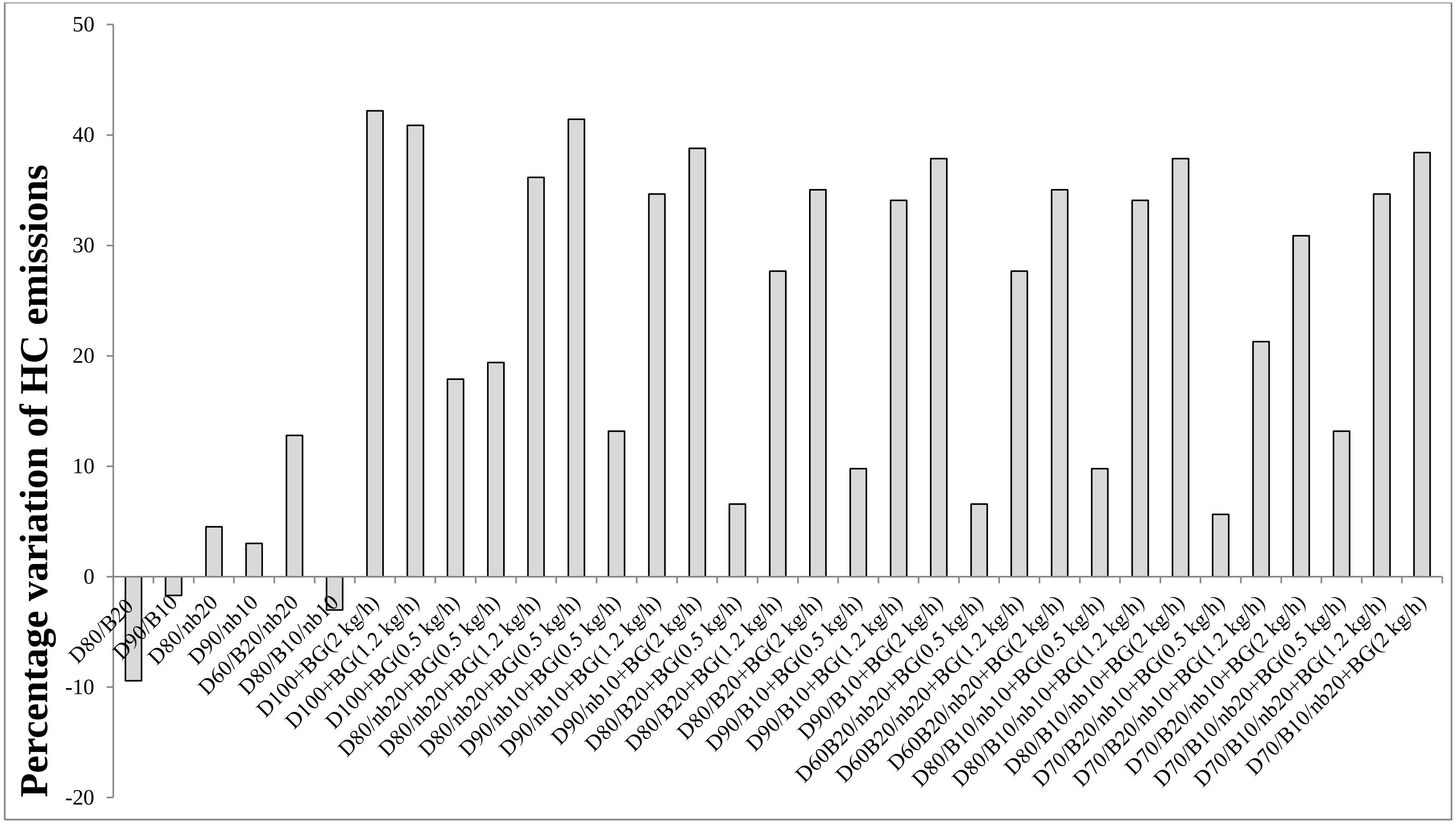

Figure 5.60 Percentage variation of HC for all test fuels at full load relative to diesel

Figure 5.61 Percentage variation of NOx for all test fuels at full load relative to diesel

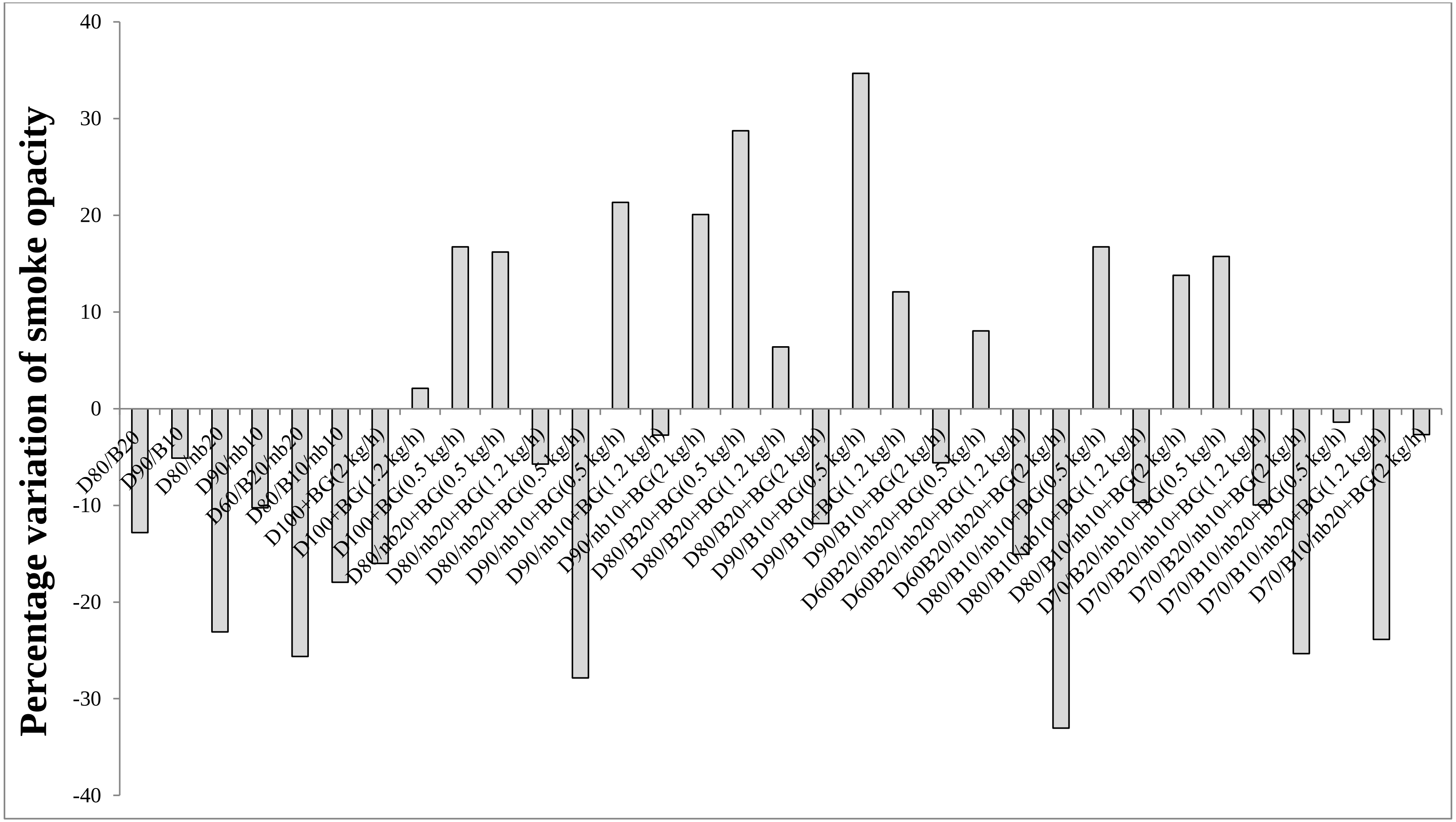

Figure 5.62 Percentage variation of smoke for all test fuels at full load relative to diesel

Chapter-6

Conclusions and Future scope

6.1 Conclusions

Diesel engines are one of the important perspectives of today’s life which include applications such as transportation, power generation etc. In this experimental study various blends of diesel, biodiesel, n-butanol, and biogas were used in different fuel matrix and at different load conditions and following were concluded:

6.1.1 Combination of Diesel and biodiesel

When diesel and biodiesel was used as fuel BSFC and NOx increases whereas BTE, CO, HC, and smoke decreases in comparison with conventional diesel.

- BSFC increases by 21.1% and 11.6% while BTE decreases by 4.9% and 1.5% for D80/B20 and D90/B10 fuel blend respectively with biodiesel blends in comparison with baseline diesel.
- Relative to pure diesel, NOx emissions are on higher side by 18.5% and 11.9% for D80/B20 and D90/B10 fuel blend respectively, whereas a decrement of 16.9% and 6.3% for CO, 10.4% and 2.8% HC, and 22.8 and 14.3% is found for Smoke exhalations for D80/B20 and D90/B10 fuel blends respectively.

6.1.2 Combination of Diesel and n-butanol

BSFC and HC enhanced whereas BTE, CO, NOx, and smoke falls down related to fossil diesel when diesel and biodiesel was used as fuel.

- BSFC increases by 24.7% and 18.2% while BTE decreases by 13.2% and 14.3% for D80/nb20 and D90/nb10 fuel blend respectively with biodiesel blends compared to natural diesel.
- An increment in HC emissions is observed by 4.2 and 2.7% for nB20 and nb10 fuel blend respectively. Reduction of 15.1% and 20.3% in CO, 20.4%

and 10.3% in NOx, and 35.3% and 14.3% is recorded in smoke emissions for D80/nb20 and D90/nb10 respectively than pure diesel.

6.1.3 Combination of Diesel and biogas

Compared to pure diesel BSFC, HC, and CO was on higher side whilst BTE, NOx, and smoke diminished when diesel and biogas was used in the engine.

- Compared to fossil diesel, BSFC was more by 31.2%, 25.5%, and 14.6% and BTE was less by 41.6%, 29%, and 18.2% for D100+BG(2 kg/h), D100+BG(1.2 kg/h), and D100+BG(0.5 kg/h) respectively.
- HC emissions increases by 30.1%, 27.9%, and 15.8%, CO exhalations are more by 16.1%, 13.4%, and 8% for D100+BG(2 kg/h), D100+BG(1.2 kg/h), and D100+BG(0.5 kg/h) respectively.
- NOx exhalations reduced by 33.1%, 21%, and 10.9% and smoke opacity decrease by 56.9%, 45.4%, and 29.7% for D100+BG(2 kg/h), D100+BG(1.2 kg/h), and D100+BG(0.5 kg/h) respectively.

6.1.4 Combination of Diesel, Biodiesel, and n-butanol

When blends of diesel, biodiesel, and n-butanol were utilized in the diesel engine, BSFC and HC increased, whereas BTE, CO, NOx, and smoke reduced in relation with traditional diesel.

- BSFC increased with increase in the quantity of biodiesel and n-butanol in the blends and is higher than diesel fuel. Enhanced BSFC was found for D80/B10/nb10 and D60/B20/nb20 fuel blends by 31% and 28% respectively relative to traditional diesel.
- BTE reduced by 15.1% and 11.5% for fuel blends D60/B20/nb20 and D80/B10/nb10 respectively correlated to natural diesel.
- CO emissions are reduced with the introduction of RBME and n-butanol in fuel blends. For D60/B20/nb20 and D80/B10/nb10 CO exhalations deteriorate by 32.9% and 31.1% respectively in comparison with baseline diesel.
- Smoke opacity is noted to be decreased with the inclusion of rice bran biodiesel in the blends and further decreased with n-butanol relative to pure

diesel. It is found that smoke exhalations reduced by 44.9% and 36.6% for D60/B20/nb20 and D80/B10/nb10 respectively.

- D60/B20/nb20 fuel blend illustrates an increase in HC emissions as compared to diesel, whereas a marginal reduction is found by using D80/B10/nb10 fuel blend. 8.9% increased and 1.9% decreased HC exhalations are reported for D60/B20/nb20 and D80/B10/nb10 fuel blends respectively.
- NOx emissions reported lesser for fuel blends containing the combination of diesel biodiesel and n-butanol. For D60/B20/nb20 and D80/B10/nb10 fuel blends a reduction of 16.4% and 8.6% respectively is noted in relation with fossil diesel.

6.1.5 Combination of Diesel, Biodiesel, and Biogas

Combination of diesel, biodiesel, and biogas displays increment in BSFC, CO, and HC, however a decline in BTE, NOx, and smoke was noted when it was associated with natural diesel.

- BSFC was found to be higher for dual fuel mode as compared to pure diesel. Addition of RBME in liquid fuel and enhancing biogas mass flow rate further increases BSFC. An increment of 21.8%, 27.8%, 30.4%, 5.7%, 18.3%, and 21.1% is gained for D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), and D90/B10+BG(2 kg/h) fuel blends respectively.
- BTE decreased with dual fuel mode as compared to diesel. BTE was observed to decrease with increasing biogas mass flow rate and declining proportion of RBO in pilot fuel. D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), and D90/B10+BG(2 kg/h) shows a reduction in BTE by 1.8%, 12.1%, 26.1%, 7.8%, 18.1%, and 28.8% respectively.
- CO exhalations were on higher side with increasing biogas mass flow rate in dual fuel mode as compared to baseline diesel whereas increasing content of RBME results in the decreased amount of CO. An enhancement of 17.3%, 44.6%, 58.5%, 25.3%, 53.8%, and 25% is found for D80/B20+BG(0.5 kg/h),

D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), and D90/B10+BG(2 kg/h) fuel blends respectively.

- In comparison with pure diesel, HC emissions were more with increasing mass flow rate of biogas in dual fuel mode whilst with enhancing amount of biodiesel in fuel blend helps in decreasing HC emissions. D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), and D90/B10+BG(2 kg/h) illustrates an increment in HC exhalations by 5.6%, 18.4%, 23.7%, 9.2%, 23.8%, and 26.9% respectively.
- Reduction in NOx emissions was observed when biogas was introduced and its mass flow rate was increased in dual fuel mode in relation to fossil diesel. Deterioration of 2.8%, 10.8%, 20.2%, 4.7%, 14.8%, and 26% is noted for D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), and D90/B10+BG(2 kg/h) fuel blends respectively.
- The use of biogas as primary fuel and RBME blends as pilot fuel resulted in lowering the smoke opacity when compared with conventional diesel for all engine loads. D80/B20+BG(0.5 kg/h), D80/B20+BG(1.2 kg/h), D80/B20+BG(2 kg/h), D90/B10+BG(0.5 kg/h), D90/B10+BG(1.2 kg/h), and D90/B10+BG(2 kg/h) depicts a decrement in smoke emissions by 20.7%, 38.4%, 51.2%, 17.4%, 34.1%, and 46.3% respectively.

6.1.6 Combination of Diesel, Biogas, and n-butanol

When blends of diesel and n-butanol were used as pilot fuel and biogas was used as primary fuel, BSFC, BTE, CO, and HC depicts enhancement, whilst NOx and smoke emanations were on the lower side vis-à-vis conventional diesel.

- In comparison with ordinary diesel, BSFC was more for fuel blends containing n-butanol in the dual fuel mode. It is found that BSFC keeps on increasing with increment in n-butanol in the fuel blends and increasing mass flow rate of biogas. Increase of 24%, 29.8%, 31.7%, 6%, 20.9%, and 23.4% is reported for D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), and D90/nb10+BG(2 kg/h) fuel blends respectively.

- An increment in BTE is noted for blends containing n-butanol in dual fuel mode than the diesel-only mode. There was a further increase in BTE with the increasing proportion of n-butanol and biogas in the fuel blends. D80/nb20BIO(0.5), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), and D90/nb10+BG(2 kg/h) facilitates enhancement in BTE by 14%, 15.6%, 17.6%, 5%, 9%, and 10.3% respectively.
- Increasing amount of biogas mass flow rate and n-butanol in fuel blends helps in enhancing the exhalations of CO for dual fuel mode when compared with natural diesel. Enhancement of 34.5%, 57.8%, 68.7%, 26.7%, 54.3%, and 62.9% is recorded for D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), and D90/nb10+BG(2 kg/h) fuel blends respectively for CO emissions.
- HC emissions also increase for fuel blends containing n-butanol and biogas when related to baseline diesel. D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), and D90/nb10+BG(2 kg/h) shows increment in HC exhalations by 14%, 15.6%, 17.6%, 5%, 9%, and 10.3% respectively.
- NOx emissions have a decreasing trend for fuels having n-butanol and biogas as compared to traditional diesel. With decrease in n-butanol and increase in biogas in the fuel, NOx exhalations are found to decrease. Reduction of 16.1%, 36.4%, 53.2%, 26.6%, 48.2%, and 61.7% is noticed for D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), and D90/nb10+BG(2 kg/h) fuel blends respectively for NOx emissions.
- The opacity of smoke decreases for fuel blend containing n-butanol when the engine runs on dual fuel mode. Increase in n-butanol and biogas further decreases smoke when correlated with natural diesel. D80/nb20+BG(0.5 kg/h), D80/nb20+BG(1.2 kg/h), D80/nb20+BG(2 kg/h), D90/nb10+BG(0.5 kg/h), D90/nb10+BG(1.2 kg/h), and D90/nb10+BG(2 kg/h) depicts reduction

in smoke exhalations by 34.5%, 48.5%, 61.2%, 29.3%, 43%, and 29.1% respectively.

6.1.7 Combination of Diesel, Biodiesel, Biogas, and n-butanol (D60 and D80)

When diesel was used in proportion of 60% and 80% with biodiesel and n-butanol blends, and biogas was used as liquid fuel, BSFC, CO, and HC incrased whereas BTE, NOx and smoke decreased relative to fossil diesel.

- BSFC is on higher side with all other fuel blends and combinations when compared with traditional diesel. With increasing quantity of n-butanol and biogas mass flow rate BSFC increases. Enhancement of 26.6%, 30.5%, 32.9%, 7.3%, 20.2%, and 23.8% is noticed for D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) fuel blends respectively for BSFC.
- Relative to fossil diesel, BTE decreases for all other fuel blends and combinations. Enhancing quantity of biodiesel and n-butanol in fuel blends results in increasing BTE. D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) illustrates reduction in BTE by 13.1%, 10.1%, 8.1%, 21.2%, 15.6%, and 17.7% respectively.
- CO exhalations are higher for remaining fuels and combinations in comparison with natural diesel. CO emissions are reported to increase with increasing biodiesel, n-butanol and mass flow rate of biogas in fuel blends. Increment of 26.2%, 55.3%, 65.7%, 21.3%, 46.8%, and 59.2% is noted for D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) fuel blends respectively for CO exhalations.
- Increased amount of HC emissions are found for fuel blends containing biodiesel, n-butanol and biogas in relation with traditional diesel. Exhalations

of HC reported to be decreased with increasing amount of biodiesel and n-butanol in fuel blends. D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) depicts enhancement in HC emissions by 5.6%, 18.4%, 23.7%, 9.2%, 23.8%, and 26.9% respectively.

- NOx emissions are found to be lower for fuel blends containing biodiesel, n-butanol in dual fuel mode when compared with diesel fuel. NOx exhalations reduced with increasing mass flow rate of biogas. Increment of 13.1%, 33.9%, 52.3%, 24.5%, 45.2%, and 60.4% is reported for D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) fuel blends respectively for NOx exhalations.
- Smoke emissions decreases drastically for all other fuel blends and combinations when compared with conventional diesel. D60/B20/nb20+BG(0.5 kg/h), D60/B20/nb20+BG(1.2 kg/h), D60/B20/nb20+BG(2 kg/h), D80/B10/nb10+BG(0.5 kg/h), D80/B10/nb10+BG(1.2 kg/h), and D80/B10/nb10+BG(2 kg/h) illustrates reduction in smoke opacity by 40.4%, 54.9%, 67%, 35.4%, 49.2%, and 36.2% respectively.

6.1.8 Combination of Diesel, Biodiesel, Biogas, and n-butanol (D70)

Combination of diesel, biodiesel, biogas, and n-butanol when used with 70% diesel illustrates an enhancement in BSFC, CO, and HC, whilst, BTE, NOx, and smoke were on the lower side compared to traditional diesel.

- BSFC increases with all other fuel blends and combinations when compared with traditional diesel. With increasing quantity of n-butanol and biogas mass flow rate BSFC is on higher side. Enhancement of 22.6%, 26.5%, 30.9%, 11.3%, 23.2%, and 27.8% is noticed for D70/B20/nb10+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D70/B10/nb20+BG(0.5 kg/h), D70/B10/nb20+BG(1.2 kg/h), and D70/B10/nb20+BG(2 kg/h) fuel blends respectively for BSFC.

- Relative to fossil diesel, BTE decreases for all other fuel blends and combinations. Enhancing quantity of biodiesel and n-butanol in fuel blends results in increasing BTE. D70/B20/nb10+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D70/B10/nb20+BG(0.5 kg/h), D70/B10/nb20+BG(1.2 kg/h), and D70/B10/nb20+BG(2 kg/h) illustrates reduction in BTE by 6.1%, 2.1%, 0.4%, 28.2%, 24.6%, and 26.7% respectively.
- CO exhalations are higher for remaining fuels and combinations in comparison with natural diesel. CO emissions are reported to increase with increasing biodiesel, n-butanol and mass flow rate of biogas in fuel blends. Increment of 14.2%, 50.3%, 63.7%, 31.3%, 52.8%, and 61.2% is noted for D70/B20/nb10+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D70/B10/nb20+BG(0.5 kg/h), D70/B10/nb20+BG(1.2 kg/h), and D70/B10/nb20+BG(2 kg/h) fuel blends respectively for CO exhalations.
- Increased amount of HC emissions are found for fuel blends containing biodiesel, n-butanol and biogas in relation with traditional diesel. Exhalations of HC reported to be decreased with increasing amount of biodiesel and n-butanol in fuel blends. D70/B20/nb10+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D70/B10/nb20+BG(0.5 kg/h), D70/B10/nb20+BG(1.2 kg/h), and D70/B10/nb20+BG(2 kg/h) depicts enhancement in HC emissions by 4.6%, 16.4%, 21.7%, 10.2%, 25.8%, and 27.9% respectively.
- NOx emissions are found to be lower for fuel blends containing biodiesel, n-butanol in dual fuel mode when compared with diesel fuel. NOx exhalations reduced with increasing mass flow rate of biogas. Increment of -8.1%, 14.9%, 34.3%, 43.5%, 59.2%, and 73.4% is reported for D70/B20/nb10+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D70/B10/nb20+BG(0.5 kg/h), D70/B10/nb20+BG(1.2 kg/h), and D70/B10/nb20+BG(2 kg/h) fuel blends respectively for NOx exhalations.

- Smoke emissions decreases drastically for all other fuel blends and combinations when compared with conventional diesel. D70/B20/nb10+BG(0.5 kg/h), D70/B20/nb10+BG(1.2 kg/h), D70/B20/nb10+BG(2 kg/h), D70/B10/nb20+BG(0.5 kg/h), D70/B10/nb20+BG(1.2 kg/h), and D70/B10/nb20+BG(2 kg/h) illustrates reduction in smoke opacity by 26.4%, 42.9%, 57%, 48.4%, 58.2%, and 48.2% respectively.

6.1.9 Biogas energy share

Maximum amount of biogas energy share found to be 64.7 % for D100+BG(2 kg/h) at 20% engine load and minimum amount was 11.5% for D100+BG(0.5 kg/h) at full load. So diesel replacement of 64.7% is possible while using D100+BG(2 kg/h) at low engine loads.

6.1.10 Comparison of all tested fuels at 100% load for all the performance and emission characteristics

By comparing all the tested fuels at full loading conditions it was enamurated that BSFC, BTE, CO, HC, NOx, and smoke were found superlative for natural diesel, D70/B20/nb10+BG(2kg/h), D80/B10/nb10+BG(1.2kg/h), D80/B20, D70/B10/nb20+BG(2kg/h), and D60/B20/nb20+BG(2kg/h) respectively.

6.1.11 Comparison of achieved results with results of other researchers

Table 6.1 illustrates the comparison of results obtained from the current research work with results of other researchers. Results depicts that out of 42 experimental studies compared, 24 studies are exactly similar to this study, 15 studies are similar to current study excluding one or two parameters, and only 3 studies are dissimilar to present study and that too, except a few performance and emission characteristics.

Table 6.1 Comparison of achieved results with results of other researchers

S. No	Fuel combination	Ref. No.	Result obtained by other researchers						Result obtained by this experimentation						Similar/ Dissimilar
			BTE	**BSFC**	**CO**	**HC**	**NOx**	**Smoke**	**BTE**	**BSFC**	**CO**	**HC**	**NOx**	**Smoke**	
1	Combination of Diesel and biodiesel	138	NM	↑	↓	↓	↑	NM	↓	↑	↓	↓	↑	↓	Similar
2		139	↓	↑	↓	↓	↑	↓							Similar
3		85	↓	↑	NM	NM	NM	↓							Similar
4		143	↓	↑	↓	↓	↑	NM							Similar
5		148	↓	↑	↓	↓	↓	↓							Similar except NOx
6		149	↓	↓	↓	↓	↑	NM							Similar except BTE
7		154	↓	↑	↓	↓	↑	NM							Similar
8		154	↓	↑	↓	↓	↑	↑							Similar except Smoke
9		160	↓	↑	NM	NM	↑	↓							Similar
10		162	↓	↑	↓	↓	↑	NM							Similar
11	Combination of Diesel and n-butanol	219	↓	↑	NM	NM	↓	NM	↓	↑	↓	↑	↓	↓	Similar
12		188	↑	↑	↓	↑	↓	↓							Similar except BTE
13		203	NM	↑	NM	NM	↓	NM							Similar
14		206	↑	↑	NM	↑	↑	NM							Dissimilar except BSFC and NOx
15		208	↓	↑	NM	↑	↓	NM							Similar

16	Combination of Diesel and n-butanol	210	↓	NM	↓	↑	↓	↓	↓	↑	↓	↑	↓	↓	Similar
17		211	↑	↑	NM	NM	↓	NM							Similar except BTE
18		213	↑	NM	↑	↑	↑	NM							Dissimilar except HC
19		214	↑	↑	↓	↑	NM	↓							Similar except BTE
20	Combination of Diesel and biogas	261	↑	NM	NM	↑	NM	↓	↓	↑	↑	↑	↓	↓	Similar except BTE
21		35	↓	NM	↑	↑	↓	↓							Similar
22		263	NM	NM	↑	↑	↓	↓							Similar
23		34	↑	↑	↑	↑	NM	↓							Similar except BTE
24		265	↓	↑	↑	↑	↓	↓							Similar
25		266	↑	↑	↑	↑	↓	↓							Similar except BTE
26		269	↓	↑	NM	↑	↓	↑							Similar except smoke
27		270	NM	↑	↑	↑	↓	NM							Similar
28		249	↓	NM	↑	↑	↓	NM							Similar
29		278	↓	↑	↑	↓	↑	↓							Similar except HC and NOx
30	Combination of Diesel, Biodiesel,	201	↓	↑	↓	↓	NM	NM	↓	↑	↓	↓	↓	↓	Similar
31		202	NM	↑	↓	↓	↑	NM							Similar except NOx
32		127	NM	↑	↑	↑	↑	NM							Dissimilar except BSFC

33	and n-butanol	218	↓	↑	NM	NM	NM	NM							Similar
34		204	↑	↑	↓	↓	NM	NM							Similar except BTE
35		200	↑	NM	↓	↓	↑	↓							Similar except BTE and NOx
36	Combination of Diesel, biodiesel and biogas	265	↓	NM	↑	↑	↓	↓	↓	↑	↑	↑	↓	↓	Similar
37		268	↓	↑	↑	↑	↑	↑							Similar except NOx and smoke
38		271	NM	NM	↑	↑	↓	↓							Similar
39		65	↓	NM	↑	↑	↓	NM							Similar
40		279	↓	↑	↑	↑	↓	NM							Similar
41		247	↓	↑	↑	↑	↓	↓							Similar
42		250	↓	↑	↑	↑	↓	↓							Similar

NM- Not mentioned by researcher

Combination of Diesel, Biogas, and n-butanol and Combination of Diesel, Biodiesel Biogas, and n-butanol has not been tested by any researcher till now.

6.2 Future scope

In this experimental work, various proportions of fuel blends containing diesel, biodiesel, and n-butanol were tested on a dual fuel engine at different loading conditions and varying mass flow rate of biogas. However, still there are scopes for further experimentation and study which can help in enlightening the field of substitute fuels, which are mentioned underneath:

- EGR technology can be employed in the same experimental setup and the same set of fuel matrix to check the effect of EGR.
- Biodiesel procured from any other plant or animal fat oil can be utilized with the same combination of alcohol and gaseous fuel.
- Only one type of biodiesel is used in this work. Combination of two or more biodiesel blends can be utilized together or separately to check the effect of various biodiesels.
- Any other higher alcohol can be used with the same combination of biodiesel and gaseous fuel.
- More than one higher alcohol can be tested as fuel blends by blending them with diesel and biodiesel to check the effect of various types of higher alcohols.
- Gaseous fuel other than biogas can be used with the same combination of biodiesel and higher alcohol.
- More than one gaseous fuel can be tested with the same combination of biodiesel and higher alcohol.
- The mass flow rate of gaseous fuel can be changed.
- Gaseous fuel’s composition can be changed to check its effect on the performance and emission characteristics.
- Injection timing of the engine can be changed, either retarding or advancing.
- Injection pressure of the engine can be changed, i.e. effect of higher injection pressure can be studied
- Nanoparticles can be added in the engine along with biodiesel, n-butanol, and biogas to check its effect.

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Appendix 1

Alternator Specifications

Make & Model	Kirloskar Deniki A.C. Generator
Output	5 kVA
Volts	230 V
Current	21.7 A
Power Factor	1.0
Phase	1
Frequency	50 Hz
R.P.M.	1500

Appendix 2

Specifications of Pressure Transducer

Type	Piezo-Electric, Kistler 701A
Range	0-250 bar
Calibrated partial range	0-25 bar 0-2.5 bar
Overload	400 bars
Sensitivity	~ -80 pC/bar
Natural frequency	~ 70 kHz
Linearity	≤ ± 0.5 % FSO
Acceleration sensitivity	< 0.001 bar/g
Operating temperature range	-150…….200^0 C
Temperature coefficient of sensitivity	$< 10^{-4}\ {}^{o}C^{-1}$
Insulation resistance	$\geq 10^{13}$
Shock resistance	5000 g
Capacitance	9 pF
Weight	8.5 g
Connector	10-32 UNF

Appendix 3

Pressure transducer calibration

S.No.	Pressure(bars)	Voltage (forward)	Voltage (reverse)	Average Voltage
1	0	0.08	0.00	0.00
2	10	0.92	1.09	1.00
3	20	1.93	2.19	2.06
4	30	2.95	3.10	3.02
5	40	3.97	4.10	4.03
6	50	4.98	5.10	5.04
7	60	6.00	6.10	6.05
8	70	7.02	7.15	7.08
9	80	8.03	8.11	8.07
10	90	9.10	9.28	9.19
11	100	10.11	10.18	10.15

Appendix 4

Specifications of Charge Amplifier

Make & Model	AVL, HICF 3059
Measuring range, Continuous setting	PC ± ……999’000
Transducer sensitivity	PC/M.U. 0.01....999’000
Output Voltage	V ± 15
Current (short circuit protected)	mA ± 0….5
Impedance	Ohm 10
Linearity	% FS ± ≤ 0.05
Accuracy	% ≤ ± 3
Drift (25^0 C) MOSFET leakage	PC/S < ± 0.03
Insulation resistance	Ohm > 10^{14}
Adjusting range for zero point	mV Ca ± 250

Appendix 5

Specifications of Biogas Flowmeter

Make & Model	Flow Star, FSC-300
Instrument Serial No.	05D14384
Flow Rate	4-50 LPM
Test Fluid	Biogas
Error as % of full scale	± 3 %
Calibrated by	National Physical Lab, New Delhi
Method of Test	Volumetric
Calibration Certificate of Flowmeter	003/FSIPL/05-06

Appendix 6

Technical Data of AVL DiGas Gas Analyzer (Model 4000)

Measuring principle	CO, HC, CO_2	Infrared measurement
Measuring principle	O_2 , NOx	Electrochemical measurement
Operating temperature accuracy	+5………+ 45 ^{o}C	Keeping measurement
	+1………+50 ^{o}C	Ready for measurement
	+5………+35 ^{o}C	with integral NO sensor (peaks of: +400 ^{o}C)
Storage temperature	-20……..+60 ^{o}C	
	-20……..+50 ^{o}C	with integrated O_2 sensor
	-10……..+45 ^{o}C	with integrated NO sensor
	0………+50 ^{o}C	with water in filter and/or pump
Air humidity	90% max., non-condensing	
Power drawn	150 VA	
Dimension	470 X 431 X 230 mm	
Weight	17.7 Kg	

Appendix 7

Technical Data of AVL Smoke Meter (Model 437)

Accuracy and Reproducibility	± 1% full scale reading
Measuring range	0……00% capacity in % 0……α absorption m-1
Measuring chamber effective length	0.430 m ± 0.005
Heating Time	220 V…… appox. 20 min
Light source	halogen bulb 12V/15W
Colour temperature	3000K ± 150 K
Detector	selenium photocell dia. 45 mm
Max. Smoke temperature at entrance	250^{o} C

List of publications

Journals:

1. G. Goga, B.S. Chauhan, S.K. Mahla, H.M. Cho, Performance and emission characteristics of diesel engine fueled with rice bran biodiesel and n-butanol, **Energy Reports by Elsevier** 2019; 5:78–83. (SCI – Impact factor 3.83)

2. G. Goga, B.S. Chauhan, S.K. Mahla,, A. Dhir, Combined impact of varying biogas mass flow rate and rice bran methyl esters blended with diesel on dual fuel engine, **Energy Sources, Part A: Recovery, Utilization, and Environmental Effects by Taylor and Francis**. https://doi.org/10.1080/15567036.2019.1623948. (SCI – Impact factor 0.55)

3. G. Goga, B.S. Chauhan, S.K. Mahla, H.M. Cho, A. Dhir, H.C. Lim, Properties and characteristics of various materials used as biofuels: A review, **Material Todays: Proceedings by Elsevier** 2018; 5:28438–28445. (Scopus)

4. G. Goga, B.S. Chauhan, S.K. Mahla, A.Dhir, H.C. Lim, Effect of varying biogas mass flow rate on performance and emission characteristics of a diesel engine fuelled with blends of n-butanol and diesel, **Journal of thermal analysis and calorimetry by Springer** (under review). (SCI – Impact factor 2.042)

5. G. Goga, B.S. Chauhan, S.K. Mahla, Effect of exhaust gas recirculation on performance and emission characteristics of a diesel engine fuelled with rice bran biodiesel, **Renewable Energy by Elsevier** (under review). (SCI – Impact factor 5.439)

6. G. Goga, B.S. Chauhan, S.K. Mahla, H.M. Cho, A. Dhir, H.M. Cho, Separate effect of biodiesel, n-butanol and biogas on performance and emission characteristics of diesel engine, **Renewable and Sustainable Energy Reviews by Elsevier** (communicated). (SCI – Impact factor 10.556)

7. S.K. Mahla, S.M.S. Ardebili, M. Mostafaei, A. Dhir, G. Goga, B.S. Chauhan, Performance and emission characteristics of a diesel engine fueled with biogas-diesel using multi-objective optimization by response surface methodology, **Environmental**

Science and pollution research by Springer (communicated). (SCI – Impact factor 2.800)

8. S.K. Mahla, A.P. Papreja, V. Singla, A. Dhir, S. Singh and G. Goga, Investigations on the performance evaluation and emission characteristics of compressed natural gas (CNG) fueled small utility diesel engine, International Journal on Emerging Technologies (Special Issue NCETST-2017) 2017; 8(1): 78-81.

Patent:

1. A patent "A system of production of biodiesel from rice bran oil by transesterification and process optimization" was filed in official **journal of the patent office India** on 9/11/2017 vide application no. 201711040039 A and published on 1/12/2017 in issue no. 48/2017.

Conferences:

1. J. Singla, G. Goga, S.K. Mahla, B.S. Chauhan, Performance and emission characteristics of a diesel engine fueled with blends of diesel and n-butanol, presented in International conference on advanced research and innovations held on 20 January 2019 in Delhi State Centre, Institution of Engineers (India), (Engineers Bhawan), 2, Bahadur Shah Zafar Marg, New Delhi-110002, India.

2. J. Singla, G. Goga, S.K. Mahla, B.S. Chauhan, Performance and emission characteristics of a diesel engine using rice bran oil methyl esters, presented in International conference on advanced research and innovations held on 20 January 2019 in Delhi State Centre, Institution of Engineers (India), (Engineers Bhawan), 2, Bahadur Shah Zafar Marg, New Delhi-110002, India.

3. J. Singla, G. Goga, S.K. Mahla, B.S. Chauhan, Performance and emission characteristics of a dual fuel engine fueled with diesel and biogas, presented in International conference on advanced research and innovations held on 20 January 2019 in Delhi State Centre, Institution of Engineers (India), (Engineers Bhawan), 2, Bahadur Shah Zafar Marg, New Delhi-110002, India.