



# Energy and cost evaluation for biodiesel production using conventional heating and microwave heating (batch and continuous)

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## Abstract

The cost of raw materials and the production process remain major challenges hindering the expansion of biodiesel production on a large scale. Several technologies have been developed to reduce production costs. This research aims to investigate the energy recovery and economic aspects of biodiesel production from used cooking oil (WCO) using conventional and microwave (batch and continuous) transesterification technology. Used cooking oils are an alternative source of energy, given their high potential for use in biofuels production, especially biodiesel. The production of biodiesel in this study relies on a basic esterification reaction using calcium oxide prepared from willow leaves as a catalyst. The results showed that the optimal operating conditions include a catalyst concentration of 3% wt.%, a methanol content of up to 70wt%, and an operating temperature of 65 °C. The reaction time varied depending on the heating technique; the conventional method required 90 minutes, while the time decreased to 20 minutes with batch microwave heating, and to only 5 minutes with continuous microwave heating. These conditions resulted in the highest biodiesel yields of 93.852%, 96.313%, and 93.43%, respectively, for the three methods. From an economic perspective, the cost of producing one liter of biodiesel for conventional and microwave heating (batch and continuous) was approximately 1074.190, 483.588, and 510.162 Iraqi dinars/liter, respectively. The analysis also showed that the total energy consumption of the three methods was 0.945, 0.026666 and 0.03433 kWh respectively, demonstrating that microwave technologies offer a significant reduction in reaction time and higher energy efficiency, thus potentially leading to greater economic returns and operational benefits compared to traditional methods. Finally, the findings result calculated the energy payback period for producing 1 liter of biodiesel using microwave technology. The results showed that the system is sustainable, making it a suitable means of reducing the cost of biodiesel production and supporting its future commercialization.

*Keywords: Biodiesel; Transesterification; CaO catalyst; willow leaves Extract; Energy recovery; cost.*

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## 1- Introduction

The world has witnessed a significant increase in demand for liquid fuels, which has prompted research into alternative energy sources. Fossil fuels are the primary source of this type of fuel, but their formation takes millions of years, raising concerns about their depletion. Furthermore, heavy reliance on coal, natural gas, and oil directly contributes to the exacerbation of global warming and climate change, two of the most prominent environmental challenges of our time. The use of fossil fuels is also associated with several other negative effects, such as greenhouse gas emissions, ozone layer depletion, and air pollution, which increases the need to search for more sustainable and environmentally friendly fuel alternatives [1-2].

Biodiesel is one of the most promising alternatives. It is defined as a clean-burning monoester composed of long-chain fatty acids, extracted from natural and renewable sources such as vegetable oils or animal fats, and used in

compression combustion engines [3]. Since crude vegetable oils cannot be used directly as a diesel fuel substitute due to their high viscosity, they require chemical treatments to improve their properties and make them suitable for operation in engines. The most prominent methods used to achieve this include dilution, microemulsions, pyrolysis (thermal cracking), and transesterification, the most common and effective method for reducing viscosity and improving combustion properties [4].

Biodiesel is typically produced in discontinuous batch reactors that employ conventional heating methods, such as fuel combustion or electric coils, to generate the necessary heat for the reaction. Nevertheless, this approach necessitates a substantial amount of energy and a prolonged period of time to accomplish high yields. Conversely, the utilization of microwaves is an alternative thermal method that has the potential to enhance the efficiency of processes and reduce energy consumption.



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The application of microwaves in ester exchange processes within batch reactors has been the subject of numerous studies [5-8]. Additionally, reports have suggested that household microwave ovens could be employed to operate the process in continuous flow mode, the findings indicated that microwave irradiation expedites the chemical reaction, resulting in high yields in a brief period of time [9].

The choice of catalyst is a key factor in ester exchange biodiesel production processes, as it directly contributes to improving the reaction efficiency and quality of the final product. Among the available solid catalysts, calcium oxide (CaO) has emerged as an ideal choice due to its numerous advantages: it is inexpensive, readily available, non-corrosive, environmentally friendly, easy to use, highly basic, and low solubility, in addition to the possibility of regenerating and reusing it multiple times. Numerous studies have demonstrated its high efficiency in catalyzing ester exchange reactions to produce biodiesel from various raw materials [10-13]. These properties have attracted the interest of researchers to further develop it. One of the most prominent methods for improving its catalytic performance is to increase its specific surface area by preparing it in a nano formulation, which opens up broader prospects for raising its efficiency and enhancing its performance in industrial applications [14].

Several studies indicate that 70–75% of the total cost of biodiesel production is related to the feedstock source [15, 16], making the selection of a suitable, low-cost feedstock a critical factor in economic feasibility. From this perspective, used cooking oil is an ideal choice, as it helps reduce the negative environmental impacts resulting from the accumulation of grease and free fatty acids, while simultaneously providing a low-cost alternative for the production of renewable and environmentally friendly fuels that support sustainable development [16, 17]. Furthermore, a microwave heating system was used to reduce energy consumption during the production process, and waste-based catalysts were adopted as used fallen willow leaves, all of which contribute to reducing the overall cost of biodiesel production.

This study aims to evaluate the energy and economic performance of biodiesel production processes from used cooking oil (WCO) by comparing three different technologies: conventional transesterification, batch microwave heating, and continuous microwave heating. The research focuses on determining the energy efficiency and cost-effectiveness of each method to identify the most viable and efficient technology for producing biodiesel from sustainable and low-cost sources.

## **2- Material and method**

### **2.1. Collection of raw material**

Used cooking oil was obtained from a fast-food restaurant in Baghdad. After collecting the oil, it was filtered to remove impurities being introduced into the

conversion process. The necessary chemicals such as methanol, calcium nitrate tetra hydrate, KOH, Ethanol, and phenolphthalein were also sourced from local markets. and willow leaves collected from a local farm.

### **2.2. Laboratory-based biodiesel production**

This study conducted A liter of biodiesel by using conventional and microwave (batch and continuous) technology.

From an economic perspective, costs were concentrated on the raw materials such as used cooking oil, alcohol (methanol), and CaO Catalyst product from fallen willow extract and calcium nitrate, as well as electricity, and equipment. The main economic returns included the produced biodiesel.

Before the conversion process began, the percentage of free fatty acids in the sample was determined by titration using phenolphthalein, Ethanol, and KOH. The results showed that the percentage reached approximately 2.4%.

The calcium oxide catalyst was prepared from fallen willow leaves by thoroughly washing, drying, and grinding them. The resulting powder was then boiled with deionized water for 30 minutes at 60°C to obtain an extract, then the extract characterized by EDX analysis showed a high calcium content of approximately 10% and FTIR analysis also revealed the presence of calcium-bound active groups. This extract was then heated to 55°C, and calcium nitrate tetrahydrate with sodium hydroxide NaOH was added until a yellow paste was formed. Finally, this paste was dried in an oven at 600°C for two hours, yielding a white powder representing calcium oxide nanoparticles, after that the catalyst was characterized by FTIR, XRD, BET, SEM-EDX, XRF.

Biodiesel was produced from used cooking oil using three different techniques. In the conventional method, the transesterification process was carried out using a 500-ml boiling flask connected to a reflux condenser. 30 grams of oil was heated with methanol and a catalyst at 65°C and stirred at 700 rpm for 1.5 hours. The effects of different methanol-to-oil ratios (30-80%) and catalyst concentrations ranging from 1–4% by weight were studied. In the batch microwave method, a WB20230745 atmospheric pressure microwave reactor was used, equipped with a three-necked glass flask, a condenser, and a temperature sensor, allowing precise control of reaction conditions. In each experiment, 30 grams of oil was used, with methanol-to-oil ratios ranging from 50–80%, and varying catalyst levels (1–4%). Reaction times ranged from 10–25 minutes and temperatures from 45–75°C were tested, under microwave radiation power equivalent to 10–20% of the device's total power. The continuous microwave method relied on mixing 30 grams of oil with methanol and a CaO nano catalyst in a three-necked flask equipped with a magnetic stirrer at 700 rpm to prevent phase separation. The mixture was then continuously pumped into a dedicated Teflon tube inside the reactor at different flow rates to control the radiation exposure time. Catalyst concentrations ranging from 1–4% by weight, methanol to oil ratios ranging from 50–

80%, short reaction times ranging from 0.5–7 min and different temperatures ranging from 45–75°C were studied, while the microwave radiation power was set at 20% of the total device power.

The experimental evaluation was based on calculating the yield percentage according to the Eq. 1:

$$Yield = \frac{\text{amount of biodiesel}}{\text{amount of waste cooking oil}} * 100\% \quad (1)$$

After obtaining the product left for one day to settle and then separate the biodiesel (upper layer) from glycerin (lower layer) and put the biodiesel in dryer to remove any excess methanol. It was making it ready to test its physicochemical properties. Fig. 1 shows a simplified flowchart of the steps involved in producing biodiesel from used cooking oil.

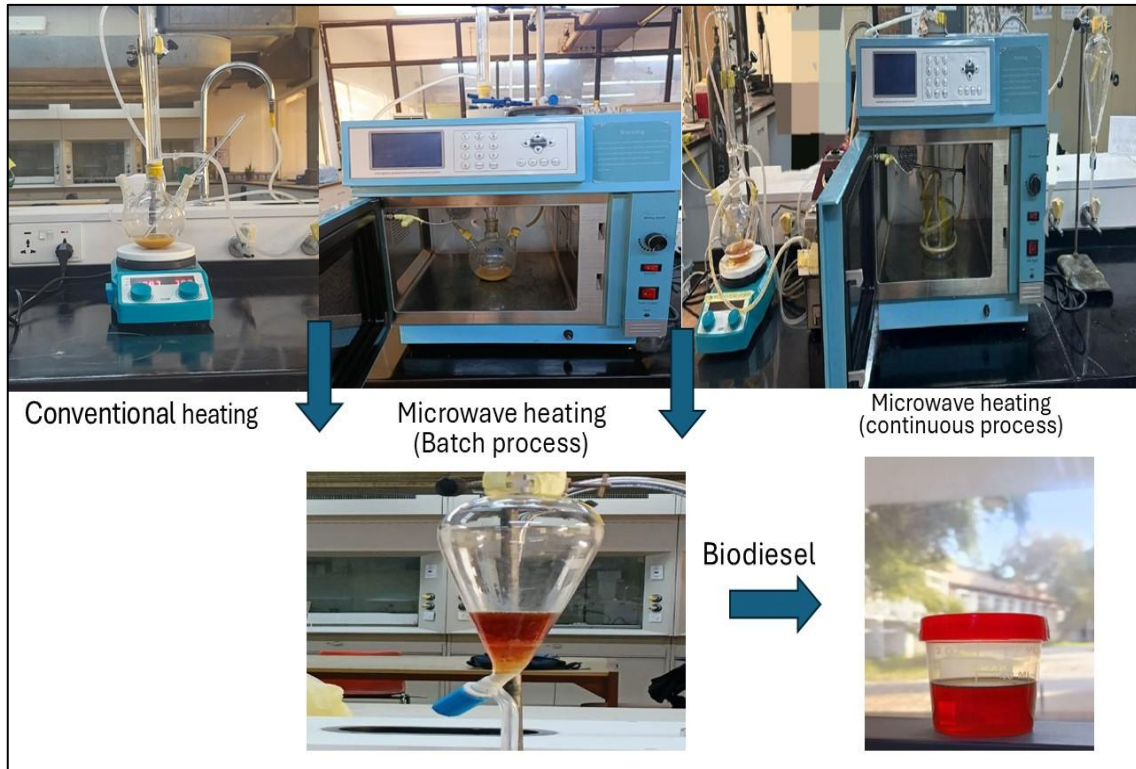


Fig. 1. The flowchart of biodiesel production in conventional and microwave (batch and continuous) technology

### 2.3. Energy analysis

To assess the sustainability of the microwave heating (batch and continuous) biodiesel production system, the electrical energy consumption during the reaction process was calculated. The total energy consumption includes both the microwave power and the power of the magnetic stirrer.

The total energy consumption (TEC) was calculated based on the device power and the reaction time using the following equation:

$$TEC = t * P \quad (2)$$

Where P represents the microwave power (watts), and t represents the reaction time (hours). To determine the amount of energy needed to make 1 kilogram of biodiesel (BERK) in microwave heating batch process, (CERK) in microwave heating continuous process, and (TERK) in traditional heating batch process, using Eqs. 3, 4, 5 [18]:

$$BERK = \frac{BTEC}{BPB} \quad (3)$$

$$CERK = \frac{BTEC}{CPB} \quad (4)$$

$$TERK = \frac{TTEC}{TPB} \quad (5)$$

The quantity of biodiesel products is denoted by (PB). To Produce One liter of biodiesel requires multiple the amount of energy to its density. Biodiesel engines have a base-specific fuel consumption of 0.47 kg/kWh, as reported by Chauhan et al. [19]. A kilogram of biodiesel (ECKB) burned to produce energy is:

$$ECKB = \frac{\text{kg of biodiesel}}{0.47} = 2.1277 \text{ kWh} \quad (6)$$

Comparing the energy consumed to produce each kg versus the energy generated from its use (2.1277 kWh), it is clear if the system produces excess energy or not.

### 2.4. Economic analysis

This study conducted an economic analysis of the biodiesel production process, focusing on the costs associated with raw materials and operational processes. The economic inputs included the cost of used cooking

oil, methanol, and a catalyst, as well as the costs of electricity, labor, and equipment used in the production process. This data was organized in a table showing the materials used and their costs, as shown in Table 1.

Based on this data, the cost of biodiesel production was calculated using simple mathematical equations. The cost of producing one kilogram of biodiesel was calculated by dividing the total production cost by the total quantity of biodiesel produced in kilograms, as shown in Eq. 7. The cost of producing one liter of biodiesel was calculated using the same equation, but with a mass-to-volume

conversion using the density of the biodiesel. The quantity produced in kilograms was multiplied by the density of the biodiesel to obtain the volume in liters, as shown in Eq. 8.

$$\text{Total cost of produce 1 kg of biodiesel} = \frac{\text{cost of the biodiesel produce}}{\text{weight of biodiesel produce(g)}/1000} \quad (7)$$

$$\text{Total cost of produce 1 L of biodiesel} = \text{cost of biodiesel IQD/kg} * \text{density of biodiesel} \quad (8)$$

**Table 1.** Materials used and their cost in the conventional heating and microwave heating (batch, continuous) process

Input particular	Units	Cost (IQD)
Human labor	h	0
Waste cooking oil	g	0
Alcohol (methanol)	g	500/Kg
Catalyst (calcium nitrate)	g	0.../Kg
electricity	KWh	19.375/KWh

### 3- Results and discussion

#### 3.1. Optimum operating conditions for biodiesel production

Experimental results showed that the best biodiesel yields were achieved under optimal operating conditions that varied depending on the reaction technology. In the conventional method, the highest conversion rate was recorded 93.852% at 65°C, a reaction time of 1.5 hours, and a stirring speed of 700 rpm, using a methanol-to-oil ratio of 70% by weight and a CaO catalyst concentration of 3wt.%. In the batch microwave system, a significant improvement in efficiency was observed 96.313%, with the reaction time reduced to 20 minutes at 65°C, with an irradiation power equivalent to 10% of the total system power, with the best yield achieved at a methanol-to-oil ratio of 70% by weight and a catalyst concentration of 3wt.% as reported by Mohammed and Al-Yaqoobi [20].

While the continuous microwave technique demonstrated a clear advantage in terms of short reaction time, the highest yield 93.43% was achieved at a temperature of 65°C and an irradiation time of no more than 5 minutes, with a methanol-to-oil ratio of 70% by weight, a catalyst concentration of 3wt.%, and an appropriate flow rate that maintained reaction stability and product quality. Comparing the three methods, the continuous microwave technique was found to be the most efficient in terms of reaction speed and energy consumption, achieving the highest biodiesel yield under ideal conditions and in a shorter time compared to other methods.

#### 3.2. Sustainability of microwave (batch and continuous) biodiesel production systems and compared with conventional heating technology

One of the most well-known contemporary approaches to enhancing the efficiency of biodiesel synthesis is microwave-assisted transesterification. This process

decreases operating costs by raising conversion ratios and decreasing reaction time. Here, at energy efficiency and environmental friendliness of a basic microwave-based system as a case study. This research showed that using a 160-watt microwave oven (representing 20% of the microwave's total power), 93.43% biodiesel was obtained within 5 minutes in microwave heating (continuous process). It should be noted that the mixture was preheated conventionally at 630 watts for 2min before being pumped into the microwave. In the microwave heating (batch process), the required reaction time was 20 minutes at a mixing speed of 600 rpm and a heating power of 80 watts (10% of the microwave power) to achieve a yield of 96.313%. Eq. 1 was used to calculate the energy consumed in biodiesel production were necessary [19].

In batch reactor the total energy consumed to produce was 28.8939 grams of biodiesel and 28.029 grams of biodiesel with continuous reactor. Using the Eq.3,4 we can determine the amount of energy needed to make 1 kilogram of biodiesel (BERK) in batch and (CERK) in continuous [18].

The quantity of biodiesel products is denoted by (PB). One liter of biodiesel requires the following amount of energy due to its density, which is 0.9005 kg/L in batch reactor and 0.9128 kg/L in continuous flow, this means that producing 1 L of biodiesel requires 0.8326 kWh of energy using microwave technology in batch reactor and 0.43412 kWh as shown in Table 2.

Biodiesel engines have a base-specific fuel consumption of 0.47 kg/kWh, as reported by Chauhan et al. [19]. As Eq. 6 kilogram of biodiesel (ECKB) burned to produce energy is 2.1277 kWh, it is evident that the system generates an excess of 1.20304 kWh/kg in batch mode and 0.902791 in continuous mode when comparing the energy consumed to create each kg of energy 0.924650 kWh and 1.224909 with the energy generated from its consumption 2.1277 kWh as Fig. 2.

This proves that the system is good at recovering energy and that the technology for generating microwave

biodiesel is sustainable, efficient, and very successful, so it could be used in renewable energy and industrial settings.

### 3.3. Evaluation in relation to traditional heating

On the other hand, traditional heating equipment that uses 630 watts was employed for 90 minutes and produced 93.852% of the yield. The energy usage is determined by Eq.5. There was a production of 28.1556 grams of biodiesel at a temperature of 6° degrees Celsius,

a time constant of 90 minutes, and total energy consumed of 945 watt-hours. As a result, the amount of energy needed to generate 1 kilogram is 33.56419kWh, when comparing this amount with what microwave ovens consume, it becomes clear that conventional heating methods require more than 36 times more electrical energy compared to microwave-assisted transesterification processes, which naturally leads to a higher cost of biodiesel production when using conventional heating.

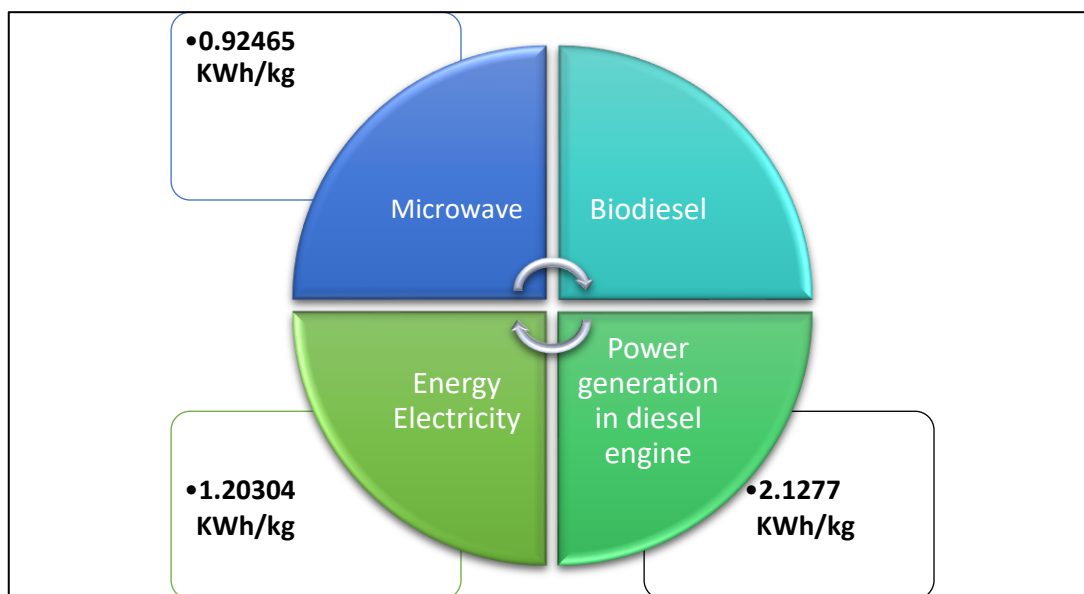


Fig. 2. Results from traditional heating methods and those from microwave-assisted

Table 2. Total energy required to produce 1kg and 1L of biodiesel

Method	Total energy required to Produce 1kg	Total energy required to Produce 1L
Conventional Heating (Batch Process)	33.564	30.637
Microwave Heating (Batch Process)	0.924	0.8326
Microwave Heating (Batch Process)	1.224	1.118097

### 3.4. Economic evaluation of biodiesel production

The economic cost of biodiesel production was calculated based on the quantities and prices of the materials used, as shown in Table 3, Table 4, and Table 5. The cost of each material was calculated by multiplying the quantity used by its unit price, and then summing all the values to obtain the total production cost for each process. The calculations were performed using an initial quantity of 30 grams of used cooking oil, which yielded a biodiesel output with a conversion rate of 93.852% in conventional heating (batch process), 96.313% in microwave heating (batch process), and 93.43% in microwave heating (continuous process).

The resulting cost from this laboratory quantity was then converted to a larger-scale production cost. The cost of producing one kilogram of biodiesel was calculated using Eq. 7. This cost was then converted to the cost of

producing one liter of biodiesel using the density of biodiesel for mass-to-volume conversion.

Table 3 - Table 5 detail the partial costs of each of the materials involved in the three production processes, while Table 6 shows the final comparison between the three processes in terms of the total cost of producing one kilogram and one liter of biodiesel. The results indicate a cost difference between the studied processes due to varying material and energy consumption in each, directly impacting the final production cost. These findings suggest that improving process efficiency and reducing material or energy consumption can contribute to lowering biodiesel production costs and making the process more economically viable

Since the yield in conventional heating is 93.852% the weight of biodiesel product is 28.1556 g, so the total cost of produce 1kg of biodiesel is 1183.030 IQD/kg. After measuring the physical properties of biodiesel, the density

of biodiesel in conventional is 0.908Kg/L so the cost of biodiesel in liters is 1074.190 IQD/L.

Since the yield in Microwave heating (batch technique) is 96.313% the weight of biodiesel product is 28.8939 g, so the total cost of produce 1kg of biodiesel is 537.021 IQD/kg. After measuring the physical properties of biodiesel, the density of biodiesel in Microwave heating (Batch technique) is 0.9005Kg/L so the cost of biodiesel in liter is 483.588 IQD/L.

Since the yield in Microwave heating (Continuous technique) is 93.43% the weight of biodiesel product is 28.029 g, so the total cost of producing 1kg of biodiesel is 558.892 IQD/kg. After measuring the physical properties of biodiesel, the density of biodiesel in Microwave heating (continuous technique) is 0.9128 kg/L so the cost of biodiesel in liter is 510.162 IQD/L as shown in Table 6.

**Table 3.** The Economic evaluation of the biodiesel production in conventional heating techniques

Input particular	Units	Cost (IQD)	Quantity	Total cost
Human labor	h	0	0	0
Waste cooking oil	g	0	30	0
Alcohol (methanol)	g	500/kg	21	10.5
Catalyst (calcium nitrate)	g	5000/kg	0.9	4.5
electricity	KWh	19.375/kWh	0.945	18.309
Total cost	-----	-----	-----	33.309

**Table 4.** The Economic evaluation of the biodiesel production in microwave heating (batch process)

Input particular	Units	Cost (IQD)	Quantity	Total cost
Human labor	h	0	0	0
Waste cooking oil	g	0	30	0
Alcohol (methanol)	g	500/kg	21	10.5
Catalyst (calcium nitrate)	g	5000/kg	0.9	4.5
electricity	KWh	19.375 /kWh	0.02666	0.51665
Total cost	-----	-----	-----	15.51665

**Table 5.** The Economic evaluation of the biodiesel production in microwave heating (continuous process)

Input particulars	Units	Cost (IQD)	Quantity	Total cost
Human labor	h	0	0	0
Waste cooking oil	g	0	30	0
Alcohol (methanol)	g	500/kg	21	10.5
Catalyst (calcium nitrate)	g	5000/kg	0.9	4.5
Electricity	KWh	19.375 /kWh	0.03433	0.6652
Total cost	-----	-----	-----	15.6652

**Table 6.** Total cost of produce 1kg and 1L of biodiesel

Method	Total cost of producing 1kg	Total cost of Producing 1L
Conventional Heating (Batch Process)	1183.03	1074.190
Microwave Heating (Batch Process)	537.021655	483.588
Microwave Heating (Batch Process)	558.8926	510.162

#### 4- Conclusion

Based on the results of this study, it can be confirmed that biodiesel is a sustainable alternative to conventional diesel fuel, due to its environmental and economic advantages. Three biodiesel production technologies were compared: conventional heating, batch microwave heating, and continuous microwave heating. The results showed that both microwave technologies, particularly the continuous system, achieve higher efficiency in accelerating the reaction and improving the quality of the produced fuel compared to the conventional method. The energy assessment showed that the total energy consumption for the three heating methods – conventional heating, batch microwave, and continuous microwave –

was 0.945, 0.026666, and 0.03433 kWh, respectively. Economically, the cost of producing one liter of biodiesel using these methods was approximately 1074.190, 483.588, and 510.162 Iraqi dinars per liter, respectively. These results demonstrate that microwave heating, particularly batch heating, significantly reduces energy consumption and costs compared to conventional heating, confirming its efficiency and suitability as a more economical and effective option for biodiesel production.

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Baghdad, for their continuous support and valuable assistance throughout the completion of this work.

### Nomenclature

Symbol	Unit	Definition
BP	----	Biodiesel Product
TEC	Wh	Total energy composition
BTEC	Wh	Batch total Energy composition
CTEC	Wh	Continuous total energy composition
TTEC	Wh	Traditional total energy composition
BERK	Wh/kg	amount of energy required to make 1 kilogram of biodiesel in Batch mode
CERK	Wh/kg	Amount of energy required to make 1 kilogram of biodiesel in Continuous mode
TERK	Wh/kg	Amount of energy required to make 1 kilogram of biodiesel in Traditional mode
ECKB	Wh/kg	A kilogram of biodiesel burned to produce energy
CaO	-----	Calcium oxide
NaOH	-----	Sodium hydroxide
WCO	-----	Waste cooking oil
IQD	-----	Iraqi Dinar

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## تقييم الطاقة والتكلفة لإنتاج الديزل الحيوي باستخدام التسخين بالطريقة التقليدية والتسخين بطريقة ميكروويف (دفعه، ومستمر)

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### الخلاصة

لا تزال تكلفة المواد الخام وعملية الإنتاج تُشكلان تحديين رئيسيين يُعيقان التوسع في إنتاج الديزل الحيوي على نطاق واسع. وقد طُوّرت العديد من التقنيات لخفض تكاليف الإنتاج. يهدف هذا البحث إلى دراسة استرداد الطاقة والجوانب الاقتصادية لإنتاج الديزل الحيوي من زيت الطهي المُستعمل باستخدام تقنية الأسترة التبادلية التقليدية والميكروويف (على دفعات وبشكل مستمر). تُعدّ زيوت الطهي المُستعملة مصدرًا بديلًا للطاقة، نظرًا لإمكاناتها العالية للاستخدام في إنتاج الوقود الحيوي، وخاصةً الديزل الحيوي. يعتمد إنتاج الديزل الحيوي في هذه الدراسة على تفاعل أسترة أساسي باستخدام أكسيد الكالسيوم المُحضّر من أوراق الصفصاف كمُحفّز. أظهرت النتائج أن ظروف التشغيل المثلى تشمل تركيزًا للمُحفّز بنسبة ٣% وزنيًا، ومحتوى ميثانول يصل إلى ٧٠% وزنيًا، ودرجة حرارة تشغيل تبلغ ٦٥ درجة مئوية. تفاوت زمن التفاعل باختلاف تقنية التسخين؛ حيث تطلبت الطريقة التقليدية ٩٠ دقيقة، بينما انخفض الزمن إلى ٢٠ دقيقة مع التسخين بالميكروويف على دفعات، وإلى ٥ دقائق فقط مع التسخين بالميكروويف المُستمر. أدت هذه الظروف إلى أعلى إنتاجية للديزل الحيوي بنسبة ٩٣,٨٥٢% و ٩٦,٣١٣% و ٩٣,٤٣% على التوالي للطرق الثلاث. من منظور اقتصادي، بلغت تكلفة إنتاج لتر واحد من الديزل الحيوي للتسخين التقليدي والميكروويف (دفعه ومستمر) حوالي ٥١٠,١٦٢,٤٨٣,٥٨٨,١٠٧٤,١٩٠ دينار عراقي / لتر على التوالي. أظهر التحليل أيضًا أن إجمالي استهلاك الطاقة للطرق الثلاث كان ٠,٩٤٥ و ٠,٢٦٦٦٦ و ٠,٣٤٣٣ كيلو واط ساعة على التوالي، مما يدل على أن تقنيات الميكروويف توفر انخفاضًا كبيرًا في وقت رد الفعل وكفاءة طاقة أعلى، مما قد يؤدي إلى عوائد اقتصادية وفوائد تشغيلية أكبر مقارنة بالطرق التقليدية. أخيرًا، حسبت هذه الدراسة فترة استرداد الطاقة لإنتاج لتر واحد من الديزل الحيوي باستخدام تقنية الميكروويف. أظهرت النتائج أن النظام مستدام، مما يجعله وسيلة مناسبة لتقليل تكلفة إنتاج الديزل الحيوي ودعم تسويقه في المستقبل.

**الكلمات الدالة:** وقود الديزل الحيوي، الأسترة المتبادلة، محفز أكسيد الكالسيوم، مستخلص أوراق الصفصاف، استعادة الطاقة، التكلفة.