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A circular economy approach to convert waste dairy scum oil into biodiesel for the development of sustainable environment

Luqman Razzaq*

Department of Mechanical Engineering Technology, University of Gujrat, Gujrat 50700, Pakistan

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ABSTRACT

The present study is an effort to examine a technique for evaluating the expenses associated with the production of biodiesel from waste dairy scum oil in Pakistan, to create an economic assessment of this option. A survey was conducted on ten dairies in Gujrat to encourage them participation in the biodiesel supply chain. The survey aimed to collect data on waste dairy scum creation, disposal methods and quantity, as well as purchase cost. The waste dairy scum oil was extracted by solvent extraction method. Acetone solvent has been used to extract the waste dairy scum oil. A two-step acid treatment was done to reduce the FFA value of WDSO from 4.6 to 0.98 mg KOH/g. The independent variables of the transesterification process parameters including catalyst concentration, methanol to oil ratio, temperature, speed, and reaction time were kept 0.25 w/w, 8.50:1, 57.50°C, 600 rpm, and 1h respectively. The maximum biodiesel yield at these operating parameters was observed 93%. The economic feasibility of the conversion of WDSO into biodiesel was assessed using the information obtained from the surveys conducted by the different dairy's owners. Approximately 70% of diaries produced scum and wanted to convert this waste dairy scum into biodiesel. The net biodiesel production cost was found to be 171 rupees. The logistic cost of biodiesel produced from the WDSO was found to be 22 rupees. The overall cost of 1L biodiesel would be 193 rupees. A two-way sensitivity analysis was performed to determine the profit of the conversion of the WDSO into biodiesel. The environmental analysis revealed that the emissions like CO, HC, and NOx significantly reduced during the combustion of biodiesel as compared to conventional diesel.

Keywords: Biodiesel, Circular Economy, Dairy scum oil, Transesterification.

1. Introduction

Energy consumption is steadily rising as the population continues to grow. Fossil fuels are extensively utilized to provide this energy requirement (Wang and Azam 2024). As a result of the accelerated consumption of fossil fuels, the reserves of these fuels are fast diminishing (Kalair et al. 2021). Around half of the fossil fuels are utilized in the transportation industry (Friedemann 2021). The combustion of these fossil fuels had a profound impact on climate change (Paraschiv and Paraschiv 2020). The abundance of fossil fuels presents a significant challenge to efforts aimed at mitigating climate change (Fawzy et al. 2020). These challenges prompted researchers to seek alternate fuels that can substitute diesel in the transportation and industrial sectors (Burchart-Korol, Gazda-Grzywacz, and Zarębska 2020), (Sandaka and Kumar 2023). Scientists have discovered that biofuels are the most appealing option among alternative fuels, primarily because they are capable of being broken down naturally (Malode et al. 2021). Utilizing waste materials as a feedstock can effectively decrease the production cost of biodiesel (Etim, Musonge, and Eloka-Eboka 2020).

The economy of developing nations, such as Pakistan, have suffered from a lack of accessible energy, which has hindered their competitiveness (Asghar et al. 2023). Given its vast agricultural territory and status as the second fifth most populous country in the world, Pakistan possesses the capacity to generate renewable energy on a significant scale (Ahmad et al. 2022). Pakistan is the leading country in milk production, contributing 65.7 million metric tonnes of milk in the 2021/2022 period (Chandio et al. 2017). A total of one million tonnes of waste dairy scum has been produced, which contains a variety of fatty acids (Mohd Johari et al. 2022). If the dairy scum oil is not treated before disposal, it can cause significant pollution in the environment. However, if it is properly treated, it has the potential to substitute a portion of the fossil fuels currently used for energy production in transportation, domestic, and industrial sectors.

* Corresponding author.
E-mail address: luqman.razzaq@uog.edu.pk (Luqman Razzaq).

The dairy farms produce a substantial amount of waste per day, which poses challenges for disposal (Durham and Hourigan 2007). Scum oil is composed of fat, proteins, and lipids. The majority of dairy farms dispose of this slime either in solid waste disposal sites or via incineration (Adesra, Srivastava, and Varjani 2021). However, these procedures are not cost-effective and produce pollutants. In addition, scum poses both direct and indirect operational challenges for effluent treatment. Industries dealing with raw and chilled milk, as well as dairy products such as butter, ghee, cheese, yoghurt, ice cream, etc., produce dairy waste scum (Choudhary et al. 2021). It is challenging to dispose of the 250–300 kg of effluent scum produced daily by a large dairy. Dairy scum refers to a buoyant solid mass that is less compact and is created when fats, lipids, proteins, and other substances are mixed together. This can provide challenges when it comes to managing and operating wastewater treatment plants. Due to the high concentration of triglycerides, these materials were chosen as a feedstock in the current investigation.

A limited amount of research has been conducted regarding the production of biodiesel from waste products from the dairy sector. According to Abreu et al. (Abreu-Jaureguí, Reynel-Ávila, and Bonilla-Petriciolet 2023)and Castillo et al. (Castillo et al. 2021), for instance, general guidelines and suggestions were provided for the extraction and conversion of these wastes. Biodiesel production utilizing dairy leftovers under identical operating conditions was the focus of research conducted by Sivakumar et al. (Sivakumar, Anbarasu, and Renganathan 2011), Srikanth et al. (Srikanth et al. 2017), and Balasubramanian et al. (Balasubramanian et al. 2018). To enhance the overall performance of the procedure, these authors suggested doing an analysis of a variety of extraction methods. The predominant techniques for lipid extraction include solvent extraction, thermal treatment, microwave- and ultrasound-assisted methods, and mechanical separation (Baskar et al. 2019). Initial investigations have shown that the use of solvent extraction and thermal treatment can provide further benefits for extracting lipids from this leftover biomass (Kumar et al. 2017). Santos et al. (Rosa et al. 2019) utilized ethyl acetate as an environmentally friendly solvent to extract cocoyol oil using an ultrasound-assisted extraction method.

There are many different catalysts and methods available for the production of biodiesel, and one of them is the synthesis of biodiesel with acid and alkaline, which is capable of producing up to 93% yield (Athar and Zaidi 2020). The literature review focuses on economic research connected to the production of biodiesel. When it comes to the production of biodiesel from waste feedstock, there are not a lot of papers that examine the economic analysis part of the process. Techno-economic studies that use the raw materials of WCO are carried out by Karmee et al. (Karmee, Patria, and Lin 2015), and they demand a significant initial investment because the process involves employing the super-critical method. The study also calculated the market price of biodiesel goods from different providers. The results indicate that biodiesel production can compete with fossil fuels. By integrating a cost-effective production process that utilizes potential waste dairy scum as a source to produce biodiesel. This initiative aligns with the Corporate Social Responsibility program and the principles of the circular economy. It aims to reduce waste and pollution in our neighborhood while also generating profit.

The circular economy is an economic model that optimizes the utilization of resources by maximizing the value generated by the flow of materials and energy between civilization and the environment (Hanumante, Shastri, and Hoadley 2019). The use of renewable energy sources, energy flows of a cascade nature, and cyclical materials fluxes accomplish this. All three aspects of sustainable development benefit from a well-functioning circular economy. The circular economy restricts the flow of resources to a level that is acceptable to nature and incorporates the natural cycles of ecosystems into economic cycles, while respecting their inherent rates of reproduction (Korhonen, Honkasalo, and Seppälä 2018).

The present study is an effort to analyze the economic feasibility of converting the waste dairy scum oil into biodiesel. Acetone has been used to extract scum oil form waste dairy scum via solvent extraction method. A two-step acid treatment was performed on the extracted dairy scum oil before the conversion of oil into biodiesel. The acid treated scum oil converted into biodiesel via transesterification process. The maximum biodiesel yield obtained was 93%. The economic feasibility of the conversion of waste dairy scum oil into biodiesel was assessed with the help of a questionnaire. The survey was conducted from the 10 diary owners, to get the data and propose the feasibility of the biodiesel at a commercial level.

2. Materials and Methods

2.1. Materials

The feedstock selected for this investigation was Dairy Scum, which was obtained from the butter effluent section of a local dairy company in Gujrat. All of the chemicals used in the procedure, including analytical grade methanol (99.5% purity), hexane, sulfuric acid, potassium hydroxide, and others, were purchased from Sigma Aldrich and did not undergo any additional purification processes.

2.2. Preparation of dairy scum oil

The composition of dairy waste consists of organic matter, fats, lipids, protein, lactose minerals, and some other microorganisms. Among these components the lipids and fats are used to produce biodiesel. The scum from the dairy was heated to 110°C until it became completely dry. After that, any contaminants that may be floating are filtered out using a stainless-steel mesh. Solvent extraction method has been used to extract lipids from waste dairy scum. In solvent extraction different types of solvents are available such as polar and non-polar solvents. Acetone is a polar solvent which is used in the solvent extraction process. Acetone is less volatile than hexane and cyclohexane and also biodegradable.

2.3. Biodiesel production

The dairy scum oil has higher free fatty acid (FFA) as compared to other oils. The FFA of dairy scum oil was found to be 4.6 mg KOH/g, it was necessary to reduce this high value before the conversion of dairy scum oil into biodiesel. Dairy scum oil has been treated with a mixture of sulfuric acid and methanol in a process known as acid esterification. The exact quantity of both sulfuric acid and methanol was determined by using relations, 0.05×FFA and 2.25×FFA respectively. The FFA reduced in two steps, in first step it was reduced to 2.45 and in second step it was reduced to 0.98 mg KOH/g. After reducing FFA value, dairy scum oil was converted to biodiesel in a process known as transesterification process. In this process, homogenous catalyst KOH and methanol was mixed in a ratio (catalyst concentration 0.25 w/w and methanol to oil ratio 8.50:1 v/v) and other operating parameters such as (reaction speed 600 rpm, reaction temperature 57.50°C, and reaction time 1h) were kept at specific values where optimum biodiesel yield should be obtained. Figure 1 illustrates the whole process from scum derived from the dairy to biodiesel ready to be used in diesel engines. After the completion of reaction, the mixture was poured into a separating funnel for the overnight and crude methyl ester (golden layer) was floated at the top while by product glycerin (dark brown layer) was obtained at the bottom of the separating funnel. Biodiesel washed with hot distilled water to remove the impurities and rotary evaporator was used to remove the moisture content.

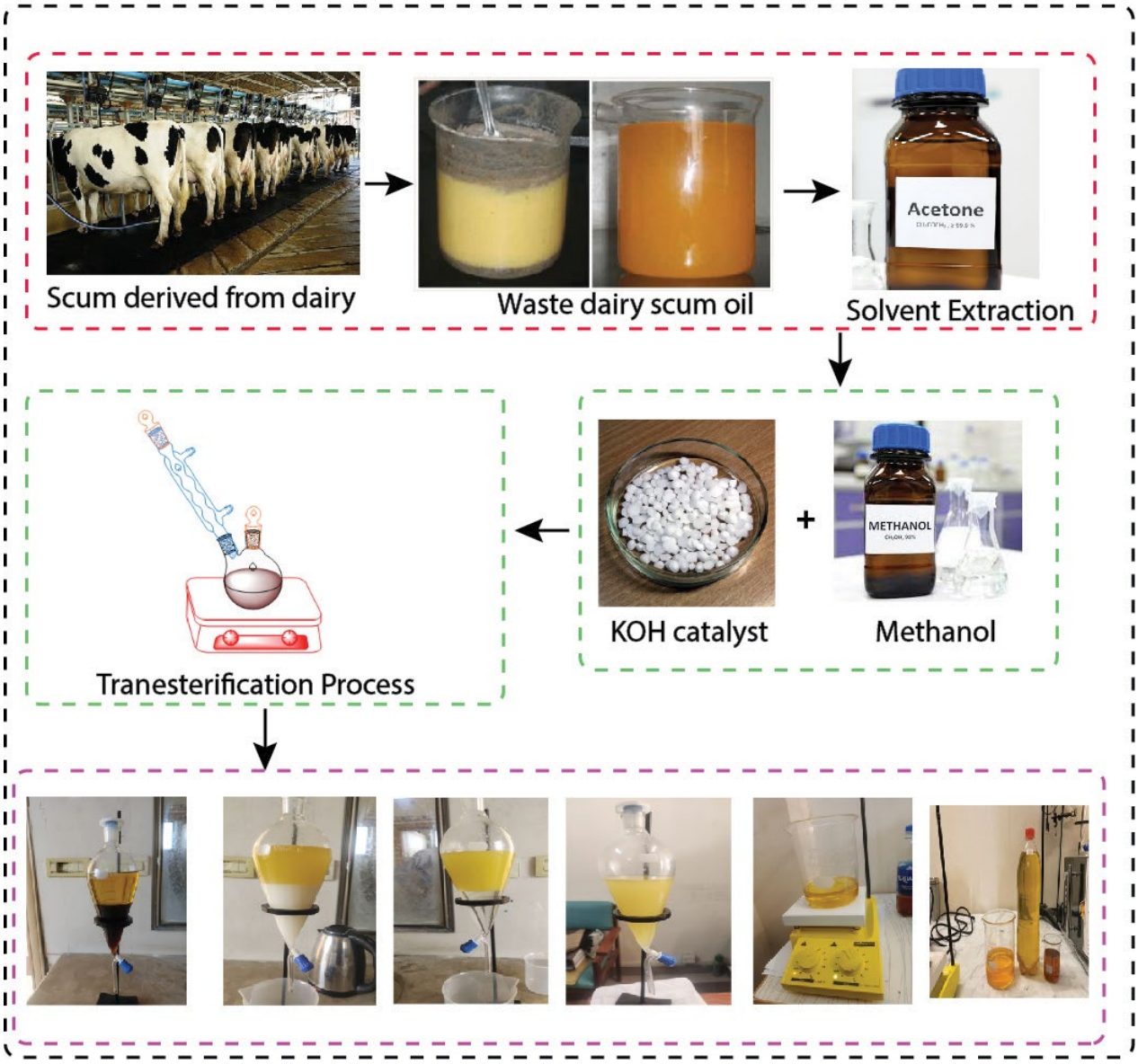

Fig. 1. Schematic diagram of conversion process of waste dairy scum to biodiesel

2.4. Economic Analysis

The project encompassed the production of biodiesel from waste dairy scum oil on a small scale in a laboratory setting, as well as doing field research by visiting dairy owners, conducting interviews, and distributing a standardized questionnaire to collect data. Circular economy analysis consists of four important factors such as design a questionnaire, logistics cost formation, cost calculation, and biodiesel cost analysis. Figure 2 depicts the details of components of the circular economy model used to produce biodiesel from the WDSO. A structured questionnaire was devised to survey 10 dairies in Gujrat to get information and opinions on WDSO commercialization and their potential application in biodiesel production. The questionnaire used in this study asked about how waste dairy scum oil is produced and disposed of, recycling methods, reasons for recycling, and the willingness of companies to participate in the waste dairy scum oil supply chain for biodiesel production. Several cost categories were examined to evaluate the viability of producing biodiesel from WDSO. The costs included the acquisition cost of the WDSO, logistics cost for collection, inputs cost for reagents and chemicals in biodiesel production, production costs for general expenses and equipment, and labor and taxes costs.

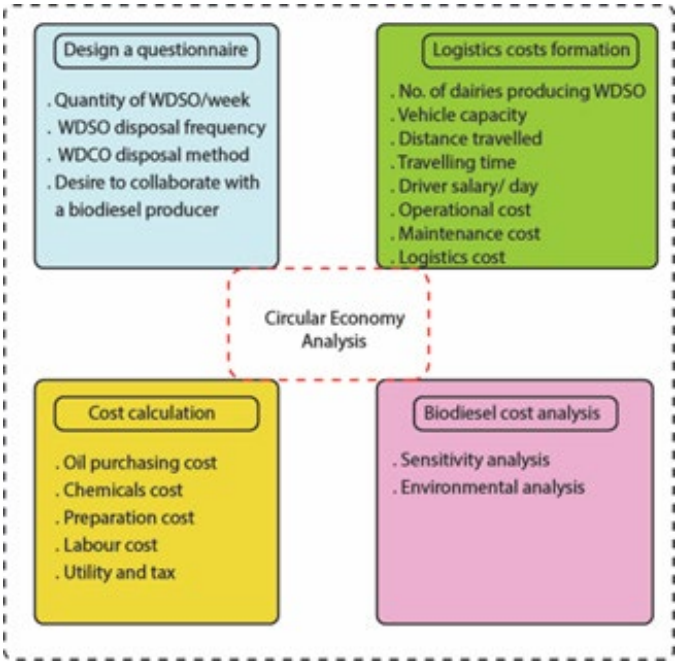

Fig. 2. Components of circular economy model.

Table 1. Survey form developed for the collection of data from dairy owners.

Does the processing of milk result in the formation of dairy scum?	Yes/No
What is the process for collecting dairy scum?	
What is the approximate daily amount of dairy scum that you produce?	Please enter your estimate in liters or kilograms
In what ways might the accumulated dairy scum be preserved?	
How long dairy scum is usual storage time until it is processed or disposed of?	
Are you currently converting the dairy scum into oil?	Yes/No
What are the current methods that you use to get rid of the waste dairy scum?	
Do you know of any possible use for the oil generated from dairy scum?	Yes/No
What applications are you most interested	• Biodiesel • Feed for animals • Manufacturing of soap and cosmetics goods
In the process of managing dairy scum, what are the most significant problems you face?	• Gathering and storing • Controlling odors • Charges for disposal • Lack of familiarity with the various processing choices
To what extent would you be interested in the possibility of converting dairy scum into oil?	• Benefits to one's finances • Advantages to the environment • Conditions imposed by regulations • Having access to both instruction and technology
Regarding the management of dairy scum, what kind of assistance would be beneficial for you to receive?	• Support with technical matters • Rewards in the form of money • The availability of processing facilities

3. Results and discussion

3.1. Biodiesel characterization

A bomb calorimeter was utilized to ascertain the calorific value of biodiesel. The Cleveland open cup apparatus was utilized to determine the flashpoint and fire point of biodiesel. A GCMS 5975C equipped with a triple I detector was utilized to ascertain the composition of the biodiesel, The usage of helium gas as a carrier gas was employed. Table 2 shows the physiochemical properties of biodiesel, while the composition of fatty acid methyl ester has been illustrated in Table 3. Oil extracted from the scum of dairy waste was found to contain fatty acids. Saturated fatty acids make up 52.61% of its composition, whereas unsaturated fatty acids make up 43.63%. Among the primary fatty acids, palmitic acid accounts for 43.8%, while oleic acid accounts for 29.05%. When it comes to the development of a fuel, the high proportions of saturated and mono-saturated fatty acids are a significant advantage. This is because the polymerization that takes place during burning will be far less than what takes place whenever a fuel is formed from polyunsaturated fatty acids happens.

Table 2. Physiochemical characteristics of biodiesel

Property	Units	Values	EN14214
Density @ 15°C	Kg/m³	822	800 to 900
Kinematic Viscosity @ 40°C	mm²/s	4.56	3.5 to 5
Acid Value	mg KOH/g	0.732	0.5
Flash Point	°C	135	>120
Fire Point	°C	140	---
Pour point	°C	3	---
Calorific Value	MJ/kg	35.5	Min. 35

Table 3. Composition of fatty acid methyl ester of waste dairy scum oil

Common Name	Structure	WDSOME
Methyl Decanoic	$C_{10}H_{20}O_2$	0.2
Methyl Lauric	$C_{12}H_{24}O_2$	0.8
Methyl myristate	$C_{15}H_{30}O_2$	1.29
Methyl Palmitate	$C_{17}H_{34}O_2$	43.81
Methyl Palmitoleate	$C_{17}H_{32}O_2$	2.94
Methyl Stearate	$C_{19}H_{38}O_2$	10.89
Methyl Oleate	$C_{19}H_{36}O_2$	29.05
Methyl Linoleate	$C_{19}H_{34}O_2$	1.14
Methyl Linoleic	$C_{18}H_{32}O_2$	8.36
Methyl Behenic	$C_{22}H_{44}O_2$	1.52

3.2. Questionnaire Analysis

Dairy scum oil is a valuable byproduct of the dairy business. Approximately 200–300 kg of dairy scum is generated daily by a significant dairy sector and can be efficiently transformed into biodiesel. Primarily, utilizing this feedstock has the benefits of creating jobs, decreasing greenhouse gas emissions, and lowering a nation's reliance on imported crude oil. The current study suggests the transesterification of WDSO using an alkali base catalyst in the presence of methanol. This process is commonly employed for converting vegetable oil into biodiesel.

A comprehensive questionnaire was created to assess 10 dairies in Gujrat regarding WDSO commercialization and their prospective use in biodiesel production. Information obtained from the survey was collected and illustrated in Figure 3. According to figure 3a, it has been estimated that 70% dairy owners produced dairy scum and 30% produced no scum. It was observed from figure 3b more than 70% dairy owners were interested into the conversion of scum oil into biodiesel while 20% wanted to produce animal feeds, only 10% were interested into manufacturing soap and cosmetic products. The responses to the next question of the survey form showed in figure 3c, 90% owners wanted to get financially benefits from their waste dairy scum, while only 10% interested to environmental sustainability. Approximately 80% of dairy owners did not have knowledge about the different waste dairy scum processing techniques, while 10% diary owners have faced

difficulties in storing and 10% in disposal charges. The dairy owners showed great interest in the conversion of waste dairy scum oil into biodiesel, approximately 80% owners wanted to get reward in the form of money from their waste dairy scum. While 20% owners wanted to know the technology behind the conversion of the waste dairy scum oil into biodiesel and they showed a positive intention to build their own biodiesel companies. The last but not the least response obtained from the survey form was about the disposal method, approximately 60% dairy owners sell their waste dairy scum to different vendors and 40% discharged directly, while no one has the idea of selling this waste diary scum to biodiesel companies due to lack of knowledge.

3.3. Logistics Cost Analysis

The logistics cost is important for the overall biodiesel production cost. WDSO must be gathered from diverse supply sources dispersed over different geographical locations. The expenses associated with collecting WDSO from dairies and transporting them to the biodiesel production units should be accepted, since the findings suggest that biodiesel generation from WDSO is economically feasible. Various routing scenarios were created, evaluated, and compared to calculate the logistics cost using data obtained from the survey. Table 4 illustrated the logistic cost analysis. There were 7 diaries out of 10 which were producing scum oil. There 7 diaries named as D1 to D7, the per day capacity of each dairy varies from 180 to 300 kg scum oil. An idea was proposed to the dairies owners to sell their waste scum to a biodiesel production company. A detailed plan of logistic cost was shared with the dairy owners to attract their intentions to contribute towards development of sustainable environment.

Table 4. Logistic cost analysis of different dairies producing dairy scum

No. of dairies producing WDSO	7						
	D1	D2	D3	D4	D5	D6	D7
Amount of WDSO daily (kg)	200	180	240	250	280	300	220
WDSO collection (days)	4	5	3	3	3	3	4
Vehicle capacity (ton)	1	1	1	1	1	1	1
Distance travelled (km)	12	5	4	8	10	14	9
Travelling time (minutes)	150	63	50	100	125	175	112
Driver salary per month (PKR)	20000	20000	20000	20000	20000	20000	20000
Logistic cost per month (PKR)	9072	3240	4320	8640	10800	15120	6804

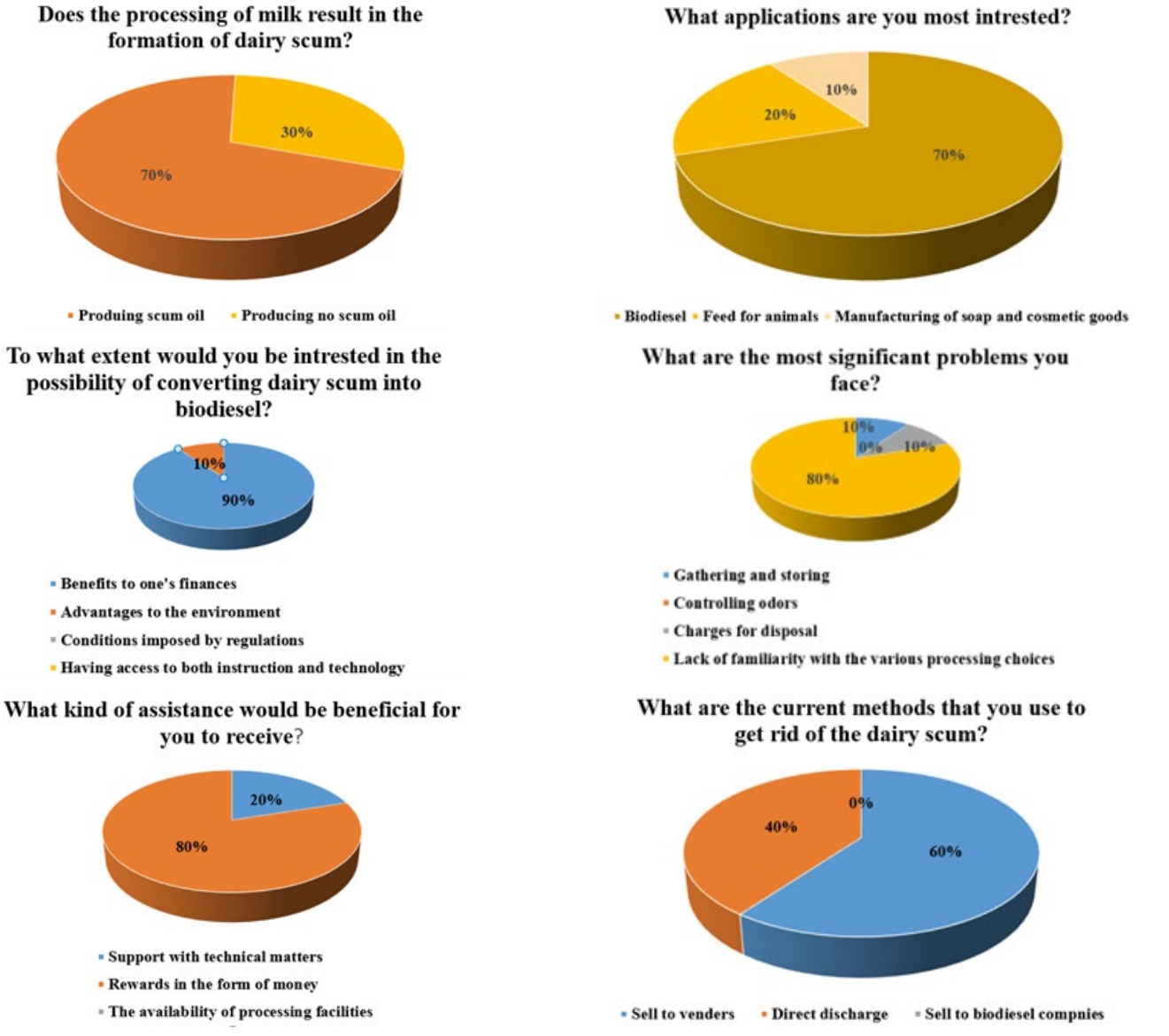

Fig. 3. Data collected from survey form.

3.4. Biodiesel cost analysis

Waste dairy scum oil has been converted to biodiesel via transesterification process. The cost of biodiesel depends on the raw materials, chemicals, operational cost, maintenance cost. In a nutshell, biodiesel cost is divided into two costs variable cost and fixed cost, which are responsible for cost calculation of biodiesel. The biodiesel production cost is determined for 1L biodiesel. The operating parameters of the transesterification process were kept as catalyst concentration 0.25 w/w, methanol to oil ration 8.50:1, reaction speed 600 rpm, reaction temperature 57.50°C, and reaction time 1 hr. The conversion rate of WDSO at these operating conditions was found to be 93%. The details of the variable and fixed costs are enlisted in Table 5. Approximately 70% dairy owners produced dairy scum and also interested to produce biodiesel form their waste dairy scum oil. The net biodiesel production cost was found to be 171 rupees. The logistic cost of biodiesel produced from the WDSO was found to be 22 rupees. The overall cost of 1L biodiesel would be 193 rupees.

Table 5. Biodiesel cost analysis

Variable costs		Fixed Cost	
Material	Price (PKR)	Utility	Price (PKR)
WDSO per kg	10	Operational cost	5
Methanol used (300g)	120	Labor cost per liter	5
KOH used (8.5g)	17	Total fixed cost	10
Acetone used (20g)	14		
Total variable cost	161		
Net Cost of biodiesel per liter		171	

3.5. Sensitivity Analysis

The sensitivity analysis performed on the biodiesel produced from the WDSO revealed the factors affecting the production and economic feasibility of biodiesel production. The key input parameters include feedstock type and cost and process parameters such as catalyst concentrations, methanol to oil ratio, operating temperature, and time, while biodiesel price and government policies determine the economic factors. Biodiesel is considered as an alternative renewable fuel which has potential to reduce the consumption of conventional fossil fuels due to its comparable engine performance and emission characteristics with high-speed diesel fuel. The most important factor is environmental sustainability. The sensitivity analysis also includes the environmental factors and land used for the biodiesel production.

In this present study two-way sensitivity analysis were performed to calculate the net profit of biodiesel produced from WDSO for 7 different dairies. The total cost of 1L biodiesel was found to be 179 PKR, and the net profit depended on the two factors price of biodiesel and quantity of biodiesel produced monthly. Table 6 illustrates the two-way sensitivity analysis to determine the net profit should be earned by diaries if they produced biodiesel. The price of biodiesel varies from 180 to 190 PKR while the quantity of biodiesel depends on the dairy scum produced by each dairy. The quantity of biodiesel produced varies from 1000 liter to 2800 liter. These analyses were performed on the capacity of 7 different dairies producing scum oil. Figure 4 depict the graphical representation of the two-way sensitivity analysis.

Table 6. Two-way sensitivity analysis on the profit of biodiesel production

Quantity of bio-diesel produced (L)	Effect of varying price of biodiesel (PKR)					
	192	194	196	198	200	202
1000	21000	23000	25000	27000	29000	31000
1200	25200	27600	30000	32400	34800	37200
1400	29400	32200	35000	37800	40600	43400
1600	33600	36800	40000	43200	46400	49600
1800	37800	41400	45000	48600	52200	55800
2000	42000	46000	50000	54000	58000	62000
2200	46200	50600	55000	59400	63800	68200
2400	50400	55200	60000	64800	69600	74400
2600	54600	59800	65000	70200	75400	80600
2800	58800	64400	70000	75600	81200	86800

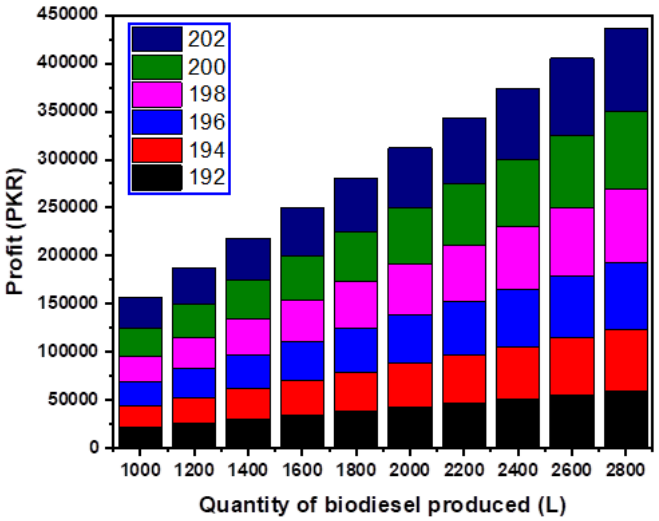

Fig. 4. Graphical representation of two-way sensitivity analysis.

3.6. Environmental Analysis

The utilization of waste dairy scum to produce biodiesel not only solve the disposal problem but also brings economical incentives to the dairy industry as well as for the development of sustainable environment. Biodiesels possess the oxygen atoms which are responsible for the complete combustion in diesel engines. Complete combustion raised the temperature and heat release rate inside the cylinder, causing the oxidation of unburned hydrocarbons. As a result of complete combustion, the HC emissions and CO emissions significantly reduced. The particulate matter emissions significantly reduced by using biodiesel blends in diesel engines. Table 7 illustrates the comprehensive details of emissions of biodiesel burned into diesel engines by different researchers.

Table 7. Comparative analysis of emissions associated with biodiesel

Author	Feedstock for biodiesel production	HC	CO	NO_x	References
Fayaz	Palm oil	↓	↓	↑	(Fayaz et al. 2021)
Luqman	Waste cooking oil	↓	↓	↑	(Razzaq et al. 2023)
Manzoore Elahi	Moringa Oleifera	↓	↑	↑	(Soudagar et al. 2021)
M.A. Mujtaba	Palm-sesame oil blend	↓	↓	↑	(Mujtaba et al. 2020)
Asif Afzal	Milk scum oil	↓	↓	↓	(Afzal et al. 2021)

4. Conclusions

To efficiently meet the demand for biodiesel, it is essential to shift attention towards utilizing low-cost feedstocks like waste dairy scum oil. The study's analysis suggests that WDSO has the potential to be used as a feedstock for biodiesel production. Pakistan is among the major milk producing country, which has potential to provide dairy scum as a primary or supplementary feedstock for large-scale biodiesel production. The following conclusions obtained from the preset study:

1. The composition of biodiesel consists of saturated fatty acids make up 52.61%, whereas unsaturated fatty acids make up 43.63%.
2. 70% dairy owners produced dairy scum and 30% produced no scum.
3. 90% dairy owners wanted to get financially benefits from their waste dairy scum, while only 10% interested to environmental sustainability.
4. Around 60% of dairy proprietors sell their waste dairy scum to various vendors, 40% dispose of it directly, and no one considers selling this material to biodiesel firms due to a lack of information.
5. The net cost of producing biodiesel was determined to be 157 rupees. The logistics cost of biodiesel derived from the WDSO was determined to be 22 rupees. One liter of biodiesel costs 179 rupees.
6. By comparing 1 liter of conventional diesel to 1 liter of biodiesel, it was discovered that the percentage of savings was 37.63%.

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