World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Biofuels for traction systems: A comparative analysis

Manju RB * and Lakshmana HK

Department of Mechanical Engineering, Government Polytechnic, Holenarasipura, Karnataka, India.

World Journal of Advanced Research and Reviews, 2019, 02(02), 048–054

Publication history: Received on 02 June 2019; revised on 15 June 2019; accepted on 22 June 2019

Article DOI: https://doi.org/10.30574/wjarr.2019.2.2.0136

Abstract

This paper examines the application of biofuels in traction systems, focusing on their potential as sustainable alternatives to conventional fossil fuels. Through a comprehensive review of literature published prior to 2019, we analyze various biofuel types, their production methods, and performance characteristics when applied to rail and road traction systems. A comparative analysis reveals that while first-generation biofuels offer immediate applicability with moderate environmental benefits, advanced biofuels present superior long-term potential despite current technological and economic barriers. This research highlights the critical factors influencing the successful implementation of biofuels in traction applications and identifies key challenges that must be addressed to facilitate wider adoption.

Keywords: Biofuels; Traction systems; Biodiesel; Bioethanol; Sustainability; Railway transportation; Renewable energy

1 Introduction

The transportation sector accounts for approximately 25% of global energy-related greenhouse gas emissions, with a significant portion attributed to traction systems in railway and heavy-duty road applications (IEA, 2018). As environmental concerns mount and fossil fuel resources diminish, the development of sustainable alternative fuels has become imperative. Biofuels represent one of the most promising renewable energy sources for traction applications due to their potential carbon neutrality and compatibility with existing infrastructure.

Traction systems, which convert fuel energy into mechanical energy for propulsion, have historically relied on diesel fuel for non-electrified operations. The integration of biofuels into these systems offers a pathway toward reducing carbon emissions while maintaining operational performance. This paper aims to evaluate the viability of various biofuels for traction applications by examining their technical characteristics, environmental impact, and economic feasibility.

The research questions addressed in this paper include:

- What are the primary biofuel types suitable for traction system applications?
- How do these biofuels compare in terms of energy density, emissions profile, and compatibility with existing engines?
- What are the technical, economic, and regulatory barriers to widespread adoption of biofuels in the traction sector?

2 Methodology

This research employs a systematic literature review methodology focusing on peer-reviewed publications, technical reports, and industry white papers published prior to 2019. The following databases were utilized for information

*Corresponding author: Manju R B

gathering: ScienceDirect, IEEE Xplore, Transportation Research Board, and specialized railway engineering repositories.

Selection criteria for the literature included:

- Relevance to biofuel applications in traction systems
- Technical analysis of biofuel performance characteristics
- Comparative studies of different biofuel types
- Case studies of biofuel implementation in rail or heavy-duty transportation
- Economic and environmental impact assessments

The reviewed publications were categorized based on biofuel type, application context, and analytical focus to facilitate systematic comparison and synthesis of findings.

3 Biofuel Classifications

3.1 First-Generation Biofuels

First-generation biofuels are derived primarily from food crops and utilize conventional technologies for production. The most common types applied in traction systems include:

Biodiesel: Produced through transesterification of vegetable oils or animal fats, biodiesel (fatty acid methyl esters or FAME) serves as a direct substitute for petroleum diesel. Studies by Labeckas and Slavinskas (2006) demonstrated that biodiesel could be utilized in conventional diesel engines with minimal modifications, though with approximately 10% lower energy content than petroleum diesel.

Bioethanol: Derived from the fermentation of sugar and starch crops such as corn, sugarcane, and wheat. While widely used in light-duty vehicles, its lower energy density and corrosive properties present challenges for heavy traction applications. Bioethanol is typically blended with gasoline (E5-E85) rather than used in pure form in most applications (Lin et al., 2012).

Pure Plant Oil (PPO): Minimally processed vegetable oils used directly as fuel, requiring significant engine modifications due to their high viscosity. Hemmerlein et al. (1991) documented early experiments with rapeseed oil in modified diesel engines for agricultural traction applications.

3.2 Second-Generation Biofuels

Second-generation biofuels are produced from non-food biomass, including:

Lignocellulosic Bioethanol: Derived from woody biomass, agricultural residues, and dedicated energy crops through advanced enzymatic hydrolysis and fermentation processes. Moriarty and Honnery (2012) highlighted its reduced land use competition compared to first-generation alternatives.

Hydrotreated Vegetable Oil (HVO): Also known as renewable diesel, HVO is produced through hydroprocessing of vegetable oils and animal fats. It offers superior cold flow properties and energy content comparable to conventional diesel. Aatola et al. (2008) demonstrated its compatibility with existing diesel engines without modifications.

Biomass-to-Liquid (BtL) Fuels: Produced through thermochemical conversion processes like gasification and Fischer-Tropsch synthesis. These synthetic fuels closely resemble conventional diesel with potentially superior combustion characteristics (Sajjadi et al., 2016).

3.3 Third-Generation Biofuels

Third-generation biofuels represent emerging technologies focused on:

Algae-based Biofuels: Derived from microalgae cultivated in specialized systems, offering high oil yields per hectare and reduced land use requirements. Chisti (2007) projected theoretical yields up to 100 times greater than conventional oilseed crops, though commercial-scale production remained challenging before 2019.

Biohydrogen: Produced through biological processes for potential use in hydrogen fuel cells for traction applications, offering zero-emission operation. However, Nikolaidis and Poullikkas (2017) noted significant barriers in hydrogen storage and distribution infrastructure.

4 Technical Performance Analysis

4.1 Energy Density and Power Output

Energy density represents a critical parameter for traction applications, directly influencing vehicle range and performance. Table 1 compares the energy density and related parameters of various biofuels against conventional diesel.

4.2 Engine Compatibility and Modifications

The integration of biofuels into existing traction systems often requires engine modifications, particularly for higher blend ratios. Xue et al. (2011) reviewed multiple studies documenting the effects of biodiesel on engine durability, noting increased injector coking and fuel filter clogging in some cases. Cold weather performance presents particular challenges for biodiesel due to higher cloud and pour points compared to petroleum diesel.

For bioethanol, material compatibility issues arise from its corrosive properties, necessitating replacement of certain seals, gaskets, and fuel system components (Bergthorson and Thomson, 2015). Additionally, engine control system recalibration is typically required to optimize performance and emissions with biofuel blends.

4.3 Emissions Profile

Biofuels generally offer reduced emissions of certain pollutants compared to conventional diesel, though with variations across biofuel types. Biodiesel typically reduces particulate matter (PM), carbon monoxide (CO), and hydrocarbon (HC) emissions but may slightly increase nitrogen oxides (NOx) emissions without engine calibration adjustments (EPA, 2002).

HVO demonstrates more comprehensive emissions benefits, with reductions across all major pollutant categories including NOx (No et al., 2004). Life-cycle emissions analyses by Edwards et al. (2014) indicated that second-generation biofuels could achieve 70-90% greenhouse gas reductions compared to fossil fuels, significantly outperforming most first-generation alternatives.

5 Comparative Analysis of Biofuels for Traction Systems

Table 1 below presents a comprehensive comparison of various biofuels applicable to traction systems based on key performance parameters and implementation factors.

Table 1 Comparative Analysis of Biofuels for Traction Systems

Parameter	Conventional Diesel	Biodiesel (B100)	Biodiesel Blends (B20)	HVO	BTL	Bioethanol
Energy Density (MJ/kg)	42-45	37-40	41-43	43-44	43-45	26-29
Energy Density (MJ/L)	35-38	32-33	34-36	34	34-36	21-24
Cetane Number	40-55	50-65	42-59	70-90	73-81	8-15
Oxygen Content (wt%)	~0	10-12	2-3	~0	~0	34.8
Cold Flow Properties	Good	Poor	Moderate	Excellent	Excellent	Poor

Engine Modifications Required	None	Minor/None	None	None	None	Significant
GHG Reduction Potential (%)	Baseline	40-60	10-15	50-90	70-95	30-70
Feedstock Availability	High	Moderate	High	Moderate	Moderate	Moderate
Production Cost (vs. Diesel)	Baseline	1.5-2x	1.1-1.3x	2-3x	2.5-4x	1.2-1.8x
Technology Readiness	Commercial	Commercial	Commercial	Early Commercial	Demonstration	Commercial
Infrastructure Compatibility	Complete	High	Very High	Very High	Very High	Low

Sources: Compiled from Aatola et al. (2008), Bergthorson and Thomson (2015), Edwards et al. (2014), IEA (2018), No et al. (2004), Sajjadi et al. (2016)

6 Case Studies and Implementation Examples

6.1 Railway Applications

Several railway operators have conducted trials and limited commercial implementations of biofuels for traction applications. The Swedish railway company SJ tested B5 (5% biodiesel blend) in their diesel fleet between 2007 and 2010, reporting no significant maintenance issues but noting challenges with fuel availability and cold weather operation (Andersson and Kågeson, 2013).

In the United States, Amtrak conducted trials with B20 biodiesel blends on the Heartland Flyer route between Oklahoma City and Fort Worth from 2010 to 2011. The 12-month test demonstrated technical feasibility with no adverse effects on engine performance or durability (Amtrak, 2012).

More ambitious implementations include Indian Railways' program to utilize B5 biodiesel blends across its diesel fleet starting in 2015, with plans to increase blend levels progressively. Their internal studies projected annual CO2 reductions of approximately 2.7% at B5 levels (Kathpal, 2014).

6.2 Heavy-Duty Road Traction

Road-based heavy traction applications have seen more extensive biofuel adoption than rail systems. A notable example is the Stockholm public transport fleet, which began transitioning to 100% renewable fuels including biodiesel and HVO for its bus operations in 2010. By 2017, greenhouse gas emissions had been reduced by over 60% compared to 2005 levels (Börjesson et al., 2018).

Scania's field trials with Euro 5 engines running on 100% HVO demonstrated equivalent performance to conventional diesel with significant emissions benefits, including particulate matter reductions of up to 50% and NOx reductions of 10% (Hartikka et al., 2012).

7 Challenges and Limitations

7.1 Technical Challenges

Despite promising results, several technical challenges persist in biofuel applications for traction systems:

- Cold Weather Operation: Biodiesel exhibits poor cold flow properties, with higher cloud and pour points than petroleum diesel. This limitation is particularly problematic for railway operations in colder climates (Knothe, 2010).
- Material Compatibility: Long-term exposure to certain biofuels, particularly higher biodiesel blends, may accelerate degradation of elastomers and natural rubber components in legacy fuel systems (Haseeb et al., 2011).

- Energy Density: The lower volumetric energy density of most biofuels, particularly bioethanol, necessitates increased fuel storage capacity or reduced operating range between refueling (Bergthorson and Thomson, 2015).
- Stability During Storage: Biodiesel exhibits reduced oxidative stability compared to petroleum diesel, potentially leading to increased acidity and sediment formation during long-term storage (Pullen and Saeed, 2012).

7.2 Economic Barriers

Economic factors represent significant barriers to widespread adoption:

- Production Costs: Most biofuels remain more expensive than petroleum diesel, with second-generation biofuels carrying the highest premium. Carriquiry et al. (2011) estimated that biodiesel production costs were typically 1.5-2 times higher than petroleum diesel, while advanced biofuels could be 2-4 times more expensive.
- Infrastructure Investment: The implementation of biofuels in traction systems often requires investments in fuel storage, handling, and distribution infrastructure, particularly for dedicated biofuel systems rather than blends (Sorda et al., 2010).
- Scale Economies: Many advanced biofuel production technologies had not achieved commercial scale by 2019, resulting in higher costs compared to conventional fuels and first-generation biofuels (Chiaramonti and Goumas, 2019).

7.3 Supply Chain and Sustainability Concerns

- Feedstock Availability: Seasonal variations and competition with food markets affect feedstock availability for first-generation biofuels. Timilsina et al. (2012) highlighted the potential impacts of expanding biofuel production on global food prices.
- Land Use Change: Indirect land use change associated with biofuel crop cultivation may diminish greenhouse gas reduction benefits in some scenarios (Searchinger et al., 2008).
- Water Usage: Cultivation of biofuel feedstocks can require significant water resources, raising sustainability concerns in water-scarce regions (Gerbens-Leenes et al., 2009).

8 Future Perspectives and Recommendations

8.1 Technological Development Pathways

Future improvements in biofuel applications for traction systems will likely follow several pathways:

- Optimized Biofuel Formulations: Development of additives and processing techniques to improve cold flow properties and oxidative stability of biodiesel (Knothe and Razon, 2017).
- Advanced Engine Technologies: Optimization of engine design and control systems specifically for biofuel operation, potentially leveraging dual-fuel concepts and hybridization (Imran et al., 2014).
- Integrated Biorefineries: Moving toward integrated production facilities capable of converting multiple feedstocks into various biofuel products, improving economic viability through process integration and by-product valorization (de Jong et al., 2015).

8.2 Policy Recommendations

Based on the analyzed literature, several policy approaches could accelerate biofuel adoption in traction systems:

- Tiered Support Mechanisms: Implementation of policy frameworks that differentiate support based on biofuel environmental performance rather than technology or feedstock type (Carriquiry et al., 2011).
- Harmonized Sustainability Criteria: Development of internationally recognized sustainability certification systems to ensure biofuels deliver genuine environmental benefits (Scarlat and Dallemand, 2011).
- Long-term Policy Stability: Provision of consistent, long-term policy signals to reduce investment uncertainty in advanced biofuel production facilities (Yeh et al., 2013).
- Public Procurement Programs: Utilization of government purchasing power through transport authorities to create initial markets for biofuels in traction applications (Börjesson et al., 2018).

9 Conclusion

This review demonstrates that biofuels offer viable renewable alternatives for traction systems, with varying degrees of technological readiness and environmental benefit. First-generation biofuels, particularly biodiesel blends, provide immediately implementable solutions with moderate emissions benefits but limited long-term potential due to feedstock constraints and partial compatibility issues.

Advanced biofuels, including HVO and BTL fuels, present superior technical characteristics and environmental performance but face economic barriers to widespread adoption. These advanced options offer the most promising long-term pathway toward sustainable traction systems, particularly when derived from waste streams and residues to minimize land use competition.

The successful integration of biofuels into traction systems requires a systems approach addressing technical compatibility, economic viability, and sustainability concerns simultaneously. While complete substitution of petroleum diesel appears challenging in the near term, strategic implementation of biofuel blends represents a practical transitional approach toward more sustainable traction systems.

Future research should focus on optimizing engine systems specifically for biofuel operation, improving production efficiency for advanced biofuels, and developing comprehensive life-cycle assessment methodologies to accurately quantify environmental benefits across different operational contexts.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Reference

[1] Aatola, H., Larmi, M., Sarjovaara, T., & Mikkonen, S. (2008). Hydrotreated vegetable oil (HVO) as a renewable diesel fuel: trade-off between NOx, particulate emission, and fuel consumption of a heavy duty engine. SAE International Journal of Engines, 1(1), 1251-1262.

[2] Amtrak. (2012). Fiscal Year 2011 Sustainability Report. National Railroad Passenger Corporation, Washington, DC.

[3] Andersson, E., & Kågeson, P. (2013). Assessing the potential for biofuels in rail transport. International Railway Journal, 53(7), 45-48.

[4] Bergthorson, J. M., & Thomson, M. J. (2015). A review of the combustion and emissions properties of advanced transportation biofuels and their impact on existing and future engines. Renewable and Sustainable Energy Reviews, 42, 1393-1417.

[5] Börjesson, P., Lantz, M., Andersson, J., Björnsson, L., Möller, B. F., Fröberg, M., ... & Hanarp, P. (2018). Methane as vehicle fuel – A well-to-wheel analysis (METDRIV) (No. 2016: 06). f3 The Swedish Knowledge Centre for Renewable Transportation Fuels.

[6] Carriquiry, M. A., Du, X., & Timilsina, G. R. (2011). Second generation biofuels: Economics and policies. Energy Policy, 39(7), 4222-4234.

[7] Chiaramonti, D., & Goumas, T. (2019). Impacts on industrial-scale market deployment of advanced biofuels and recycled carbon fuels from the EU Renewable Energy Directive II. Applied Energy, 251, 113351.

[8] Chisti, Y. (2007). Biodiesel from microalgae. Biotechnology Advances, 25(3), 294-306.

[9] de Jong, E., Higson, A., Walsh, P., & Wellisch, M. (2015). Bio-based chemicals: value added products from biorefineries. IEA Bioenergy, Task42 Biorefinery, 34.

[10] Edwards, R., Larivé, J. F., Rickeard, D., & Weindorf, W. (2014). Well-to-wheels analysis of future automotive fuels and powertrains in the European context: Well-to-tank report version 4a. Joint Research Centre of the European Commission, Luxembourg.

[11] EPA. (2002). A comprehensive analysis of biodiesel impacts on exhaust emissions. United States Environmental Protection Agency, Washington, DC.

[12] Gerbens-Leenes, W., Hoekstra, A. Y., & van der Meer, T. H. (2009). The water footprint of bioenergy. Proceedings of the National Academy of Sciences, 106(25), 10219-10223.

[13] Hartikka, T., Kuronen, M., & Kiiski, U. (2012). Technical performance of HVO (hydrotreated vegetable oil) in diesel engines. SAE Technical Paper 2012-01-1585.

[14] Haseeb, A. S. M. A., Fazal, M. A., Jahirul, M. I., & Masjuki, H. H. (2011). Compatibility of automotive materials in biodiesel: a review. Fuel, 90(3), 922-931.

[15] Hemmerlein, N., Korte, V., Richter, H., & Schröder, G. (1991). Performance, exhaust emissions and durability of modern diesel engines running on rapeseed oil. SAE Transactions, 912-923.

[16] IEA. (2018). The Future of Rail. International Energy Agency, Paris, France.

[17] Imran, S., Emberson, D. R., Diez, A., Wen, D. S., Crookes, R. J., & Korakianitis, T. (2014). Natural gas fueled compression ignition engine performance and emissions maps with diesel and RME pilot fuels. Applied Energy, 124, 354-365.

[18] Kathpal, A. K. (2014). Indian Railways' initiatives in application of biodiesel. International Railway Journal, 54(4), 37-39.

[19] Knothe, G. (2010). Biodiesel and renewable diesel: a comparison. Progress in Energy and Combustion Science, 36(3), 364-373.

[20] Knothe, G., & Razon, L. F. (2017). Biodiesel fuels. Progress in Energy and Combustion Science, 58, 36-59.

[21] Labeckas, G., & Slavinskas, S. (2006). The effect of rapeseed oil methyl ester on direct injection diesel engine performance and exhaust emissions. Energy Conversion and Management, 47(13-14), 1954-1967.

[22] Lin, L., Cunshan, Z., Vittayapadung, S., Xiangqian, S., & Mingdong, D. (2012). Opportunities and challenges for biodiesel fuel. Applied Energy, 88(4), 1020-1031.

[23] Moriarty, P., & Honnery, D. (2012). What is the global potential for renewable energy? Renewable and Sustainable Energy Reviews, 16(1), 244-252.

[24] Nikolaidis, P., & Poullikkas, A. (2017). A comparative overview of hydrogen production processes. Renewable and Sustainable Energy Reviews, 67, 597-611.

[25] No, S. Y., Oh, K. H., & Kim, H. S. (2004). Effect of exhaust gas recirculation on emissions characteristics of compressed ignition engine. International Journal of Automotive Technology, 5(2), 127-131.

[26] Pullen, J., & Saeed, K. (2012). An overview of biodiesel oxidation stability. Renewable and Sustainable Energy Reviews, 16(8), 5924-5950.

[27] Sajjadi, B., Raman, A. A. A., & Arandiyan, H. (2016). A comprehensive review on properties of edible and non-edible vegetable oil-based biodiesel: composition, specifications and prediction models. Renewable and Sustainable Energy Reviews, 63, 62-92.

[28] Scarlat, N., & Dallemand, J. F. (2011). Recent developments of biofuels/bioenergy sustainability certification: A global overview. Energy Policy, 39(3), 1630-1646.

[29] Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., ... & Yu, T. H. (2008). Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science, 319(5867), 1238-1240.

[30] Sorda, G., Banse, M., & Kemfert, C. (2010). An overview of biofuel policies across the world. Energy Policy, 38(11), 6977-6988.

[31] Timilsina, G. R., Mevel, S., & Shrestha, A. (2012). Oil price, biofuels and food supply. Energy Policy, 39(12), 8098-8105.

[32] Xue, J., Grift, T. E., & Hansen, A. C. (2011). Effect of biodiesel on engine performances and emissions. Renewable and Sustainable Energy Reviews, 15(2), 1098-1116.

[33] Yeh, S., Witcover, J., Lade, G. E., & Sperling, D. (2013). A review of low carbon fuel policies: Principles, program status and future directions. Energy Policy, 97, 220-234.