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Review

Energy Audit Perspectives on Biodiesel-Fuelled Diesel Engines

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Abstract: Energy auditing provides a systematic framework for quantifying energy flows, identifying losses, and improving system efficiency. In diesel engines that increasingly use biodiesel blends as renewable fuels, energy audits serve as diagnostic tools to determine performance, emission behavior, and sustainability. This review synthesizes recent research about the use of energy audits to diesel engines using diesel with biodiesel. It examines performance metrics such as brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), and brake specific energy consumption (BSEC), as well as emission indices and heat-flow distribution. The analysis shows that biodiesel blends, especially up to B20, maintain comparable performance to diesel while reducing emissions of smoke, carbon monoxide, hydrocarbons, and particulates. Slight increases in NO_x are observed, which can be mitigated by timing optimization and exhaust-gas recirculation. The paper proposes a standardized audit methodology that integrates thermodynamic, environmental, and economic indicators. This framework can harmonize biodiesel evaluation procedures, reduce duplication of experiments, and accelerate the adoption of sustainable fuels.

Keywords: energy audit; biodiesel blends; diesel engine; performance; emissions; thermal efficiency; sustainability

1. Introduction

Energy auditing has become an essential technique in modern energy management. It involves systematic measurement, analysis, and interpretation of energy data to determine how effectively a system uses energy and where improvements can be made [1]. Traditionally applied in industrial and building sectors, auditing now extends to mechanical and transport systems, including internal-combustion (IC) engines.

Diesel engines dominate global transportation, agriculture, and stationary power because of their robustness and fuel efficiency. Yet they rely on finite fossil resources and emit pollutants such as CO_2, CO, particulate particles (PM), nitrogen oxides (NO_x), and unburned hydrocarbons. With growing environmental concerns, researchers have turned toward biodiesel—an oxygenated, renewable fuel derived from vegetable oils, animal fats, or waste cooking oils [2].

Biodiesel blends offer a promising pathway toward carbon-neutral operation. They generally improve combustion due to inherent oxygen but have lower calorific values and higher viscosity than mineral diesel, factors that slightly affect performance. Therefore, evaluating biodiesel's technical and environmental feasibility requires an analytical approach beyond conventional engine testing.

An energy audit fulfils this need by mapping the entire energy balance of the engine—tracking how input chemical energy divides into radiation, cooling loss, brake power, and exhaust loss. It also links thermodynamic efficiency with emission outcomes, enabling comparisons among fuels under uniform criteria. The purpose of this study is to consolidate prior research on energy auditing for biodiesel-fuelled diesel engines, highlight methodological gaps, and recommend a unified framework for future audits.

One approach to assess the viability of biodiesel blends as fuel is an energy audit. One crucial factor in the energy audit of diesel engines powered by blends of biodiesel is the choice of performance and emission characteristics. This review and study includes heat flow analysis, which includes heat usage in brake-specific energy consumption, Brake power, heat losses to cooling water, exhaust gas and radiation, friction power, and smoke emission have been identified as critical performance and emission characteristics that ought to be included in an energy audit of diesel engines running on biodiesel blends. Their impact on other parameters is the basis for this choice. To harmonize research on biodiesel as fuel, this energy audit will be standardized [3].

To assess diesel engines powered by diesel and biodiesel blends by energy audit at the primary level, the following performance and emission characteristics of the diesel engine have been selected as crucial parameters.

1. Brake Specific Energy Consumption
2. Analysis of Heat Flow
   (a) Brake power using heat
   (b) Jacket cooling water heat loss
   (c) Exhaust gas heat loss
   (d) Radiation Heat Loss
3. Frictional power
4. Emissions of Smoke

To save time, this might be used as a preliminary energy audit method to assess diesel engines powered by blends of biodiesel [4].

2. Energy Audit of Biodiesel

An energy assessment might be defined as the systematic evaluation of energy consumption in any system, identifying where and how energy is employed and recommending improvements for effectiveness and financial savings. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recognizes four levels of audits—from preliminary walkthroughs to detailed investment-grade analyses [5]. Each level progressively increases data precision and analytical depth.

In mechanical systems such as engines, audits determine how input energy converts into mechanical work and where losses occur. Typical energy components include:

- Input energy (E_{in}): fuel mass × calorific value.
- Brake power (E_{br}): useful mechanical output.
- Heat through exhaust gases (E_{exh}), coolant (E_{cl}), and unaccounted radiation (E_r).

Mathematically: $E_{in} = E_{br} + E_{exh} + E_{cl} + E_r$ ($+E_{unacc}$) [6].

Energy auditing is not limited to measurement; it serves multiple objective-environmental compliance, cost optimization, maintenance scheduling, and design benchmarking. In the context of biodiesel, it provides clarity on how chemical differences in fuels influence thermodynamic behavior, helping industries choose optimal blends and tune engine parameters accordingly.

2.1. Applications of Energy Auditing

Energy audits find applications in almost every energy-intensive sector.

2.1.1. Buildings and Industry

In buildings, audits assess lighting, HVAC systems, and insulation. Studies report 20–30% savings after implementing audit recommendations [7]. In industries, audits focus on boilers, motors, and compressed-air system identifying inefficiencies that account for up to 40% of total energy waste [8]. Process-integration audits use thermodynamic pinch analysis to minimize heat losses and recover waste energy.

2.1.2. Power Generation and Utilities

In conventional and renewable power plants, audits evaluate the thermal efficiency of turbines, condensers, and heat exchangers [9]. By comparing actual performance against design values, energy managers can reduce auxiliary consumption and CO_2 emissions.

2.1.3. Transportation and Marine Applications

Transport audits, including for ships and trains, identify propulsion inefficiencies and opportunities for fuel saving [10,11]. In automotive systems, audits are used to measure energy distribution in IC engines and hybrid vehicles, providing essential feedback for emission regulations and design improvements.

Applications of energy auditing across multiple sectors, including buildings, industry, power generation, transportation, and diesel engines, are summarized in Table 1, which highlights the focus areas and typical improvements achieved through energy audits.

Table 1. Representative Applications of Energy Auditing [12].

S. No	Sector	Focus Area	Typical Improvement
1	Buildings	HVAC and Lighting	20–30% energy savings
2	Industrial plants	Boilers and motors	Reduced process losses
3	Power plants	Turbines and condensers	2–5% efficiency gain
4	Transportation	Propulsion systems	Lower fuel use and emissions
5	Diesel engines	Energy distribution	Performance benchmarking

2.2. Research Gaps

Despite progress in industrial and building audits, there remains a scarcity of standardized methods for diesel engines operating on biodiesel blends. Existing studies typically examine isolated parameters—performance, emissions, or exergy—without integrating them into a holistic audit. Data inconsistency is another challenge; researchers often employ different dynamometers, ambient conditions, and measurement protocols, making cross-comparison difficult [13].

Furthermore, most available audits are steady-state assessments, ignoring the transient conditions experienced by engines in real-world operation. Economic and environmental factors are seldom incorporated into energy-balance equations. Hence, there is a need for a unified methodology combining thermodynamic efficiency, emission indices, and life cycle impacts to evaluate biodiesel performance comprehensively.

3. Methodology

Performance indicators have been defined as below:

- Brake Specific Energy Consumption (BSEC): It is a product of calorific value and brake specific fuel consumption. Because it considers the fuels' calorific value in blends, Brake Specific Energy Consumption is a crucial measure for assessing performance characteristics [4].
- Brake Specific Fuel Consumption (BSFC): BSFC stands for fuel flow rate per unit brake power output. It shows how efficient the engine is. BSFC is used to gauge an engine's fuel efficiency [4].
- Brake Thermal Efficiency (BTE): The engine's work output to fuel energy ratio is known as brake thermal efficiency [4].
- Exhaust Gas Temperature (EGT): EGT gauges the engine's exhaust gas temperature, which provides information on the engine's capacity to convert heat energy and combustion efficiency [4].

Emission indicators have been defined as below:

- Carbon monoxide (CO): Carbon monoxide (CO) is a colorless, odorless, tasteless, and poisonous gas formed by the incomplete combustion of carbon-containing fuels such as coal, wood, petrol, diesel, natural gas, or LPG [4].
- Hydrocarbons (HC): Hydrocarbons are organic compounds composed only of carbon and hydrogen atoms. They are the basic constituents of fuels such as petrol, diesel, natural gas, and coal. They are classified into alkanes, alkenes, alkynes, and aromatic hydrocarbons [4].
- Oxides of nitrogen (NO_x): Oxides of nitrogen (NO_x) are gaseous compounds formed by the reaction of nitrogen and oxygen, mainly at high temperatures such as during fuel combustion in engines and power plants. Common oxides include nitric oxide (NO) and nitrogen dioxide (NO_2). They contribute to air pollution, smog, acid rain, and respiratory problems [4].
- Smoke opacity: Smoke opacity is a measure of how much light is blocked or obscured by smoke emitted from a source, such as an engine exhaust. It indicates the density or thickness of smoke. Higher smoke opacity means darker, denser smoke and higher particulate pollution [4].

- Particulate matter (PM): Particulate Matter (PM) refers to a mixture of extremely small solid particles and liquid droplets suspended in the air, which can penetrate the human respiratory system and cause adverse health and environmental effects [4].
- Heat-flow indicators*:*
- Percentage distribution of input energy into useful work: When losses are deducted from the input energy, we get the net useful work [4].
- Exhaust losses: Exhaust losses are the portion of energy from fuel combustion that is carried away by exhaust gases and not converted into useful work in an engine or thermal system [4].
- Cooling losses: Cooling losses are the portion of heat energy produced during combustion that is removed from the engine or system by the cooling medium (such as water or air) to prevent overheating, instead of being converted into useful work [4].
- Unaccounted losses: Unaccounted losses are the portion of energy input to an engine or thermal system that cannot be directly measured or individually identified in an energy balance analysis. Include losses due to radiation, convection, incomplete combustion, friction, sound, and vibration. Represent the difference between total input energy and the sum of measured useful output and known losses [4].

A comparative economic evaluation of petroleum diesel and biodiesel blends is presented in Table 2, summarizing production costs, operational considerations, and potential emission-related incentives.

Table 2. Cost analysis of Petroleum Diesel and Biodiesel Blends. [6]

Cost Category	Petroleum Diesel	Biodiesel	Citations
Production Cost	Lower Baseline: Driven by established crude oil refining processes.	Higher: Feedstock costs (e.g., vegetable oils, waste fats) typically account for 70–80% of total production costs.	[14,15]
Maintenance and Operational Cost	Baseline: Standardized for modern internal combustion engines	Variable: Potential for increased costs due to fuel filter clogging or material compatibility issues in older engines; modern systems (B20) show negligible differences.	[2,16]
Emission Credits and Subsidies	Minimal to Negative: Often subject to carbon taxes or environmental penalties	Significant Benefit: Producers often receive Renewable Identification Numbers (RINs) or Low Carbon Fuel Standard (LCFS) credits that offset high production costs.	[17,18]

The economic, environmental, and social benefits promised by biofuels are highly dependent on regional variability, particularly in a diverse landscape like India. In the Indian context, biofuels are an essential component of the global energy transition, but their feasibility is dictated by the localized availability of feedstocks, which vary significantly across states. According to [19], the production of biodiesel in India is decentralized, with Southern and Western states (such as Karnataka and Maharashtra) leading in Used Cooking Oil (UCO) and Pongamia collection, while Central India (Madhya Pradesh and Chhattisgarh) focuses on non-edible oils like Jatropha from wasteland cultivation.

A comparative economic analysis reveals that feedstock costs account for approximately 70-80% of the total production expenditure in India, matching the global trends discussed in our conversation history. In real-world market terms, while the price of conventional petroleum diesel in India fluctuates between ₹88 and ₹100 per liter depending on state taxes, the cost of biodiesel (B100) produced from UCO can range from ₹75 to ₹95 per liter, provided there is a robust collection mechanism [20]. in their techno-economic assessment, the cost of biodiesel from Jatropha remains higher (often exceeding ₹100/L) due to low seed yields and high labor costs for harvesting, making it less competitive without government subsidies or emission credits.

Furthermore, the resilience of the supply chain is critical; regional clusters that integrate localized collection and processing reduce transportation costs, which are a major barrier in India. Validating these feasibility claims, studies suggest that while biodiesel offers a renewable alternative to fossil fuels, its widespread adoption in India requires a “feedstock-ladder” approach—transitioning from expensive first-generation oils to waste-based and multi-feedstock biorefineries to stabilize market prices against the volatility of the petroleum sector.

4. Results and Discussion

4.1. Brake Thermal Efficiency (BTE)

The engine’s work output to fuel energy ratio is known as brake thermal efficiency. Fuel conversion efficiency is another name for it [21]. Improved work production from the energy of fuel is indicated by a higher

BTE. One performance metric that shows how much chemical energy of fuel is converted to the usable work output in diesel engines is known as BTE. In comparison to diesel, researchers tested engines using biodiesel from soyabean oil and looked at comparable engine performance with butyl, ethyl, and methyl esters. They didn't investigate how using different fuels affected thermal efficiency. When using biodiesel, there was a slight loss of power, which was explained by lower heating values [22].

Because cottonseed oil biodiesel has a higher viscosity and a lower calorific value, researchers found that torque decreased as the amount of biodiesel in the blends increased [23]. When biodiesel is added to fuel mixes, BTE falls. This is because biodiesel having a lower heating value leads to an increase in BSFC. The B10 (B10 stands for 90% diesel and 10% biodiesel by volume) to B20 (B20 stands for 80% diesel and 20% biodiesel by volume) fuel mix had a higher BTE value of 35% at CR (Compression Ratio) of 17.9, while the B30 (B30 stands for 70% diesel and 30% biodiesel by volume) to B40 (B40 stands for 60% diesel and 40% biodiesel by volume) fuel blend had a lower BTE value at CR of 17.7 [24]. For B0 (B0 stands for 100% diesel and 0% biodiesel by volume), a greater BTE value of 21.1% was discovered. For blends like B10, B20, B30, and B50 (B50 stands for 50% diesel and 50% biodiesel by volume), higher Brake Thermal Efficiency values of 20.51%, 20.4%, 20.4%, and 20.3% were discovered, respectively. reduced calorific values and higher blend fuel consumption relative to diesel may be the cause of reduced BTE for fuel blends [25].

The performance and emission characteristics of the mixed oil biodiesel blend have been assessed using the energy audit method. This study's goal is to apply an energy audit method for biodiesel engines, which shortens the time needed to research biodiesel engines by prioritizing key performance and emission metrics. If such parameters are confirmed to be satisfactory after investigation, more parameters will be examined. Additionally, there is no need for additional analysis if those parameters are determined to be inadequate, saving time and money. The best suited regression equation and coefficient of determination were found in this experimental investigation using the least squares method. By using this strategy, time and energy can be saved. Smoke, friction power, heat flow analysis, and brake-specific energy consumption have all been assessed. Every one of these parameters has been deemed satisfactory. The association between these attributes and biodiesel blends has been determined at 3.5 kW using the least squares approach. Additionally, the coefficient of determination and regression's best fit equation have been calculated. Of all the evaluated biodiesel blends, B10 mix oil biodiesel had the most efficient heat energy conversion. Diesel, however, has the best brake thermal efficiency [26].

4.2. Brake Specific Fuel Consumption (BSFC)

BSFC stands for fuel flow rate per unit brake power output. It shows how efficient the engine is. BSFC is used to gauge an engine's fuel efficiency. A lower BSFC value is necessary. When utilizing different test fuels, this is determined to be one of the crucial parameters to compare. The link between the fuel's density, viscosity, calorific value, and amount injected is proven to be crucial in determining BSFC. For all fuels, BSFC is observed to decrease as load increases. This could be because the proportion of fuel needed to run the engine increases, yet it is less than total brake power percentage. The decrease in heat losses in increasing loads is the source of this. A diesel engine with multi cylinders and turbocharging was tested at 1400 rpm under complete load. Due to biodiesel's decreased calorific value compared to diesel, its BSFC was 13.8% higher. BSFC also increases when significantly greater than those of diesel in biodiesel blends. Biodiesels have a 12% less calorific value when compared with diesel. The lower calorific value of the fuel may account for the rise in particular fuel consumption following the introduction of biodiesel. It is seen that biodiesel has a lower specific energy content than diesel. BSFC rises when the amount of biodiesel in the blends grows since biodiesels have a lower heating value than diesel [27–29].

The significance of various performance and emission characteristics has been examined and contrasted in this review study. The following topics have been covered: brake thermal efficiency, exhaust gas temperature, brake-specific fuel consumption, volumetric efficiency, mechanical efficiency, air–fuel ratio, unburned hydrocarbon emission, carbon monoxide emission, nitrogen oxide emission, brake-specific energy consumption, parameters of heat flow analysis, friction power, and smoke emission. There has been discussion of the significant findings for the investigation and review of the significance of energy audits in diesel engines powered by blends. Its goal is to obtain a standard energy audit approach that determines whether using a blend of biodiesel as fuel is feasible. It has been discovered that researching every trait at once is a waste of time. Initially, it was discovered that the most crucial factors for estimating and assessing the viability of biodiesel blends in diesel are brake-specific energy consumption, heat flow analysis parameters, smoke opacity, and friction power [26].

4.3. Brake Specific Energy Consumption (BSEC)

It is the product of calorific value and brake specific fuel consumption. Because it considers the fuels' calorific value in blends, Brake Specific Energy Consumption is a crucial measure for assessing performance characteristics. The energy input required to generate unit brake power can alternatively be referred to as BSEC. Consequently, BSEC has been chosen as an essential criterion for an energy audit of a diesel engine using a biodiesel blend. Additionally, it makes it easier to properly assess mix fuels based on their ability to power a diesel engine [30,31]. Due to a decrease in brake-specific fuel consumption at greater loads, a decrease in BSEC is seen as the load increases. As the proportion of biodiesel in blend fuel increases, so does the BSEC. Because BSEC is a product of calorific value and brake-specific fuel consumption, it may be directly dependent on BSFC [21]. Researchers investigated how using blends of biodiesel increased BSEC. Using JB 100 at 1200 rpm was found to boost BSEC by 20.21% compared with diesel. When compared with diesel at 2200 rpm, BSEC enhances by 2.68%, 5.84%, and 13.31% for KB (Karanja Biodiesel) 20, KB 50, and KB 100, respectively. Similarly, BSEC increased by 2.86%, 6%, 12.37%, 173 2.59%, 5.84%, and 13.31% for JB (Jatropha Biodiesel) 20, JB 172 50, JB 100, PB20, PB 50, and PB (Polonga Biodiesel) 100 at the rated speed compared to diesel. Compared to all test fuels, PB20 fuel had the lowest BSEC increment (2.59%) at rated speed, making it the optimum BSEC. Because biodiesel blends have a lower calorific value than diesel, higher concentrations of biodiesel in blend fuels raise BSEC [22]. BSEC may demonstrate the engine's efficiency in utilizing the fuel's energy during combustion. BSEC reduction requires that fuel's chemical energy be properly converted into useful work output. BSEC reduction implies proper conversion of chemical energy of fuel into productive work output. A rise in BSEC may be interpreted as a depletion in combustion quality [32]. Specific energy consumption is the amount of energy required to produce one unit of electricity. This metric can be used to compare fuels with varying calorific levels. BSEC is directly linked to the fuel's calorific value and the quantity of fuel supplied to the combustion chamber. Researchers looked on how BSEC decreased as load increased from 0% to 100%. It was discovered that the engine's BSEC increased at lower loads and reduced at greater loads [33,34].

4.4. Exhaust Gas Temperature (EGT)

EGT gauges the engine's exhaust gas temperature, which provides information on the engine's capacity to convert heat energy and combustion efficiency. It was found that the temperature of burning was determined by the amount of energy emitted. The distance between the combustion chamber and the EGT, which gauges combustion temperature, was found to be 30 mm. It was discovered that the EGT of B20 and diesel fuel were almost identical. Diesel was found to have the lowest EGT when compared to blends of biodiesel at low speeds. This is because biodiesel burns properly due to its oxygenated composition [25]. Additionally, the researchers looked into how different biodiesel blends had no effect on EGT. EGT generally rises with load. The researchers also investigated how various biodiesel mixes had no impact on EGT. Researchers investigated the possibility that an increase in blends' biodiesel concentration would result in an increase in EGT. The EGT of B20, B40, B60, B80, and B100 was found to be 2.3%, 6.3%, 8.7%, 11.3%, and 14% greater than diesel fuel.

Furthermore, it has been noted that a 20% increase in blend fuels' biodiesel percentage results in a 50^0C increase in EGT. This is because fuel blends lose more heat. At 0%, 25%, 50%, 75%, and 100% load, the EGT of diesel was found to be 131°C, 160°C, 186°C, 212°C, and 240°C, while the EGT of B100 biodiesel was found to be 152°C, 182°C, 211°C, 243°C, and 272°C. Other researchers also obtained similar results [35]. Exhaust energy decreases as engine efficiency rises. Additionally, it was shown that one of the causes of the decline in EGT was a drop in the adiabatic flame temperature [36].

A comparative summary of performance indicators for diesel and biodiesel blends, including BTE, BSFC, BSEC, and EGT, is presented in Table 3, highlighting the general trends observed in biodiesel-fueled engines.

Table 3. Comparative Performance Indicators for Diesel and Biodiesel Blends [37].

Parameters	Diesel (Baseline)	B20 Blend	B50 Blend	Trend/Observations
Brake Thermal Efficiency (BTE)	33–35%	32–34%	31–33%	Slight decrease (≤4%)
Brake Specific Fuel Consumption (BSFC, kg/kWh)	0.26–0.28	0.27–0.29	0.29–0.31	Increases with blend ratio
Brake Specific Energy Consumption (BSEC, MJ/kWh)	9.2–9.5	9.5–9.8	9.9–10.2	Moderate rise
Exhaust Gas Temperature (EGT, °C)	340–360	355–380	370–395	Higher for biodiesel blends
NO_x	Baseline	1–3% increase [38]	5–8% increase [39]	Increase in NO_x emissions

4.5. Emission Characteristics

The cleaner emission profile of biodiesel is one of the most significant conclusions drawn from energy-audit-based assessments.

4.5.1. Carbon Monoxide Emission

Emissions of carbon monoxide are undesirable and indicate a loss of chemical energy that the engine is not using to its full potential [40]. Compared to gasoline engines, diesel engines have very low CO emissions since they run on an overall lean mixture. CO emissions may be a representation of the chemical energy that is wasted when an engine's power output is not fully used. Biodiesel blends were shown to significantly reduce CO emissions at all engine speeds. This is because biodiesel contains more oxygen than diesel, which promotes proper combustion and lowers CO emissions. Fuel-based oxygen has been shown to speed up the combustion process [41]. Researchers investigated how increasing brake power at all loads reduced CO. Because biodiesel contains more oxygen than diesel, CO emissions from biodiesel blends are said to be lower [42]. When compared to diesel fuel, biodiesel blends have been shown to lower CO emissions. This is because biodiesel contains oxygen. This is because biodiesel has a lower C/H ratio than diesel. Additionally, it is discovered that the amount of biodiesel in blends has no bearing on the reduction in CO [43].

Linseed crops can be grown in India due to the country's weather and soil. The linseed plant and its oil, the manufacturing of linseed biodiesel, its physiochemical properties, the benefits and disadvantages of biodiesel, a comparison between diesel and biodiesel, energy audits, biofuel certification, and the authors' conclusions are all covered in this paper. Standard energy audits and biofuel performance certification are future challenges. After the transesterification process, the viscosity of linseed oil biodiesel considerably decreased.

Compared to diesel, there is a decrease in smoke, carbon monoxide, and unburned hydrocarbon emissions. To enhance fuel quality, metal-based, oxygenated, cetane number-increasing, and antioxidant additives are used with biodiesel [44].

4.5.2. Nitrogen Oxide Emission

Nitrogen oxides have been found in engine exhaust gases. Nitric oxide (NO) makes up most of them, with minor levels of nitrogen dioxide (NO_2) and other nitrogen oxides. Additionally, photochemical haze, which is undesirable, is caused by NO_x emissions [40]. Atomic oxygen and nitrogen react chemically to form NO_x during the process of combustion in combustion chamber. NO_x emissions are lowest under lower loads because the temperature during the reaction influences the chemical reactions that result in NO_x. At all engine speeds, it was shown that employing biodiesel mixes increased NO_x emissions.

The following factors led to higher NO_x emissions when using biodiesel blends [25]:

1. Complete combustion of biodiesel at higher adiabatic flame temperatures raises temperature and emits NO_x. Biodiesel has more double-bonded molecules than diesel. Biodiesel releases more NO_x due to the higher adiabatic flame temperatures of these double-bonded molecules.
2. In the combustion chamber, nitrogen oxidation produces NO_x. It was discovered that the temperature of the flame (combustion), the length of time nitrogen remained at that temperature, and the concentration of oxygen in the combustion chamber all affects the rate of NO_x generation. Oxygen (O_2) and Nitrogen (N_2) split into separate atomic states at high flame temperatures in the combustion chamber, which is discovered to be involved in several processes. For every test blend fuel, NO_x was found to increase with load. This is because when engine load increases, more fuel is injected and burned in the cylinder, raising the gas temperature and producing more NO_x [43].

4.5.3. Smoke Emission

Engine efficiency losses were discovered to be caused by soot radiation. It was discovered that the soot was a significant source of radiation and that it glowed as it burned [45]. Smoke opacity rises with load because of increased fuel consumption. Because biodiesel contains more oxygen than diesel, its smoke opacity decreases. Biodiesel contains fewer aromatic compounds and a lower carbon to hydrogen ratio than diesel. Smoke opacity is reduced when there are less carbon and more oxygen in the air, which reduces smoke generation. Conversely, a high sulphur concentration causes diesel's smoke opacity to rise. The concentration of soot rose as the load increased. The concentration of soot was found to be lower when diesel fuel was substituted with biodiesel blend fuels. This is because biodiesel burns fuel properly because it contains oxygen, sulphur, and no aromatic chemicals [43]. When compared to diesel, it was shown that using biodiesel decreased smoke opacity by roughly 22.5% [46].

Numerous researchers reported similar trends. It has been discovered that the diesel engine's high temperature burnt gases and soot particles are radiation sources [47]. As a result, smoke is found to be more detrimental and to contribute to increased radiation-induced heat loss. This feature needs to be chosen as a critical parameter in the Energy Audit, unlike other emission parameters. Thus, radiation-induced heat loss increases as smoke emissions rise. Thus, there is a direct correlation between heat loss and smoke emissions.

Using an energy audit, performance and emission characteristics are assessed using a new technique. This technique assesses the viability of using blends of biodiesel in diesel engines. This is a quick and easy way to save time and effort. Utilization in brake power, cooling water heat loss, exhaust gas heat loss, and radiation heat loss are all included in this method's estimated and compared heat flow analysis. Smoke, friction power losses, and brake-specific energy consumption have all been selected as crucial performance and emission parameters in energy audits. These energy audit parameters have been computed and contrasted. These energy audit parameters were discovered using blends of 10, 20, and 30% biodiesel at different brake powers of 0.5–3.5 kW at 1500 rpm. It has been determined that these parameters are satisfactory. At brake power of 3.5 kW with less smoke, the higher limit of fuel's heat energy conversion into practical work output is found to be 29.04 for B20, 29% for diesel, 28.3% for B10, and 27.92% for B30. The preliminary energy audit method has determined that the Karanja B-20 blend test fuel is more appropriate, and it will be further examined for other aspects [48].

4.5.4. Particulate Matter Emission

It has been shown that biodiesel blends B10, B20, B50, and B100 reduce PM emissions by 28.6%, 50%, 62%, and 74%, respectively. This is because, in comparison to diesel, biodiesel has a lower carbon content, less or no sulphur and aromatic content, and a higher oxygen concentration, all of which minimize PM emissions [49]. 87.7% of research discovered that biodiesel lowers PM emissions as compared to diesel. Additionally, researchers discovered a significant decrease in smoke, ranging from 50% to 72.73%, while using eight different types of biodiesel fuels in place of diesel. As the content of biodiesel in the mix increased, PM emissions significantly decreased [50].

These results demonstrate that biodiesel blends significantly reduce incomplete-combustion pollutants while maintaining acceptable efficiency.

The overall emission trends associated with biodiesel blends are summarized in Table 4, which highlights reductions in CO, HC, smoke, and particulate matter along with slight increases in NO_x emissions.

Table 4. Comparative Performance Indicators for Diesel and Biodiesel Blends [39].

Emission Type	Direction of Change	Primary Reason
CO	↓ Decreases (30–50%)	Oxygenated fuel → complete combustion
HC	↓ Decreases (40–60%)	Better atomization and oxidation
NO_x	↑ Increases (5–10%)	Higher combustion temperature
Smoke	↓ Decreases (40–70%)	Lower aromatic content
PM	↓ Decreases (40–60%)	Absence of sulphur and aromatics

4.6. Heat Flow Analysis and Energy Distribution

A summary of Heat Flow analysis and Energy Distribution for a biodiesel performance energy audit is essential for validating that these fuels remain an essential component of the global energy transition. Because biofuels offer a renewable alternative to fossil fuels, auditing their production processes ensures they deliver the intended economic, environmental, and social benefits.

Heat Flow Analysis In the context of a performance energy audit, Heat Flow analysis focuses on quantifying the thermal energy consumed and lost during the biodiesel production stages, such as feedstock pretreatment and transesterification. According to [51], the largest thermal requirements often occur during the heating of raw oils and the recovery of methanol through distillation. Auditors utilize Sankey diagrams to visualize these flows, identifying specific areas where energy is lost to the environment. This analysis is critical for implementing Heat Integration strategies, which maximize thermal recovery and minimize the carbon footprint. By refining these heat flows, producers ensure that the environmental benefits of the fuel—specifically the reduction of greenhouse gas emissions—are not compromised by high processing energy demands.

Energy Distribution Energy Distribution analysis evaluates the efficiency of the entire system by comparing total energy inputs to the energy contained in the final products. A key metric used by [15] is the Net Energy Ratio (NER). A favorable energy distribution indicates that the energy output of the biodiesel and its by-products (like glycerol) significantly exceed the fossil fuel energy used for cultivation, transport, and refining. Ref. [52]

highlighted that advanced biofuels from microalgae require specialized distribution analysis due to their high lipid content and the potential for energy-negative residues.

Optimizing these distributions is vital for achieving the economic benefits of biofuels, such as rural development and energy security, by making domestic production more cost-competitive than imported petroleum. Furthermore, a positive energy balance supports the social benefits of the industry by proving the sustainability of the fuel to the public and policy makers.

The distribution of heat energy between brake power, exhaust losses, coolant losses, and radiation losses for diesel and biodiesel blends is summarized in Table 5.

Table 5. Comparative Heat-Energy Distribution [53].

Energy Component	Diesel (%)	B20 Blend (%)	Observation
Brake Power	33	32	Slight drop in efficiency
Exhaust Loss	33	29	Improved combustion, lowers exhaust loss
Coolant Loss	27	30	Higher in-cylinder temperature
Radiation/Unaccounted	7	9	Minor change

The typical energy distribution in biodiesel-fuelled diesel engines is illustrated in Figure 1, which shows the proportion of input energy converted into brake power and losses through exhaust, cooling, and radiation.

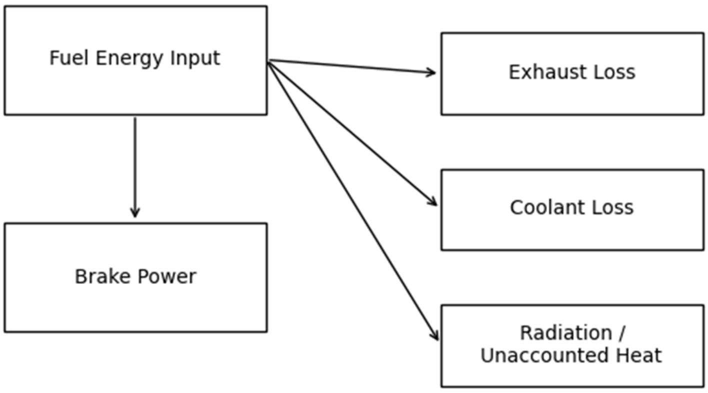

Figure 1. Typical Energy Flow in Diesel Engines Powered by Blends of Biodiesel.

4.7. Lubricity and Frictional Power

Methyl esters of long-chain fatty acids are present in biodiesel which enhances lubricity, reducing friction between moving parts. Frictional losses, typically representing 10–15% of total mechanical losses in diesel engines, decline by 2–4% when biodiesel is introduced [54]. This improvement reduces component wear and prolongs engine life.[55]

Endurance tests [56] show less liner and ring wear with biodiesel blends, and deposit formation remains within permissible limits. Hence, biodiesel not only serves as a renewable energy source but also contributes to mechanical reliability**.**

4.8. Exergy and Economic Considerations

While this review centers on energy auditing, exergy analysis provides deeper insight into fuel quality and irreversibility. Biodiesel exhibit slightly lower exergy efficiency due to its molecular oxygen content but compensates through lower entropy generation during combustion. From an economic standpoint, biodiesel production costs remain 10–15% higher than diesel, yet long-term savings emerge through emission credits and reduced maintenance [57]. Integrating energy audits with cost–benefit analysis strengthens decision-making for policymakers and industries.

The evolution of biodiesel in India is described in the article examines the benefits and drawbacks of biodiesel, a comparison between diesel and biodiesel, economic analysis, and a comparison of the conclusions and outcomes of different authors. Future challenges and opportunities for biodiesel are identified as standard energy audit methodologies and biofuel performance certification systems [58].

5. Proposed Energy Audit Framework

To ensure consistent and comparable results across different studies, a standardized audit of energy framework of diesel engines blended with biodiesel blends is proposed. This framework integrates thermodynamic, environmental, and economic analyses, forming a comprehensive approach that can be replicated in academic and industrial research.

To promote uniformity, each audit should report:

- Engine specifications (bore, stroke, compression ratio)
- Fuel characteristics (density, viscosity, flash point, and calorific value)
- Test conditions (speed, load, ambient temperature)
- Energy balance in tabular and graphical form
- Emission data and corresponding energy efficiency indicators

6. Conclusions

This paper reviewed and synthesized global research on energy auditing in diesel engines operated with biodiesel blends. The findings demonstrate that biodiesel provides a viable renewable substitute for conventional diesel with minor efficiency penalties and significant environmental benefits.

Key conclusions are as follows:

- Biodiesel blends up to 20% (B20) maintain near-identical engine performance compared to pure diesel, with only 2–4% reduction in BTE.
- Emission reductions are substantial: CO and HC decrease by up to 50%, smoke by nearly 70%, and PM by 40–60%.
- A marginal NO_x increase (5–10%) occurs, but this can be mitigated with injection timing adjustments and EGR systems.
- Energy distribution patterns confirm biodiesel's efficient conversion of chemical energy into mechanical work with slightly lower exhaust losses.
- Implementing a standardized audit framework ensures reproducibility, comparability, and accuracy in evaluating biofuels.

The study underlines that energy auditing is not just a diagnostic tool but a strategic decision-making instrument for industries and policymakers aiming for cleaner transportation and energy security.

7. Future Scope

Future research directions include:

(1) Real-Time Energy Auditing:

Integration of IoT-based sensors and cloud platforms can enable live monitoring of fuel flow, exhaust temperature, and engine load, providing instant feedback for efficiency improvement.

(2) AI-Assisted Optimization:

Machine learning models could analyze large data sets from audits to predict performance, recommend optimal blends, and reduce emissions dynamically.

(3) Lifecycle and Exergy Integration:

Future audits should include lifecycle assessment (LCA) to quantify the total environmental footprint from biodiesel production to combustion. Exergy analysis can further pinpoint irreversibility and potential improvements.

(4) Expansion to Hybrid and Electric Systems:

Extending audit methodologies to cover hybrid engines and electric vehicles will make the framework more inclusive and relevant for next-generation mobility.

(5) Global Standardization:

International bodies such as ISO and ASME should collaborate to publish guidelines on biodiesel engine energy audits, ensuring consistency across nations and industries.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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