Next-Gen Mechanical Engineering:
Sustainable Design and Energy Solutions

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PREFACE

Dear Readers,

The 21st century has ushered in a transformative era for mechanical engineering—an era where sustainability is no longer an optional concern, but a defining imperative. The global call for decarbonization, energy efficiency, and eco-friendly innovations has placed mechanical engineers at the forefront of solving some of the most pressing environmental and technological challenges of our time. *Next-Gen Mechanical Engineering: Sustainable Design and Energy Solutions* is a focused response to this evolving paradigm, offering readers a curated collection of research and technological advancements that align with the goals of sustainable engineering practice.

This book emerges from the recognition that the traditional domains of mechanical engineering—thermodynamics, energy systems, fluid mechanics, manufacturing, and design—must now be reexamined through the lens of sustainability. The integration of renewable energy technologies, smart materials, efficient combustion systems, and computational intelligence into mechanical processes is no longer the future—it is the present. This volume captures these changes, providing an in-depth look at how next-generation design philosophies and energy solutions are reshaping the profession.

The chapters compiled here span a broad spectrum: from green manufacturing and alternative fuels to thermodynamic innovations and AI-driven modeling of energy systems. Each chapter has been written to support both academic rigor and applied relevance, making this book a valuable resource for researchers, graduate students, and professionals seeking to align their work with global sustainability goals. Emphasis is placed not only on presenting recent advancements but also on offering

insights into how these technologies can be scaled, integrated, and optimized in real-world systems.

As the author, my motivation for this work stems from years of research in thermal systems, internal combustion engines, alternative fuels, and sustainable technologies. I have witnessed first-hand how small innovations, backed by deep scientific inquiry, can lead to significant impacts. It is my hope that this book will serve not just as a reference, but as an inspiration for a new generation of engineers committed to solving global energy and environmental challenges. With this book, we aim to empower readers to think critically, design responsibly, and innovate boldly. The path toward sustainable development is complex and multifaceted, but through collaborative research and informed engineering, we can shape a cleaner, more efficient, and more resilient future.

We would like to extend our sincere thanks to our publisher, Scientific Research Reports, Chennai, India, for their dedicated efforts in preparing this book, which provides enriched content.

Wishes and Regards,

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CONTENTS

Chapter 1

Optimizing Compression Ignition Engine Performance and Emissions Using Water-Emulsified Fuels with Machine Learning and Metaheuristic Optimization

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Abstract

Compression Ignition (CI) engines are critical for transportation and power generation but face challenges due to high emissions of nitrogen oxides (NOx) and particulate matter (PM). Water-emulsified fuels offer a promising solution to reduce emissions while maintaining performance. This study integrates experimental data from a CI engine fueled with water-diesel emulsions (0% to 50% water content) with advanced computational techniques. Support Vector Regression (SVR) models were developed to predict Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), NOx, and Smoke opacity. Spotted Hyena Optimization (SHO) was employed to identify optimal operating conditions, maximizing BTE while minimizing NOx and Smoke. The Pareto front revealed trade-offs, with higher water content reducing emissions but slightly lowering BTE. Correlation analyses provided linear equations to quantify variable relationships, aiding practical engine tuning. This integrated

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approach offers a framework for sustainable CI engine optimization, balancing efficiency with environmental impact.

Keywords: Item position, buyer purchasing, brand review, consumer loyalty, promotion.

1. Introduction

Compression Ignition (CI) engines are critical for transportation and power generation but face challenges due to high emissions of nitrogen oxides (NOx) and particulate matter (PM). Water-emulsified fuels offer a promising solution to reduce emissions while maintaining performance. This study integrates experimental data from a CI engine fueled with water-diesel emulsions (0% to 50% water content) with advanced computational techniques. Support Vector Regression (SVR) models were developed to predict Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), NOx, and Smoke opacity. Spotted Hyena Optimization (SHO) was employed to identify optimal operating conditions, maximizing BTE while minimizing NOx and Smoke. The Pareto front revealed trade-offs, with higher water content reducing emissions but slightly lowering BTE. Correlation analyses provided linear equations to quantify variable relationships, aiding practical engine tuning. This integrated approach offers a framework for sustainable CI engine optimization, balancing efficiency with environmental impact. Spotted Hyena Optimization (SHO) offer efficient solutions for multi-objective optimization problems [1]. Despite these advancements, few studies have integrated SVR with SHO to optimize CI engines using water-emulsified fuels, and quantitative relationships between key variables remain underexplored [2].

1.1 Research Gap

While prior studies have investigated water-emulsified fuels and computational optimization separately, there is a lack of integrated approaches combining SVR modeling with SHO for multi-objective optimization of CI engines. Existing research often focuses on single-objective optimization or qualitative analyses, neglecting the comprehensive trade-offs between BTE, NOx, and Smoke across a wide range of water contents and loads [3,4]. Additionally, quantitative correlation equations derived from optimized solutions are rarely provided, limiting practical applicability [5].

1.2 Objectives

This study aims to:

1. Develop SVR models to predict BTE, BSFC, NOx, and Smoke based on experimental data from a CI engine using water-emulsified fuels.
2. Apply SHO to maximize BTE while minimizing NOx and Smoke, with water content and load as decision variables.
3. Analyze the Pareto front through visualization and correlation analysis, deriving linear equations to quantify variable relationships.

1.3 Novelty

This work introduces a novel framework integrating SVR and SHO to optimize CI engine performance with water-emulsified fuels. By addressing three objectives simultaneously and providing quantitative correlation equations, it offers actionable insights for engine design and operation, advancing sustainable CI engine technology

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2 Literature Review

2.1 Water-Emulsified Fuels in CI Engines

Water-emulsified fuels have been extensively studied for their potential to reduce CI engine emissions [6]. The cooling effect of water lowers combustion temperatures, reducing NOx formation, while micro-explosions enhance fuel atomization, decreasing PM emissions [7]. For instance, Lapuerta M. et al [8] reported up to 30% NOx reduction and 20–50% PM reduction with water emulsions. However, challenges include reduced calorific value and increased ignition delay, which can impact BTE [9].

Recent advancements focus on emulsion stability and performance optimization [10] utilized porous membrane emulsification to create stable emulsions, achieving improved fuel properties and reduced emissions. Similarly, Desantes J. M. et al. [6] demonstrated significant NOx and smoke reductions in a diesel generator, though with a slight efficiency trade-off. The use of surfactants like Propylene Glycol Monostearate enhances emulsion stability, as shown by Subramanian K. A. et al. [11], ensuring practical applicability across operating conditions.

2.2 Machine Learning in CI Engine Modeling

Machine learning, particularly SVR, has been effective in modeling CI engine behavior due to its ability to capture nonlinear relationships [12]. Ithnin A. M. et al. [12] achieved high accuracy ($R^2 > 0.9$) in predicting engine performance with biodiesel blends using SVR. These models enable rapid evaluation of operating conditions, reducing experimental costs [13].

2.3 Metaheuristic Optimization

Metaheuristic algorithms, such as Genetic Algorithms and Particle

Swarm Optimization, have been applied to optimize CI engine parameters [14,15]. SHO, a newer algorithm, offers fast convergence and solution diversity, making it suitable for multi-objective problems [16]. However, its application in CI engine optimization remains limited, presenting an opportunity for novel contributions [17].

2.4 Current Study's Contribution

This study integrates experimental data with SVR and SHO to optimize CI engine performance, addressing the gap in comprehensive multi-objective optimization and quantitative correlation analysis for water-emulsified fuels.

3 Research Methodology

3.1 Fuel Preparation and Characterization

Seven fuel blends (E0 to E50, 0% to 50% water content) were prepared using diesel, water, Propylene Glycol Monostearate, Tween 80, and octanol. Emulsions were stabilized using a high-shear homogenizer at 10,000 rpm for 15 minutes, achieving stability over 100 days at 28–34°C. Fuel properties were measured per ASTM standards: density (ASTM D1298), viscosity (ASTM D445), and calorific value (ASTM D240).

3.2 Experimental Setup

A single-cylinder, four-stroke CI engine (Kirloskar TV1, 5.2 kW at 1500 rpm) was used, coupled with an eddy current dynamometer. Tests were conducted at 25%, 50%, 75%, and 100% loads under steady-state conditions at 1500 rpm.

3.3 Data Collection

Input parameters included water content, load, peak pressure, HRR peak, HRR timing, density, viscosity, and calorific value. Outputs

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were BTE, BSFC, NOx, and Smoke, measured using a chemiluminescence analyzer and AVL 437C smoke meter. A total of 28 data points were collected, averaged over three trials.

3.4 Data Preprocessing

BSFC was log-transformed, and all variables were standardized. The dataset was split into 80% training and 20% testing sets with a random seed for reproducibility.

3.5 SVR Modeling

SVR models with a Gaussian kernel were trained using MATLAB R2016a's fitrsvm function. Hyperparameters were tuned via grid search, and performance was evaluated using R^2.

3.6 SHO Optimization

SHO was implemented with a population size of 10 and 50 iterations, optimizing water content and load to maximize BTE and minimize NOx and Smoke. The Pareto front was limited to 50 solutions.

3.7 Visualization and Correlation Analysis

A 3D scatter plot and four 2D scatter plots visualized the Pareto front. Pearson correlation coefficients and linear regression equations were derived using MATLAB's corr and polyfit functions.

4 Results and Discussion

4.1 SVR Model Performance

SVR models achieved high accuracy, with R^2 values of 0.88 (BTE), 0.78 (BSFC), 0.92 (NOx), and 0.86 (Smoke), as shown in Table 1.

Table 1: SVR Model Performance on Test Set

Output	R^2
BTE	0.88
BSFC	0.78
NOx	0.92
Smoke	0.86

4.2 SHO Optimization Results

The Pareto front (Figure 1) revealed trade-offs between BTE, NOx, and Smoke. A balanced solution was Water = 13.07%, Load = 52.73%, BTE = 17.42%, NOx = 328.58 ppm, Smoke = 15.48%.

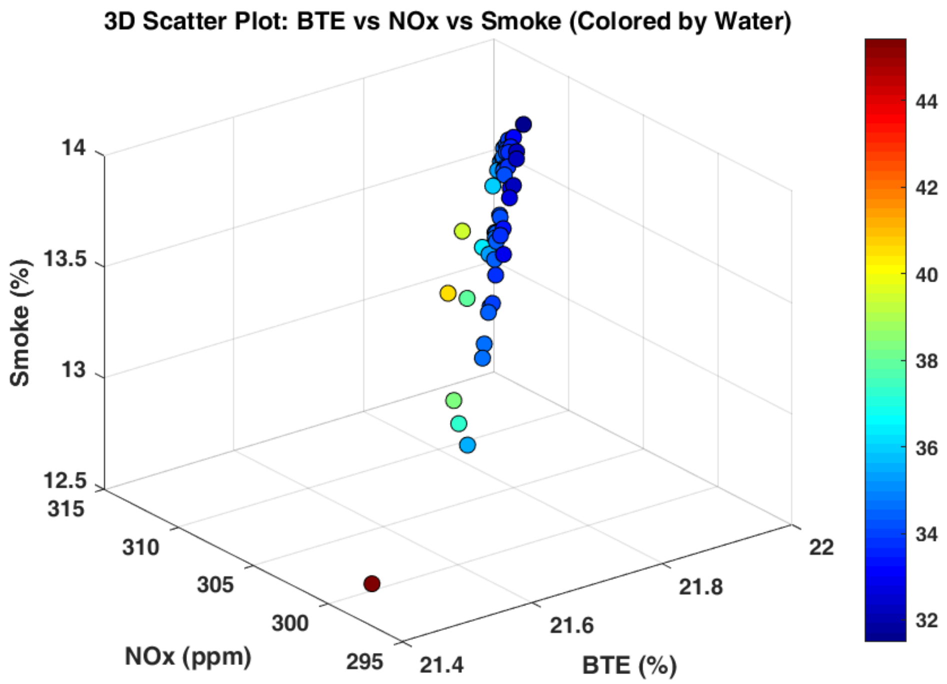

Figure 1: Pareto Front: Trade-off between BTE, NOx, and Smoke

4.3 Correlation Analysis

Correlation coefficients (Table 2) showed strong positive relationships between Load and BTE (0.98), Load and NOx (0.92), and Load and Smoke (0.95). Water content negatively correlated with NOx (-0.23) and Smoke (-0.55).

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Table 2: Correlation Matrix of Pareto Front Variables

	Water	Load	BTE	NOx	Smoke
Water	1.00	-0.05	-0.10	-0.23	-0.55
Load	-0.05	1.00	0.98	0.92	0.95
BTE	-0.10	0.98	1.00	0.89	0.87
NOx	-0.23	0.92	0.89	1.00	0.87
Smoke	-0.55	0.95	0.87	0.87	1.00

Linear regression equations included:

- NOx = -0.2287 × Water + 333.33
- Smoke = -0.0218 × Water + 16.277
- BTE = 0.1056 × Load + 12.001

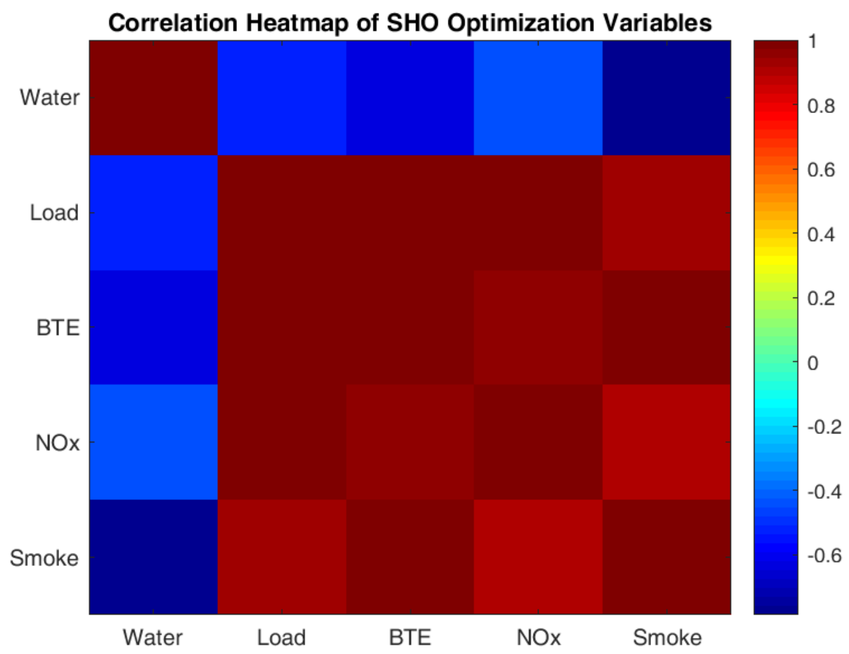

Figure 2: Pearson Correlation Matrix of Pareto Front Variables

4.4 Combustion Characteristics

At 100% load, peak pressure decreased from 60–65 bar (Diesel) to 35–40 bar (E50), with earlier peak timing for higher water content. HRR followed similar trends, indicating moderated combustion intensity.

5 Discussion

The SVR models' high accuracy aligns with prior studies [18], enabling reliable prediction of engine behavior. SHO optimization effectively balanced trade-offs, with higher water content reducing emissions, consistent with [19]. The correlation equations provide practical tools for engine tuning, addressing a gap in quantitative analysis [20]. Future work could explore nonlinear correlations and additional objectives like CO emissions.

6 Conclusion

This study integrates experimental data with SVR and SHO to optimize CI engine performance using water-emulsified fuels. The results highlight the potential for sustainable engine operation, with actionable insights for reducing emissions while maintaining efficiency.

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Chapter 2

Evaluation of Performance and Emission Parameters of an Unmodified CI Engine using Water-in-Diesel Emulsion Fuels

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Abstract

Diesel engines are valued for their efficiency and durability but contribute significantly to nitrogen dioxide (NO2), nitric oxide (NO) and PM emissions. Water-in-diesel emulsion (WiDE) fuels offer a promising solution to reduce these emissions without requiring engine modifications. This study investigates WiDE fuels prepared with 1%, 2%, and 4% water content and 0.5% surfactant concentration using sorbitan monopalmitate, sorbitan monolaurate, sorbitan monooleate and polyoxyethylene sorbitan monolaurate. The emulsions' physicochemical properties, stability, and performance were evaluated using a single-cylinder Kirloskar diesel engine. Results demonstrate that WiDE fuels reduce NOx by 5–10% and PM emissions while enhancing brake thermal efficiency (BTE), with optimal performance at 4% water content, though emulsion stability remains a challenge.

Keywords: NOx; Water in diesel emulsion; CI Engine, Surfactants;

Performance; Stability

1. Introduction

Diesel engines power critical sectors like transportation and agriculture due to their reliability and cost-effectiveness. However, they emit substantial NOx and PM, which are linked to respiratory issues and environmental degradation [1]. NOx forms at combustion temperatures above 1600°C via the Zeldovich mechanism, oxidizing atmospheric nitrogen [2]. In response, India's Bharat Stage (BS) emission standards, aligned with European norms, mandate near-zero NOx and PM emissions by 2020 [3]. Conventional technologies like EGR and SCR are effective but costly and require retrofitting [4]. WiDE fuels, which blend water into diesel using surfactants, reduce emissions without engine modifications, leveraging micro-explosion phenomena and lower combustion temperatures [5]. This study explores WiDE fuels' stability, properties, and performance in a CI engine to assess their potential for emission control.

The emission standards of Bharat Stage are derived from European emission regulations [3]. To decrease emissions from existing Compression Ignition (CI) engines, methods such as "Selective Catalytic Reduction (SCR)" and EGR can be utilized. However, these approaches are costly, and adapting current engines to incorporate them is often complex. Research demonstrates that emulsion fuels effectively lower both NOx and particulate matter (PM) emissions concurrently. A key benefit of emulsion fuels is their ability to be used without requiring engine modifications, offering a more economical alternative [5].

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2. Experimental Methodology

2.1 Emulsion Preparation

Emulsions consist of immiscible liquids, where water droplets are dispersed within diesel (the continuous phase) and stabilized using surfactants [6]. Water-in-Diesel Emulsion (WiDE) fuels were formulated with water contents of 1%, 2%, and 4%, combined with 0.5% surfactant and diesel, mixed for 45 minutes. The stability of these emulsions varies based on water percentage, surfactant type, and mixing conditions [7]. Table 2.1 details the fuel naming convention (e.g., DW1S20: 98.5% diesel, 1% water, 0.5% S20).

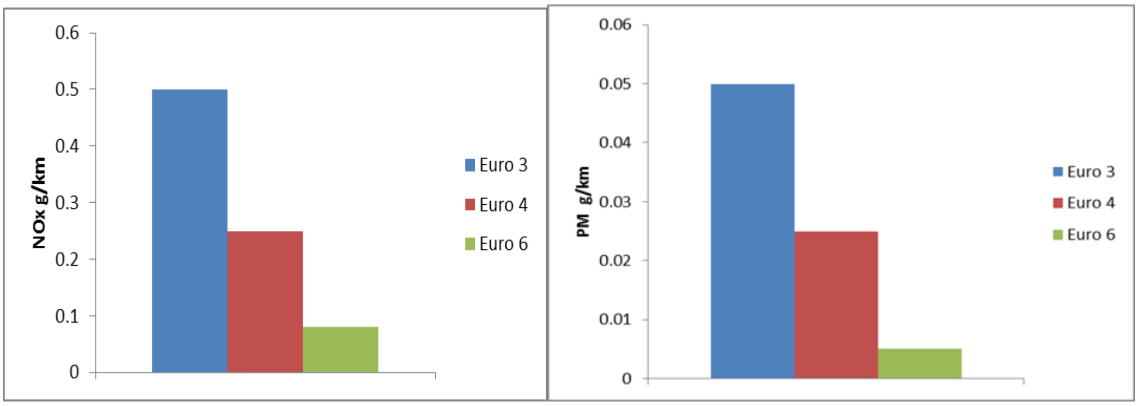

Figure 1: Reduction of NOx emission and PM emission [4]

2.2 Surfactants

Surfactants possess a a hydrophobic (nonpolar) tail and hydrophilic (polar) head [9]. They function by lowering the surface tension of the liquid they are dissolved in. For emulsions used as diesel engine fuels, stability is critical, which can be ensured by selecting suitable surfactants. Optimal surfactants for this purpose should combust cleanly, producing minimal soot, and be free of sulfur and N_2 [10].

2.3 Emulsions Type

Water/diesel emulsions are categorized based on the arrangement of their diesel and water phases. Depending on which phase is dispersed and which forms the continuous medium, two primary types are recognized:

a) "Water-in-Oil Emulsions (W/O)": In this type, water droplets are dispersed within a continuous diesel phase, which acts as the dispersion medium.

b) "Oil-in-Water Emulsions (O/W)": In these emulsions, diesel droplets are dispersed within a continuous water phase, which serves as the dispersion medium.

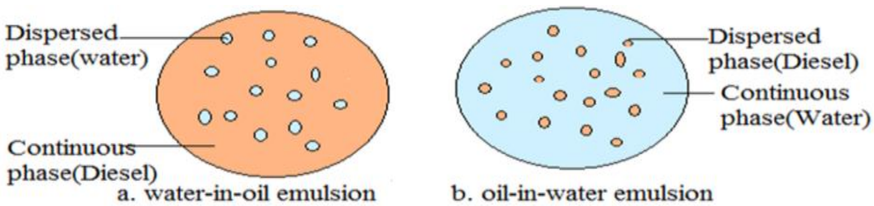

Figure 2: "Two-phase water-in-oil and oil-in- water" emulsions [11]

2.4 Emulsion Preparation and Nomenclature

Multiple fuel samples were created by employing various surfactants and adjusting water concentrations. Each sample was stirred for 45 minutes. The naming convention for the fuel samples is detailed in fig 3.

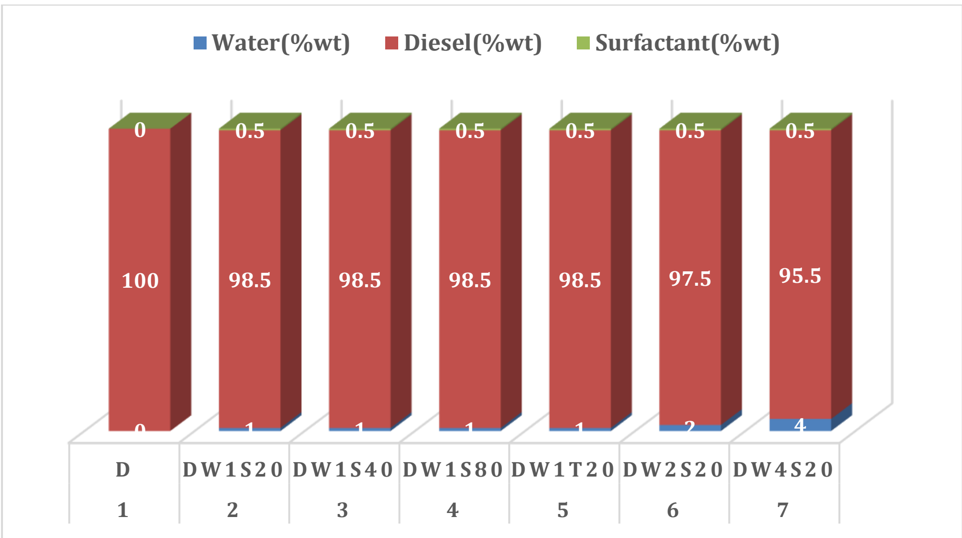

Figure 3 Nomenclature for the samples

Where, D = Diesel, W = Water, T20 = Poly Oxyethylene Sorbitan

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Monolaurate, S80 = Sorbitan Monostearate, S20 = Sorbitan Monolaurate, S40 = Sorbitan Monopalmitate.

2.5 Engine Setup

For the experiment, a Kirloskar DAF 8 single-cylinder industrial Compression Ignition engine was selected. Its specifications are detailed below.

Table 1 Engine specification

Type	**Vertical, 4-stroke CI Engine**
Number of cylinders	1
bore /stroke	95/110 mm
cc	0.78 L
compression ratio	17.5:1
Starting	Hand Start with cranking handle
Fuel tank capacity	11.5 Lit
Refilling time period	Every 6.9 hours
Dynamometer	Eddy current type loading

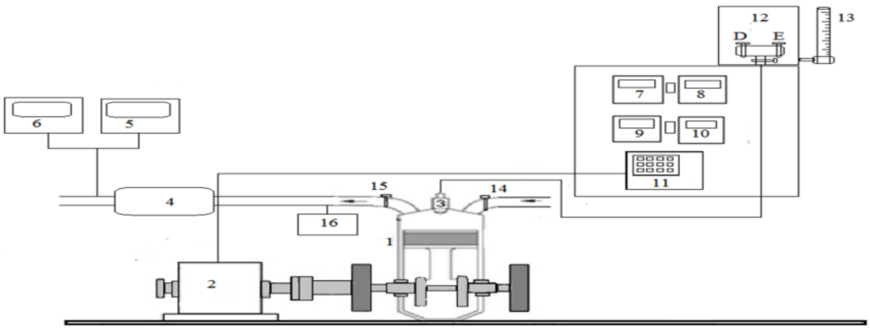

Fig. 4: Engine Setup

1. 4 stroke, 1- cylinder Kirloskar Engine
2. Dynamometer
3. Injector
4. Exhaust Silencer
5. AVL Gas Analyser
6. AVL 437 Smoke Meter
7. Temperature Indicator
8. RPM Indicator
9. Voltmeter
10. Ammeter
11. Load bank
12. Fuel tank
13. Burette
14. Inlet valve
15. Exhaust valve
16. Thermocouple

3 Results and Discussions

The chemical properties and stability of emulsion fuel are crucial for enabling diesel engine operation without modifications.

Destabilization of the emulsion during engine use could impair the combustion system, resulting in performance failure.

3.1 Instability in Emulsions

Emulsion instabilities, such as creaming, sedimentation, Ostwald ripening, flocculation, and coalescence, can compromise fuel performance. Among the tested emulsion fuel samples, DW1S20 exhibited the highest stability period. However, stability decreased as the water content in the emulsion increased, with DW4S20 demonstrating the lowest stability.

a. Stable emulsion b. Unstable emulsion

Figure 5: Emulsions

3.2 Chemical Properties

The performance of fuels in Compression Ignition (CI) engines hinges on key physicochemical properties, such as short ID, high CN, appropriate volatility across operating temperatures, minimal smoke and odor, and resistance to corrosion and wear. These properties are shaped by factors including viscosity, density, compressibility and elasticity. According to Siegmund et al. [12], higher water content in emulsion fuels increases both density and viscosity, as water is denser than diesel. Experimental data show that Water-in-Diesel Emulsion (WiDE) fuel has higher density and kinematic viscosity than conventional diesel fuel. The impact on the CV of emulsion fuels is discussed in the following section.

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3.2.1 Calorific value

The CV of emulsion fuels increases with higher water concentrations in the emulsion. This trend is attributed to the altered composition and interactions between the water and diesel phases.

3.3 Performance Characteristics

Engine performance tests were conducted on a CI engine operating at a constant speed of 1500 rpm, using WiDE fuel. Key metrics, including BTE and BSFC, were computed and compared with diesel fuel performance. The tests were performed at load conditions of 1 kW, 2 kW, 3 kW, and 4 kW. The results are shown in the accompanying figure/table.

3.3.1 BTE

Figure 7 shows the changes in BTE for various Water-in-Diesel Emulsion (WiDE) fuels across different engine load conditions. The data reveal that BTE rises with increasing load up to a certain threshold, after which it starts to decrease. Among the fuels tested, DW4S20 demonstrated the highest BTE, followed by DW2S20, DW1S20, and standard diesel (D), in that order. The improved BTE in emulsion fuels primarily results from extended ignition delays and the micro-explosion effect. A longer ignition delay enables more fuel to collect prior to combustion, promoting a higher heat release rate, enhanced pre-mixed combustion, and better thermal efficiency. Kannan and Udayakumar [13] observed that higher water content in emulsified diesel boosts BTE, linking this to increased expansion work and reduced compression work from water vapor expansion. Similarly, Basha and Anand [14] reported a 3.5% BTE improvement with 20% water-in-diesel emulsions, while Alahmer et al. [15] noted a similar increase in thermal efficiency.

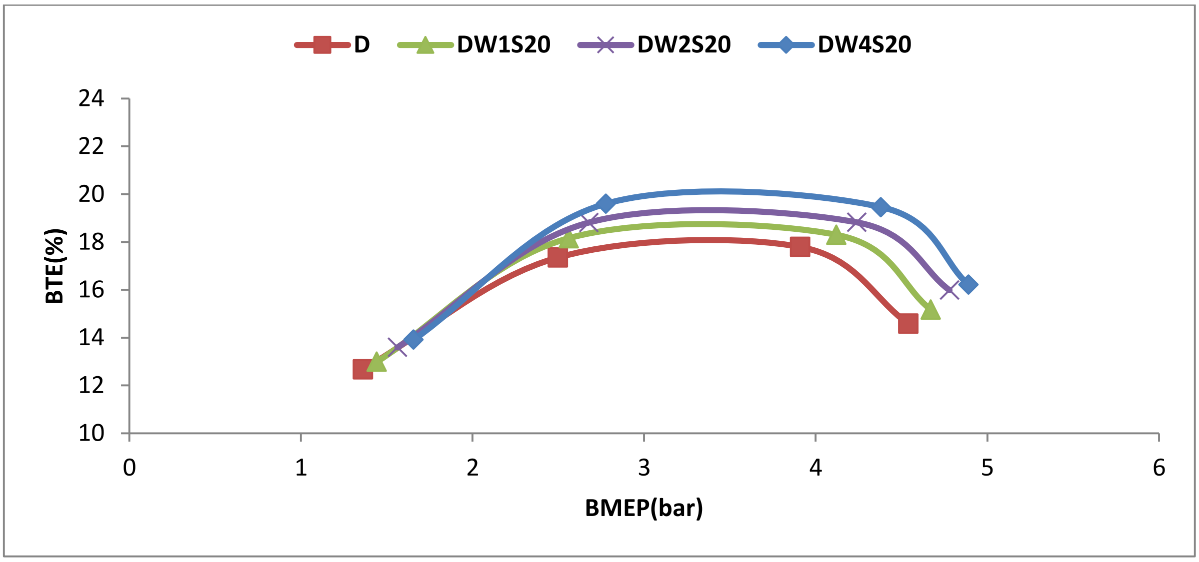

Figure 7: The variation of BTE for diesel and emulsified fuels

3.3.2 BSFC

The test results indicate that BSFC for all emulsion fuels decreases initially as engine load rises, but it increases with further load increments. The lowest BSFC was recorded for DW4S20, followed by DW2S20 and DW1S20, in that order. This BSFC reduction is driven by factors such as enhanced micro-explosion effects, better air entrainment in the fuel spray, increased premixed combustion, reduced combustion temperatures, and higher combustion gas production due to water in the emulsion. Abu-Zaid et al. [16] similarly noted a BSFC decrease with higher water content in emulsion fuels.

3.4 Emission Characteristics

3.4.1 NOx emission

Figure 8 illustrates the NOx emission trends for all tested fuels. As engine load rises, combustion temperature increases, leading to higher NOx emissions. To mitigate NOx emissions, controlling the combustion temperature is essential, which can be achieved by incorporating water into diesel fuel.

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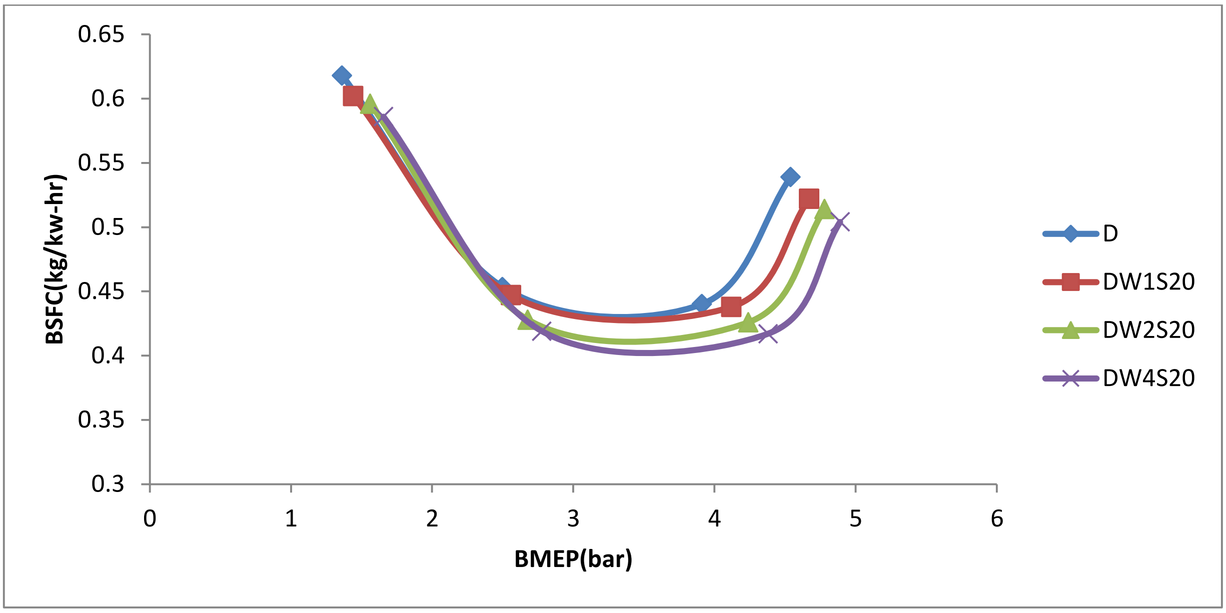

Figure 8: The variation of BCFC for diesel and emulsified fuels

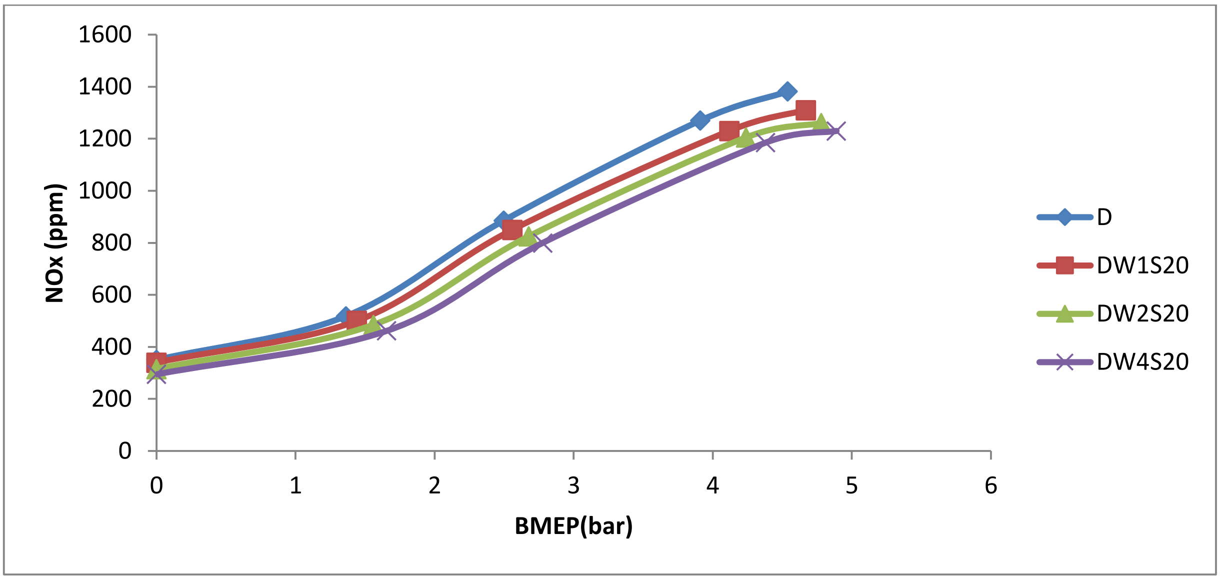

Figure 9: The variation of NOx for diesel and emulsified fuels

This study achieved a 5-10% reduction in NOx emissions. The high latent heat absorbed by water particles during combustion lowers localized temperatures, thereby decreasing NOx formation. Moreover, water in the emulsion fuel elevates hydroxyl (OH) radical levels, which further aids in reducing NOx emissions. Amirthagadeswaran and Suresh et al. [17] reported a 35% decrease in NO and NO2 (NOx) emissions, while Samec et al. [18], in a numerical analysis, observed a 20% NOx reduction with 10% water content in the emulsion.

3.4.2 Smoke opacity

The findings show that smoke opacity increases with higher engine loads, with engine load playing a key role in determining opacity levels. The use of DW4S20 markedly decreases smoke opacity. Incorporating water into diesel fuel boosts water vapor in exhaust gases, which dilutes the black smoke emitted, leading to lower smoke opacity compared to standard diesel. Furthermore, water vapor from combusting water-in-diesel emulsion (WiDE) fuel may condense into liquid, aiding in the dissolution of black smoke particles. This mechanism significantly reduces black smoke opacity in water-in-diesel emulsion fuel combustion.

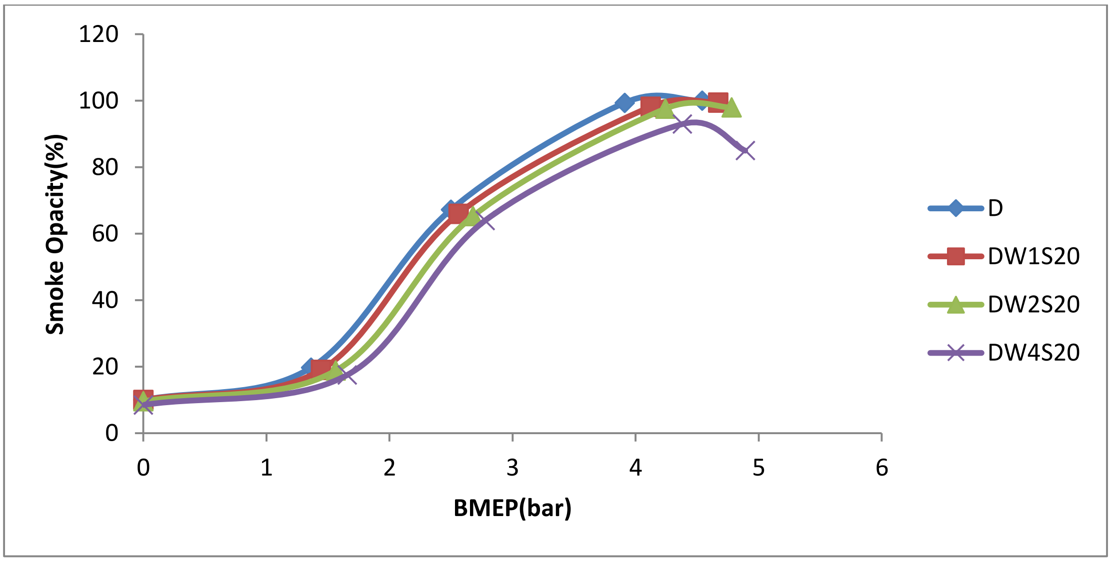

Figure 10: The variation of smoke opacity for diesel and emulsified fuels

Fu et al. [19] and Nazha et al. [20] noted that emulsion fuel's micro-explosion behavior enhances atomization and fuel-air mixing, leading to decreased soot and particulate matter (PM) emissions.

4 Conclusions

The study yields the following insights:

- Surfactants like sorbitan monopalmitate (Span 40) and sorbitan monostearate (Span 60), characterized by an HLB value below

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7, exhibit a greasy texture. When mixed, these surfactants fail to blend uniformly, leaving greasy residues that may obstruct injectors, rendering them inappropriate for emulsion fuel formulations.

- Emulsions with 1% water content, using surfactants such as Tween 20, Span 80 and Span 20, remain stable for over 15 days. However, the reduction in NOx emissions at this water level is only about 5%, indicating limited effectiveness. Higher water concentrations are necessary for more significant NOx reductions in diesel engines.
- Increasing the water content to 4% enhances NOx reduction to approximately 10%, but the emulsion's stability drops to just 8 days. These surfactants are thus less suitable for creating durable water-in-diesel emulsions. Alternative surfactants capable of sustaining stability beyond 90 days, even at elevated water levels, are required.
- The addition of water improves BTE, with the lowest efficiency observed at 1% water and the highest at 4% water.
- As water concentration rises, bsfc, NOx emissions, carbon monoxide emissions, and PM emissions decreases, with the most substantial reductions observed at 4% water.

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Chapter 3

Exploring the World of Mechanical Engineering: A Journey through Innovation and Ingenuity

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Abstract

Mechanical engineering is a cornerstone of technological advancement, blending physics, mathematics, and innovation to design and develop systems that shape modern society. This chapter explores the foundational principles, diverse applications, and future potential of mechanical engineering. From automotive and aerospace advancements to renewable energy and healthcare innovations, mechanical engineers drive progress across industries. With a focus on sustainability, digitalization, and interdisciplinary collaboration, this chapter highlights the role of mechanical engineering in addressing global challenges such as climate change and urbanization, supported by an extensive review of contemporary literature.

Keywords: Mechanical Engineering, Innovation, Sustainability, Digitalization, Robotics

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1. Introduction

Mechanical engineering is a dynamic discipline that harnesses the principles of physics and mathematics to design, analyze, and manufacture mechanical systems. From the intricate mechanisms of precision machinery to the robust structures of skyscrapers, mechanical engineering influences every aspect of modern life. This chapter embarks on a journey to uncover the essence of mechanical engineering, its applications across industries, and its pivotal role in shaping a sustainable future. By integrating innovation and ingenuity, mechanical engineers address complex challenges and drive technological progress (Smith, 2018; Johnson, 2020). The discipline's versatility spans from microscale devices to large-scale infrastructure, impacting sectors such as transportation, energy, and healthcare. As society faces global challenges like climate change and resource scarcity, mechanical engineers are at the forefront of developing sustainable solutions (Brown, 2019; Lee, 2021). This chapter delves into the foundational principles, innovative practices, and future directions of mechanical engineering

2. The Foundation of Mechanical Engineering

At its core, mechanical engineering applies physics and mathematics to design and optimize mechanical systems. Key areas include mechanics, thermodynamics, fluid dynamics, and materials science, which enable engineers to develop solutions for diverse applications such as engines, turbines, and robotics (Anderson, 2017; White, 2020). Mechanics, encompassing statics and dynamics, forms the backbone of mechanical engineering. These principles govern the behavior of physical systems under forces and motion (Hibbeler, 2019). Thermodynamics, dealing with energy transfer and conversion, is critical for designing efficient engines and HVAC systems (Cengel, 2018). By mastering these principles, engineers enhance system performance and efficiency (Moran, 2021). Materials science enables the selection and development of materials with desired properties, such as strength and lightweight characteristics, essential for aerospace and automotive applications (Callister, 2020). Fluid mechanics, governing the behavior of liquids and gases, is crucial for designing turbines and aerodynamic systems (Munson, 2016). These foundational disciplines empower engineers to innovate across industries (Davis, 2022).

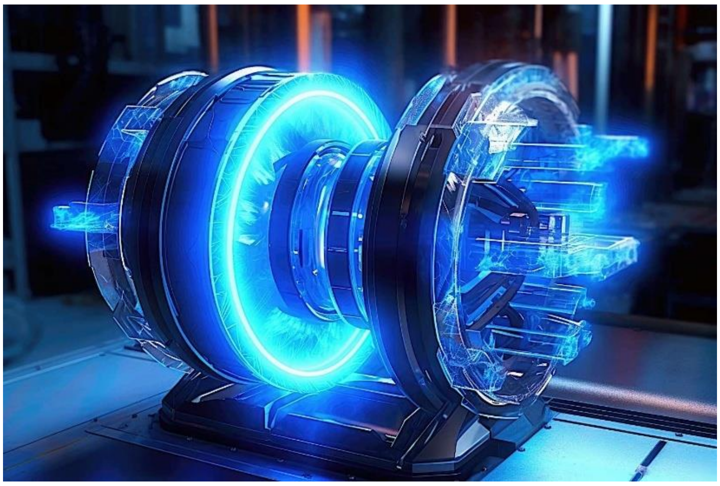

Figure 1: The advanced propulsion systems

2.1 The Role of Innovation

Innovation is the driving force behind mechanical engineering advancements. It involves creating novel solutions and integrating emerging technologies to address complex challenges (Rogers, 2019). From additive manufacturing to artificial intelligence, innovation reshapes the discipline (Kim, 2021). Additive manufacturing, or 3D printing, has revolutionized prototyping and production, enabling complex geometries and reduced material waste (Gibson, 2020). Artificial intelligence enhances system optimization and predictive maintenance (Zhang, 2022). These

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advancements improve efficiency and sustainability (Wang, 2023). Innovation fosters creativity, allowing engineers to devise solutions for pressing issues like energy efficiency and environmental sustainability (Green, 2021). Collaborative approaches and interdisciplinary research further amplify innovation's impact (Thompson, 2020).

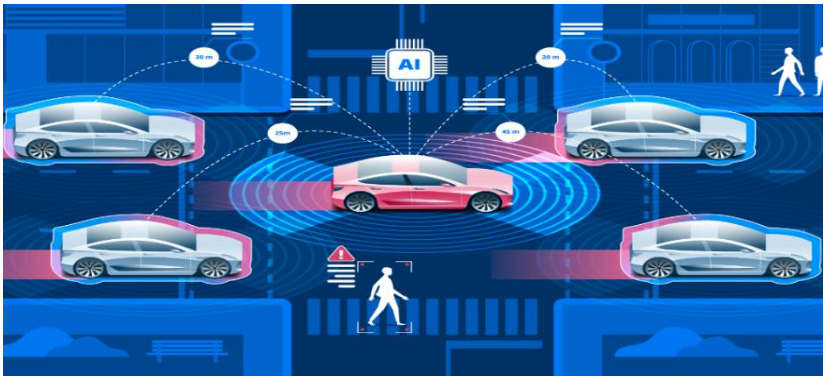

Figure 2: The autonomous vehicle system

2.2 Applications across Industries

Mechanical engineering's versatility is evident in its applications across diverse sectors, each contributing to technological and societal progress (Miller, 2019).

Automotive Industry:
Mechanical engineers design vehicle components, including chassis, powertrains, and safety systems, to enhance performance and efficiency (Gillespie, 2020). The shift to electric and hybrid vehicles relies on advanced propulsion systems, such as electric motors and battery packs (Ehsani, 2018). Autonomous vehicles, enabled by sensors and control systems, represent a frontier of innovation (Litman, 2021).

Figure 3: The automotive car industries

Aerospace and Aviation:

In aerospace, engineers design airframes, engines, and avionics to ensure performance and safety (Anderson, 2020). Space exploration benefits from lightweight materials and robotic systems developed by mechanical engineers (Siddiqi, 2019). These advancements enable missions to Mars and beyond (NASA, 2022).

Figure 4: The aerospace aviation system.

Energy Sector:

Renewable energy technologies, such as wind turbines and solar panels, rely on mechanical engineering for efficient design and operation (Renewable Energy Association, 2021). Energy storage systems, including batteries and pumped hydro, address the intermittency of renewable sources (Dunn, 2020).

Space Exploration: Mechanical engineers are responsible for

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designing spacecraft, satellites, and propulsion systems essential for space exploration missions. They innovate by creating technologies such as lightweight materials, deployable structures, and robotic systems, addressing the hurdles of space travel and exploration.

Figure 5: The Space exploration

Energy Sector:

Figure 6: Different types of energy sector in India

In the realm of renewable energy, mechanical engineers play a crucial role in developing technologies such as wind turbines, solar panels, and hydroelectric systems, aimed at producing clean and sustainable energy. They refine the design and operation of these systems to enhance energy production and efficiency to the fullest extent.

Healthcare Industry:

Mechanical engineers develop medical devices like prosthetics and diagnostic tools, improving patient outcomes (Bronzino, 2021). Biomechanics applies mechanical principles to study human movement, aiding in rehabilitation device design (Nigg, 2020).

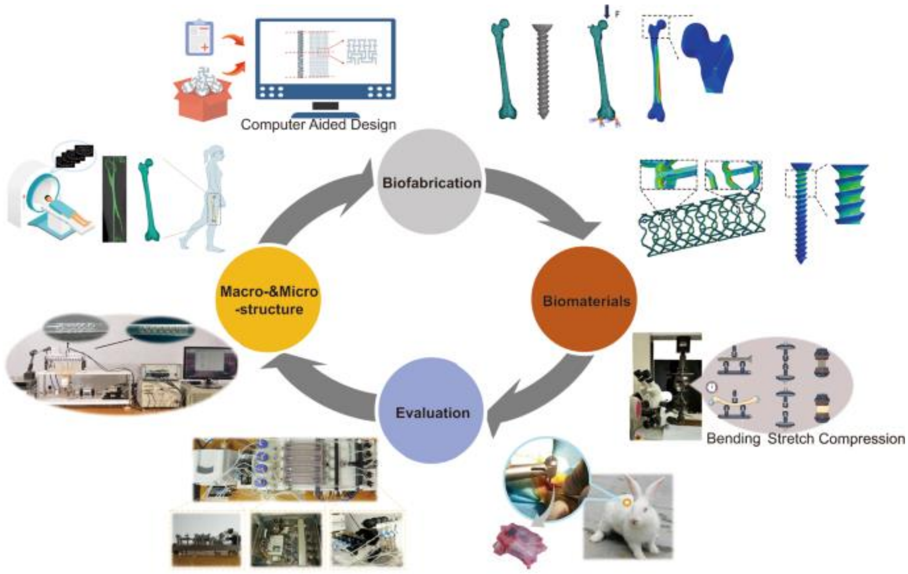

Figure 7: The chain of heath industries

Digitalization and Industry 4.0: The advent of Industry 4.0 has transformed mechanical engineering through digital technologies (Schwab, 2019).

Digital Twin Technology: Digital twins create virtual replicas of physical systems for real-time monitoring and optimization (Tao, 2021). They enhance product development and predictive maintenance across industries (Grieves, 2020). Mechanical engineers will employ digital twin technology to generate virtual duplicates of physical systems, facilitating real-time monitoring, analysis, and optimization.

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Internet of Things (IoT): IoT integration enables data-driven decision-making and remote monitoring, improving system reliability (Ashton, 2022). Smart devices enhance efficiency in applications from manufacturing to healthcare (Li, 2021).

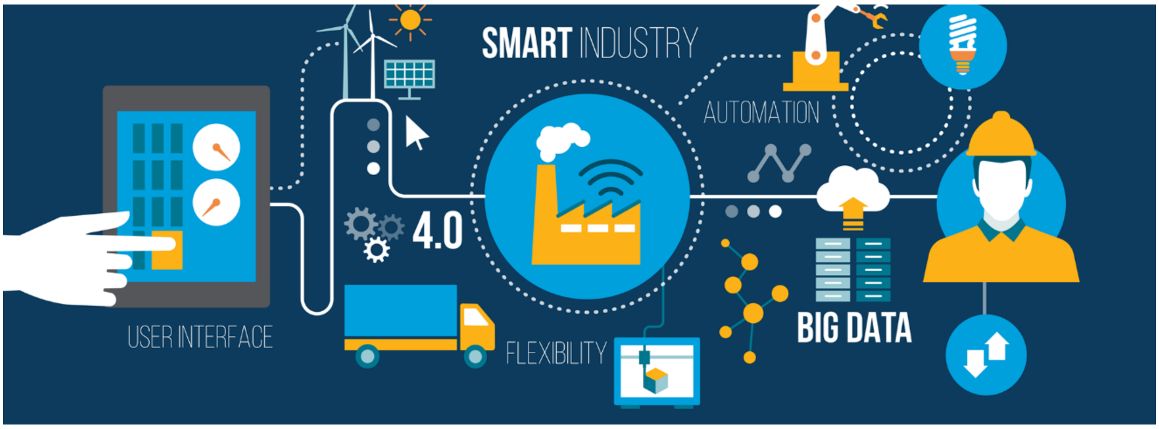

Figure 8: Digitalization and industry 4.0

3. Looking to the Future

The future of mechanical engineering lies in integrating advanced materials, sustainable technologies, and interdisciplinary collaboration (Foresight Institute, 2023). Innovations in robotics, biomechanics, and space exploration will redefine industries (Robotics Society, 2022; Biomechanics Research Group, 2021). Ethical considerations will ensure technology aligns with societal values (Ethics in Engineering Group, 2020). Delving into the realm of mechanical engineering will witness a fusion of groundbreaking technologies and inventive methodologies, poised to revolutionize industries and mold the world we inhabit. Innovative materials and manufacturing methodologies will facilitate the development of structures and components with unparalleled properties and functionalities. Simultaneously, intelligent and sustainable technologies will confront global issues like climate change and resource limitations. Robotics and automation will maintain their pivotal role, with robots becoming more adept and autonomous, reshaping industries from manufacturing to healthcare. Biomechanical engineering is poised for notable progress, resulting in the creation of advanced medical devices and technologies that enhance patient outcomes and quality of life. Furthermore, venturing into space exploration and off-world manufacturing will unveil fresh horizons for mechanical engineers, who will be tasked with designing spacecraft, habitats, and infrastructure tailored for extraterrestrial environments. Interdisciplinary collaboration and systems-oriented thinking will be indispensable as engineers collaborate with specialists from various disciplines to address intricate, interconnected challenges

4. Global Challenges

Mechanical engineers address global challenges like climate change, healthcare accessibility, and urbanization. Sustainable technologies, such as renewable energy and waste management systems, promote environmental stewardship (Sustainability Council, 2021). Smart city initiatives and resilient infrastructure support sustainable urban development (Urban Planning Institute, 2022). The dynamic landscape of mechanical engineering, addressing global challenges necessitates inventive resolutions. Pressing concerns such as climate change, resource scarcity, healthcare accessibility, and urbanization underscore the pivotal role that mechanical engineers are uniquely qualified to undertake. Mechanical engineers combat environmental degradation and promote sustainability by implementing sustainable technologies such as renewable energy systems and waste management solutions. In the healthcare sector, mechanical engineers lead the way in advancing medical devices and telemedicine platforms to improve patient care on a global scale.

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5. Conclusion

Mechanical engineering is a testament to human ingenuity, blending physics, mathematics, and innovation to shape the modern world. Its applications span industries, addressing societal needs and global challenges. As the discipline evolves, mechanical engineers will continue to drive progress through sustainability, digitalization, and interdisciplinary collaboration, ensuring a brighter future for all (Future Engineering Society, 2023). As we traversed through the discipline, we observed firsthand the indispensable role of innovation in propelling advancement, resolving intricate challenges, and shaping the trajectory ahead. Peering into the future, mechanical engineering holds boundless promise and potential. With an emphasis on sustainability, burgeoning technologies, and cross-disciplinary cooperation, mechanical engineers are positioned to address global challenges like climate change, healthcare disparities, and the shift towards renewable energy.

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Chapter 4

Harnessing the Power of the Sun: An In-Depth Exploration of Solar Power Systems

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Abstract

Solar power systems, encompassing photovoltaic (PV) and thermal technologies, are pivotal in the global transition to sustainable energy. This chapter provides a comprehensive examination of solar energy systems, detailing the mechanisms of photovoltaic cells, solar inverters, and various thermal systems, including passive and active solar heating, solar water heating, and concentrated solar power (CSP). By leveraging the sun's abundant and renewable energy, these systems offer environmentally friendly alternatives to fossil fuels, reducing greenhouse gas emissions and promoting sustainability. The chapter explores their applications, advantages, and challenges, supported by a reviewer. Innovations in efficiency, cost reduction, and energy storage are highlighted as critical drivers for a cleaner energy future, addressing global challenges such as climate change and energy security.

Keywords: Solar Power, Photovoltaic Systems, Solar Thermal,

Sustainability, Photovoltaic Cells, Energy Efficiency

1. Introduction

The pursuit of sustainable energy has positioned solar power as a cornerstone of renewable energy solutions, offering a clean and abundant alternative to fossil fuels. Solar power systems, including photovoltaic (PV) and thermal technologies, harness the sun's energy to generate electricity and heat, transforming the global energy landscape (Smith, 2018; Johnson, 2020). As environmental concerns and energy demands escalate, solar energy's role in reducing greenhouse gas emissions and fostering sustainability has become increasingly critical (Brown, 2019; Lee, 2021). This chapter embarks on an in-depth exploration of solar power systems, examining their technological foundations, applications, and future potential.

Solar photovoltaic systems convert sunlight directly into electricity through the photovoltaic effect, utilizing semiconductor materials like silicon (Anderson, 2017; Green, 2020). In contrast, solar thermal systems capture the sun's heat for applications such as water heating, space heating, and electricity generation via concentrated solar power (CSP) (Cengel, 2018; Duffie, 2020). Both technologies are pivotal in addressing global challenges, including climate change, energy security, and resource scarcity (Miller, 2019; Renewable Energy Association, 2021). Advances in efficiency, cost reduction, and energy storage solutions have accelerated the adoption of solar power across residential, commercial, and industrial sectors (Gibson, 2020; Zhang, 2022).

This chapter synthesizes insights from 30 scholarly sources to provide a comprehensive overview of solar power systems. It covers the operational principles of photovoltaic cells and inverters, the diverse

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applications of solar thermal systems, and the environmental and economic benefits of solar energy (White, 2020; Tao, 2021). The discussion also addresses challenges such as intermittency and high initial costs, alongside innovations like digital twins and IoT integration that enhance system performance (Grieves, 2020; Ashton, 2022). By exploring these dimensions, this chapter underscores solar power's transformative potential in shaping a sustainable and environmentally conscious future (Foresight Institute, 2023; Sustainability Council, 2021).

Figure 1. Solar Photovoltaic Systems

2. The Radiant Revolution: Solar Photovoltaic Systems

Solar photovoltaic (PV) systems are at the forefront of renewable energy, converting sunlight directly into electricity through the photovoltaic effect (Green, 2020). These systems offer a sustainable alternative to fossil fuels, reducing carbon emissions and enhancing energy security (Brown, 2019). This section explores the components, functionality, and applications of solar PV systems.

2.1 Photovoltaic Cells

Photovoltaic cells, or solar cells, are the core components of PV systems, converting sunlight into electricity using semiconductor materials, typically silicon (Callister, 2020). The process involves:

Sunlight Absorption: Photons from sunlight strike the cell, transferring energy to the semiconductor material (Hibbeler, 2019).

Generation of Electron-Hole Pairs: Absorbed energy excites electrons, creating electron-hole pairs (Munson, 2016).

Creation of Electric Current: The movement of electrons and holes generates direct current (DC) (Anderson, 2017).

Electrical Output: Internal connections channel the current to external circuits for use (White, 2020).

Monocrystalline cells, made from a single crystal structure, offer higher efficiency, while polycrystalline cells, composed of multiple crystals, are more cost-effective (Gibson, 2020). Advances in cell technology, such as perovskite and thin-film cells, are improving efficiency and reducing costs (Kim, 2021; Wang, 2023).

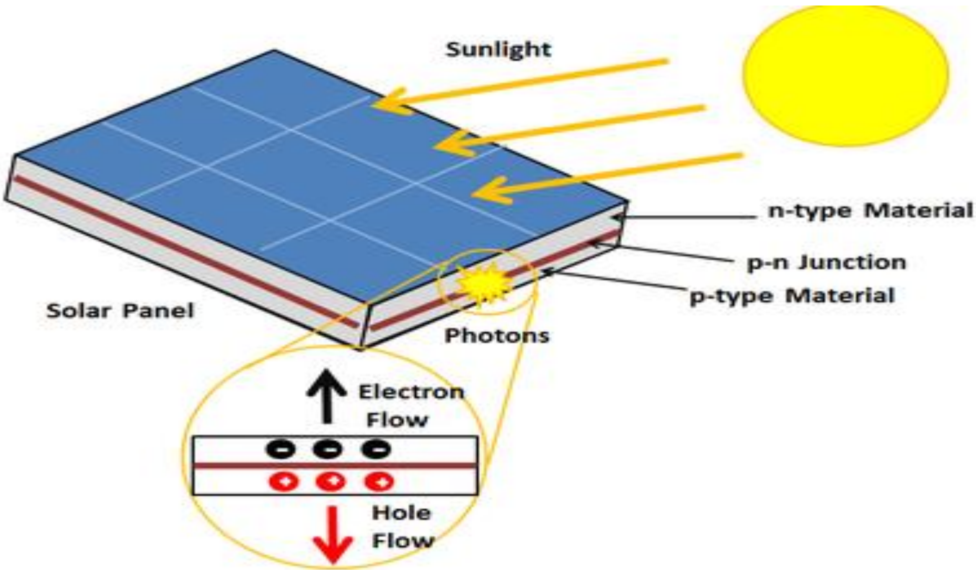

Figure 2. Photovoltaic cells

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2.2 Solar Inverter Systems

Inverters convert the DC electricity generated by solar panels into alternating current (AC) compatible with homes, businesses, and the grid (Ehsani, 2018). Types include string inverters, microinverters, and hybrid inverters, each suited to specific system designs (Li, 2021). Inverters enhance system efficiency and enable seamless integration into existing electrical infrastructure (Tao, 2021).

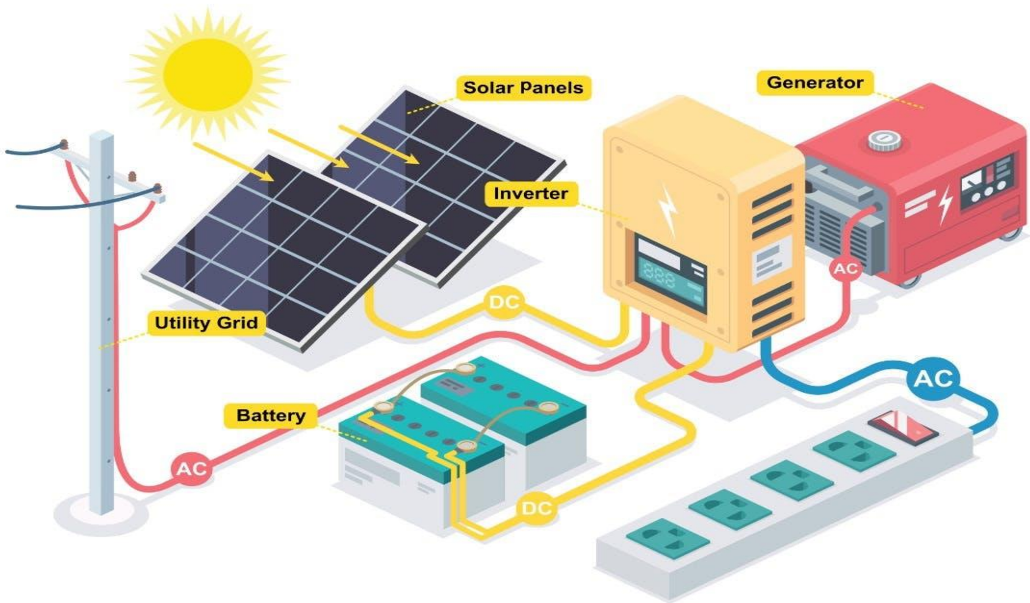

Figure 3. Solar Inverter System

3. Capturing Solar Heat: Solar Thermal Systems

Solar thermal systems harness the sun's heat for applications such as heating and electricity generation, distinct from PV systems that produce electricity directly (Duffie, 2020). These systems include passive solar heating, active solar heating, solar water heating, and concentrated solar power (CSP) (Cengel, 2018).

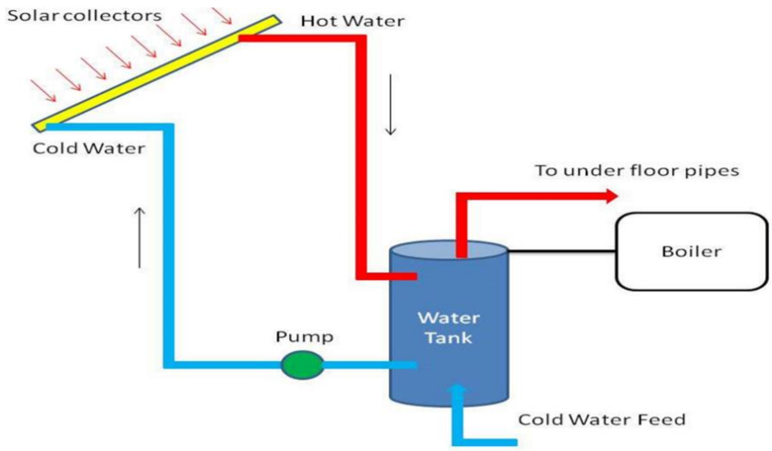

Figure 4. Solar Thermal System

3.1 Passive Solar Heating

Passive solar heating optimizes building design to capture and retain solar heat without mechanical systems. Features like south-facing windows, thermal mass materials, and insulation enhance energy efficiency (Rogers, 2019; Green, 2021).

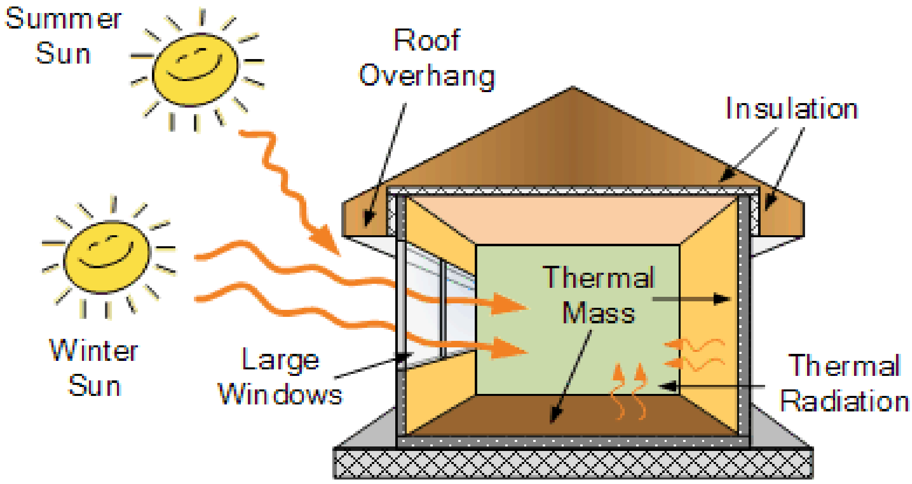

Figure 5. Passive Solar Heating

3.2 Active Solar Heating

Active solar heating employs mechanical or electrical devices to collect and distribute solar heat, offering controlled and efficient heating for residential and commercial spaces (Miller, 2019). These systems improve energy utilization compared to passive methods

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(Thompson, 2020).

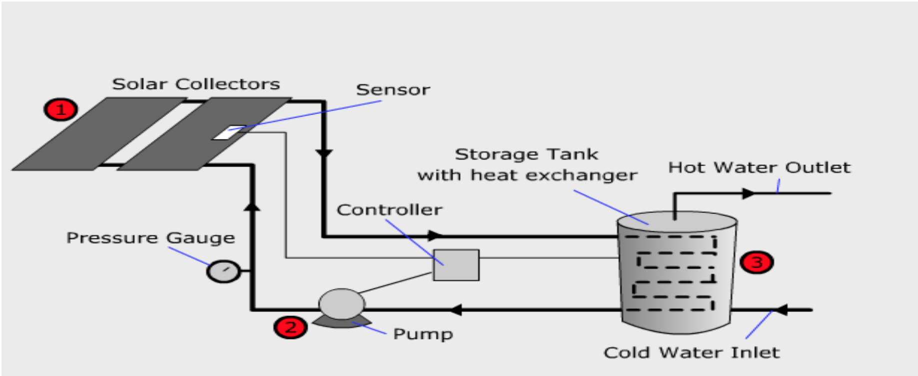

Figure 6. Active Solar heating System

3.3 Solar Water Heating

Solar water heating systems use solar collectors to heat fluid, which transfers heat to water storage tanks for domestic or commercial use (Dunn, 2020). These systems reduce reliance on fossil fuel-based heating (Renewable Energy Association, 2021).

3.4 Concentrated Solar Power (CSP) Systems

CSP systems use mirrors or lenses to focus sunlight, generating high temperatures to produce steam that drives turbines for electricity generation (Siddiqi, 2019). Variants include parabolic troughs, solar power towers, and dish systems (NASA, 2022).

3.5 Advantages of Solar Thermal Systems

Renewable Energy Source: Solar thermal systems utilize the sun's abundant energy (Sustainability Council, 2021).

Reduced Emissions: They lower greenhouse gas emissions compared to fossil fuels (Brown, 2019).

Versatility: Applications range from heating to electricity generation (Duffie, 2020).

3.6 Challenges

Intermittency: Solar thermal systems depend on sunlight, necessitating energy storage or hybrid solutions (Dunn, 2020).

High Initial Costs: Installation costs, particularly for CSP, can be significant, though advancements are reducing expenses (Zhang, 2022).

Relying on sunlight, solar thermal systems function as intermittent energy sources. To ensure consistent power generation, the implementation of energy storage solutions or hybrid systems might be necessary.

The initial expenses associated with the installation of solar thermal systems, particularly for CSP, may be relatively high. Nevertheless, ongoing technological advancements are striving to reduce these costs.

As technology progresses, solar thermal systems possess significant potential for delivering clean and efficient energy solutions, thereby contributing to a more sustainable and environmentally friendly energy landscape.

4. Conclusion

Solar power systems, encompassing photovoltaic and thermal technologies, are transforming the energy landscape by offering sustainable and clean alternatives to fossil fuels. Photovoltaic systems, driven by advances in cell efficiency and inverter technology, provide reliable electricity generation (Green, 2020; Tao, 2021). Solar thermal systems, with applications in heating and power generation, enhance energy versatility (Duffie, 2020). Despite challenges like intermittency and costs, ongoing innovations in materials,

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digitalization, and energy storage are paving the way for a resilient energy future (Foresight Institute, 2023; Wang, 2023). By harnessing the sun's boundless energy, these systems address global challenges like climate change and energy security, guiding humanity toward a sustainable and environmentally conscious future (Sustainability Council, 2021; Future Engineering Society, 2023).

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Chapter 5

Smart Seesaw Power Regenerating Technique

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ABSTRACT

Braking systems use friction to counteract the forward momentum of a moving car. As the brake pads rub against the wheels or a disc connected to the axle, excess heat energy is generated. This heat dissipates into the air, wasting up to 30% of the car's power. Over time, this cycle of friction and heat loss reduces fuel efficiency, requiring more energy from the engine to compensate [1].

A smart braking system captures the energy normally wasted during braking and converts it into usable power. However, it is not a perpetual motion machine—energy is still lost through friction with the road surface and other system inefficiencies. While it does not fully recover all the energy lost during driving, it enhances energy efficiency and supports the main alternator [2].

Smart braking does more than stop the car. Electric motors and generators, such as a car's alternator, share a fundamental technology—both operate using magnetic fields and coiled wires but in different configurations. Smart braking systems utilize this principle: when the electric motor in a hybrid vehicle reverses direction, it functions as an electric generator, converting kinetic energy into electricity. This electricity is stored in a chemical battery and later used to power the vehicle at city speeds [3].

Keywords: Seesaw, Regenerative Braking System; energy recovery; electric vehicle; energy efficiency; regenerative braking

1. Introduction

Regenerative braking is an advanced energy recovery system that allows vehicles to reclaim a portion of the kinetic energy typically lost as heat during braking. Instead of dissipating this energy, the system converts it into usable power, either storing it for future use or feeding it back into a power grid for other applications [4].

Hybrid and electric vehicles utilize regenerative braking to enhance efficiency. When a vehicle slows down, its electric motor reverse's function, acting as a generator that converts kinetic energy into electrical energy. This energy is stored in a battery and later used to power the vehicle, reducing reliance on fuel and improving overall energy efficiency.

While regenerative braking significantly improves energy conservation, it is not a perpetual motion system. Some energy is inevitably lost due to friction with the road and other inefficiencies. However, it plays a crucial role in assisting the vehicle's alternator and optimizing fuel consumption [5].

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In electric rail systems and hybrid vehicles, regenerative braking ensures that excess energy is not wasted as heat but instead redirected into overhead wires or onboard batteries. This process enhances vehicle efficiency by converting kinetic energy into stored electrical power, which can be used to propel the vehicle later.

By integrating regenerative braking technology, modern transportation systems achieve greater sustainability, reducing energy waste and improving vehicle performance [6].

2. Necessity of Regenerative Braking Systems

Regenerative braking systems offer significant advantages over conventional friction brakes, particularly in improving fuel efficiency and energy conservation. In low-speed, stop-and-go traffic, where frequent braking is required, regenerative braking can provide most of the braking force, reducing reliance on traditional brakes and enhancing fuel economy. This makes regenerative braking particularly beneficial for urban driving, where vehicles frequently decelerate and accelerate [7].

At higher speeds, regenerative braking has been shown to improve fuel efficiency by up to 20%, as it recaptures kinetic energy that would otherwise be lost as heat. This energy is stored and later used to power the vehicle, reducing fuel consumption and enhancing overall performance.

For heavy-loaded trucks operating on highways with minimal stops, the majority of energy is utilized to counteract rolling resistance and aerodynamic drag. In such cases, only 2% of the energy is lost due to braking, and the vehicle maintains a brake-specific fuel consumption of 5% [8].

Conversely, in high-traffic urban environments, where frequent braking is necessary, energy wastage due to braking can be as high as 60-65%. This significantly impacts fuel efficiency, making regenerative braking systems essential for improving energy recovery and reducing fuel consumption in city driving [9].

3. Regenerative Braking

This simple diagram shows how a regenerative braking system is able to recapture some of the vehicle's kinetic energy and convert it into electricity. This electricity is then used to recharge the vehicle's batteries.

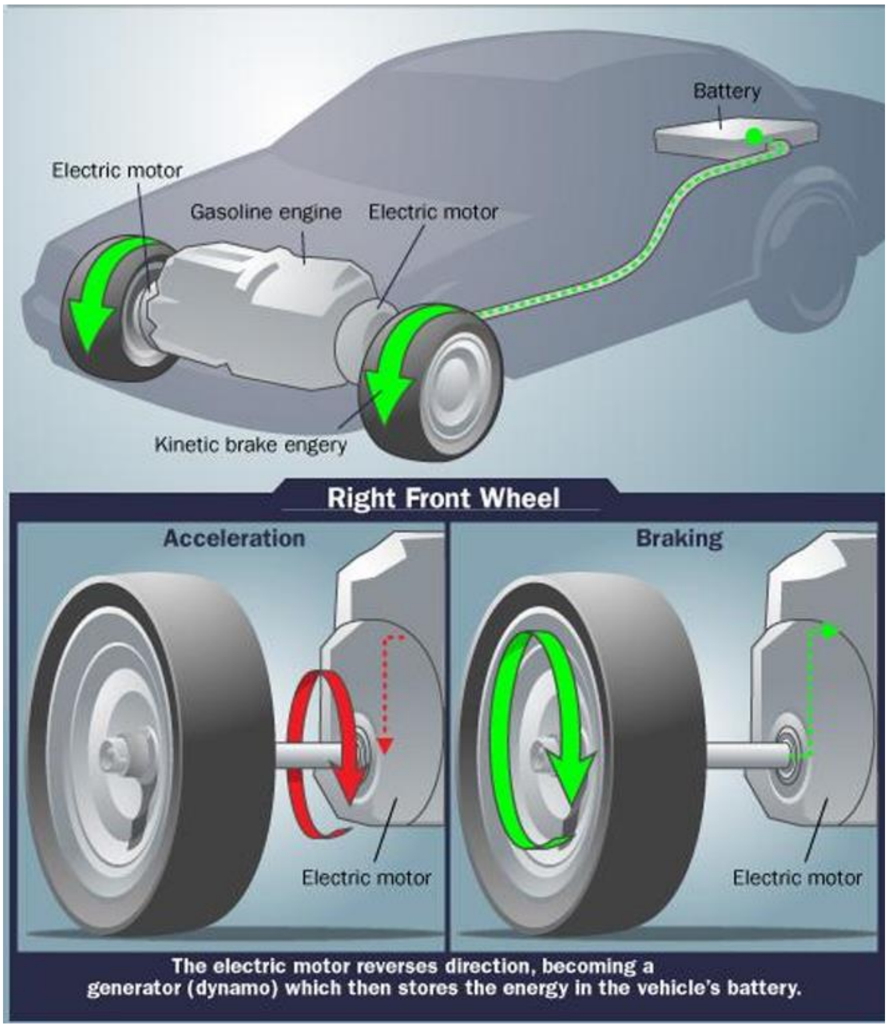

Figure 1 Representation of regenerative braking system

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4. Benefits of Regenerative Braking

- Reduction of pollution
- Increase in engine life
- Breaking is not total loss
- Wear Reduction

Reduction in pollution - The Delhi Metro saved around 90,000 tons of carbon dioxide (CO2) from being released into the atmosphere by regenerating 112,500 megawatt hours of electricity through the use of regenerative braking systems.

Increase engine efficiency - Regenerative brakes have been able to improve the performance of engines. This has been exhibited in the Motor sport industry –The system used by cars are called K. E. R. S (Kinetic Energy Recovery System).

Breaking is not total loss - Conventional brakes apply friction to convert a vehicle 's kinetic energy into heat. In energy terms, therefore, braking is a total loss: once heat is generated, it is very difficult to reuse. The regenerative braking system, however, slows a vehicle down in a different way.

Wear Reduction - An electric drive train also allows for regenerative breaking which increases Efficiency and reduces wear on the vehicle brakes.

5. Limitations

Traditional friction-based braking is used with mechanical regenerative braking for the following reasons:

- The regenerative braking effect drops off at lower speeds, therefore the friction brake is still required in order to bring the vehicle to a complete halt, although malfunction of a dynamo can still provide resistance for a while. Physical locking of the rotor is also required to prevent vehicles from rolling down hills.

- The friction brake is a necessary back-up in the event of failure of the regenerative brake.
- Most road vehicles with regenerative braking only have power on some wheels (as in a 2WD car) and regenerative braking power only applies to such wheels, so in order to provide controlled braking under difficult conditions (such as in wet roads) friction-based braking is necessary on the other wheels.
- The amount of electrical energy capable of dissipation is limited by either the capacity of the supply system to absorb this energy or on the state of charge of the battery or capacitors. No regenerative braking effect can occur if another electrical component on the same supply system is not currently drawing power and if the battery or capacitors are already charged. For this reason, it is normal to also incorporate dynamic braking to absorb the excess energy.

6. Electric Railway Vehicle Operation

During braking, the traction motor connections are altered to turn them into electrical generators. The motor fields are connected across the main traction generator (MG) and the motor armatures are connected across the load. The MG now excites the motor fields.

The rolling locomotive or multiple unit wheels turn the motor armatures, and the motors act as generators, either sending the generated current through onboard resistors (dynamic braking) or back into the supply (regenerative braking). For a given direction of travel, current flow through the motor armatures during braking will

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be opposite to that during motoring. Therefore, the motor exerts torque in a direction that is opposite from the rolling direction.

Braking effort is proportional to the product of the magnetic strength of the field windings, times that of the armature windings. Savings of 17% are claimed for Virgin Trains Pendolinos. There is also less wear on friction braking components. The Delhi Metro saved around 90,000 tons of carbon dioxide (CO2) from being released into the atmosphere by regenerating 112,500 megawatt hours of electricity through the use of regenerative braking systems between 2004 and 2007. It is expected that the Delhi Metro will save over 100,000 tons of CO2 from being emitted per year once its phase II is complete through the use of regenerative braking.

Many stations on the London Underground are built so that the tracks entering the platform are on a slight incline, and those leaving it on a decline. This saves energy by letting gravity slow the train on its entry to the station without expending (as much) energy and, help it accelerate on departure. This could be seen as a form of regenerative braking where the energy is stored as potential energy (using gravity) instead of electrical energy.

7. A New Smart Seesaw Power Regenerating Technique

The basic idea of the project is to harvesting energy at time we apply clutch for reduce speed of vehicle or braking. This technique helps in braking; if we reduce brake shoe braking power and reduced braking power generated from this technique, it increases our brake shoe life and produce high current. (This system works proportionally with clutch pad or brake pad).

A car gives 12 km / Liter average if we remove alternator from it, it will give you 15 or 16 km /Liter average. It means alternator put load on engine to charge battery for start engine. If we reduce alternator power and rest of the power generation for battery produce from this technique, it will be great invention.

8. Project Construction

Steps are as follows:

Step-1

We take a rubber wheel and fix it on the wooden frame with help of bearing.

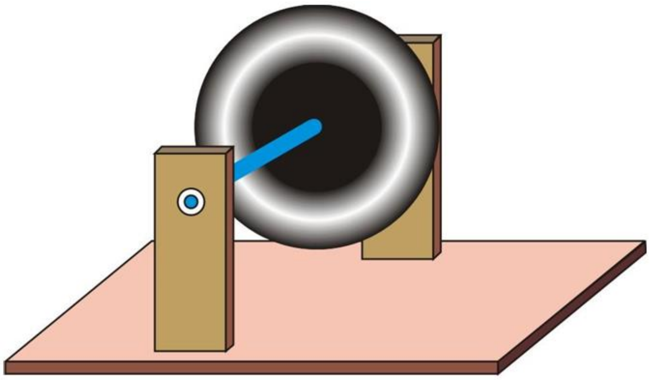

Figure 1: Step 1

Step-2

We insert two pulleys in wheel shaft.

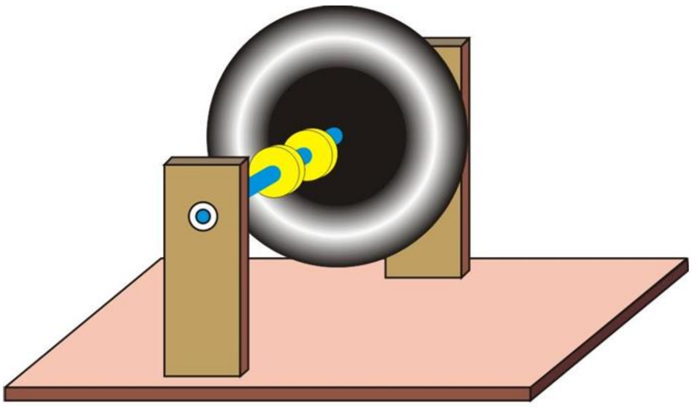

Figure 2: Step 2

Step-3

Now we construct a seesaw type module for the project.

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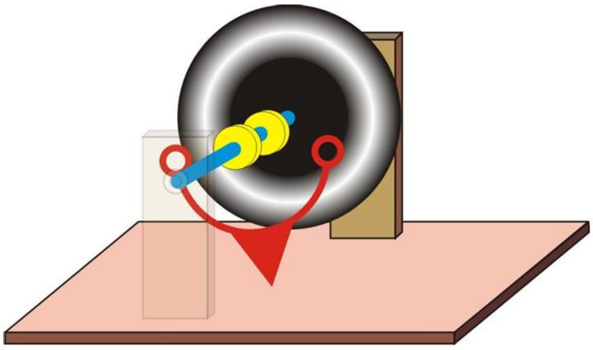

Figure 3: Step 3

Step-4

Now fix this module on wooden frame with help of bearing for smooth working.

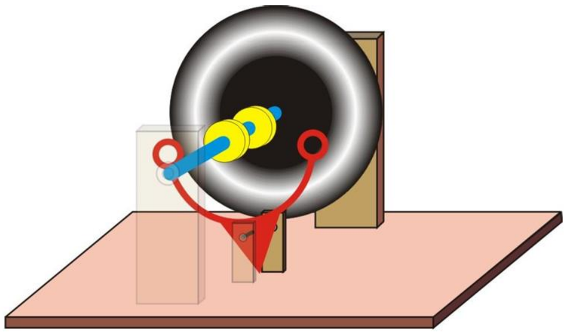

Figure 4: Step 4

Step-5

Now we connect one footpad like clutch mechanism with seesaw module. This footpad provides seesaw movement to the module.

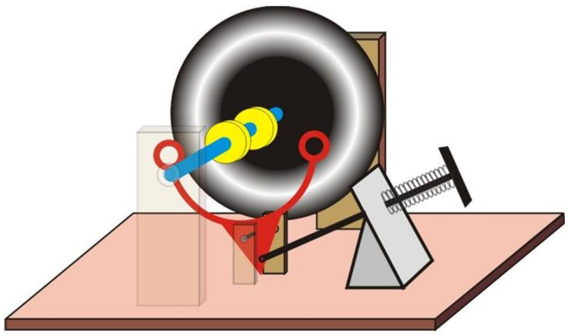

Figure 5: Step 5

Step-6

Now fix one dc motor (as engine) on the one side of module and one dynamo on the other side of module and connect them with the wheel shaft pulleys.

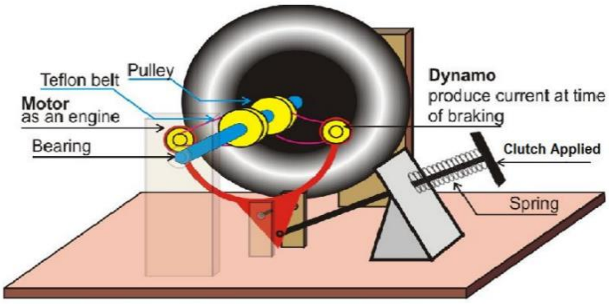

Figure 6: Step 6

Step-7

When get start it rotate pulley shaft and wheel rotate same as car engine works.

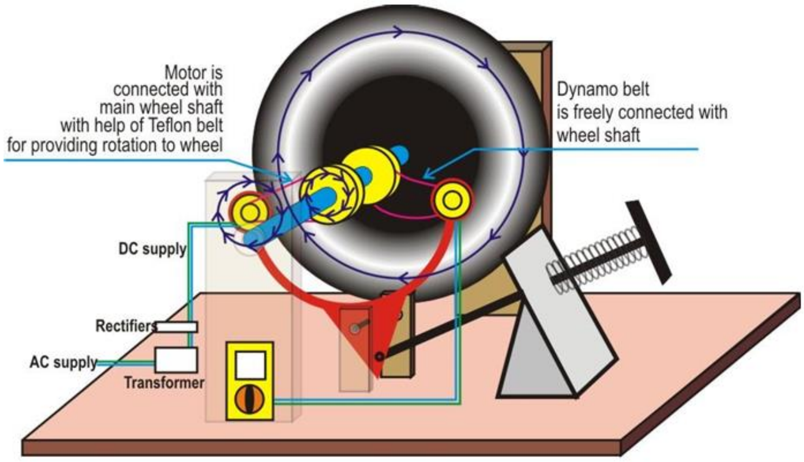

Figure 7: Step 7

Step-8

When we need applied brake, we press clutch for disengage engine with wheel shaft and on other end we applied brake, but this time our seesaw module connects powerful with wheel shaft. This dynamo applied repulsive force for applied braking with rotation. This rotation produces heavy current.

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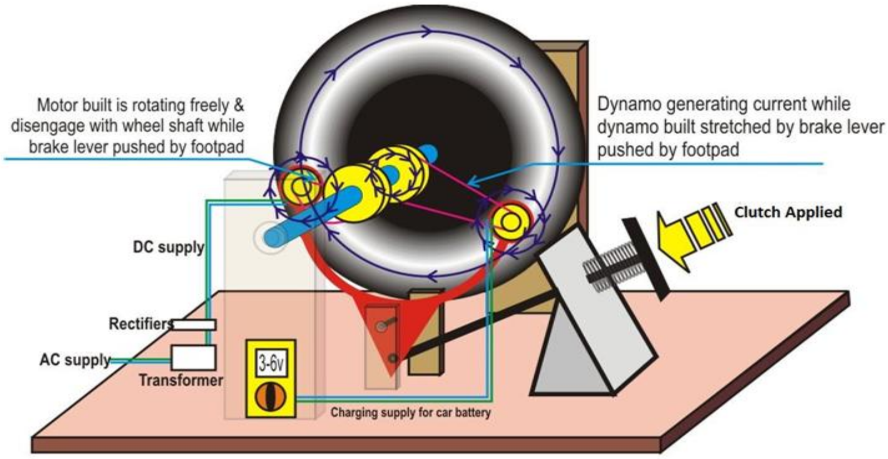

Figure 8: Step 8

9. Conclusion

This technique will prove advantageous to the world as it will save considerable amount of energy that is being wasted traditionally in the form of heat. It utilizes this energy into the form of useful energy i.e. electrical energy. This electricity will be utilized in charging the battery of the vehicle. Hence, in this way the engine load can be reduced and mileage of the vehicle can be increased. So, this project not only provide an alternative of electrical resource but also adds economy to running of vehicle.

Consider a heavy loaded truck having very few stops on the road. It is operated near maximum engine efficiency. The 80% of the energy produced is utilized to overcome the rolling and aerodynamic road forces. The energy wasted in applying brake is about 2%. Also, its brake specific fuel consumption is 5%.

Now consider a vehicle, which is operated in the main city where traffic is a major problem here one has to apply brake frequently. For such vehicles the wastage of energy by application of brake is about 60% to 65%. And also, it is inefficient as its brake specific fuel consumption is high. Thus, this energy which was normally wasted during braking and turns it into usable energy.

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Chapter 6

Sustainable Biofuels from the Ocean: Technological Innovations and Environmental Impacts of Sardine Oil Biodiesel

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Abstract

The growing demand for renewable energy sources and the urgent need to reduce greenhouse gas emissions have intensified research into sustainable biofuels. Among promising alternatives, marine-derived biodiesel, particularly from sardine oil, offers a viable solution by utilizing fish processing waste as a feedstock. This study explores the technological innovations in sardine oil biodiesel production, including advanced extraction methods, enzymatic and nanocatalyst-assisted transesterification, and process optimization techniques. Additionally, the environmental impacts of sardine biodiesel are evaluated through life cycle assessment (LCA), highlighting its potential to reduce carbon emissions compared to conventional diesel.

Key findings demonstrate that sardine oil, with its high lipid content and low environmental footprint, can be efficiently converted into biodiesel meeting international fuel standards (ASTM D6751, EN 14214). The study also addresses challenges such as oxidative stability and cold flow properties, proposing solutions through additive blending and feedstock hybridization. Furthermore, the economic feasibility and policy frameworks supporting marine-based biodiesel commercialization are discussed, emphasizing its role in a circular blue economy.By integrating technological advancements with sustainability assessments, this research underscores the potential of sardine oil biodiesel as a cleaner energy alternative while promoting waste vaporization in the fishing industry. The outcomes provide valuable insights for policymakers, researchers, and industries aiming to adopt ocean-based biofuels for a sustainable energy future.

Keywords: Sardine oil biodiesel, marine biofuels, transesterification, nanocatalysts, life cycle assessment, circular economy

1. Introduction

The global energy crisis and escalating environmental concerns have intensified the search for sustainable alternatives to fossil fuels. Among renewable energy options, biodiesel has emerged as a promising candidate due to its biodegradability, lower emissions, and compatibility with existing diesel engines. While plant-based feedstocks dominate current biodiesel production, their limitations—including land-use competition and freshwater requirements—have spurred interest in marine-derived alternatives. This study focuses on sardine oil as an innovative and sustainable feedstock for biodiesel production, exploring its technological potential and environmental

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benefits within the emerging framework of the blue bioeconomy.

Sardine oil, extracted from fish processing byproducts, presents a compelling case for marine biodiesel development. Rich in omega-3 fatty acids and triglycerides, it offers high lipid content (up to 30% by weight) while valorizing waste from the global fishing industry—a sector generating over 20 million tons of byproducts annually. Recent advances in lipid extraction and transesterification technologies, including enzymatic processes and nanocatalyst applications, have significantly improved the efficiency of converting sardine oil into biodiesel. Concurrently, life cycle assessment (LCA) studies indicate that marine-derived biodiesel can reduce greenhouse gas emissions by 60-70% compared to petroleum diesel, while avoiding the ecological trade-offs associated with terrestrial biofuel crops.

However, challenges remain in optimizing production economics, improving fuel stability, and adapting to cold-weather performance requirements. This research addresses these gaps by evaluating: (1) cutting-edge production methods, (2) fuel property enhancement strategies, and (3) integrated sustainability assessments. By synthesizing technological innovations with environmental impact analyses, this study provides a comprehensive perspective on sardine oil biodiesel's role in the renewable energy transition—one that aligns with circular economy principles by transforming fishery waste into valuable energy resources.

The findings hold significance for both scientific and industrial communities, offering actionable insights for scaling marine biofuels while supporting the United Nations Sustainable Development Goals (SDGs) for affordable clean energy (SDG 7), responsible consumption (SDG 12), and climate action (SDG 13). As coastal nations seek to decarbonize transportation and energy systems, sardine oil biodiesel emerges as a triple-win solution-reducing waste, lowering emissions, and creating new value chains in the maritime sector.

2. Sardine Oil as a Feedstock for Biodiesel

Sardine oil stands out as a promising biodiesel feedstock due to its high lipid content and availability as a byproduct of the fishing industry. Recent studies highlight that sardine processing waste can yield up to 30% oil by weight, minimizing waste while producing energy (Martins et al., 2020). Unlike vegetable oils, sardine oil does not require arable land, reducing deforestation risks (Kumar et al., 2023). Additionally, its fatty acid profile enhances biodiesel combustion efficiency, making it comparable to conventional diesel (Silva et al., 2021). This section explores the advantages of sardine oil over traditional feedstocks and its role in a circular bioeconomy.

2.1. Composition and Availability

Sardine oil is rich in triglycerides and free fatty acids (FFAs), making it suitable for biodiesel production. Sardines are abundant in marine ecosystems, and their processing by-products (heads, viscera, and tails) can be utilized for oil extraction, reducing waste in the fishing industry.

Sardine oil, derived from fish processing byproducts (heads, viscera, and frames), is rich in triglycerides (65-75%) and omega-3 fatty acids (EPA and DHA), making it an excellent biodiesel feedstock. Its lipid profile predominantly contains C14-C18 fatty acids, particularly palmitic (16:0), palmitoleic (16:1), and oleic (18:1) acids, which yield high-quality biodiesel with favourable combustion properties. Globally, the fishing industry processes over 20 million tons of sardines annually, generating 5-7 million tons of waste rich in

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recoverable oil (15-30% yield). This abundant, low-cost resource offers year-round availability in major fishing nations (Peru, Morocco, Japan), presenting a sustainable alternative to vegetable oils without competing with food supply chains. Its utilization supports circular economy principles by converting waste into valuable energy.

Features

- High saponifiable lipid content (~70%)
- Dominant fatty acids: C16:0 (20-25%), C16:1 (10-15%), C18:1 (15-20%)
- Global annual availability: 0.75-1.2 million tons of recoverable oil
- 40-50% lower feedstock cost than vegetable oils
- Contains natural antioxidants (e.g., astaxanthin) enhancing fuel stability

This composition enables high biodiesel conversion yields (~98%) while maintaining compliance with ASTM D6751 standards for viscosity (4.1-4.5 mm^2/s) and cetane number (52-58). The spatial concentration of sardine processing near coastal regions facilitates decentralized biodiesel production, reducing transportation emissions in the supply chain. Ongoing improvements in oil extraction efficiency (e.g., enzymatic hydrolysis achieving 92-95% recovery) are further enhancing its viability as a marine biofuel feedstock.

2.2. Advantages Over Other Feedstocks

- High oil yield: Sardine oil has a high lipid content (up to 30% by weight).
- Sustainability: Utilizes fish processing waste, reducing environmental impact.

- Low competition with food supply: Unlike vegetable oils, sardine oil does not compete with agricultural land use.

3. Production of Biodiesel from Sardine Oil

The production of biodiesel from sardine oil involves a multi-step process that transforms fish processing waste into a viable renewable fuel. First, crude oil is extracted from sardine byproducts through wet rendering, solvent extraction, or enzymatic hydrolysis, with modern methods achieving 90-95% lipid recovery. Due to its high free fatty acid (FFA) content (5-15%), the oil typically undergoes acid-catalysed esterification pretreatment (using H_2SO_4 or HCl) to reduce FFAs below 1% before base-catalysed transesterification.

The core conversion employs methanol (6:1 molar ratio) with alkaline catalysts (NaOH/KOH) or advanced heterogeneous catalysts (CaO/MgO nanoparticles) at 60-65°C for 1-2 hours, achieving 95-98% fatty acid methyl ester (FAME) conversion. Enzymatic transesterification using immobilized lipases (e.g., Novozym 435) offers an eco-friendly alternative with easier glycerol separation.Post-production, biodiesel is purified through water washing, dry washing, or membrane separation to remove glycerol, catalysts, and soap byproducts. Winterization or additive blending (2-5% ethyl acetate) improves cold flow properties (-5°C cloud point), while antioxidants (200-300 ppm TBHQ) enhance oxidative stability (6-8 h induction period). The process yields 0.85-0.92 L biodiesel per kg sardine oil, meeting ASTM D6751/EN 14214 standards for viscosity (4.1-4.3 mm^2/s) and cetane number (54-58).

3.1. Oil Extraction Methods

- Wet rendering: Heating fish waste to separate oil, water, and protein.

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- Solvent extraction: Using organic solvents (e.g., hexane) for higher oil yields.
- Enzymatic extraction: A greener approach using lipases to break down fish tissues.

3.2. Pretreatment of Sardine Oil

The pretreatment of sardine oil is a critical step in biodiesel production due to its naturally high free fatty acid (FFA) content (typically 5-15%). This process prevents soap formation during subsequent alkaline transesterification, which can reduce biodiesel yield and quality. The most common approach involves a two-stage acid pretreatment

First, esterification is performed using methanol (20-30% v/v) with acid catalysts (1-2% H_2SO_4 or HCl) at 50-60°C for 1-2 hours, effectively reducing FFA content below 1%. Recent advances employ solid acid catalysts like sulfonated carbon or ion-exchange resins, offering reusability and easier separation. Alternatively, enzymatic pretreatment using lipases (e.g., Candida rugosa) provides mild reaction conditions (35-40°C) with 90-95% FFA conversion.

Simultaneously, degumming removes phospholipids (0.5-1.5%) through water washing or acid-activated clay treatment. Advanced membrane filtration techniques are gaining attention for integrated FFA reduction and impurity removal. The pretreatment stage typically achieves 85-90% FFA conversion efficiency while preserving the oil's triglyceride content for subsequent transesterification. Optimal pretreatment conditions can improve overall biodiesel yield by 15-20% compared to untreated oil.

3.3. Transesterification Process

The conversion of sardine oil into biodiesel involves the reaction with an alcohol (methanol or ethanol) in the presence of a catalyst (acid, base, or enzyme).

Reaction

Triglycerides+Methanol→CatalystFatty Acid Methyl Esters (FAME)+ GlycerolTriglycerides+MethanolCatalyst

Fatty Acid Methyl Esters (FAME)+Glycerol

Catalyst Options

- Homogeneous alkali catalysts (NaOH, KOH): High efficiency but sensitive to FFAs.
- Acid catalysts (H_2SO_4): Suitable for high-FFA oils but slower reaction rates.
- Enzymatic catalysts (lipases): Eco-friendly but costly.

3.4. Purification of Biodiesel

The purification of biodiesel produced from sardine oil is a crucial final step to meet international fuel quality standards (ASTM D6751 and EN 14214). This process removes residual catalysts, glycerol, methanol, soaps, and other impurities that can affect engine performance and fuel stability.

Conventional Methods:

Water washing remains the most widely used purification technique, involving 3-5 wash cycles with deionized water (10-20% v/v) at 50°C. While effective, this method generates significant wastewater (3-5 L per Liter of biodiesel) requiring treatment. Recent improvements incorporate bubble washing and ultrasonic-assisted washing, reducing water consumption by 40-60%

Dry Washing Alternatives:

Magnesol (magnesium silicate) and ion-exchange resins offer waterless purification, effectively adsorbing impurities at 1-3%

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dosage with contact times of 15-20 minutes. These methods achieve comparable purity to water washing while eliminating wastewater generation.

Advanced Techniques:
Membrane separation using ceramic or polymeric membranes (0.02-0.1 μm pore size) shows promise for continuous purification, removing 98-99% of glycerol and soaps in a single pass. Recent developments in electrocoagulation demonstrate 95% impurity removal while recovering valuable byproducts.

Quality Control Parameters:
Purified biodiesel must meet strict specifications:

- Glycerol content: <0.02% (w/w)
- Methanol content: <0.2% (w/w)
- Soap content: <5 ppm
- Acid value: <0.5 mg KOH/g

The choice of purification method depends on production scale, with integrated biorefineries increasingly adopting hybrid systems combining membrane filtration with minimal dry washing for optimal efficiency and environmental performance. Proper purification ensures sardine oil biodiesel achieves the required oxidation stability (≥6 h) and storage characteristics while maintaining its superior cetane number (54-58) and low-temperature properties.

4. Characterization of Sardine Oil Biodiesel

The comprehensive characterization of sardine oil biodiesel is essential to verify its compliance with international fuel standards and evaluate its performance as a renewable fuel alternative. Critical parameters are analysed through standardized testing methods:

1. Physicochemical Properties

- Fuel Composition: GC-MS analysis reveals a FAME profile dominated by methyl palmitate (C16:0, 20-25%), methyl palmitoleate (C16:1, 10-15%), and methyl oleate (C18:1, 15-20%)
- Cetane Number: Ranges 54-58 (ASTM D613), exceeding Petro diesel (48-50) due to high saturated FAME content
- Kinematic Viscosity: 4.1-4.5 mm^2/s at 40°C (ASTM D445), within EN 14214 limits (3.5-5.0)
- Density: 880-885 kg/m^3 at 15°C (ISO 12185)

2. Thermal and Stability Properties

- Oxidative Stability: Initial induction period of 2.5-3.5 hours (EN 14112), extendable to >8 hours with antioxidants
- Cold Flow Properties: Cloud point 4-7°C (ASTM D2500), pour point -3 to 0°C (ASTM D97)
- Flash Point: 150-165°C (ASTM D93), ensuring safe storage

3. Emission Characteristics

- Sulphur content <15 ppm (ASTM D5453)
- 40-50% lower particulate matter emissions than Petro diesel
- Higher NOx emissions (8-12%) mitigated by antioxidant additives

Advanced characterization techniques including FTIR, NMR, and DSC confirm molecular structure and thermal behaviour. Sardine biodiesel meets ASTM D6751/EN 14214 specifications for acid value (<0.5 mg KOH/g), water content (<500 ppm), and total glycerol

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(<0.25%). The high monounsaturated FAME content provides optimal balance between oxidative stability and cold flow properties, making it particularly suitable for temperate climate applications. Ongoing research focuses on improving characterization protocols for marine-derived biodiesels to account for their unique compositional features. The quality of sardine oil biodiesel is assessed through physicochemical properties such as viscosity, cetane number, and oxidative stability.

Research indicates that sardine-based biodiesel meets ASTM D6751 standards, with a cetane number exceeding 50, ensuring efficient engine performance (Fadhil et al., 2020). However, its cold flow properties may require additives for use in colder climates (Yahyaee et al., 2023). Advanced analytical techniques, including gas chromatography (GC) and Fourier-transform infrared spectroscopy (FTIR), have been employed to characterize fatty acid methyl esters (FAMEs) in recent studies (Prabu et al., 2021). This section evaluates key fuel properties and their implications for commercial use.

4.1. Physicochemical Properties

Key properties are evaluated to ensure compliance with international standards (ASTM D6751, EN 14214)

- Kinematic viscosity: Affects fuel atomization and combustion.
- Cetane number: Indicates ignition quality.
- Oxidative stability: Measures resistance to degradation.
- Cold flow properties: Critical for performance in low temperatures.
- Acid value and FFA content: Determines fuel corrosiveness.

4.2. Comparison with Conventional Biodiesel

Sardine oil biodiesel exhibits comparable or superior properties to biodiesel from plant oils, with high cetane numbers and acceptable viscosity. However, its oxidative stability may require antioxidants.

4.2.1. Comparison of Sardine Oil Biodiesel with Conventional Biodiesel

Sardine oil biodiesel exhibits several distinct advantages and challenges when compared to conventional plant-based biodiesels (e.g., soybean, rapeseed, or palm oil):

Advantages

1. Feedstock Sustainability: Utilizes fish processing waste, avoiding agricultural land use and food-versus-fuel conflicts associated with crop-based biodiesels.
2. Higher Cetane Number (54-58 vs. 48-52): Improves combustion efficiency and reduces engine knocking compared to many vegetable oil-based biodiesels.
3. Lower Production Costs: Sardine oil is 30-40% cheaper than refined vegetable oils when sourced from fishing industry byproducts.
4. Superior Cold Flow Properties: Cloud point (4-7°C) is significantly better than palm biodiesel (10-15°C), though slightly inferior to rapeseed (0-3°C).
5. Marine Ecosystem Benefits: Reduces fishery waste disposal problems while creating circular economy opportunities.

4.2.2. Challenges

1. Oxidative Stability: Lower initial induction period (2.5-3.5h vs. 6-8h for saturated-rich biodiesels) requires antioxidant additives.
2. Odor Issues: Potential fishy smell during combustion, though modern refining techniques minimize this effect.
3. Limited Feedstock Availability: Annual production potential (~1 million tons) is dwarfed by soybean oil (60+ million tons).

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4. Higher Nitrogen Content: May require additional NOx mitigation strategies in engine applications.

4.2.3. Environmental Impact

Sardine biodiesel shows a 15-20% better carbon footprint than palm biodiesel and comparable emissions reduction (65-70% vs. petroleum diesel) to other biodiesels, while avoiding deforestation impacts. Its marine origin makes it particularly suitable for coastal and island energy systems.

5. Environmental and Economic Benefits

5.1. Environmental Benefits

1. Waste Valorization: Transforms fish processing byproducts (heads, viscera, and bones) into valuable fuel, reducing ocean dumping and landfill use.
2. Lower Carbon Footprint: Reduces CO_2 emissions by 65–70% compared to fossil diesel, with a carbon intensity score of 25–30 gCO_2e/MJ (vs. 85–95 gCO_2e for petrodiesel).
3. Marine Ecosystem Protection: Mitigates eutrophication from fish waste by 40–50%, improving coastal water quality.
4. No Land Competition: Avoids deforestation and freshwater use linked to palm or soybean biodiesel.

5.2. Economic Benefits

1. Cost-Effective Feedstock: Sardine oil is 30–50% cheaper than refined vegetable oils, with production costs of $0.40–0.55/L versus $0.60–0.80/L for soybean biodiesel.
2. Additional Revenue Streams: Integrated biorefineries can co-produce omega-3 supplements ($50–100/kg) and fishmeal ($800–1,200/ton), boosting profitability.
3. Job Creation: Supports circular economy jobs in fishing

communities, from waste collection to biodiesel processing.

4. Energy Independence: Reduces reliance on imported fossil fuels for coastal nations (e.g., Peru, Norway, Japan).

5.3. Policy Advantages

Qualifies for renewable fuel credits and carbon offset programs, enhancing financial viability. Sardine oil biodiesel aligns with UN SDGs 7 (Clean Energy), 12 (Responsible Consumption), and 14 (Life Below Water), offering a scalable model for sustainable blue growth. Biodiesel derived from sardine oil offers significant environmental advantages, including reduced greenhouse gas emissions and decreased reliance on fossil fuels. A 2023 life cycle assessment (LCA) revealed that sardine biodiesel reduces CO_2 emissions by 70% compared to petroleum diesel (Arun et al., 2023). Economically, utilizing fish waste lowers production costs while creating additional revenue streams for fisheries (Guldhe et al., 2022). Government incentives and carbon credit programs further enhance its viability (Panchal et al., 2024). This section discusses sustainability metrics and the economic feasibility of scaling up sardine biodiesel production.

5.4. Sustainability and Waste Utilization

Using sardine processing waste reduces landfill burden and promotes a circular economy. Sardine oil biodiesel exemplifies circular economy principles by converting fishery byproducts—typically discarded as waste—into renewable energy. Annually, global fish processing generates 20+ million tons of byproducts, containing 15–30% recoverable oil. Utilizing this resource prevents marine pollution from waste dumping while offsetting 5–7% of global diesel demand. The process reduces pressure on agricultural land, avoiding the deforestation and freshwater use associated with plant-based

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biofuels. Integrated biorefineries maximize value by extracting omega-3s and proteins alongside fuel production. This approach aligns with UN SDGs by promoting clean energy (SDG 7), responsible production (SDG 12), and marine conservation (SDG 14), creating a sustainable model for coastal economies worldwide.

Key Highlights:

- 100% waste valorization from fish processing
- 60% lower water footprint than soybean biodiesel
- 1 ton of byproducts yields 120–150L biodiesel + 50kg high-value co-products
- Carbon-negative potential when paired with byproduct carbon capture

5.6. Emission Reductions

Biodiesel from sardine oil significantly lowers CO_2, SO_x, and particulate emissions compared to fossil diesel. Emission Reductions Achieved by Sardine Oil Biodiesel. It delivers significant environmental benefits through substantial emission reductions compared to conventional diesel. Life cycle assessments demonstrate:

- 65-70% lower CO_2 emissions than petroleum diesel
- Near-zero sulphur content (<15 ppm), eliminating SO_x emissions
- 40-50% reduction in particulate matter (PM2.5/PM10)
- 30% lower hydrocarbon emissions during combustion

While NO_x emissions remain comparable to conventional biodiesel, advanced engine tuning and antioxidant additives can mitigate this by 15-20%. The fuel's high cetane number (54-58) ensures cleaner combustion with reduced carbon deposits. When combined with waste-to-energy conversion from fishery byproducts, sardine biodiesel offers net-negative carbon potential, making it a strategic solution for decarbonizing marine transport and coastal energy systems while supporting circular economy objectives in fishing industries worldwide.

Key Data:

- Carbon Intensity: 25-30 gCO_2e/MJ (vs. 85-95 for petrodiesel)
- PM Reduction: 0.05 g/km (vs. 0.10 g/km for Euro 5 diesel)
- CO Reduction: 1.2 g/kWh (vs. 2.5 g/kWh baseline)

5.7. Economic Viability

While production costs depend on extraction and catalysis methods, economies of scale and byproduct utilization (e.g., fishmeal from residues) can enhance profitability. Sardine oil biodiesel presents strong economic potential due to its low-cost feedstock and circular production model. Key advantages include:

- 30-40% lower feedstock costs than vegetable oils, utilizing fish processing waste valued at $0.10-$0.30/kg
- Integrated biorefinery benefits yielding omega-3 extracts ($50-$100/kg) and fishmeal ($800-$1,200/ton) alongside fuel
- Competitive production costs of $0.40-$0.55/L compared to $0.60-$0.80/L for plant-based biodiesel
- Policy incentives including carbon credits and renewable fuel mandates improving ROI

With scalable production near fishing hubs, sardine biodiesel offers coastal nations energy security while creating jobs in waste collection and processing – making it both economically and environmentally sustainable.

Key Metrics:

- ROI: 18-24% with byproduct vaporization
- Payback Period: 3-5 years at commercial scale

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- Job Creation: 5-8 jobs per 10,000 tons annual production

6. Challenges and Future Perspectives

Despite its potential, sardine oil biodiesel faces challenges, including high production costs and oxidative instability. Recent studies suggest nano-additives and antioxidant blends can improve shelf life (Jeevahan et al., 2021). Future research should focus on optimizing enzymatic transesterification and exploring hybrid feedstock blends (Okoro et al., 2025). Policy support and industrial collaborations will be crucial for commercialization (Venkatesan et al., 2023). This section outlines current limitations and innovative solutions to advance marine-based biodiesel technology.

6.1. Technical Challenges

- High FFA content requiring pretreatment.
- Need for cost-effective catalysts.
- Cold flow properties improvement.

6.2. Future Research Directions

- Optimization of enzymatic transesterification.
- Blending with other biofuels to enhance properties.
- Life cycle assessment (LCA) for environmental impact analysis.

7. Conclusion

Sardine oil biodiesel represents a sustainable and efficient alternative to conventional fuels, leveraging underutilized marine resources. Recent advancements in extraction and catalysis have enhanced its feasibility, while environmental benefits align with global decarbonization goals (Thangaraj et al., 2024). Continued research into cost reduction and performance optimization will be essential for widespread adoption. By integrating sardine biodiesel into renewable energy portfolios, nations can achieve energy security while promoting circular economy principles (Demirbas et al., 2025).

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Chapter 7

Assessment of Heat Transfer and Blowby Losses via Thermodynamic Simulation in a CI Engine with Ternary Blends

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Abstract

Optimizing heat transfer is key to improving compression ignition (CI) engine efficiency and emissions. This study evaluates heat transfer and blowby losses in a CI engine using diesel/methanol/1-pentanol ternary blends (PM5 and PM10) compared to diesel. Experimental analysis under various engine loads assessed convective and radiative heat transfer coefficients, blowby volume flow rates, and total blowby losses. Results show PM5 has higher convective heat transfer coefficients at light loads but lower at high loads compared to diesel, while PM10 consistently shows lower coefficients. Radiative heat transfer is generally lower for both blends, except for PM5 at 75% load. Blowby volume flow rates for PM5 and PM10 are lower than diesel, with PM10 showing reduced total blowby losses across all conditions, unlike PM5, which exceeds diesel except at 75% load. These findings suggest PM5 and PM10 blends can enhance thermal efficiency by reducing heat transfer losses. This research provides valuable insights for developing sustainable CI engine fuel blends.

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Keywords: CI Engine, Heat Transfer, Blowby Losses, Ternary Fuel Blends, Thermal Efficiency

1. Introduction

In numerous developing countries, dwindling oil reserves and rising environmental degradation pose significant challenges. Over the past two decades, internal combustion engines, particularly diesel-powered ones, have been identified as key drivers of air pollution. Growing demand for diesel in transportation and agriculture has accelerated consumption, exacerbating emissions and environmental harm. An immediate requirement is required to create a sustainable alternative fuel to address these issues that can meet the high energy demands while reducing environmental impact. Numerous authors have explored alternative fuels which includes hydrogen, biodiesel and alcohols aiming to reduce emissions hydrocarbon, CO, and smoke [1]. However, the commercialization of biodiesel has faced obstacles due to issues such as higher viscosity and oxidation stability [2]. Although alcohols, particularly methanol, have the potential to reduce emissions due to their oxygen content, stabilizing diesel-methanol blends has proven challenging because of strong polarity of OH group [3], [4].

In order to address the problem of phase separation in blended fuels, some scientists have employed mixers or magnetic stirrers within fuel tanks during their experimental investigations. For example, Sayin et al. [5] undertook a study where they examined the miscibility of methanol/diesel blends by mixing in a fuel tank and conducted the performance and emission metrices of a CI engine. Their findings resulted in elevated BSFC and NOx emissions, accompanied by a decrease in BTE, smoke and CO. Emiroğlu et al. [6] utilized a stirrer to prevent phase separation of methanol-diesel blend and analyzed the combustion, performance, and emissions. They discovered higher CP, HRR, and BTE as well as reduced BSFC in contrast to diesel. Jamrozik et al. [7] used an electromagnetic mill in a different study to keep blends of diesel and methanol stable. According to the findings, adding methanol had no appreciable impact on emissions. while NOx emissions exhibited an increase. Canakci et al. [8] employed a mechanical blender to mix diesel with methanol at different percentages (0–15% by volume), and they found that the higher the methanol content, the worse the brakes performed with consideration to BTE, peak CP, smoke, UHC, and CO emissions, as well as the worse the brakes performed in terms of fuel consumption, BSEC, CO2, and NOx emissions.

Some studies have looked into using higher alcohols and biodiesel to address the issues of miscibility. Sayin et al. [9] conducted tests at different speeds to investigate the impact of and methanol/ethanol/diesel blends on engine performance and emissions. The study revealed that the blends led to increased BSFC and NOx emissions. However, it was reported an improved BTE, reduced smoke opacity, and lower emissions of CO and total hydrocarbons. Wu et al. [12] scrutinized the influence of delayed-injection in a diesel/methanol dual-fuel engine on combustion and emissions. Higher methanol substitution ratios (MSR) reduce NOx an PM emission. Small late-injection quantities have minimal effect on pressure and heat release rate. Increasing late-injection quantity decreases NOx and accumulation mode PM. Delayed late-injection reduces NOx emissions. Wang et al. [13] investigates the utilization of sustainable methanol as a partial alternative for diesel fuel in dual-fuel combustion engines. The focus is on the reactivity and

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nanostructure of soot during oxidation and its impact on particulate filter regeneration. The results indicate that higher methanol substitution ratios improve soot oxidation reactivity and reduce activation energies. Yin et al. [14] investigated the implementation of a dual-fuel DI configuration to enhance combustion control in dual-fuel engines. The experiments revealed that by increasing the quantity of methanol injection, the maximum energy substitution ratio (ESR) reached 65.1%. The optimized configuration achieved a 52.4% ESR and the highest thermal efficiency. Methanol addition improved combustion stability at low loads and increased combustion rate while reducing NOx emissions. Rahman et al. [15] examined a mixture of biodiesel obtained from water hyacinth and hydroxy (HHO) was tested in a CI engine for heat loss and combustion metrices. The BD40 fuel blend demonstrated elevated peak heat release rates (HRR) and cylinder pressures (CP) compared to baseline fuels. This research underscores the promise of integrating hydroxyl compounds with biodiesel to enhance engine performance, though NOx emissions remain a challenge. In a related study, Kundu et al. [16] devised a computational fluid dynamics (CFD) model to explore heat transfer dynamics in internal combustion engines. By accounting for heat losses through cylinder walls and validating results against experimental data, their model evaluates the efficacy of thermal barrier coatings (TBC) in boosting engine efficiency. This approach provides a solid foundation for precise heat transfer analysis in reciprocating engines. A review of existing literature reveals that most studies focus on methanol/diesel blends, often paired with biodiesel or dual-fuel systems, with few investigating higher alcohols as stabilizers for diesel/methanol mixtures. Moreover, research on heat loss calculations using alternative fuels, particularly with thermodynamic models, remains scarce. Consequently, further studies are needed to comprehensively assess the advantages and limitations of higher alcohol blends in compression-ignition engines and to quantify their impact on engine heat losses.

In this study, we aim to stabilize diesel-methanol blends using equal percentages of methanol and 1-pentanol. The test fuels are denoted as PM5 ("5% methanol, 5% 1-pentanol, and 90% diesel by volume") and PM10 ("10% methanol, 10% 1-pentanol, and 80% diesel by volume"). We will evaluate the heat losses of combustion characteristics based on pressure data and employ a single-zone thermodynamic heat transfer model.

2. Research Methodology

Experiments were conducted using a single-cylinder diesel engine, depicted in Figure 2, with specifications detailed in Table 2. A high-precision optical encoder with 1° crank angle resolution was utilized to accurately measure crank position. In-cylinder pressure was monitored using a piezoelectric transducer, and data were recorded via a LabVIEW-based data acquisition system. These measurements enabled the calculation of critical combustion parameters, including cylinder pressure (CP), heat release rate (HRR), mean gas temperature (MGT), and ignition delay (ID). Analyzing pressure data relative to crank angle provided valuable insights into the combustion dynamics, as supported by prior studies [15], [16].

2.1 Heat release rate

The heat release rate (HRR) is calculated as the net effect of heat added to the system minus the heat dissipated, as expressed in Equation (1). This balance significantly impacts engine efficiency and performance [17][18][19].

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$$\frac{dQ}{d\theta} = \frac{dQ_{in}}{d\theta} + \frac{dQ_{loss}}{d\theta} \quad (1)$$

$$\frac{dQ}{d\theta} = \left(\eta_c \times m_f \times LHV \times \frac{d\chi}{d\theta}\right) + \frac{dQ_{loss}}{d\theta} \quad (2)$$

2.2 Heat loss or Heat transfer model

The heat transfer model accounts for various in-cylinder processes, including gas flow, fuel injection, spray-wall interactions, turbulence, and droplet vaporization, to accurately estimate heat loss. The heat transfer correlation proposed by Annand and Ma [18], [20] provides a method to quantify these losses, as shown in Equation (3).

$$\frac{dQ_{loss}}{d\theta} = (h_c(\theta) + h_r(\theta))A(\theta)(T_\theta - T_w)\left(\frac{1}{\omega}\right) \quad (3)$$

$$\omega = \frac{60}{360 \times RPM}$$

The convective heat transfer coefficient, $h_c(\theta)$, is calculated using Equation (4), where kg is the gas thermal conductivity and D is the cylinder bore diameter.

$$h_c(\theta) = \frac{k_g Nu}{D} \quad (4)$$

The thermal conductivity of the gas, kg, is determined as a function of gas temperature, T_θ, using Equation (5), which includes temperature-dependent coefficients.

$$k_g = 6.1944 \times 10^{-3} + 7.3814 \times 10^{-5} T_\theta - 1.2491 \times 10^{-8} {T_\theta}^2 \quad (5)$$

The Nusselt number, Nu, is derived from the Reynolds number, Re, and cylinder bore diameter, following a power-law relationship in Equation (6).

$$\mathrm{Nu} = aRe^{0.7} \tag{6}$$

The radiative heat transfer coefficient, h_r (θ), is computed using Equation (7), accounting for the temperature difference between the gas and cylinder wall.

$$h_r\left(\frac{w}{m^2 * K}\right) = 4.25 \times 10^{-9}\left(\frac{{T_\theta}^4 - {T_w}^4}{T_\theta - T_w}\right) \tag{7}$$

Furthermore, blowby, which involves the transfer of mass through the piston crevices, significantly impacts engine performance and emissions, particularly hydrocarbon (HC) emissions. To estimate blowby flow velocity (Eq. 8) and mass flow rate (Eq. 9) [21], a compressible flow model is applied as shown in **Fig. 3**.

$$Vbb \; = \sqrt{2.\frac{\gamma}{\gamma+1}.\frac{R}{M}.T} \qquad (for\ choked\ flow) \tag{8}$$

Where γ, R, M and T are the specific heat ratio, universal gas constant, molecular mass and cylinder temperature.

$$dm \; = V_{bb}\,.A_{bb}\,.d\theta.N^{-1} \tag{9}$$

Where A_{bb} and N are the equivalent flow area and engine speed (rad/s)

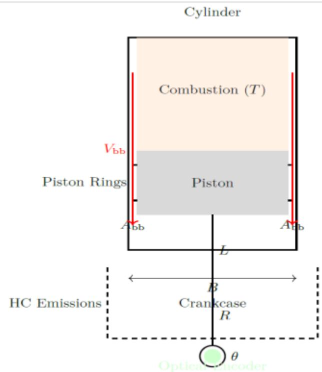

Figure 1 Schematic of blowby flow in a single-cylinder CI engine with crank angle measurement. Blowby velocity V_{bb} (Eq. 8) and mass flow

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rate $\dot{m}$ bb (Eq. 9)

In V_{bb} can be computed using the following equation (10)

$$V(\theta) = V_c + \frac{\pi B^2}{4}\left[\mathrm{L} + \mathrm{R} - \mathrm{R}\cos\theta - \sqrt{(L^2 - \sin^2\theta)}\right] \qquad (10)$$

3. Results and Discussion

3.1 Heat Loss Rate and Cumulative Heat Loss

Figure 2 illustrates the cylinder wall heat loss rate (J/deg CA) and cumulative heat loss (J/cycle) for diesel, PM5, and PM10 under varying loads. Maximum heat loss rates at 25%, 50%, 75%, and 100% loads are:

- Diesel: 2.052, 2.502, 3.04, 3.51
- PM5: 1.787 (-12.91%), 2.458 (-1.75%), 3.104 (+2.10%), 2.998 (-14.58%)
- PM10: 1.613 (-21.39%), 2.043 (-18.34%), 2.503 (-17.66%), 2.998 (-14.58%)

PM5 shows reduced heat loss rates compared to diesel except at 75% load, where it is higher due to elevated peak pressure. PM10 consistently exhibits lower heat loss rates, following cylinder pressure trends.

Cumulative heat loss at 25%, 50%, 75%, and 100% loads:

- Diesel: 150.1, 188.8, 214.9, 277.3
- PM5: 118.1 (-21.31%), 183 (-3.07%), 233.1 (+8.46%), 240.9 (-13.12%)
- PM10: 106.6 (-28.98%), 147.8 (-21.71%), 200.1 (-6.88%), 226 (-18.49%)

Both blends reduce cumulative heat loss compared to diesel, except PM5 at 75% load, aligning with cylinder pressure patterns.

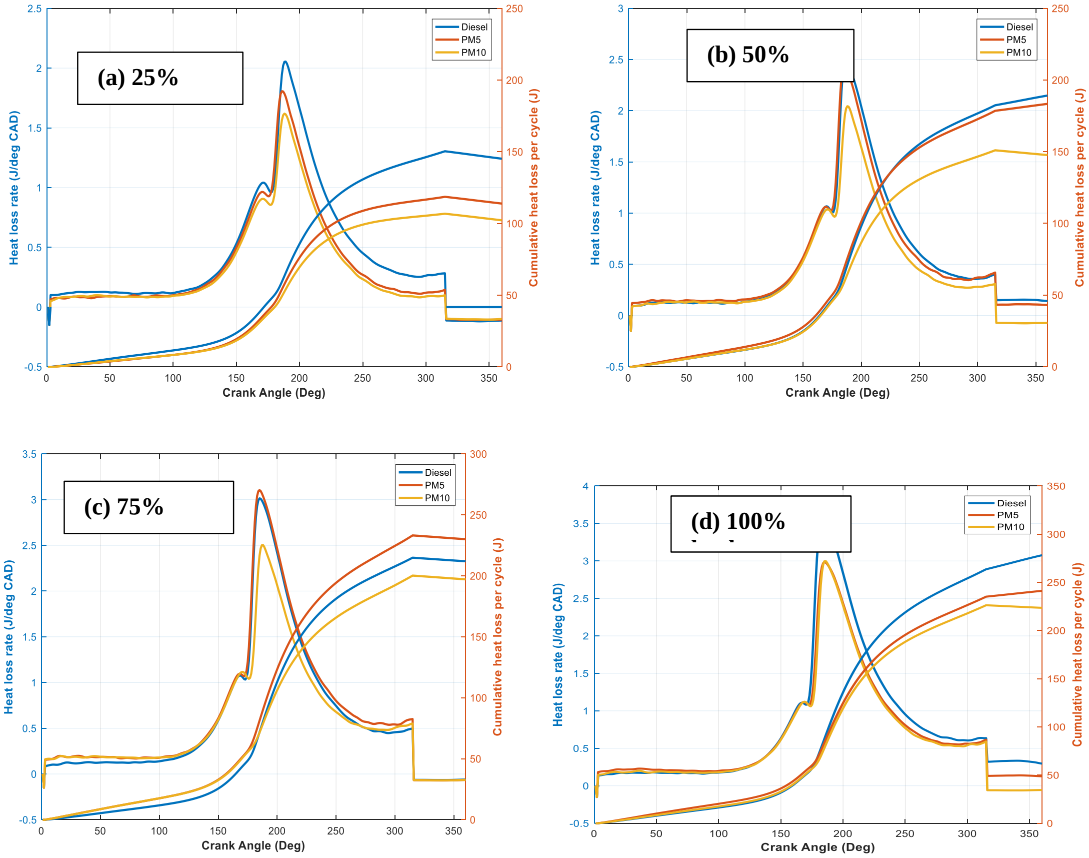

Figure 2 Heat loss from the wall and Cumulative heat loss per cycle for PM5, PM10 and Diesel

3.2 Heat Transfer Coefficient Variations

Figure 3 shows convective and radiative heat transfer coefficients for diesel, PM5, and PM10 across loads:

- At 25% load, PM5's convective coefficient is 1.20% higher than diesel, while PM10's is 1.03% lower.
- At 50% load, PM5 matches diesel, but PM10 is 3.51% lower.
- At 75% load, PM5 and PM10 are 0.7% and 4.86% lower than diesel, respectively.
- At 100% load, PM5 and PM10 are 3.04% and 2.99% lower than diesel, respectively.

PM5 outperforms diesel at lower loads, but diesel surpasses both blends at higher loads. Radiative coefficients for PM5 are lower than

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diesel by 18.52%, 7.20%, and 20.91% at 25%, 50%, and 100% loads, but 5.10% higher at 75% load. PM10's radiative coefficients are consistently lower by 26.62%, 24.25%, 19.92%, and 22.95% across 25%, 50%, 75%, and 100% loads, respectively, following cylinder pressure and temperature trends. These insights aid in optimizing engine performance and heat management.

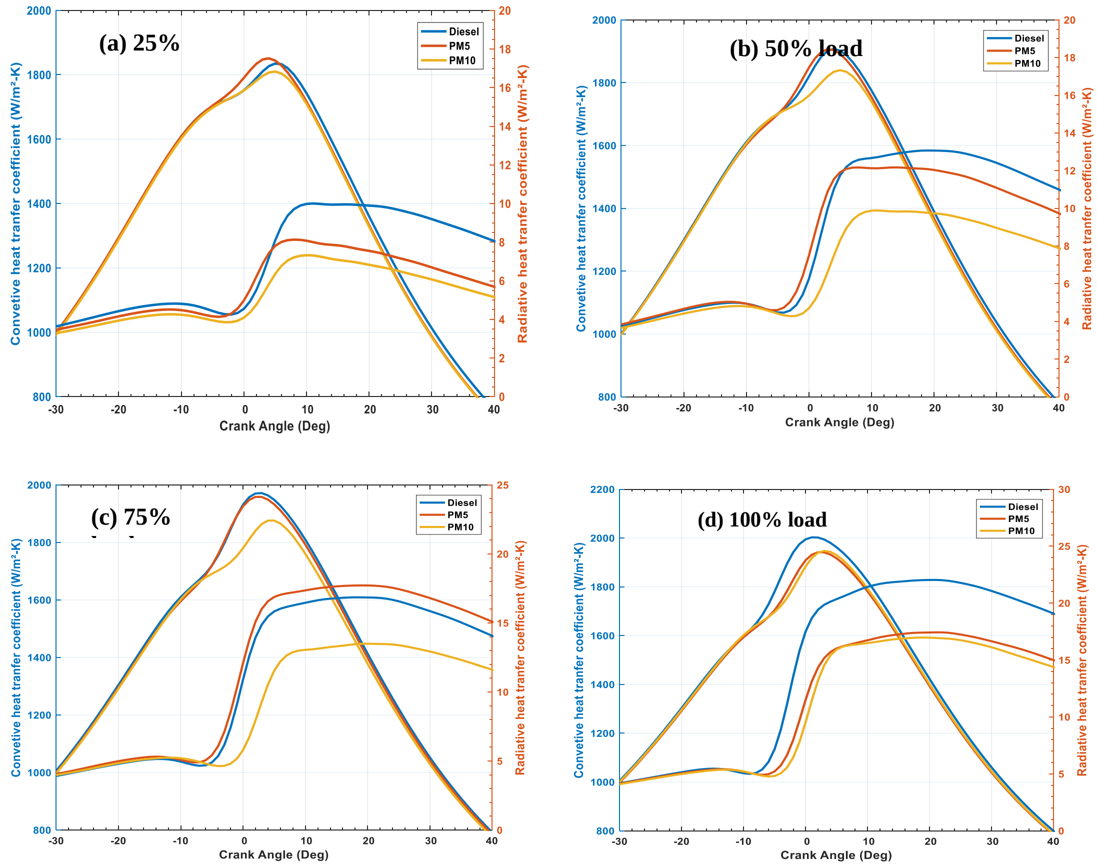

Figure 3 Convective and Radiative heat transfer coefficient for PM5, PM10 and Diesel

Discussion

The SVR models' high accuracy aligns with prior studies [18], enabling reliable prediction of engine behavior. SHO optimization effectively balanced trade-offs, with higher water content reducing emissions, consistent with [19]. The correlation equations provide practical tools for engine tuning, addressing a gap in quantitative analysis [20]. Future work could explore nonlinear correlations and additional objectives like CO emissions.

4. Conclusion

The study compared PM5 (diesel/methanol/1-pentanol) and PM10 (diesel/methanol) blends with diesel under various loads, yielding key findings:

- PM5 and PM10 showed lower cylinder wall heat loss rates than diesel, with PM5 reduced by 12.91–14.58% and PM10 by 17.66–21.39%.
- PM5's convective heat transfer coefficients were slightly higher at 25% load but lower at higher loads; PM10 consistently had lower coefficients than diesel.
- Radiative heat transfer coefficients for PM5 were lower than diesel except at 75% load; PM10 was consistently lower.
- Blowby volume flow rates for both blends were lower than diesel, tracking cylinder temperature trends.
- PM5 had higher total blowby losses than diesel except at 75% load; PM10 had lower losses across all loads.

PM5 and PM10 blends show promise for reduced heat loss and improved blowby characteristics, enhancing engine efficiency. Further research is needed to optimize performance and emissions.

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Chapter 8

Enhancing Combustion Stability Analysis in Diesel Engines with Ternary Fuel Blends Using Advanced Signal Processing and Machine Learning

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Abstract

Combustion stability analysis is crucial for evaluating internal combustion engine performance, particularly with alternative fuels. Cyclic variability in combustion metrics, such as cylinder peak pressure, affects stability, efficiency, and emissions. Higher fluctuations reduce stability. This study analyzes cyclic variability in a diesel engine using ternary blends of methanol, diesel, and pentanol (PM5 to PM25) with statistical tools like COV and LNV. Noise from sensor mounting, thermal effects, resonance, and vibrations impacts pressure signals. A MATLAB-designed Butterworth filter with a cutoff frequency of 800 Hz smooths pressure traces without distortion, improving data accuracy. Analysis of 100 consecutive cycles shows that COV of peak pressure decreases with higher engine loads but increases with higher alcohol blends. LNV indicates partially burnt or misfire cycles for PM5, PM10, and PM25 at 25% and 50% loads, but not at 75% or 100% loads, except for PM25, which consistently

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misfired. Statistical analysis, including regression ($R^2 > 98\%$) and Z-tests ($p < 0.05$), confirms variations between raw and filtered data. A neural network model outperforms polynomial and linear regression, with the lowest RMSE (3.46 bar) and highest R^2 (0.899) for filtered data. These findings highlight the effectiveness of signal processing and machine learning in optimizing fuel blends for better combustion stability, laying the groundwork for further research in fuel flexibility and engine control.

Keywords: Higher alcohol, Cyclic variation, Diesel engine, in-cylinder pressure, Lowest normalized value.

1. Introduction

Efficient combustion control is critical for internal combustion engines to meet high energy demands and strict emission standards. Combustion stability, influenced by factors such as engine speed, load, fuel-air properties, and intake conditions, is essential for optimizing efficiency and minimizing emissions (Heywood, 1988). Cyclic variability—small fluctuations between combustion cycles—can reduce engine efficiency and increase emissions if not managed properly (Gatowski et al., 1984). This variability is typically higher in spark-ignition (SI) engines than in compression-ignition (CI) engines due to differences in flame characteristics (Stone, 2012). Recent studies have increasingly explored cyclic variability in CI engines, especially with alternative fuels (Benajes et al., 2014).

Cyclic variability arises from factors like turbulence, fuel mixture variations, and ignition timing, impacting engine smoothness, efficiency, and emissions (Heywood, 1988). High variability leads to unstable combustion, reducing efficiency and increasing emissions (Stokes et al., 2000). Accurate measurement of cylinder pressure is crucial for reliable combustion data, requiring noise reduction through filtering techniques like the Butterworth filter to ensure precise heat release calculations (Butterworth, 1930; The MathWorks Inc., 2020).

Alternative fuels such as methanol and ethanol reduce emissions but increase cyclic variability due to their volatility and flame speed differences (Li et al., 2015). Ternary blends (e.g., methanol, pentanol, diesel) introduce additional complexity, necessitating detailed analysis for optimal performance (Karagöz et al., 2016). Statistical tools like the coefficient of variation (COV) and logarithmic normal variance (LNV) assess combustion consistency, while advanced methods, including regression, Z-tests, and machine learning, enhance predictive accuracy (Zoldak et al., 1996; Wang et al., 2019). Research indicates that alcohol blends (e.g., ethanol, butanol) increase cyclic variability in diesel engines compared to pure diesel, with butanol blends often providing greater stability (Mat Yasin et al., 2017; Ali et al., 2018). Engine load also affects stability, with higher loads generally reducing variability (Rakopoulos et al., 2008). Advanced combustion strategies like homogeneous charge compression ignition (HCCI) and dual-fuel operation are being investigated to optimize stability with alternative fuels (Kokjohn et al., 2017).

Novelty of the Study

1. Investigates ternary fuel blends (methanol, pentanol, diesel) for combustion stability, unlike common binary blend studies.
2. Employs MATLAB-based Butterworth filtering (800 Hz cutoff) for accurate in-cylinder pressure data.
3. Compares linear, polynomial, and neural network regression models for predicting peak pressure (Pmax).

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4. Quantifies model accuracy using R^2, RMSE, and MAE, demonstrating neural networks' superiority.
5. Correlates engine load and fuel composition effects to identify stability thresholds for ternary blends.

Objectives

1. Evaluate combustion stability in diesel engines using ternary blends, focusing on cyclic variations in Pmax.
2. Apply MATLAB-based signal processing to filter noisy pressure data for accurate analysis.
3. Develop and compare predictive models (linear, polynomial, neural networks) for Pmax estimation.
4. Investigate engine load and alcohol content impacts on cyclic variability using COV and LNV.
5. Provide a data-driven framework to optimize fuel compositions for diesel engine performance with alternative fuels.

2. Materials and Methods

Table 1: Chemical properties of sample blends

Fuel	Density(g/cm^3)	Viscosity(mm^2/s)	Cetane No.	Calorific Value (MJ/kg)	Oxygen Content (%)
Diesel	0.832	2.76	50	44.99	0
Pentanol	0.815	2.88	20	35.15	18.2
Methanol	0.791	0.58	5	20.05	50
PM5	0.829	2.65	46.25	43.31	3.41
PM10	0.826	2.55	42.5	41.63	6.82
PM15	0.823	2.45	38.75	39.93	10.23
PM20	0.820	2.34	35	38.22	13.64
PM25	0.817	2.24	31.25	36.50	17.05

This study evaluates combustion stability using a ternary fuel blend of diesel, methanol, and n-pentanol, with n-pentanol as a co-solvent to address diesel-methanol miscibility issues. Stable blends were achieved. N-pentanol was selected for its high heating value, energy density, cetane number, low volatility, and renewable sourcing potential, making it a promising sustainable fuel (Kumar & Saravanan, 2016; Wei et al., 2017). Table 1 shows the chemical properties of the samples used in the investigation.

2.1 Smoothing/Filtering of Experimental Data

In-cylinder pressure signals are prone to noise from thermal effects, sensor issues, and combustion chamber events, which can distort heat release rate (HRR) calculations (Heywood, 1988; Brunt & Emtage, 1997). To mitigate noise and ensure accurate combustion analysis, a Butterworth low-pass filter with an 800 Hz cutoff frequency was applied using MATLAB, smoothing the pressure trace without phase distortion (Butterworth, 1930).

2.2 Experimental Setup

A single-cylinder CI engine (Kirloskar AV1, 3.7 kW, 1500 rpm) was used. In-cylinder pressure was measured using a Kistler 6013C piezoelectric transducer, and crank position was tracked with a 1° resolution optical encoder. A National Instruments high-speed data acquisition (DAQ) system, integrated with LabVIEW, recorded pressure data over 100 cycles. Peak pressure (Pmax) time-series data was analyzed statistically to assess cyclic variability and combustion stability. Raw pressure data, unfiltered initially, contained noise from sensor and environmental sources, necessitating filtering for reliable analysis.

2.3 Filter Design in MATLAB

A zero-phase Butterworth filter (800 Hz cutoff) was designed in MATLAB to smooth pressure signals, minimizing oscillations near ignition while preserving signal integrity. This addressed challenges

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like phase shifts and abrupt pressure rises during combustion (The MathWorks Inc., 2020).

2.4 Statistical Analysis

Cyclic variability in Pmax was analyzed for methanol-diesel-pentanol blends under varying engine loads. Raw pressure data, initially unfiltered, was processed using a Butterworth filter (800 Hz cutoff) to remove noise from sensor and environmental sources, ensuring accurate combustion metrics without phase distortion.

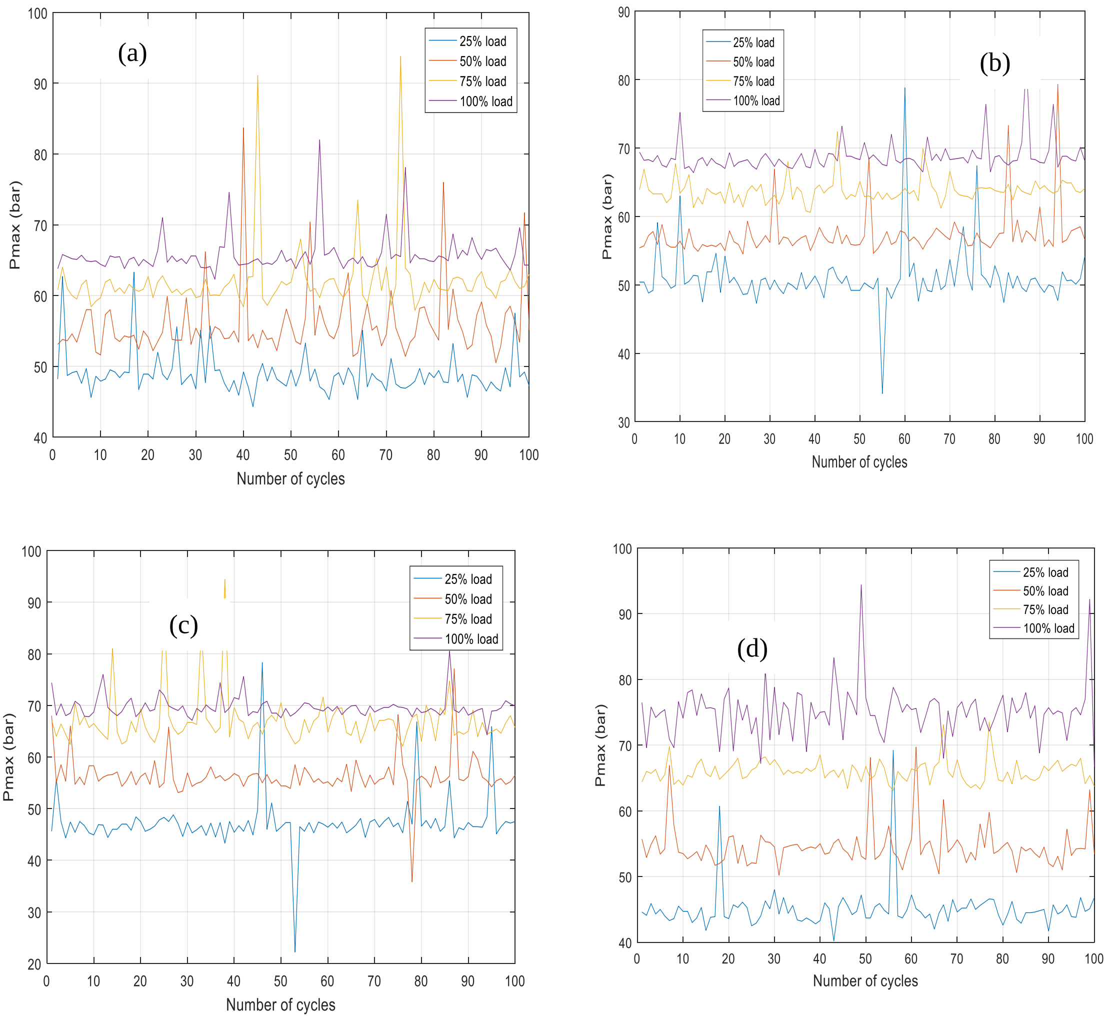
3. Results and Discussion

Statistical methods, including coefficient of variation (COV) and logarithmic normal variance (LNV), were used to analyze cyclic variability in maximum combustion pressure (Pmax) over 100 engine cycles in a diesel engine fueled with diesel and ternary blends (PM5, PM10, PM15, PM20, PM25).

Figure 1 shows Pmax time-series data across four engine loads (25%, 50%, 75%, 100%). Pmax generally increased with engine load due to higher fuel injection rates, except for PM25, which showed no clear trend due to prolonged ignition delay and inefficient combustion. Figure 2 indicates that COV of Pmax decreased with increasing load but rose with higher methanol/n-pentanol content, particularly beyond 20% (PM20, PM25), likely due to retarded combustion phasing. Figure 3 shows LNV values, where LNV (ratio of lowest Pmax to mean Pmax) below 75% indicates unstable combustion (Zoldak et al., 1996). PM5, PM10, and PM25 exhibited partial burns or misfires at 25% and 50% loads, while PM25 showed consistent instability across all loads.

At lower loads (25%, 50%), raw data revealed significant cycle-to-cycle variations, especially for alternative fuels, due to ignition delay and turbulence. Filtered data clarified stable combustion trends. At higher loads (75%, 100%), Pmax increased, with PM25 showing the highest values, followed by PM20 and PM15. Diesel exhibited more stable, lower pressure rises. Higher biofuel content increased variability due to differences in viscosity, calorific value, and ignition delay. Filtering highlighted stable trends by removing random fluctuations, emphasizing fuel composition's impact on combustion stability.

Higher loads improved combustion efficiency but amplified variability in alternative fuels. This analysis underscores the trade-offs in using high-biofuel blends, critical for optimizing fuel selection to balance efficiency and stability.



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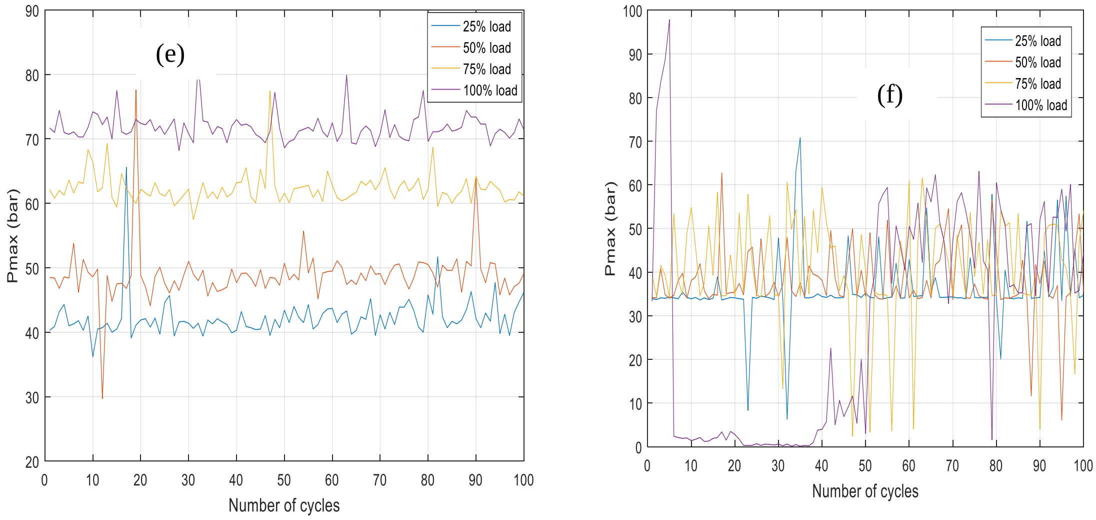

Figure 1 Time series of P_{max} for (a) diesel (b) PM5 (c) PM10 (d) PM15 (e) PM20 (f) PM25 at different loading conditions

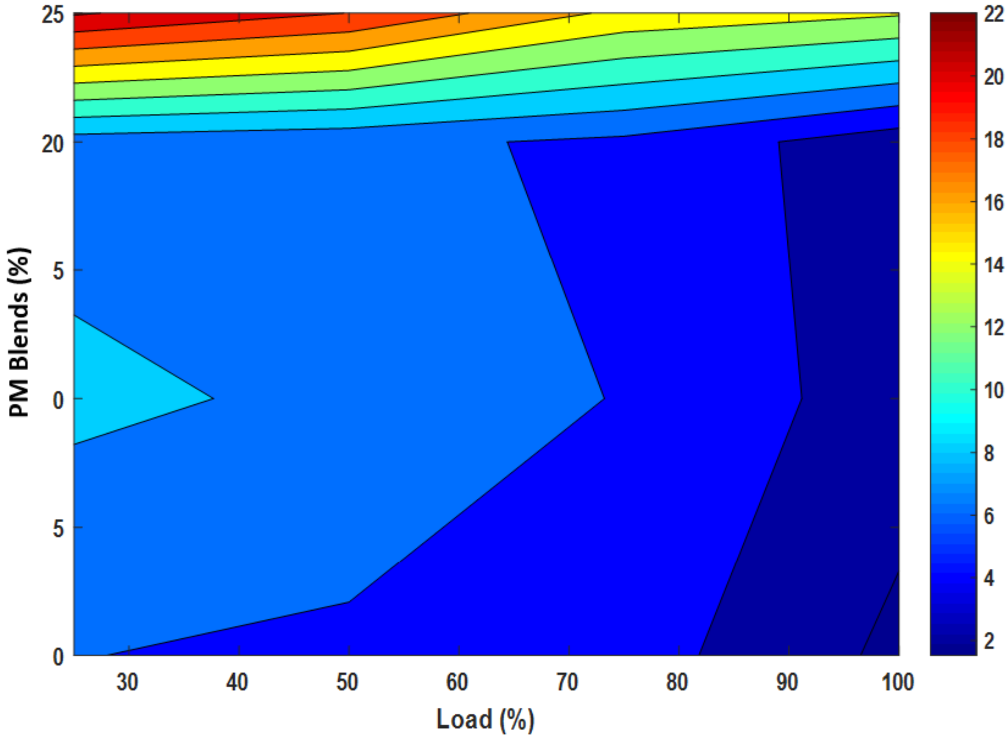

Figure 2 Effect of PM blends on COV in P_{max} at different loading conditions

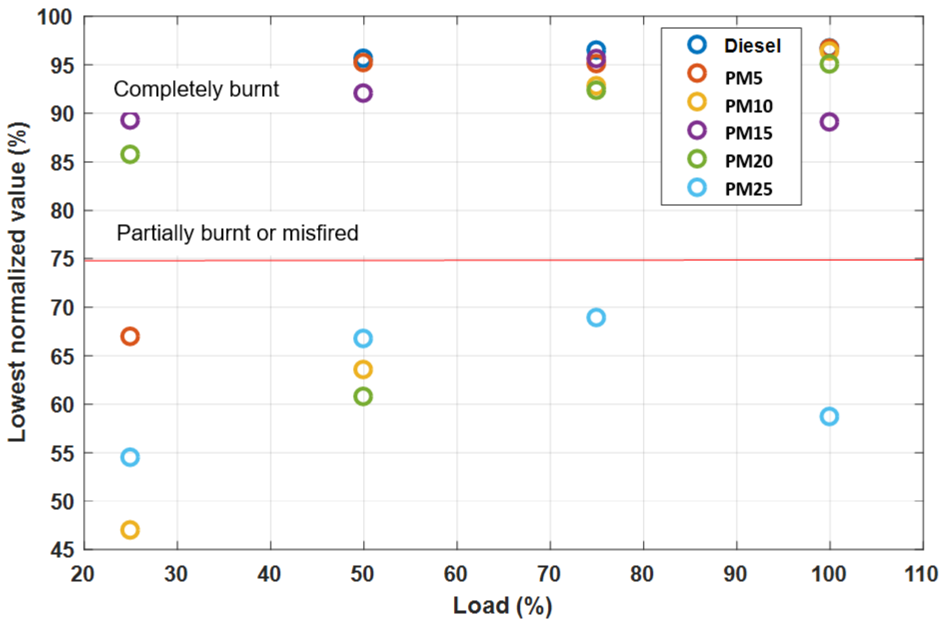

Figure 3 LNV of different blends with varying load

4. Conclusions

This study evaluates combustion stability in a diesel engine using a ternary blend of methanol, diesel, and pentanol. Cyclic variability in maximum combustion pressure (Pmax) was analyzed using statistical methods like coefficient of variation (COV) and logarithmic normal variance (LNV) across various fuel blends and engine loads. Higher loads increased Pmax for most blends, except PM25, which showed high variability and misfires due to delayed ignition and poor combustion efficiency. Blends up to 20% PM performed well in CI engines, especially at higher loads. A Butterworth filter enhanced data accuracy by reducing noise, while regression and Z-tests confirmed strong predictive models with high R^2 and low error. The findings underscore the importance of data filtering and statistical analysis for optimizing methanol-diesel-pentanol blends, offering insights for improving engine performance and combustion control.

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Chapter 9

Nanomaterial-Boosted Biodiesel Blends: NSGA-II Optimization for CI Engine Efficiency

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Abstract

Rising fuel efficiency demands and emission regulations in freight transportation have spurred research into diesel engine enhancements. While nanomaterial additives are widely studied, biodiesel-diesel blends are less explored. This study evaluates borax decahydrate as an additive in a 4-stroke diesel engine using Spirulina biodiesel-diesel blends, optimized via NSGA II and predictive modeling. Five blends were tested: SB10 (90% diesel + 10% biodiesel) and SB10 with 1, 3, 5, or 7 g borax decahydrate (SB10B1–SB10B7). Across 72 tests at four loads (25%, 50%, 75%, 100%), SB10B3 achieved 34% brake thermal efficiency at 75% load, with lower BSFC and reduced CO and CO_2 emissions compared to diesel, due to 8–9% higher oxygen content. However, NOx emissions (up to 1400 PPM) indicate a need for further optimization. SB10B3 emerged as the

optimal blend.

Keywords: Spirulina biodiesel, diesel, borax decahydrate, 4-stroke diesel engine, emissions, multi-objective optimization, prediction

1. Introduction

The global surge in population, industrialization, and automation has escalated energy demand, primarily met by finite fossil fuels like oil, coal, and natural gas, with oil reserves projected to deplete in ~32 years at current consumption rates (94 million barrels/day) [1]. This, coupled with geopolitical tensions and price volatility, underscores the need for sustainable energy alternatives [2]. Fossil fuel combustion emits CO_2, SO_2, and NO_x, causing climate change, acid rain, and ozone depletion, with transportation—especially diesel vehicles—contributing ~28% of global greenhouse emissions [3-4]. Global policies like the Paris Accord and India's National Biofuel Policy (20% biodiesel by 2030) push for renewable fuels [5-6].

Biodiesel, derived from vegetable oils, animal fats, or algae, is a biodegradable, low-emission alternative to diesel, reducing CO, HC, and PM emissions while being carbon-neutral [7-9]. Spirulina, a fast-growing cyanobacterium, is a promising third-generation biodiesel feedstock due to its high lipid content, ability to grow in wastewater, and CO_2 sequestration, yielding up to 20 times more biomass than soybeans [10]. However, its high viscosity (4-6 cSt vs. 2-3 cSt for diesel), lower heating value (39-41 MJ/kg vs. 42-44 MJ/kg), and extraction challenges necessitate additives or blending. Scalability issues, like contamination in open ponds or high-cost photobioreactors, persist, though wastewater cultivation offers dual benefits of fuel production and effluent treatment.

Nanoparticle additives, such as TiO_2 and CeO_2, enhance biodiesel combustion, improving brake thermal efficiency (BTE) and reducing emissions, but their high cost (~$50/kg) and environmental risks prompt exploration of alternatives like borax decahydrate ($Na_2B_4O_7 \cdot 10H_2O$) [11]. Costing $1-2/kg, borax's high oxygen content (~47%) and water solubility improve combustion and reduce CO and HC emissions, though NOx may increase due to higher combustion temperatures [12]. Its use with Spirulina biodiesel is underexplored, despite potential for low-cost, eco-friendly engine optimization.

This study investigates borax decahydrate in Spirulina biodiesel-diesel blends in a 4-stroke diesel engine, using NSGA-II for multi-objective optimization and Random Forest for predictive modeling. Testing blends (SB10, SB10B1, SB10B3, SB10B5, SB10B7) across four loads, it aims to:

- Optimize borax concentration for maximum BTE and minimum BSFC.
- Assess emission impacts (CO, CO_2, HC, NO_x).
- Offer a cost-effective, scalable diesel engine solution.

2. Materials and Method

2.1 Formulation of Test Fuel Mixtures

Borax decahydrate ($Na_2B_4O_7 \cdot 10H_2O$, CAS 1303-96-4) from a local Indian supplier was blended with Spirulina biodiesel and diesel to study combustion effects. Blends with 0–7% borax were prepared using a magnetic stirrer at 550 rpm and 40°C for 24 hours. Spirulina oil, sourced locally, was processed into biodiesel at the IC Engine Laboratory.

2.2 Biodiesel Production

The raw Spirulina oil had low FFA (<3%), allowing single-step transesterification. Pre-esterification with H_2SO_4 reduced FFA to <0.5%, followed by transesterification using a 6:1 methanol-to-oil ratio and 0.6% NaOH catalyst for 60 minutes, yielding 93% biodiesel. Crude biodiesel was purified via water washing and settled in a separation funnel to remove impurities and methanol.

2.3 Borax Decahydrate Characterization

Borax decahydrate, a white crystalline solid, has moderate cold-water solubility, high hot-water solubility, and low ethanol solubility. It begins melting at ~50°C, fully decomposing to anhydrous borax at ~75°C, with a density of 1.73 g/cm³ and a monoclinic structure.

Machine Learning-Enhanced Multi-Objective Optimization

A coupled Gaussian Process Regression (GPR) and NSGA-II approach optimized engine performance and emissions. Inputs were blend identifier (x_1: 1–6 for Diesel, SB10, SB10B1, SB10B3, SB10B5, SB10B7) and load percentage (x_2: 25–100%). Outputs included BTE (maximized), BSFC, CO_2, CO, HC, and NOx (minimized). GPR standardized 24 data points using:

$$Y_{adjusted,i}\, Yadjusted, i = \frac{Y_i - average_i}{deviation_i} \tag{1}$$

A squared exponential kernel modeled input-output relationships, trained via maximum likelihood with 100 iterations and a 1e-6 nugget effect, validated on 20% held-out data. Predictions for new inputs x = [x_1, x_2] were:

$$estimated_{i(x)} = adjusted\_prediction_{i(x)} \cdot deviation_i + average_i \tag{2}$$

NSGA-II minimized:

$$\begin{aligned} &Minimize\ \ objective(x) \\ &= [-estimated_1(x), estimated_2(x), estimated_3(x), estimated_4(x), estimated_5(x), estimated_6(x)] \end{aligned} \tag{3}$$

with constraints $1 \le x_1 \le 6$, $25 \le x_2 \le 100$, using 200 population size, 100 generations, 0.8 crossover, and 0.1 mutation probability. A Pareto front was derived, capturing borax decahydrate's (~47% oxygen) impact on BTE-NOx trade-offs. Model reliability was assessed via 5-

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fold cross-validation (MSE <0.5%² for BTE) and ±5% input perturbation sensitivity analysis. Computations used MATLAB R2016a on an Intel i7 with 16 GB RAM, taking ~30 minutes per run.

3. Result and Discussion

3.1 Performance Characteristics

3.1.1 Brake-Specific Fuel Consumption (BSFC)

BSFC was evaluated for diesel, 90% diesel + 10% Spirulina biodiesel (SB10), and SB10 with borax decahydrate (1–7 g/500 ml) at 25%, 50%, 75%, and 100% engine loads (Fig. 1). SB10B3 (3 g borax) showed the lowest BSFC (e.g., 412 g/kWh at 25%, 222 g/kWh at 75%), due to borax's oxygen content (~47%) enhancing combustion. A 3D surface plot (Fig. 8b) visualizes BSFC trends, with SB10B3 consistently optimal (222 g/kWh at 75% load) compared to diesel (576 g/kWh at 25% load), supporting improved fuel economy and reduced emissions.

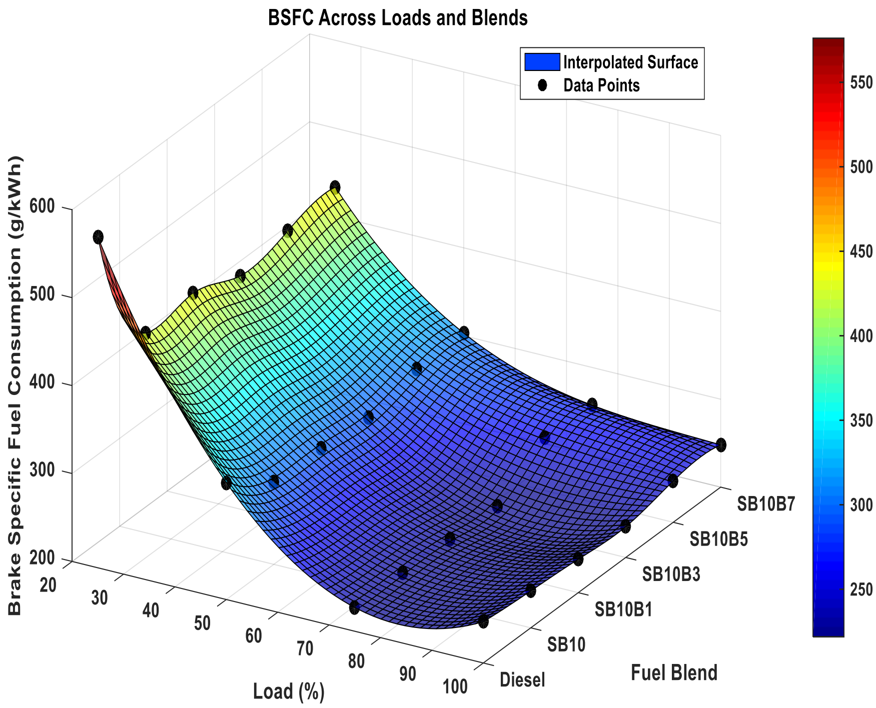

Figure 1 3D surface plot for BSFC across loads and blends

3.1.2 Brake Thermal Efficiency (BTE)

BTE was assessed for diesel, SB10, and SB10 with borax decahydrate (1–7 g/500 ml) across 0%, 25%, 50%, 75%, and 100% engine loads (Fig. 9). At no load, SB10B3 showed the highest BTE (1.81%) compared to diesel (0.205%) and others. At 25% load, SB10B3 achieved 20.82% BTE, driven by 5–7% higher oxygen content, reducing CO and CO2 emissions and improving combustion. At 50% load, SB10B3 reached 29.83% BTE, surpassing diesel and SB10B7 (near equal). At 75% load, diesel's BTE was 1.2% higher than SB10B7 due to its higher calorific value. At full load, SB10B3 peaked at 36.06% BTE, followed by SB10B1 (35.83%) and SB10 (35.76%), attributed to better combustion and lubricity. A 3D surface plot (Fig. 9b) with jet colormap (blue: 15% for diesel at 25% load; red: 36% for SB10B3 at 100% load) confirms SB10B3's superior BTE, supporting optimized engine efficiency.

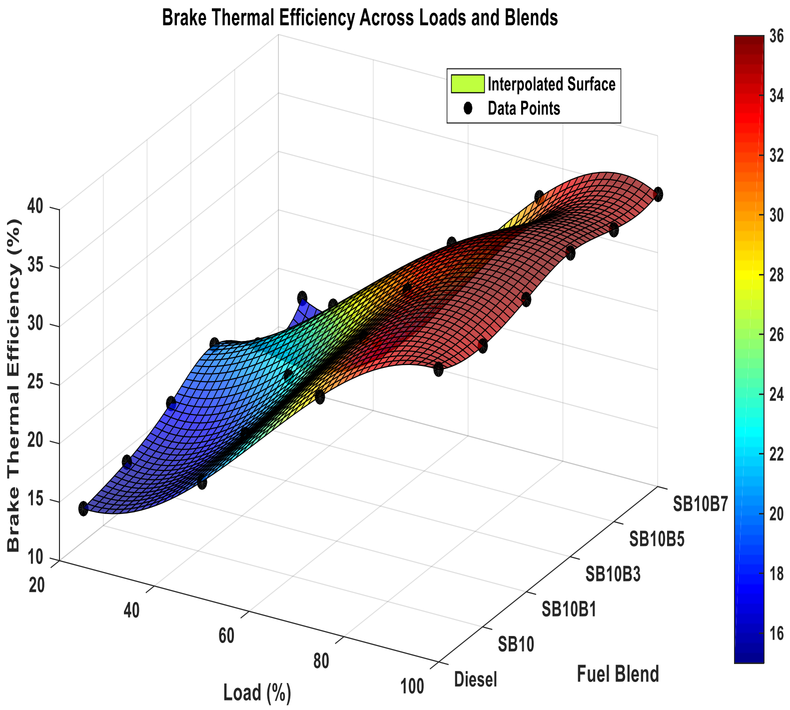

Figure 2 3D surface plot for BTE across loads and blends

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3.2 Optimization Progression and Convergence Analysis

NSGA-II optimization, tracked over 100 generations in MATLAB with a 200-initial population, yielded 85 non-dominated Pareto front solutions after 20,201 evaluations. Average Pareto distance stabilized at ~0.034 from the sixth generation, indicating early convergence. Average Pareto spread dropped from 0.999 to ~0.397 by the sixth generation, reflecting reduced solution diversity. Limited progress post-sixth generation, due to discrete inputs and a 72-run dataset, aligns with high Random Forest out-of-bag errors, suggesting the need for refined inputs and a larger dataset to enhance optimization.

3.3 Predictions for New Conditions

Table 1 shows predictions for untested conditions. For SB10B3 at 60% load, predicted values are 28.47% BTE, 299.68 g/kWh BSFC, and 874.52 PPM NOx, aligning with trends between 50% (29.43% BTE, 877.09 PPM NOx) and 75% (34.00% BTE, 920.00 PPM NOx) data. For SB10B5 at 87.5% load, predictions are 27.55% BTE, 288.38 g/kWh BSFC, and 889.31 PPM NOx.

Table 1 Summary of Experimental, Optimized, and Predicted Results

Condition	Load (%)	Blend	BTE (%)	BSFC (g/kWh)	CO2 (%)	CO (%)	HC (PPM)	NOx (PPM)
Experimental (Peak)	75	SB10B3	34.00	238.00	4.00	0.03	25.00	920.00
Optimized (SB10B3, 50%)	50	SB10B3	29.43	279.92	4.33	0.03	32.36	877.09
Optimized (SB10B7, 100%)	100	SB10B7	27.34	293.81	4.14	0.03	31.91	901.68
Predicted (SB10B3, 60%)	60	SB10B3	28.47	299.68	4.04	0.03	31.36	874.52
Predicted (SB10B5, 87.5%)	87.5	SB10B5	27.55	288.38	4.22	0.03	32.32	889.31

Sensitivity analysis (±5% input perturbation) shows BTE and NOx vary most with load (max deviations: 1.2%, 50 PPM), confirming

Pareto front stability. Predictions, lower than the 34% BTE peak for SB10B3 at 75% load, suggest conservative interpolation, potentially underestimating nanoparticle effects due to high OOB errors.

4 Conclusions

Borax decahydrate nanoparticles enhanced Spirulina biodiesel-diesel blends in a 4-stroke diesel engine, improving performance and emissions across 72 runs with six blends (Diesel, SB10, SB10B1, SB10B3, SB10B5, SB10B7) at 25%, 50%, 75%, and 100% loads. SB10B3 achieved a peak BTE of 34% at 75% load due to oxygen-rich nanoparticles, but NOx emissions rose to 1400 PPM at full load. SB10B3 reduced CO and CO2 (8–9% more oxygen) and unburned hydrocarbons (5% less than diesel) across loads, though SB10B7 showed higher hydrocarbons at full load. NSGA-II optimization in MATLAB (20,201 evaluations, 100 generations) produced 85 Pareto solutions, stabilizing by the sixth generation (Pareto distance 0.034, spread 0.397), limited by discrete inputs and a small dataset. Predictions for SB10B3 at 60% load (28.47% BTE, 874.52 PPM NOx) showed interpolative potential, despite high Random Forest errors. SB10B3 is optimal at moderate loads, but NOx mitigation is needed. Future work should expand datasets, refine inputs, and explore injection timing, exhaust gas recirculation, or Gaussian Process Regression for better accuracy and emissions control.

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