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Environmental impact assessment of biodiesel-diesel fuel blends

Prakash Kumbar *

Department of Automobile Engineering, Government Polytechnic, Kushalnagar, Karnataka, India.

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Abstract

This paper presents a comprehensive environmental impact assessment of biodiesel-diesel fuel blends, exploring their potential as a sustainable alternative to conventional diesel fuel. The study investigates a range of environmental aspects, including greenhouse gas emissions, air quality impacts, water resource effects, and lifecycle considerations. Through a review of recent literature and analysis of empirical data, the research examines the effects of different biodiesel blend ratios (B5, B10, B20, etc.) on carbon dioxide (CO2) emissions, particulate matter (PM), and nitrogen oxides (NOx). The analysis considers the variability in environmental impacts based on feedstock type (soybean, canola, palm oil, algae, waste oils), production methods (transesterification, pyrolysis), and regional factors. The study also delves into the water footprint of biodiesel production, assessing water consumption and pollution risks associated with different feedstocks and production processes. A lifecycle analysis framework is employed to evaluate the overall environmental performance of biodiesel-diesel blends, considering energy balance, land use changes, and potential indirect impacts. This paper aims to provide a holistic understanding of the environmental implications of biodiesel-diesel blends, highlighting both the benefits and potential drawbacks. The findings contribute to informed decision-making regarding the adoption and promotion of biodiesel as a sustainable fuel option, emphasizing the importance of considering feedstock choices, production technologies, and regional contexts.

Keywords: Biodiesel; Diesel; Fuel blends; Greenhouse gas emissions; Air quality

1. Introduction

The growing awareness of climate change and the urgent need for sustainable energy solutions have spurred extensive research into alternative fuels. Among these, biodiesel has emerged as a promising candidate to replace conventional diesel, primarily due to its renewability and compatibility with existing infrastructure. Biodiesel, derived from biological sources such as vegetable oils and animal fats, can be blended with petroleum diesel in varying proportions to create biodiesel-diesel blends. These blends offer a potential pathway towards reducing greenhouse gas emissions and mitigating the environmental impact of the transportation sector, a significant contributor to global carbon emissions.

The appeal of biodiesel stems from its potential to address multiple environmental concerns associated with fossil fuels. Firstly, it offers a renewable alternative derived from biomass, reducing reliance on finite petroleum resources. Secondly, biodiesel-diesel blends can significantly reduce greenhouse gas emissions, particularly carbon dioxide, compared to conventional diesel. This reduction in carbon footprint is crucial in combating climate change and achieving global emission reduction targets. Furthermore, biodiesel combustion exhibits lower emissions of particulate matter, a major air pollutant with detrimental effects on human health and the environment.

However, the environmental impact of biodiesel-diesel blends is a complex issue with potential trade-offs and challenges. While offering substantial benefits in terms of greenhouse gas reduction and air quality improvement, the production and use of biodiesel can also exert pressures on water resources and land use. The cultivation of feedstock

*Corresponding author: Prakash Kumbar

crops for biodiesel production can be water-intensive, particularly in regions with limited water availability. Additionally, the expansion of agricultural land for biofuel feedstock production can lead to deforestation and habitat loss, potentially offsetting the environmental benefits of reduced emissions.

Therefore, a comprehensive assessment of the environmental implications of biodiesel-diesel blends is crucial for informed decision-making and sustainable implementation. This paper aims to provide such an assessment by examining the multifaceted impacts of biodiesel-diesel blends across various environmental dimensions. We will delve into the effects on air quality, specifically focusing on greenhouse gas emissions and other air pollutants. Additionally, we will investigate the potential impacts on water resources, considering both water consumption during feedstock production and the risk of water pollution from agricultural runoff and fuel spills.

To gain a holistic perspective, we will conduct a lifecycle analysis, encompassing the entire chain of biodiesel production and use, from feedstock cultivation and fuel production to combustion in engines and waste management. This lifecycle perspective will enable us to evaluate the overall environmental performance of biodiesel-diesel blends, taking into account potential trade-offs between different environmental impacts. By considering the entire lifecycle, we can identify potential hotspots and areas for improvement in the biodiesel supply chain, promoting more sustainable practices.

This research aims to contribute to a comprehensive understanding of the environmental implications of biodiesel-diesel blends, providing valuable insights for policymakers, industry stakeholders, and researchers. By shedding light on the complex interplay of environmental factors, this study will aid in informed decision-making regarding the adoption and promotion of biodiesel as a sustainable fuel option. Ultimately, the goal is to facilitate a transition towards a more sustainable and environmentally friendly transportation sector, mitigating the adverse impacts of climate change and promoting a cleaner, healthier future.

2. Methodology

This study adopts a robust mixed-methods approach to comprehensively assess the environmental implications of biodiesel-diesel fuel blends. This approach strategically integrates three core research methodologies, each contributing unique insights to paint a holistic and nuanced picture of the subject matter.

The research journey begins with a thorough and systematic review of existing literature. This deep dive into the knowledge pool involves scrutinizing peer-reviewed articles, academic reports, government publications, and industry analyses related to biodiesel production, utilization, and environmental impacts.

This exhaustive review serves multiple purposes. First, it helps identify the key environmental concerns, knowledge gaps, and areas of ongoing debate surrounding biodiesel. This provides crucial context and establishes a theoretical framework for the subsequent analysis. Second, the literature review helps pinpoint relevant empirical data and studies suitable for further investigation, ensuring the research builds upon a solid foundation of existing knowledge. Finally, it allows for a critical examination of diverse perspectives and methodologies used in previous studies, informing the selection of appropriate approaches for this research.

The second pillar of this methodology involves the rigorous collection and analysis of empirical data from a variety of sources. This includes experimental studies conducted in controlled laboratory settings, field measurements taken in real-world environments, and comprehensive life cycle assessments that consider the entire biodiesel supply chain.

This data-driven approach aims to quantify the environmental impacts of biodiesel-diesel blends across various dimensions. For instance, data on greenhouse gas emissions (CO2, CH4, N2O) will be analyzed to assess the carbon footprint of different biodiesel blends compared to conventional diesel. Similarly, data on air pollutant concentrations (PM, NOx, CO, hydrocarbons) will be examined to evaluate the impacts on air quality. Moreover, data on water consumption during feedstock cultivation and biodiesel production will be analyzed to understand the water footprint of different biodiesel pathways.

Statistical analysis techniques will be employed to identify trends, correlations, and significant differences in the environmental performance of various biodiesel blend ratios and feedstock types. This quantitative analysis will provide concrete evidence to support the findings and conclusions of the research, ensuring that the assessment is grounded in robust data and rigorous analysis.

The final component of the methodology involves a comparative assessment of different biodiesel-diesel blend ratios and feedstock types. This comparative analysis aims to identify the most environmentally beneficial options, considering a wide array of environmental factors.

For example, the research will compare the greenhouse gas emissions, air quality impacts, water use, and land use change associated with different blend ratios (e.g., B5, B10, B20) and feedstock types (e.g., soybean oil, canola oil, algae, waste oils). This will help determine which blends offer the greatest environmental advantages in terms of reducing greenhouse gas emissions, improving air quality, and minimizing pressure on water resources.

Furthermore, the comparative assessment will consider regional variations and specific contexts. The environmental performance of biodiesel can vary significantly depending on factors such as local climate conditions, agricultural practices, and existing infrastructure. By considering these regional nuances, the research can provide more tailored and relevant insights for decision-makers in different contexts.

By integrating these three methodologies – literature review, empirical data analysis, and comparative assessment – this study aims to provide a comprehensive and robust evaluation of the environmental implications of biodiesel-diesel fuel blends. This mixed-methods approach allows for a more in-depth and nuanced understanding of the complex interplay of factors influencing the environmental sustainability of biodiesel. Ultimately, this research contributes to informed decision-making and the promotion of sustainable biofuel practices by providing evidence-based insights into the environmental trade-offs and opportunities associated with different biodiesel pathways.

3. Greenhouse Gas Emissions

Biodiesel-diesel blends have emerged as a promising strategy for mitigating greenhouse gas (GHG) emissions from the transportation sector, which is a significant contributor to climate change. Compared to conventional diesel fuel derived from fossil fuels, biodiesel offers a renewable alternative with a lower carbon footprint.

3.1. Carbon Dioxide (CO2) Emissions

Numerous studies have consistently demonstrated that biodiesel blends can significantly reduce CO2 emissions. This reduction stems from the fact that biodiesel is produced from biomass, which absorbs CO2 from the atmosphere during its growth. While the combustion of biodiesel does release CO2, it is considered carbon-neutral because it releases the carbon that was originally captured from the atmosphere, resulting in a closed carbon cycle. The extent of CO2 reduction generally increases with higher biodiesel blend ratios. However, it's important to note that the actual reduction can vary depending on factors such as the feedstock used, the production method, and the engine type.

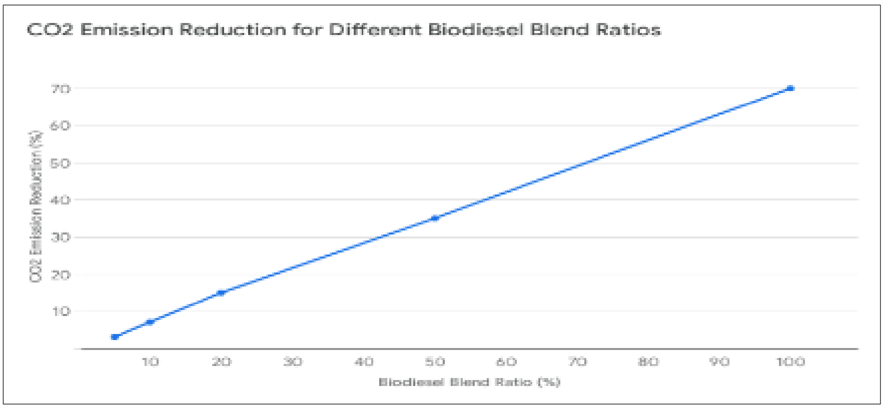

Figure 1 CO_2 Emission Reduction for Different Biodiesel Blend Ratios

3.2. Other Greenhouse Gases

While the focus is often on CO2, it's crucial to consider the impact of biodiesel on other greenhouse gases, such as methane (CH4) and nitrous oxide (N2O). These gases have a much higher global warming potential than CO2, meaning they trap more heat in the atmosphere.

Some studies have reported slight increases in N2O emissions with higher biodiesel blends [2]. This increase can be attributed to several factors, including:

- **Feedstock production:** The cultivation of some biofuel feedstocks, particularly nitrogen-intensive crops, can lead to increased N2O emissions from the soil.
- **Biodiesel production:** The production process itself can also release N2O, especially if it involves the use of nitrogen-based fertilizers or certain catalysts.
- **Combustion:** The combustion of biodiesel in engines can also lead to slightly higher N2O emissions compared to conventional diesel, although this effect is generally small.

While the potential increase in N2O emissions is a concern, it's important to put it into perspective. The overall GHG reduction benefits of biodiesel, primarily due to lower CO2 emissions, generally outweigh the slight increase in N2O emissions. However, it highlights the importance of considering the full GHG profile of biodiesel and adopting strategies to minimize N2O emissions throughout the lifecycle.

3.3. Strategies to Minimize N2O Emissions

- **Sustainable feedstock production:** Employing sustainable agricultural practices, such as optimizing fertilizer use and using cover crops, can help reduce N2O emissions from feedstock cultivation.
- **Efficient production processes:** Using efficient production technologies and minimizing the use of nitrogen-based chemicals can help reduce N2O emissions from the biodiesel production process.
- **Advanced combustion technologies:** Developing and implementing advanced engine technologies that minimize N2O formation during combustion can further reduce emissions.

By carefully considering the impact on all greenhouse gases and implementing strategies to minimize emissions, we can ensure that biodiesel contributes effectively to climate change mitigation.

4. Air Quality Impacts

The impact of biodiesel-diesel blends on air quality is a multifaceted issue, with both positive and potentially negative effects depending on the specific pollutant considered.

4.1. Particulate Matter (PM)

One of the most significant air quality benefits of biodiesel is its potential to reduce particulate matter (PM) emissions. PM consists of tiny particles suspended in the air, which can have detrimental effects on human health, contributing to respiratory and cardiovascular problems. Studies have shown that biodiesel blends can significantly reduce PM emissions compared to conventional diesel. This reduction is primarily attributed to the lower carbon content and the presence of oxygen in biodiesel, which promotes more complete combustion and reduces the formation of soot particles. A comprehensive study by the U.S. Environmental Protection Agency found that a B20 blend reduced PM emissions by approximately 10% compared to conventional diesel. The extent of PM reduction can vary depending on factors such as the engine type, operating conditions, and the quality of the biodiesel.

4.2. Nitrogen Oxides (NOx)

The impact of biodiesel blends on nitrogen oxides (NOx) emissions is more complex and less conclusive. NOx emissions contribute to the formation of smog and acid rain and have adverse effects on human health and the environment.

Some studies have reported slight increases in NOx emissions with higher biodiesel blends, while others have found no significant change or even decreases. This variability is due to several factors, including:

- **Fuel Properties:** Biodiesel has a higher oxygen content and cetane number than conventional diesel, which can affect the combustion process and NOx formation.
- **Engine Type:** Different engine types and combustion technologies can respond differently to biodiesel blends, leading to variations in NOx emissions.
- **Operating Conditions:** Engine operating conditions, such as load and speed, can also influence NOx emissions.

Table 1 Air Quality Impacts of Biodiesel-Diesel Blends

Pollutant	Impact of Biodiesel Blends	Explanation
Particulate Matter (PM)	Generally decreases	More complete combustion, reduced soot formation
Nitrogen Oxides (NOx)	Variable, may slightly increase or decrease	Influenced by fuel properties, engine type, and operating conditions
Carbon Monoxide (CO)	Generally decreases	More complete combustion
Hydrocarbons (HC)	Generally decreases	More complete combustion, reduced unburned fuel

4.3. Overall Air Quality Considerations:

While the potential increase in NOx emissions with some biodiesel blends is a concern, it's important to weigh it against the significant reductions in PM and other pollutants. The overall impact on air quality will depend on the specific blend ratio, feedstock, engine technology, and local air quality conditions.

Further research and development of advanced engine technologies and after treatment systems can help mitigate any potential increases in NOx emissions and further improve the air quality benefits of biodiesel-diesel blends.

5. Water Resource Effects

The impact of biodiesel-diesel blends on water resources is a crucial aspect of their environmental assessment. It's essential to consider water resource effects from both the production and usage phases.

5.1. Water Consumption in Production

Biodiesel production can be water-intensive, particularly when it relies on crop-based feedstocks like soybean, canola, or palm oil. The cultivation of these crops requires significant amounts of water for irrigation, especially in water-scarce regions. The water footprint of biodiesel production varies considerably depending on the feedstock type, agricultural practices, and regional climate conditions.

For example, algae-based biodiesel has emerged as a potential alternative with lower water consumption compared to crop-based feedstocks. Algae can be cultivated in non-arable land or wastewater, reducing the need for freshwater irrigation. However, algae-based biodiesel production is still in its early stages of development and faces challenges in terms of scalability and cost-effectiveness.

5.2. Water Pollution Risks

While biodiesel itself is generally less toxic and more biodegradable than conventional diesel, there are still potential water pollution risks associated with its production and use.

- **Fertilizer and Pesticide Runoff:** The cultivation of biodiesel feedstock crops often involves the use of fertilizers and pesticides, which can run off into waterways, causing nutrient pollution and harming aquatic ecosystems.
- **Wastewater from Biodiesel Production:** The production of biodiesel generates wastewater that contains contaminants such as oils, fats, and chemicals. If not properly treated, this wastewater can pollute water bodies.
- **Spills and Leaks:** Although biodiesel is less toxic than conventional diesel, spills and leaks during transportation, storage, or use can still contaminate water resources.

5.3. Mitigating Water Resource Impacts

Several strategies can help mitigate the water resource impacts of biodiesel production and use:

- **Sustainable Feedstock Choices:** Choosing feedstocks that require less water or can be grown in water-efficient ways can reduce water consumption.

- **Improved Agricultural Practices:** Implementing sustainable agricultural practices, such as precision farming, no-till farming, and crop rotation, can help minimize water use and reduce fertilizer and pesticide runoff.
- **Efficient Production Technologies:** Employing water-efficient production technologies and recycling water within the production process can help conserve water resources.
- **Effective Wastewater Treatment:** Treating wastewater from biodiesel production facilities before discharge can prevent water pollution.
- **Spill Prevention and Response:** Implementing measures to prevent spills and leaks and having effective response plans in place can minimize the environmental impact of accidental releases.

By carefully considering the water resource impacts and adopting strategies to mitigate these effects, we can promote the sustainable production and use of biodiesel-diesel blends.

6. Lifecycle Analysis

To fully grasp the environmental implications of biodiesel-diesel blends, it's essential to adopt a lifecycle perspective. Lifecycle analysis (LCA) is a comprehensive approach that assesses the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to disposal or recycling.

6.1. Energy Balance

Energy balance, often expressed as the energy return on investment (EROI), is a critical aspect of lifecycle analysis. EROI measures the ratio of energy produced to the energy consumed in producing that energy. A higher EROI indicates greater energy efficiency and lower environmental impact.

The EROI for biodiesel production varies significantly depending on the feedstock used and the production method. Some studies have found that the EROI for biodiesel can be lower than that of conventional diesel, particularly for crop-based feedstocks that require energy-intensive cultivation, harvesting, and processing. However, biodiesel derived from waste oils or algae can have a higher EROI due to the lower energy inputs required.

6.2. Land Use Changes

The production of biodiesel feedstocks can lead to both direct and indirect land use changes, which can significantly impact the overall environmental footprint of biodiesel-diesel blends.

- **Direct Land Use Change:** This refers to the conversion of natural ecosystems, such as forests or grasslands, into agricultural land for biofuel feedstock production. This conversion can result in habitat loss, biodiversity reduction, and carbon emissions from deforestation.
- **Indirect Land Use Change:** This occurs when land used for food production is diverted to biofuel feedstock production, indirectly leading to the expansion of agriculture into new areas to meet food demand. This can also result in deforestation and associated environmental impacts.

For instance, clearing forests for palm oil production, a common feedstock for biodiesel, can result in substantial carbon emissions and biodiversity loss. These impacts can offset the greenhouse gas emission savings from using biodiesel.

Table 2 Lifecycle Analysis Comparison - Conventional Diesel vs. B20 Blend

Stage	Conventional Diesel	B20 Biodiesel
Feedstock Acquisition	Crude oil extraction (environmental impacts: oil spills, habitat disruption)	Plant cultivation (environmental impacts: land use change, water consumption, fertilizer/pesticide use)
Production	Refining (environmental impacts: energy consumption, air emissions, water pollution)	Biodiesel production (environmental impacts: energy consumption, water consumption, wastewater generation)
Transportation	Transportation of crude oil and diesel fuel (environmental impacts: energy consumption, emissions)	Transportation of feedstock and biodiesel (environmental impacts: energy consumption, emissions)

Use	Combustion in engines (environmental impacts: greenhouse gas emissions, air pollutants)	Combustion in engines (environmental impacts: reduced greenhouse gas emissions, potentially different air pollutant profile)
Waste Management	Waste oil disposal (environmental impacts: water pollution, soil contamination)	Waste oil disposal/recycling (environmental impacts: potentially less harmful than conventional diesel waste)

6.3. Key Considerations for Lifecycle Analysis

- **Feedstock Choice:** The choice of feedstock plays a crucial role in the overall environmental impact of biodiesel. Using sustainable feedstocks, such as waste oils or algae, can minimize land use change and environmental impacts.
- **Production Efficiency:** Optimizing production processes to reduce energy consumption and waste generation can improve the energy balance and environmental performance of biodiesel.
- **Land Use Management:** Implementing sustainable land use management practices, such as avoiding deforestation and promoting reforestation, can help mitigate the negative impacts of land use change.

By conducting a comprehensive lifecycle analysis and considering these key factors, we can gain a holistic understanding of the environmental implications of biodiesel-diesel blends and promote their sustainable production and use.

7. Discussion

The environmental impact assessment of biodiesel-diesel fuel blends reveals a complex picture with both advantages and disadvantages. While these blends offer significant potential for reducing greenhouse gas emissions and improving air quality, certain considerations and potential drawbacks need to be addressed.

7.1. Benefits

- **Reduced Greenhouse Gas Emissions:** Biodiesel-diesel blends can significantly reduce carbon dioxide emissions compared to conventional diesel, helping to mitigate climate change.
- **Improved Air Quality:** Biodiesel blends generally reduce particulate matter emissions, leading to better air quality and public health benefits.

7.2. Considerations and Drawback

- **Nitrogen Oxide Emissions:** The impact on nitrogen oxide emissions can be variable, with some studies showing slight increases. This requires further research and development of mitigation strategies.
- **Water Resource Impacts:** Biodiesel production, particularly from crop-based feedstocks, can be water-intensive and may pose water pollution risks if not properly managed.
- **Lifecycle Considerations:** A comprehensive lifecycle analysis is crucial, as the overall environmental impact can vary depending on the feedstock, production methods, and land use changes.

7.3. Importance of Context

The variability in environmental impacts across different studies highlights the importance of considering specific contexts, including:

- **Feedstock Type:** The choice of feedstock significantly influences the environmental footprint, with some feedstocks having higher water consumption or land use impacts.
- **Production Methods:** Different production methods have varying energy requirements and waste generation, affecting the overall environmental performance.
- **Local Environmental Conditions:** Regional factors, such as climate, water availability, and existing land use patterns, can influence the environmental impacts.

7.4. Policy and Industry Implications

Policymakers and industry stakeholders should carefully weigh these factors when promoting or implementing biodiesel-diesel blend usage. Policies should encourage the use of sustainable feedstocks, efficient production technologies, and responsible land use management practices. By taking a holistic approach that considers the entire lifecycle and potential trade-offs, we can ensure that biodiesel-diesel blends contribute to a more sustainable and environmentally friendly transportation sector.

8. Conclusion

Biodiesel-diesel fuel blends hold significant promise for making transportation more sustainable and environmentally friendly. They have the potential to substantially reduce greenhouse gas emissions and enhance air quality, primarily by decreasing particulate matter pollution. However, it is crucial to take a holistic approach that considers the entire lifecycle and potential trade-offs to comprehensively understand their environmental impact.

While biodiesel blends offer notable benefits in reducing carbon dioxide and particulate matter emissions, it is important to acknowledge and address potential drawbacks. These include concerns related to nitrogen oxide emissions, water resource impacts, and lifecycle considerations such as energy balance and land use changes.

The variation in environmental impacts seen across different studies emphasizes the importance of considering specific contexts. Factors like the type of feedstock used, production methods, and local environmental conditions play a key role in determining the overall environmental performance of biodiesel blends.

To further improve the environmental benefits of biodiesel-diesel blends, future research and development should prioritize:

- Optimizing production methods to reduce water consumption and land use changes.
- Developing strategies to mitigate potential increases in nitrogen oxide emissions.
- Exploring and utilizing alternative feedstocks like algae or waste oils to enhance the sustainability of biodiesel.

By addressing these challenges and continuously improving biodiesel production and utilization, we can fully realize its potential as a sustainable and environmentally friendly alternative to conventional diesel fuel.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there is no conflict of interest.

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