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Development of a Filtration Tank for Biodiesel

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ABSTRACT

Waste cooking oil (WCO) has gained attention as a sustainable biodiesel feedstock due to its potential to reduce greenhouse gas emissions and support the global transition to eco-friendly energy sources. However, existing filtration tanks used for WCO processing are often expensive, bulky, and unsuitable for laboratory applications. To address these challenges, a laboratory-scale filtration tank prototype was developed, emphasising affordability, compactness, and ease of maintenance. The design drew inspiration from the user-friendly features of tiffin containers and bamboo steamers, enhancing stability and operational simplicity. Filtration and mixing time studies comparing mixing times of 30 and 120 minutes were used to assess the prototype's efficacy. In contrast to the 30-minute mixing time, which demonstrated incomplete blending, the results showed that the 120-minute mixing method produced a more homogenous and consistent biodiesel product with fewer indications of phase separation and better clarity. This implies that extended mixing improves biodiesel quality and intensifies the transesterification reaction.

1. Introduction

Biodiesel has become known as a possible alternative to conventional fossil fuels in recent years since there has been a growing focus on sustainable and eco-friendly energy sources. Among the candidates, researchers are interested in biodiesel as a potential alternative fuel [1-3]. The requirement implemented by governments has significantly increased demand for biofuels, which is boosting the overall initiatives [4-6]. As the demand for biodiesel grows, the necessity for efficient and dependable manufacturing procedures becomes more apparent [7,8].

Furthermore, biodiesel has various characteristics that contribute to its attractiveness as a renewable and environmentally beneficial alternative to traditional fossil fuels. It is more environmentally friendly and non-toxic than ordinary diesel, and when blended with diesel, it will improve the engine's mechanical efficiency [9,10]. One of the significant advantages of this

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alternative fuel is that it has the same energy content as traditional fuels, making it acceptable for use alone or in combination with diesel fuel. It does not require any changes to existing engines. The production of biodiesel from waste cooking oil (WCO) presents a promising opportunity to reduce waste while generating renewable energy. However, the economic feasibility of biodiesel production is influenced by several factors, including the cost of feedstocks, the efficiency of production processes, and the filtration systems employed. Feedstock cost is a major contributor to the overall production cost. Edible oils, such as soybean and palm oil, are high-quality feedstocks, but they come with higher costs and raise concerns over food security, driving up production expenses [11,12]. On the other hand, non-edible oils and waste oils, such as WCO, offer a more affordable alternative. WCO is often available at low or no cost from food establishments and households, making it an attractive feedstock for biodiesel production [13-16]. However, WCO contains impurities and contaminants, including free fatty acids (FFAs), water, and particulate matter, negatively impacting transesterification efficiency and biodiesel quality. Effective filtration is crucial in biodiesel production to ensure consistent fuel quality while minimizing process inefficiencies [17].

Several filtration methods are used to remove impurities and contaminants from WCO, ensuring that the feedstock meets the required quality standards for biodiesel production. Cellulose and paper filters are commonly used to filter WCO and remove solid particles effectively. According to previous studies, the solid removal rate using paper filters was reported to be 78.63% [18]. These filters are cost-effective and widely used in laboratory and small-scale biodiesel production because they can efficiently capture larger particulates. However, their effectiveness diminishes with smaller contaminants, and they may require frequent replacement due to clogging, especially when filtering oils with higher viscosity. To address these limitations, researchers have explored alternative purification methods. Adsorption techniques, such as starch and cellulose-based adsorbents, have shown potential in removing FFAs, water, and unwanted compounds [19]. However, adsorption is less effective in removing solid particulates, making it an insufficient standalone method for WCO purification. Another approach involves ultrafiltration membranes, such as polypropylene (PP) hollow fibre membranes, demonstrating a 95% water removal efficiency [20]. However, their impact on colour improvement was limited to 9.5%, and hydrophobicity increased, affecting overall filtration performance. More advanced techniques, such as microwave-assisted biodiesel production, have been investigated to enhance reaction efficiency and fuel properties [21]. This method has been shown to improve biodiesel yield and reduce reaction time, making it a potential solution for large-scale biodiesel production. However, it does not directly address feedstock purification challenges, which remain critical to ensuring consistent biodiesel quality. Additionally, condensate retention issues in fuel processing systems further emphasise the importance of effective feedstock filtration in maintaining process efficiency and fuel stability [22].

Despite the advancements in biodiesel production, there is still a lack of a cost-effective, scalable, and efficient filtration system to enhance WCO-based biodiesel production. Current filtration methods require expensive materials, suffer from rapid clogging, or fail to remove all impurities effectively. Ultrafiltration membranes and adsorption techniques using starch and cellulose-based materials have shown promise but remain costly, complex, or inefficient in large-scale applications. Moreover, advanced techniques such as microwave-assisted biodiesel production have improved reaction efficiency but do not specifically address filtration challenges. These limitations highlight the need for more innovative and cost-effective filtration designs to enhance the efficiency and accessibility of the biodiesel production process, especially when dealing with WCO feedstock. To address these challenges, this study aims to develop a filtration tank for biodiesel production. The filtration tank is designed to focus on efficiency and effectiveness in the biodiesel production process. Its purpose is to provide a robust solution for removing impurities from the feedstock, thereby improving the quality and performance of the biodiesel generated. This is particularly crucial in laboratory-scale biodiesel manufacturing, where researchers and scientists require a controlled environment to conduct experiments and optimise their processes. This research paper aims to design the initial concept for the biodiesel filtration tank, fabricate the prototype tank, and conduct product development testing. The design phase of the filtration tank will be executed through Fusion 360, a sophisticated design platform known for its ability to handle intricate structures and ensure precision in dimensions. Following the design phase, a prototype will be fabricated, aligning with the specifications outlined in the design stage. Finite Element Analysis (FEA) will comprehensively evaluate the filtration tank to guarantee structural integrity and performance under various operational conditions. Beyond structural considerations, the study recognises the pivotal role of material selection and manufacturing processes. Design for Manufacture and Assembly (DFMA) software will be applied to systematically choose the optimal material and manufacturing approach. This strategic decision-making process aims to enhance efficiency, mitigate costs, and ultimately, impact beyond the immediate objectives.

2. Methodology

2.1 Conceptual and Design Phase

The design and fabrication of the filtration tank went through a series of stages. It includes planning, designing, fabricating and testing. Planning was done through an extensive literature review and studies on the existing practices and technology for developing the filtration tank of biodiesel on a lab scale. This phase is defined by the filtration tank's particular aims and criteria, such as intended filtration efficiency and compatibility with biodiesel feedstock. It also included the material selection of materials, parts and equipment for developing a filtration tank. The design of the tank's equipment involves several elements that must be considered, such as the filtration tank, tank structure and tank construction materials with various biodiesel feedstocks. The conceptual and design phase outlines the following detailed design phases, functioning as a road map for creating a lab-scale filtration tank that efficiently solves technical and operational requirements.

2.2 Filtration Tank Design

Using Fusion 360, the filtration tank will be meticulously designed to handle waste cooking oil efficiently. Fusion 360 provides a comprehensive platform for crafting intricate structures with dimensional accuracy. Key design considerations for the filtration tank include component selection and placement, the main body structure and safety factors, all aimed at optimising filtration efficiency. The design prioritises simplicity to maximise material usage and cost-effectiveness. The design process begins with a hand sketch and evolves into a multidimensional prototype using Fusion 360. Accurate dimensions are essential to ensure safety, and carefully selecting materials and components will produce a reliable and efficient biodiesel filtration tank. The filter tank design contains an innovative feature similar to a tiffin food and wood steamer bamboo to facilitate easy cleaning and maintenance. Inspired by the concept of tiffin food and wood steamer bamboo shown in Figure 1, the tank structure is configured to minimise angles and gaps where contaminants or residues may build during filtering. The design creates a smooth, continuous surface, lowering the possibility of particle entrapment and allowing for simple cleaning methods. The tiffin food and wood steamer bamboo-inspired aspect facilitates access, allowing for the fast removal of any buildup of sediments or impurities. This function makes cleaning easier and improves the filtering system's general cleanliness and durability. Using a tiffin food and wood steamer bamboo-like shape emphasises the commitment to utility and user-friendliness, boosting functionality and simplicity of operation in the context of lab-scale biodiesel synthesis.

(a) Tiffin Food (b) Wood steamer bamboo

Fig. 1. Inspired concept of tiffin food and wood steamer bamboo

The disassembly concept in the filtration tank, as shown in Figure 2, inspired by the design of a tiffin food and wood steamer bamboo, focuses on ease of maintenance and cleaning by enhancing accessibility to internal components. The tank is designed to allow for simple disassembly of significant components, like how a tiffin food and wood steamer bamboo is separated from its base. This design characteristic ensures that the various components, such as filter media, may be easily accessible, removed, and changed without requiring complex disassembly. The tiffin food and wood steamer bamboo-inspired disassembly idea lowers maintenance downtime, resulting in a more efficient and user-friendly system. Quick-release mechanisms, snap-fit, connectors, or other user-friendly fastening systems may be incorporated into the tank design, allowing users to remove and reassemble the filtering components with little effort. This design simplifies everyday maintenance activities and thoroughly cleans interior surfaces, preventing impurities from accumulating and assuring the filtering process's continuous effectiveness. Moreover, the disassembly idea improves the filtration system's flexibility, allowing for changes or upgrades as needed without considerable downtime or specialised tools. The filter tank prioritises accessibility and simplicity of maintenance by drawing inspiration from the tiffin food and wood steamer bamboo's user-friendly design, contributing to a more practical and efficient lab-scale biodiesel manufacturing process.

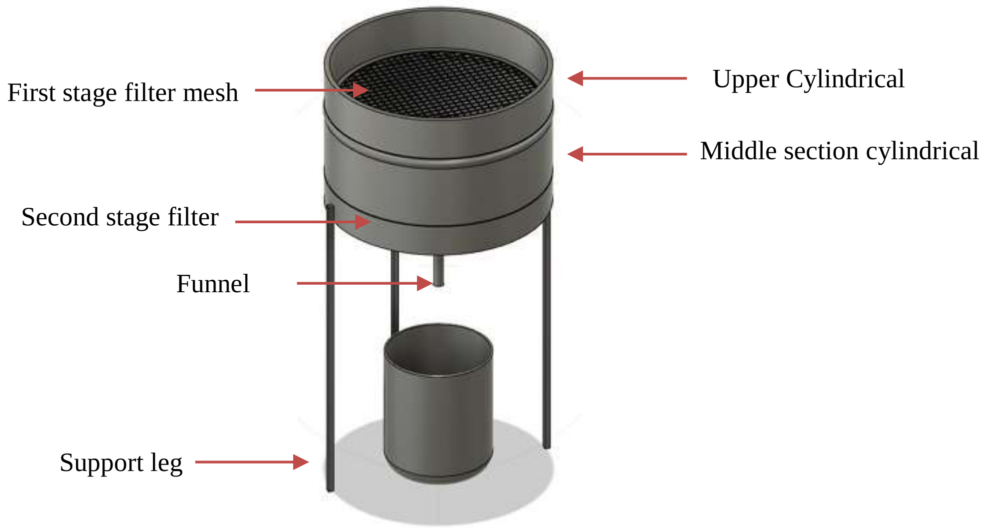

Fig. 2. Filtration tank design

2.3 *Finite Element Analysis (FEA)*

FEA will conduct a comprehensive structural analysis of the filtration tank. FEA is a computer approach for simulating and analysing the physical behaviour of the filtration tank. This analytical approach will provide insights into stress, displacement, and strain characteristics, ensuring the tank's structural integrity under various operational conditions. FEA simulation is a popular numerical method for solving structural, vibration, and heat problems by predicting the design process [23-25]. Due to the need to simulate the static strength of the chosen material, steps of the plan interaction were applied, beginning with drawing the three-dimensional model of the collapsible pot haulier with computer-aided design (CAD) programming. Then, the simulation FEA process starts by demonstrating calculations that address the genuine models. Measure displaying with CAD programming using Fusion 360 software. The material's safety factor must be analyzed to determine whether the material could stand to the load given (Table 1). The reliable value of the material's safety factor is one; if the value is less than one, the material is considered unsafe. The formula for the safety factor is expressed by Huda *et al.,* [26] and Wu *et al.,* [27].

$$The\ factor\ of\ safety = \frac{\sigma_{Maximum}}{\sigma_{Minimum}} \quad (1)$$

Where: $\sigma_{Maximum}$ is the highest stress value that causes the design model or objects to break or crack, while $\sigma_{Minimum}$ is the stress value allowed to be applied to selected materials. Table 2 lists the material properties.

Table 1
Components of the filtration tank

Component	Material	Safety factor
Upper cylindrical	Steel, Mild	Yield Strength
First stage filter mesh	Steel, Mild	Yield Strength
Middle section cylindrical	Steel, Mild	Yield Strength
Second stage filter mesh	Steel, Mild	Yield Strength
Funnel	Steel, Mild	Yield Strength
Support legs	Steel	Yield Strength

Table 2
Materials properties for each component

Properties	Steel, Mild	Steel
Density	7.850E-06 kg / mm^3	7.850E-06 kg / mm^3
Young's Modulus	220000.00 MPa	210000.00 MPa
Poisson's Ratio	0.28	0.30
Yield Strength	207.00 MPa	207.00 MPa
Ultimate Tensile Strength	345.00 MPa	345.00 MPa
Thermal Conductivity	0.05 W / (mm C)	0.06 W / (mm C)
Thermal Expansion Coefficient	1.200E-05 / C	1.200E-05 / C
Specific Heat	480.00 J / (kg C)	480.00 J / (kg C)

2.4 *Transesterification Process*

The process is conducted at two different mixing times, 30 minutes and 120 minutes, and the heating temperature is around 50°C. The WCO is mixed with 40 ml of methanol and 0.7g of potassium hydroxide and stirred using a magnetic stirrer at 2000 rpm.


Fig. 3. Magnetic stirrer

2.5 Washing Process

In this stage, the FAME is separated from the glycerol, excess methanol, and catalyst. Removing glycerol from biodiesel samples can result in the production of pure FAME. However, it is certainly not pure fuel. Water washing is a great way to get rid of both contaminants. It also eliminates any leftover substances in FAME, such as sodium salt and soaps.

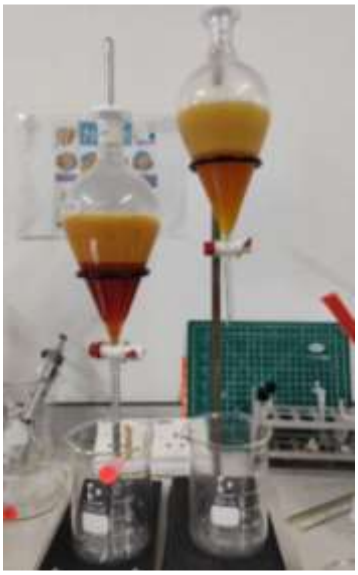
Fig. 4. Washing process to remove the impurities in FAME

3. Results
3.1 Design Efficiency

Developing a portable and easily transportable filtration tank for laboratory use focuses on balancing functionality, durability, and convenience in the design. As shown in Figure 5, this filtration tank is made from stainless steel, which provides the needed structural strength for lab tasks while remaining light enough to be easily moved. Selecting appropriate materials helps the tank withstand the chemical effects of affecting the processing of WCO biodiesel, preventing corrosion and increasing its durability. The tank's compact design ensures it can easily fit into standard laboratory spaces without taking up too much room. When not in use, it can be easily put away, freeing up more room in the lab for other tasks. The system's design considers adaptability, enabling researchers to adjust or expand the filtration setup according to specific experimental requirements. The compact, stackable nature of the tank allows for easy portability and transportation between different labs or experimental setups. The design also ensures that each stage can be accessed separately without needing cleaning, maintenance, or replacement tools. This makes the upkeep process much more manageable.

Fig. 5. Filtration tank

3.2 Structural Analysis

The structural analysis of the filtration tank was conducted to evaluate its performance under the applied static loads using Fusion 360. The results in Figure 6 indicated a von Mises stress ranging from 2.51E-05 MPa to a maximum of 55.37 MPa remains within the yield strength of mild steel, suggesting that the tank is structurally sound under the given loading conditions. The filtration tank will not experience plastic deformation under the applied loads because the maximum value is below the yield strength of mild steel. Figure 7 shows the result for the safety factor of the filtration tank. A safety factor above 1 indicates that the design can handle the stresses safely. In this case, the safety factor ranges from 3.74 to 15.00. The minimum value of 3.74 shows that the structure is more than three times stronger than necessary, providing a considerable buffer for unexpected loads or variations in material properties.

As shown in Figure 8, principal stresses represent the normal stresses acting on specific planes where shear stress is zero. The 1st principal stress ranged from -13.88 MPa to 52.53 MPa, while the 3rd principal stress ranged from -59.45 MPa to 16.44 MPa. These values describe the maximum tensile and compressive stresses experienced by the tank. Both stresses remain within acceptable limits for mild steel, indicating that the material can withstand the applied loads without cracking or failure. The balanced stress distribution confirms the tank's geometry and design effectiveness.

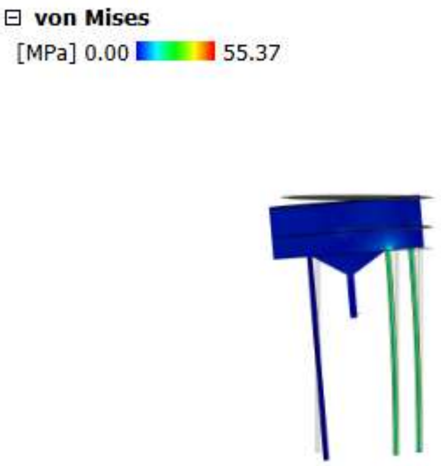

Fig. 6. von Mises stress result

Fig. 7. Safety factors result

Fig. 8. Principal stresses represent the normal stresses for the filtration tand

Whereas for the displacement (Figure 9), the results showed a maximum deformation of 5.16 mm, which is minimal and unlikely to impact the tank's functionality or performance. Reaction forces were also analyzed, with a total force of 129.82 N distributed across the tank's supports, indicating that the tank's support structure is adequate for handling the applied loads. It was noting that the filtration tank performs well under the given static loading conditions. The von Mises stress remains well below the yield strength of mild steel, and the safety factor provides a generous margin of reliability. The principal stress distribution further validates the structural integrity, while the minimal displacement ensures operational stability. These results confirm that the tank design is robust and suitable for its intended application, ensuring durability and reliable performance during its operational lifecycle.

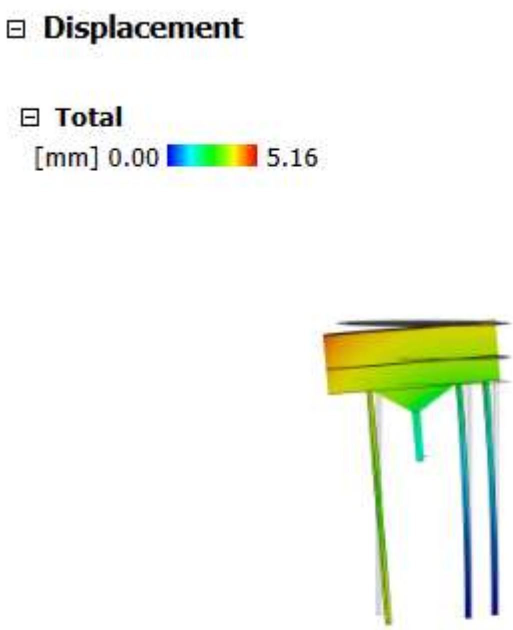

Fig. 9. Displacement results of the filtration tank

3.3 Filtration Process

Developing a two-stage filtration tank (upper cylindrical and middle section cylindrical) for WCO purification in biodiesel production significantly results in filtration efficiency, oil quality and operational sustainability.

As shown in Figure 10, the first stage (upper cylindrical) is equipped with a 30 mesh (0.6 mm) filter, effectively removing bigger particles like leftover food and sediments, protecting the finer stage in second-stage filter (middle section cylindrical) and enhancing overall system efficiency. This first filtering process prevents contaminants from reaching the second stage.

Fig. 10. First stage of filtration

The second stages (middle section cylindrical), as shown in Figure 11, where the 40-mesh (0.45 mm) filter purifies the oil by eliminating smaller particles, enhance overall filtration efficiency, ensuring that the biodiesel feedstock is cleaner of the filtered oil and prolongs the lifespan of the filter of both filters by distributing the filtration load efficiently. This leads to reduced maintenance costs and downtime associated with filter replacement. Moreover, the dual-stage filtration tank design improves operational flexibility and scalability, making it adaptable for varying feedstock conditions in lab or small-scale production. This dual-mesh approach guarantees the complete elimination of impurities while keeping the flow rates at their best during filtration. The final stages involve using filter paper, which offers precise filtration to eliminate minimal impurities like tiny particles and small amounts of pollutants that could impact biodiesel quality. This thorough three-step process leads to increased purity of filtered oil, improving the effectiveness and quality of biodiesel production.

Fig. 11. Second stage (middle section cylindrical) of filtration

3.4 Transesterification Process

The results of the two samples of WCO biodiesel, which are transesterified at different mixing times, can be seen in Table 1. The colour of biodiesel samples from waste cooking oil for the mixing time of 30 minutes appears much darker than waste cooking with a mixing time of 120 minutes. The biodiesel produced at different mixing times using a magnetic stirrer can show noticeable differences due to the extent of the transesterification process and impurities. Biodiesel is produced with a shorter mixing time of 30 minutes, often darker and cloudier. This is because the transesterification reaction is incomplete, leaving higher levels of unreacted triglycerides and other impurities in the mixture. These leftover materials can present a yellow-brown shade to the biodiesel and reduce its transparency, making it appear less clear. In contrast, biodiesel produced with a longer mixing time of 120 minutes generally shows a brighter and more transparent tone. The longer mixing time allows the reaction to reach completion, converting more triglycerides into methyl esters and reducing the presence of impurities. As a result, the biodiesel has fewer suspended particles and contaminants, resulting in a consistent pale yellow. The increase in transparency and paler colour are indicators of higher-quality biodiesel with better purity and fewer impurities. The sample from the mixing times 30 minutes seems relatively homogenous but may show early stages of phase separation or incomplete mixing. This could indicate that 30 minutes is insufficient to thoroughly blend the reactants (e.g., oil, catalyst, alcohol) for optimal biodiesel production. Incomplete mixing might lead to unreacted oil or uneven distribution of the additives, resulting in lower biodiesel quality. For the mixing times of 120 minutes, the sample appears more settled and possibly more uniform in texture and consistency. The longer mixing time facilitates better reactant interaction, promoting a more complete transesterification reaction. This could lead to improved biodiesel properties, such as reduced viscosity and better phase clarity, which are desirable for fuel performance.

Table 1
Transesterification of WCO biodiesel at 30 and 120 mixing times

Mixing Times (minutes)	30	120
WCO Biodiesel Samples		

4. Conclusions

In conclusion, biodiesel is mainly produced from waste cooking oil through transesterification. Several issues, such as economic and environmental factors, have led to the development of biodiesel production technologies from waste cooking oil as a feedstock using various processes. The filtration tank's design emphasizes the selection of robust materials to withstand the chemical effects of waste cooking oil, ensuring its durability and structural integrity while remaining compact and manageable. The two-stage filtration method has successfully removed larger and smaller impurities from the waste cooking oil, resulting in better biodiesel quality and operational sustainability. Furthermore, comparing biodiesel samples produced at different mixing times demonstrates how the transesterification process influences the result, highlighting the importance of reaction completion in achieving higher-quality biodiesel. The innovative design ideas and thorough testing validate the filtration tank's ability to significantly enhance the biodiesel production process, aligning with the aim of sustainable and environmentally friendly energy for the future.

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