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# Thermodynamic Simulation and Optimization of a Compression Ignition Engine Fueled with Oil Derived from Mixed Plastic Waste

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**ABSTRACT :**

In recent years, waste-to-energy systems have gained significant attention due to their dual benefits of reducing environmental pollution and decreasing reliance on fossil fuels. Owing to its high calorific value and abundant availability, plastic waste has emerged as a promising energy resource. Mixed plastic feedstock can be rapidly pyrolyzed to produce Waste Plastic Oil (WPO), which serves as a potential alternative fuel for internal combustion engines. In the present study, oil derived from mixed plastic waste was evaluated through thermodynamic simulation using Diesel-RK software on a four-stroke, single-cylinder, direct injection CI engine. Simulation results revealed that WPO produced 14.4% higher brake power, increasing from 4.04 kW (diesel) to 4.62 kW (WPO), along with a 7.4% lower specific fuel consumption (SFC) compared to diesel, indicating improved thermal efficiency. However, higher in-cylinder temperatures led to a notable increase in nitrogen oxide ($NO_x$) emissions.

To address this, Exhaust Gas Recirculation (EGR) was introduced at rates of 5%, 10%, and 15%. While performance metrics such as brake power and thermal efficiency slightly declined under EGR conditions, $NO_x$ emissions were significantly reduced from 2529.6 ppm to 831.34 ppm. Further optimization was conducted using 1D and 2D scanning techniques to fine-tune compression ratio and injection timing both independently and simultaneously. Finally, a 3D multi-variable optimization was carried out by simultaneously controlling compression ratio, injection timing, and EGR using four search algorithms. The Rosenbrock method yielded the best result, achieving the lowest Summary of Emissions (SE = 1.6189) at CR = 15.104, SOI = 17.212° CA BTDC, and EGR = 17.457%

Index Terms - Waste plastic oil,diesel replacement, CI engine, Diesel-RK, emissions, thermodynamic simulation, Compression Ratio, start of injection (SOI),Summary of Emissions (SE),2D Scanning, Optimization, Heat Release rate, Nitrogen oxides, Rosenbrock Method, Exhaust Gas Recirculation (EGR),Emission characteristics

## I INTRODUCTION

### *1.1 Plastic Production*

Plastics have become integral to modern life, offering versatility, durability, and convenience across a wide range of applications including packaging, construction, automotive, electronics, and healthcare. Despite these advantages, the extensive use of plastics has resulted in significant environmental and health challenges due to their non-biodegradable nature and improper disposal.

#### *1.1.1 Global Scenario*

Globally, plastic production has increased exponentially over the past few decades. As of 2022, the world produced approximately 390 million tonnes of plastic annually, and this figure is projected to surpass 500 million tonnes by 2030 if current consumption patterns continue. The packaging sector accounts for the largest share of plastic use, contributing over 40% of global demand, followed by construction, automotive, and consumer goods.

Unfortunately, the environmental cost of this growth is steep:

Only 9–10% of global plastic waste is effectively recycled.

Around 12% is incinerated, often releasing toxic emissions.

The remaining 79% ends up in landfills, water bodies, or as litter in natural environments.

Microplastics have become a global concern, contaminating oceans, entering food chains, and posing health risks to both wildlife and humans.

Global Recycling and Waste Trends

Less than 10% of all plastic waste generated globally is recycled.

Around 12% is incinerated, often contributing to air pollution.

The remaining ~79% ends up in landfills, oceans, or open environments.

Each year, approximately 11 million tonnes of plastic waste enter the ocean, posing a severe threat to marine biodiversity.

### *1.1.2 Indian Scenario*

India, as a rapidly developing economy, has also witnessed a surge in plastic production and consumption. The country produces around 9.4 million tonnes of plastic annually, making it one of the leading plastic producers in the developing world.

Industrial Landscape

Plastic Processing Units: Over 50,000 units, with more than 90% classified as small and medium-sized enterprises (SMEs).

Employment: The sector provides direct and indirect employment to over 4 million people.

Key facts about plastic production in India:

Contributes roughly 2.5% to global plastic production.

The industry is growing at a rate of 8–10% per annum.

India has over 50,000 plastic processing units, predominantly small and medium enterprises.

Major polymer types produced include PE (Polyethylene), PP (Polypropylene), PVC (Polyvinyl Chloride), PET (Polyethylene Terephthalate), and PS (Polystyrene).

Top plastic-producing states: Gujarat, Maharashtra, Tamil Nadu, and Uttar Pradesh.

Driving Factors

Rising demand from urban infrastructure and packaging industries.

Make in India and other industrial development policies have encouraged domestic manufacturing.

Growth in consumer goods and e-commerce sectors, which rely heavily on plastic packaging.

Despite India's relatively high plastic recycling rate (~60%), a significant portion of plastic waste, particularly multi-layered and single-use plastics, is not recycled and contributes to environmental degradation.

### *1.2 Plastic Waste Generation*

The extensive use of plastic materials across various sectors has led to a sharp increase in plastic waste generation worldwide. While plastics offer utility and convenience, their improper disposal and non-biodegradable nature make them a major contributor to environmental pollution.

### *1.2.1 Global Scenario*

Globally, plastic waste generation has become a critical environmental challenge. Out of the estimated 390 million tonnes of plastic produced annually (as of 2022), a significant portion eventually turns into waste due to short usage cycles, especially in packaging and single-use items.

Key global statistics:

Over 300 million tonnes of plastic waste is generated each year.

Only about 9–10% of this waste is recycled.

12% is incinerated, releasing greenhouse gases and harmful pollutants.

The remaining ~79% ends up in landfills, oceans, or the environment.

An estimated 11 million tonnes of plastic enter the oceans annually, threatening marine life and ecosystems.

The persistence of plastic waste in the environment—especially in the form of microplastics—has led to severe ecological and human health risks, prompting global efforts to reduce, recycle, and repurpose plastic waste.

Major Contributors to Plastic Waste

High-income countries (e.g., USA, Canada, EU nations) generate the highest per capita plastic waste.

Asia accounts for over 45% of global plastic production and is a major source of ocean-bound plastic waste.

Inadequate waste management in developing countries leads to open dumping and river discharge.

### *1.2.2 Plastic Waste Generation in India*

India is one of the largest plastic consumers in the world, and the generation of plastic waste has seen a steady rise in recent years, driven by urbanization, population growth, and increased packaging demand.

According to the Central Pollution Control Board (CPCB):

India generates approximately 3.5 million tonnes of plastic waste annually.

Per capita plastic waste generation is estimated at 3 kg/year, but is higher in urban areas.

60% of plastic waste is collected and recycled, mostly by the informal sector.

The remaining 40% is uncollected, leading to open dumping, clogging of drainage systems, and littering of public spaces.

Sources of Plastic Waste in India

Packaging waste (food wrappers, plastic bags, bottles)

Agricultural films and sheets

Household products (toys, containers, disposables)

Industrial and medical waste

Multi-layered plastics, which are difficult to recycle, make up a significant portion of unrecyclable waste.

Despite these efforts, more comprehensive measures are needed to address the scale of the problem. This includes strengthening enforcement mechanisms, investing in infrastructure for waste collection and recycling, and raising public awareness about the importance of reducing plastic consumption and proper waste management practices. With concerted efforts, India can move towards a more sustainable approach to plastic waste management, minimizing its environmental and health impacts.

### *1.3 Types of Plastic*

The most common types of plastics and their uses:

Polyethylene (PE): This is the most widely produced plastic globally, used in things like bags, bottles, and films.

Polypropylene (PP): Another common plastic used in packaging, textiles, and medical devices.

Polyvinyl Chloride (PVC): Used in pipes, flooring, and some medical devices. (Note: Due to environmental concerns, PVC use is declining in some regions.)

Polyethylene Terephthalate (PET): Commonly used for beverage bottles, food containers, and polyester fibers.

High-density polyethylene (HDPE): Known for its strength and chemical resistance, used in milk jugs, pipes, and some toys.

Low-density polyethylene (LDPE): Offers flexibility and is used in grocery bags, films, and squeezable bottles.

Polystyrene (PS): Used in packaging materials, disposable cups, and some insulation. (Note: Polystyrene recycling is challenging, and its use is being restricted in some areas.)

Polycarbonate (PC): Strong and heat-resistant, used in medical devices, eyeglass lenses, and bulletproof windows.

Acrylonitrile Butadiene Styrene (ABS): Known for its toughness, used in pipes, car parts, and appliance housings.

Nylon: Used in textiles, carpets, and some engineering applications.

Polytetrafluoroethylene (PTFE): Known as Teflon, used for non-stick cookware and various industrial applications.

Polyurethane (PU): Versatile plastic with many uses, including foams, coatings, and spandex fibers.

Epoxy Resin: Used as adhesives, coatings, and composite materials.

Phenolic Resins: Used in bonding materials, laminates, and some electrical applications.

Bioplastics: A growing category of plastics made from renewable resources like plant starches. (Note: Bioplastic production is still a small fraction of overall plastic production.)

## II PYROLYSIS

### *2.1 Pyrolysis*

Pyrolysis of waste plastics is a thermochemical process that involves heating plastic waste in the absence of oxygen to break down the long polymer chains into smaller molecules of gases, liquids (pyrolysis oil), and solid residue (char). The specific product yields and their composition depend on the type of plastic, reactor design, operating temperature, heating rate, and residence time.

Here's a detailed look at the process:

1. Feedstock Preparation:

Sorting: While some pyrolysis processes can handle mixed plastics, sorting by type (e.g., polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET)) can improve the quality and yield of specific products.

Cleaning: Removal of contaminants like labels, dirt, and food residues is often necessary to prevent reactor fouling and improve product quality.

Size Reduction: Shredding or granulating the plastic waste increases the surface area, facilitating better heat transfer and a more uniform reaction.

Drying: Removing moisture content improves the efficiency of the pyrolysis process.

2. Pyrolysis Reaction:

The prepared plastic feedstock is fed into a pyrolysis reactor. Common reactor types include:

Fixed Bed Reactors: Simple design, suitable for batch or semi-batch operation.

Fluidized Bed Reactors: Offer good heat transfer and temperature control, suitable for continuous operation.

Rotary Kiln Reactors: Can handle a wider range of feedstocks and provide good mixing.

The reactor is heated externally or internally to a specific temperature range, typically between 400°C and 700°C.

In the oxygen-free environment, the heat causes the long polymer chains to undergo thermal cracking, breaking down into smaller hydrocarbon molecules.

### *3. Product Separation and Collection:*

The products of plastic pyrolysis are a mixture of:

Pyrolysis Oil (Plastic Pyrolysis Oil - PPO): A complex mixture of liquid hydrocarbons, similar in some aspects to crude oil fractions. Its composition depends heavily on the type of plastic being pyrolyzed.

Syngas (Pyrolysis Gas): A mixture of non-condensable gases, primarily hydrogen ($H_2$), methane ($CH_4$), carbon monoxide (CO), and other light hydrocarbons like ethane and propane. The composition varies with the plastic type.

Char (Carbon Black/Solid Residue): A carbon-rich solid residue containing ash and any non-pyrolyzable components. The amount and properties of char depend on the plastic type and process conditions.

These products are separated using various techniques:

Condensation: The vapor stream containing pyrolysis oil is cooled to condense the liquid hydrocarbons. Different temperature stages can be used to separate fractions with varying boiling points.

Gas-Liquid Separation: Cyclones or separators are used to remove any entrained liquid droplets from the gas stream.

Gas Scrubbing: The syngas may be scrubbed to remove impurities like hydrogen chloride (HCl) from PVC pyrolysis.

Solid Separation: Char is typically separated from the gas and vapor streams within the reactor or downstream using cyclones or filters.

### *2.2 Chemical Equations*

The pyrolysis of plastics can vary depending on the type of plastic, but here are simplified general reactions:

For Polyethylene (PE):

$$n\ (C_2H_4) \rightarrow n\ (C_nH_{2n}) + n\ H$$

For Polypropylene (PP):

$$n(C_8H_8) \rightarrow n(C_6H_6) + n(C_2H_4) + H_2$$

For Polypropylene (PP):

$$n(C_3H_6) \rightarrow n(C_nH_{2n}) + H_2$$

### *2.3 Applications of Waste Plastic Pyrolysis*

Pyrolysis of waste plastics offers several promising applications:

Production of Alternative Fuels:

Pyrolysis Oil (PPO): Can be used as a fuel for heating, industrial boilers, or power generation. It can also be further refined into transportation fuels like gasoline and diesel through upgrading processes (e.g., hydrotreating, catalytic cracking).

Syngas: Can be used as a fuel for heat and power generation or as a feedstock for producing chemicals like methanol and hydrogen.

Chemical Feedstock Recovery:

The pyrolysis oil contains various hydrocarbons that can be separated and used as feedstock for the petrochemical industry to produce new plastics or other chemicals.

In the case of PS pyrolysis, the recovery of styrene monomer is a significant application for recycling back into polystyrene production.

Production of Carbon Materials:

The char produced can be used as a low-grade carbon black substitute in certain applications or further processed to produce activated carbon for filtration and adsorption purposes.

Waste Volume Reduction: Pyrolysis significantly reduces the volume of plastic waste, alleviating pressure on landfills.

### *2.4 Advantages of Waste Plastic Pyrolysis*

Waste Diversion: Provides a valuable alternative to landfilling and incineration of plastic waste.

Resource Recovery: Converts a waste product into valuable energy resources and chemical feedstocks.

Potential for Circular Economy: Can contribute to a circular economy for plastics by closing the loop and reducing the need for virgin resources.

Lower Emissions (compared to some incineration methods): When properly controlled, pyrolysis can have lower emissions of certain pollutants compared to uncontrolled incineration.

Handles Mixed Plastics (to some extent): While sorting improves product quality, some pyrolysis technologies can process mixed plastic waste streams, reducing the complexity of pre-processing.

### *2.5 Disadvantages of Waste Plastic Pyrolysis*

Product Quality Variability: The quality and composition of pyrolysis oil can vary significantly depending on the type of plastic in the feedstock, making it challenging to directly use without further upgrading.

Presence of Contaminants: Contaminants in the plastic waste can affect the process efficiency, product quality, and potentially cause corrosion in the reactor.

Pre-treatment Requirements: While some processes tolerate mixed plastics, efficient and high-quality product generation often requires sorting, cleaning, and size reduction, adding to the cost and complexity.

Handling of Hazardous Byproducts: Pyrolysis of certain plastics like PVC releases corrosive and toxic gases like HCl, requiring specialized materials and gas treatment systems.

Energy Intensive: The pyrolysis process requires energy input for heating, and the overall energy balance needs to be carefully considered.

Technological Maturity and Scalability: While the technology is advancing, the widespread commercialization and scalability of cost-effective and environmentally sound plastic pyrolysis plants are still under development in many regions.

## III METHODOLOGY OF WORK


Fig.No.1 Methodology of Work

1. Oil Production from Catalytic Pyrolysis

Waste plastic is converted into oil through catalytic pyrolysis, producing Waste Plastic Oil (WPO) as a fuel.

2. Property Testing of WPO

Viscosity (flow behavior)

Density (mass per unit volume)

Flash & Fire Point (ignition characteristics)

Calorific Value (energy content)

3. Loading Fuel Properties into Diesel-RK

The measured fuel properties are entered into Diesel-RK's fuel library for simulation.

4. Simulation Using Diesel-RK

Diesel-RK software is used to simulate engine performance using WPO as fuel.

5. Comparison of Diesel vs. WPO

The results of WPO are compared with conventional diesel fuel in terms of:

Combustion Characteristics (ignition delay, heat release rate)

Performance Characteristics (power, efficiency, fuel consumption)

Emission Characteristics (CO, NOx, PM levels)

6. Optimization of Engine Parameters

Adjustments are made to optimize engine settings (e.g., injection timing, compression ratio) for better WPO performance.

This approach helps determine if WPO can be a viable alternative to diesel fuel in engines.

Table 1

Engine specifications

| **Parameter** | **Value** |
|---|---|
| Make | Kirloskar |
| Model | AVI |
| Bore | 80 mm |
| Stroke | 110 mm |
| Number of cylinders | 1 |
| Rated Speed | 1500 rpm |
| Maximum Brake Power | 3.75 kw |
| Compression Ratio | 16.5:1 |

Table 2

Fuel Properties of test fuels

| **S. No** | **Property** | **Diesel** | **WPO** |
|---|---|---|---|
| 1 | Density (kg/m$^3$) | 820 | 780 |
| 2 | Dynamic viscosity coefficient (Pa-s) | 0.003 | 0.0028 |
| 3 | Calorific Value (KJ/kg) | 42600 | 44800 |
| 4 | Cetane Index | 50 | 48 |
| 5 | C, H, O (%) | 0.87,0.13,0 | 0.84,0.14,0.02 |
| 6 | Molecular mass(g/mol) | 190 | 150 |
| 7 | Specific vaporization of heat (KJ/Kg) | 250 | 300-380 |

## IV RESULTS AND DISCUSSIONS

Table 3

Simulation Results

| **Parameter** | **Diesel** | **WPO** |
|---|---|---|
| BP (KW) | 4.136 | 4.4109 |
| SFC(Kg/KWh) | 0.24996 | 0.23517 |
| Brake Thermal Efficiency (ɳ %) | 33.81% | 34.18% |
| Max Pressure(bar) | 91.009 | 93.614 |

| | | |
|---|---|---|
| Max Temperature(ºK) | 1926.4 | 1971.8 |
| Ignition Delay (crank angle, deg) | 9.4565 | 10.109 |
| $CO_2$ (g/KWh) | 805.43 | 731.63 |
| $NO_x$ (ppm) | 2003.9 | 2529.6 |
| PM (g/KWh) | 0.36011 | 0.3324 |
| Summary of Emissions (SE) | 3.2608 | 4.8499 |
| BSI | 1.4312 | 1.4165 |

Performance Analysis

Brake Power (BP)

The data showcases the performance difference between these two fuel types in terms of power generation.

Diesel exhibits a power output of 4.136 KW, while WPO demonstrates a significantly higher power output of 4.4109 KW, highlighting the potential of WPO as an alternative fuel source.

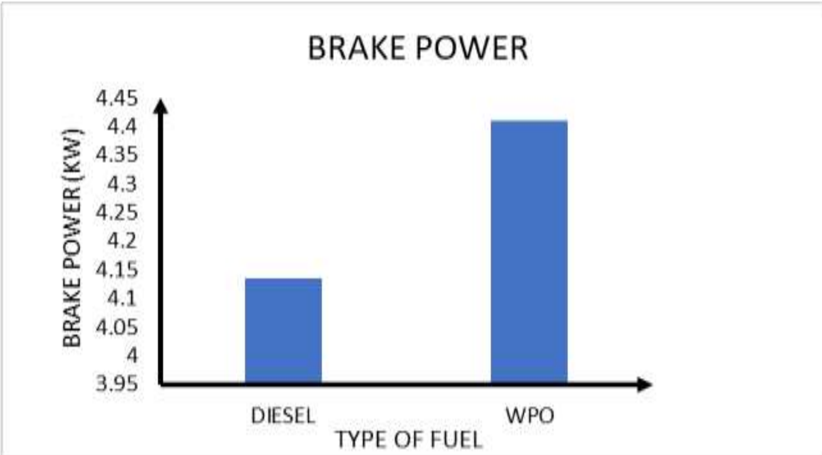


Fig.No.2 Brake Power (BP)

Specific Fuel Consumption (SFC)

This graph presents the comparison of Specific Fuel Consumption (SFC) in kilograms per kilowatt-hour (Kg/KWh) between Diesel and Waste Plastic Oil (WPO).

The data reveals that Diesel has an SFC of 0.24996 Kg/KWh, while WPO demonstrates a lower SFC of 0.23517Kg/KWh. This suggests that WPO exhibits improved fuel efficiency compared to Diesel, indicating its potential as an environmentally friendly alternative fuel option.

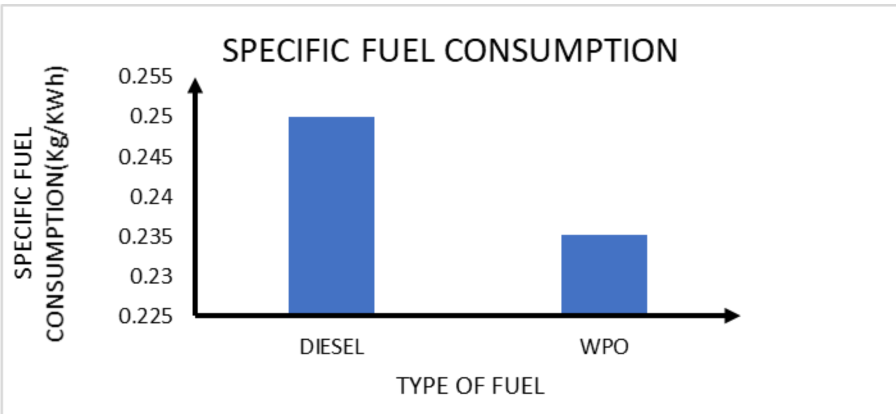


Fig.No.3 Specific Fuel Consumption (SFC)

Heat Release Rate (HRR)

HRR represents the rate at which energy is released during the combustion process and is critical for analyzing combustion characteristics.

Both Diesel and WPO show a sharp increase in HRR shortly after the start of combustion.

WPO exhibits a slightly higher peak HRR (~58 J/deg) than Diesel (~55 J/deg), indicating a more intense combustion in the premixed phase.

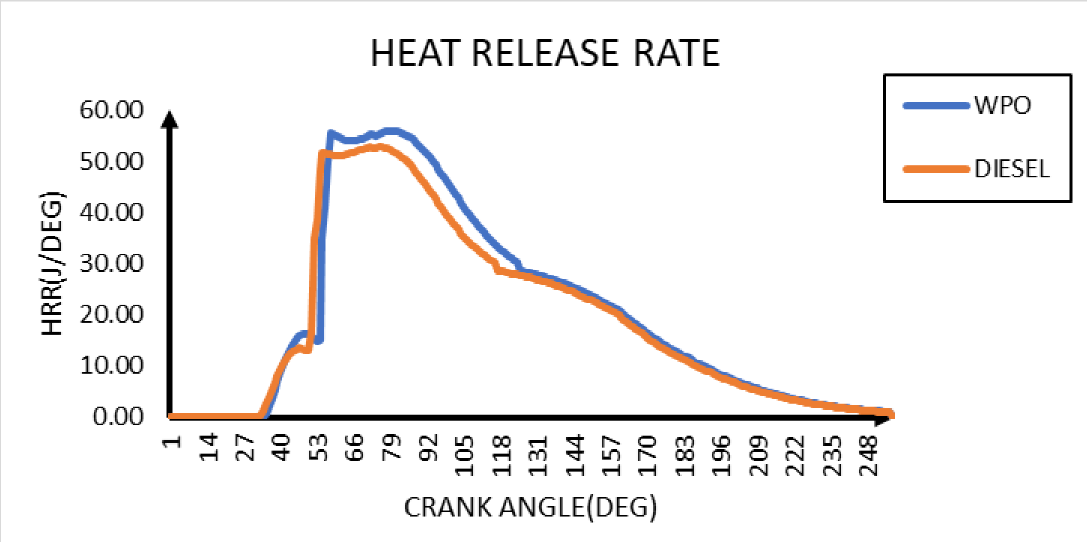


Fig.No.4 Heat Release Rate (HRR)

Nitrogen Oxides (NOx)

This graph presents the comparison of nitrogen oxide (NOx) emissions, measured in parts per million (PPM), between Diesel and Waste Plastic Oil (WPO).

The data reveals that Diesel emits 2003.9 PPM of NOx, while WPO emits a higher amount of 2529.6 PPM of NOx.

This highlights the difference in NOx emissions between the two fuels, suggesting the need for further consideration of emissions control strategies when using WPO as a fuel alternative.

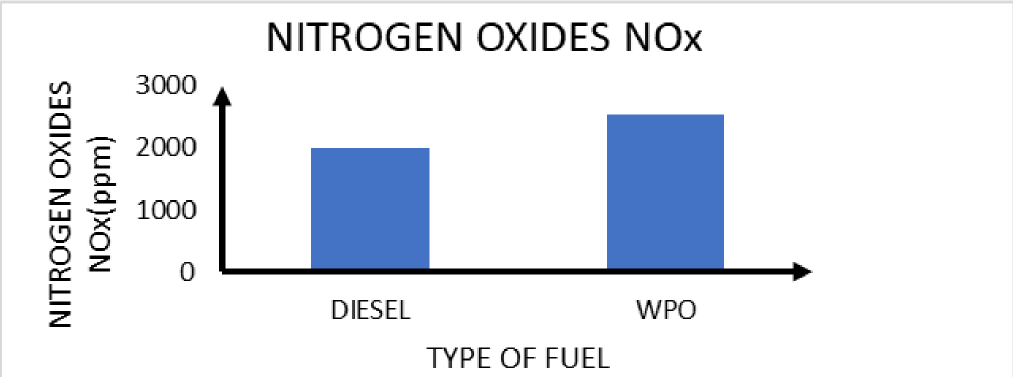


Fig.No.5 Nitrogen Oxides (NOx)

Optimization

Following the 2D scanning procedure, a comprehensive optimization was conducted in Diesel-RK by simultaneously adjusting three key parameters—Compression Ratio (CR), Start of Injection (SOI), and Exhaust Gas Recirculation (EGR) rate. The objective of this optimization was to minimize the Summary of Emissions (SE), which integrates major pollutants such as $NO_x$, PM, and smoke.The optimization was performed within predefined parameter ranges: CR from 15 to 19, SOI from 17° to 21° CA BTDC, and EGR from 0% to 20%. Four numerical search algorithms were employed to explore the parameter space and identify the optimal configuration:

Rosenbrock Method

Powell Method

Quickest Descent Method

Heavy Ball Method

Table 4

Optimization Results

| **Method** | **Compression Ratio (CR)** | **Start of Injection (SOI) [°CA BTDC]** | **EGR (%)** | **Summary of Emissions (SE)** |
|---|---|---|---|---|
| **Rosenbrock** | **15.104** | **17.212** | **17.457** | **1.6189** |
| **Powell** | 13.546 | 17.166 | 17.246 | 1.6693 |
| **Quickest Descent** | 14.406 | 21.149 | 20 | 1.8859 |
| **Heavy Ball** | 15.107 | 18.316 | 20 | 1.8976 |

Among these, the Rosenbrock Method produced the best result, achieving the lowest SE value of 1.6189. This was obtained at the optimal combination of:

Compression Ratio (CR) = 15.104

Start of Injection (SOI) = 17.212° CA BTDC

EGR Rate = 17.457%

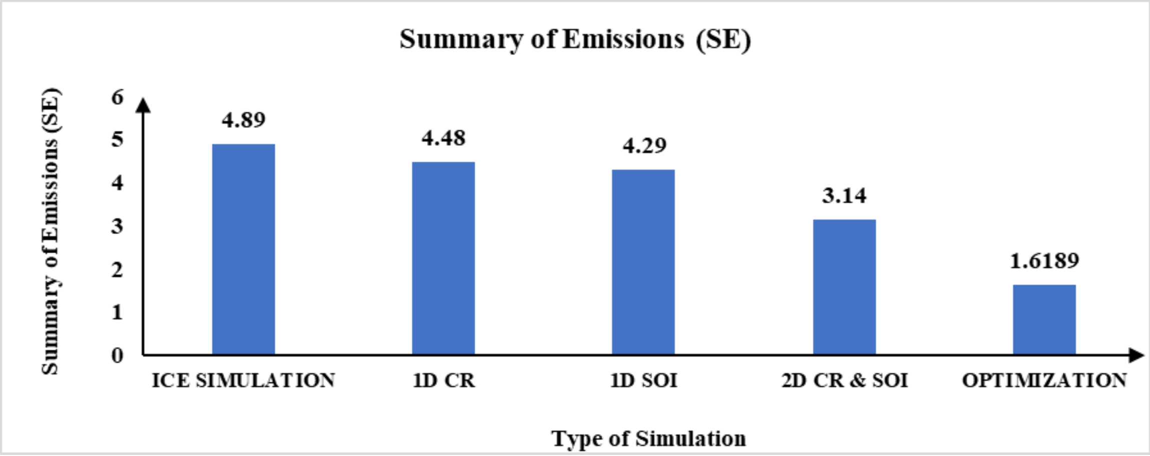


Fig.No.6 Combined Effect of CR , SOI and EGR Adjustments on Emissions

The Summary of Emissions (SE) was reduced from 4.89 to 1.6189.

The graph clearly shows a progressive reduction in emissions from the baseline ICE simulation to the final optimization scenario. Each stage of tuning contributes to improved combustion efficiency, with the "Optimization" case achieving the lowest emissions, highlighting the value of integrated and advanced engine calibration strategies.

This configuration effectively reduced the emissions without compromising the combustion process, as the compression ratio remains within an efficient range, the injection timing supports controlled heat release, and the EGR reduces peak combustion temperatures to suppress $NO_x$ formation. The result demonstrates the strength of combining algorithmic optimization techniques with thermodynamic engine modeling to arrive at a highly efficient and low-emission setup for engines operating on alternative fuels such as Waste Plastic Oil.

## V CONCLUSION

The comprehensive thermodynamic simulation and optimization of a Kirloskar AV1 CI engine fueled with Waste Plastic Oil (WPO) demonstrated that WPO is a promising alternative to conventional diesel, offering a 14.4% increase in brake power, a 7.4% reduction in specific fuel consumption, and a 1.3% improvement in brake thermal efficiency, along with notably lower $CO_2$ emissions, particulate matter, and smoke levels. However, the elevated $NO_x$ emissions due to WPO's higher combustion temperature were effectively mitigated through a multi-stage strategy involving Exhaust Gas Recirculation (EGR), 1D and 2D parametric scanning of compression ratio and injection timing, and advanced multi-variable optimization using numerical algorithms. The Rosenbrock Method yielded the most efficient configuration (CR = 15.104, SOI = 17.212° CA BTDC, EGR = 17.457%), achieving a minimum emissions summary index (SE = 1.6189) while preserving high engine performance. This study validates WPO as a sustainable, high-performance fuel option when integrated with strategic emission control and optimization techniques, contributing meaningfully to cleaner combustion and plastic waste valorization in CI engine applications.

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