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RESEARCH ARTICLE

Thermo-environmental and economic evaluation of waste oil biodiesel as a green energy vector

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Abstract

This study aids understanding of various aspects of energy conversion, including losses due to irreversibilities in the system, ecological footprint, long-term feasibility, and financial factors, and provides a holistic framework for assessing kitchen waste biodiesel (KWBD) as an alternative to petro-diesel fuels. For this purpose, experiments were conducted on a constant-speed diesel engine under varying loads, and energy analysis revealed that, at 75% load, KWBD achieved a brake thermal efficiency of 32.22%, similar to that of diesel fuel. observed fuel consumption is higher for KWBD than for diesel fuel, due to KWBD's higher viscosity and density. The exergy results identified the different losses KWBD at 75% and 100% load and their associated improvements. Similarly, the environmental and sustainability metrics indicate total CO_2-equivalent emissions of 4.665 tons/year, a social carbon cost of $821/year, and a sustainability index of 2.16, thereby highlighting better resource utilization and a lower environmental impact. In addition, economic analysis reveals promising indicators: a specific capital cost of $372/kW, a present worth factor of 8.974, a net cash flow of $542/year, a net present value of $4112, an internal rate of return of 65.6% per year, and a payback period of 1.667 years. These results highlight KWBD's viability as a sustainable alternative fuel, offering both environmental and economic benefits. When key energy, exergy, environmental, sustainability, and economic parameters are integrated and their impact on neat waste oil biodiesel is assessed, the engine data stand alone as significant contributors to the development of clean-burning fuels.

Keywords: Biodiesel, kitchen wastes oils, sustainability index, exergy, economy

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1. Introduction

Global energy demands are increasing continuously, especially when hydrocarbon fuels are used for various heat-energy applications. Additionally, the availability of hydrocarbon fuels is declining due to geographical, political, and economic factors. Therefore, various approaches have been proposed to meet the increasing energy demands associated with global population growth. Some of them are searching for renewable and alternative energy sources, as well as for approaches to reuse and recycle materials to improve economic efficiency. Reusing an item, either for its original purpose orfor a different use is a feasible technique for achieving low-cost applications. For instance, kitchen waste, especially cooking oils, is one of the best sources to utilize as a renewable and sustainable fuel to mitigate the challenges of pollution caused by burning hydrocarbon fuels [1].

Statistics on kitchen waste and the global availability of cooking oils indicate that the market is estimated to be approximately 7.54 billion ($) in 2024 and is projected to grow to 13.96 billion ($) by 2032, at a compound annual growth rate of 8% from 2024 to 2032. Developed nations, such as the United States, are among the largest producers of used cooking oils. Similarly, populous nations such as China and India generate large quantities of used cooking oil. From this, it is evident that kitchen waste cooking oils are abundant and can be utilized for different value-added products that promote sustainable energy and safeguard the environment [2,3]. Some of the applications where the kitchen waste is successfully converted into sustainable products, such as bio-lubricants [4], bio-plasticizers

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[5], bio-asphalt [6], bio-surfactants [7], 3D-printing resins [8], and bio-diesels [9]. One promising product derived from kitchen waste oils is biodiesel, which is our topic of interest; it is very popular and is considered an alternative to traditional petro-diesel fuels.

The combustion of petro-diesel releases high heat energy and toxic exhaust emissions, which are considered one of the global challenges to mitigate [10]. Due to the varying percentages of carbon, hydrogen, sulfur, and salts of vanadium and sodium in hydrocarbon fuels, they release toxic gases such as CO, CO_2, NOx, SOx, HC, PM, and black smoke during the combustion process [11]. These toxic gases pollute the environment and are also a contributing factor to the increase in the Earth's surface temperatures [12]. Therefore, alternative fuels are urgently needed, and the development of such clean-burning fuels will remain a topic of interest.

Biodiesel from kitchen waste oils is the most promising, economically feasible option [13]. The unique features of this biodiesel are that it is environment-friendly, exhibits improved physicochemical properties such as a high cetane number and flash and fire points, improves engine performance, and regulates exhaust emissions to a greater extent [13]. On the other hand, biodiesel has some limitations, such as lower shelf life, reduced heating values, and higher viscosity and density, which can negatively affect combustion performance [14]. Literature studies on kitchen waste oils or waste cooking oil as potential feedstocks for biodiesel production reveal that the high cetane index for these oils lowers the delay period and helps achieve better combustion [15]. The overall production costs of biodiesel have been significantly reduced by using kitchen waste oils as feedstocks. Waste cooking oils are promising sources for biodiesel, but their collection methods, filtration, and purification techniques need improvement [16,17].

Biodiesel, in its pure form (B100) or when blended with other fuels, also yields promising results in reducing toxic exhaust gases. The brake thermal efficiency of the engine is also improved when biodiesel is used compared with petro-diesel fuels. Similarly, the engine cylinder vibrations recorded at maximum speed with biodiesel operations are lower than those of petro-diesel fuels, which can be considered a clear indication of improved reliability with biodiesel application [18,19].

These discussions indicate that considerable potential for kitchen waste as a source of various sustainable products, and that biodiesel derived from kitchen waste oil is a promising fuel for achieving clean combustion. This study aims to examine the benefits of converting kitchen waste oils into biodiesel and analyze significant parameters related to exergy, energy, environmental sustainability, and economic aspects. Analyzing these significant parameters will help understand energy utilization, energy conversion, and the ecological footprint of biodiesel through assessments using environmental and sustainability indices. The economic evaluation aimed to determine whether the recommended biodiesel could be a financially viable and competitive solution in the current market, thereby achieving the Sustainable Development Goals of clean energy and a net-zero emissions policy. All these parameters are discussed in this study, and an integrated energy, exergy, and economic assessment of neat waste-oil biodiesel based on engine data makes a significant contribution to the development of clean-burning fuels.

2. Materials and methods

The present study focuses on environment and economic analysis, and for the calculations of these significant parameters, the data was obtained from our previous findings [20], which comprises of combustion pressures, fuel consumptions, brake thermal efficiencies, exergy and emissions. The procedure involves collecting kitchen waste oil (KWO) from various food courts and restaurants to produce biodiesel from kitchen waste (KWBD). Conversion of KWO to KWBD was achieved using a widely used transesterification process. The chemical process begins with the cleaning and filtration of KWO. Initially, the raw KWO was washed with deionized water, filtered, and preheated to 110 °C to remove suspended impurities. The filtered KWO was examined for its acid value, and then the transesterification chemical process was initiated using sodium hydroxide (NaOH) as the catalyst and methanol (CH_3OH) as the reactant. The reaction was maintained at a temperature range of 45 °C to 60 °C and lasted for 240 minutes, as previously reported in the literature [15]. The final kitchen waste biodiesel (KWBD) is examined for its key fuel properties in accordance with the recommended international standards(ASTM D6751), compared with the literature [21], and the results are presented in Table 1.

Table 1. Properties of KWBD [20] compared to DFO [21]

S.No	Properties	Units	KWBD	DFO
1	Density at 25°C	Kg/m^3	882	827
2	Viscosity at 40°C	cSt	4.29	3.60
3	Calorific Value	kJ/Kg	38000	42000
4	Cetane Number	-	52	49
5	Flash and Fire Points	°C	168 & 178	58 & 66

To examine energy, exergy, and environmental aspects, KWBD is used as an alternative fuel in a four-stroke single-cylinder engine with a 24:1 compression ratio. The engine runs at a fixed rpm of 1500, and significant parameters, such as combustion pressures, fuel consumption, efficiency, and exhaust emissions, are measured at loads of 25% (0.77kW), 50%(1.54kW),75%(2.31kW), and 100% (2.92kW). The thermodynamic model of the experimental setup, including the necessary components, is illustrated in Figure 1. The mathematical relations used for calculating exergy parameters and their limitations are presented in Eqs.(1-5),are obtained from our previous findings [20]. The experimental engine specifications, along with their uncertainties, are presented in Table 2.

Table 2. Test engine specifications and uncertainties

S.No	Components	Specification/ Uncertainty (%)
1	No of Cylinders	Single
2	Bore and Stroke	86 and 77mm
3	No of Strokes	4
4	Compression Ratio	24.1:1
5	Injection Pressure	150 Bar
6	Loading Device	Eddy current Dynamometer
7	Exhaust Measurement	AVL Emission meters
8	Crank Angle least count	1Degree
9	Engine Speed (Rated)	1500rpm
10	Engine Torque	±1.5
11	Brake-Specific Fuel Consumption	±2.10
12	Combustion Pressures	±0.12
13	Temperatures	±0.1
14	Exhaust Emissions	±0.2

The experiments began with diesel fuel, and the engine was maintained at a constant speed (1500 rpm). At a fixed speed, the engine load is varied using an eddy current dynamometer, and, at varying loads, the key parameters of fuel consumption, combustion pressures, and exhaust emissions are measured for the diesel fuel. After the engine performance was examined using diesel fuel, the fuel line was changed to the KWBD and the engine was run for 15 minutes to attain thermal equilibrium. Using the diesel fuel readings as a reference, the experiments with KWBD were repeated three times, and the average results were used for comparison and discussion.

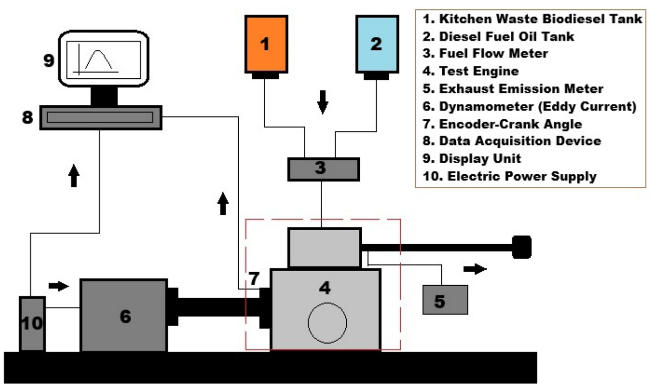

Figure 1. Experimental test rig and thermodynamic model

$$Ex_f = Ex_{bp} + Ex_w + Ex_g + Ex_{des} \quad (1)$$

$$Ex_{bp} = \text{brakepower} \quad (2)$$

$$Ex_w = \dot{m}_w c_{pw}\left[(T_{wo} - T_0) - T_0 \ln\left(\frac{T_{wo}}{T_0}\right)\right] \quad (3)$$

$$Ex_g = \dot{m}_g c_{pg}\left[(T_{go} - T_0) - T_0\left(\ln\left(\frac{T_{go}}{T_0}\right) - \frac{R}{c_{pg}}\ln\left(\frac{P_g}{P_0}\right)\right)\right] \quad (4)$$

$$Ex_f = \left[1.0401 + 0.1728\left(\frac{h}{c}\right) + 0.0432\left(\frac{o}{h}\right) + 0.2169\frac{s}{o}\left(1 - 2.0628\frac{h}{c}\right)\right] \times \dot{m}_f \times LHV \quad (5)$$

3. Results and discussion

3.1. Energy analysis

The analysis of energy parameters in combustion science is crucial, particularly in terms of engine cylinder pressures and variations in fuel consumption with respect to engine load and brake thermal efficiency and this significant data is obtained from the previous findings [20]. These parameters will provide a clear understanding of the energy released during combustion and help establish its potential for practical application. Therefore, these parameters are examined for kitchen waste biodiesel (KWBD), and the reported results, compared with diesel fuel oil (DFO), are presented in Figures. 2-3.

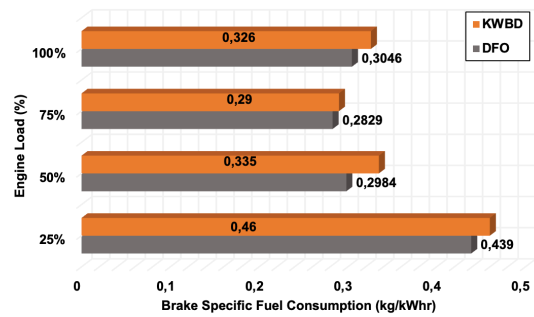

Figure 2. (a) Brake-specific fuel consumption at varying loads

Figure 2. (a) shows that fuel consumption (Kg/kWh for KWBD is higher at the measured loads than for DFO, which is unsurprising given the fuel oil properties of KWBD. Low energy content, higher density and viscosity in KWBD are some of the reasons for high fuel consumption [18]. Due to lower energy content (calorific value), more fuel is required to produce the same power output, and high viscosity affects the fuel atomization and air-fuel mixing; as a result, chances of incomplete combustion increase, and to compensate for it, a large fuel quantity is required [19]. In addition, the molecular oxygen content of biodiesel (~10-12%) enhances the combustion efficiency and increases the stoichiometric air-fuel ratio. As a result, a higher fuel flow rate is needed to maintain the required energy output [15]. Similarly, the higher bulk modulus of biodiesel leads to an early injection timing, and a high diffusion combustion phase also results in increased fuel consumption [22].

The brake thermal efficiency for KWBD and DFO at varying loads, as shown in Figure 2 (b), indicates that KWBD exhibited higher efficiency at lower and half loads (25% & 50%), which may be due to improved combustion from the oxygen content in KWBD; at part loads, biodiesel combustion is more controlled, enhancing energy conversion efficiency. Additionally, at lower loads, heat loss to the cylinder walls is relatively low, allowing higher useful work output from the fuel. At moderate (75%) loads, DFO and KWBD become comparable because the balancing effects of low heating value and oxygen content, together with improved combustion that compensates for the high fuel consumption, result in equal efficiency. Finally, poor atomization, higher fuel consumption, and heat losses lower the efficiency (6.45%) of KWBD compared to DFO at maximum load [23].

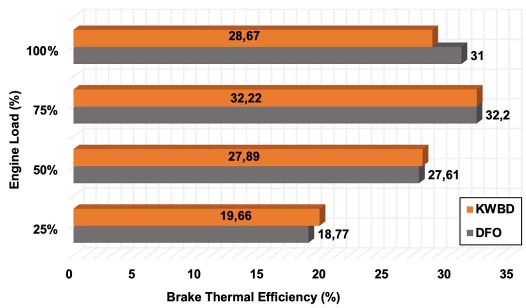

Figure 2. (b) Brake thermal efficiency at varying loads

Measurement of in-cylinder combustion pressures is vital for performance evaluation, as cylinder pressures directly indicate the engine's ability to convert chemical energy in the fuel into mechanical power. Cylinder peak pressures generally lead to higher indicated power and brake thermal efficiency [24]. The combustion pressure profiles can also indicate the smoothness of combustion; pressure spikes may indicate abnormal combustion, potentially leading to engine knock. On the other hand, a smooth and consistent rise in combustion pressure may ensure knock-free operation [25].

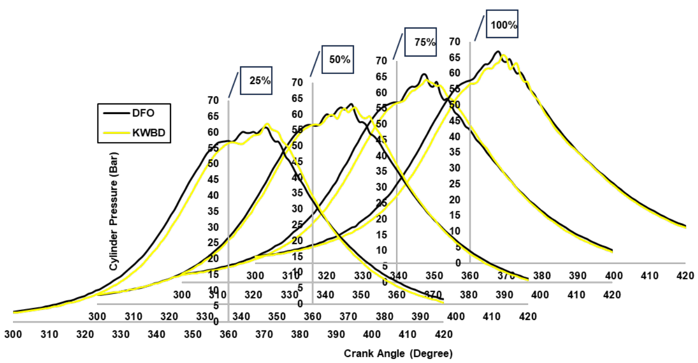

Figure 3. Combustion pressures at different engine loads

To examine these significant characteristics, plots of combustion pressure versus crank angle are the most appropriate choice; Figure 3 shows the combustion pressure profiles for KWBD and DFO at various loads (25% to 100%). At lower loads (25%), biodiesel outperforms diesel fuel by achieving higher combustion pressures, which may be due to faster ignition, improved combustion, and increased oxygen concentration, thereby further increasing peak pressures. At mid-load (50%), KWBD and DF exhibit similar combustion patterns because of a balanced combustion phase. The peak cylinder pressure occurs slightly after TDC, where the oxygen content advantage and diesel's higher energy content balance each other. Finally, at the higher loads (75% & 100%), the pressure patterns still look similar; however, KWBD shows a slight delay in pressure rise due to higher fuel injection rate, slower combustion, increased heat losses and longer combustion duration [26], and DFO dominates with higher heating value and faster burning resulting in peak cylinder pressure.

3.2. Exergy analysis

Unlike energy analysis(which is conserved),exergy analysis is also one of the most powerful tools that represents the maximum useful work that can be extracted from a given system as it approaches thermodynamic equilibrium with its surroundings and this exergy data was obtained from the previous findings [20]. Because Exergy is destroyed by irreversibilities, such as combustion and heat transfer losses, it is a powerful tool for examining engine efficiency and identifying loss sources. In this study, an exergy analysis is conducted to assess the efficiency of the conversion of KWBD energy into useful work and to identify the major losses. Figure 4. (a, b) represents the exergetic efficiency (II-Law) and exergy destruction, which shows that the fuel's available energy is converted into useful work, accounting for irreversibilities such as heat losses and incomplete combustion [27]. The exergy efficiency increased with engine load, reaching 38.62%, 46.53%, 53%, and 50% at loads of 25%, 50%, 75%, and 100%, respectively. A higher cetane number and the use of molecular oxygen can help mitigate lower losses and achieve better efficiency [21].

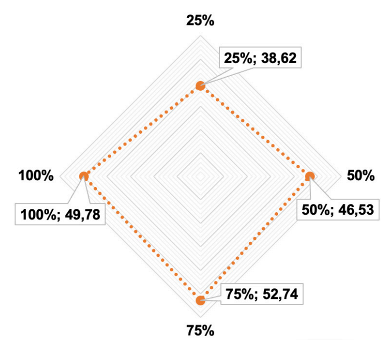

Figure 4. (a) Exergy efficiency for KWBD at varying loads

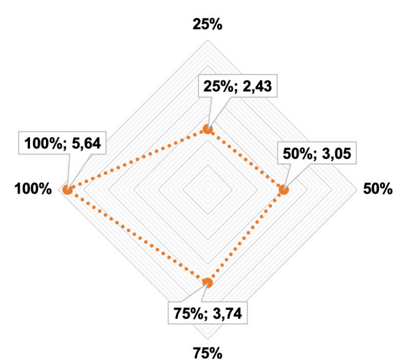

Figure 4. (b) Exergy Destruction for KWBD at varying loads

Similarly, exergy destruction, which represents the irreversibility of combustion, is also examined; Figure 4(b) illustrates these results for KWBD at varying loads. It is evident that exergy destruction increased with engine load, reaching 5.64 at 100% load for KWBD. This may be attributed to the poor spray breakup and slower flame speed, causing incomplete burning and heat loss spikes [28]. The fuel properties, such as high viscosity and low heating value, exacerbate combustion losses, resulting in maximum exergy destruction [27].

Evaluatingthe energy distribution from internal combustion engines operating on alternative fuels, such as useful work output, cooling losses, exhaust losses, and unaccounted losses, is crucial for examining performance, efficiency and sustainability. Therefore, the distribution of heat energy into various losses is also analyzed for KWBD, which may help accurately identify losses and potential measures for further improvement. Figure 5(a, b) depicts the various heat energy losses and useful work output computed at 75% and 100% load for KWBD. Higher loads typically convert more energy into useful brake power, whereas lower loads may exhibit increased thermal and other unaccounted-for losses. It is observed that 29.21% and 31.09% of the useful brake power are recorded for KWBD at 100% and 75% loads, respectively. Meanwhile unaccounted, cooling, and exhaust losses increase with engine load.

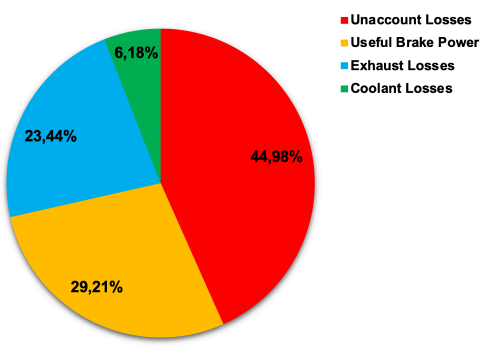

Figure 5. (a) Distribution of heat energy losses at 100% load

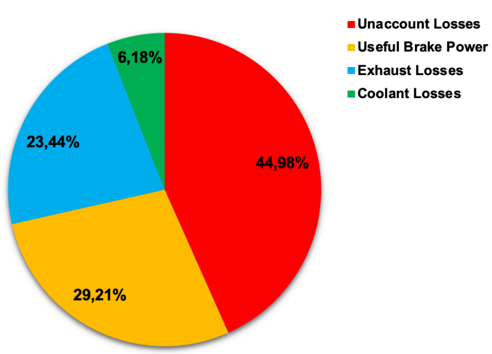

Figure 5. (b) Distribution of heat energy losses at 75% load

Unaccounted losses are energy losses that cannot be directly attributed to measurable outputs, such as cooling and exhaust. Therefore, the chances of improvement are limited due to radiation heat loss, mechanical friction and incomplete combustion process [29]. Exhaust losses can be mitigated through low-temperature combustion, exhaust gas recirculation, and turbocharging. By implementing these techniques, the energy carried away by the exhaust can be controlled and successfully reused [23,24]. The cooling losses are also unavoidable, as the heat energy absorbed by the engine coolant is essential for preventing overheating. However, precision thermal management systems, variable cooling systems, and protective coatings (ceramic) help lower cooling losses further [29].

3.3. Environment and sustainability analysis

In this study, KWBD stands out as a promising alternative fuel, offering the dual benefits of waste valorization and reduced greenhouse gas emissions. However, a comprehensive analysis must account for not only direct emissions but also the broader economic and environmental trade-offs that result from these emissions. Environmental and sustainability assessments of alternative fuels are crucial for evaluating their long-term viability and ecological impact. Therefore, the key metrics such as CO_2 equivalent emissions (Eq.6), social cost of carbon (SCC) and the enviroeconomic factor (EEF) are computed (Eq.7). The impact of gases on global warming is measured using their Global Warming Potential (GWP), with CO_2 set as the reference value of 1. Other gases are converted into CO_2 equivalent based on this [30]. The GWP values of CO_2, CO, NOx, and Unburnt hydrocarbons (UHC) are taken as 1, 2, 8.5, and 21 [31-33], respectively. The exhaust emissions, including CO_2, CO, NOx, and UHC, released by KWBD at varying loads are shown in Figure 6.

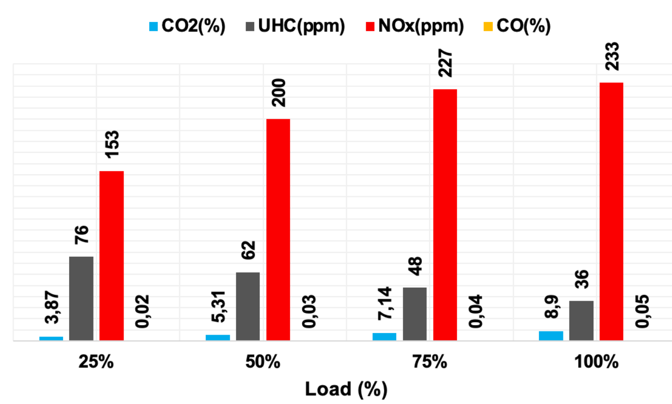

Figure 6. Engine exhaust emission of KWBD at varying loads.

$$CO_{2_{eq}} = \text{Emission of a gas} \times \text{GWP of the gas} \quad (6)$$

The CO_2 equivalent emissions [34], as shown in Eq 6, are also considered during the production of KWBD based on the electricity used for production. The CO_2 emissions per year are calculated based on 8 hours of engine operation per day at 75% engine load. The CO_2 equivalent emissions of electricity used during preparation are calculated using a value of 0.99 kg of CO_2 eq./kWh [35]. Similarly, the preparation of biodiesel requires stirring for 3 hours per liter at 50W.

3.3.1. The social cost of carbon (SCC)

The SCC is a measure, in dollars, of the long-term damage done by a ton of CO_2 emissions in a given year. This dollar figure also represents the value of damages avoided for a small emission reduction (i.e., the benefit of a CO_2 reduction). The SCC is intended to provide a comprehensive estimate of climate change damages, encompassing changes in net agricultural productivity, changes in human health, property damage resulting from increased flood risk, and adjustments to energy system costs, such as reduced heating costs and increased air conditioning costs.

3.3.2. The enviroeconomic factor (EEF)

The environmental economic analysis is determined by the environmental economic factor (EEF) as follows:

$$C_{env} = x_{CO_2} c_{CO_2} \quad (7)$$

Where C_{env} is the cost of environmental damage in a year, x_{CO_2} is the social cost of CO_2 in \$/kg, and c_{CO_2} is the emissions in CO_2 equivalent in kg/year. x_{CO_2} is taken as \$ 0.176/kg [36].

Finally, the total CO_2 equivalent emissions are calculated to be 4.66 Tons/year, and the social cost of CO_2 emissions is \$ 821/year. The CO_2 equivalent emissions capture the global warming potential of all greenhouse gases, allowing a fair comparison with conventional fuels. The SCC reflects the broader social costs of carbon emissions, translating environmental damage into economic terms.

3.3.3. Sustainability index (SI) analysis

The sustainability index (SI), as shown in Eq.8[37], derived from the second law of thermodynamics, serves as a comprehensive metric to examine the viability of energy systems by quantifying the balance between useful energy output and irreversible losses. It bridges the gap between thermodynamic performance and environmental responsibility by providing a nuanced perspective on resource utilization, emissions control, and long-term liabilities. Therefore, SI is carried out for KWBD as it supports circular economy principles by promoting waste valorization and regulating reliance on fossil fuels. From the computed results, the SI was observed to be 2.16, with an exergy efficiency of 52.74% for KWBD at 75% load. An SI less than 1 indicates an unsustainable process, an SI equal to 1 indicates a purely reversible process, and an SI greater than 1 indicates a sustainable process that can produce more useful work relative to its irreversible losses. A higher SI indicates better resource utilization and lower environmental impact; an SI of 2.16 suggests a more sustainable alternative, potentially driven by improved combustion characteristics and reduced exergy losses.

$$\text{Sustainability Index(SI)} = \frac{1}{1 - \eta_{ex}} \quad (8)$$

3.4. Economic analysis

The economic analysis for KWBD uses economic metrics to compare current biodiesel and diesel fuels. These metrics include: Specific capital cost (SCC), Present worth factor (PWF), Net cash flow (NCF), Net present value (NPV), Internal rate of interest (IRR), Simple payback period (SPP), and Payback period (PP). Some metrics use discount and inflation rates. Table 3 presents the overall results of the economic analysis; individual calculations for each parameter are as follows.

3.4.1. Total capital cost

The total capital cost is the initial cost of the engine, including the costs of all components, assembly, and profit from sales; it is calculated to be \$860.

3.4.2. Specific capital cost (SCC)

The specific capital cost (SCC) shown in Eq.9 in this study is \$372/kW, and the capital cost per unit of brake power is taken at a 75% load [37].

$$\text{Specific capital cost} = \frac{\text{Total capital cost}}{\text{Engine brake power at 75\% load}} \quad (9)$$

3.4.3. Present worth factor (PWF)

The present worth factor (PWF) is 8.97, and in the present analysis the inflation and discount rates used to calculate the PWF in Eq.10.

$$PWF = \sum_{j=1}^{n} \frac{(1+i)^{j-1}}{(1+d)^{j}} \quad (10)$$

Where i is the inflation rate, j is the year number, d is the discount rate, and n is the total number of years of operation, taken as 3%, 4.5% and 10 years. [38]

3.4.4. Net cash flow (NCF)

The net cash flow (NCF), as shown in Eq.11**,** is the resulting cash inflow in the first year [31] and is calculated as:

Net cash flow = Engine operating cost with Diesel fuel - Engine operating cost with the present Biodiesel (11)

The engine's annual operating cost is calculated assuming 8 hours of daily operation at 75% load. The above equation does not include engine maintenance engine maintenance costs, assuming maintenance costs are the same for both fuels. The difference in operating costs between diesel fuel and KWBD is considered operating-cost savings.

Engine operating cost per year with Diesel fuel = BP in kW × BSFC in kg/kWh × 8 h × 365 days × cost of present diesel fuel in \$/Litre of fuel × (1/density of fuel in kg/L) (12)

Engine operating cost with present Biodiesel fuel = BP in kW × BSFC in kg/kWh × 8 h × 365 days × cost of biodiesel fuel in \$/Litre of fuel × (1/density of fuel in kg/L) (13)

Using Eqs. 12 and 13 above, the engine operating costs for diesel and biodiesel are \$2121/year and \$1579/year, respectively; the net cash flow is \$542/year.

3.4.5. Net present value

Net present value (NPV), as shown in Eq. **1**4, is the sum of all cash inflows and outflows from the manufacturing or purchase stage until the system can no longer perform its functions and is sold as scrap, discounted to the present. Scrap value is assumed to be 15% of the initial capital cost. This economic metric is used to compare various projects [39].

NPV = -Initial cost + Net cash flow × Present Worth Factor (PWF) + Present value of scrap value

Scrap value of the engine = 15% of the engine cost = \$129 (14)

$$\text{The present value of the scrap value} = \text{scrap value} \times \frac{(1+i)^{j-1}}{(1+d)^{j}} \quad (15)$$

Where j is the number of operating years (taken as 10 years), and i and d are the inflation and discount rates (taken as 3% and 4.5%), respectively. The present value of the scrap value by using Eq.15 is obtained as \$ 108 and the NPV as \$ 4112

3.4.6. Internal rate of return

Another metric used to compare various projects is the internal rate of return (IRR). It is the discount rate at which the NPV equals zero at the end of the operational year. This is calculated by considering both the discount rate and the inflation rate in the present work. NPV is calculated for various discount rates, keeping the rate of inflation constant. The discount rate at which NPV equals zero at the end of the operational years is taken as the IRR. This is done by iterative methods, and the higher value of IRR is considered beneficial for investing in the project [37], and the IRR is calculated as 65.6% per year.

3.4.7. Simple payback period

A simple payback period (SPP) [35] is the simplest way to calculate the number of years it takes to recover the investment capital. It is given by Eq.16, yielding a result of 1.59 years.

$$\text{Simple payback period (SPP)} = \frac{\text{Total capital cost}}{\text{Net cash flow}} \quad (16)$$

3.4.8. Payback period

The discounted payback period, or payback period (PP), accounts for the time value of money. In the present calculation, the discount rate and inflation rate are included. The NPV is calculated for various operating years, and the number of operating years for which NPV equals zero is determined. This is calculated by interpolation between the number of years within which a negative value of NPV changes into a positive value [35], and the payback period is calculated as 1.66 years.

Table 3. Results of the economic analysis for KWBD

S.No	Parameters	Variables
1	Total capital cost	\$860
2	Specific capital cost (SCC)	\$372 /kW
3	Present worth factor (PWF)	8.974
4	Net cash flow (NCF)	\$542 /year
5	Net present value (NPV)	\$4112
6	Internal rate of return (IRR)	65.6% per year
7	Simple payback period (SPP)	Years
8	Payback period (PP)	1.66 Years

4. Conclusion

The following conclusions are drawn from the key results and discussion.

- Waste kitchen oils are successfully converted into sustainable biodiesel, and their key fuel properties meet international standards (ASTM D6751). The combustion pressures and brake thermal efficiency results of KWBDfollow trends similar to those of DFO. However, KWBD incurs a penalty in the form of high fuel consumption due to its high viscosity and density.
- Exergy efficiency represents the effective utilization of available energy (exergy) in KWBD for useful work. At 75% load, the exergy efficiency of KWBD reaches its maximum (52.74%), indicating reduced irreversibility. Similarly, identifying various losses within the thermodynamic system helps improve it, and it is observed that 31.09% and 29.21% of useful work are recorded at 75% and 100% loads, respectively, for KWBD.
- The total CO_2 equivalent emissions are calculated as 4.66 Tons/year, and the social cost of CO_2 emission is \$ 821 /year. Lower CO_2-equivalent emissions demonstrate the environmental advantage of KWBD over conventional diesel. The social cost of carbon estimates highlight the broader economic benefits of reducing emissions, and potentially support policy recommendations or carbon credit opportunities. Together with the sustainability index (2.16), these metrics strengthen the case for KWBD as an environmentally friendly and socially responsible alternative fuel.
- The economic assessment further reinforces the viability

of KWBD, with a total capital cost of $860 and a specific capital cost (SCC) of $372/kW. The net cash flow (NCF) is $542 per year, leading to an impressive net present value (NPV) of $4112 and an exceptionally high internal rate of return (IRR) of 65.6% per year, indicating a highly profitable investment. Additionally, the system achieves a simple payback period (SPP) of 1.59 years and a payback period (PP) of 1.66 years, thereby ensuring rapid recovery of the initial investment. These economic parameters highlight the long-term economic sustainability of KWBD implementation.

These results support the conclusion that KWBD is an economically and environmentally viable alternative fuel that contributes to sustainable energy solutions and offers rapid payback, high returns, and reduced environmental impact.

Given that the present study is confined to a single-cylinder engine, future investigations could extend this work to multi-cylinder engine configurations. Such studies should incorporate various low-cost biodiesel fuels and include comprehensive lifecycle assessments to evaluate their environmental and economic viability.

Author contributions statement

Aditya Kolakoti: Conceptualization, methodology, formal analysis, writing – original draft, writing – review & editing. K Sivasami: Investigation, supervision, editing, formal analysis, writing – original draft, writing – review & editing.

Declaration of interests

Authors declare no potential conflicts of interest or any competing financial or personal interests related to this work.

Data availability

Authors conform that the data that supports the findings of this study are available within the article.

Declaration of generative AI and AI-assisted technologies in the writing process

No generative AI or AI-assisted technologies were used in the writing process.

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Nomenclature

Ex	Exergy, kW
$\dot{m}$	Mass flow rate, kg/s
c_p	Specific heat, kJ/kg-K
T	Temperature, °C
R	Characteristic gas constant, kJ/kg-K
P	Pressure, kN/m^2
LHV	Lower calorific value

Subscripts

f	Fuel
bp	Brake power
w	Water
g	Exhaust gases
des	Destruction
o	Exit
0	Standard atmospheric state

Acronyms

PWF	Present worth factor
NCF	Net cash flow
BSFC	Brake-specific fuel consumption
NPV	Net present value
IRR	Internal rate of interest
SPP	Simple payback period

Greek letters

η	Efficiency

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