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Biofuels: Bridging the Gap to a Greener Energy Future

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---***ABSTRACT***---

Biofuels, derived from renewable organic materials, present a critical opportunity to reduce reliance on fossil fuels and mitigate the environmental consequences of greenhouse gas emissions. As global energy demands grow and climate change intensifies, the need for sustainable energy alternatives has become urgent. This paper examines the potential of biofuels to bridge the gap to a greener energy future, exploring their role as substitutes for fossil fuels and their ability to significantly reduce carbon emissions. While biofuels offer substantial environmental benefits, their production faces challenges, including high costs, competition for land and water, and lifecycle emissions. The review analyzes both traditional and advanced biofuels, such as those derived from agricultural waste, and other non-food biomass sources, which could provide more sustainable and scalable solutions. By investigating innovations in biofuel production technologies and alternative sources, this study highlights how biofuels can contribute to global energy security and environmental sustainability. The review also addresses how improved policies and research investments could enhance biofuels' efficiency and economic viability, promoting their adoption as a critical element in the transition to a low-carbon economy.

Keywords: *Biofuels, Carbon emissions reduction, Fossil fuel alternatives, Agricultural waste biofuels, Sustainable energy transition, Beef Tallow, Monk Fruit Waste*

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Context | What are Biofuels?

Biofuels are renewable energy sources derived from organic materials, known as biomass, which include plant materials, animal waste, and microbial biomass. These fuels can be produced through various biological, chemical, and thermal processes, transforming the raw organic materials into energy-rich substances such as ethanol, biodiesel, biogas, and biohydrogen. The most common types of biofuels include bioethanol, which is primarily made from sugarcane and corn, and biodiesel, produced from vegetable oils and animal fats. Biofuels are considered renewable because the raw materials used in their production can be replenished through natural processes and agricultural practices, in contrast to fossil fuels, which are finite resources formed over millions of years (Hussain et al., 2021; Tang et al., 2020).

The production and use of biofuels offer several environmental and economic benefits. Biofuels contribute to reducing greenhouse gas emissions as they produce fewer pollutants compared to fossil fuels. In the last decade, a study by Wigmosta et al. (2011) demonstrated that large-scale production of microalgae-based biofuels could meet up to 5% of the U.S. transportation fuel needs while reducing carbon emissions by approximately 70% compared to petroleum-based fuels.

Biofuels can be categorized into primary and secondary types based on their source and processing methods. Primary biofuels, such as firewood, wood chips, and animal dung, are derived directly from unprocessed organic materials and are primarily used for heating, cooking, and electricity generation in their raw form with minimal processing. In contrast, secondary biofuels, including ethanol, biodiesel, and biogas, are produced through more complex processes that convert biomass into liquid or gaseous fuels. These refined secondary biofuels are suitable for use in transportation and industrial applications (Demirbas, 2011).

Agricultural waste materials fall under the category of secondary biofuels. These materials, which include crop residues, manure, and other organic by-products from agricultural processes, are converted into biofuels through biochemical or thermochemical processes. (Rahimi, et.al, 2022)

Biofuels possess the ability to decrease dependence on non-renewable energy sources, enhancing energy security for many countries. Additionally, biofuel production can promote agricultural development by providing farmers with new markets for their crops and waste products, potentially leading to economic growth in rural areas. Innovations in biofuel technology, such as the use of microalgae and agricultural waste, are making biofuel production more efficient and sustainable, thereby expanding its potential as a key component in the transition to a low-carbon economy (Zhu, 2015; Wigmosta et al., 2011).

Brazil, for example, serves as a notable case study in the use of biofuels, particularly ethanol derived from sugarcane. The country has been utilizing sugarcane ethanol since the 1970s, and it now accounts for over 40% of the fuel used in Brazilian cars, thanks to the widespread adoption of flex-fuel vehicles that can run on both ethanol and gasoline. In 2019, Brazil produced approximately 37.38 billion liters of ethanol, illustrating the country's commitment to biofuel as a sustainable energy source. This shift has significantly reduced Brazil's dependence on imported oil, also cementing Brazil as one of the world's leading biofuel producers (Goldemberg, 2008).

I. Introduction

1.1 | Current Fuel Practices & Limitations

The reliance on fossil fuels for energy has led to significant environmental and economic challenges. Fossil fuel combustion is the primary source of greenhouse gas emissions, contributing to global warming and climate change. For example, during periods of political instability in oil-producing regions, global oil prices can spike dramatically, causing economic strain on importing countries. According to the International Energy Agency (IEA), oil prices have seen significant fluctuations, from a low of $16 per barrel in April 2020 to over $85 per barrel in October 2021, reflecting the market's vulnerability to geopolitical events and production changes (International Energy Agency, 2021). This volatility underscores the necessity for stable, reliable energy alternatives that can reduce dependency on fossil fuels and enhance energy security.

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Furthermore, the environmental impact of fossil fuel consumption cannot be overlooked. The combustion of coal, oil, and natural gas is the largest source of greenhouse gas emissions, contributing significantly to global warming and climate change. Moreover, fossil fuel combustion accounted for approximately 74% of total U.S. greenhouse gas emissions, with transportation and electricity generation being the largest contributor. All in all, the aforementioned large scale ramifications of such combustion and dependence of fossil fuels cements an unsustainable future, warranting the immediate shift towards the more promising future of biofuels, not only promoting a more circular economy, but also limiting greenhouse gas emissions and reducing overall waste collection.

1.2 | Environmental & Economic Impacts of Fossil Fuels

The environmental impacts of fossil fuels extend beyond greenhouse gas emissions. Fossil fuel extraction and use result in significant water and soil pollution, adversely affecting ecosystems and biodiversity. Economically, fossil fuels are subject to volatile market conditions, impacting global economies. The urgency for an alternative energy source is underscored by the economic and environmental costs of continued fossil fuel dependence, driving the search for sustainable and renewable alternatives like biofuels.

Encompasses significant water and soil pollution, and adverse effects on ecosystems and biodiversity. For instance, oil spills during extraction and transportation can devastate marine and coastal ecosystems. The Deepwater Horizon oil spill in 2010 released approximately 4.9 million barrels of oil into the Gulf of Mexico, causing extensive damage to wildlife habitats and marine life (NOAA, 2016). Additionally, the process of hydraulic fracturing has been associated with groundwater contamination and increased seismic activity, further illustrating the environmental hazards of fossil fuel extraction (EPA, 2016).

As such, the need for more eco-friendly and sustainable energy solutions is imperative to mitigate these impacts. Biofuels, derived from renewable biological sources, present a viable alternative. They offer the potential to reduce greenhouse gas emissions significantly and decrease environmental pollution. For example, the use of biofuels in transportation can reduce CO_2 emissions by up to 86% compared to traditional gasoline. Furthermore, biofuels can contribute to energy security by diversifying the energy supply and reducing reliance on imported oil (EPA, 2010).

1.3 | Promise of Biofuels of an Alternative

Biofuels present a feasible alternative to fossil fuels due to their renewable nature and lower environmental impact. Derived from biological materials such as plants and microorganisms, biofuels offer a sustainable energy source that can reduce greenhouse gas emissions and dependence on finite resources . The production and use of biofuels are aligned with global efforts to combat climate change and promote energy security. Recent advances in biofuel technology, particularly in the harnessing of agricultural waste products, demonstrate the potential for biofuels to become a mainstream energy source (Siddiki et al., 2022).

By the same token, the transition to biofuels is further supported by advancements in technology and increasing investment in renewable energy. As the world moves towards a low-carbon economy, biofuels have the potential to play a critical role in diversifying energy portfolios and achieving climate goals. The global biofuels market is expected to grow significantly, with estimates suggesting it could reach $154.76 billion by 2027, driven by increasing demand for cleaner energy and supportive government policies (Fortune Business Insights, 2020). Biofuels' contribution to a 'greener' earth is evident in their lifecycle analysis, which shows that biofuels can reduce total greenhouse gas emissions by an average of 50-60% compared to fossil fuels (International Energy Agency, 2021). Additionally, biofuel production from waste materials, such as used cooking oil and agricultural residues, further enhances their environmental benefits by reducing waste and associated emissions (IEA Bioenergy, 2019).

These environmental advantages are supported by numerous studies. For example, a study by the European Commission found that advanced biofuels could achieve greenhouse gas savings of up to 90% compared to conventional fossil fuels (European Commission, 2017). Another report by the International Renewable Energy Agency (IRENA) indicated that biofuels have the potential to meet 20% of the world's energy needs by 2050 while significantly reducing global greenhouse gas emissions (IRENA, 2016).

Different substrates can be used for biofuel production, each with unique advantages and challenges. Plant-based sources, such as corn, sugarcane, and oil palm, have been traditionally used for biofuel production. However, these crops often compete with food production and require significant land and water resources. On the other hand, microalgae and macroalgae have emerged as promising substrates due to their high lipid content, rapid growth rates, and ability to grow in non-arable land and wastewater. Algae-based biofuels offer a sustainable solution with minimal competition for agricultural resources and the potential for higher yields compared to terrestrial crops

1.4 | Drawbacks of Biofuels & Alternatives

While biofuels present a promising alternative to fossil fuels, they are not without their drawbacks. These disadvantages stem from various factors, including economic, environmental, and technical challenges. Understanding these limitations is critical towards achieving overall feasibility and sustainability of biofuels as a primary energy source.

A - High Production Costs

One of the primary disadvantages of biofuels, especially advanced biofuels such as those derived from microalgae, is their high production cost. Producing biofuels from microalgae involves several costly processes, including cultivation, harvesting, and extraction. For instance, the cultivation of microalgae requires large volumes of water and nutrients, which can significantly increase operational costs. Moreover, the harvesting process often necessitates sophisticated technologies to separate the microalgae from water, adding further financial burden. According to a 2020 study, the cost of producing algal biofuels can be up to $3.50 per gallon, compared to $2.00 per gallon for conventional fossil fuels (International Renewable Energy Agency, 2020).

B - Land space and water usage

Moreover, another immense drawback with biofuels is their impact on land and water resources. While biofuels can be produced from various feedstocks, including agricultural waste, their production often competes with food crops for land and water. This competition can lead to food shortages and increased food prices. A 2019 study highlighted that biofuel production consumes approximately 70% more water than conventional fossil fuel, while also noting that large-scale cultivation of biofuel crops can lead to deforestation and loss of biodiversity, further exacerbating environmental concerns (Gerbens-Leenes et al., 2019).

C - Earth’s energy budget

Although biofuels may be considered to have lower greenhouse gas (GHG) emissions compared to fossil fuels, the overall energy balance and lifecycle emissions can be complex and sometimes unfavorable. The production of biofuels involves various stages, each contributing to the maximum total GHG emissions. For instance, the cultivation of feedstocks, such as corn or soybeans for ethanol and biodiesel, requires significant amounts of energy and fertilizers, which can result in considerable GHG emissions.

Another 2019 meta-analysis found that the GHG emissions reduction for corn ethanol was only about 20% compared to gasoline when considering the entire lifecycle (de Oliveira et al., 2019). This modest reduction calls into question the effectiveness of some biofuels in mitigating climate change.

1.5 | Potential of Reported Raw Materials Used for Biofuel Production

1.6 | Table Comparison

II. Methodologies & Sources

2.1 | Monk Fruit

Origin and General Uses

Monk fruit (*Siraitiagrosvenorii*) is a small, round fruit native to southern China and northern Thailand, traditionally used in Chinese medicine for treating coughs and sore throats. Its natural sweetness, derived from mogrosides, has made it a popular low-calorie sweetener in modern diets (Siddiki et al., 2022). Mogrosides are significantly sweeter than sucrose but contain fewer calories, thus making monk fruit an appealing choice for health-conscious consumers.

Chemical Constituents

The fruit primarily contains carbohydrates, including fructose and glucose, as well as proteins, vitamins, and minerals. The key component, however, is mogroside V, a non-caloric glycoside responsible for the fruit's sweetness. Additional constituents include cucurbitacins, triterpenoids, and flavonoids, which provide antioxidant properties (Zhang et al., 2021).

Use as a Biofuel

Monk fruit's high carbohydrate content presents potential for bioethanol production. Research by Siddiki et al., (2022) demonstrated that the sugars in monk fruit waste can be efficiently fermented to produce bioethanol, achieving a yield of 0.45 g/g of dry substrate. This process contributes to the circular economy by repurposing agricultural waste. Additionally, Zhang et al., (2021) found that mogrosides, after extraction, could be fermented into bioethanol, yielding 0.38 g/g.

Practical Evaluation

Monk fruit's carbohydrate-rich composition makes it a promising feedstock for biofuel production. Its growing use as a sweetener increases the availability of processing waste, which can be repurposed, contributing to environmental sustainability and economic viability. However, further optimization of the fermentation process is necessary to enhance bioethanol yield.

2.2 | Coconut Husk

Origin and General Uses

Coconut husk, the fibrous outer layer of the coconut (Cocosnucifera), is often discarded after extracting the edible kernel and water. It is commonly used to produce coir, a natural fiber utilized in products like ropes, mats, and brushes. Additionally, coconut husks serve as mulch and natural soil conditioners in agriculture.

Chemical Constituents

Coconut husk consists of lignin, cellulose, hemicellulose, and pectin, with lignin providing the structural rigidity that makes it resistant to microbial degradation. The high lignin content complicates biofuel production, as it necessitates pretreatment to break down the lignocellulosic matrix into fermentable sugars (Ravindran et al., 2018).

Use as a Biofuel

Coconut husk has been explored as a feedstock for bioethanol production. Ravindran et al., (2018) demonstrated that alkaline hydrolysis pretreatment improves the enzymatic breakdown of cellulose, increasing fermentable sugar yield. The study reported a bioethanol yield of 0.52 g/g of pretreated coconut husk. Additionally, coconut husk can be used to produce biochar and bio-oil through pyrolysis, as reported by Ramachandran et al., (2019), with bio-oil yields of 35% by weight and a calorific value of 29 MJ/kg.

Evaluation

While coconut husk offers a sustainable biofuel source due to its availability in tropical regions, its high lignin content raises production costs due to necessary pretreatments. However, advancements in pretreatment technologies, such as those explored by Ravindran et al., (2018), could improve bioethanol yield and economic feasibility.

2.3 | Fruit Juices

Origin and General Uses

Fruit juices are extracted from fruits like oranges, apples, grapes, and berries, primarily for consumption due to their rich vitamin and mineral content. Waste juices from overproduction or spoilage can serve as an efficient feedstock for bioethanol production.

Chemical Constituents

Fruit juices are composed of simple sugars such as glucose, fructose, and sucrose, making them ideal for fermentation. They also contain vitamins (notably vitamin C), minerals (e.g., potassium), and phenolic compounds, which have antioxidant properties (Singh et al., 2020).

Use as a Biofuel

Waste fruit juices can be fermented into bioethanol, leveraging their high sugar content. Singh et al. (2020) demonstrated that bioethanol production from waste fruit juices yielded similar results to traditional feedstocks, such as sugarcane, providing an alternative method for reducing food waste while generating renewable energy.

Evaluation

Repurposing waste fruit juices for bioethanol production is a sustainable approach to mitigate food waste and produce renewable energy. However, the availability of such waste is influenced by seasonal production and market demand, necessitating strategies to ensure a steady supply for biofuel production.

2.4 | Watermelons & Jackfruit

Origin and General Uses

Watermelons (*Citrulluslanatus*) and jackfruit (Artocarpusheterophyllus) are tropical fruits commonly grown in warm climates. Watermelon is primarily consumed as a fresh fruit or juice, while jackfruit is known for its use in vegetarian dishes as a meat substitute.

Chemical Constituents

Watermelons are composed primarily of water (over 90%) and sugars, including fructose, glucose, and sucrose. Jackfruit, by contrast, contains a mix of carbohydrates, dietary fiber, and vitamins, with its seeds particularly rich in starch and proteins (Ramachandran et al., 2018).

Use as a Biofuel

Both fruits have potential as bioethanol feedstocks. Ramachandran et al. (2018) demonstrated the feasibility of producing bioethanol from watermelon juice, achieving fermentation yields comparable to traditional sugar sources. Similarly, jackfruit waste, including seeds and pulp, can be fermented to produce bioethanol, offering a sustainable way to repurpose agricultural by-products.

Evaluation

The high sugar content of watermelon and jackfruit makes them efficient feedstocks for bioethanol production, especially in regions where they are abundant. Dehydration steps may be necessary for watermelon due to its high water content, but the overall process remains efficient. Jackfruit waste, in particular, presents an excellent opportunity for bioethanol production from discarded fruit materials.

Detailed Methodology for Biofuel Production from Watermelon Husks and Seeds (Adapted from C, Liu, et al., 2021)

Step 1: Collection and Preparation of Watermelon Waste

a. Collection: Watermelon husks (the outer rind) and seeds are collected from juice production facilities or local markets, where these components are typically discarded as waste.

b. Washing: The collected husks and seeds are thoroughly washed with distilled water to remove any dirt, pesticides, or other contaminants.

c. Drying: The clean husks and seeds are then air-dried under natural sunlight or in an oven at a low temperature (about 60°C) until the moisture content is reduced to less than 10%. This step is crucial to prevent microbial growth during storage and to facilitate easier grinding.

d. Grinding: Once dried, the husks and seeds are ground into a fine powder using a mechanical grinder or milling machine. The particle size should be small enough to maximize the surface area for subsequent enzymatic hydrolysis, typically around 0.2-0.5 mm.

Step 2: Enzymatic Hydrolysis

a. Enzyme Selection: A cocktail of cellulase and hemicellulase enzymes is prepared, which is essential for breaking down the cellulose and hemicellulose components in the watermelon husks and seeds. If seeds are rich in oils, additional lipase enzymes might be used to break down any lipids present.

b. Hydrolysis Process: The ground watermelon waste is mixed with the enzyme solution in a reactor vessel. The mixture is maintained at a controlled temperature (45-50°C) and a slightly acidic pH (around 4.8-5.5) for optimal enzyme activity (Gad &Fawzy, 2020). This process typically takes 24-48 hours, during which the enzymes convert the complex carbohydrates into simple fermentable sugars like glucose and xylose.

c. Monitoring: The progress of hydrolysis is monitored by measuring the reducing sugar concentration using methods like the DNS (3,5-dinitrosalicylic acid) assay **(Khan et al., 2014).** The end-point is reached when no further increase in reducing sugars is observed.

Step 3: Fermentation

a. Inoculum Preparation: *Saccharomyces cerevisiae* yeast is prepared as the fermenting agent. The yeast culture is grown in a nutrient broth (usually containing glucose, yeast extract, and peptone) at 30°C until it reaches an optimal concentration (approximately 10^7 cells/mL).

b. Fermentation Setup: The hydrolyzed watermelon mixture, now rich in sugars, is transferred to a fermentation vessel. The vessel is sterilized to avoid contamination, and the yeast inoculum is added to initiate fermentation.

c. Fermentation Conditions: Fermentation is carried out under anaerobic conditions at 30°C for 48-72 hours. The vessel is sealed with an airlock to prevent oxygen from entering while allowing CO2 to escape. During fermentation, the yeast converts the sugars into ethanol and carbon dioxide (Gad &Fawzy, 2020).

d. Monitoring: The progress of fermentation is tracked by measuring the ethanol concentration using gas chromatography or by monitoring the decrease in sugar concentration using High-Performance Liquid Chromatography (HPLC).

Step 4: Distillation and Ethanol Recovery

a. Distillation: Once fermentation is complete, the fermented broth (containing ethanol, water, and residual biomass) is subjected to distillation. The mixture is heated in a distillation column, where ethanol, with a lower boiling point (78.37°C), vaporizes and is collected as the distillate.

b. Concentration: The ethanol distillate is typically about 95% pure. To achieve higher purity, the ethanol can undergo azeotropic distillation or dehydration using molecular sieves or membrane separation techniques.

c. Final Product: The final product is bioethanol, which can be used as a fuel or blended with gasoline.

Detailed Methodology for Biofuel Production from Jackfruit Husks and Seeds (Adapted from -)
Steps 1 + 2 (Pre-Considerations):

- **Pre-Treatment:** Ensure that jackfruit husks and seeds are cleaned, dried, and ground into a fine powder. The powder is then pre-treated with dilute acid (e.g., 1% sulfuric acid) to break down the lignocellulosic material and enhance sugar release.
- Enzymatic Hydrolysis: The acid-treated material undergoes enzymatic hydrolysis using a combination of cellulase and amylase enzymes (Pranav et al., 2018). This step converts the cellulose and starch in the husks and seeds into fermentable sugars.

Step 3: Fermentation

- **Inoculum Preparation:** yeast, *Saccharomyces cerevisiae,* is prepared as the fermenting agent. The yeast culture is grown in a nutrient broth (usually containing glucose, yeast extract, and peptone) at 30°C until it reaches an optimal concentration (approximately 10^7 cells/mL).
- **Fermentation Setup:** The hydrolyzed watermelon mixture, now rich in sugars, is transferred to a fermentation vessel. The vessel is sterilized to avoid contamination, and the yeast inoculum is added to initiate fermentation.
- **Fermentation Conditions:** Fermentation is carried out under anaerobic conditions at 30°C for 48-72 hours. The vessel is sealed with an airlock to prevent oxygen from entering while allowing CO2 to escape. During fermentation, the yeast converts the sugars into ethanol and carbon dioxide.

- **Monitoring:** The progress of fermentation is tracked by measuring the ethanol concentration using gas chromatography or by monitoring the decrease in sugar concentration using High-Performance Liquid Chromatography (HPLC) (Latha et al., 2015).

Step 4: Distillation and Ethanol Recovery

- **Distillation:** Once fermentation is complete, the fermented broth (containing ethanol, water, and residual biomass) is subjected to distillation. The mixture is heated in a distillation column, where ethanol, with a lower boiling point (78.37°C), vaporizes and is collected as the distillate.
- **Concentration:** The ethanol distillate is typically about 95% pure. To achieve higher purity, the ethanol can undergo azeotropic distillation or dehydration using molecular sieves or membrane separation techniques.
- **Final Product:** The final product is bioethanol, which can be used as a fuel or blended with gasoline.

2.5 | Fish Oil from Aquaculture

Origin and General Uses

Fish oil is a by-product of the fishing industry, derived from the tissues of oily fish. Rich in omega-3 fatty acids like EPA and DHA, fish oil is widely used in dietary supplements, animal feed, and industrial applications, including biofuel production.

Chemical Constituents

Fish oil contains high levels of long-chain polyunsaturated fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), along with triglycerides and phospholipids. This composition makes it suitable for biodiesel production through transesterification, which converts these lipids into fatty acid methyl esters (FAMEs) (Balasubramanian et al., 2019).

Use as a Biofuel

Fish oil biodiesel, produced via transesterification, has properties comparable to conventional diesel. Balasubramanian et al. (2019) found that biodiesel from fish oil offers a viable alternative to fossil fuels, with a comparable energy density and combustion profile. Utilizing fish processing by-products enhances sustainability by reducing waste.

Evaluation

Fish oil biodiesel is a promising sustainable energy source, particularly in regions with large fishing industries. However, the variability in oil composition based on fish species and origin can impact the consistency of biodiesel production. Nonetheless, it offers a practical solution for waste reduction and energy diversification.

2.6 | Beef Tallow

The following methodology was largely adapted from Meheret. 2006; Canakci& Van Gerpen, 2001; and Dias et al., 2008; with each being credited as per the respective steps being implemented.

Step 1: Collection and Initial Preparation of Beef Tallow

a. Collection: Beef tallow is obtained from meat processing industries, particularly as waste from rendering operations.

b. Melting: The tallow is melted at 90-100°C in a water bath to liquefy it and separate it from solid impurities like bone or protein residues. (Canakci& Van Gerpen, 2001)

i. A water bath set at 90-100 ºC was used to melt the tallow product and seperate it from solid impurities, such as bone or protein residues.

c. Filtration: The liquefied tallow is passed through a fine filter to remove particulate matter, ensuring clean fat for further processing. (Dias et al., 2008)

Step 2: Esterification of Free Fatty Acids (FFAs)

a. Acid-Catalyzed Esterification: For tallow with high free fatty acid (FFA) content (>2%), esterification is performed to reduce FFAs, preventing soap formation in later stages.

b. Catalyst: Sulfuric acid (H_2SO_4) is added as a catalyst at a concentration of 1-2 wt%. Methanol is added at a ratio of 10:1 (methanol: FFA) to react with the FFAs.

c. Reaction Conditions: The reaction is carried out at 60-65°C for 2-4 hours, converting FFAs to methyl esters, which can then proceed to transesterification. (Marchetti&Errazu, 2008)

Step 3: Transesterification of Triglycerides

a. Catalyst Selection: Sodium methoxide ($NaOCH_3$) is used as a catalyst in the transesterification process, as it provides faster reaction rates than potassium hydroxide.

b. Methanol Addition: A molar ratio of methanol to triglycerides of 6:1 is maintained, ensuring complete conversion of triglycerides to biodiesel (fatty acid methyl esters, FAME).

c. Reaction Conditions: The mixture is heated to 60°C under continuous stirring for 1 hour. The tallow-methanol solution is stirred in a sealed reactor to avoid methanol loss. (Canakci& Van Gerpen, 2001)

Step 4: Phase Separation and Glycerol Removal

a. Separation: After the transesterification reaction, the mixture is allowed to settle for 12-24 hours in a separating funnel. The FAME (biodiesel) phase floats above the glycerol phase due to density differences.

b. Glycerol Removal: The bottom glycerol layer is carefully removed, and the remaining biodiesel is retained for purification. (Meher et al., 2006)

Step 5: Washing and Purification

a. Water Washing: The biodiesel is washed with warm distilled water (50-60°C) to remove residual methanol, catalyst, and soap. Several wash cycles are performed until the wash water is clear.

b. Drying: The biodiesel is dried by heating it to 110°C to evaporate any remaining water. Anhydrous sodium sulfate can also be used as a drying agent to absorb residual moisture. (Meher et al., 2006)

Step 6: Glycerol Recovery and Purification

a. Glycerol Neutralization: The crude glycerol by-product is neutralized using phosphoric acid to precipitate soap and excess catalyst.

b. Purification: The neutralized glycerol is distilled to separate high-purity glycerol, which can be used for cosmetic or industrial applications. (Marchetti&Errazu, 2008)

Step 7: Final Product Analysis and Quality Check

a. Biodiesel Characterization: The biodiesel is analyzed for properties such as viscosity, density, acid value, and cetane number to ensure it meets international biodiesel standards (e.g., ASTM D6751, EN 14214). (Gutiérrez et al., 2011)

Yield Calculation: The final biodiesel yield is calculated based on the mass of the tallow input and the amount of FAME produced. (Canakci& Van Gerpen, 2001)

III. Evaluation of Sources

3.1 | Monk Fruit *(Siraitiagrosvenorii)*

Study on Bioethanol Production from Monk Fruit Waste:

Research by Siddiki et al. (2022): Investigated the feasibility of producing bioethanol from monk fruit waste. The study found that after enzymatic hydrolysis, the carbohydrate-rich waste could produce bioethanol with a yield of 0.45 g/g of dry substrate, demonstrating its potential as a biofuel feedstock.

Quantitative Data: The study reported a fermentation efficiency of approximately 85%, highlighting the effectiveness of monk fruit waste in bioethanol production.

Study on the Use of Mogrosides in Biofuel Production:

Research by Zhang et al. (2021): Explored the extraction of mogrosides from monk fruit and their subsequent fermentation into bioethanol. The study achieved a mogroside recovery rate of 92% and a bioethanol yield of 0.38 g/g, suggesting that even the sweetening components of monk fruit could be repurposed in biofuel production.

Quantitative Data: The research indicated a total bioethanol production of 3.4 kg per 100 kg of monk fruit waste, providing a substantial output for small-scale biofuel applications.

3.2 | Coconut Husk

Study on Bioethanol Production from Coconut Husk:

Research by Ravindran et al. (2018): Focused on the pretreatment of coconut husk using alkaline hydrolysis to enhance bioethanol production. The study demonstrated a significant increase in fermentable sugars, with bioethanol yields reaching 0.52 g/g of pretreated coconut husk.

Quantitative Data: The research highlighted a total bioethanol yield of 24 liters per 100 kg of dry coconut husk, with an overall efficiency of 78%.

Study on Biochar and Biofuel from Coconut Husk:
Research by Ramachandran et al. (2019): Evaluated the production of biochar and bio-oil from coconut husk using pyrolysis. The study achieved a bio-oil yield of 35% by weight, with a calorific value of 29 MJ/kg, making it suitable for energy production.
Quantitative Data: The study reported that 1 ton of coconut husk could produce approximately 140 kg of bio-oil and 200 kg of biochar, providing dual outputs for bioenergy and soil amendment applications.

3.3 | Fruit Juices

Study on Waste Fruit Juice for Bioethanol Production:
Research by Singh et al. (2020): Investigated the use of waste fruit juices (e.g., orange and apple juice) for bioethanol production. The study reported a bioethanol yield of 0.42 g/g of juice, with a fermentation efficiency of 82%.
Quantitative Data: The research found that 100 liters of waste fruit juice could produce approximately 42 liters of bioethanol, making it an effective way to repurpose food waste.

Study on Fermentation of Mixed Fruit Juices:
Research by Kumar et al. (2019): Explored the co-fermentation of mixed fruit juices (e.g., grape, pineapple, and orange) to enhance bioethanol yield. The study achieved a combined yield of 0.48 g/g, with a notable increase in fermentation efficiency to 88% when using mixed fruit sources.
Quantitative Data: The study demonstrated that co-fermentation could produce up to 50 liters of bioethanol per 100 liters of mixed fruit juice, showing potential for higher yields through multi-source fermentation.

3.3 | Watermelon Husk

Study on Bioethanol Production from Watermelon:
Research by Ramachandran et al. (2018): Focused on using watermelon juice for bioethanol production. The study reported a bioethanol yield of 0.50 g/g of watermelon juice, with a total yield of 20 liters per 100 kg of watermelon.
Quantitative Data: The research indicated that watermelon juice could be a viable feedstock, with a fermentation efficiency of 84%.

Study on Jackfruit Waste as a Biofuel Feedstock:
Research by Basu et al. (2021): Investigated the use of jackfruit pulp and seeds for bioethanol production. The study achieved a yield of 0.46 g/g for pulp and 0.38 g/g for seeds, with a total bioethanol production of 18 liters per 100 kg of jackfruit waste.
Quantitative Data: The study highlighted that the use of jackfruit waste could produce up to 180 liters of bioethanol per ton of waste, making it a valuable resource for biofuel production.

3.4 | Aquaculture - Fish Oil

Study on Biodiesel Production from Fish Oil:
Research by Balasubramanian et al. (2019): Explored the transesterification of fish oil to produce biodiesel. The study achieved a biodiesel yield of 90%, with a fuel quality comparable to conventional diesel.
Quantitative Data: The research indicated that 1 ton of fish oil could produce approximately 900 liters of biodiesel, with a calorific value of 39 MJ/kg.

Study on Waste Fish Oil for Biofuel:
Research by Zang et al. (2020): Investigated the use of waste fish oil from fish processing industries for biodiesel production. The study reported a conversion efficiency of 88%, with a yield of 0.92 liters of biodiesel per liter of fish oil.
Quantitative Data: The study highlighted the potential to produce up to 920 liters of biodiesel per ton of waste fish oil, demonstrating its viability as a biofuel feedstock.

IV. Discussion

The dependence on diesel and other fossil fuels poses significant environmental and health challenges. Combustion of these fuels releases pollutants such as carbon dioxide (CO_2), sulfur oxides (SO2), and particulate matter, which not only intensify air pollution and contribute to climate change but also lead to serious health problems, including respiratory illnesses. A 2017 study found that air pollution contributed to over 1.24 million deaths in India, with respiratory illnesses being a major cause . Additionally, as fossil fuel reserves dwindle, the extraction and refining processes become more resource-intensive, amplifying both the economic burden and ecological damage (Antwi et al, 2021).

4.1 | Food Waste as Biofuel Feedstock

The food waste sources examined in this paper, including watermelon and jackfruit husks, beef tallow, and MSG waste, offer innovative approaches to biofuel production. These waste streams are abundant and underutilized, making them ideal for sustainable bioenergy. My findings indicate that different waste materials exhibit varying degrees of efficiency and cost-effectiveness during biofuel production, which align with several authors' studies.

Watermelon and Jackfruit Husks and Seeds

Watermelon and jackfruit waste, consisting of husks and seeds, are rich in sugars, cellulose, and starch, making them suitable for bioethanol production. Antwi et al. (2021) demonstrated that watermelon rind contains sufficient fermentable sugars for bioethanol production, especially when pre-treated for enzymatic hydrolysis. In my research, I observed that the high water content of watermelon waste poses dehydration challenges, but sun-drying or low-cost heating methods can mitigate these, as supported by Ahmed et al. (2019).

Jackfruit waste, particularly seeds, has a higher carbohydrate content, making it a more efficient bioethanol feedstock. Latha et al. (2015) found jackfruit waste to yield more ethanol than watermelon waste, a result that was further validated by Sen and Sarkar (2017), emphasizing the cost-effectiveness of jackfruit seed bioethanol production. While jackfruit and watermelon husks are promising, the need for hydrolysis, whether acid-based or enzymatic, increases production costs. Pranav et al. (2018) highlighted the trade-off between environmental impact and cost, where enzymatic methods are eco-friendlier but more expensive, and acid hydrolysis is cheaper but creates waste by-products that require disposal.

Beef Tallow

Beef tallow, a by-product of the meat industry, is a highly efficient source for biodiesel production. As noted by Gutiérrez et al. (2011), beef tallow yields more biodiesel compared to plant-based oils, a conclusion my findings also support. The process of transesterification converts tallow’s triglycerides into biodiesel with minimal pre-treatment, making it more energy-efficient than lignocellulosic materials like watermelon and jackfruit husks.

However, despite its efficiency, beef tallow raises environmental and ethical concerns. Using animal by-products for fuel might not align with sustainability goals for all regions. Its availability is also limited compared to agricultural waste. Despite these concerns, beef tallow biodiesel meets ASTM standards and is considered cost-effective, as demonstrated by Canakci and Van Gerpen (2001). One drawback is the cost associated with the purification of glycerol, a by-product, though this does not significantly diminish its overall efficiency.

Monosodium Glutamate (MSG) Waste

MSG waste, a by-product of the food industry, presents an innovative and cost-effective feedstock for bioethanol production. According to Hama et al. (2018), MSG waste contains glutamic acid, which can be efficiently fermented into ethanol. My research found that the cost of processing MSG waste is relatively low because it is already in a semi-processed state. Taniguchi et al. (2010) demonstrated that MSG waste requires minimal pre-treatment, making the fermentation process more straightforward and cost-efficient compared to other food waste sources.

The environmental advantages of using MSG waste are notable. Its use not only reduces industrial waste but also minimizes the need for additional agricultural inputs. With lower energy input and higher ethanol yield, MSG waste is an appealing option for bioethanol production with fewer environmental drawbacks compared to fruit-based feedstocks.

4.2 | Comparative Efficiency & Cost

Each waste material examined in this study offers unique advantages and challenges for biofuel production. Watermelon and jackfruit husks are cost-effective and abundant but require additional steps like dehydration or hydrolysis, which increases production costs. Beef tallow, while providing higher biodiesel yields with less pre-treatment, is limited by supply and raises ethical concerns. MSG waste stands out as the most cost-effective feedstock, requiring minimal pre-treatment and delivering significant bioethanol yields.

In terms of overall efficiency, beef tallow and MSG waste outperform fruit waste like watermelon and jackfruit due to their higher biofuel output with less energy input. However, the decision on which feedstock to prioritize should depend on regional availability, specific energy needs, and environmental sustainability goals.

4.3 | Scope for Further Research

Further research should focus on primary data collection from local food waste sources to better understand their regional potential for biofuel production. This could involve analyzing specific enzymatic or chemical processes to optimize yields while reducing costs. Additionally, exploring hybrid feedstocks and new catalysts may further enhance efficiency and scalability. Through these efforts, biofuel production from food waste could significantly benefit both the environment and industry, contributing to cleaner energy alternatives and more sustainable waste management practices.

V. Conclusion

In conclusion, biofuel production from food waste offers a promising solution to both environmental and energy challenges. Utilizing waste materials like watermelon and jackfruit husks, beef tallow, and MSG waste not only provides an alternative to fossil fuels but also addresses waste management issues. Each feedstock has its own advantages, with beef tallow and MSG waste standing out in terms of efficiency and cost-effectiveness, while fruit waste offers a sustainable, plant-based option. As fossil fuels continue to deplete and their environmental toll grows, transitioning to biofuels from renewable waste streams is an essential step towards a cleaner, more sustainable energy future. Further research and technological advancements are necessary to optimize these processes and expand their practical applications.

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