Study of Performance and Combustion Parameters of a dual fuel engine runs on Blends of Diesel and Producer Gas using Forest Residue

(Pine Cone and Coconut shell)

A Dissertation

Submitted in partial fulfillment of the requirement for the award of degree of

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in

Thermal Engineering

by

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(Ramay Raj Singh Bisht)

Certification

I hereby declare that the thesis entitled, **"Study of Performance Parameters of Dual Fuel Engine Run on Diesel and Producer Gas Produced from Forest Residue (Cone Pine and Coconut Shell)"** is an authentic record of my work carried out as requirements for the award of the degree of Master of Engineering in Thermal Engineering at Thapar University, Patiala, under the supervision of Dr S.K. Mohapatra, HOD, Mechanical Engineering Department, Thapar University, Patiala during July, 2024 to July, 2025.

No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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Nomenclature

Symbol / Term	**Definition / Description**	**Unit**
RPM	Revolutions Per Minute	RPM
DFCI	Dual Fuel Compression Ignition Engine	—
CI	Compression Ignition	—
VM	Volatile Matter	%
FC	Fixed Carbon	%
MC	Moisture Content	%
Ash	Ash Content	%
BP	Brake Power	kW
IP	Indicated Power	kW
FP	Frictional Power	kW
BTE	Brake Thermal Efficiency	%
ITE	Indicated Thermal Efficiency	%
SFC	Specific Fuel Consumption	kg/kWh
BSFC	Brake Specific Fuel Consumption	kg/kWh
CR	Compression Ratio	—
HRR	Heat Release Rate	J/°CA
CHR	Cumulative Heat Release	J
MGT	Mean Gas Temperature	°C
Pmax	Maximum Cylinder Pressure	bar
CO	Carbon Monoxide	ppm or %vol
CO_2	Carbon Dioxide	%vol
HC	Hydrocarbons	ppm
NOx	Nitrogen Oxides	ppm
O_2	Oxygen	%vol
H_2	Hydrogen	%vol
CH_4	Methane	%vol
N_2	Nitrogen	%vol
LHV	Lower Heating Value	MJ/Nm^3
CV	Calorific Value	MJ/kg
PG	Producer Gas	—

Abstract

India's economy is mostly agricultural-based and India's forest cover covers approximately 24% of land area. Subsequently, tons and tons of biomass in the form of wastage are generated every year in the nation.In the global arena, the three key fossil fuels, namely oil, coal, and natural gas, presently supply nearly 81.4% of the primary energy requirements in the world. The next largest share, i.e., approximately 9.7%, comes from biomass (mostly ethanol and biodiesel) and waste. Installed power generation capacity in India is 456747 MW as on Dec 2024. Total power generated capacity through Renewable energy is 46.3% of the total capacity out of which Approximately 32% of India's total primary energy demand comes from biomass. Biomass is produced in different forms like agriculture residue, forest residue, sewage sludge, herb residue, landfill gas and biogas, and alcohol fuels .Biomass gasification is a prevalent utilized thermochemical procedure for the transformation of biomass to useful products which are more useful and have more uses than the raw material. Gasification transforms biomass feedstocks into burnable gas (producer gas), which may be utilized in order to generate mechanical and electrical energy, synthetic fuel, and chemicals.

Growing fears of depleting energy resources and adverse environmental conditions have driven the world towards more green energy production methods. Faced with these new challenges, renewable energy sources have become the number one priority industry. Amongst these, biomass too has been foremost in the list of promising energy providers, providing a natural, green, and abundant source of fuel for replacement of traditional fossil fuels. The work in this research is centered on the production of syngas through gasification of dry coconut shells and pine cones in a downdraft gasifier and experimentation with this syngas in a variable compression ratio dual-fuel engine. Key parameters like gas composition, major fuel parameters (proximate analysis), elemental chemical content (ultimate analysis), and energy content (calorific value) were measured to determine the quality of dried coconut shells and pine cones as a fuel. Engine performance and other performance characteristics were also tested to see how well the syngas derived from these biomass samples can be utilized. The research shows that the syngas from dried coconut shells and pine cones can improve engine performance. This places it in a good position to be used as a substitute fuel in dual-fuel systems.

Chapter1 Introduction

Energy plays an important role as a catalyst of economic growth for a developing nation like India. With the nation achieving a 10% high economic growth, the energy demand is rising sharply in agriculture, industry, transport, commercial businesses, and domestic use.[1] Carbon emissions and per capita energy use will rise by 12% and 25%, respectively, by 2035.[13] Wood forestry is the dominant source of bioenergy with more than 85% of the entire biomass utilized for the end-use of energy generation.[7] Forest biomass can be converted into bioenergy and assist in reducing greenhouse gas (GHG) emissions and conserving the environment. For example, in British Columbia, utilizing available forest biomass for bioenergy production can lower GHG emissions by 7.1 to 8%.[2] Indian forest cover is approximately 0.71 million square kilometers and accounts for nearly 21.71% of the nation's overall geographical area.[3] When population is growing and industries are expanding their operations, fossil fuels are utilized at a greater rate. Most of India's energy is oil and coal-based. They are limited fuels, so one day they will deplete. It is for this reason that we need to find out other sources in order to fulfill our energy demands.[4] Biomass is more handy compared to other renewable energy since it does not heavily depend on geographical location or weather. It is easy to store and transport as well, hence easier to utilize.[5] Biomass is converted into energy with the help of different processes like burning (combustion), decomposing it thermally without air (pyrolysis), gasifying it (converting it into gas), or splitting it into liquid fuel (liquefaction) with the help of biochemical and thermochemical processes.[6] Gasification plays an equally significant role in fulfilling the world's future energy requirement. This thermochemical process transforms biomass into useful products such as syngas of high quality, fuels, and chemical feedstocks. In comparison to combustion and pyrolysis, gasification yields a cleaner gas, that is, greater energy efficiency with more heat produced.[7] Syngas, which consists of carbon monoxide (CO) and hydrogen (H_2), is formed in the process of gasification of carbonaceous material. It is most widely employed in the generation of electricity and industrial fuels and other chemicals.[8] Syngas may also be used directly as a fuel for both spark ignition (SI) and compression ignition (CI), internal combustion engines.[9] Dual-fuel engines can also be operated with a combination of syngas and standard fuels, where burning is more efficient. This adaptability is generally accountable for better fuel economy as well as greater overall engine efficiency compared to conventional single-fuel systems.[10] Energy generation from various biomass fuels such as coconut shell, rice husk, cotton stalk, and wood remains to be studied. Such conventional methods of using biomass are not efficient enough, so it has a fair chance of maximizing its usage by making it into better substitute fuels. [11] Compared to petrol, operation of a dual fuel engine running on producer gas and fossil fuel significantly reduces the emissions of hydrocarbons. (HC), carbon monoxide (CO), and nitrogen oxides (NOx). The results obtained can be used by researchers working on gasifier design and investigating the potential of using producer gas as an auxiliary fuel for spark ignition (SI) and compression ignition (CI) engines. Use of producer gas derived from biomass feedstocks in internal combustion engines has the capability of bringing down the fossil fuel reliance of industrialized nations.[12] The paper in this analysis investigates the use of coconut shells and Cone Pine as possible downdraft gasifier fuels and also reviews the behavior of the syngas generated in dual-fuel engines. The research therefore attempts to improve the understanding of renewable energy by analyzing the composition of syngas and assessing the efficiency of syngas in variable compression ratio dual-fuel engine.

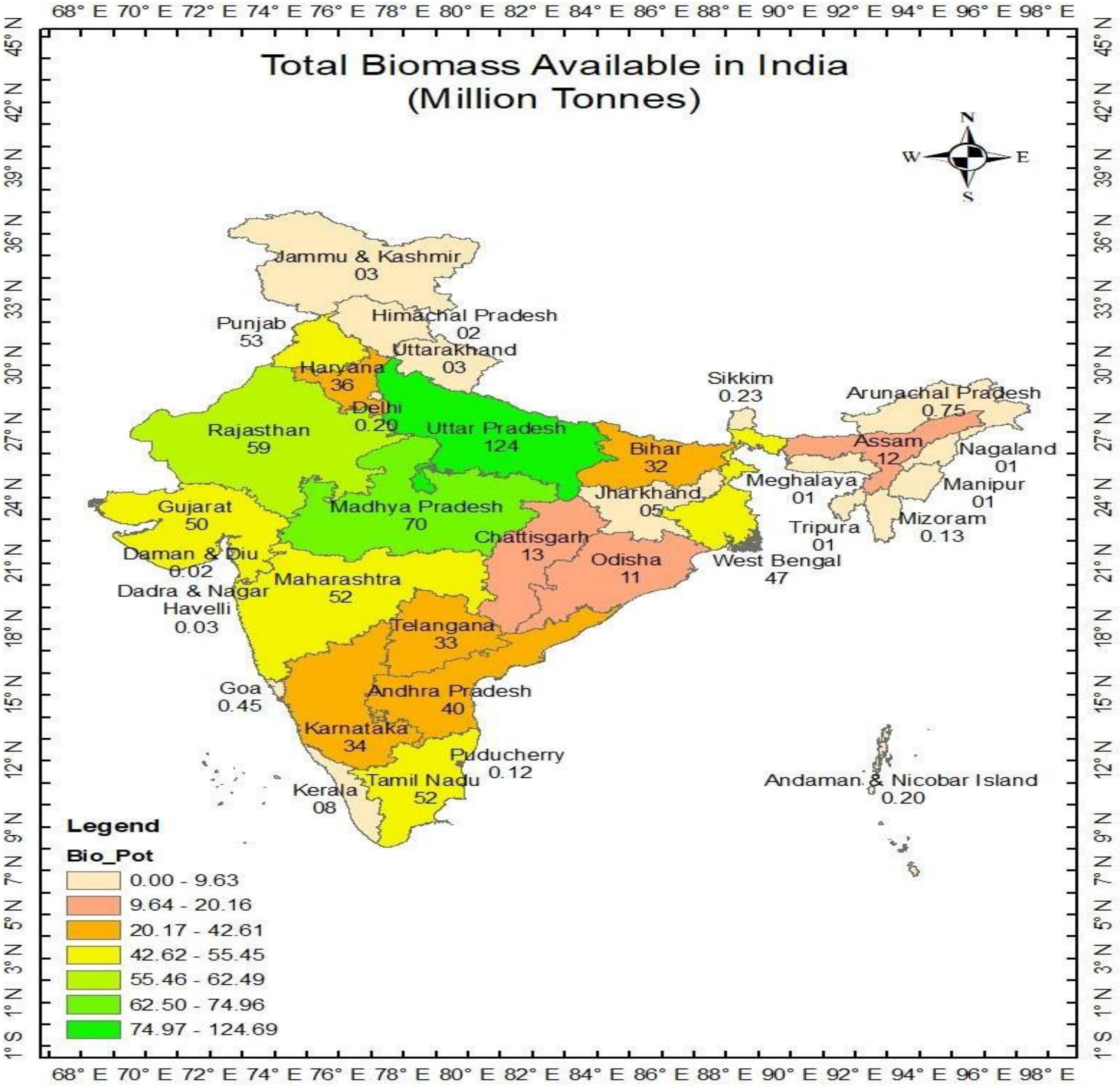


Fig.1 Biomass Potential in India State wise
(Source site - https://nibe.res.in/english/biomass-atlas.php)

States	Total	Power Potential (MW)
Andaman & Nicobar	131.7	18.1
Andhra Pradesh	17093	1999.5
Arunachal Pradesh	173.8	18.5
Assam	2541	321.9
Bihar	7983	964.4
Chandigarh	1.11	0.1
Chhattisgarh	2651.8	353.7
Dadra & Nagar Haveli, and Daman &Diu	12.16	1.6
Goa	231.4	33
Gujarat	21740.3	2637.8
Haryana	10907.5	1353.3
Himachal Pradesh	572.2	69.7
Jammu & Kashmir	652.3	82.8
Jharkhand	1201.8	146.3
Karnataka	14048.5	1793.9
Kerala	6042.1	778.4
Madhya Pradesh	19928.3	2516.4
Maharashtra	21493.8	2629.5
Manipur	484.9	62.3
Meghalaya	561.3	68.5
Mizoram	22.9	2.9
Nagaland	438.3	54.1
Odisha	227.6	298.7
Puducherry	37.8	5
Punjab	2251	3022.1
Rajasthan	10211	1299.5
Sikkim	40	4.7
Tamil Nadu	12217.4	1560.1
Telangana	13761.6	1678.4
Tripura	254.9	34.3
Uttar Pradesh	21600.7	2800.3
Uttarakhand	723.3	93.3
West Bengal	16277.3	1741.7
Total	**228516.9**	**2844.5**

Table 1 List of states with biomass energy production capacity.
(Source site- https://nibe.res.in/english/biomass-atlas.php)

Total includes –Arhar/Tur, Bajra, Banana, Barley, Coriander, Cowpea (Lobia), Dry chillies, Garlic, Ginger, Gram, Groundnut, Guar seed, Jowar, Jute, Linseed, Maize, Masoor, Mesta, Moong (Green Gram), Moth, Onion, Other Kharif pulses, Other oil seeds, Peas & beans (Pulses), Potato, Ragi, Rapeseed & Mustard, Rice, Sesamum, Small millets, Soyabean, Sugarcane, Sunflower, Sweet potato, Tobacco, Turmeric, Urad, Wheat.

The biomass is available in 1000 tons per year.[31]

1.1 International Biomass Status

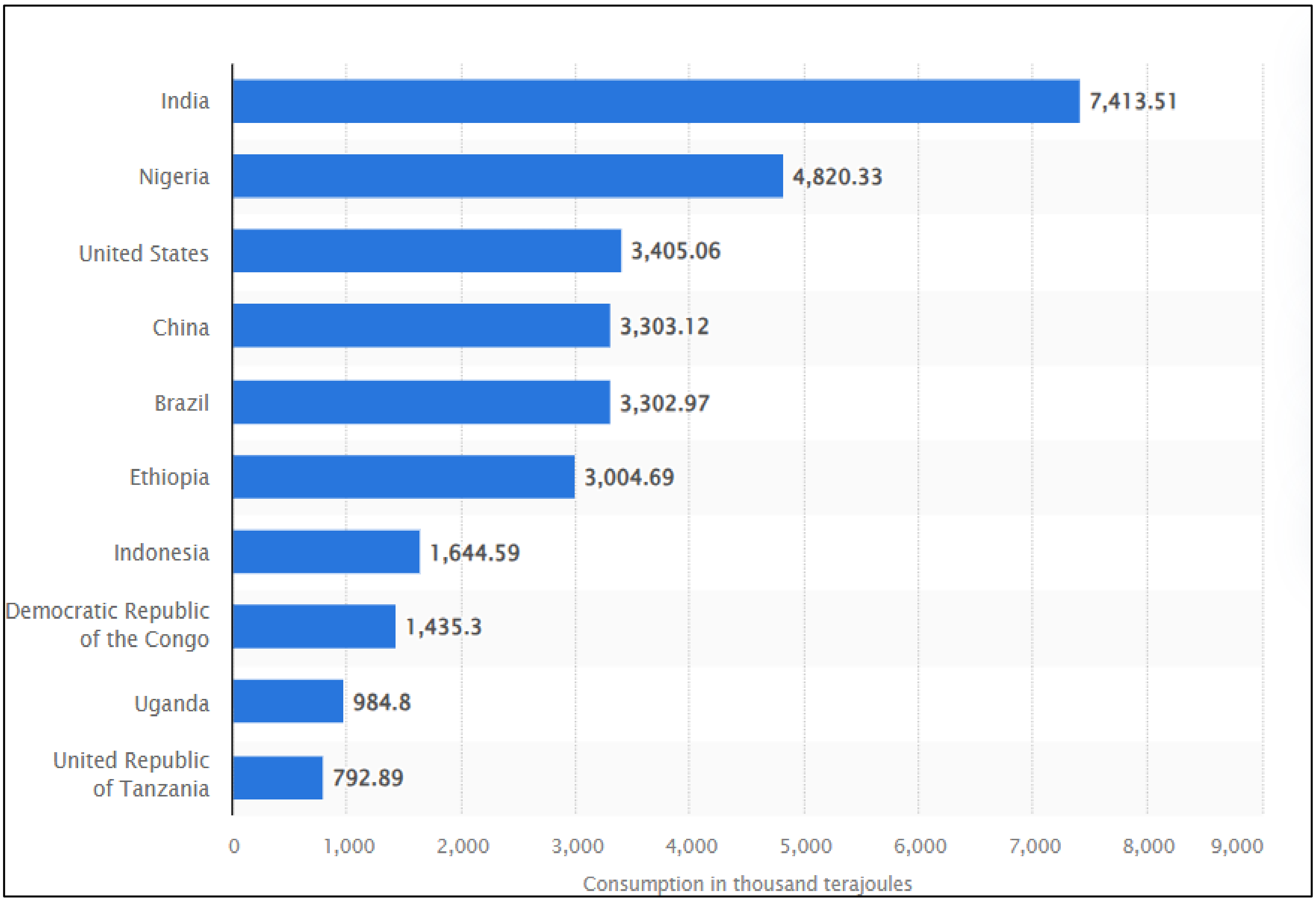


Fig.2 Total consumption of bioenergy worldwide in 2022.
(Source Site- https://www.statista.com/statistics/1495674/global-consumption-of-bioenergy-by-leading-country/?utm_source)

Upto 2022 , the countries that used the most bioenergy were India, Nigeria, China, the United States, and Brazil. India was the top user, followed by Nigeria. These countries mostly use bioenergy from sources like firewood, crop waste, and biofuels. In many parts of India and Africa, people still use traditional methods like burning wood and charcoal for cooking and heating. In contrast, countries like the U.S., China, and Brazil also use modern systems that turn plants, waste, or sugarcane into electricity and fuel. Overall, Asia and Africa together used more than half of the world's bioenergy, showing how important it is in both rural and industrial areas.[32]

1.2 Motivation of My Work

The motivation behind this project is to use the biomass residue which is not being used from several years.It helps create a renewable fuel that can work with existing engines with only minor changes needed.Producer gas is a cleaner alternative to traditional fuels like coal and petroleum, as it produces fewer pollutants and greenhouse gases, helping to reduce environmental impact and combat climate change.

- It helps decrease reliance on traditional fuels, resulting in cost savings.
- Provides energy to rural areas where there are economic constraints.
- To address the problem of air pollution from open biomass burning and the release of harmful gases like CO2, CH4, N2O, H2S, O3, and smog and also in reduction of forest fires.
- Offer farmers a different way to earn money by providing new opportunities or revenue streams.

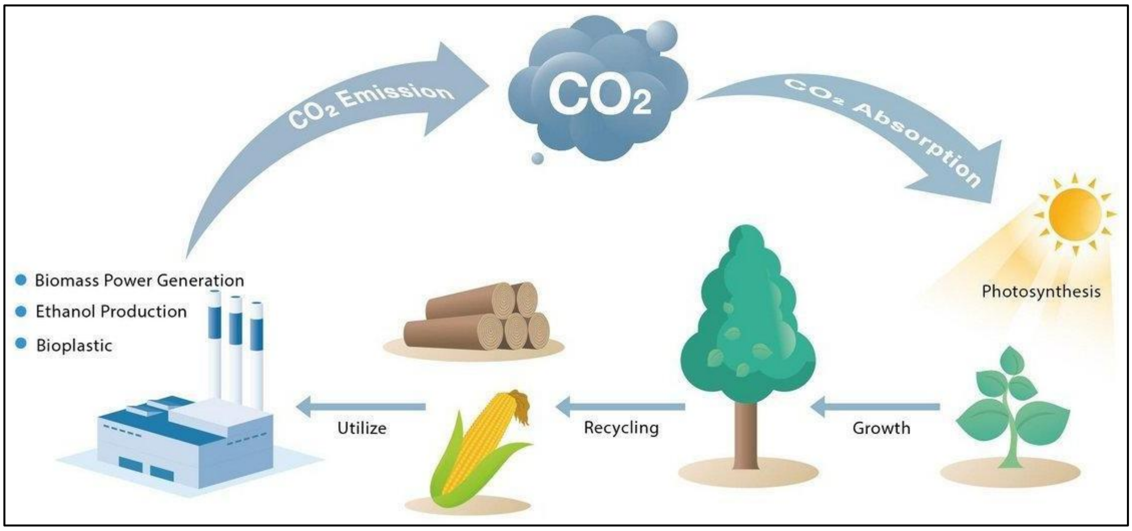


Fig.3 Power Generation from Biomass
(source site -https://www.horiba.com/aut/processand-environmental/industries/biomass-power-generation)

Chapter 2 Literature Review

2.1 Biomass

Biomass refers to the organic material that comes from plants and animals. Unlike fossil fuels, it doesn't take millions of years to form. Biomass is created when carbon dioxide from the air and water from the ground are turned into carbohydrates using sunlight and chlorophyl. [33].Chemically, biomass is made up of organic compounds mainly hydrocarbons that contain carbon, hydrogen, and oxygen. It can be generally represented by the formula $C_{6n}(H_2O)_5$, which reflects its carbohydrate-like structure.[39] It is generated in various forms such as agriculture residue, forest waste, sewage sludge, herb residue, landfill gas and biogas, and alcohol fuels [33]

2.2 Composition of biomass

2.2.1 Cellulose

Cellulose is the part of biomass that gives it strength because it has a strong fiber-like structure. In woody biomass, about 45–50% of the weight is cellulose. It is made from many glucose (sugar) units joined together, so it has a high weight. One cellulose chain can have 5000 to 10000 glucose units. When biomass is heated quickly, a cracking or popping sound can be heard. This happens because thin layers of cellulose are twisted into tube shapes that hold moisture inside. Cellulose starts to break down when the temperature reaches 240°C to 360°C. At this point, most of it changes into gases, and a small part becomes tar and char.[34]

2.2.2 Hemicellulose

Hemicellulose is an important part of wood, making up about 25–30% of its dry weight. It is lighter than cellulose and has shorter chains, with around 150 units. Unlike cellulose, it is made from different kinds of small molecules and has a branched shape. It is also called polyose. Hemicellulose breaks down at lower temperatures (200°C to 260°C). When it breaks, it makes more gases and less tar and char compared to cellulose. So, it gives a higher amount of gas than cellulose.[35]

2.2.3 Lignin

Lignin is an important part of lignocellulosic biomass and makes up about 10–35% of the dry weight, providing around 40% of the energy. In industries like paper, sugar, and ethanol, lignin is often treated as waste. Hard types of biomass have less lignin, while softer ones have more. Lignin doesn't have a fixed shape (it's amorphous), and its exact structure isn't fully known. It has a complex, branched 3D structure. There are two natural types: guaiacyl lignin (found in hard biomass) and guaiacyl-syringyl lignin (found in soft biomass). Guaiacyl lignin comes from coniferyl units, while the second type is made from both coniferyl and sinapyl units. Lignin breaks down at high temperatures (280°C–500°C), producing phenols and mostly char. The liquid that comes out during heating is called pyroligneous acid, which contains 20% water and 15% leftover char.[36]

2.2.4 Volatiles

Volatiles are substances that easily vaporize at relatively low temperatures, typically referring to compounds that can evaporate or gasify, such as alcohols, oils, and certain chemicals.[37]

2.2.5 Organic Matter

Organic matter refers to substances that are primarily composed of carbon-based compounds originating from living organisms. It exists in both non-crystalline and crystalline solid forms. The non-crystalline form includes key structural components such as cellulose, hemicellulose, and lignin, which are commonly found in plant biomass and agricultural residues. On the other hand, the crystalline form comprises organic minerals like calcium, magnesium, potassium, and sodium oxalates, among others. These forms of organic matter play an essential role in energy production processes such as anaerobic digestion, where they are broken down to generate biogas.[38]

2.2.6 Inorganic Matter

Inorganic matter consists of non-living, mineral-based substances and is found in various solid states: crystalline, semi-crystalline, and amorphous. The crystalline form includes well-defined mineral species such as phosphates, carbonates, silicates, chlorides, sulphates, and nitrates. Semi-crystalline inorganic matter contains poorly crystallized minerals like some silicates, phosphates, and hydroxides, representing transitional phases between amorphous and fully crystalline materials. The amorphous form lacks an ordered structure and includes materials like glasses and silicates. Inorganic matter is crucial in determining the chemical and physical stability of materials, particularly in waste treatment and soil composition.[38]

2.3 Four Major Types of Biomass

Biomass is generally grouped into **four main types** based on its origin:

1. Wood and Agricultural Residues
2. Animal Waste
3. Municipal Solid Waste
4. Industrial and Commercial Waste [33]

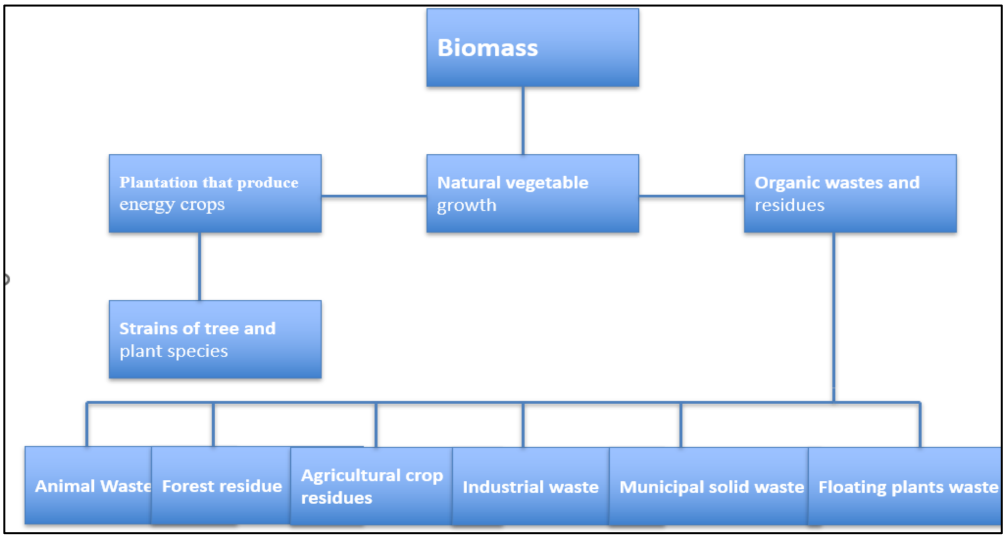


Fig.4 Flow Chart of Types of Biomass

2.4 Biomass Gasification

Biomass gasification is the process of incomplete combustion of biomass, which results in producing a blend of combustible gases such as carbon monoxide (CO), hydrogen (H_2), and traces of methane (CH_4). This blend of gas is referred to as producer gas. It is used to fuel internal combustion engines (diesel and petrol types)[14] It is a very effective process for control of waste, production of chemicals, and energy production from novel materials such as forest residues, agricultural residues, poultry dung, municipal waste, and sewage.[15] Biomass is natural biopolymers made largely of cellulose (35–55%), hemicellulose (20–40%), and lignin (10–25%) by weight.[17] As a general rule, increasing the proportion of (cellulose + hemicellulose) relative to lignin tends to lead to higher synthesis gas yield.[18] Gasification of biomass requires a gasifying medium to generate synthesis gas, primarily carbon monoxide (CO) and hydrogen (H_2), which can be further converted into valuable chemicals and biofuels. Typical gasifying agents are air, steam, oxygen, or supercritical water . Air is the most readily available and least expensive gasifying agent in gasification.[16] During gasification, the air-to-fuel ratio employed is typically 1.5:1 to 1.8:1, whereas the greater proportion of 6:1 to 6.5:1 is necessary for full combustion of biomass, hence resulting in half burning during gasification.[19,20].

2.5 Gasifiers

Generator gas (or producer gas) is produced through the gasification process, which includes partial combustion of solid biomass in a temperature range of approximately 1000°C in a reactor referred to as a gasifier. Complete combustion has by-products that are typically nitrogen, water vapor, carbon dioxide, and excess oxygen. But in gasification, when oxygen is less than there is of solid fuel (incomplete combustion), the products that are produced are volatile flammable gases such as carbon monoxide (CO), hydrogen (H2), and traces of methane, alongside unwanted by-products such as tar and dust.[40]

Types of Zones

2.5.1 Drying Zone

This is the first step in gasification where extra moisture is removed from the biomass. The temperature in this zone is between 100°C and 130°C.[43] The moisture content of biomass can differ depending on the material's nature and condition.[41] If biomass has too much moisture, it needs to be dried before using it for gasification a s having too much moisture wastes energy and lowers the quality of the final output.[42] In the drying zone, the moisture in the biomass turns into water vapor. The heat needed for this comes from the hotter combustion zone below. Drying is an endothermic process, meaning it absorbs heat, using about 2400 kJ of energy to evaporate each kilogram of water.[44]

2.5.2 Pyrolysis zone

This is below the drying zone. This is the zone where heat is first deconstructing the biomass, pyrolysis.[43] Here, large molecules are reduced to small molecules to form biochar, liquid by-products, and gases.[45] Organic materials are broken down by heating them to around 200°C without any oxygen present. General reaction for the pyrolysis process is given by:[46]

$CnHmOp\ (\text{Biomass}) \rightarrow \sum \text{Liquid}\ CxHyOz + \sum \text{Gas}\ CaHbOc + H2O + C\ (\text{Char})$

2.5.3 Combustion Zone

Here, biomass begins to burn by using a small quantity of oxygen and a controlled oxidation process occurs.[47] In this zone, the final products formed include char, tar, and gases like CO, CO_2, H_2, and H_2O. The heat released is partly used to dry the biomass and partly to support the pyrolysis process.[49,50 The overall heat produced in the combustion of biomass is lower compared to the heat produced in the gasification process.[48] The temperature of this zone varies between 850°C and 900°C.[49].

2.5.4 Reduction Zone

This is the central region where gasification occurs. Products in the combustion region are also reduced to CO, CH_4, H_2, and CO_2. Nitrogen (N_2) is produced too, although the temperature of this region of the gasifier is quite low.[51]This region is called the reduction region as it reduces tar particles in the gas by taking them to a high temperature level of about 1000°C.[52]The process of biomass gasification involves a series of chemical reactions, which can be described as follows: [21]
Oxidation zone

$C + O_2 \rightarrow CO_2$ $\Delta H = -406$ kJ/mol.............................. (1)

$2C + O_2 \rightarrow 2CO$ $\Delta H = -123$ kJ/mol............................(2)

Reduction zone

Water-gas reaction:

$C + H_2O \rightarrow CO + H_2$ $\Delta H = 131.4$ kJ/gmol………………(3) .

Boudouard reaction:

$C + CO_2 \rightarrow 2CO$ $\Delta H = 172.6$ kJ/gmol.............................. (4)

Water-gas shift reaction:

$CO_2 + H_2 \rightleftharpoons CO + H_2O$ $\Delta H = 42$ kJ/gmol.........................(5)

Methane formation reaction:

$C + 2H_2 \rightleftharpoons CH_4$ $\Delta H = -75$ kJ/gmol [21] .... (6)

2.6 Types of Gasifier

1. Downdraft Gasifier
2. Updraft Gasifier
3. Cross draft gasifier
4. Fluidized Bed Gasifiers

2.6.1 Downdraft Gasifier

The upper cylindrical part of a downdraft gasifier is used as a hopper or chamber for receiving wood chips or other biomass fuel.[29] The fuel is charged through the top, and the gas produced comes out from the bottom.[26] The gasifying agent is placed in the center of the gasifier, where burning takes place.[27] Air inlets are sloping so that air is taken into the combustion chamber in a downward direction.[28] Below the cylindrical portion of the gasifier radially positioned air nozzle creates room for air to enter and get mixed with the biomass chips as they travel downward for gasification. Since air interacts with the pyrolyzing biomass prior to entering the char, it fuels combustion, resulting in a flame. Because of the insufficient supply of air within the gasifier, the available oxygen is rapidly depleted, resulting in a heightened flame as pyrolysis increases [29] Because the biomass and gas flow in the same direction in a downdraft gasifier, it is also referred to as a co-current gasifier.[30]

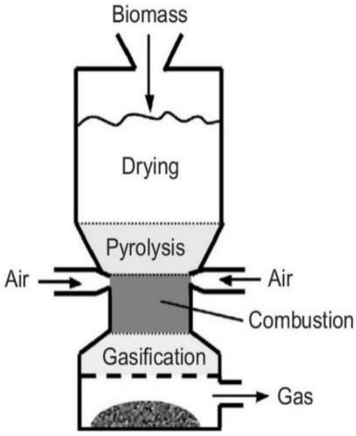


Fig.5 DownDraft Gasifier [125]

2.7 Dual Fuel Engine

In a dual fuel engine, two different fuels are used together generally, one as a gas and the other as a liquid. In some arrangements, both the fuels can be gaseous; however, it is required that at least one of the fuels is in a gaseous form to provide a stable dual fuel operation.[53] Syngas, a fuel gas that is mostly hydrogen (H_2) and carbon monoxide (CO), can be produced from diverse sources like biomass and waste products.[54] In this arrangement, syngas is used as the main fuel, and a small amount of diesel is injected as pilot fuel for the purpose of ignition. This two-fuel strategy not only enhances the performance of the engine but also helps in reducing emissions, especially the greenhouse gases and the unburned hydrocarbons.[58] In World War I, there was a lack of conventional fuels, and hence Dr. Rudolf Diesel conceived the concept of a dual fuel engine.[55] In World War I, the infrastructure had progressed enough to generate a good quantity of natural gas. But because there was limited technology then, natural gas was mostly utilized for domestic requirements or in certain steel plants. Afterwards, owing to some circumstances, it began to be utilized in dual fuel engines. Now, since natural gas is clean and does not pollute significantly, it is now widely suggested for the use in light and heavy transport vehicles, particularly for use in populated cities.[56,57]

Natural gas is a fuel that does not emit smoke, therefore nowadays it is widely suggested for use in both small and large vehicles.[59] Because gaseous fuels require a greater compression ratio, they can generally burn self-sustainingly because they have a high self-ignition temperature. But in certain instances where they can't burn on their own,a small quantity of another fuel is used to initiate the combustion[60].

Diesel engines are robust and designed for heavy duty. They have a high compression ratio in itself, making them ideal for modification into dual fuel engines. Diesel engines also react fast to changes in speed, load, and fuel supply. For the experiments in this study, a diesel engine operated in dual fuel mode was employed.[61,62]

2.8 Performance Characteristics of DF Engine

Dual-fuel engines are unique engines with the ability to combust diesel and another form of fuel such as natural gas or hydrogen simultaneously. It thus makes them more convenient because they can utilize any fuel that is in supply or most affordable. They are also less harmful in terms of gases, particularly carbon-based ones, which is good for the environment. Another advantage is that such engines can run at higher compression, thus making them more efficient fuel-wise in general.[63,64] Dual-fuel engines are relatively inefficient when operating with low loads.[65] During low loads, there is a poor mixture of fuel and air, and this results in retardation of ignition. This ignition delay is the primary cause of loss of engine performance under these conditions.[66] Earlier experimental research had indicated that dual-fuel engines have much superior performance compared to conventional fuel engines at high load conditions. In such conditions, the air-fuel mixture is more evenly distributed within the cylinder and the gas particles occupy the interparticle space. This is a very combustible state, thus improving the combustion efficiency of the engine. Therefore, combustion occurs faster and more thoroughly, reducing the risk of incomplete combustion.[67] On average, it was noted that the efficiency of the dual fuel system is almost comparable to the pilot fuel mode. For example, whereas the engine efficiency in pilot fuel mode is an average of approximately 32%, in dual fuel mode it is approximately 28%.[68] Dual-fuel engines have the ability to produce less nitrogen oxides (NOx) and particulate matter (PM) under certain conditions and based on the fuel being used, compared to diesel-only engines. Yet, this decrease is not always uniform and may differ based on factors like the selection of secondary fuel, injection timing, and the operating load of the engine.[69] Both dual-fuel engines and diesel engines can keep the high compression ratios characteristic of the diesel engine, something that helps them to preserve their fuel efficiency.[70] The engines can operate very well even when operating on gas solely. This means that they operate effectively in all three modes using only diesel (pilot fuel), only gas, or both together (dual fuel). They can also transition quickly and easily between these modes, which renders them very flexible and effective.[71]

2.9 Emission Characteristics of DF Engine

Dual-fuel compression ignition (DFCI) engines, running on a gaseous fuel like natural gas mixed with a small amount of diesel as pilot fuel, have distinctive emission characteristics. These engines can reduce nitrogen oxides (NOx) emissions considerably compared to conventional diesel engines. But under low load conditions or in case of the pilot diesel fuel injection being negligible, a rise in unburned hydrocarbons (UHC) and carbon monoxide (CO) emission is typically seen because of incomplete combustion.[72,73] During low load operation, the engine has a different emission trend. The restricted oxygen supply within the combustion chamber causes incomplete combustion of the fuel. This leads to an impressive boost in the emission of unburned hydrocarbon (HC) and carbon monoxide (CO). But the amount of nitrogen oxides (NOx) and exhaust gas temperature is less. This is due to the lowered combustion efficiency, which reduces the heat produced, and the operating chamber at a reduced temperature means the production of NOx is significantly reduced. Under dual-fuel combustion, this impact is even more pronounced, with NOx emission reduced by some 40% to 75%.[74]

2.10 Advantages of Dual Fuel (DF) engine

1. Can run on both gas and diesel (fuel flexibility)
2. Lower fuel cost due to cheaper gaseous fuels
3. Reduced emissions (CO, HC, NOx) at higher loads
4. High thermal efficiency, especially at full load
5. Maintains power and torque like diesel engines
6. Smooth switching between fuel modes
7. Less knocking compared to spark ignition engine.
8. Easy to modify existing diesel engines
9. Cleaner combustion leads to longer engine life.

2.11 Review of Previous Research Work

In this, the comparison of some important research papers in terms of the gasifier, emission characteristics of the engine and dual fuel engine performance under different operating conditions has been discussed.

Singh et al. (2016) did an experiment using a downdraft gasifier where they mixed sugarcane bagasse and carpentry waste in equal amounts. Gas from this blend was utilized together with diesel fuel in a dual-fuel engine. They found that using this setup reduced the use of diesel and also lowered NOx emissions. However, the sound level increased by 3.4 dB, and there was also a rise in CO and HC emissions. They mentioned that with some small changes, the system's pollution and performance could be improved. They also suggested that the gasifier design should be changed a bit, especially the throat part, because it causes blockage when using low-density fuels.[72]

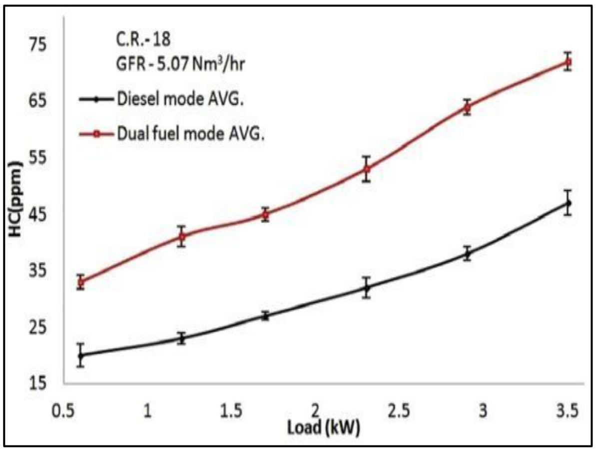


Fig.6 HC emissions with load variation

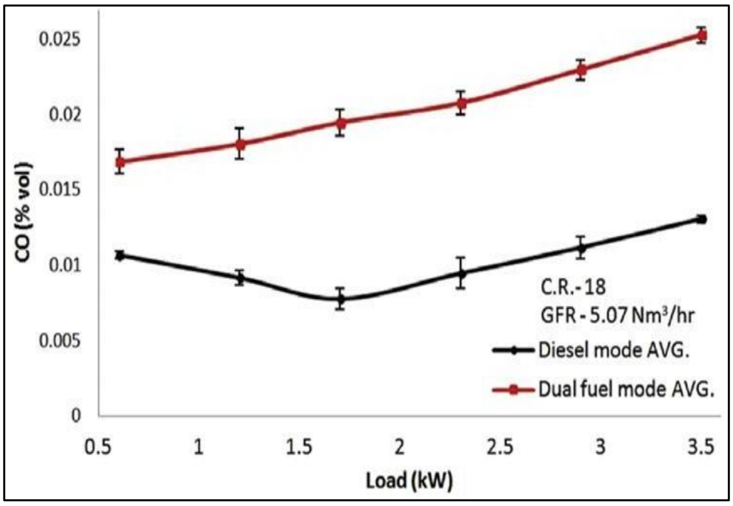


Fig.7 10 CO emissions with load variation.

Malik et al. (2016) compared the performance of a dual-fuel engine on operation with gas generated from cotton stalks using a downdraft gasifier. They determined that operation on dual-fuel mode consumed less diesel than when only diesel was used, conserving around 51% diesel. CO emission in dual-fuel mode was higher, yet NOx emission went down. There was an improvement of 40% in brake thermal efficiency because of the high methane content in the producer gas. They further demonstrated that power generation through biomass gasification is economically less expensive compared to conventional practices since it uses waste or low-cost biomass as fuel.[76]

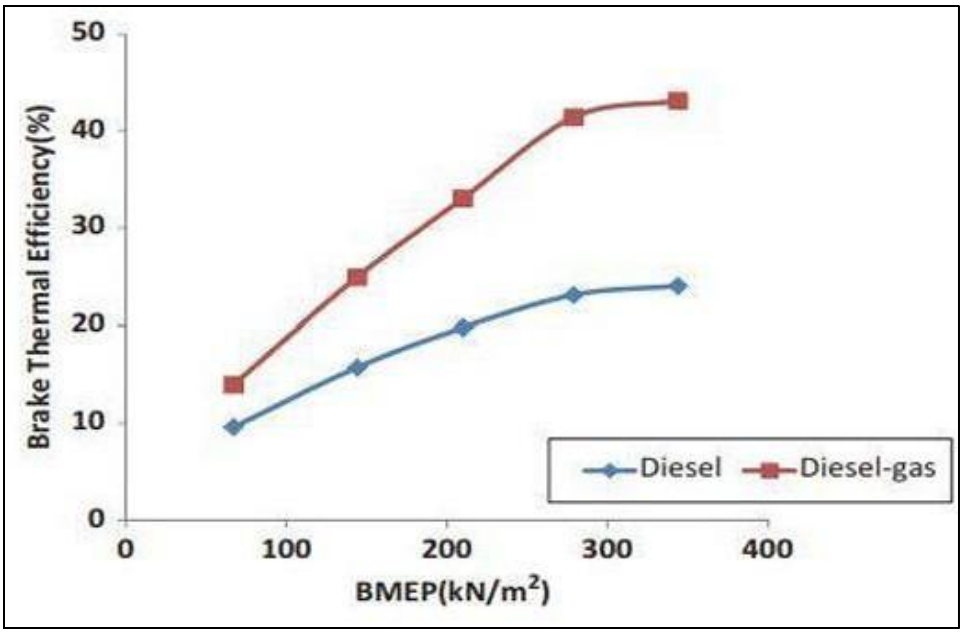


Fig.8 Brake thermal efficiency of engine w.r.t. BMEP

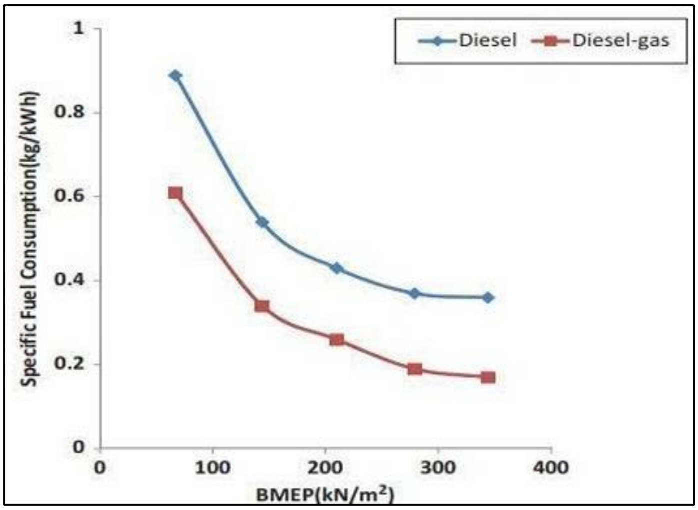


Fig .9 Specific fuel consumption of engine w.r.t. BMEP

R. Uma et al. (2004) analyzed the emission characteristics of a dual-fuel engine at various load conditions. The exhaust NOx, CO, HC, SOx, and particulate matter emissions were measured and compared under dual-fuel operation and pure diesel operation. They also examined the percentage of diesel that can be substituted during dual-fuel operation and emissions. Their findings indicated that the NOx and SOx emissions were higher at low loads. The CO and HC emissions were significantly higher for all the loads in dual-fuel operation. The NOx and SOx emissions were lower at high loads. They also found that most of the diesel fuel can be substituted by the secondary fuel in dual-fuel operation.[77]

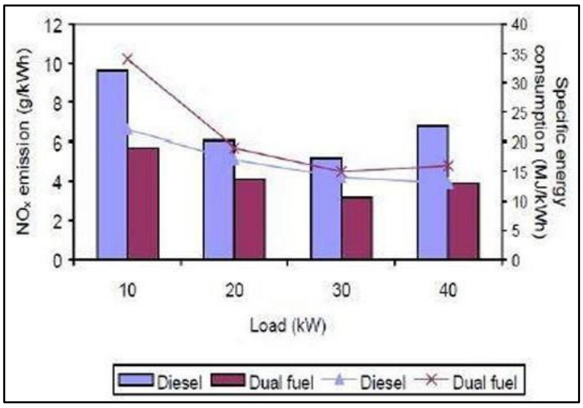
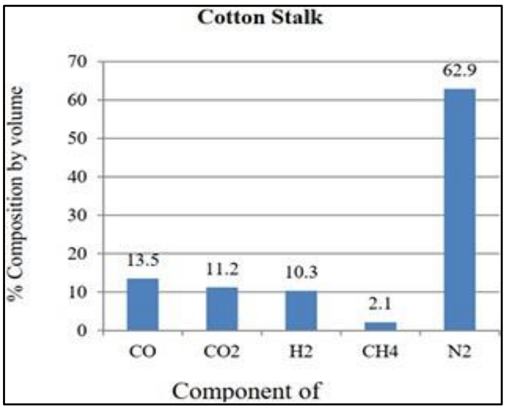


Fig.10 Comparison of NOx emission in diesel and dual fuel

S. Kumar, N. Saini, and S. K. Mohapatra et al. (2017) The research is based on the examination of producer gas composition for different uses. The process in the study involves the use of a process known as gasification, which is a sub-stoichiometric combustion process that converts solid biomass into a workable gas. Cotton stalks and sugarcane bagasse are the primary biomass feedstocks used. The resultant gas was experimented upon and compared. Pilot-scale downdraft gasifier was employed at Thapar University to employ the process with cotton stalk waste and sugarcane bagasse waste. The results indicated producer gas from cotton stalks held 13.5% carbon monoxide (CO) and 10.3% hydrogen (H_2) and sugarcane bagasse gas held 11.1% CO and 9.45% H_2 by volume.



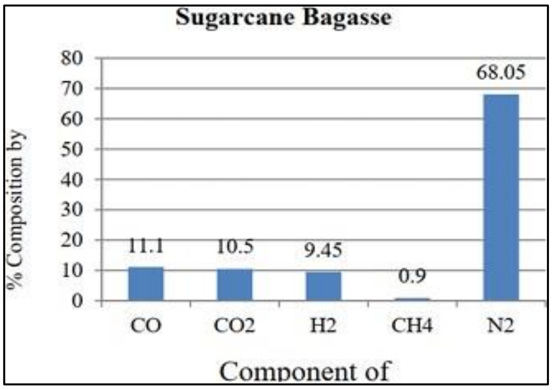


Fig.11 Producer gas composition of cotton stalk

Fig.12 Producer gas composition of sugarcane

A. E. Dhole, et al. (2014) In the current paper, the performance of dual-fuel engines has been evaluated based on brake thermal efficiency, fuel consumption, and engine operation at various loads and speeds. The engine was run with diesel as pilot fuel only and diesel and gas as pilot fuel. Relative to the diesel fuel alone run, greater speed at the same loads was attained by the engine on the diesel-gas fuel mixture. The study targets a 4-cylinder, 62.5 kW turbocharged and intercooled diesel engine operating under dual-fuel mode on hydrogen, producer gas, and their combination as secondary fuels. Emissions of unburnt hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) were compared with thermal efficiency. The paper also generates effective output on the engine performance at various loads and under variable conditions with various gaseous fuels. By the use of a 60:40 ratio of producer gas to hydrogen as the secondary fuel, brake thermal efficiency drops by 3%. But this blend evades the loss in efficiency typical at low loads in dual-fuel engines, provided the engine is operating above a 13% level of load.[79]

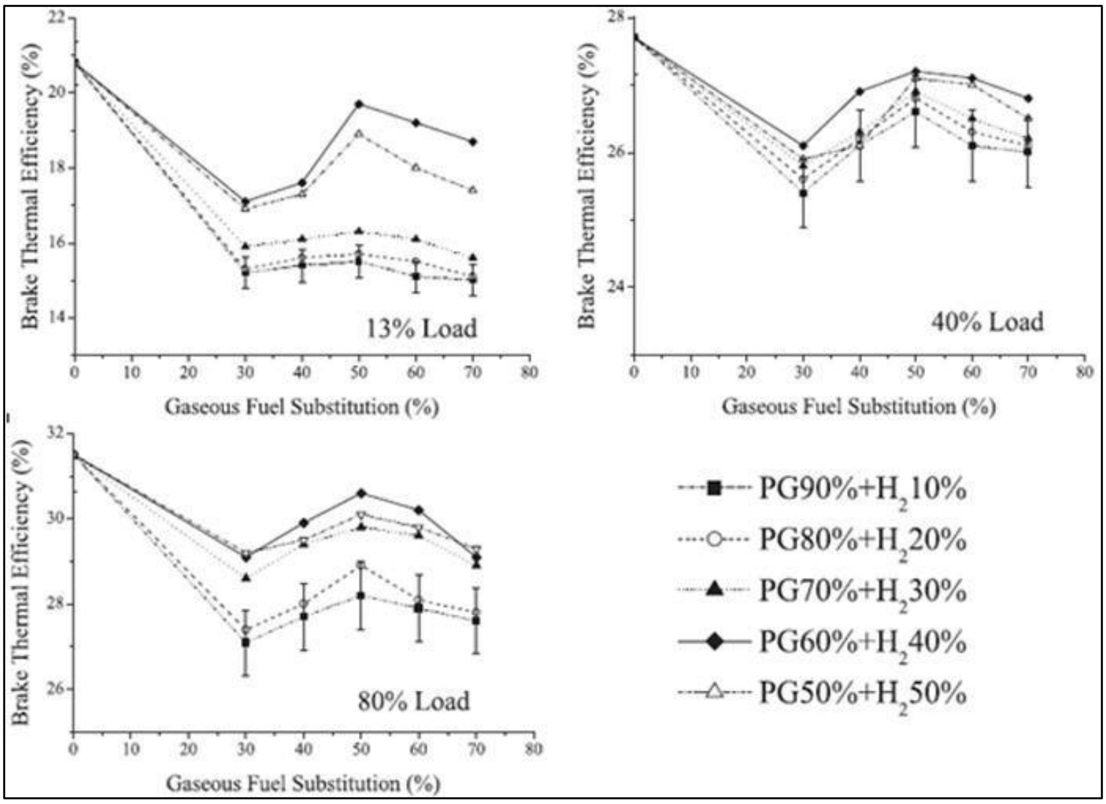


Fig.13 brake thermal efficiency (%) vs diesel + mixture gaseous fuel substitution (%) at different loads.

H Singh et al. (2019) For the present study, a downdraft biomass gasifier was tested by supplying it three different feedstocks, viz., sugarcane bagasse, cotton stalks, and wood chips. The two biomass blends were considered: (a) 1:1 mixture of wood chips and sugarcane bagasse, (b) 1:1 mixture of wood chips and cotton stalks. The results suggested that producer gas produced through these blends was capable of replacing diesel up to 54% in a dual-fuel engine with a corresponding reduction of about 6% in brake thermal efficiency. Further, dual-fuel operation increased hydrocarbon (HC) emissions and the severity of engine noise, while nitrogen oxide (NOx) emissions were significantly lower.[80]

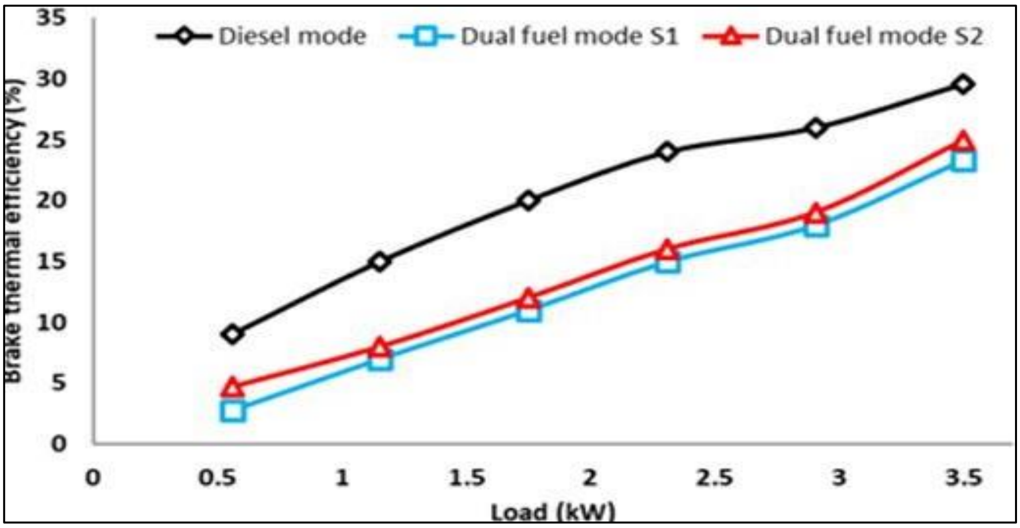


Fig.14 Variation of brake power with variation of load.

Shrivastava V. et al. (2013) have developed a downdraft gasifier with the feedstock blend of mustard oil cakes and wood chips in the proportion 7:3. An experiment was carried out to evaluate the performance and exhaust properties of a 4.4 kW rated, single-cylinder, four-stroke, air-cooled engine operating at 1500 rpm in dual-fuel mode. In this configuration, producer gas was supplied into intake manifold at 40 L/min, 60 L/min, and 80 L/min flow rates and diesel was the primary fuel. The performance of the engine in dual-fuel mode was compared with traditional diesel-only mode. The outcome showed a considerable decrease in diesel consumption during dual-fuel use but at a loss of brake thermal efficiency. A tremendous reductionin NOx emissions was observed in dual-fuel mode, which is a notable benefit over traditional dieseluse. On the contrary, carbon monoxide (CO) and unburned hydrocarbon (HC) emissions were recorded to be greaterin dual-fuel mode compared to diesel operation.[81]

D. Shaw et al. (2016) performed an experiment on the performance of a dual-fuel engine with different load conditions and engine speeds with high-speed diesel and producer gas-diesel blended fuel. Diesel was employed as the pilot fuel while producer gas served as the major source of energy in this dual-fuel engine. Key performance parameters like brake thermal efficiency, specific fuel consumption, and fuel consumption were compared and analyzed relative to conventional diesel-alone operation. The observations in the findings indicated that the engine ran at higher speeds when running on diesel–producer gas mixture relative to diesel alone. It was also observed with a significant decrease of 64.7% in the consumption of diesel although at the expense of 45% loss in brake thermal efficiency.[82]

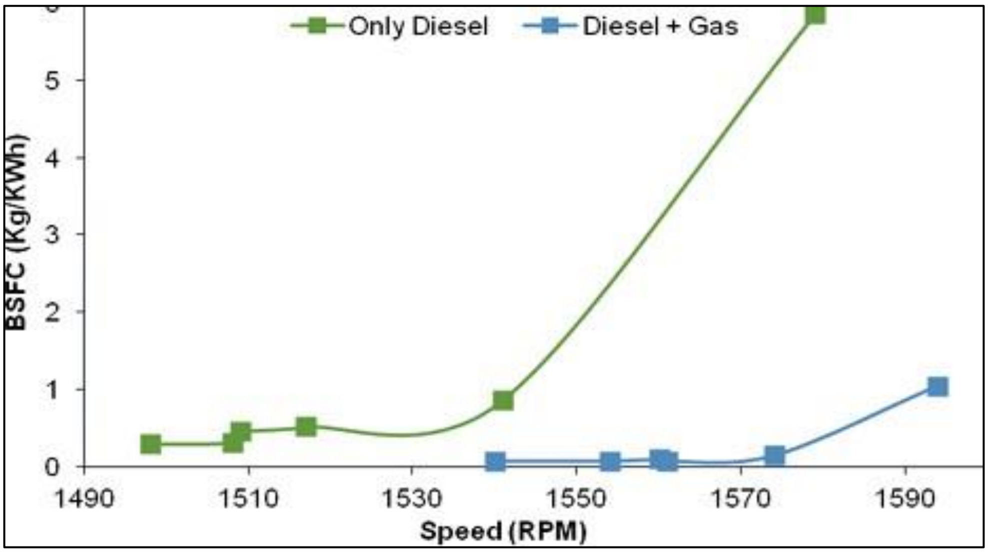


Fig.15 Variation of bsfc with speed (rpm)

Olgun H. et al. (2011) suggested a downdraft biomass gasifier system integrated with gas cleaning and cooling units. A throat was introduced inside the gasifier in their design innovation, and this led to an ample reduction in the tar content of the producer gas. Moreover, its calorific value (CV) went up accordingly. During the operation, the system maintained consistent performance without any problems of tar plugging and ash melting. The gasifier was operated using different biomass fuels like wood residues, bark, hazelnut shells, and olive pulp waste. When the equivalence ratio was 0.35, the best quality of gas was generated by the gasifier, whose maximum calorific value was 5.5 MJ/Nm^3.[83]

J. Singh et al. (2020) examined the hybridization of a downdraft gasifier with a dual-fuel engine system. The gasifier was utilized for the production of syngas from agricultural waste residues, i.e., cotton stalks and wheat straw, via the pathway of biomass gasification. This syngas when mixed with diesel was used as a fuel in a dual-fuel compression ignition (DFCI) engine. Its emissions and performance were also benchmarked against a standard diesel engine. The test saw the DFCI engine run effectively in dual-fuel mode with a decline of around 44.4% in diesel fuel consumption. Indicated power declined marginally by 3.49% as well. The research also indicated a significant drop in the emission of nitrogen oxides (NOx) and sulfur oxides (SOx) while operating in dual-fuel mode.[84]

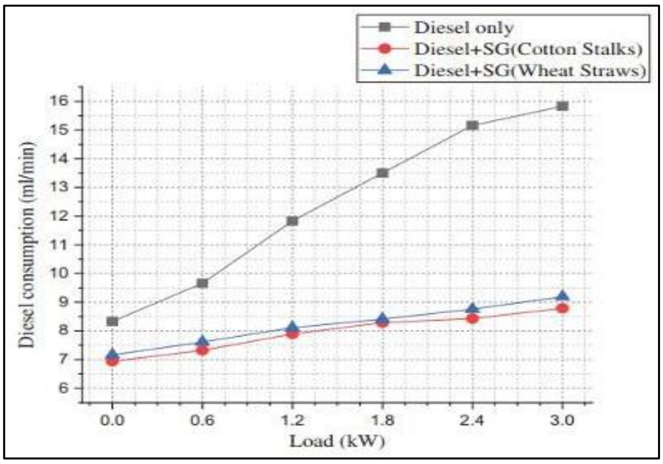


Fig.16 Load vs Diesel Consumption

Sivakumar et al. (2010) experimented with a downdraft gasifier to check the performance of various biomass materials during gasification. They chose three biomass materials—rice husk, groundnut shell, and coconut shell—and performed the experiments under a constant temperature of 800°C. They were primarily looking for the quality of producer gas from all these materials. The test indicated that the coconut shells provided the best performance. The coconut shell producer gas was 23% calorific value higher compared to groundnut shell and 45% higher compared to rice husk. It contained higher carbon monoxide: it was 17% higher than groundnut shell gas and 21% higher than rice husk gas. Gas from groundnut shells contained the highest hydrogen level. For methane, coconut shells even surpassed groundnut shells, emitting 6.1% more methane and rice husk 38% more methane. Based on the results, the study arrived at the conclusion that coconut shells are the best biomass to be used for gasification because they have higher carbon content and the emitted gas is of better quality.[85]

Tripathi et al. (1998) have studied how various residues from agriculture are present in various locations and times of India. Eight residue types were covered in the study: groundnut shells, rice husk, cotton stalk, maize stalk, mesta and jute sticks, arhar stalk, and maize cobs. They came to know that there is around eight million tonnes of the residue material per year, which can be utilized in order to produce some 1200 Peta Joules of power. In order to forecast the actual cost of utilizing the materials, the cost of residue and transportation distance was taken into consideration. The overall cost was between Rs. 132 and Rs. 628 per tonne, which is relatively inexpensive compared to coal in India. The research concluded that application of these residues in briquetting plants and electricity generation via gasification is a highly remunerative and cost-effective measure.[86]

D.K. Das et al. (2012) conducted a research by retrofitting a single-cylinder four-stroke 5.3 kW capacity diesel engine to operate in dual fuel and diesel-diesel mode. The dual fuel mode involved the operation of the engine using diesel and producer gas obtained from biomass. The thermal efficiency, specific fuel consumption (SFC), and the amount of diesel replaced by producer gas were experimented on by the team for engine performance. Wood chips, pea stalks, and corn cobs were the three types of biomass used. The gasification was done using a downdraft gasifier system with gas cleaning, cooling, and filtration and a specially designed gas-air mixing carburetor was used to supply the gas to the engine. Under the tests, the engine was operated at 1550 rpm as constant, and biomass with a moisture content between 8% and 21% was used. The research revealed that the engine thermal efficiency was very low under the dual fuel mode when compared to diesel-alone mode. The diesel consumption, however, fell significantly—by 60% to 64%—but continued to provide the same amount of energy output. Diesel replacement efficiency was also significant: 74% for wood chip, 78% for corn cob, and 82% for pea stalk. This indicates that biomass gas blending with diesel can be employed as an efficient substitute for fuel saving and economy.[87]

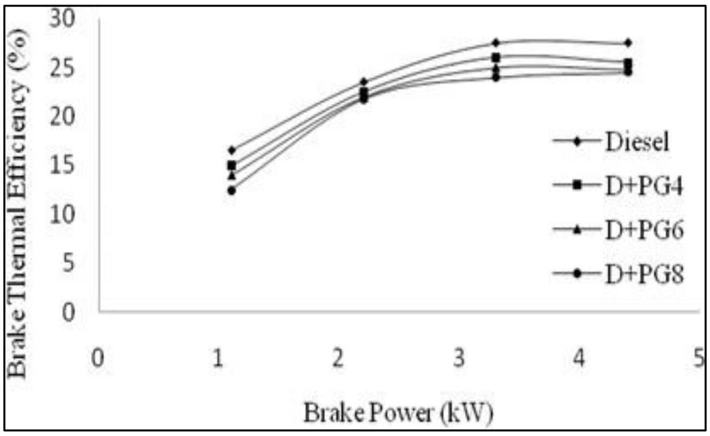


Fig.17 Break power influence on brake thermal efficiency under dual fuel operation

Lin J. et al. (2007) conducted an experimental research using a fixed-bed updraft gasifier fed with carpentry waste. This gasifier was integrated with a Stirling engine, and finally, with an electrical generator to generate electricity. A data acquisition system and an exhaust gas analyzer were also incorporated into the experimental setup to monitor engine performance parameters. The research noted that the hot flue gases entering the Stirling engine had a total thermal energy of 95 kW. The Stirling engine, however, only converted 26% of the energy, and it came out to 25 kW as mechanical power. Once electrical conversion and a slight loss in the voltage step-down process (from 400V to 220V) were accounted for, the net electrical output resulting was 24.5 kW. The remaining 0.5 kW was lost during the transformer operation.[88]

Wu et al. (2003) conducted a performance analysis of an electric power generation system of 1- MW capacity from biomass gasification. From their research, the performance of the gasifier is highly sensitive to the air-to-fuel ratio and operating temperature. They obtained the maximum conditions of wood powder fuel to be 780°C temperature, 0.26 equivalence ratio, 70% gasification efficiency, 80% carbon conversion efficiency, and 5.8 MJ/m³ lower heating value. The other crucial problem in the gasification of biomass is the production of fly ash and tar, which results in interruption of continuous operation. Fly ash also leads to heat loss, thus decreasing the efficiency of the system. The research also found the emission of SO_2 and NO_2 to be less than 20 ppm, which was significantly lower than that emitted from coal-fired power plants. The dual-fuel operation can be conducted on the diesel engine, where diesel is substituted by 67–86%. When the part load is supplied at the engine, if the emissions are high, the engine efficiency reduces. For every range of loads, carbon monoxide emissions from two-stroke dual-fuel engines were larger than emissions from diesel-only engines.[89]

Tripathi et al. (1999) compared the cost of biomass gasifier-based institutional cooking systems with that of LPG and coal-based systems. They developed a mathematical model based on different factors including maintenance and labour charges to find the unit cost of the thermal energy. Their estimations showed that for a 29 kW_{th} capacity biomass gasifier plant, the price reduced to Rs. 0.38/MJ and again to Rs. 0.24/MJ in the case of a greater 291 kW_{th} capacity plant. In comparison, LPG and coal plants had hardly any cost decrease since their heat capacity increased. The results, as noted in Table 2.5, indicate that biomass gasifier systems are increasingly cost-effective when capacity is more than 58 kW_{th}, and are therefore a lower-cost and preferable alternative compared to LPG and coal for use in larger scales of cooking.[90]

Thermal Ranking (kW_{th})	**Gasifier Based System (Rs/MJ)**	**LPG Burner (Rs/MJ)**	**Coal Oven (Rs/MJ)**
17.5	0.44	0.34	1.26
29	0.37	0.34	1.25
58	0.32	0.34	1.25
116	0.28	0.34	1.24
291	0.23	0.34	1.24

Table 2. Unit cost of thermal energy in industrial cooking system.

Homdoung et al. (2014) conducted an experiment where a naturally aspirated diesel single-cylinder engine was converted into a spark ignition (SI) engine. The engine was fueled using producer gas, which was produced by a downdraft charcoal gasifier, and provided gas at a rate of 27 Nm^3/h. For the purpose of using clean and cool fuel, gas cleaning and cooling systems were installed after the gasifier. The engine ran entirely on this producer gas without the need for any additional fuel. The main aim of the study was to identify the most suitable ignition timing for the gas so that maximum and stable power output could be achieved at different engine speeds. The ignition timing was set to get the highest brake torque. It was established that with an increase in engine speed, an adjustment of ignition time was necessary. For the low speed engine between 1100 RPM, the finest ignition timing is obtained when it is advanced to 21–25° BTDC. The medium engines at speeds close to 1500 RPM exhibited an ideal range from 33° to 38° BTDC. For higher speeds or about 1900 RPM, the timings were further advanced to 40°–45° BTDC. The engine showed its best performance at 1700 RPM under full load conditions, where the specific fuel consumption was at its lowest—0.93 kg/kWh—with a brake thermal efficiency of about 19%.[91]

Sohan Lal et al. (2017) evaluated the performance and emission behavior of a variable compression ratio diesel engine run on downdraft gasifier in dual-fuel mode. Their work proposed that the maximum diesel replacement, valued at 64.3%, was realized at a compression ratio of 18. They also observed that hydrocarbon (HC) emissions decreased by almost 63% when the compression ratio was raised from 12 to 18. The impact of the compression ratio on engine efficiency was more critical during diesel-only operation than during dual-fuel operation. Maximum cylinder pressure at compression ratio 18 was 47.19 bar for diesel and 54.49 bar for dual-fuel operation, where combustion was better in dual-fuel operation at high compression. Further, carbon dioxide (CO_2) emission was observed to rise with engine load in both operations and had greater CO_2 concentration in dual-fuel operation. Overall, the research found that the engine operates better and produces more efficient results when operating at a higher compression rate of 18.[92]

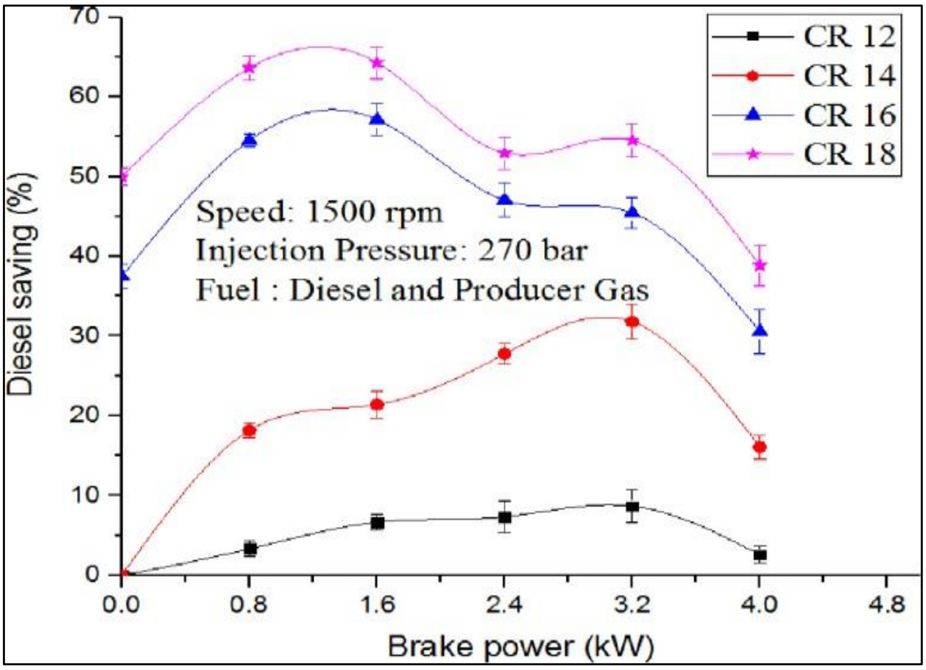
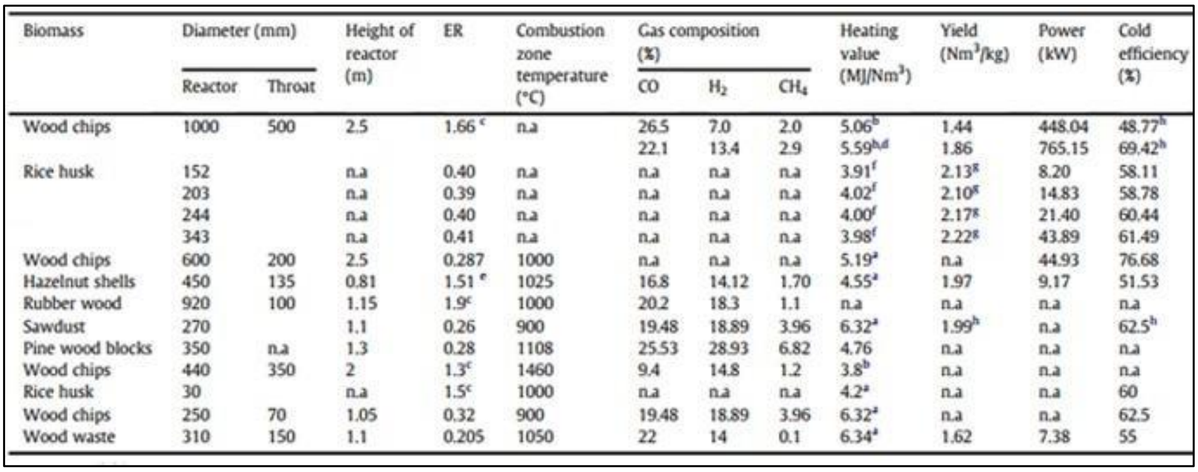


Fig.18 Variation of Diesel saving with Break Power at Different Compression Ratio

J. Daniel et al. (2012) discussed some research articles to see what influence different factors like biomass particle size, moisture level, and air–fuel equivalence ratio have on producer gas quality in the gasification process. The authors' research involved gasifiers working with atmospheric air as the oxidizing agent. It was noted that the performance of the system as well as the quality of the produced gas relies significantly on these operating conditions and the design of the gasifier. The downdraft gasifiers produce gas with low heating value of between 4 to 6 MJ/Nm^3 and have cold gas efficiencies of between 50–70%. One of the primary causes for poor engine performance when operating on producer gas is its poor energy density and loss of volumetric efficiency. In order to enhance engine efficiency, the authors recommended the spark ignition timing must be retuned. Because the mixture of gas has high flame speed—hydrogen is present in it—a retardation of ignition assists in obtaining proper combustion and efficient engine operation.[93]



Biomass	Diameter (mm)		Height of reactor (m)	ER	Combustion zone temperature (°C)	Gas composition (%)			Heating value (MJ/Nm³)	Yield (Nm³/kg)	Power (kW)	Cold efficiency (%)
	Reactor	Throat				CO	H_2	CH_4				
Wood chips	1000	500	2.5	1.66^{c}	n.a	26.5	7.0	2.0	5.06^{b}	1.44	448.04	48.77^{h}
						22.1	13.4	2.9	$5.59^{b,d}$	1.86	765.15	69.42^{h}
Rice husk	152		n.a	0.40	n.a	n.a	n.a	n.a	3.91^{f}	2.13^{g}	8.20	58.11
	203		n.a	0.39	n.a	n.a	n.a	n.a	4.02^{f}	2.10^{g}	14.83	58.78
	244		n.a	0.40	n.a	n.a	n.a	n.a	4.00^{f}	2.17^{g}	21.40	60.44
	343		n.a	0.41	n.a	n.a	n.a	n.a	3.98^{f}	2.22^{g}	43.89	61.49
Wood chips	600	200	2.5	0.287	1000	n.a	n.a	n.a	5.19^{a}	n.a	44.93	76.68
Hazelnut shells	450	135	0.81	1.51^{e}	1025	16.8	14.12	1.70	4.55^{a}	1.97	9.17	51.53
Rubber wood	920	100	1.15	1.9^{c}	1000	20.2	18.3	1.1	n.a	n.a	n.a	n.a
Sawdust	270		1.1	0.26	900	19.48	18.89	3.96	6.32^{a}	1.99^{h}	n.a	62.5^{h}
Pine wood blocks	350	n.a	1.3	0.28	1108	25.53	28.93	6.82	4.76	n.a	n.a	n.a
Wood chips	440	350	2	1.3^{c}	1460	9.4	14.8	1.2	3.8^{b}	n.a	n.a	n.a
Rice husk	30		n.a	1.5^{c}	1000	n.a	n.a	n.a	4.2^{a}	n.a	n.a	60
Wood chips	250	70	1.05	0.32	900	19.48	18.89	3.96	6.32^{a}	n.a	n.a	62.5
Wood waste	310	150	1.1	0.205	1050	22	14	0.1	6.34^{a}	1.62	7.38	55

Table 3. Design characteristics of downdraft gasifiers and experimental results published in open literature

S. Jun et al. (2012) examined rice husk gasification efficiency and rice husk pellets in a downdraft fixed-bed bench-scale gasifier. Gasification tests were conducted in the temperature range of 600°C–850°C under air as the gasifying agent at the rate of 50–75 Nm³/h. A constant feed rate of 40–60 kg/h was held of the biomass. The research indicated a gasification efficiency of more than 70%, and producer gas heating value was approximately 1300 kcal/Nm³. The tests revealed that rice husk pellets provided greater heating value and improved cold gas efficiency compared to raw rice husk. In order to determine whether producer gas would be safe for power generation, the test was conducted by running a reciprocating engine specially constructed to run on LPG. The test also validated that consistent power output of approximately 10 kW was possible by using the producer gas from rice husk pellets.[94]

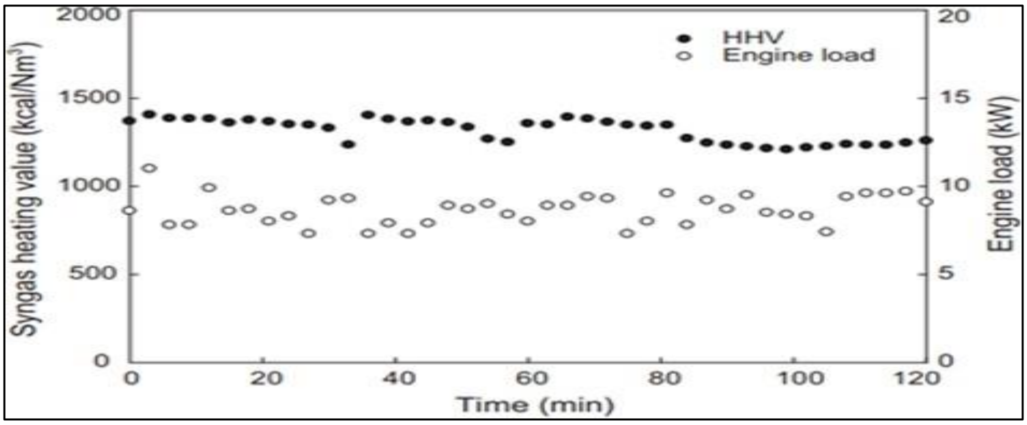


Fig.19 Power generation using synthetic gas produced from rice husk pellet gasification.

Jain et al. (2014) examined the air pollutant emissions as a consequence of open-field burning of biomass in different parts of India. In their study, they recognized Punjab, Uttar Pradesh, Haryana, and

Maharashtra as the top states responsible for crop residue burning. Of the major crops, rice, wheat, and sugarcane residue was the most frequently put up for on-field burning. Specifically, the widespread use of rice and wheat straw burning in Punjab and Uttar Pradesh was said to be a cause for concern with regard to its contribution to pollution and greenhouse gas (GHG) emissions.The authors emphasized that instead of burning, adopting alternative technologies such as biomass gasification offers a more sustainable and environmentally friendly solution for managing agricultural residues.[95]

H. Ambarita et al. (2017) have performed an experimental study on a 4.41 kW rated compression ignition (CI) engine operated in dual fuel mode. The engine needed minimum alteration to perform the experiments. The study aimed to explore the impact of variation in methane content of biogas and flow rate of biogas on engine performance when utilized as a secondary fuel. Tests were conducted at different load conditions from 600 W to 1500 W and engine speeds ranging from 100 to 1500 rpm. The outcome of the experiments indicated that brake thermal efficiency of the CI engine was significantly dependent on the ratio of methane and flow rate of biogas. Apart from it, it was found in dual fuel operation that power output along with specific fuel consumption in comparison to conventional diesel operation were greater.[96]

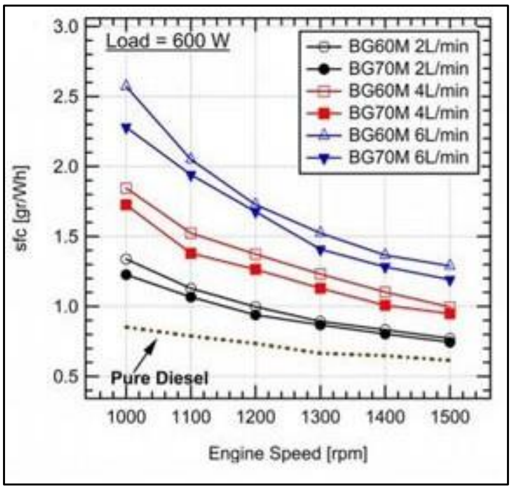


Fig.20 Specific fuel consumption vs. Engine speed

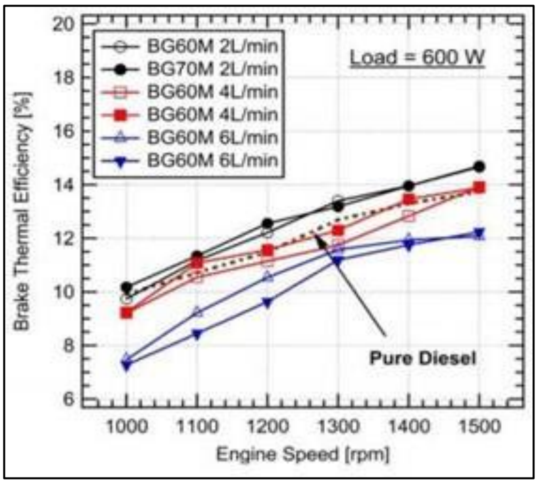


Fig.21 Brake thermal efficiency vs. Engine

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2.12 Literature Review of previous Work

S. No.	Author(s)	Year	Biomass Used	Key Findings	Remarks
1	Singh, H. and Mohapatra, S.K.	2016	Sugarcane Bagasse + Carpentry Waste	Reduced diesel and NOx; increased CO, HC; suggested redesign of throat area.	Design improvements needed for low-density fuel to avoid blockages.
2	Malik, A. and Mohapatra, S.K.	2016	Cotton Stalks	51% diesel saving; higher CO; lower NOx; 40% rise in BTE.	Demonstrates cost-effectiveness and emission compromises.
3	Uma, R., Kandpal, T. and Kishore, V.	2004	Not specified	Higher CO & HC in dual-fuel mode; partial diesel replacement possible.	Highlights emissions trade-off in dual-fuel operation.
4	Kumar, S., Saini, N., and Mohapatra, S.K.	2017	Cotton Stalks & Sugarcane Bagasse	CO (13.5%) and H_2 (10.3%) in cotton; slightly lower in sugarcane bagasse.	Indicates syngas quality from agricultural residues.
5	Dhole, A.E., Yarasu, R.B., Lata, D.B., Priyam, A.	2014	Hydrogen + Producer Gas	3% drop in BTE; better performance above 13% load.	Blending hydrogen helps stabilize low-load efficiency.
6	Singh, H., Mohapatra, S.K., and Kaler, M.S.	2019	Mixed Biomass (Wood, Bagasse, Cotton)	54% diesel replacement; 6% BTE drop; increased HC and noise.	Fuel mix offers diesel saving but increases HC and sound levels.
7	Shrivastava, V., Jha, A.K., Wamankar, A.K., Murugan, S.	2013	Wood Chips + Mustard Oil Cake	Reduced NOx; increased CO & HC; decreased BTE.	Emission reduction at cost of lower thermal efficiency.
8	Shaw, D., Akhtar, S.J., Priyam, A., Singh, R.K.	2016	Producer Gas + Diesel	64.7% diesel saving; 45% drop in BTE.	High diesel saving comes with significant efficiency loss.
9	Olgun, H., Ozdogan, S., Yinesor, G.	2011	Wood Waste, Bark, Hazelnut Shells	Throat reduced tar; max CV of 5.5 MJ/Nm^3.	Tar control through structural modification

					improves gas quality.
10	Singh, J., Singh, S., and Mohapatra, S.K.	2020	Cotton Stalks + Wheat Straw	44.4% diesel cut; 3.49% drop in IP; NOx/SOx decreased.	Good balance between emissions and power loss.
11	Sivakumar, K. and Krishna Mohan, N.	2010	Rice Husk, Groundnut Shell, Coconut	Coconut shell gave highest CV and CO; best among tested fuels.	Confirms coconut shell as a superior feedstock.
12	Das, D.K., Dash, S., and Ghosal, M.	2012	Wood, Corn Cobs, Pea Stalks	Up to 82% diesel replacement; slight drop in thermal efficiency.	Very high substitution possible with minimal performance drop.
13	Lin, J.-C.M.	2007	Carpentry Waste	26% conversion efficiency; 24.5 kW electricity output.	Stirling engine integration viable for electrical generation.
14	Wu, Z., Wu, C., and Huang, H.	2003	Wood Powder	70% efficiency; CO higher in dual-fuel mode; low SO_2/NO_2.	Shows biomass dual-fuel as cleaner alternative to coal.
15	Tripathi, A.K., Iyer, P.V.R., Kandpal, T.C., Singh, K.K.	1998	Various Agri-residues	Biomass cheaper than LPG/coal above 58 kW_{th} capacity.	Demonstrates cost benefits of large-scale gasifier systems.
16	Homdoung, N., Tippayawong, N., and Dussadee, N.	2014	Charcoal	19% BTE; best ignition timing varied with speed.	Full substitution feasible with careful ignition control.
17	Lal, S. and Mohapatra, S.K.	2017	Not specified	64.3% diesel replacement at CR 18; better performance at high CR.	Higher compression ratio enhances dual-fuel efficiency.

18	Daniel, J., Mahkamov, K.,	2012	General Biomass	Cold gas efficiency 50–70%; low gas	Engine tuning and spark delay crucial for efficiency.
	Andrade, R.V., Silva, E.E.			heating value (4–6 MJ/Nm³).	
19	Jun, S., Son, Y., Kim, Y., and Lee, J.	2012	Rice Husk, Pellets	10 kW power with higher CV from pellets; >70% gasification efficiency.	Pellets offer better performance than raw husk.
20	Jain, N., Bhatia, A., and Pathak, H.	2014	Crop Residues	Punjab and UP major burners; gasification advised over open burning.	Emphasizes environmental need for clean biomass utilization.
21	Ambarita, H.	2017	Biogas (Methane variation)	BTE depends on methane % and flow rate; SFC increased.	Gas composition directly affects engine performance.

3.1 Gap in Literature

Literature review indicates that a lot of work has been conducted on various applications of biomass, such as the production of biogas, biodiesel, and landfill gas, where innovation in these fields goes on. Scholars have suggested numerous factors and mechanisms for the production of biodiesel and biogas. The following literature gap is demonstrated in the current topic.

- Pine cones are easily available as forest waste but not much comprehensive research on the specific properties of pine cones has been carried compared to other biomass sources like wood chips or agricultural waste

- Most studies use common gasifier designs without changing them to match the unique features of different biomass types, like the hard coconut shells or the light pine cones.

- Most experiments are done in labs, with very few studies on using this technology in real-world rural or remote locations where it could make the most impact.

- Few studies deeply analyze pollutant emissions (CO, NOx, particulate matter) during combustion or gasification of coconut shells, especially under different load or air–fuel ratio conditions.

- It is largely a few studies that have investigated important in-cylinder combustion parameters such as cylinder pressure, net heat release, cumulative heat release, and mean gas temperature, particularly when employed with producer gas produced from forest residues such as coconut shells and pine cones. These parameters are important to understand the complete combustion process and engine efficiency but are often overlooked.

- Coconut shells have been used in some experiments, but detailed information on the emissions they produce—such as CO, NOx, and unburnt hydrocarbons—is still missing, especially under different engine loads.

3.2 Scope of future Research

- Use of Pine Cone and Coconut Shells as biomass for production of syngas along with diesel as a feedstock.
- Comparison of the emission performance and trends of a compression ignition (CI) engine operated on two different fuels.
- Use of producer gas in diesel engine as principal fuel in CI engine with diesel as pilot fuel.
- Further investigation can also be undertaken on significant engine parameters such as cylinder pressure, net heat release, and gas temperature to understand syngas burning in more detail.
- This system can be pilot-tested in power generation in a village or distant places where electricity is difficult to obtain. It can be a low-cost and environmentally friendly source of power.
- More research can be done to understand how these forest wastes can be used more efficiently for gas production and as fuel in engines.
- Future research can explore ways to reduce harmful gases like CO, NOx, and HC using filters, exhaust treatment, or adjusting the fuel mixture.

Chapter 4 Methodology and Experimental Investigation

4.1 Introduction

Here in this study thermal gasification of biomass has been employed for the gasification into a gaseous product suitable for, i.e., producer gas or synthesis gas. This chapter presents the experimental equipment, test procedure used, and data acquisition and analysis procedure. It also addresses the equipment used and parameters monitored.

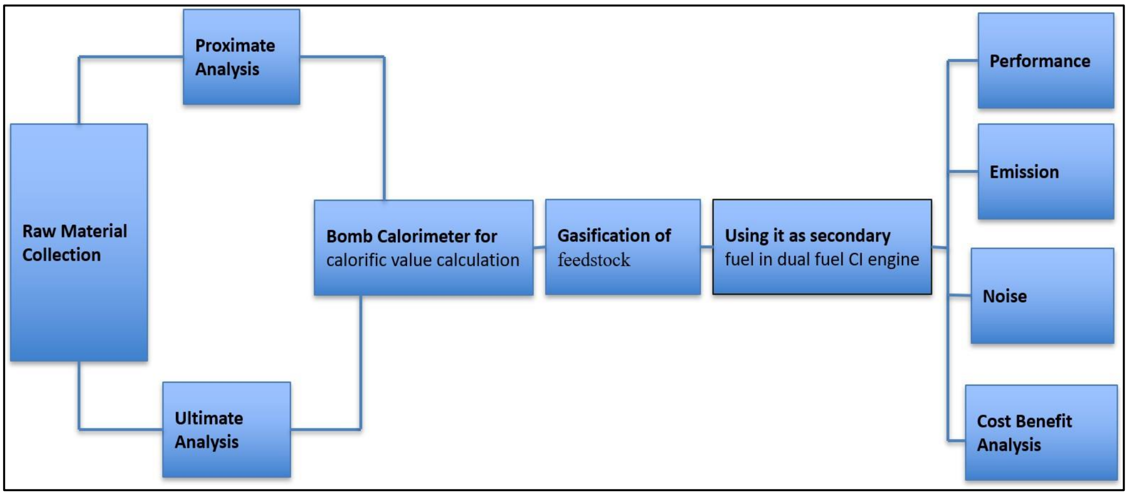


Fig .22 Flow Chart of Methodology used for experimentation.

Biomass products that are utilized for gasification are like forestry residue, agricultural residues, sewage sludge, and plant waste.[22] In the initial phase, wastes contain a lot of water and thus are pre-dried.[23]Biomass particle size is significant in the determination of gasification energy requirement and the efficiency in heat transfer. Moreover, using smaller particles can improve syngas quality and minimize tar formation.[24] The extra moisture present in the biomass is first eliminated through different drying methods. After drying, the biomass is cut into smaller pieces and then either manually loaded or transported via a conveyor into the hopper. After it has penetrated, the feedstock is partially oxidized with a measured quantity of air or oxygen to produce syngas.[25]

4.2 Biomass Collection

4.2.1 Pine Cones

Pine cones are usually found around pine trees, especially in forests, parks, and gardens during the fall and winter. Most of them fall between September and December, but some can stay on the tree for years before they finally drop.[97] The pine cones used in this study were collected from Himanchal Region.The collected pine cones were left to dry in the sunlight to lower their moisture content. Once dried, they were broken into smaller pieces, making them suitable for the gasification process.


(a) (b)

(c)

Fig.23 (a) Biomass(Conepine) Collected from forest. (b) Biomass after dried in Sun. (c) Biomass Chopped into small pieces.

4.2.2 Coconut Shells

To carry out the experiment, coconut shells were gathered from a shop within the Thapar Institute of Engineering and Technology campus. They were sun-dried in an attempt to decrease their moisture level. They were then crushed into fragments once they had dried in preparation for gasification. Before being loaded into the gasifier, the crushed pieces were manually cleaned.


(a)

(b)

(c)

Fig.24 (a) Biomass(Coconutshell) Collected from Shop. (b) Biomass after dried in Sun.

(c) Biomass Chopped into small pieces.

4.3 Proximate Analysis

Proximate analysis of biomass measures the amounts of moisture, volatile substances, ash, and fixed carbon present. The results are given as percentages of the total sample weight.[98]

4.3.1 Moisture Content:

Moisture content is a significant parameter that influences biomass combustion quality and the amount of energy that can be generated. First, an empty dish was weighed, and then about 10 grams of the sample was placed in it and weighed again. The dish containing the sample was then kept in a 105°C oven at low pressure (less than 100 mm Hg) and dried for approximately 5 hours. After drying, the dish was taken out, allowed to cool, and then weighed again. This drying and weighing process was repeated every hour until the weight remained the same, meaning all the moisture had been removed. The last moisture content was also calculated as a percentage of dry sample weight. [98]

The moisture content was calculated using the formula:

$$\%\ \text{moisture} = \frac{[(\text{weight of sample before drying- weight of dry sample})\ \text{X}\ 100]}{\text{weight of sample before drying}}$$

4.3.2 Ash Content

The ash content in the biomass was analyzed with ASTM E1755-II standard through the use of a muffle furnace. Ash is the incombustible component of the biomass and includes all mineral contents. It was calculated by charging 5 grams of the pre-treated sample in a crucible and dried first at 100°C for 24 hours in an oven. The crucible was dried and afterward it was put in a muffle furnace and the temperature was increased to 550±5°C and held at that for 8 hours. The heating was followed by removing the crucible and letting it cool down in a desiccator. On cooling, it was measured and the ash weight was taken.[98]

The ash content was expressed as a percentage on a dry basis using the formula below:[98]

$$\%\ \text{Ash} = (\text{Weight of ash} / \text{Weight of dry sample}) \times 100$$

4.3.3 Volatile Matter

Volatile matter (VM) is the component of the gases emitted when the fuel begins to burn. It contributes significantly to the speed at which the fuel burns and the symmetry of the burning process.[100] Volatile matter plays a big role in how well a fuel works. Fuels with more volatile matter catch fire more easily and don’t need much energy to get burning.[101] Volatile matter is measured by heating the sample at

900°C for 7 minutes and calculating how much weight it loses, not counting the weight lost from moisture.[102]

The volatile matter content was calculated using the difference in weight before and after heating, as shown below:[103]

% VM = [(Initial mass of the sample – Final constant mass of the sample) / Initial mass of the sample] × 100

4.3.4 Fixed Carbon

Fixed carbon means that portion of the carbon which occurs in biomass in the form of organic molecules and combined with other elements, rather than as individual carbon. [105] It is the part of the fuel that stays behind after the volatile gases have been released.[104] In gasification, fixed carbon is important because it's the part of the biomass that doesn't turn into gas it stays solid and continues to react during the process.[106]

The fixed carbon (FC) content was calculated using the formula below:-[103]

% FC = 100 – (% Moisture Content + % Volatile Matter + % Ash Content)

Table 4. Results of Proximate Analysis of Previous samples

Biomass Type	Moisture (%)	Volatile Matter (%)	Ash (%)	Fixed Carbon (%)
Corncob [107]	12.44	69.58	2.58	15.4
Pinecone [108]	6.4	73.2	4.1	16.3
Coconut Shell [109]	9.66	71.92	0.67	17.75
Sugarcane Bagasse [110]	8.23	67.18	10.21	14.38
Agri Residue Pellet [111]	7	43.17	36.52	13.31
Wheat Straw (WS) [112]	6.13	68.89	13.8	11.18
Eucalyptus Bark [113]	6.7	82.9	3.2	13.9
Olive Branches [113]	11.2	81.5	1.8	16.7
Acacia Branches [113]	6.2	77.8	0.7	21.5

Table 5. Results of Proximate Analysis of Current samples (Cone Pine and Coconut Shell)
Source- Sai Lab Thapar University

Sr. No.	Parameter	Test Method	Unit	Cone Pine	Shell
1	Moisture @ 108 °C	IS: 17655 (Part 1):2021	%	8.69	7.54
2	Ash @ 815 °C	IS: 17653:2021	%	1.32	2.36
3	Volatile Matter @ 900 °C	IS: 17844:2022	%	69.11	63.32
4	Fixed Carbon (By Difference)	IS: 1350 (Part 1):1984	%	20.88	26.78

The proximate analysis of the existing biomass samples, cone pine, and coconut shell was compared with the existing samples.The current coconut shell had the highest fixed carbon (26.78%), meaning it can burn for a longer time and provide more energy. It also had low moisture and moderate ash, making it a good-quality fuel. The current cone pine also showed better results than before, with very low ash (1.32%) and higher fixed carbon (20.88%), which improves its performance as a fuel. Compared to other samples like corncob, sugarcane bagasse, and agri residue pellets, these two current samples were better in terms of low ash and high energy content. On the other hand, agri residue pellets had too much ash (36.52%), which makes them less useful. Fuels like eucalyptus bark and olive branches had high volatile matter, which helps in quick ignition but may burn out faster. Overall, current cone pine and coconut shell are among the best fuels in this group because they are cleaner, drier, and more energy-rich.

4.4 Ultimate Analysis

Total analysis involves the determination and quantification of the gases produced on combustion of a sample of fuel in an excess of oxygen, to determine the quantities of the major constituents such as carbon, hydrogen,, nitrogen, and sulfur in the fuel.[99] This is typically accomplished by using a CHNSO analyzer that employs the Dumas method.[114].

This Method include [115] :-

Sample Preparation: Samples are air-dried and stored in airtight bags to maintain integrity. They are ground to a fine powder to ensure uniform combustion in the analyzer.

Instrument Used: A CHNS analyzer is used for ultimate analysis. The analyzer burns a measured amount of the sample biomass at elevated temperatures in the presence of oxygen. During combustion, elements in the sample (Carbon, Hydrogen, Nitrogen, Sulfur) are converted into measurable gases:

$C \rightarrow CO_2$

$H \rightarrow H_2O$

$N \rightarrow N_2$ or Nox

$S \rightarrow SO_2$

These gases are then detected and quantified using thermal conductivity detectors or infrared sensors.

Calculation of Oxygen: Oxygen is not measured directly**.** Instead, it is calculated by Formula:

$$O (\%) = 100 – (C + H + N + S + Ash)\}$$

Table 6. Ultimate analysis of previous sample

Biomass Type	Carbon (C) %	Hydrogen (H) %	Nitrogen (N) %	Sulphur (S) %
Corncob[107]	39.88	6.56	0.94	Not reported
Pinecone[108]	46.3	6.2	0.6	Not reported
Coconut Shell[109]	47.29	4.91	0.19	0.37
Agri Residue Pellets[111]	28.06	3.52	0.96	0.49
Eucalyptus Bark[113]	55.9	7.55	1.44	0.01
Olive Branches[113]	49.4	6.95	0.24	0.88
Acacia Branches[113]	52.4	7.38	3.21	0.04
Sugarcane bagasse[110]	40.2	5.4	0.3	0.04

Table 7. Ultimate Analysis current sample of Cone Pine and coconut shell
Source- Sai Lab Thapar University

Sr. No.	Parameter	Test Method	Unit	Cone Pine	Coconut Shell
1	Carbon (C)	CHNSO Analyzer	%	43.18	43.76
2	Hydrogen (H)	CHNSO Analyzer	%	5.65	5.49
3	Nitrogen (N)	CHNSO Analyzer	%	0.16	0.81
4	Sulphur (S)	CHNSO Analyzer	%	0.03	Not Detected

The ultimate analysis results of the current samples—Cone Pine and Coconut Shell—were compared with previous biomass types such as Corncob, Pinecone, Agri Residue Pellets, Eucalyptus Bark, Olive Branches, Acacia Branches, and Sugarcane Bagasse. In terms of carbon content, the current samples showed good values, with Coconut Shell at 43.76% and Cone Pine at 43.18%. These are slightly lower than the earlier Coconut Shell (47.29%) and Pinecone (46.3%), but still better than Corncob, Agri Residue Pellets, and Sugarcane Bagasse. Eucalyptus Bark and Acacia Branches had the highest carbon levels overall.

For hydrogen, the current values (5.65% for Cone Pine and 5.49% for Coconut Shell) fall in the middle range. They are lower than Olive Branches, Eucalyptus Bark, and Acacia Branches, but higher than Agri Residue Pellets. Nitrogen content in Cone Pine was the lowest among all samples (0.16%), which is good for reducing harmful NOx gases during combustion. Coconut Shell had slightly higher nitrogen (0.81%) compared to most earlier samples, except for Acacia and Eucalyptus which showed much higher values.

Sulphur was very low in Cone Pine (0.03%) and not detected in Coconut Shell, showing that both fuels are environmentally friendly with very low SOx emissions. This trend is similar to most previous samples where sulphur was either not reported or very low. The current biomass samples are clean fuels with low nitrogen and sulphur, and have good carbon content. Their composition makes them suitable for energy applications while keeping emissions low.

4.5 Gross Calorific Value

Calorific value is the energy released per unit mass of fuel when it is completely burnt.[116] It provides an estimate of the energy stored in the fuel.[117].Method to Find GCV of Biomass:-[118]

1. Sample Preparation

Dry the biomass at 105 ± 3°C for 24 hours

Grind and sieve to pass through a 60-mesh (250 µm) screen.

2. Pellet Formation

Take 0.4–0.5 g of dried sample.

Compress into a 13 mm diameter pellet using a 10-ton hydraulic press.

3 Calibration

Calibrate the bomb calorimeter using benzoic acid (standard).

4 Measurement

Place the pellet in the combustion dish inside the bomb.

Fill the bomb with oxygen**.**

Ignite and record the temperature rise**.**

5 Calculation

The calorimeter automatically calculates GCV based on the heat released.

Table 8. Results of gross calorific value of previous samples

S.No	Biomass Type	GCV (kcal/kg)
1	Corncob[119]	3,227.78
2	Pinecone[120]	4,914
3	Coconut Shell[121]	4,446
4	Sugarcane Bagasse[122]	3,847
5	Agri Residue Pellets[123]	4,131
6	Eucalyptus Bark[124]	4,324
7	Olive Branches[124]	4,297
8	Acacia Branches[124]	4,316

Table 9. Result of gross calorific value of current sample(Cone Pine and coconut shell)
Source- Sai Lab Thapar University

Sr.No	Parameters	Test Method	Unit	Coconut Shell	Cone Pine
1	Gross Calorific Value	IS: 17654:2021 Lab Test (Sai Lab)	Kcal/kg	4229	4579

In the current test, the coconut shell gave a calorific value of 4229 kcal/kg, which is a bit lower than its previous value of 4446 kcal/kg. Similarly, the cone pine showed 4579 kcal/kg, which is slightly less than the earlier value of 4914 kcal/kg for pinecone. Even though the values are a little lower now, both fuels still have good energy content. When we compare them with other older biomass samples like corncob at 3227 kcal/kg and sugarcane bagasse at 3847 kcal/kg, the current coconut shell and cone pine are still better. Some other fuels like eucalyptus bark, olive branches, and acacia branches have values around 4300 to 4324 kcal/kg, which are close to coconut shell but still lower than cone pine. Overall, both current samples, especially cone pine, show good potential for use as biofuels.

4.6 Gasifier System Specification.

For the experiment, a throat downdraft gasifier was employed, which is situated on the university campus. The gasifier generates producer gas by processing biomass into a fuel gas. The gas, after it has been generated, must be cleaned before utilization as it has impurities in the form of tar, dust, and water. Therefore, a gas cleaning system is also available after the gasifier. This configuration assists in filtering out unwanted particles from the gas, and it is clean and safe to use on engines or equipment.

Table 10. Specification Table of DownDraft Gasifier used in Lab

Parameters	**Description**
Model	WBG-10 in Ultra clean Gas Mode
Makers	Ankur Scientific Energy Technology Pvt.Ltd
Gasifier Type	Downdraft
Number of air inlets	2
Fuel Capacity of the hopper	60 Kg
Permissible moisture content	Upto 20%
Thermal Output	26000 kCal/h
Biomass consumption rate	4-5 kg/hr
Maximum gas flow rate	25 Nm3/hr

Gasification efficiency	Approx. 75%
Start-up	Through blower

4.7 Gasification Effeciency

The Gasification Effeciency can be calculate as:

Gasification Efficiency (%) = (V × LCV_syngas) / (m × GCV_biomass) × 100

V = Volume of syngas produced (Nm^3 or m^3)

LCV_syngas = Lower Calorific Value of syngas (MJ/Nm^3 or MJ/m^3)

m = Mass of biomass fed (kg)

GCV_biomass = Gross Calorific Value of biomass (MJ/kg)

LCV Formula by Gas Composition

LCV = Σ (Vol% of gas × LCV of gas)

Or

LCV = (CH_4 × LCV_CH_4) + (CO × LCV_CO) + (H_2 × LCV_H_2)

Standard LCVs:

- CO = 12.63 MJ/Nm^3
- CH_4 = 35.8 MJ/Nm^3
- H_2 = 10.79 MJ/Nm^3

4.7.1 Gasification Effeciency Cone Pine

The LCV of syngas produced from Cone Pine biomass was calculated based on the measured gas composition:

Given Gas Composition of Cone Pine:

- CO: 8.81%
- CH_4: 7.03%
- H_2: 2.28%

The LCV of syngas was calculated as:

LCV_syngas = (0.0881 × 12.63) + (0.0703 × 35.8) + (0.0228 × 10.79)

= 1.113 + 2.516 + 0.246 = 3.875 MJ/Nm³

GCV (MJ/kg) = 4579kcal/Kg × 0.004184 = 19.16 MJ/kg

V = 25 Nm³/h (syngas flow rate)

m = 8 kg/h (biomass feed rate)

Efficiency = (25 × 3.875) / (8 × 19.16) × 100 = (96.875 / 153.28) × 100 = 63.21%

The Effeciency of Cone Pine is 63.21%

4.7.2 Gasification Effeciency of Coconut Shell

Given Values for Coconut Shell

- CO = 3.23%
- CH_4 = 8.99%
- H_2 = 1.90%
- Syngas flow rate (V) = 25 Nm³/h
- Biomass feed rate (ṁ) = 7.5–8.5 kg/h
- GCV of biomass = 4229 kcal/kg

The LCV of syngas produced from Coconut Shell biomass was calculated based on the measured gas composition:

LCV_syngas = (CO × 3010) + (CH_4 × 8550) + (H_2 × 2550)

= (3.23 × 3010) + (8.99 × 8550) + (1.90 × 2550)
= 9732.3 + 76834.5 + 4845.0

= 91411.8 kcal per 100 Nm³

LCV_syngas = 914.12 kcal/Nm³

Gasification Efficiency (%) = (V × LCV_syngas) / (ṁ × GCV_biomass) × 100

= (25 × 914.12) / (8 × 4229) × 100

= 22853 / 33832 × 100

= 67.54%

The Effeciency of Coconut Shell is 67.5

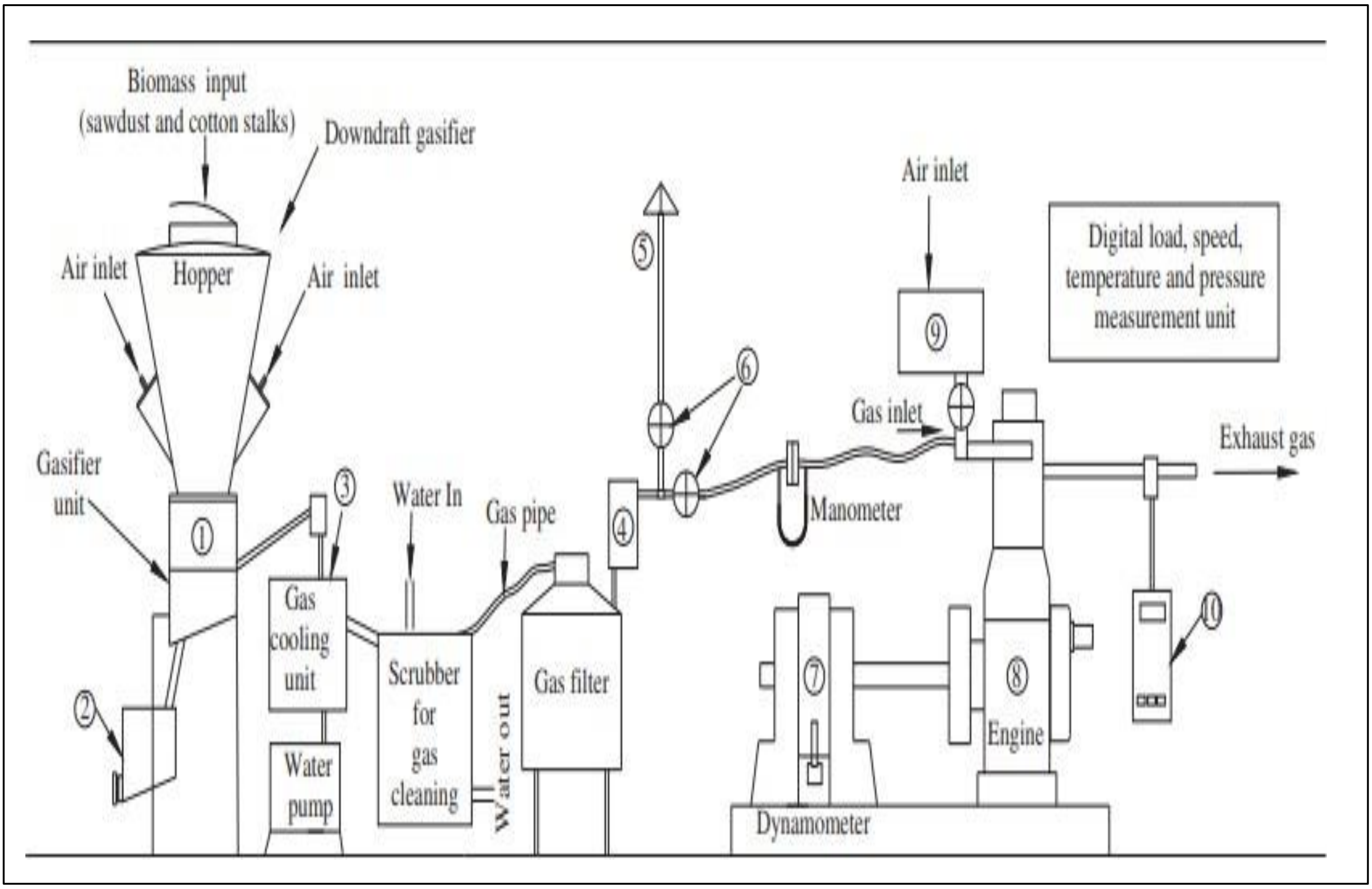


Fig.25 Schematic diagram of downdraft gasifier coupled with diesel engine

(Source-The effect of compression ratio on the performance and emission characteristics of a dual fuel diesel engine using biomass derived producer gas Sohan Lal ⇑ , S.K. Mohapatra)

4.8 Gas Cleaning and Cooling

The gas that comes out of the gasifier is extremely hot and not suitable to be sent directly into the engine. Besides the heat, the gas also carries tar and tiny dust-like soot particles, which can create problems if they enter parts like the carburetor, causing blockages and reducing engine performance. To solve this issue, a gas cooling and purification system is placed just after the gasifier. This setup cools down the gas and removes harmful particles before the gas is used.

4.8.1 Scrubber

The scrubber is the first part of the cleaning unit where the hot gas enters after leaving the gasifier. Here, the gas is cooled by spraying it with cold water. This helps bring down the gas temperature and also removes dust, tar, and water-soluble gases such as HCl, H_2S, SO_2, and NH_3. Some tar is also washed out at this stage.

4.8.2 Secondary Filter:

After the gas is cleaned in the scrubber, it goes through a secondary filter. This filter is a drum filled with a mix of wood powder and wood chips. As the gas moves through this filter, the small particles and any extra moisture get trapped. This filter helps in making the gas 99% clean, and the gas temperature at this point is usually around 40°C to 50°C.

4.8.3 Safety Filter

To make the gas even cleaner, it is then passed through a security filter. The filter is smaller than the second filter and has a paper filter inside it. The paper filter assists in catching very fine soot particles that were not caught earlier. Through this filter, the gas is 99.9% clean, and its temperature is normally between 30°C and 40°C.

Fig.26 Downdraft Gasifier

Fig.27 Small Narrow intake air/oxygen

Fig.28 Passive Filter

Fig.29 Saftey Filter

4.9 Engine Setup

The producer gas or syngas generated through the gasification process is supplied to a Dual Fuel Compression Ignition (DFCI) engine.

The DFCI engine has the following configuration:

Parameters	Description
Model	AV-1
Make	Kirlosker
Engine Type	Single cylinder diesel engine
Rated power	3.5KW @1500rpm
No. of strokes	4
Fuel	Diesel, blends of diesel and producer gas
Cooling	Water cooled
Stroke length	110mm
Cylinder diameter	87.5mm
Compression ratio	12 to 18
Orifice meter	20mm
Dynamometer arm length	185mm
Dynamometer	Eddy current type

Table 11. DFCI engine Specifications

The cleaned producer gas, after it has broken out of the safety filter, is piped into the inlet manifold of a dual-fuel compression ignition engine in which it is mixed with atmospheric air. The engine employed for this research is a single-cylinder, water-cooled electric start diesel engine whose speed is regulated to have a practically uniform value of 1500 RPM.

Although the engine can be used with varying compression ratios, experiments were conducted at a constant compression ratio of 18:1. This was chosen based on some earlier research that showed an enhanced performance under this setup. The engine runs in dual-fuel mode, diesel fuel being the main fuel and producer gas being the secondary fuel.

The test arrangement is used to test various performance parameters like brake power, indicated power, thermal efficiency, volumetric efficiency, air-fuel ratio, and fuel consumption. A flow control valve is used for regulating the flow rate of producer gas. The flow rate of producer gas was kept constant at 5 to 8 Nm^3/hr during trial.

Cold water is passed through the engine jacket prior to running the engine and the flow rate should be maintained between 70 and 260 LPH in order to avoid overheating. The engine was run for various load conditions of 0 to 10 kg. To measure air flow and gas flow, orifice meters of 20 mm and 15 mm diameters were used respectively.

All the tests were done thrice under identical conditions to establish validity and reproducibility of data. The mean of the recorded values was utilized in plotting the performance-emission characteristics of the engine in dual-fuel operation.

To analyze the performance and emission characteristics of the dual-fuel engine, experiments were conducted in two distinct operating modes**:**

- Single-fuel mode (only diesel)
- Dual-fuel mode **(**blend of producer gas and diesel)

The engine's performance under both modes was evaluated and compared based on key performance indicators such as **brake power, brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE).** These parameters were evaluated under different load conditions to identify the suitability of utilizing producer gas as secondary fuel and its impact on overall engine performance.

Fig.30 Dual fuel CI engine with variable CR

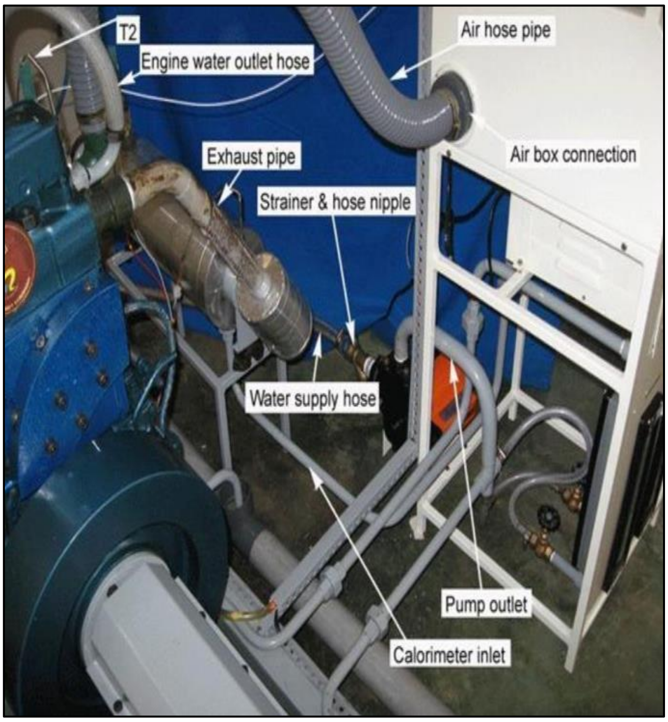


Fig.31 Different positions in the engine setup

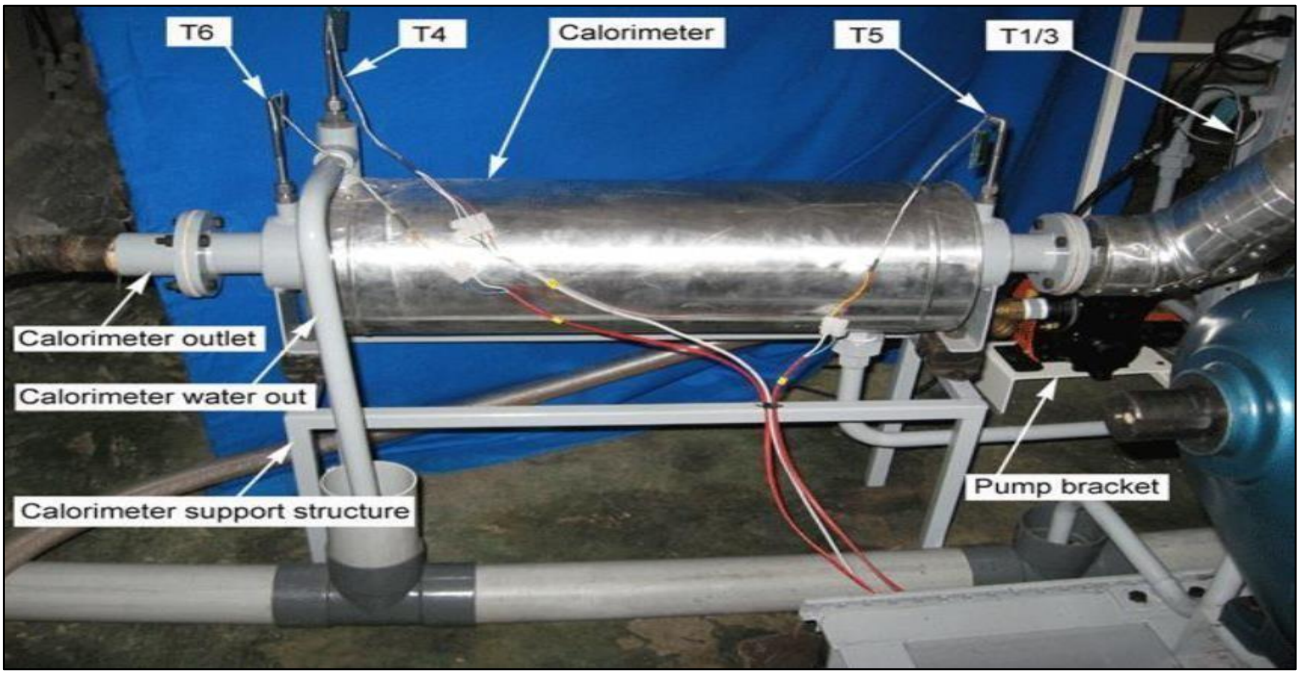
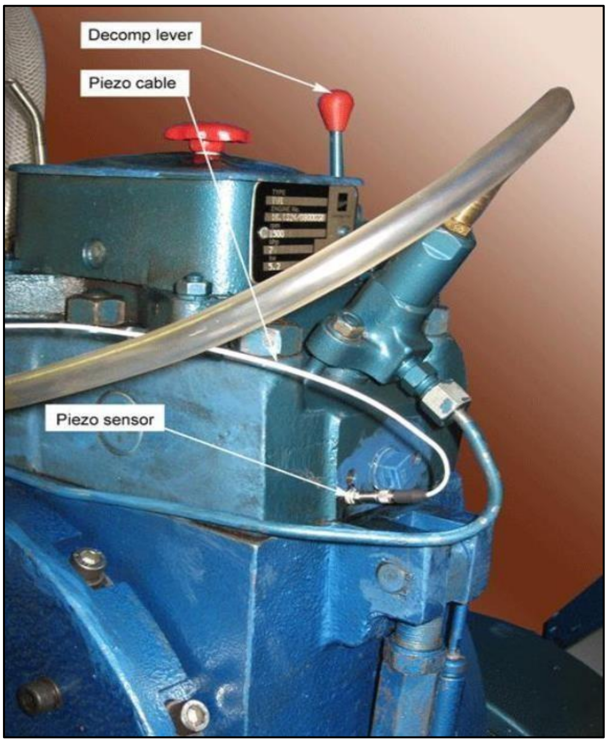


Fig.32 Calorimeter setup and Temperature



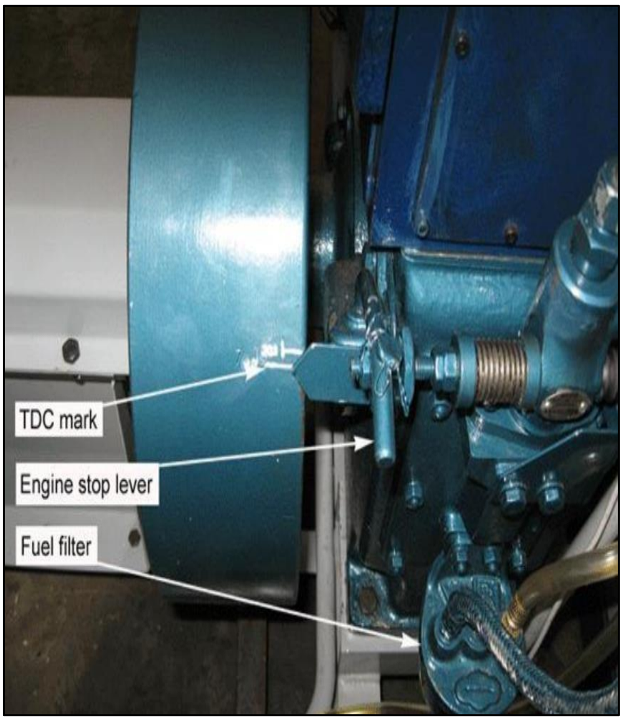


Fig.33 Piezo sensor for injection pressure.

Fig.34 Fuel filter and engine stop

Fig.35 Schematic representation of setup.

4.10 Gas Analyser

For the measurement of exhaust gases released by the engine, an AMB Portable Gas Analyzer was used in the test rig. This is a portable, suitcase-sized analyzer designed to be used in the field for engine exhaust gas analysis. The analyzer includes a sampling hose, filter unit, and onboard display unit for real-time presentation of results. Electrical power is needed by the analyzer, which is provided from the main control panel.

The AMB gas analyzer can detect major gas constituents that are typically present in internal combustion engine exhaust. The analyzer allows for the detection of important gases like methane (CH_4), which is one of the major constituents of producer gas and an important gas in combustion. The analyzer also detects hydrogen (H_2), an explosive gas that extends quicker combustion and influences engine performance. Furthermore, it senses carbon dioxide (CO_2), a marker of complete combustion, as well as carbon monoxide (CO), a marker of incomplete combustion and energy loss in the fuel. Nitrogen (N_2), although not part of the combustion reaction, is sensed and forms the majority of the gas mixture and dilutes other gases. These readings help to study the performance of the engine and the purity of the combustion.

Fig.36 Gas Analyser used for Syn gas Composition

4.11 Experimental Procedure

1. All electrical contacts were carefully examined for safety and proper earthing prior to system start-up.
2. The water supply was verified to be adequate in the main storage tank.
3. The diesel fuel tank was filled, and the fuel knob was set to the regular operating position.
4. After switching on the water pump, the cooling water flow rate was set to 80 LPH for the calorimeter and 300 LPH for the engine. Adequate cooling was also ensured for the dynamometer.
5. The computer system was powered on, and the engine monitoring software was launched.
6. Engine load was applied using the rotary knob provided on the control panel.
7. The flue gas analyzer was switched on to monitor exhaust gas emissions.
8. The engine was started using the electric switch and allowed to run at minimum load.
9. Within the software interface, the fuel properties such as specific gravity and calorific value were set using the “Configure” option.
10. The "Run" position was chosen to start engine operation, and the engine was permitted to stabilize for 15 minutes. After stabilization, the fuel supply knob was moved to the metering position.
11. The "Log" option was therefore chosen under the software. In one minute, the screen proceeded to input mode where the user would input the cooling water flow rates and give a file name (only for the first reading).
12. Reading was initially taken under no-load conditions. Then, the fuel knob was reset to normal position.
13. Shut back-pressure valve to open the valve for the flue gas analyzer. Flue gas data were taken after the instruments had stabilized on the analyzer.
14. The load was then raised to 2 kg and time given to the engine to stabilize for 10 minutes. The fuel knob was put back to the metering position after the engine stabilized, and the "Log" mode was chosen in the software
15. To one minute, the water flow values were input and knob set at the initial position. The corresponding flue gas reading was recorded.The same procedure was repeated for increasing loads of 4 kg, 6 kg, 8 kg, and 10 kg.
16. After completing the test runs, the load was gradually reduced to minimum, ensuring that the engine speed remained below 1500 RPM.
17. Once all data were saved, the engine and computer system were shut down.
18. The cooling water pump was allowed to run for an additional 10 minutes to cool down the engine before switching it off completely.

5.1 Compression Ratio Analysis :Diesel

Experimental test was conducted for the present investigation to study the impact of various compression ratios (C.R. 12, 14, 16, and 18) on engine performance with diesel as a single fuel. Tests were performed under varying load conditions of 2, 4, 6, 8, and 10 kg in order to simulate various working conditions. The main performance parameters like indicated power (IP), brake power (BP), and friction power (FP) were found and compared. The aim was to detect the most efficient compression ratio that would subsequently be applied for biomass gasification with comparable engine conditions.

5.1.1 Load vs Break Power (BP) : Diesel

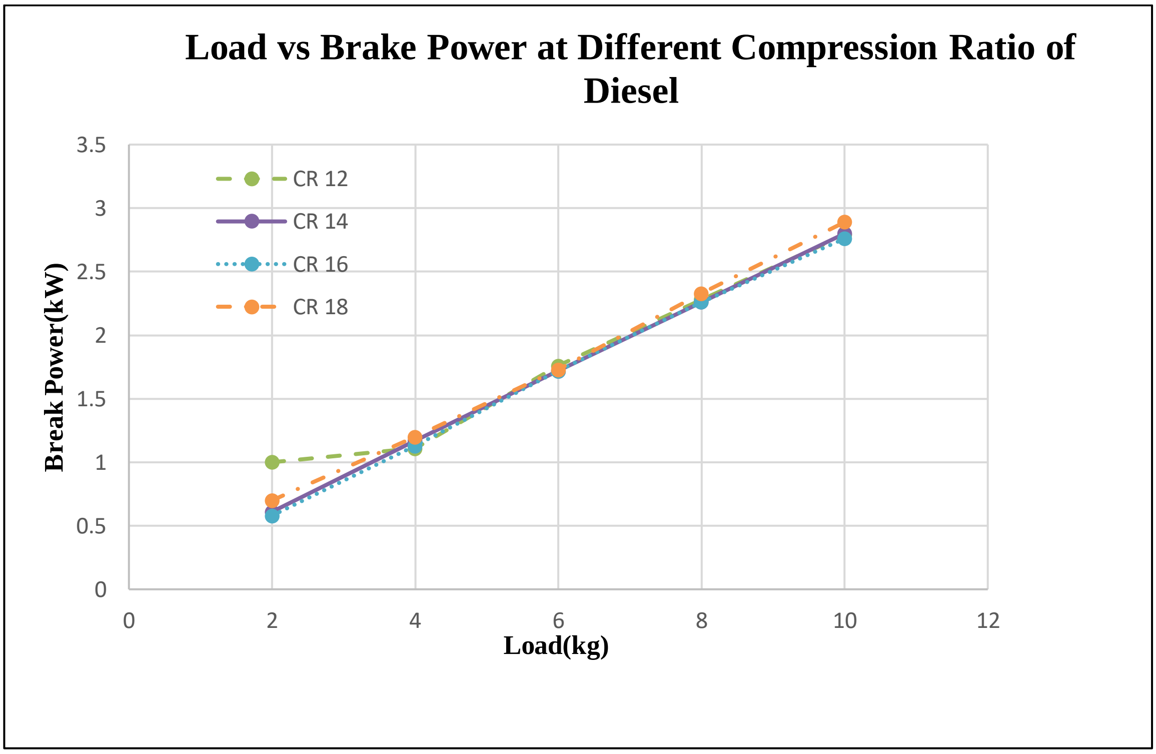


Fig.37 Load vs Break Power (BP) : Diesel

As the load on the engine increases from 2 kg to 10 kg, the brake power (BP) shows a consistent upward trend. At very low load (2 kg), CR 12 delivers the maximum brake power (1.0 kW), whereas CR 14 and CR 16 show the lowest values. As the load increases, CR 18 consistently provides higher brake power compared to the other ratios, particularly at medium to high loads (4–10 kg). For instance, at 10 kg load, CR 18 achieves the highest brake power of 2.89 kW, followed closely by CR 14 (2.80 kW) and CR 12 (2.79 kW). This trend indicates that while CR 12 performs better under very light load, CR 18 is the most effective compression ratio overall, especially in higher load conditions where engine performance is more critical. Therefore, CR 18 can be considered the best compression ratio in terms of brake power output.

5.1.2 Load vs Indicated Power (IP) : Diesel

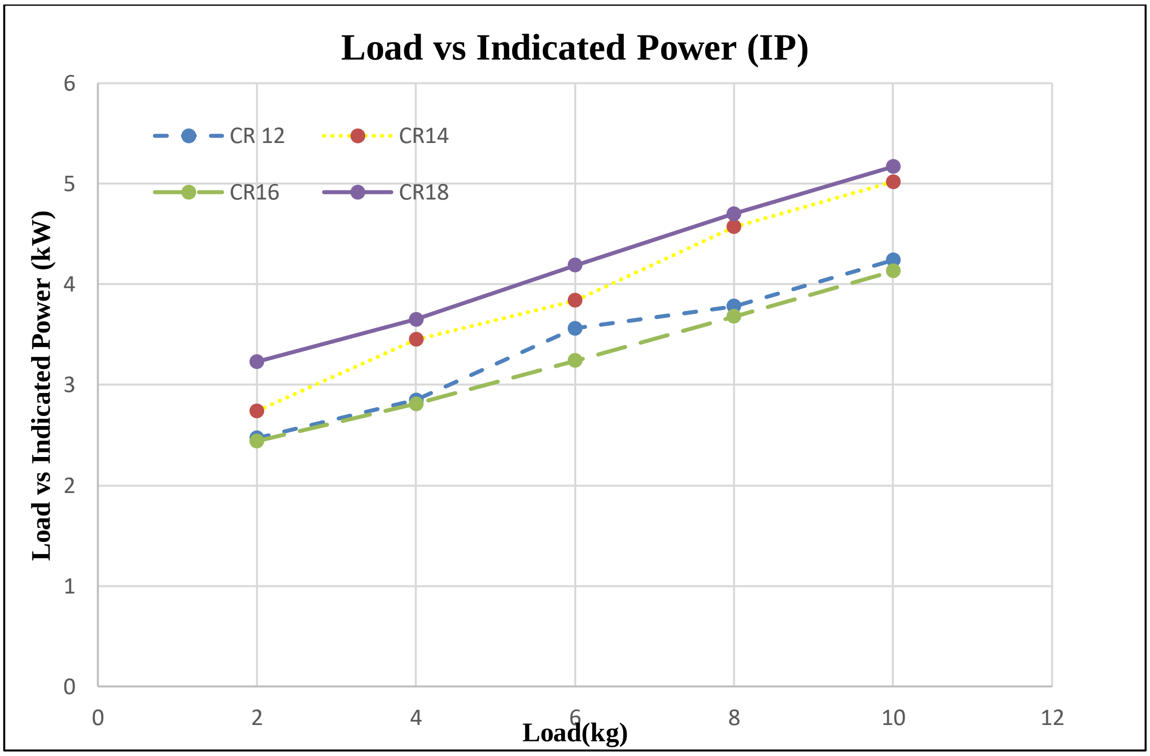


Fig.38 Load vs Break Power (BP) : Diesel

In the analysis of indicated power (IP), it was observed that the compression ratio had a significant influence on the engine performance. Across all load conditions, CR 18 consistently produced the maximum indicated power, followed closely by CR 14, while CR 12 and CR 16 delivered comparatively lower values. For instance, at a load of 10 kg, the maximum indicated power of 5.17 kW was achieved at CR 18, whereas CR 14 recorded 5.02 kW, CR 12 reached 4.24 kW, and CR 16 gave the lowest at 4.13 kW. This consistent trend confirms that higher compression ratios enhance the combustion process, thereby improving indicated power output. Hence, CR 18 can be considered the most suitable compression ratio in terms of indicated power performance.

5.1.3 Load vs Friction Power (FP) : Diesel

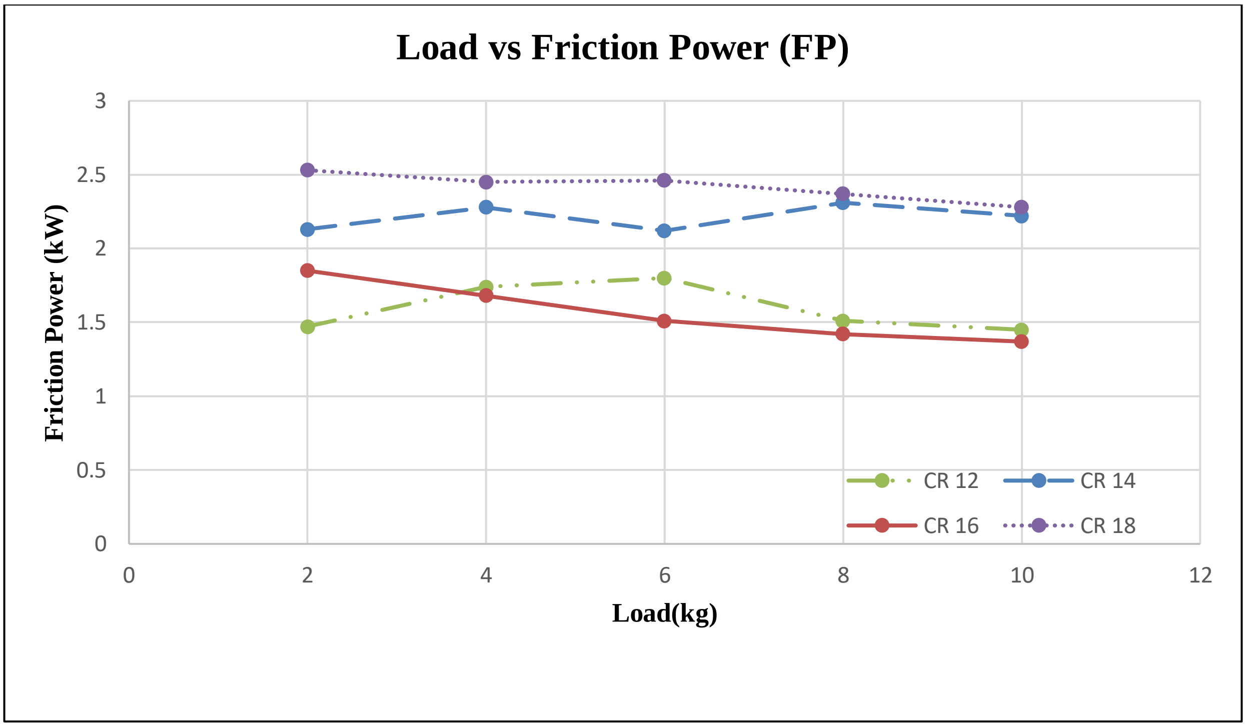


Fig.39 Load vs Break Power (BP) : Diesel

The analysis of friction power (FP) revealed that higher compression ratios tend to increase frictional losses within the engine. Across all load conditions, CR 18 consistently exhibited the maximum friction power, indicating greater mechanical resistance, while CR 16 recorded the lowest values. For example, at 10 kg load, the lowest friction power of 1.37 kW was observed at CR 16, followed by CR 12 with 1.45 kW, whereas CR 14 and CR 18 showed significantly higher frictional losses of 2.22 kW and 2.28 kW respectively. This trend highlights that although CR 18 enhances indicated power, it also increases frictional power considerably, whereas CR 16 demonstrates the most favorable performance in minimizing mechanical losses.

5.1.4 Conclusion

The experimental analysis clearly demonstrates that compression ratio significantly affects engine performance parameters. While CR 12 shows a slight advantage at very low loads and CR 16 minimizes frictional power, CR 18 consistently achieves the highest values of brake power and indicated power across all load conditions. Although higher frictional losses are observed at CR 18, the substantial gain in useful power output outweighs this drawback. Hence, **CR 18 can be considered the optimal compression ratio**, offering the best overall performance in terms of power generation and efficiency under practical operating conditions.

5.2 Load vs Break Power(BP)

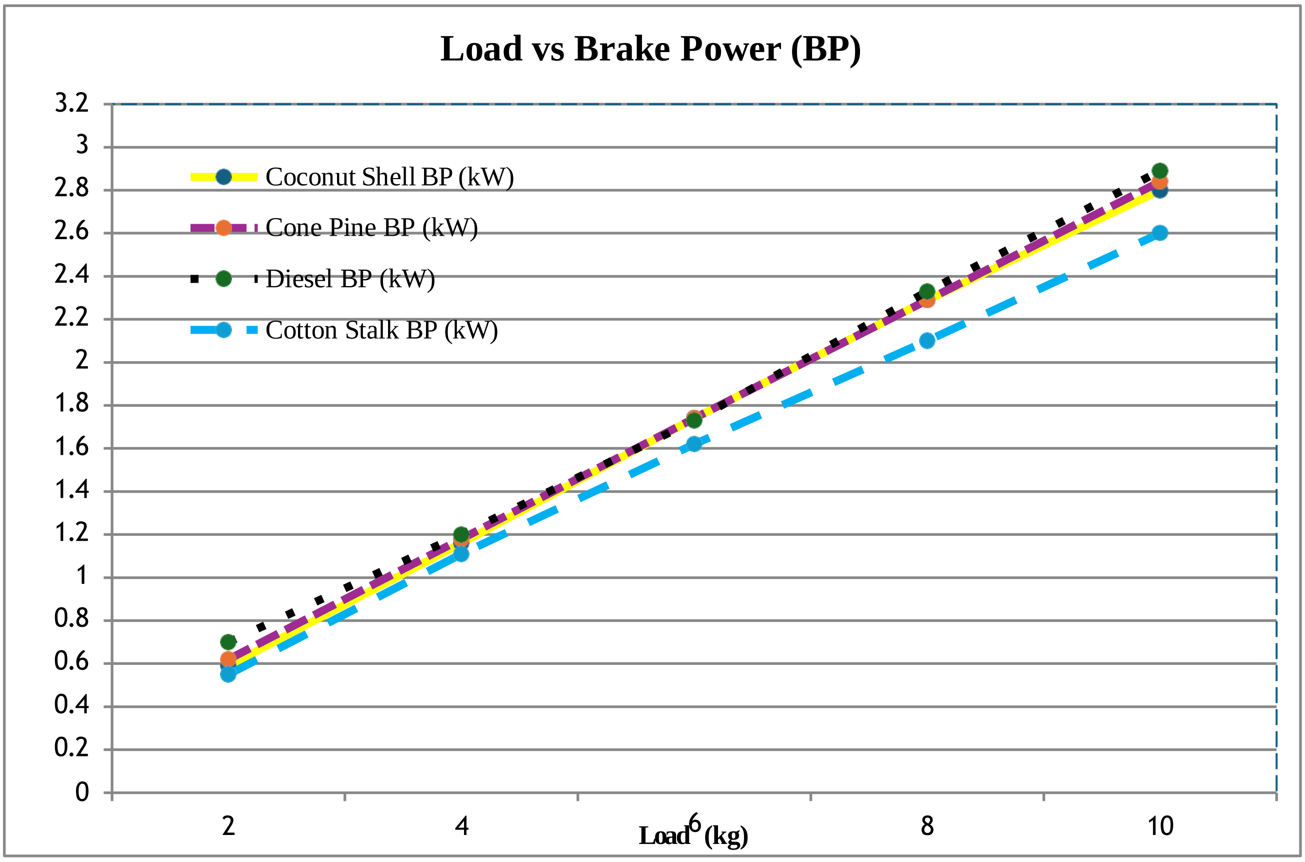


Fig.40 Load vs BP (Break Power)

The graph illustrates the way in which brake power (BP) is enhanced as the load is enhanced for four fuels: Diesel, Coconut Shell, Cone Pine, and Cotton Stalk. It shows a clear upward trend for all fuels, indicating that brake power increases as load increases. The Load vs Brake Power (BP) analysis reveals that Diesel consistently delivers the highest brake power across all load conditions, indicating superior efficiency in converting fuel energy into mechanical output. Coconut Shell and Cone Pine show similar performance trends, with Cone Pine slightly outperforming Coconut Shell at higher loads. Both serve as promising biomass alternatives to Diesel. Diesel reaches the highest peak brake power of approximately 2.95 kW, followed closely by coconut shell and cone pine, which both deliver around 2.85 to 2.88 kW. In comparison, cotton stalk shows the lowest peak value at about 2.7 kW. This indicates that coconut shell and cone pine perform nearly as well as diesel at maximum load, making them strong alternatives for use in biomass-based energy systems. On the other hand, Cotton Stalk exhibits the lowest brake power values at all load levels, suggesting lower energy conversion efficiency compared to the other fuels.

5.3 Load vs IP (Indicated Power)

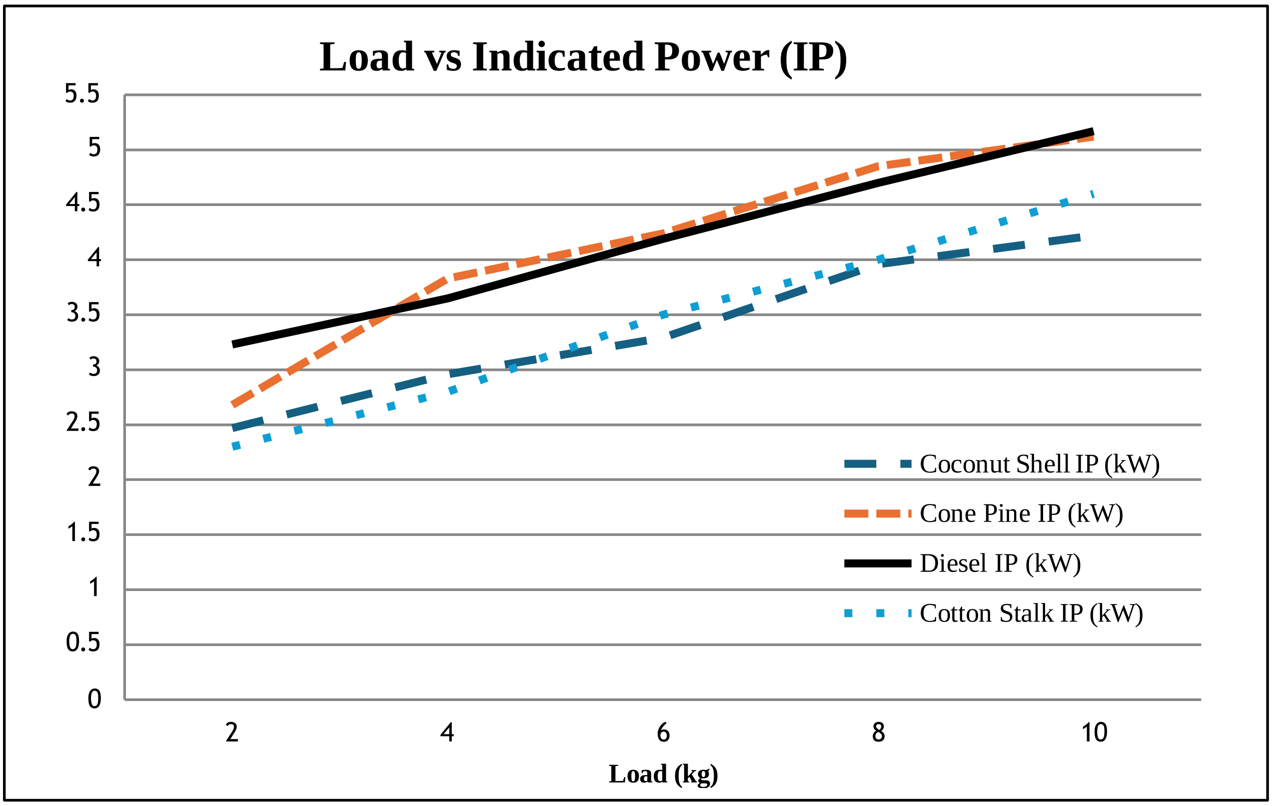


Fig.41 Load vs Indicated Power(IP)

The graph of Load versus Indicated Power (IP) provides a clear comparison of engine performance using different fuel types—Coconut Shell, Cone Pine, Diesel, and Cotton Stalk. As the load increases, the indicated power also increases for all the fuels, following the same pattern of increased power output with increased engine load.Diesel produces the highest indicated power across the entire load range, reaching about 5.2 kW at the maximum load. Cone pine performs very similarly, achieving around 5.1 kW, which shows its strong potential as a biomass fuel. Cotton stalk reaches approximately 4.5 kW, while coconut shell gives the lowest indicated power at about 4.3 kW. Although diesel shows the best performance, cone pine comes very close, and both cotton stalk and coconut shell also demonstrate consistent and reliable output. This indicates that all three biomass fuels can be used effectively in place of diesel, with cone pine showing the most promising results among them.

5.4 Load vs FP (Friction Power)

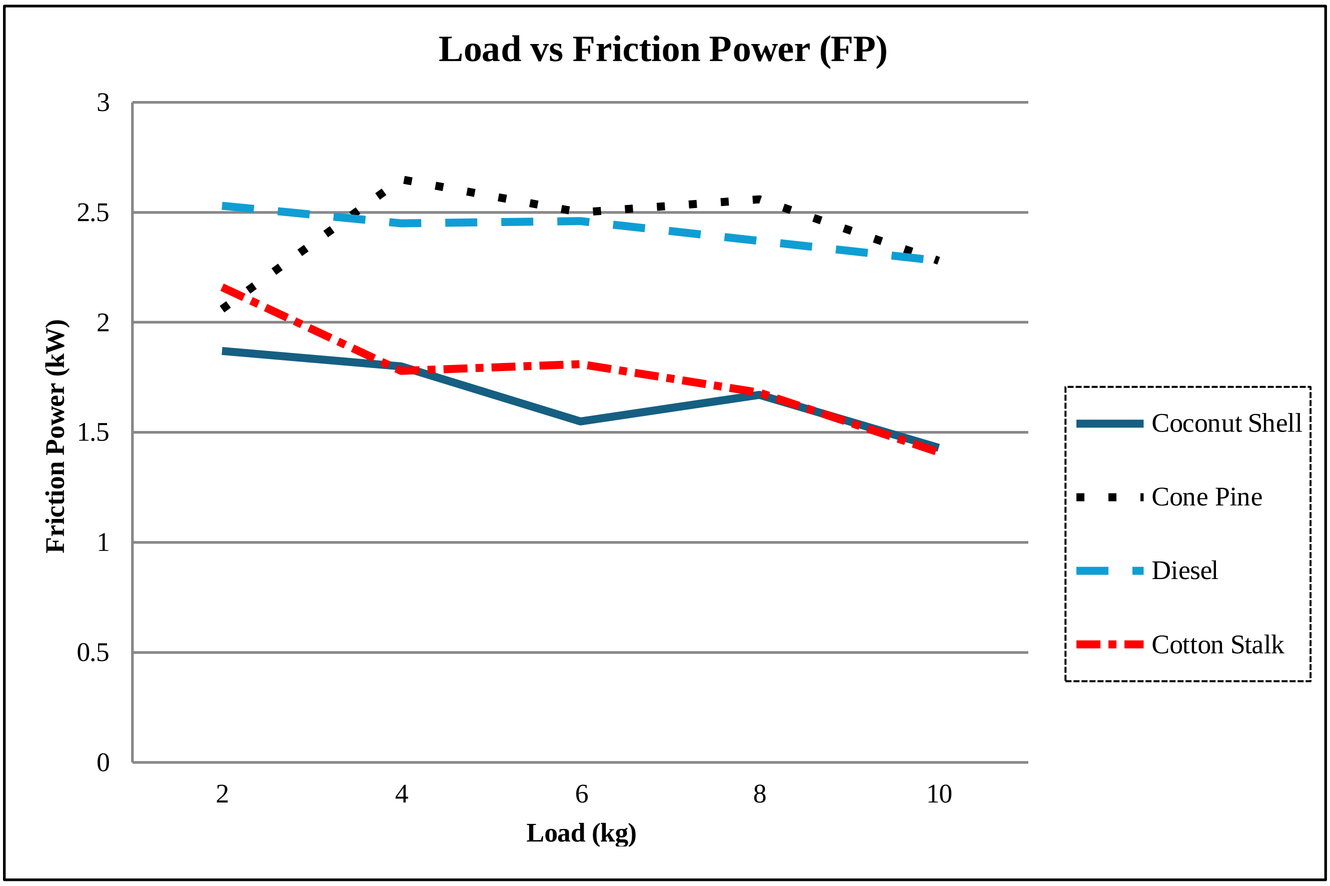


Fig.42 Load vs Friction Power(FP)

The graph displays how friction power changes with varying engine loads for different fuels: diesel, cone pine, coconut shell, and cotton stalk.Diesel consistently shows high friction power across the entire load range, staying close to 2.5 kW. This suggests that diesel operation involves higher internal resistance within the engine components. Cone pine begins at around 2.1 kW and peaks above 2.6 kW at mid loads before gradually decreasing. This peak may be due to increased cylinder pressure or mechanical stress during combustion.Coconut shell and cotton stalk both demonstrate relatively lower friction power, especially at higher loads. Coconut shell starts at about 1.9 kW and drops to around 1.4 kW, showing a smooth and steady decline. Similarly, cotton stalk follows a comparable pattern, slightly above coconut shell at low loads but nearly equal at higher loads.This behavior indicates that biomass fuels like coconut shell and cotton stalk may generate less internal mechanical resistance, especially under increased loads. Lower friction power suggests reduced wear and tear on engine parts, improved mechanical efficiency, and potentially better fuel economy. Therefore, in terms of frictional losses, coconut shell and cotton stalk offer a more favorable performance compared to diesel and cone pine.

5.5 Load vs Indicated Thermal Efficiency

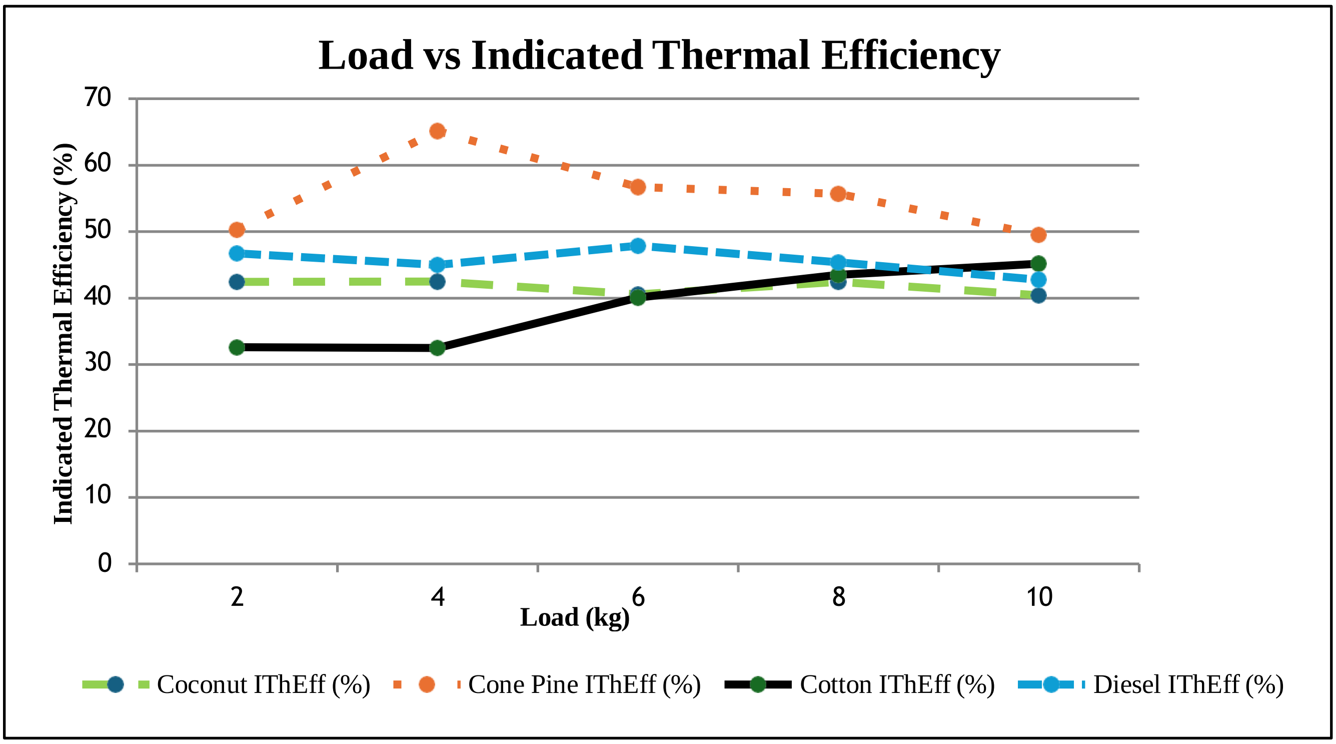


Fig.43 Load vs Indicated Thermal Efficiency

The Load vs Indicated Thermal Efficiency (IThEff) chart shows the efficiency with which various fuels convert chemical energy into usable engine work for various loads.As the load increases from 2 kg to 10 kg, Cone Pine stands out with the highest efficiency, peaking at 65.14% at 4 kg and gradually declining thereafter, indicating optimal performance at moderate loads. Diesel shows a stable trend, peaking at 47.88% at 6 kg, and maintaining moderate efficiency across all loads. Coconut maintains a relatively flat curve with efficiencies around 42–43%, showing consistent but comparatively lower performance. Cotton starts with the lowest efficiency at 32.63% (2 kg), but increases steadily to 45.17% at 10 kg, suggesting that it performs better under higher loads.

5.6 Load vs Break Thermal Efficiency

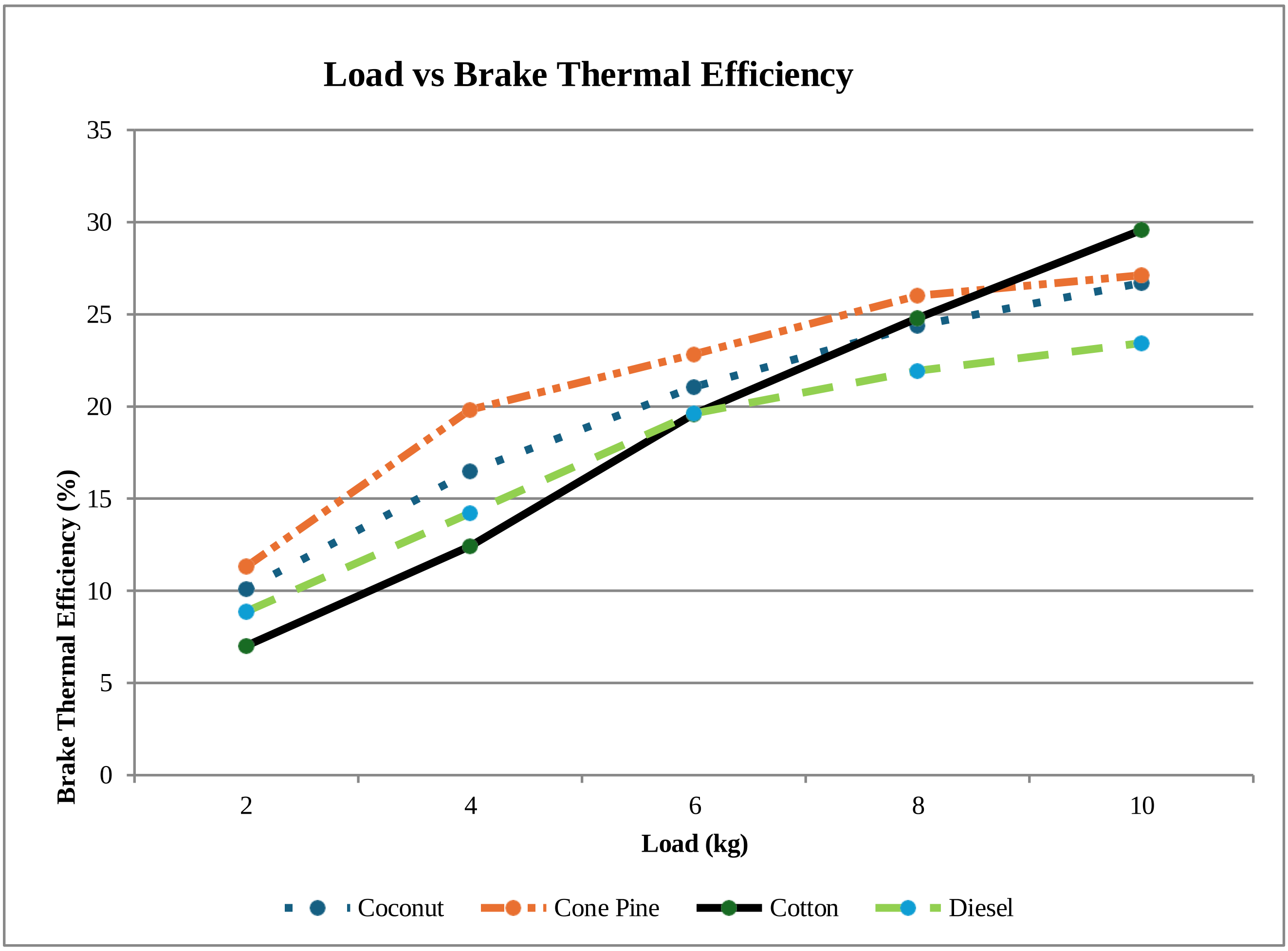


Fig.44 Load vs Break Thermal Effeciency

The graph represents the brake thermal efficiency as a function of load for the various fuels: cone pine, coconut shell, cotton stalk, and diesel. As the load increases, all fuels show an improvement in brake thermal efficiency. Among them, cotton stalk performs the best at higher loads, reaching close to 30% efficiency, which indicates good energy conversion to useful power. Cone pine also shows strong performance, rising quickly and staying slightly below cotton at higher loads. Coconut shell follows a steady upward trend, reaching around 27% at the highest load. Diesel, while commonly used, shows the lowest brake thermal efficiency across all loads, peaking below 25%. This suggests that biomass fuels—especially cotton stalk and cone pine—can be more efficient than diesel at higher engine loads, making them promising alternatives for cleaner and more efficient energy use. his outcome highlights that biomass fuels, especially cotton stalk and cone pine, not only compete with but also surpass diesel in terms of brake thermal efficiency at higher loads. Therefore, they stand out as strong and cleaner alternatives to conventional diesel fuel for thermal energy conversion in engines.

5.6 Load vs Specific Fuel Consumption (SFC)

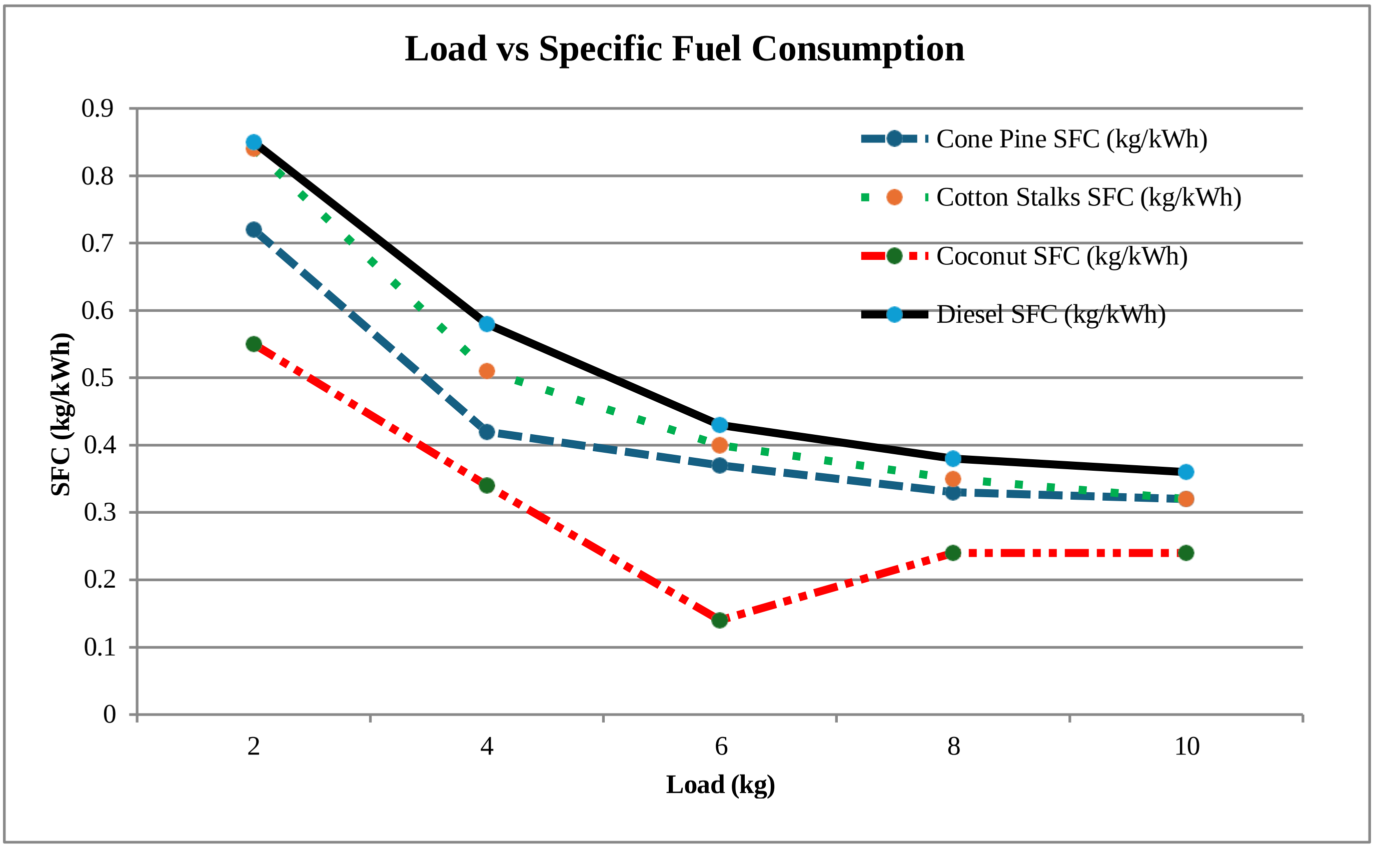


Fig.45 Load vs Specific Fuel Consumption (SFC)

The graph reflects the relationship between engine loading and Specific Fuel Consumption (SFC) by various fuels: coconut shell, cone pine, cotton stalks, and diesel. SFC serves as a measure of the efficiency with which an engine produces power from fuel, smaller values indicating higher efficiency.Across all fuels, SFC decreases significantly as the load increases. This is expected, as engines generally operate more efficiently under higher loads due to improved combustion and reduced relative energy losses. Among the tested fuels, coconut shell shows the lowest specific fuel consumption across most load conditions, dropping to around 0.24 kg/kWh at full load. This suggests it uses fuel more efficiently and can be a strong alternative to diesel. Cone pine also performs efficiently, steadily improving with load and settling at about 0.33 kg/kWh at higher loads.Cotton stalk follows a similar pattern, staying slightly behind cone pine but still better than diesel for most of the load range. Diesel has the highest specific fuel consumption, beginning close to 0.85 kg/kWh under low load and decreasing only to approximately 0.36 kg/kWh under full load. Coconut shell is generally most efficient, followed by cone pine and cotton stalks. All three of the biomass fuels are better than diesel, indicating good promise as cleaner and more efficient sources of power for engines.

5.7 Gas Composition

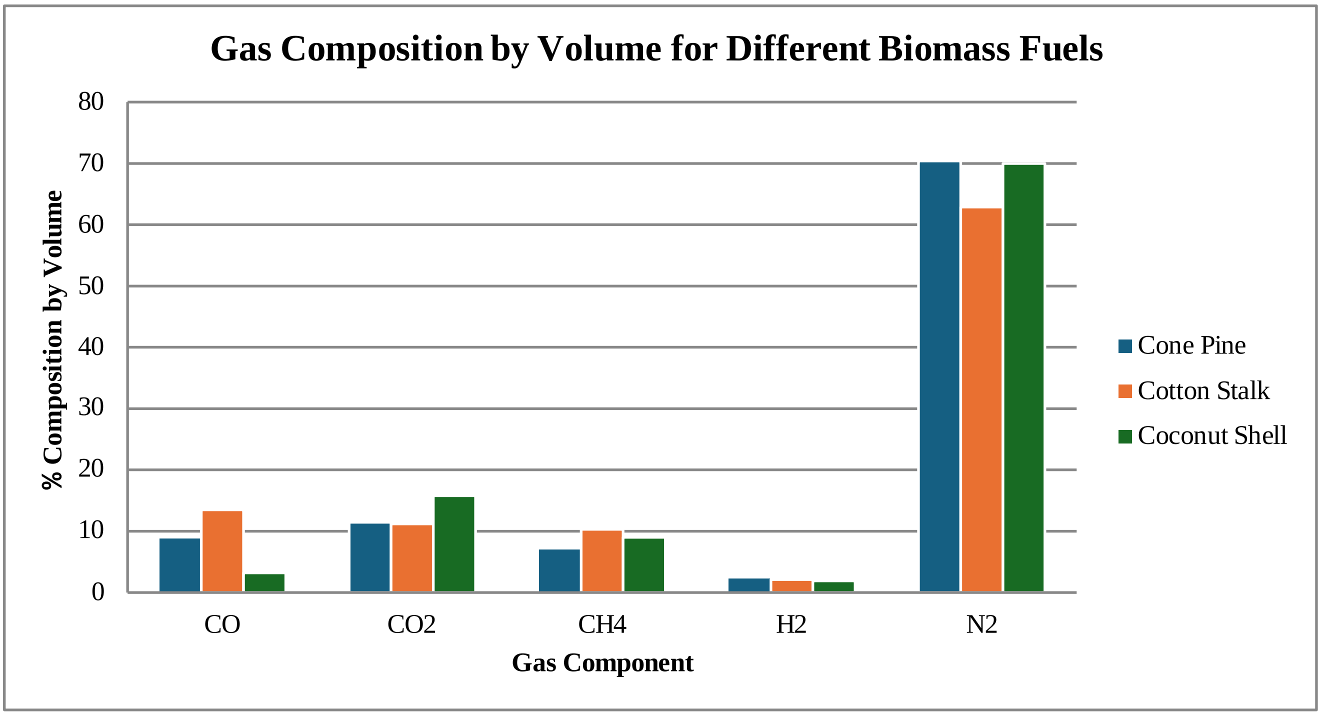


Fig.46 Gas Composition of Different biomass fuel

The bar graph shows the percentage of different gases like CO, CO_2, CH_4, H_2, and N_2 present in the producer gas obtained from three biomass fuels: Cone Pine, Cotton Stalk, and Coconut Shell. From the graph, it is observed that Cotton Stalk has the highest amount of CO (13.5%) and CH_4 (10.3%), which indicates a better quality of combustible gas. Cone Pine has moderate levels of these gases, while Coconut Shell shows lower CO (3.23%) but a slightly higher CH_4 value (8.99%). The CO_2 content is found to be highest in Coconut Shell (15.79%), which may be due to better oxidation. Hydrogen is present in small amounts in all three samples, with Cone Pine showing slightly more. Nitrogen content is very high in all cases, especially in Cone Pine (70.4%) and Coconut Shell (70%), which may lower the heating value of the gas. Overall, Cotton Stalk shows a better gas composition for energy use compared to the other two fuel

5.9 Cylinder Pressure

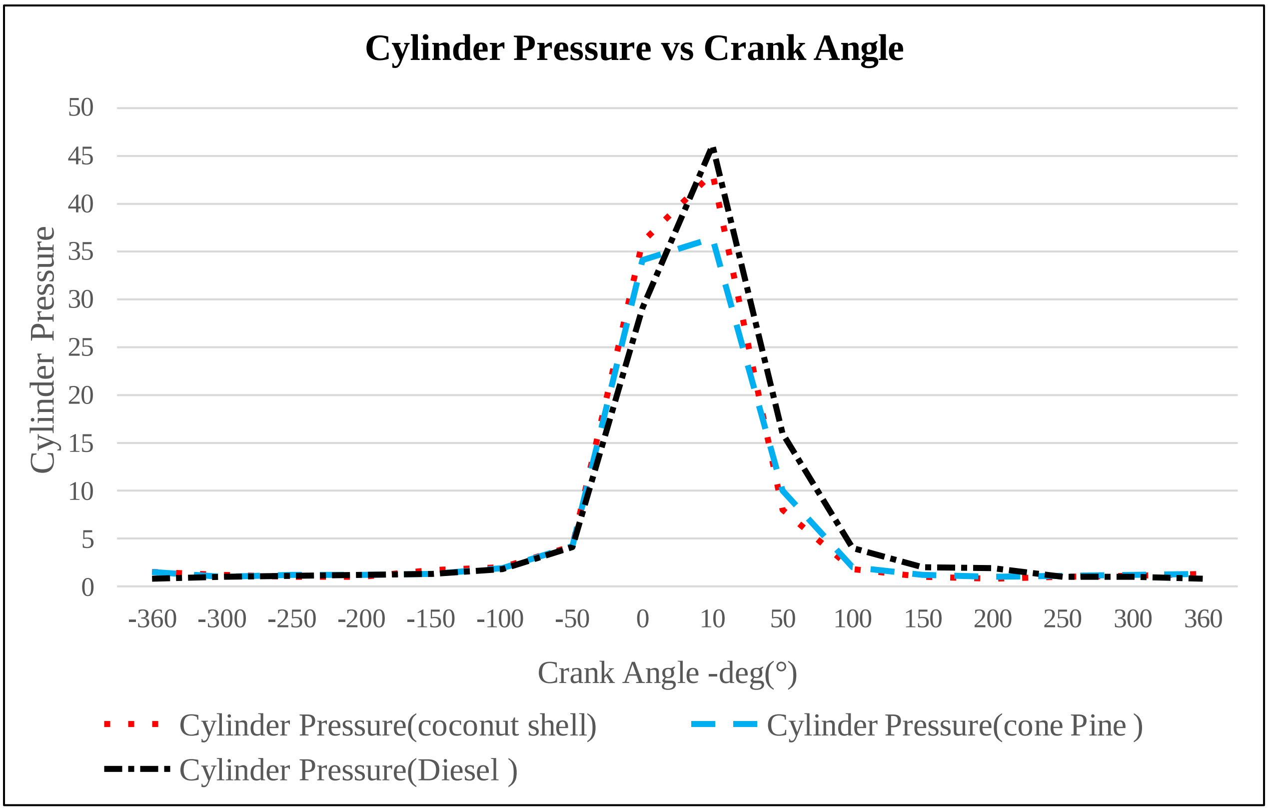


Fig.47 Cylinder Pressure vs Crank Angle

Cylinder pressure chart vs. crank angle tells us about combustion of Diesel, Cone Pine, and Coconut Shell within the engine. The three fuels have a pattern such that pressure rises before it reaches close to the top dead center (TDC) and goes on to reach the peak just after, i.e., approximately 10° crank angle. Diesel achieves the highest pressure of nearly 46 bar and hence burns immediately and more fiercely.On the other hand, coconut shell and cone pine reach lower peak pressures—around 43 bar and 36 bar—showing that they burn more slowly and in a more controlled way. Before combustion starts, diesel has the lowest pressure, while the biomass fuels (cone pine and coconut shell) have slightly higher pressure. After combustion, the pressure in diesel drops suddenly, while in the biomass fuels it falls more slowly, meaning they release energy over a longer time. Even though diesel gives more power, the smoother pressure changes with cone pine and coconut shell can help reduce engine wear, make the engine quieter, and lower emissions. This shows that cone pine and coconut shell are good options for biomass gasification, offering cleaner and more reliable performance compared to diesel

5.8 Cumulative Heat Release

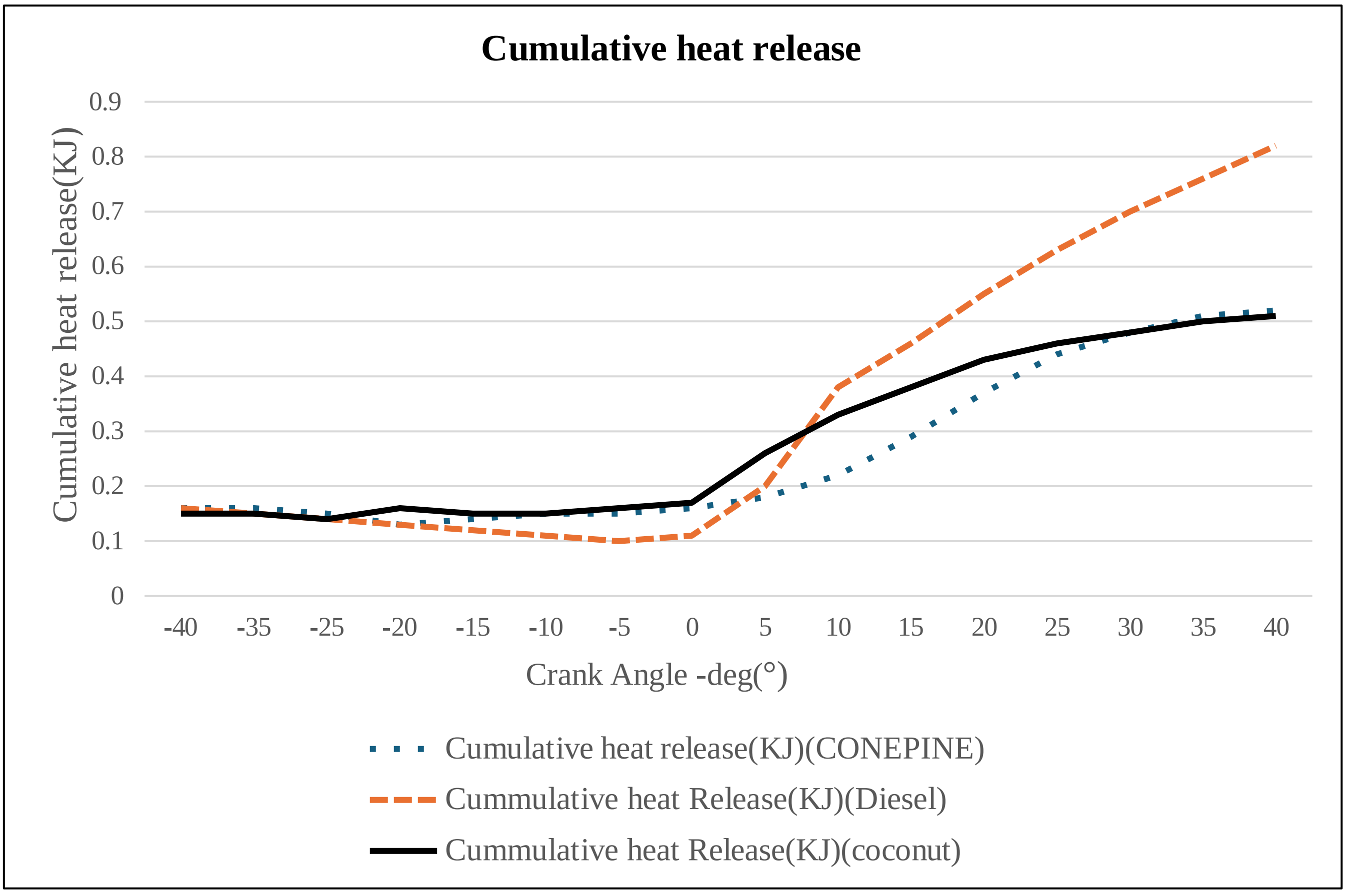


Fig.48 Cumulative Heat Release vs Crank Angle

The graph shows how heat is released over time for diesel, coconut shell, and cone pine fuels by comparing their cumulative heat release against crank angle. In the early stages, before combustion (from -40° to 0° crank angle), all three fuels show low and nearly constant heat release. After 0° crank angle, which marks the beginning of the combustion phase, diesel shows the fastest and highest increase in heat release, reaching nearly 0.8 kJ by 40°. Coconut shell follows closely, releasing heat more gradually but still significantly, while cone pine shows the slowest and smoothest heat release pattern. This suggests that diesel combusts more rapidly and with more energy, while coconut shell and cone pine burn more steadily and in a controlled way. The more gradual heat release of the biomass fuels makes them good candidates for gasification, as they provide stable combustion and help reduce sudden pressure spikes in the engine.

5.9 Net Heat Release

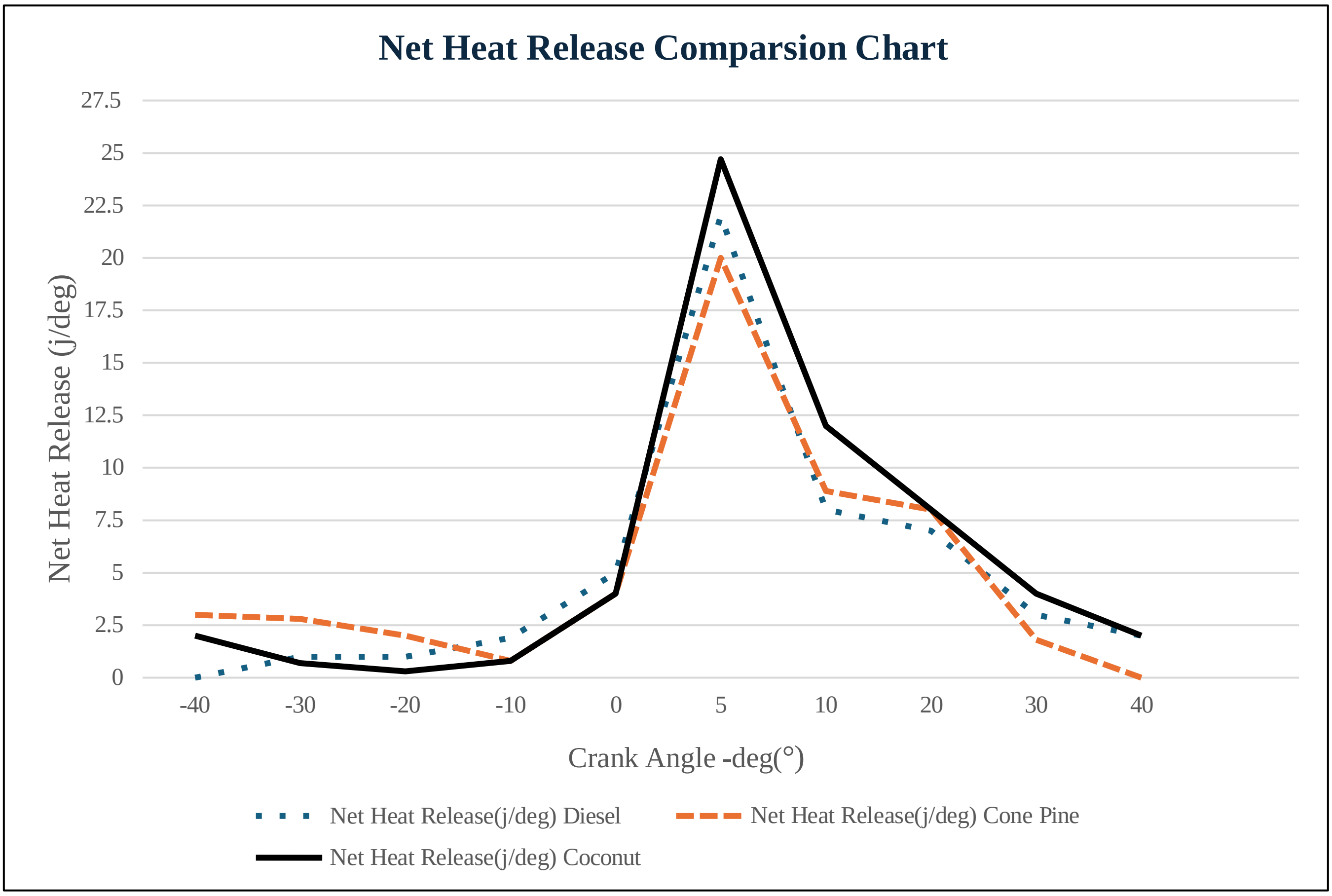


Fig.49 Net Heat Release vs Crank Angle

The variation of net heat release with respect to crank angle was analyzed for Diesel, Cone Pine, and Coconut Shell fuels. Before the top dead center (negative crank angles), all fuels exhibit minimal heat release, indicating the delay period before actual combustion. After the peak, the heat release gradually decreases for all fuels, showing the completion of combustion.It was observed that all three fuels exhibited a peak in heat release around 5° crank angle, slightly after the top dead center (TDC), indicating the main combustion phase. Among the fuels tested, Coconut Shell showed the highest net heat release rate of 24.7 J/deg at 5°, followed by Diesel at 22 J/deg and Cone Pine at 20 J/deg. This suggests that Coconut Shell undergoes a more intense and efficient combustion process compared to the other fuels. Prior to TDC, Diesel and Cone Pine displayed a gradual increase in heat release, whereas Coconut Shell showed a relatively delayed but sharper rise. Overall, the higher heat release from Coconut Shell indicates better combustion reactivity and energy output, making it a viable alternative biofuel to Diesel.

5.10 Mean Gas Temperature

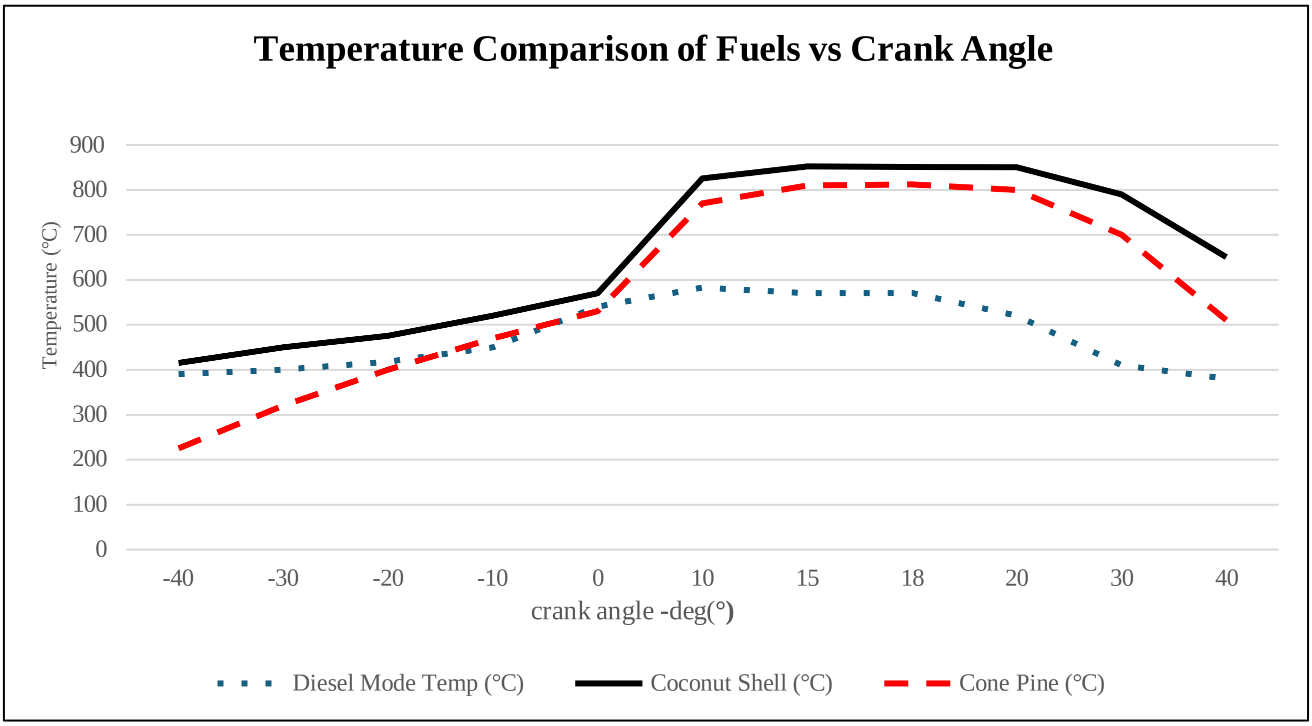


Fig. 50 Temperature comparison of fuels vs Crank Angle

The cylinder temperature variation with crank angle is a comparison of Diesel, Coconut Shell, and Cone Pine thermal efficiency over the engine cycle.At the start of the cycle, from -40° to 0° crank angle, the temperature gradually increases due to compression. Diesel shows a rise from 390°C to 540°C, while Coconut Shell and Cone Pine show a steeper increase, reaching 570°C and 530°C at 0°, respectively. A sharp rise in temperature occurs just after Top Dead Center (TDC), between 10° and 20°, as combustion takes place. Among the three fuels, Diesel reaches its maximum temperature of 582.56°C at 10°**,** Coconut Shell records the highest peak of 852°C at 15°, and Cone Pine peaks at 812°C at 18°. After reaching their respective peak temperatures, all three fuels show a gradual drop as the gases expand during the power stroke. This trend shows that Coconut Shell and Cone Pine achieve higher combustion temperatures than Diesel, which indicates stronger heat release and efficient combustion. In general, this comparison indicates that Cone Pine and Coconut Shell are both potential alternatives for Diesel to be used in internal combustion engines.

Chapter 6 Conclusion

- Gasification technology can be a great way to produce energy from renewable sources, but additional efforts are needed to overcome the challenges that prevent it from being widely used.
- The coconut shell and pine cone producer gas was successfully utilized in a dual-fuel diesel engine using a downdraft gasifier
- Various nations have conducted numerous tests with producer gas from biomass as an alternative to fuel for internal combustion engines.
- Downdraft gasification yielded producer gas from coconut shell and cone Pine with a good calorific value and combustible contents (CO, H_2, CH_4).
- Typical fuel can be substituted with this gasifier dual fuel Engine system.
- In terms of combustion characteristics, biomass fuels follow trends similar to those of Diesel.
- Test of the engine revealed that: Brake Power (BP) and Indicated Power (IP) were higher with the increase in load for both fuels. Brake Thermal Efficiency (BTE) was lower than diesel but elevated at high loads. Specific Fuel Consumption (SFC) reduced with the rise in load, reflecting improved fuel usage.
- Pine cone and coconut shell demonstrated reliable performance as biomass feedstocks, supporting their suitability as renewable, forest-based alternatives for use in dual-fuel engine applications.
- Dual-fuel operation through cococnut shell and cone pine achieved up to 64% substitution of diesel at a compression ratio of 18:1, demonstrating significant fuel savings without compromising overall performance.

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Appendix

Test Report of Cone Pine

Sophisticated Analytical Instruments Laboratories Society *(Registered as Society with Registrar of Firms & Societies, Punjab, Chandigarh)*
Thapar Technology Campus, Bhadson Road, Patiala-147 004 (India)

TEST REPORT

Sample ID	NN/24-25/024	Date:	18.04.2024
Service No.	NN/24-25/024 (01)	Customer's Ref.	Sample Submitted by Mr. Ramay Raj Bisht on dtd. 08.04.2024

Customer's name and address:

Mechanical Engineering Department
Thapar Institute of Engineering & Technology
Thapar Technology Campus
Bhadson Road Patiala-147004
Kind Attn: Dr. S.K.Mohapatra

Sample Description	~~Kiwi Pallets~~ Cone Pine
Condition of the sample received	OK
Customer's sample identification No. (if any)	--
Quantity/number of samples	100 gm / 1
Sampling Procedure (if any)/ Standard/Specification	--
Mode of Sampling / Environmental Conditions During Transportation	Not applicable
Test parameters	GCV , Proximate Analysis, Ultimate Analysis
Method followed	As mentioned below
Deviations (if any)	--

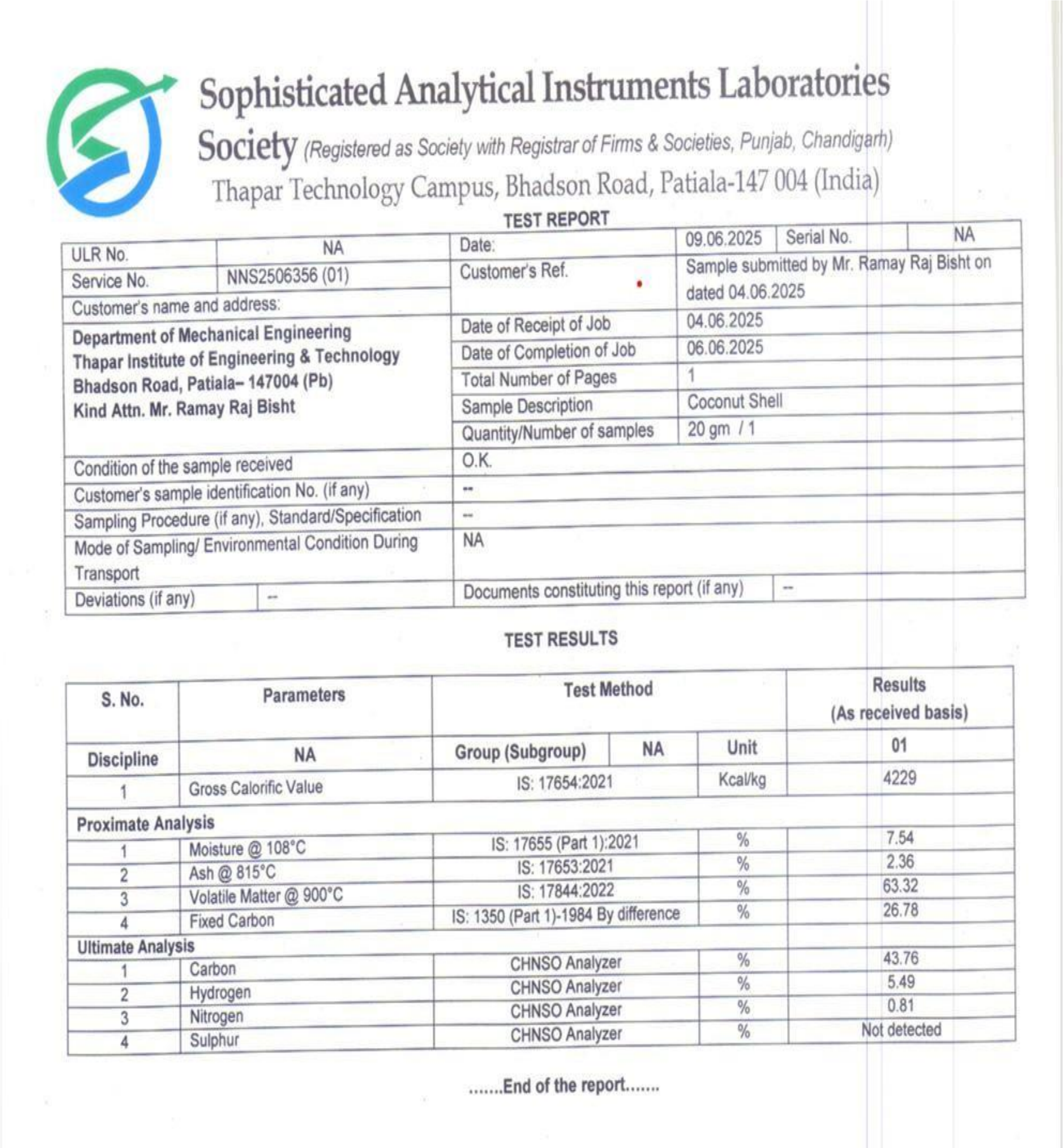
Date of Receipt of Job	Date of Completion of Job	Total Number of Pages
09.04.2024	16.04.2024	1

TEST RESULTS

Sr. No.	**Parameters**	**Test Method**	**Unit**	**Results (As received basis)**
				01
1	Gross Calorific Value	IS: 1350 (Part II), 2022, Isothermal	Kcal/kg	4579
Proximate analysis				
1	Moisture @108°C	IS: 1350 (Part 1)-1984 (2nd revision) Reaffirmed 2019 Gravimetric	%	8.69
2	Ash @815°C	IS: 1350 (Part 1)-1984 (2nd revision) Reaffirmed 2019 Gravimetric	%	1.32
3	Volatile Matter @900°C	IS: 1350 (Part 1)-1984 (2nd revision) Reaffirmed 2019 Gravimetric	%	69.11
4	Fixed Carbon	IS: 1350 (Part 1)-1984 (2nd revision) Reaffirmed 2019 By difference	%	20.88
Ultimate Analysis				
1	Carbon as C	CHNSO Analyzer	%	43.18
2	Hydrogen as H	CHNSO Analyzer	%	5.65
3	Nitrogen as N	CHNSO Analyzer	%	0.16
4	Sulphur as S	CHNSO Analyzer	%	0.03

End of the report....

Test Report of Coconut Shell



Sophisticated Analytical Instruments Laboratories Society *(Registered as Society with Registrar of Firms & Societies, Punjab, Chandigarh)*
Thapar Technology Campus, Bhadson Road, Patiala-147 004 (India)

TEST REPORT

ULR No.	NA	Date:	09.06.2025	Serial No.	NA
Service No.	NNS2506356 (01)	Customer's Ref.	Sample submitted by Mr. Ramay Raj Bisht on dated 04.06.2025		
Customer's name and address:					
Department of Mechanical Engineering **Thapar Institute of Engineering & Technology** **Bhadson Road, Patiala– 147004 (Pb)** **Kind Attn. Mr. Ramay Raj Bisht**		Date of Receipt of Job	04.06.2025		
		Date of Completion of Job	06.06.2025		
		Total Number of Pages	1		
		Sample Description	Coconut Shell		
		Quantity/Number of samples	20 gm / 1		
Condition of the sample received		O.K.			
Customer's sample identification No. (if any)		--			
Sampling Procedure (if any), Standard/Specification		--			
Mode of Sampling/ Environmental Condition During Transport		NA			
Deviations (if any)	--	Documents constituting this report (if any)	--		

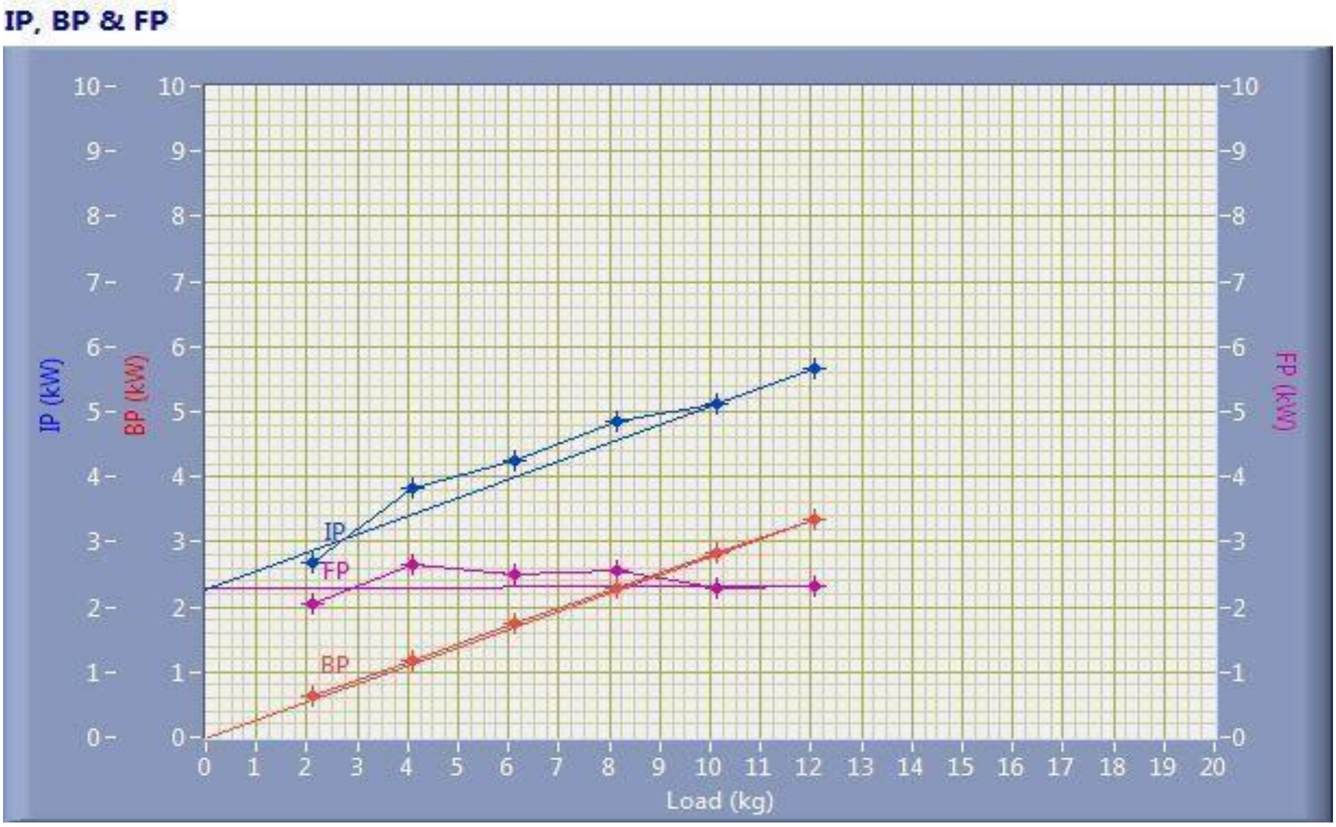
TEST RESULTS

S. No.	**Parameters**	**Test Method**			**Results (As received basis)**
Discipline	**NA**	**Group (Subgroup)**	**NA**	**Unit**	**01**
1	Gross Calorific Value	IS: 17654:2021		Kcal/kg	4229
Proximate Analysis					
1	Moisture @ 108°C	IS: 17655 (Part 1):2021		%	7.54
2	Ash @ 815°C	IS: 17653:2021		%	2.36
3	Volatile Matter @ 900°C	IS: 17844:2022		%	63.32
4	Fixed Carbon	IS: 1350 (Part 1)-1984 By difference		%	26.78
Ultimate Analysis					
1	Carbon	CHNSO Analyzer		%	43.76
2	Hydrogen	CHNSO Analyzer		%	5.49
3	Nitrogen	CHNSO Analyzer		%	0.81
4	Sulphur	CHNSO Analyzer		%	Not detected

.......End of the report.......

Cone Pine

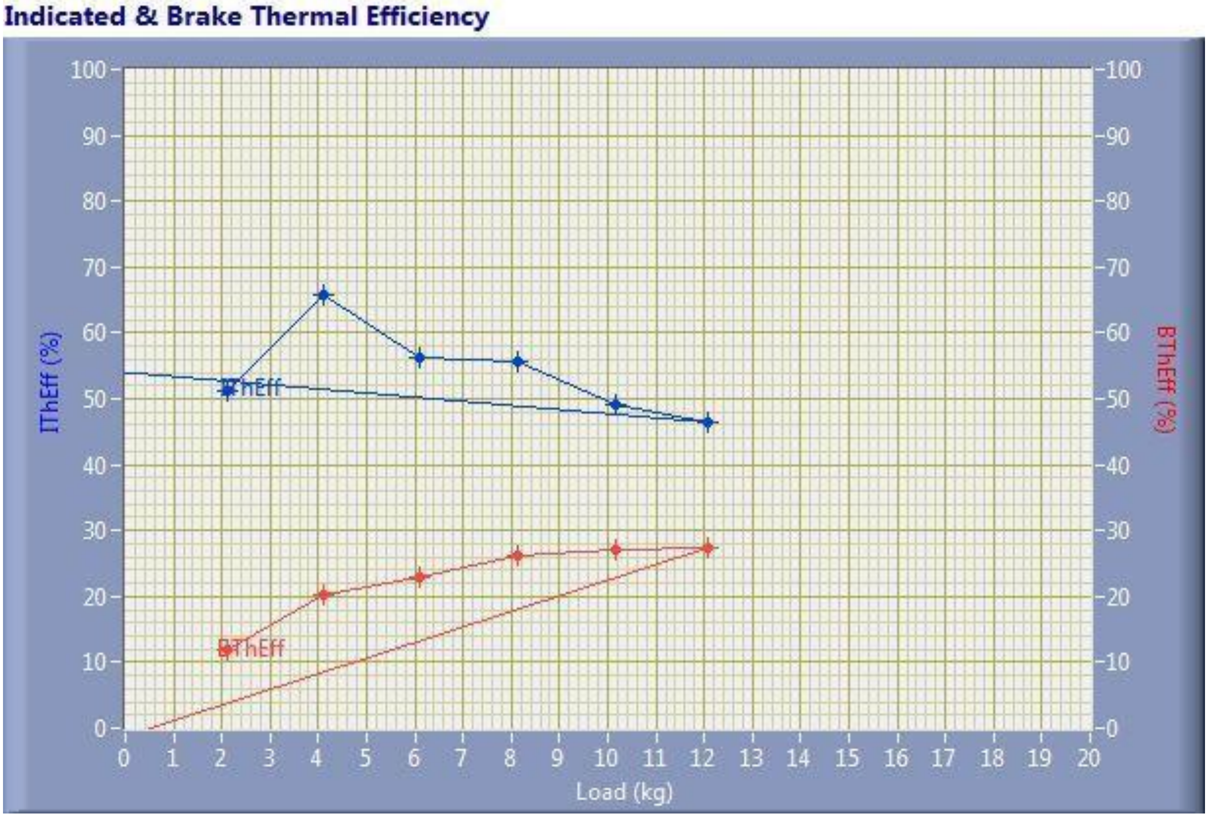
IP, BP & FP-Cone Pine



IP, BP & FP

Speed (rpm)	Load (kg)	IP (kW)	BP (kW)	FP (kW)
1534.00	2.12	2.68	0.62	2.06
1510.00	4.10	3.83	1.18	2.65
1494.00	6.12	4.24	1.74	2.50
1477.00	8.14	4.85	2.29	2.56
1474.00	10.15	5.13	2.84	2.28
1455.00	12.07	5.65	3.34	2.31
1522.00	-0.26	2.20	-0.08	2.28

Indicated & Brake Thermal Efficiency-Cone Pine



Indicated & Brake Thermal Efficiency

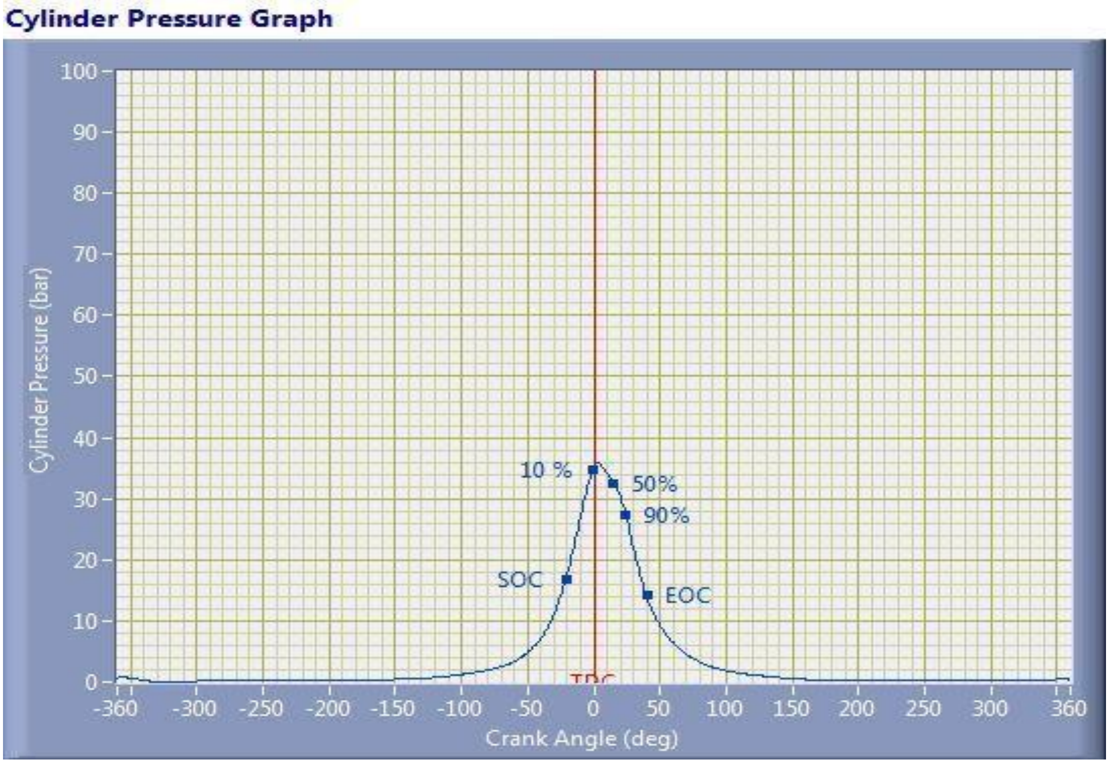
Speed (rpm)	Load (kg)	IThEff (%)	BThEff (%)
1534.00	2.12	51.20	11.83
1510.00	4.10	65.89	20.26
1494.00	6.12	56.12	23.00
1477.00	8.14	55.66	26.23
1474.00	10.15	49.01	27.19
1455.00	12.07	46.29	27.36
1522.00	-0.26	54.15	-1.86

SFC & Fuel Consumption-Cone Pine

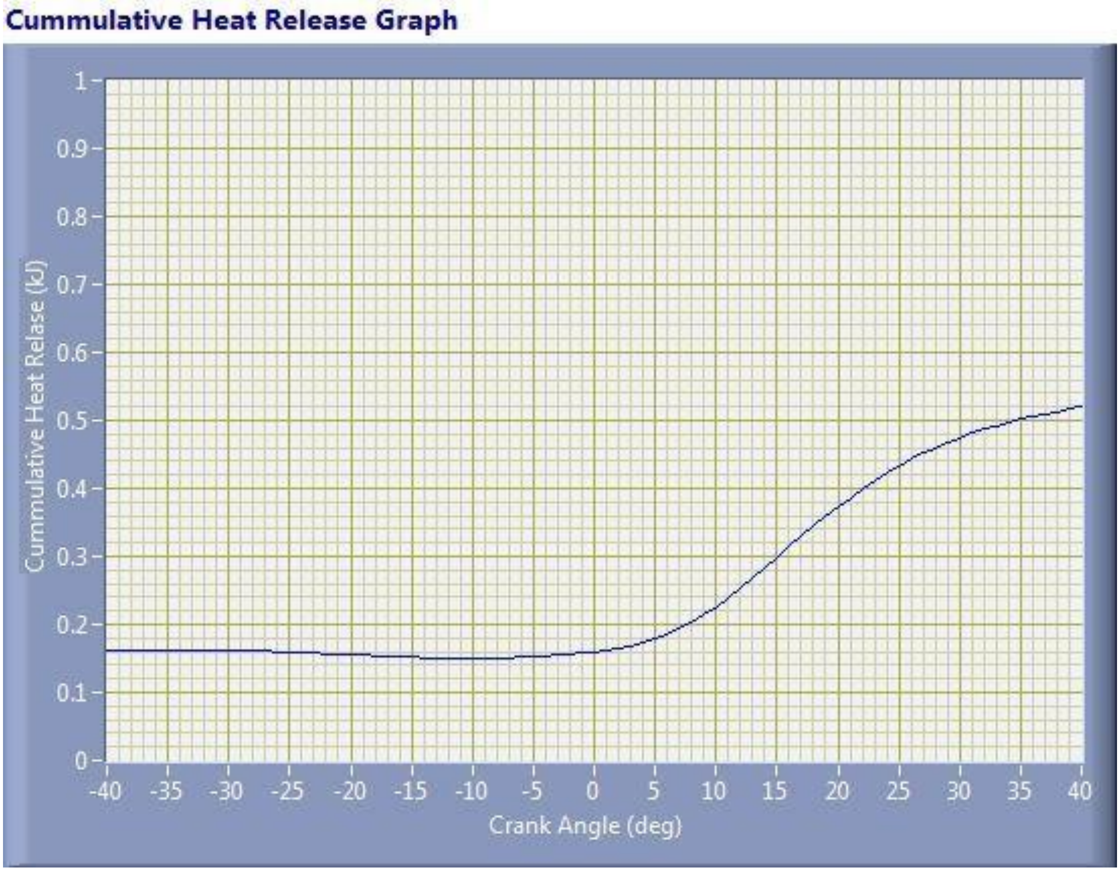
SFC & Fuel Consumption

Speed (rpm)	Load (kg)	SFC (kg/kWh)	Fuel (kg/h)
1534.00	2.12	0.72	0.45
1510.00	4.10	0.42	0.50
1494.00	6.12	0.37	0.65
1477.00	8.14	0.33	0.75
1474.00	10.15	0.32	0.90
1455.00	12.07	0.31	1.05
1522.00	-0.26	0.00	0.35

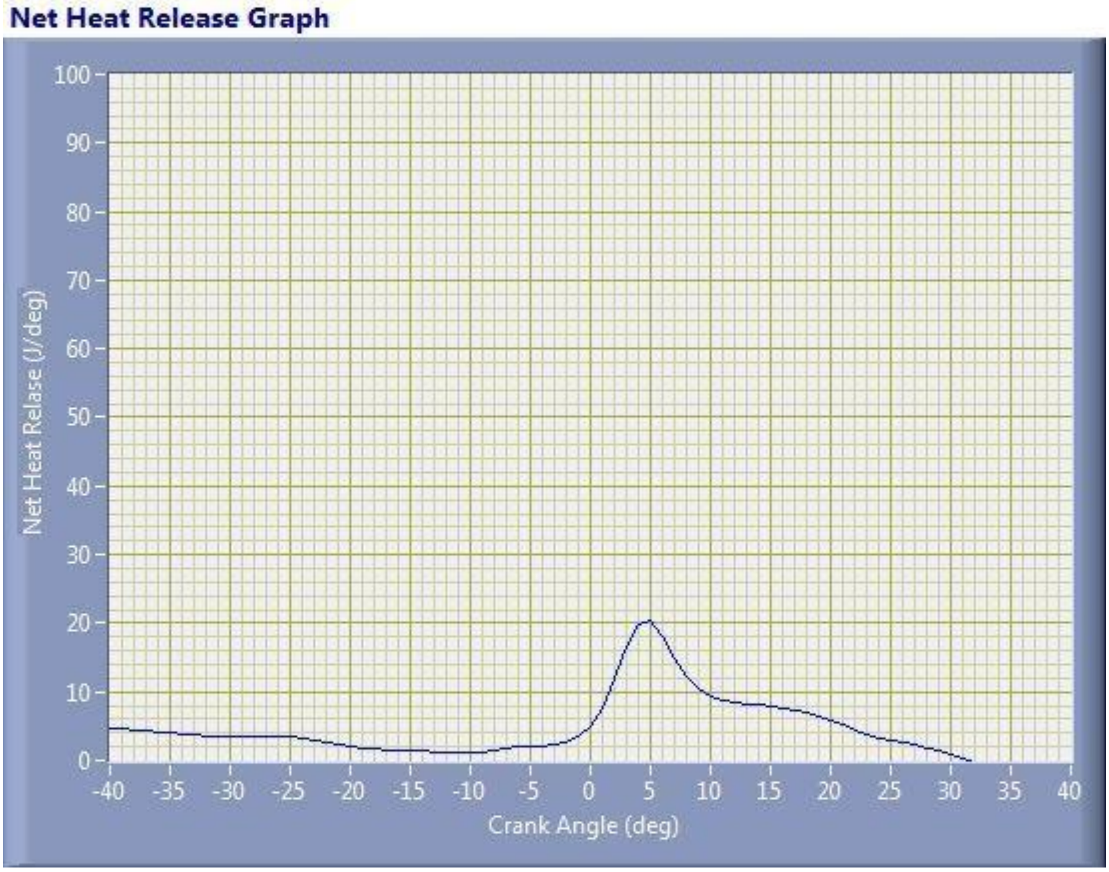
Cylinder Pressure Graph-Cone Pine



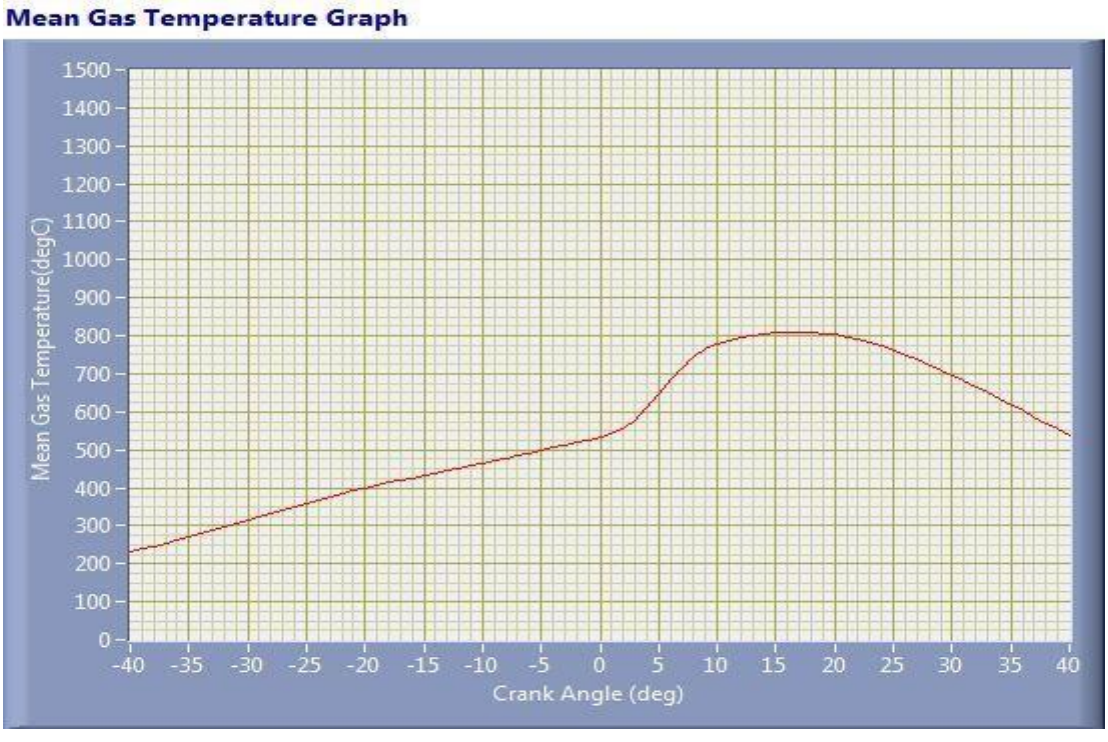
Cumulative Heat Release -Cone Pine



Net Heat Release- Cone Pine

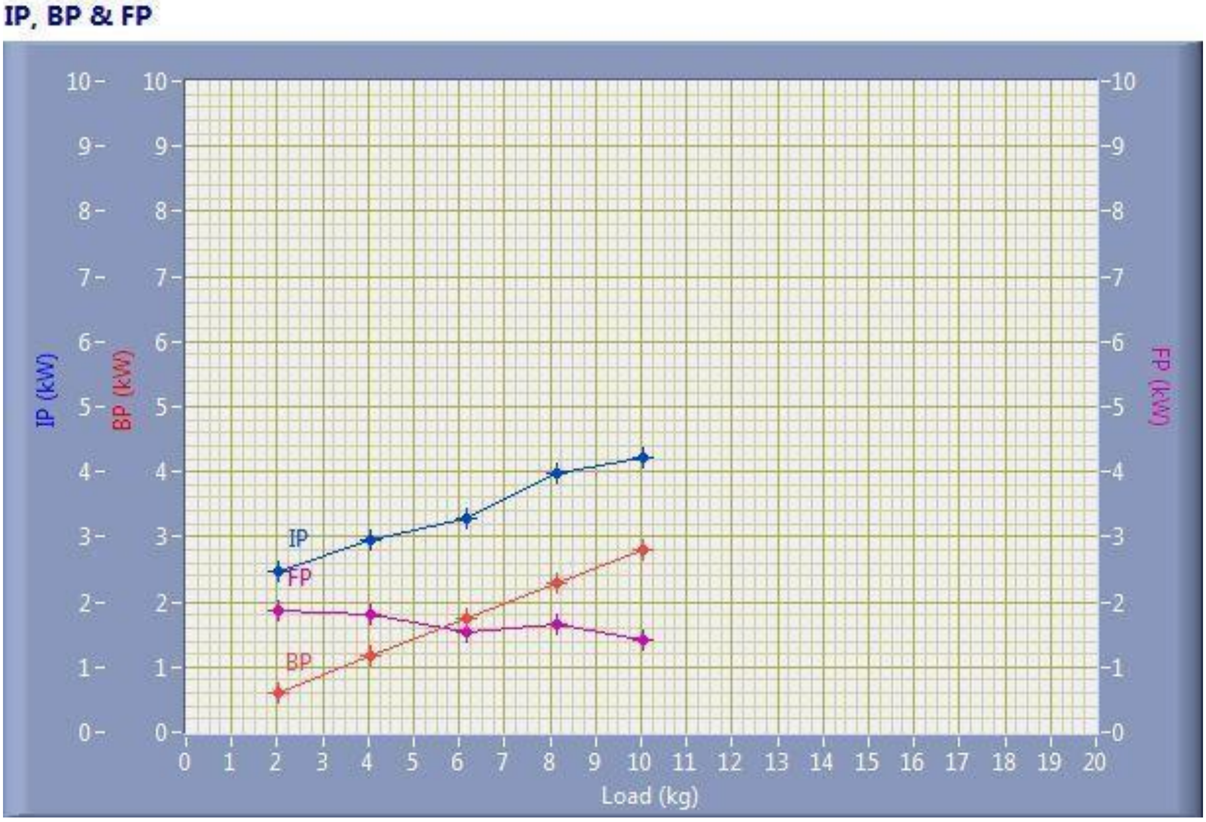


Mean Gas Temperature- Cone Pine



Coconut Shell

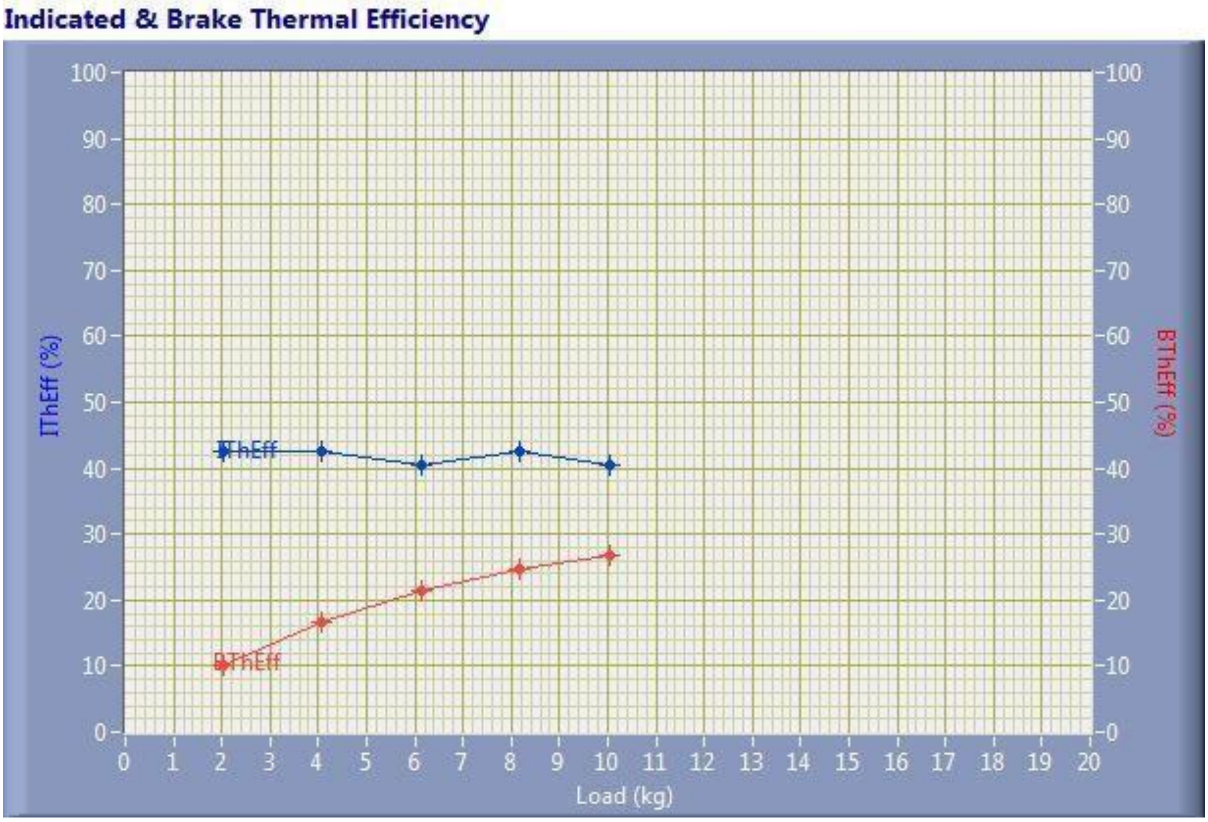
IP, BP & FP-Coconut Shell



IP, BP & FP

Speed (rpm)	Load (kg)	IP (kW)	BP (kW)	FP (kW)
1534.00	2.04	2.47	0.60	1.87
1505.00	4.06	2.96	1.16	1.80
1489.00	6.14	3.29	1.74	1.55
1478.00	8.16	3.96	2.29	1.67
1467.00	10.03	4.22	2.80	1.43

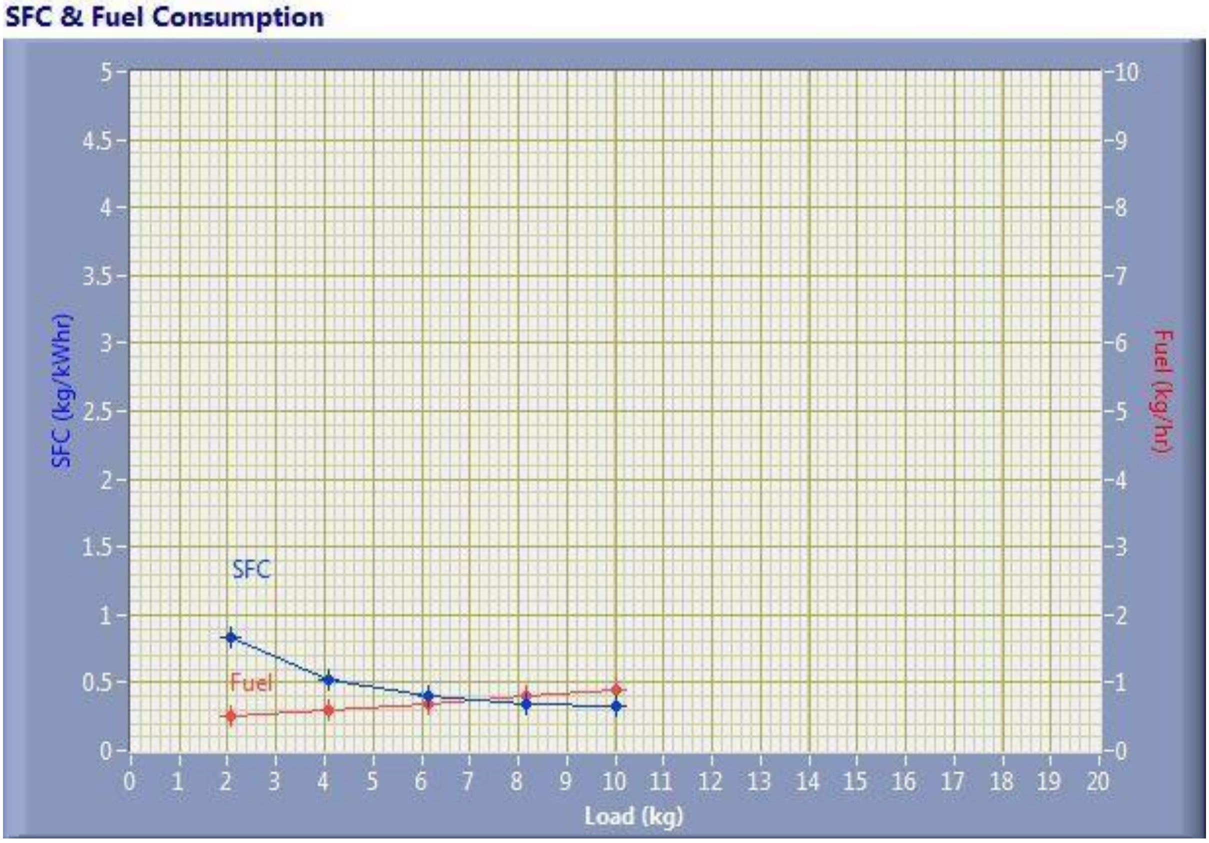
Indicated & Brake Thermal Efficiency-Coconut Shell



Indicated & Brake Thermal Efficiency

Speed (rpm)	Load (kg)	IThEff (%)	BThEff (%)
1534.00	2.04	42.46	10.24
1505.00	4.06	42.49	16.67
1489.00	6.14	40.42	21.38
1478.00	8.16	42.63	24.65
1467.00	10.03	40.38	26.73

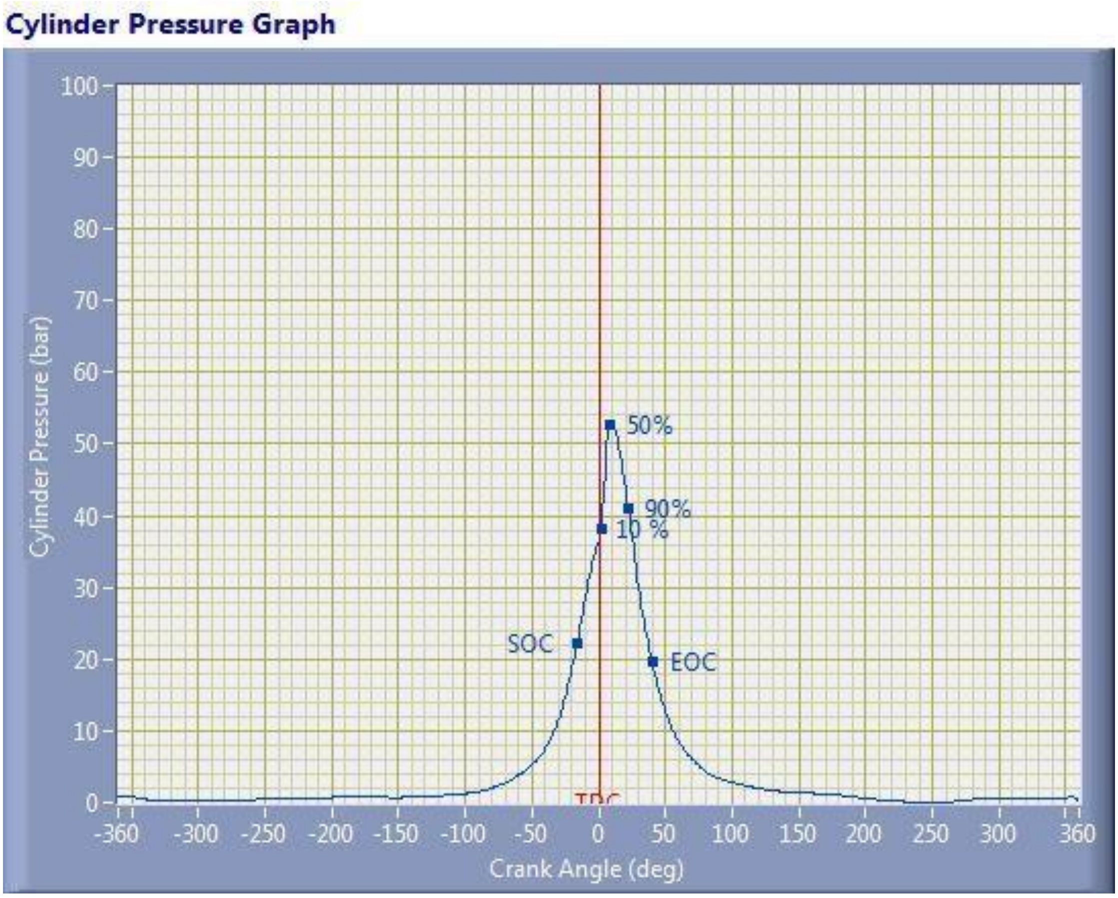
SFC & Fuel Consumption-Coconut Shell



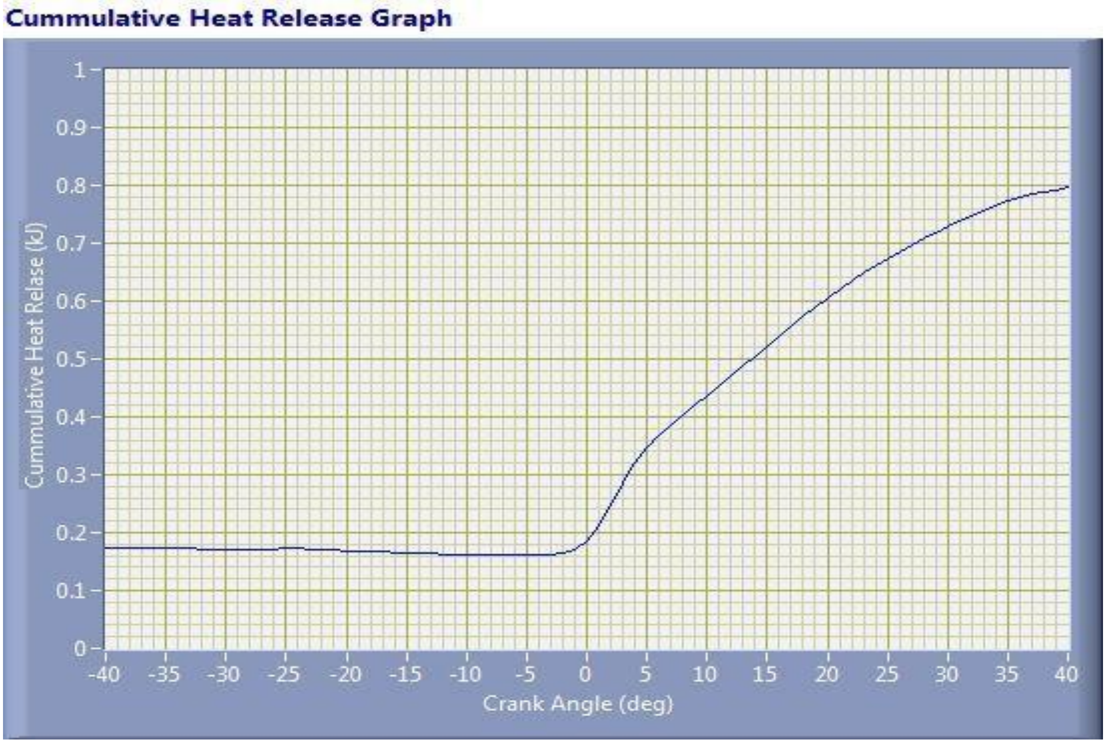
SFC & Fuel Consumption

Speed (rpm)	Load (kg)	SFC (kg/kWh)	Fuel (kg/h)
1534.00	2.04	0.84	0.50
1505.00	4.06	0.51	0.60
1489.00	6.14	0.40	0.70
1478.00	8.16	0.35	0.80
1467.00	10.03	0.32	0.90

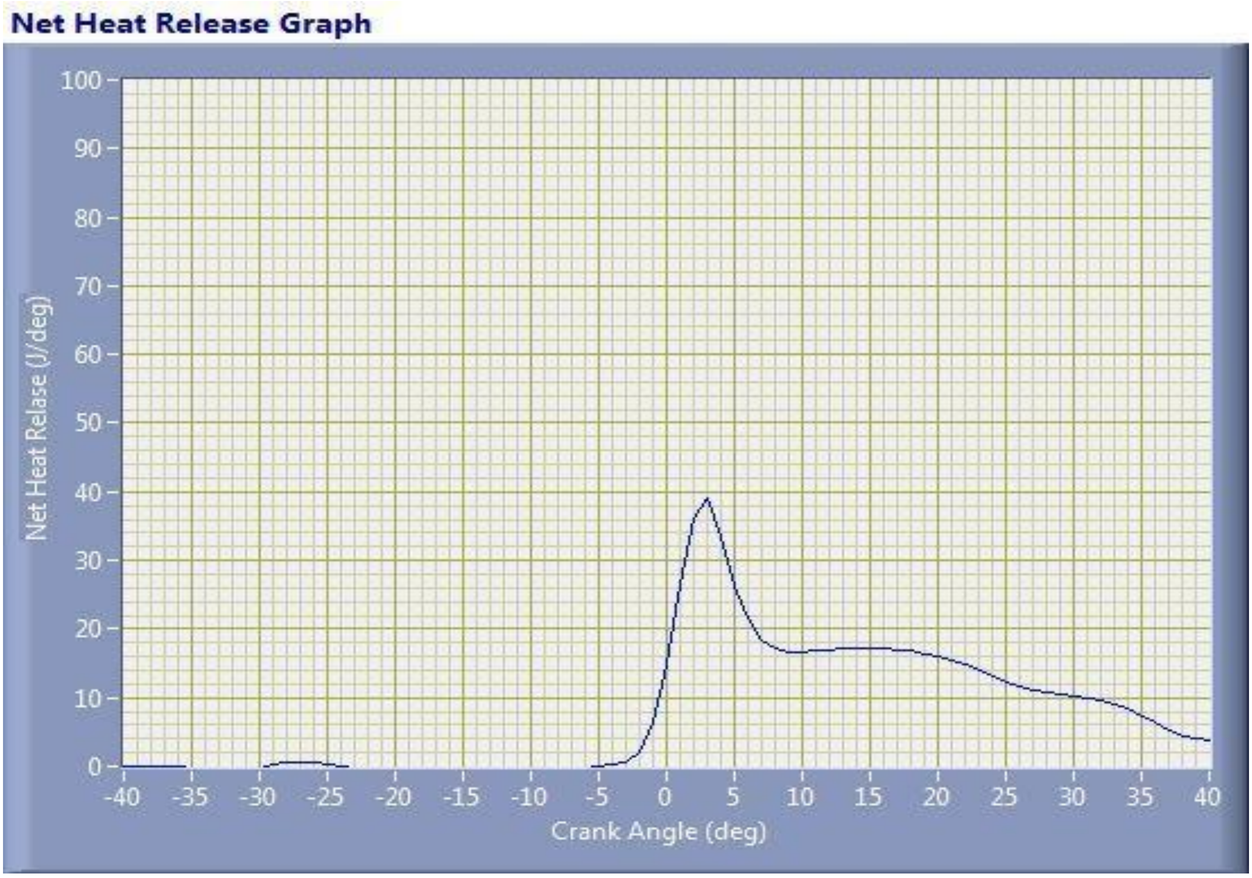
Cylinder Pressure-Coconut Shell



Cummulative Heat Pressure-Coconut Shell



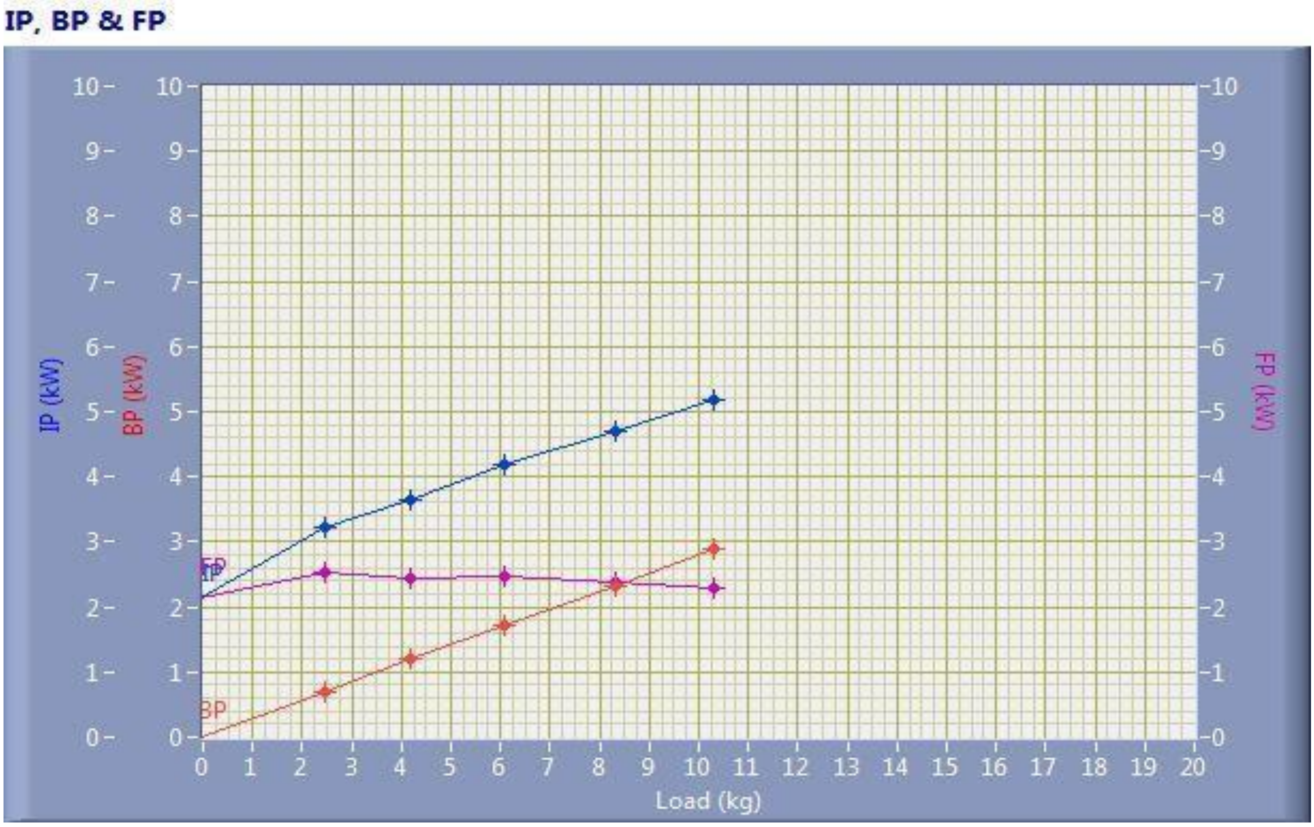
Net Heat Release-Coconut Shell



Mean Gas Temperature-Coconut Shell

Diesel

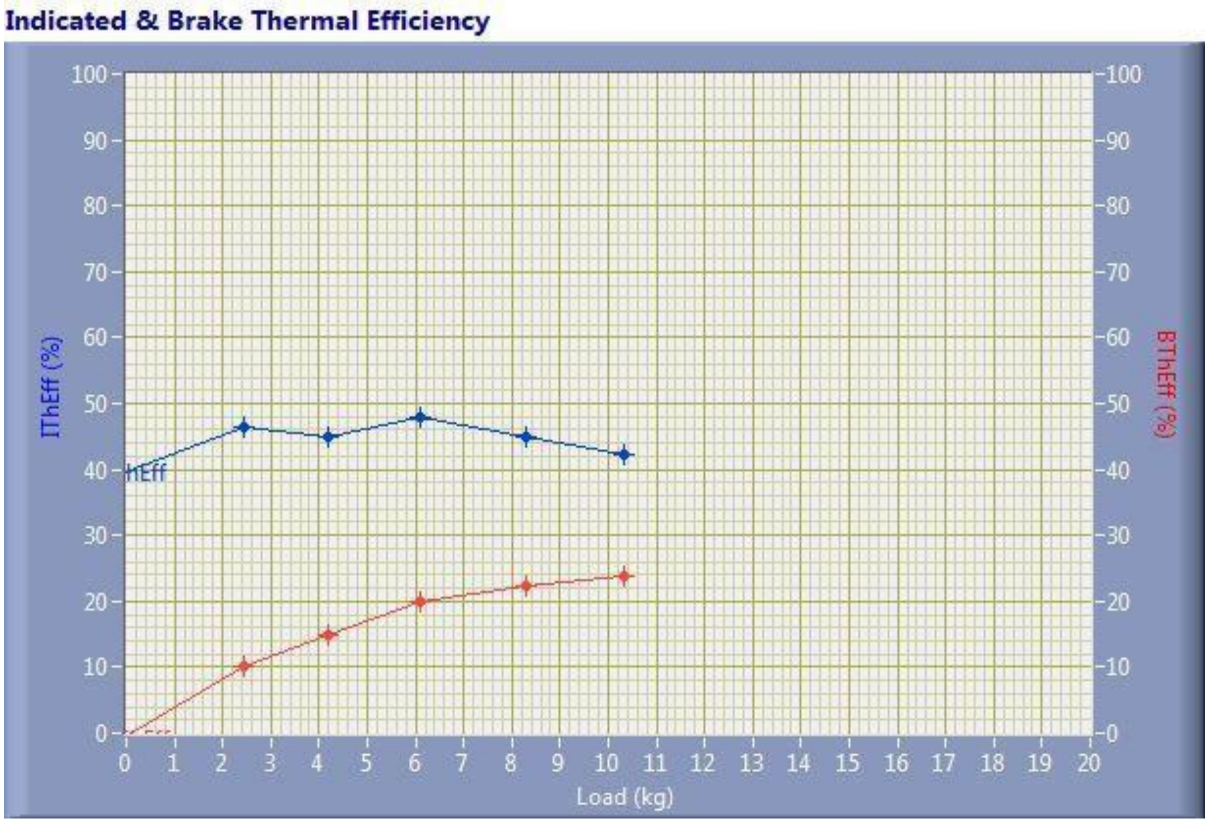
IP, BP & FP-Diesel



IP, BP & FP

Speed (rpm)	Load (kg)	IP (kW)	BP (kW)	FP (kW)
1532.00	-0.24	2.04	-0.07	2.11
1513.00	2.44	3.23	0.70	2.53
1503.00	4.20	3.65	1.20	2.45
1497.00	6.08	4.19	1.73	2.46
1475.00	8.31	4.70	2.33	2.37
1473.00	10.31	5.17	2.89	2.28

Indicated & Brake Thermal Efficiency-Diesel



Indicated & Brake Thermal Efficiency

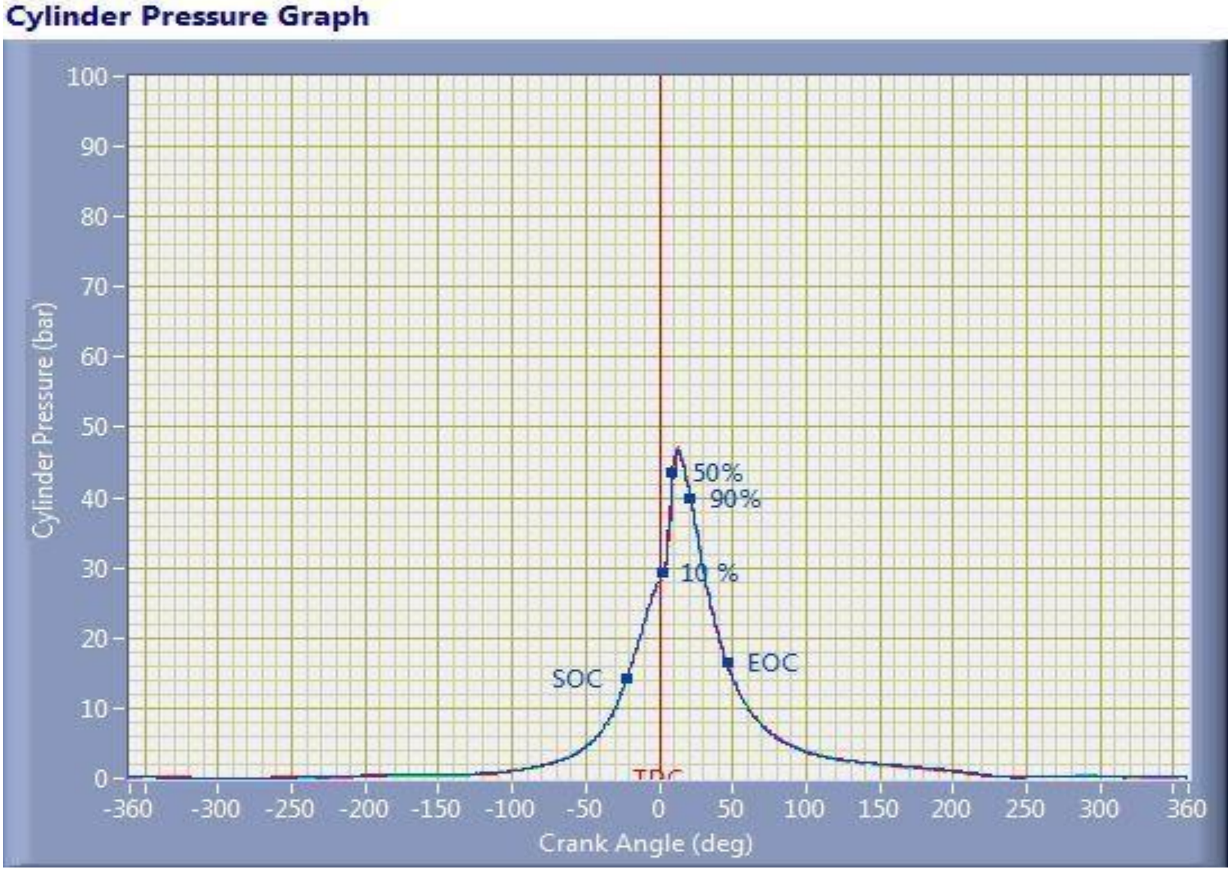
Speed (rpm)	Load (kg)	IThEff (%)	BThEff (%)
1532.00	-0.24	38.99	-1.35
1513.00	2.44	46.35	10.05
1503.00	4.20	44.82	14.75
1497.00	6.08	48.02	19.85
1475.00	8.31	44.95	22.27
1473.00	10.31	42.35	23.66

SFC & Fuel Consumption-Diesel

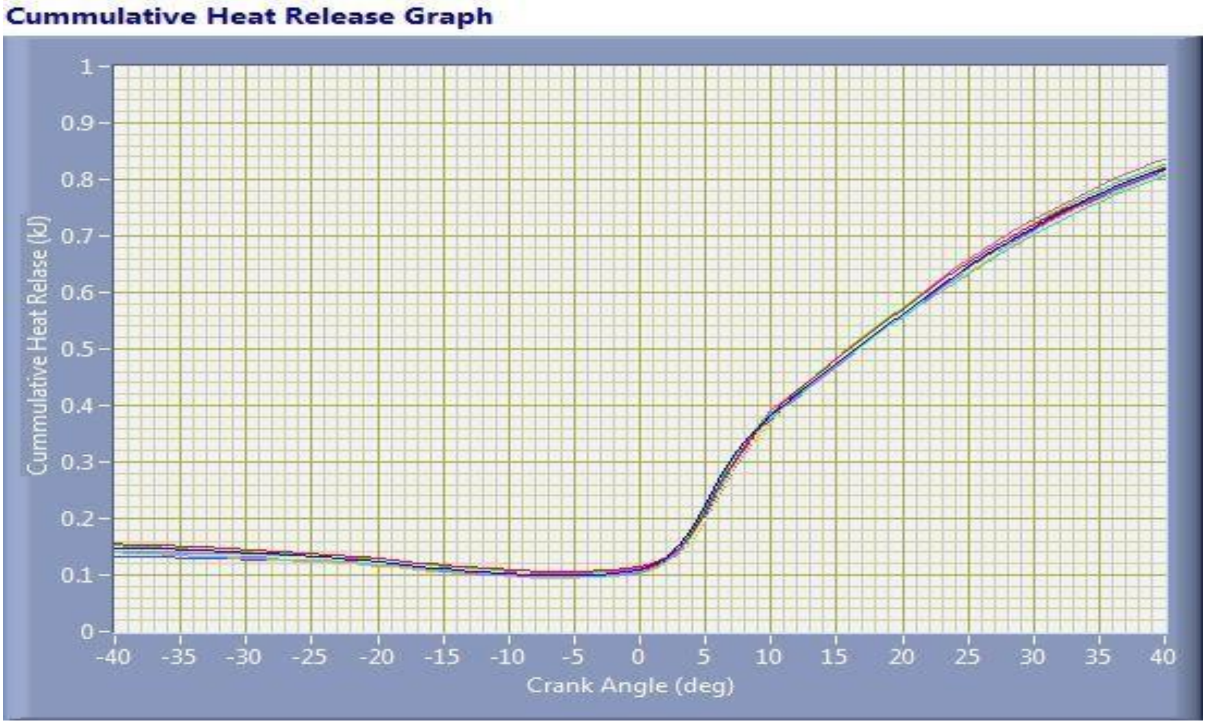
SFC & Fuel Consumption

Speed (rpm)	Load (kg)	SFC (kg/kWh)	Fuel (kg/h)
1532.00	-0.24	0.00	0.45
1513.00	2.44	0.85	0.60
1503.00	4.20	0.58	0.70
1497.00	6.08	0.43	0.75
1475.00	8.31	0.38	0.90
1473.00	10.31	0.36	1.05

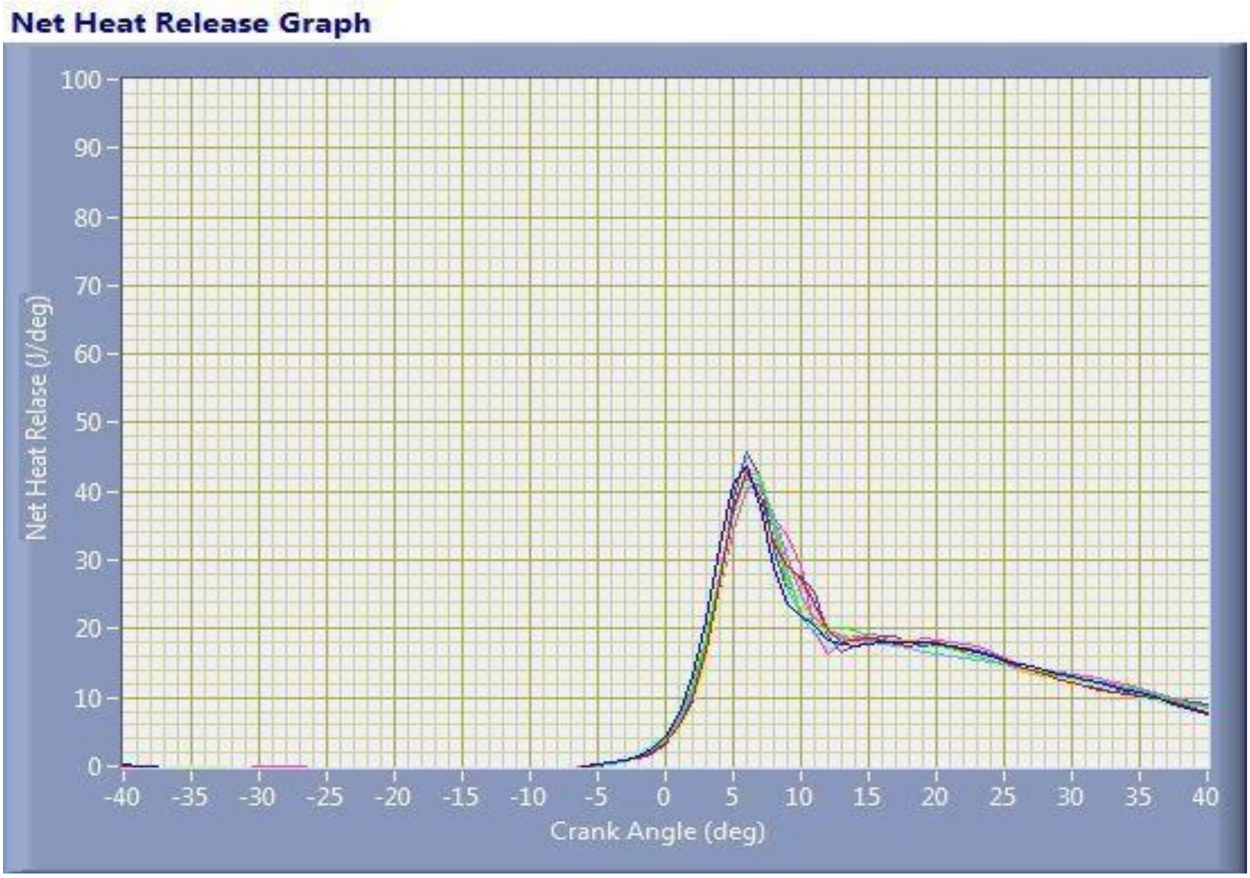
Cylinder Pressure Graph- Diesel



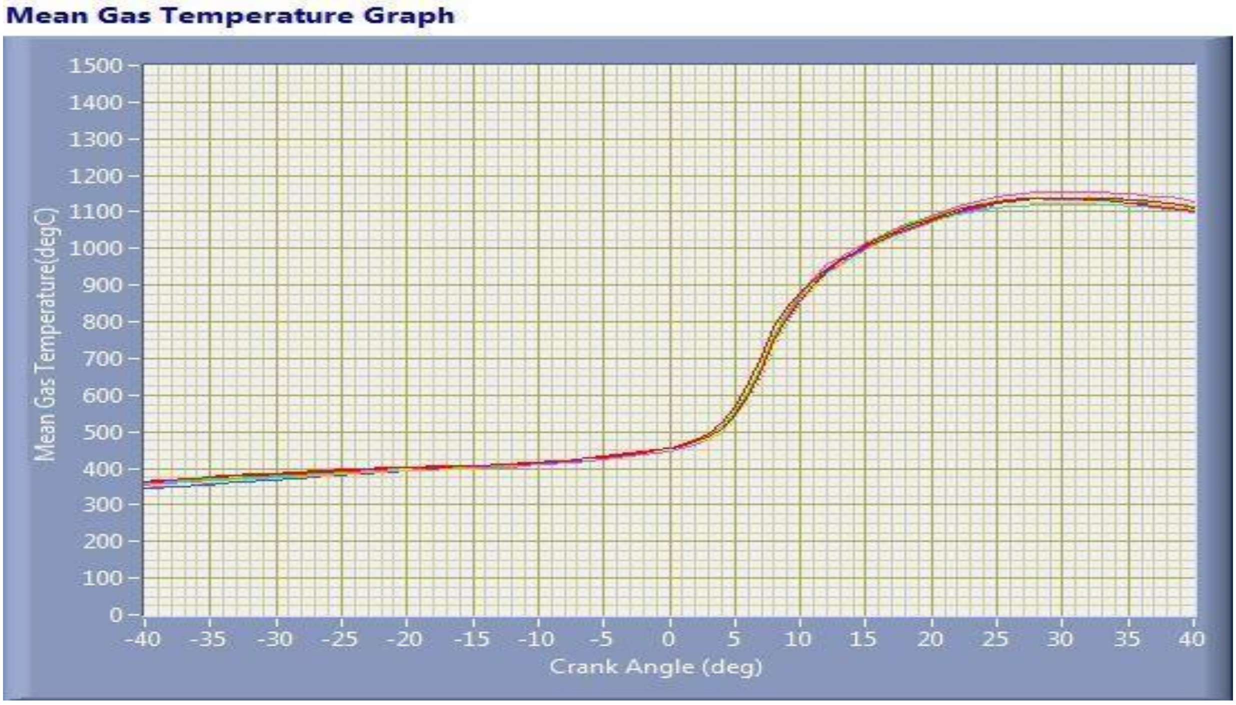
Cummulative Heat Release- Diesel



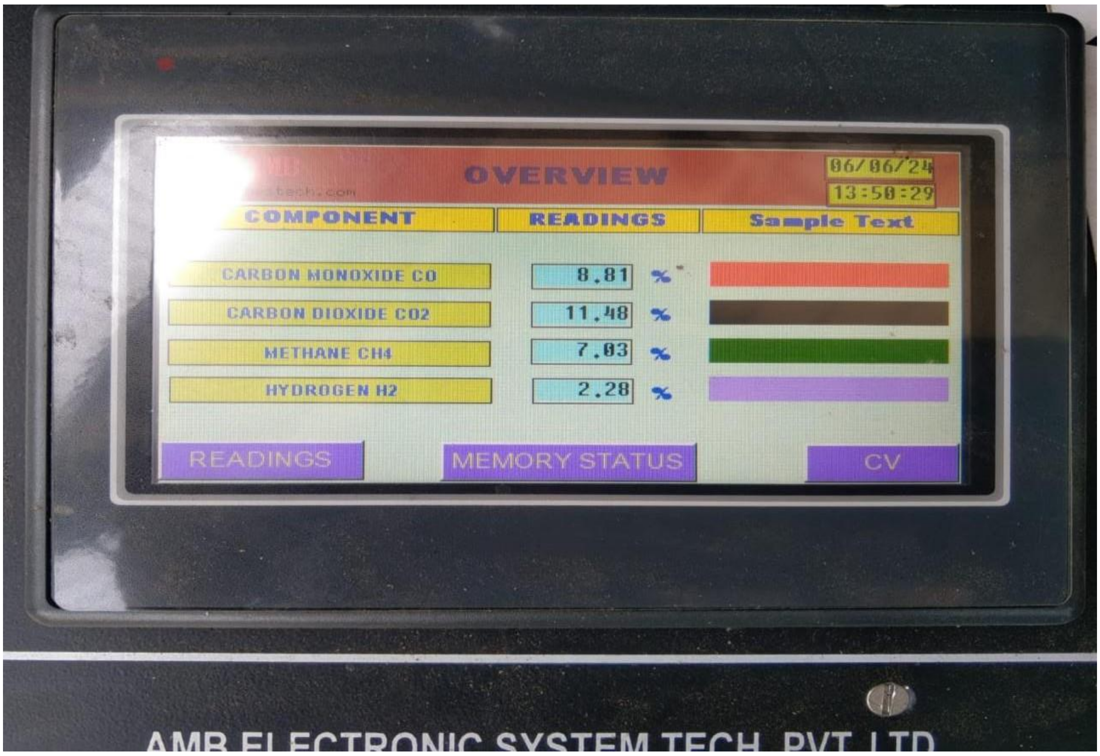
Net Heat Release- Diesel



Mean Gas Temperature-Diesel

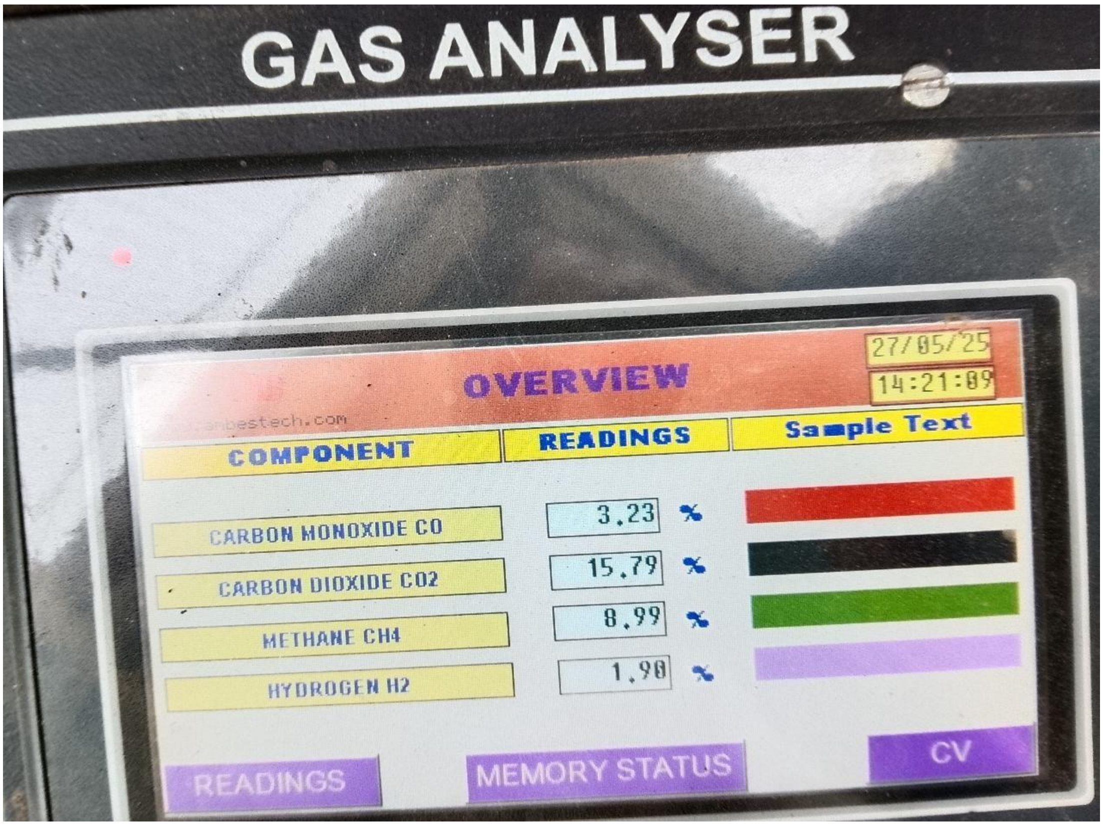


Gas Composition-Cone Pine



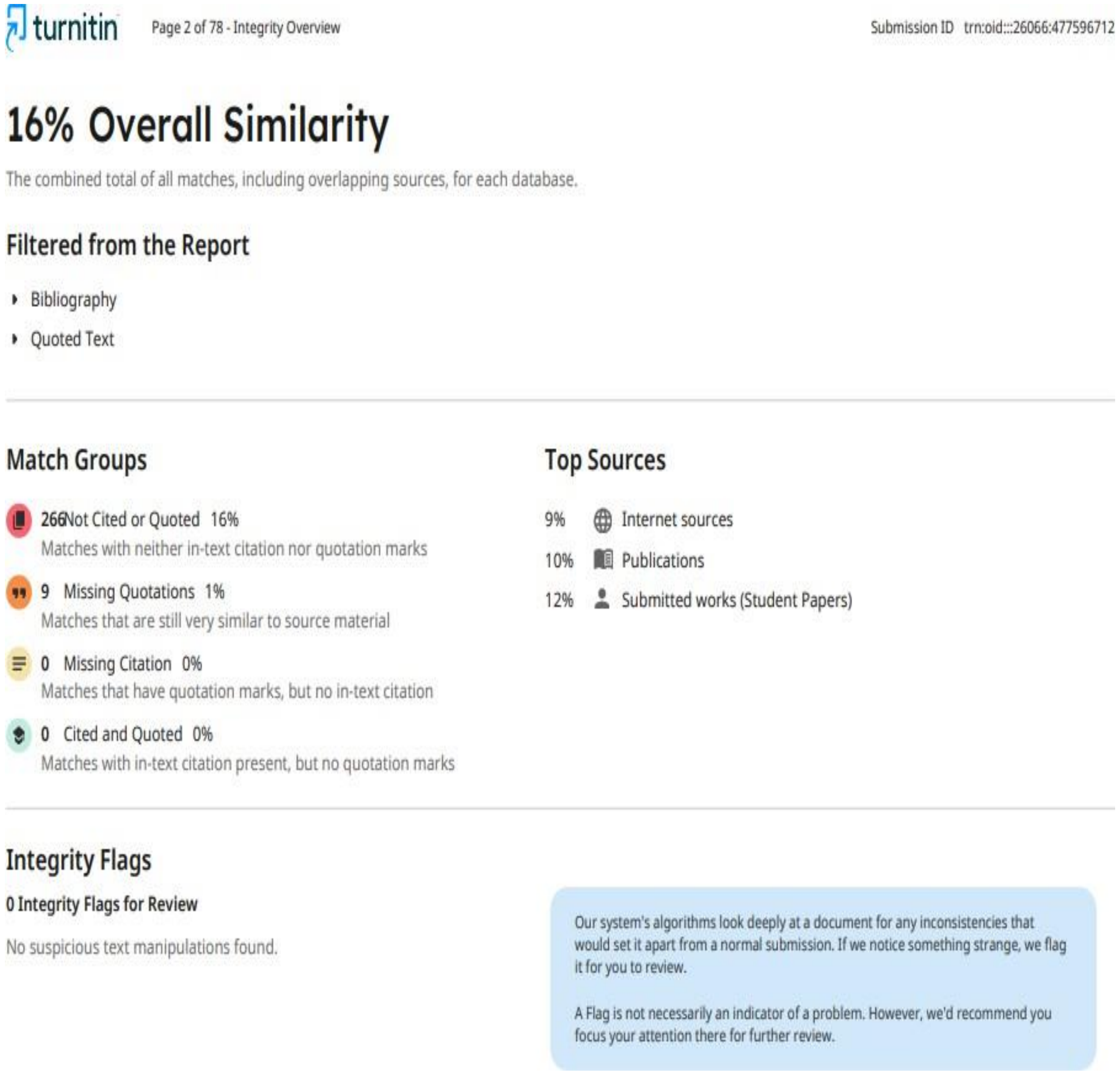
COMPONENT	READINGS		Sample Text
CARBON MONOXIDE CO	8.81	%	🟥
CARBON DIOXIDE CO2	11.48	%	🟫
METHANE CH4	7.03	%	🟩
HYDROGEN H2	2.28	%	🟪

Gas Composition-Coconut Shell



COMPONENT	READINGS		Sample Text
CARBON MONOXIDE CO	3.23	%	🟥
CARBON DIOXIDE CO2	15.79	%	⬛
METHANE CH4	8.99	%	🟩
HYDROGEN H2	1.90	%	🟪

Plagrism



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