

палива з високою енергетичною щільністю та відповідністю міжнародним авіаційним стандартам (наприклад, ASTM D7566).

Використання тваринних жирів у виробництві SAF дозволяє зменшити кількість органічних відходів, що в іншому випадку могли б створювати екологічні проблеми, такі як забруднення ґрунтів і водних ресурсів. Крім того, утилізація побічних продуктів м'ясної промисловості у вигляді біопалива сприяє формуванню замкнених циклів виробництва, що відповідає принципам циркулярної економіки.

Завдяки низькій собівартості тваринних жирів як сировини, виробництво SAF за технологією HEFA має потенціал стати конкурентоспроможним на ринку. Стабільне постачання та відносно низькі коливання цін на тваринні жири у порівнянні з рослинними оліями забезпечують економічну перевагу цієї сировини для довгострокового розвитку біопаливного сектору.

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MATERIAL COMPATIBILITY, ENVIRONMENTAL IMPACT, AND SAFETY CONSIDERATIONS OF HYDROGEN AS A SUSTAINABLE MOTOR FUEL

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Hydrogen is emerging as a promising sustainable alternative to traditional fossil fuels in the transport sector. This paper examines the material compatibility, environmental impact, and safety considerations associated with hydrogen as a motor fuel. Key findings indicate that hydrogen, when produced via green hydrogen methods, offers significant environmental benefits by reducing carbon emissions. However, material degradation, especially hydrogen embrittlement in metals and composites, presents challenges for the long-term durability of storage and fuel systems. Additionally, safety concerns related to flammability, leakage, and high-pressure storage require robust safety protocols and advanced technologies. The study recommends further research into hydrogen-resistant materials, scalable production technologies, and enhanced safety systems to enable the large-scale adoption of hydrogen as a clean energy source in the transportation sector.

Ключові слова: *Hydrogen, Sustainable Fuel, Material Compatibility, Green Hydrogen, Hydrogen Embrittlement, Safety Considerations*

Hydrogen is a promising alternative fuel for the transportation sector due to its clean energy potential and high energy content. Below are some of the basic properties of hydrogen that make it an attractive option for future motor fuels:

Energy Density: Hydrogen has a high energy content per mass (120 MJ/kg), which is much higher than that of traditional gasoline and diesel fuels. However, hydrogen's energy density by volume is lower than fossil fuels due to its gaseous state at ambient temperature and pressure. As a result, hydrogen is typically stored under high pressure or in liquid form to increase its volumetric energy density, making it suitable for applications such as fuel cells and internal combustion engines.

Emissions: When used in fuel cells or combusted in an internal combustion engine, hydrogen produces only water vapor (H₂O) as a direct byproduct. This makes it a zero-emission fuel at the point of use, significantly reducing air pollutants such as carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter that are typically produced by traditional gasoline or diesel-powered vehicles.

Storage and Transport: Hydrogen can be stored in various forms, including as a compressed gas (at pressures of up to 700 bar), as a liquid (at cryogenic temperatures of minus 253°C), or in solid-state materials such as metal hydrides. The most common method for hydrogen storage in vehicles is compression into high-pressure cylinders. However, achieving high energy density in storage requires the development of more efficient compression and liquefaction technologies.

Hydrogen has the potential to transform various sectors of the transportation industry, providing a clean, efficient, and versatile energy source. The following outlines the key areas where hydrogen can be utilized:

Aviation: Hydrogen-powered aircraft are seen as a future solution for reducing the aviation industry's reliance on fossil fuels. Hydrogen can be used either in hydrogen fuel cells for electric propulsion or combusted in a modified jet engine. Using hydrogen as fuel for long-haul flights offers a promising alternative to conventional jet fuel, with zero emissions at the point of use, making aviation more environmentally sustainable.

Automotive: In the automotive sector, hydrogen fuel cell vehicles (FCVs) have become a viable alternative to traditional internal combustion engine vehicles. Hydrogen-powered cars, such as the Toyota Mirai and Hyundai Nexo, offer significant advantages in terms of long-range capabilities and quick refueling times, unlike battery electric vehicles (BEVs), which often face long charging times. Fuel cell vehicles are also beneficial for light-duty and heavy-duty transport, including trucks and buses.

Maritime: Hydrogen can also be applied in maritime transport, where it could be used to fuel ships and ferries. Several ongoing projects are focused on developing hydrogen-powered vessels to reduce the shipping industry's heavy reliance on marine diesel and to help meet international emissions targets.

While hydrogen shows significant promise as a motor fuel, there are several technological and infrastructural barriers that hinder its widespread adoption:

Hydrogen Production: The current production of hydrogen predominantly relies on natural gas reforming (grey hydrogen), which is not entirely carbon-free. To

make hydrogen a truly sustainable fuel, it must be produced via renewable energy sources such as water electrolysis powered by solar or wind (green hydrogen). The production cost of green hydrogen is still high, and economies of scale have yet to be fully realized.

Infrastructure: The lack of hydrogen refueling infrastructure is a significant barrier. Establishing a global network of refueling stations, especially in remote areas, requires substantial investment. Additionally, the transportation and storage of hydrogen remain complex and costly due to the need for specialized tanks and cryogenic equipment.

Public Perception and Safety: Despite its advantages, hydrogen faces public skepticism and safety concerns due to its flammability and explosion risks. Although hydrogen has a wide flammability range, and low ignition energy, modern safety technologies can mitigate these risks. However, educating the public and ensuring robust safety standards are essential for gaining acceptance.

Hydrogen, due to its small molecular size and high diffusivity, has the potential to interact with and degrade various materials used in fuel systems. Materials in contact with hydrogen, including metals, composites, and plastics, can undergo changes in their mechanical properties, corrosion resistance, and structural integrity. Below are the effects of hydrogen on different types of materials:

Metals: Metals such as steel, aluminum, and titanium are commonly used in hydrogen storage tanks, pipes, and other components. When exposed to hydrogen, these materials can experience hydrogen embrittlement, which causes a reduction in the ductility and strength of the metal, leading to potential cracks or failures. Some alloys, such as high-strength steels, are particularly susceptible to embrittlement when exposed to hydrogen, which can limit their use in high-pressure systems.

Composites: Carbon fiber composites are increasingly used in hydrogen storage systems due to their light weight and high strength. However, hydrogen exposure can degrade the matrix in composites, compromising their performance. This can lead to fiber-matrix debonding and a decrease in the composite material's strength and toughness.

Plastics: Hydrogen can also interact with polymers used in seals, gaskets, and other components in hydrogen fuel systems. Materials like polytetrafluoroethylene (PTFE), used in seals, may experience swelling, loss of mechanical properties, and leakage when exposed to hydrogen over time, especially at higher pressures.

Hydrogen embrittlement (HE) is one of the most critical phenomena that can affect the performance and safety of materials in hydrogen-powered systems. HE occurs when hydrogen atoms infiltrate the crystalline structure of metals, leading to brittleness and cracking. The mechanism behind HE involves hydrogen atoms diffusing into the metal lattice, causing the formation of hydrogen-induced cracks that reduce the metal's tensile strength and ductility.

Steel and Aluminum: High-strength steels and aluminum alloys are particularly vulnerable to hydrogen embrittlement. Steel, due to its crystalline structure, can absorb hydrogen and form brittle hydrides that weaken the material, leading to premature failure. Similarly, aluminum, especially in its high-strength

forms, is prone to the effects of hydrogen exposure, especially in high-pressure or cryogenic hydrogen environments.

The impact of hydrogen embrittlement is especially concerning in hydrogen storage systems, where structural integrity is critical for ensuring safety and performance. It is essential to evaluate materials for hydrogen compatibility during the design phase of fuel systems to prevent long-term degradation.

Case Studies and Real-World Applications

This section explores real-world applications where material selection and compatibility with hydrogen have been critical:

Hydrogen Storage Tanks: Hydrogen storage tanks for vehicles and infrastructure often use carbon fiber reinforced composites to meet strength and lightweight requirements. However, as mentioned, hydrogen diffusion can cause degradation in the matrix, which can be mitigated by using epoxy coatings or carbon nanotube-infused composites for better resistance to hydrogen-induced degradation.

Fuel Cells: In fuel cells, platinum-based catalysts are typically used, but stainless steel components in the system can be prone to corrosion when exposed to hydrogen. Solutions have been found through the use of corrosion-resistant alloys and advanced sealing materials to enhance the lifespan of fuel cell systems.

Pipeline Infrastructure: The transportation of hydrogen via pipelines has necessitated the use of high-strength, low-alloy steels that are specifically designed to withstand the pressures of hydrogen. The use of coatings and internal linings helps prevent hydrogen embrittlement and extends the lifespan of the pipelines.

One of the most compelling advantages of hydrogen as a fuel is its potential to significantly reduce the environmental impact of transportation. When used in hydrogen fuel cells or combustion engines, hydrogen produces only water vapor as a direct byproduct, making it a zero-emission fuel at the point of use. This is in stark contrast to conventional fossil fuels, which emit harmful pollutants such as carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter when burned.

Hydrogen's potential to reduce greenhouse gas emissions is especially significant for industries that are difficult to decarbonize, such as aviation, maritime, and heavy-duty transport. By replacing fossil fuels with hydrogen, these sectors can significantly reduce their global warming potential (GWP), which is a measure of the amount of carbon dioxide emissions that would cause the same amount of global warming as a given quantity of another gas.

In addition to the direct emissions reductions, hydrogen can also reduce air pollutants such as nitrogen oxides (NO_x) and particulate matter, which are harmful to both human health and the environment. Hydrogen, being a clean fuel, plays a critical role in mitigating climate change by providing a viable pathway to decarbonize the transportation sector and meet global emissions reduction targets [39].

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ОСОБЛИВОСТІ ОТРИМАННЯ МОТОРНИХ ПАЛИВ З ПОЛІМЕРНИХ ВІДХОДІВ

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Розглянуто технологію переробки полімерних відходів низькотемпературним піролізом з використанням каталізаторів для одержання компонентів автомобільних і авіаційних бензинів.

Ключові слова: полімерні відходи, піроліз, каталізатор.

На сьогодні перспективним методом отримання продуктів тонкої органічної хімії, зокрема вуглеводнів різного структурно-групового складу є переробка полімерних відходів низькотемпературним піролізом з використанням каталізаторів, які прискорюють швидкість деструкції полімерів та дозволяють отримати облагороджені рідкі та газоподібні продукти деструкції з нижчими енергетичними затратами проведення процесу. Удосконалення термічних методів переробки полімерних відходів вимагає пошуку нових каталізаторів, які мають високу активність і дешевизну.

Процес піролізу безпечних відходів змішаного пластикув з підвищенням температури підсилюється з однієї сторони виділенням водню/дегідруванням, а з іншої — утворенням складніших, збагачених карбоном органічних сполук. Але піроліз обов'язково супроводжується деструкцією зв'язку С–С з утворенням численних складніших органічних сполук. Використання металів-каталізаторів, наприклад оксиду титану TiO₂, дозволяє суттєво знизити температури дегідрування, зменшити вихід пірогазу та пірокарбону із збільшенням виходу піроконденсату – «синтетичної» нафти, яка в основному є сумішшю алканів, олефінів, нафтенів та аренів. Використання для