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A COMPARATIVE REVIEW OF BIOFUELS AND ELECTRIC PROPULSION FOR SMALL-SCALE MARINE TRANSPORTATION IN NIGERIA

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Abstract

Nigeria's small-scale marine transport sector which encompasses inland waterways, coastal ferries, fishing vessels, and naval patrol craft operating across approximately 10,000 kilometres of waterways, remains heavily dependent on petrol and diesel, generating significant air pollution, greenhouse gas emissions, and energy insecurity. This review systematically compares two alternative energy pathways; biofuels (biodiesel, bioethanol, and biogas), and electric propulsion (battery-electric and hybrid-electric), for applicability to Nigerian small-scale marine vessels (5–50 m). Evaluated against technical feasibility, environmental performance, economic viability, and infrastructural readiness, the analysis demonstrates that hybrid setups utilizing battery-electric systems with biofuel-powered engines provide the best results across various metrics, and biodiesel offers the most immediately deployable pathway through drop-in compatibility with existing engines; while battery-electric propulsion is superior for short-route urban ferries contingent on grid improvements. The exploration closes with a phased, portfolio-based transition strategy with clear regulatory and financing recommendations.

Keywords: *Alternative marine fuels; biofuels; electric propulsion; Nigeria; inland waterways; decarbonization*

1. Introduction

Nigeria occupies a strategically significant maritime position on the Gulf of Guinea, with an 853-kilometre coastline, a 200-nautical-mile Exclusive Economic Zone, and approximately 10,000 kilometres of inland waterways, roughly 3,800 kilometres of which are navigable year-round, traversing 28 of the country's 36 states and connecting five neighbouring countries (Bassey and Ekpenyong, 2018; Lloyd *et al.*, 2019; National Inland Waterways Authority, 2025). The country's maritime transportation history extends to pre-colonial times, with modern operations commencing in 1892 through Elder Dempster's pioneering vessel (Igberi and Ogunniyi, 2013), followed by the establishment of the Nigerian National Shipping Line in 1958 (Ekpo, 2012).

Despite this rich heritage, Nigeria has yet to fully harness its waterway potential for economic development, with inland water transport presently accounting for less than 1% of total daily trips in major urban centres.

The small-scale marine transport sector serves critical roles in passenger transport, cargo movement, artisanal fishing, oil-field support, and naval patrol operations. Recent developments underscore the sector's growing strategic importance. Lagos State's 30-year development plan targets an increase in inland water transport's modal share from under 1% to 8% by 2032 (Lagos State Government, 2023). The European Investment Bank-supported Lagos Waterways Sustainable Transport project involves the procurement of fully electric small-scale vessels and construction of new jetties (EIB, 2024), and Afreximbank's partnership with Nigeria to develop navigational charts for the 456-kilometre Lower River Niger represents a milestone in trade facilitation (Afreximbank, 2024). The Nigerian Navy's modernisation programme, encompassing patrol boats from 37-metre Chamsuri-class vessels to 76-metre offshore patrol vessels, further highlights the sector's security and strategic dimensions (Ekene, 2025). The current operational paradigm is environmentally and economically unsustainable. Global shipping accounts for approximately 2.6% of anthropogenic CO_2 emissions and 13% of global sulfur oxide emissions, with vessels consuming an estimated 400 million metric tonnes of marine fuel annually (Sofiev *et al.*, 2018; Olmer *et al.*, 2017; IMO, 2020). Nigeria's small-scale fleet, dominated by two-stroke outboard engines burning petrol and diesel, discharges 15–30% of fuel unburned into waterways, exacerbates local air pollution in riparian communities, and exposes operators to extreme fuel price volatility.

The International Maritime Organization's revised GHG strategy mandates a 40% reduction in carbon intensity by 2030 and net-zero shipping emissions by approximately 2050, creating both regulatory pressure and technological opportunity for Nigeria's maritime sector (Tanzer *et al.*, 2019; Tan *et al.*, 2021). By early 2025, alternative-fuel newbuild orders had risen to 63% of all vessel orders globally, while orders for conventionally fuelled vessels had nearly disappeared (Al-Asmakh *et al.*, 2025). Two technologies have emerged as viable candidates for small-scale marine applications in Nigeria: biofuels (biodiesel, bioethanol, biogas), and electric propulsion (battery-electric and hybrid-electric). Biofuels offer drop-in compatibility and substantial domestic feedstock potential (Gilbert *et al.*, 2018; Ben-Iwo *et al.*, 2016); while electric propulsion offers little to no operational emissions, increasingly competitive economics, and reduced maintenance demands.

Existing literature bifurcates between general Nigerian biomass assessments (Ben-Iwo *et al.*, 2016; Jekayinfa *et al.*, 2020) and global decarbonisation studies targeting large ocean-going vessels (Sofiev *et al.*, 2018; Tan *et al.*, 2021), neither of which addresses Nigeria's small-scale marine sector with the specificity required for policy action. This review bridges that gap, providing the first multi-criteria comparative analysis of biofuels and electric propulsion specifically for Nigerian small-scale marine vessels (5–50 metres) operating in inland waterways, coastal waters, and territorial seas. The analysis integrates technical, environmental, economic, and infrastructural dimensions to identify optimal technology-vessel pairings and chart a realistic, phased transition pathway.

2. Small-Scale Marine Transport in Nigeria

2.1 Vessel Types and Fleet Composition

Nigeria's small-scale marine fleet exhibits considerable diversity, reflecting the varied geographical, economic, and functional demands of different stakeholder groups. Wooden boats constructed from tropical hardwoods including iroko (*Milicia excelsa*) and mahogany (*Khaya spp.*) using traditional techniques, remain predominant in rural waterways, classified as dugout canoes, half-dugouts, or plank-built vessels. Of approximately 1,000 canoes recorded on Lagos Lekki Lagoon in 2010, plank-built construction accounted for 54%, dugouts 24%, and half-dugouts 21% (Babatunde, 2010). A proposed ban on wooden boats announced in early 2026 by the Ministry of Marine and Blue Economy signals growing recognition of their safety and environmental limitations (The Guardian, 2026).

Fiberglass (fiber-reinforced plastic, FRP) vessels are increasingly adopted in urban waterways, offering superior structural integrity, lower maintenance costs, resistance to rot and marine borers, and improved hydrodynamic efficiency compared to wooden craft (Okuma *et al.*, 2023). Aluminium and steel-hulled vessels serve higher-capacity passenger ferry routes, cargo transport on major rivers, and naval patrol functions. The fleet encompasses five principal operational categories: (1) short-route urban passenger ferries (30–100 passengers, 10–25 km routes on Lagos Lagoon and Niger Delta creeks); (2) artisanal fishing boats (5–15 m, inshore and offshore operations); (3) river cargo vessels (10–30 m, bulk transport on the Niger and Benue rivers); (4) naval and government patrol craft (37–76 m offshore patrol vessels and smaller rigid-hull inflatable boats); and (5) oil-field support vessels serving offshore installations in the Gulf of Guinea.

2.2 Engine Configurations and Fuel Consumption

Engine configurations range from 5–25 kW two-stroke outboard motors on dugout canoes to 100–500 kW four-stroke inboard diesel engines on ferries and cargo vessels. Two-stroke engines, while lightweight and low-cost, are particularly problematic environmentally. They typically release 10-25% of their fuel (petrol/oil mixture) unburned into the waters (NIWA, 2007), with these emissions proving to be much more toxic than that of four-stroke engines of equal power (Jüttner *et al.,* 1995). It is said that a 15 kW two-stroke engine that operates for 1 h makes 11,000 m^3 of water undrinkable (Jüttner *et al.,* 1995). This creates localised hydrocarbon pollution and contributing to aquatic ecosystem degradation in the ecologically sensitive Niger Delta and Lagos Lagoon. Four-stroke inboard diesel engines, used on larger vessels, offer superior fuel efficiency but contribute to NO_x and particulate matter emissions that affect the health of waterfront communities (Balamurugan and Nalini, 2014). Both engine categories are predominantly fuelled by imported petrol and diesel, creating supply chain vulnerability and exposure to global oil price fluctuations amplified by Nigeria's periodic domestic refinery underperformance (Obasi and Eke, 2022).

2.3 Key Operational Challenges

Three interconnected challenges define the sector's current inadequacy. First, fuel supply disruptions stemming from Nigeria's refinery underperformance, distribution bottlenecks, and subsidy policy volatility have produced extreme price volatility (e.g. petrol prices tripling between 2022 and 2025 following subsidy removal) that directly threatens the viability of small-scale marine operations and disproportionately impacts low-income passengers dependent on waterway transport (Obasi and Eke, 2022). Second, two-stroke outboard engines generate NO_x, SO_x, particulate matter, CO, and unburned hydrocarbons, while diesel engines on larger vessels contribute substantially to air quality degradation (Jüttner *et al.,* 1995; Balamurugan and Nalini, 2014), especially in densely populated waterfront areas such as Lagos Waterside, Onitsha River Port, and the creeks of Rivers State . Third, persistent safety deficits including overcrowded wooden vessels, inadequate life-saving equipment, poor navigation aids, and fuel-related fire hazards from petrol's high volatility, result in a disproportionate number of fatal waterway accidents, reinforcing the urgency of fleet modernisation and fuel transition.

3. Alternative Fuel Pathways

3.1 Biofuels

Nigeria's bioenergy resource base is exceptional in scale and diversity. Agricultural residues, forest products, and municipal solid waste exceed 200 billion kilograms annually, representing an energy potential greater than 61 million tonnes of oil equivalent (Edeh and Okpo, 2023). Theoretical energy potential from agricultural residues alone is estimated at 1.09 exajoules, with an additional 0.65 exajoules from animal waste convertible to biogas (Jekayinfa *et al.*, 2020). Traditional biomass and waste constitute approximately 80% of Nigeria's total primary energy consumption (U.S. EIA, 2015), underscoring the deep integration of bioenergy into the national energy system and the potential for upgrading this resource base into higher-value transportation fuels. Three principal biofuel pathways warrant detailed assessment for Nigerian marine applications: biodiesel, bioethanol, and biogas.

3.1.1 Biodiesel

Biodiesel (fatty acid methyl ester, FAME) is produced by transesterifying triglycerides from vegetable oils, animal fats, or algae, with methanol in the presence of an alkali catalyst such as KOH or NaOH (Jariah *et al.*, 2021).). Nigeria possesses substantial resources across multiple feedstock generations suitable for biodiesel production, classified into first-, second-, third-, and fourth-generation categories based on their origin, sustainability profile, and technological maturity (Dutta *et al.*, 2014). Among first-generation feedstocks, palm oil is most significant: Nigeria ranks as the world's fourth-largest producer, cultivating over 3 million hectares with approximately 7.8 million tonnes of production in 2017 (FAOSTAT, 2019; Jekayinfa *et al.*, 2020), and achieves oil yields of 3.74 tonnes/hectare annually; nearly ten times higher than soybean (0.38 t/ha) or rapeseed (0.67 t/ha) (Munonye *et al.*, 2023; Elbehri *et al.*, 2013). Solid wastes from palm oil processing, including empty fruit bunches, palm press fibre, and palm kernel shells, represent additional feedstocks with combined energy potentials of 40–85 PJ/year, avoiding food-fuel competition (Ben-Iwo *et al.*, 2016). Soybean oil presents a further first-generation option, with an estimated national biodiesel production potential of 284.5 million litres from 638,000 hectares of cultivated soybeans (Ben-Iwo *et al.*, 2016).

Second-generation feedstocks address the food-versus-fuel conflict through non-edible oil crops. Jatropha curcas (*Jatropha curcas* L.) emerges as the most extensively studied second-generation biodiesel feedstock in Nigeria (Adewuyi, 2020; Aransiola *et al.*, 2012). Jatropha oil produces nearly 100% biodiesel yield during transesterification under both homogeneous and heterogeneous catalytic conditions (Brahma *et al.*, 2022). Following Nigeria's rainfall distribution patterns, jatropha can be cultivated across all ecological zones with minimal rainfall requirements of approximately 250 mm annually (Abila, 2010). With an estimated yield of 1,892 liters per hectare per year and biodiesel productivity of 656 kg/ha/year, jatropha demonstrates significantly higher land-use efficiency than soybean while avoiding food crop competition (Mata *et al.*, 2010; Munonye *et al.*, 2023). Additional non-edible oil feedstocks including castor (*Ricinus communis*), mahua (*Madhuca indica*), yellow oleander (*Cascabela thevetia*), tung (*Aleurites fordii*), and pongamia (*Millettia pinnata*) have been identified as viable second-generation options, though cultivation and processing studies remain limited in the Nigerian context (Banković-Ilić *et al.*, 2012; Brahma *et al.*, 2022)

Third-generation biodiesel production utilizes microalgae as feedstock, with theoretical productivity ranging from 51,927 kg/ha/year (30% oil content) to 121,104 kg/ha/year (70% oil content) (Mata *et al.*, 2010; Bošnjaković and Sinaga, 2020). It however remains at Technology Readiness Level (TRL) 4–5 in Nigeria but presents a compelling long-term research frontier given Nigeria's tropical climate and abundant water resources. Fourth-generation biodiesel feedstocks represent the frontier of biofuel technology, employing genetically modified microorganisms including engineered microalgae and cyanobacteria, to enhance lipid production, increase CO_2 capture efficiency, and reduce the number of process steps required to convert solar energy into liquid fuel (Alalwan *et al.*, 2019; CDP, 2023). However, fourth-generation feedstock research remains in developmental and experimental stages globally, with limited studies or pilot-scale demonstrations in Nigeria.

Biodiesel's critical advantage for Nigerian marine applications is drop-in compatibility: B20 blends (20% biodiesel, 80% diesel) can be used in existing marine diesel engines without modification, while higher blends (B50–B100) may require minor seal material upgrades. Biodiesel possesses an energy content of approximately 33 MJ/L, which is approximately 12% lower per unit mass than petroleum diesel (Igwebuike, 2023; Department of Transport, 2022). The lower heating value of biodiesel ranges from 119,550 to 128,500 Btu/gallon compared to petroleum diesel's 129,488 to 138,490 Btu/gallon (Alleman *et al.*, 2016). This energy density differential translates to marginally higher volumetric fuel consumption; approximately 10–13% more biodiesel by volume is required to deliver equivalent energy output compared to petroleum diesel, though this is partially offset by biodiesel's superior lubricity and more complete combustion characteristics (Oghenejoboh and Umukoro, 2011). Other key fuel properties are operationally comparable to diesel: cetane number 47–65 vs. 40–55 for diesel (Alleman *et al.*, 2016; Karmakar *et al.*, 2018), kinematic viscosity of 1.9 to 6.0 mm²/s at 40°C compared to petroleum diesel's 1.3 to 4.1 mm²/s (Alleman *et al.*, 2016), 11% oxygen by weight compared to 0% for petroleum diesel, with corresponding reductions in carbon content (77% versus 87%) and hydrogen content (12% versus 13%) (Alleman *et al.*, 2016). This intrinsic oxygen content promotes more complete combustion, reducing emissions of unburned hydrocarbons, carbon monoxide, particulate matter, and smoke opacity. These are all environmental benefits of particular importance for marine applications where exhaust gases are discharged directly over waterways and in proximity to riparian communities (Karmakar *et al.*, 2018; Oghenejoboh and Umukoro, 2011).

3.1.2 Bioethanol

Bioethanol, produced through fermentation of carbohydrate-rich biomass materials by microorganisms such as *Saccharomyces cerevisiae*, offers a high-octane, oxygen-rich alternative to petroleum-based gasoline with substantial greenhouse gas reduction potential (Bušić *et al.*, 2018; Tan *et al.*, 2015). As the most prevalent biofuel globally, accounting for approximately 73% of the 135.3 billion liters of biofuel produced in 2016, bioethanol has demonstrated technical and commercial viability across diverse feedstock and production contexts (Franziska *et al.*, 2017). Nigeria's substantial biomass endowment, including agricultural crops, lignocellulosic residues, and aquatic biomass, provides multiple pathways for bioethanol production, though the country currently produces negligible fuel ethanol despite importing between 300 and 350 million liters annually at a cost of approximately 1.2 trillion Naira (equivalent to about 2.7 billion US dollars) (The Nations, 2016; Advanced Biofuels USA, 2019; Femi, 2019).

Bioethanol feedstocks in Nigeria can be classified into three principal categories based on their chemical composition and the conversion processes required: sugar-based feedstocks, starch-based feedstocks, and lignocellulosic (cellulose-based) feedstocks. Each category corresponds approximately to generational classifications commonly used in biofuel literature, with sugar and starch feedstocks representing first-generation biofuels and lignocellulosic materials representing second-generation biofuels (Manochio *et al.*, 2017; Naik *et al.*, 2010).

Sugar-based feedstocks contain readily fermentable sugars that can be directly converted to ethanol through microbial fermentation without requiring prior saccharification steps, making them the most straightforward and technologically mature category for bioethanol production. Sugarcane (*Saccharum officinarum*) represents the most important sugar-based feedstock globally and holds substantial potential for Nigeria. Although Nigeria is not among the world's largest sugarcane producers, the country cultivated approximately 89,000 hectares of sugarcane producing 1.5 million tons in 2017, with considerably greater production potential given suitable climatic conditions and available arable land (FAOSTAT, 2019; Jekayinfa *et al.*, 2020). Beyond its direct juice content, sugarcane offers the additional advantage of lignocellulosic residue (bagasse) remaining after juice extraction, which can be converted to bioethanol through second-generation processes or combusted for process heat and electricity cogeneration. Sugarcane bagasse has a lower heating value of 7,700–8,000 kJ/kg and an energy potential of 7.11 PJ/year in Nigeria (Jekayinfa *et al.*, 2020). Both sugarcane bagasse and leaves possess significant potential as substrates for organic acids, biofuels, and biopolymer production from their cellulosic fractions (Machado *et al.*, 2018).

Sweet sorghum (*Sorghum bicolor*) represents an alternative sugar-rich feedstock with significant advantages for Nigerian conditions. Sorghum stalks are rich in fermentable sugar with high extractability, containing juice with composition suitable for bioethanol production (Regassa and Wortmann, 2014). Sweet sorghum has a relatively short growing season of three to four months, requires lower agronomic inputs than many other crops, demonstrates good drought tolerance, and is well-suited to the semi-arid conditions prevalent across Nigeria's northern regions (Billings, 2015).

Starch-based feedstocks contain complex carbohydrates (polysaccharides) that require enzymatic or acid hydrolysis to break down starch polymers into fermentable glucose monomers before microbial fermentation can proceed. This additional processing step increases production complexity and cost relative to sugar-based feedstocks but enables utilization of widely cultivated staple crops and their processing residues. Cassava (*Manihot esculenta*) emerges as the most promising starch-based feedstock for Nigeria, with the country ranked as the world's largest producer, harvesting approximately 59.5 million tons from 6.79 million hectares in 2017 (FAOSTAT, 2019; Wossen *et al.*, 2018; Jekayinfa *et al.*, 2020). Cassava produces the highest carbohydrate quantities per unit land area of any crop except sugarcane and requires at least 8 months of warm weather to produce substantial tuber yields (Adeoti, 2010). Other starch-based feedstocks investigated in Nigeria include maize (corn), yam tubers, potato, and mixed tuber combinations, though these exhibited significantly lower bioethanol yields than cassava in laboratory studies and similarly raise food security concerns (Braide *et al.*, 2016).

Lignocellulosic biomass, comprising agricultural residues, forest residues, dedicated energy grasses, and food processing wastes, represents the most abundant and sustainable category of bioethanol feedstock in Nigeria, addressing food-versus-fuel concerns while providing waste valorization benefits. Lignocellulosic materials contain cellulose (38–50% by weight), hemicellulose (15–30%), and lignin (10–25%), with the cellulose and hemicellulose fractions convertible to fermentable sugars through pretreatment and enzymatic hydrolysis processes (Zabed *et al.*, 2016; Robak and Balcerek, 2018). However, the highly recalcitrant nature of lignin (which forms a protective matrix around cellulose fibers) demands complex pretreatment processes (physical, chemical, thermal, or biological) to increase surface area, decrease crystallinity, eliminate hemicellulose, and break lignin seals before enzymatic saccharification can proceed (Aditiya *et al.*, 2016). These additional processing requirements increase overall production costs and technical complexity relative to first-generation feedstocks, positioning lignocellulosic bioethanol as an advanced biofuel still approaching full commercial maturity (Robak and Balcerek, 2018; IRENA, 2013).

Bioethanol's marine applications face inherent constraints. Its volumetric energy density of 21.1 MJ/L is approximately 34% lower than gasoline (32 MJ/L), necessitating larger fuel tanks or more frequent refuelling to maintain equivalent range (U.S. Department of Energy, 2023). Ethanol's high octane number (RON) of 107-110 compared to gasoline's 91-95 (Tan *et al.*, 2015) enables high compression ratios delivering improved thermal efficiency, partially offsetting the energy density disadvantage, but requires engine modification for blends above E20 (20% ethanol, 80% gasoline). Corrosive properties require bioethanol-compatible fuel system materials (ethanol-resistant seals, fuel lines, and tank linings) most critical at higher blend concentrations. These constraints make bioethanol most applicable to smaller spark-ignition outboard engines and less suitable for the four-stroke diesel engines prevalent in larger Nigerian marine vessels. The oxygen content in ethanol promotes more complete combustion, reducing carbon monoxide (CO) emissions by 10–30% and unburned hydrocarbon (UHC) emissions by 15–30% compared to pure gasoline (Ohimain, 2010; Tan *et al.*, 2015). Particulate matter emissions decrease substantially with ethanol blends due to the absence of aromatic compounds and the promotion of complete combustion, though particulate emissions are already low from gasoline engines compared to diesel engines (Bušić *et al.*, 2018).

3.1.3 Biogas and Bio-CNG

Biogas, a methane-rich gaseous fuel produced through anaerobic digestion of organic matter by microbial consortia in oxygen-free conditions, represents a particularly attractive biofuel pathway for Nigeria given the country's substantial waste generation and the technology's proven suitability for decentralized, small-scale applications (Adeleke *et al.*, 2023). Anaerobic digestion involves multi-stage biochemical decomposition wherein hydrolytic bacteria initially break down complex organic compounds into simpler molecules, acidogenic bacteria subsequently convert these to volatile fatty acids and alcohols, and methanogenic archaea finally transform intermediates into methane (CH_4) and carbon dioxide (CO_2) through methanogenesis (Adeleke *et al.*, 2023). Biogas typically contains 50–75% methane, 25–50% carbon dioxide, and trace quantities of hydrogen sulfide, water vapor, and other gases, with energy content of 20–25 MJ/m^3 depending on methane concentration (Suberu *et al.*, 2013).

The anaerobic digestion process offers multiple concurrent benefits beyond fuel production, including organic waste treatment and disposal, pathogen reduction, odor control, and production of nutrient-rich digestate suitable for agricultural fertilizer use, making it a genuinely circular economy technology that addresses waste management, energy security, and agricultural productivity simultaneously (Orakwe *et al.*, 2011; Suberu *et al.*, 2013). For Nigeria, where solid waste management constitutes one of the greatest challenges facing environmental protection agencies and where approximately 74,428.85 tons of municipal solid waste are generated daily with potential biogas production capacity of 2.04 million m^3/day, biogas represents both an energy opportunity and a waste management solution (Adeleke *et al.*, 2023).

Municipal solid waste in Nigeria exhibits substantial organic content suitable for anaerobic digestion, with the putrescible (biodegradable) fraction ranging from 25% to 78% of total waste composition depending on location, socioeconomic characteristics, and seasonal factors (Ogwueleka, 2009). National average waste generation is approximately 0.53 kg/capita/day, translating to annual generation of 27,166,530.25 tons with theoretical biogas production potential of 0.44 EJ, corresponding to technical energy potential of 0.11 EJ after accounting for collection efficiency and conversion losses (Amber *et al.*, 2012; Jekayinfa *et al.*, 2020).

Nigeria's substantial livestock population generates approximately 227,500 tons of fresh animal waste daily, equivalent to potential biogas production of 6.8 million m^3/day assuming 0.03 m^3 biogas per kilogram of fresh waste (Suberu *et al.*, 2013; Adeleke *et al.*, 2023). The country's animal population as of 2017 included approximately 20.8 million cattle, 78.0 million goats, 42.5 million sheep, 140.7 million chickens, and 7.5 million pigs (FAOSTAT, 2019), generating daily dung quantities across these livestock categories with well-established biogas yield potential per kilogram of waste. The theoretical energy potential of animal waste in Nigeria is estimated at 2.17 EJ using an average biogas energy content of 22.6 MJ/m^3, with technical energy potential of 0.65 EJ after applying availability factors (Jekayinfa *et al.*, 2020).

Different animal waste types exhibit varying biogas yields and methane contents based on diet, age, and waste characteristics. Cattle manure demonstrates biogas yields of 0.20–0.33 m^3/kg with extended retention times, pig manure yields 0.49–0.75 m^3/kg with 58–61% methane content and 10–15 day retention periods, goat manure requires approximately 20-day retention with yields of 0.37–0.61 m^3/kg at 64% methane content, and poultry manure exhibits the highest biogas yield potential at 0.31–0.56 m^3/kg with 58–60% methane content and 9–30 day retention times (Jekayinfa *et al.*, 2020). The relatively short retention times for poultry and pig waste make these particularly attractive feedstocks for biogas production systems where rapid throughput and compact digester sizing are advantageous.

Agricultural crop residues represent the largest single category of biomass feedstock in Nigeria with technical energy potential of approximately 1.09 EJ, though biogas production from agricultural residues through anaerobic digestion has received comparatively less attention than solid biofuel combustion or lignocellulosic bioethanol pathways (Jekayinfa *et al.*, 2020). However, agricultural residues are suitable for co-digestion with animal waste or municipal solid waste to improve overall biogas yields and process stability.

When purified to biomethane through removal of CO_2, H_2S, water vapor, and other impurities, biogas achieves methane content exceeding 95–98%, with heating value approaching that of pipeline natural gas at 35–40 MJ/m³ (Suberu *et al.*, 2013). This upgraded biomethane can be compressed to 200–250 bar pressure as compressed biogas (Bio-CNG), enabling storage and transportation in forms compatible with natural gas vehicle and infrastructure (Atelge *et al.*, 2020).

In marine engines, compressed Bio-CNG at 200 bar pressure achieves approximately 2.4 kWh/L compared to diesel at 10.0 kWh/L and gasoline at 8.9 kWh/L, representing an energy density disadvantage (Atelge *et al.*, 2020). However, it achieves exceptional environmental performance: Carbon monoxide (CO) emissions from biogas engines are typically 50–90% lower than gasoline engines and 30–70% lower than diesel engines due to more complete combustion of methane and the absence of complex hydrocarbon species that form CO during incomplete combustion (Suberu *et al.*, 2013; Karavalakis *et al.*, 2016). Unburned hydrocarbon (UHC) emissions are similarly reduced by 50–80% compared to liquid fuels, and particulate matter (PM) emissions are negligible (typically 95% lower than diesel engines). Dual-fuel diesel-biogas conversion (enabling 60–80% biogas substitution while retaining diesel fuel capability for periods when biogas is unavailable) represents the most practical marine deployment pathway, avoiding complete engine replacement and providing operational flexibility during infrastructure build-up. Key infrastructure requirements include anaerobic digestion plants, gas cleaning and upgrading units, compression systems rated to 200–250 bar, high-pressure onboard storage cylinders, and marine-rated dispensing equipment.

3.2 Electric Propulsion

Electric propulsion systems represent the technologically most advanced alternative fuel pathway for marine transportation, offering zero operational emissions, substantially reduced noise pollution, and significantly lower maintenance requirements compared to internal combustion engines. Driven by mounting regulatory pressure to decarbonize global shipping, electric and hybrid propulsion technologies have experienced rapid adoption in maritime sectors globally. However, this global adoption trajectory has been almost entirely concentrated in developed maritime economies, particularly Northern Europe, where robust electricity grid infrastructure, renewable energy availability, government subsidies, and stringent environmental regulations create favorable conditions for electric vessel deployment (Kolodziejski and Michalska-Pozoga, 2023). In developing economies such as Nigeria, electric marine propulsion remains essentially unexplored despite potentially compelling applications in the small-scale inland waterway and coastal transport sectors.

3.2.1 Battery-Electric Propulsion

Battery-electric propulsion systems employ electric motors powered exclusively by onboard Battery Energy Storage Systems (BESS), with batteries charged from shore-based electricity supply during mooring or layover periods. This configuration eliminates all onboard combustion processes, resulting in zero direct emissions of greenhouse gases, particulate matter, nitrogen oxides, sulfur oxides, and unburned hydrocarbons during vessel operation (SINTEF, 2022). The environmental benefits of battery-electric vessels depend critically on the carbon intensity of the electricity grid from which batteries are charged. Vessels charged from renewable energy sources (solar, wind, hydroelectric) achieve genuinely zero lifecycle emissions, while those charged from fossil fuel-dominated grids merely relocate emissions from the vessel to the power generation facility (European Maritime Safety Agency, 2020).

The dominant application domain for battery-electric vessels is short-range, high-frequency services where predictable routes, fixed schedules, and regular port calls enable systematic recharging without operational disruption. Ferry services exemplify this operational profile, and indeed ferries constitute the largest category of battery-electric vessel deployment globally. The MF Ampere, which entered service in Norway in May 2015 as the world's first large-scale all-electric battery-powered car ferry, operates a 5.7 km route making 34 trips daily with a 1,090 kWh battery pack charged in 9-minute bursts between crossings (Corvus Energy, 2022a). Compared to a conventional diesel ferry on the same route, MF Ampere achieves annual savings of 1,000 m^3 of diesel fuel with maintenance cost reductions of 20–25% attributable to elimination of engine oil changes, reduced wear on moving parts, and simplified mechanical systems (Corvus Energy, 2022a).

Fishing vessels represent another application domain directly relevant to Nigeria's marine sector. The 11-meter fishing vessel Karoline operated as the world's first all-battery-powered fishing vessel using a 195 kWh ESS consisting of 30 Corvus AT6500 lithium polymer battery modules (Corvus Energy, 2022c). Operating faultlessly over three years, Karoline demonstrated significant improvements in crew working conditions through noise reduction; a benefit particularly valuable for small artisanal fishing operations where engine noise constitutes an occupational health concern and interferes with fish detection (Corvus Energy, 2022c). The operational model employed diesel engines for transit to fishing grounds and electric power for loading, unloading, and fishing operations, demonstrating that hybrid configurations can address range limitations while capturing emissions benefits in ecologically sensitive fishing zones.

3.2.2 Hybrid-Electric Systems

Hybrid-electric propulsion systems combine battery energy storage with onboard diesel generators, creating operational flexibility that addresses the fundamental range limitation of pure battery-electric vessels while capturing substantial fuel savings and emissions reductions. Hybrid configurations enable multiple operational modes including: battery-only propulsion during port approach, maneuvering, and berthing where emissions and noise are most problematic; diesel-electric propulsion for sustained cruising where battery capacity would be insufficient; peak shaving where batteries supplement diesel generators during high-power demand periods without requiring additional generator sets to be started; and shore power charging where batteries are replenished from grid electricity during port layovers, reducing or eliminating diesel generator operation in port (Kolodziejski and Michalska-Pozoga, 2023; Bø *et al.*, 2019).

One of the earliest and most thoroughly studied marine hybrid-electric installations was the offshore supply vessel Viking Lady, retrofitted as part of the FellowSHIP research programme; a collaboration between Eidesvik, Wärtsilä Norway, and DNV GL. A 442 kWh lithium-ion battery integrated into the vessel's power system demonstrated fuel consumption reductions of 10–15%, NO_x emission reductions of 25%, greenhouse gas reductions of 30%, and significant maintenance savings due to reduced engine running hours (DNV GL, 2018a). Following these results, three additional platform support vessels (Viking Queen, Viking Energy, and Viking Princess) were similarly converted; after one year of operation, fuel savings of 10–17% and emission reductions up to 20% were recorded (DNV GL, 2018a).

For Nigerian applications, hybrid-electric configurations offer particular advantages during the infrastructure development phase when shore-based charging availability may be limited or uncertain. Hybrid vessels can operate independently of charging infrastructure by generating all electricity onboard while still capturing efficiency benefits from load optimization and peak shaving. As shore charging infrastructure is progressively deployed at major terminals and harbors, the same hybrid vessels can transition to greater reliance on battery-electric operation, progressively reducing diesel fuel consumption without requiring vessel replacement or major system modifications.

A particularly instructive hybrid model for Nigerian contexts is the biofuel-battery configuration demonstrated by the UK's Thames Clipper hybrid high-speed passenger ferries. These vessels combine biofuel engines with BESS in a configuration where battery power is used in urban emission-sensitive zones while batteries are recharged by biofuel engines outside those zones (Offshore Energy, 2022; Danfoss, 2022). This biofuel-battery hybrid approach addresses both the charging infrastructure limitation (as batteries are charged onboard using locally producible biofuels rather than grid electricity) and the emissions objective, as biofuels from sustainable feedstocks offer carbon neutrality while battery-electric operation in populated areas eliminates local air pollution. For Nigeria, where palm oil, jatropha, cassava, and other biofuel feedstocks are abundantly available while electricity grid reliability remains severely constrained, this dual-fuel hybrid configuration may represent the most pragmatic near-term pathway to cleaner marine propulsion.

4. Comparative Analysis

4.1 Technical and Operational Performance

Table 1 presents a systematic comparison of the five principal alternative fuel pathways against key technical and operational parameters relevant to Nigerian small-scale marine applications. The assessment reflects literature-derived performance data contextualised for Nigeria's tropical operating environment, fuel quality limitations, and technical workforce capacity.

Table 1: Technical and Operational Comparison of Alternative Fuel Pathways for Nigerian Small-Scale Marine Applications

Parameter	Biodiesel (B20–B100)	Bioethanol (E10–E85)	Biogas / Bio-CNG	Battery-Electric	Hybrid-Electric
Engine compatibility	High – drop-in for diesel engines; no modification for B20	Moderate – suited to spark-ignition engines; limited in compression-ignition fleet	Moderate – requires conversion or dedicated new engine	Low – full system replacement needed	Moderate – complex integration; retrofit possible
Energy density	33–37 MJ/L (B100)	21.4 MJ/L (ethanol)	~8 MJ/L equiv. at 200 bar	0.5–0.9 MJ/kg ($LiFePO_4$ cell)	Hybrid – combined range
Range suitability	High (diesel-equivalent tanks)	Moderate – larger tanks required for E85	Moderate – 200–400 km typical at 200 bar	30–100 km typical (short routes)	Extended (biofuel backup)
Infrastructure needs	Low – blending, storage at depot level	Low-moderate – production + blending stations	High – compression stations, pipeline access	High – grid/solar charging at terminals	Moderate-High – dual system
Maintenance burden	Similar to diesel; better lubricity	Similar to petrol; corrosion checks	15–30% lower than diesel	50–70% lower than diesel	20–40% lower than diesel
Technology	TRL 9 –	TRL 8–9 – Mature	TRL 8–9 – Mature	TRL 7–9 – Mature	TRL 7–9 – Mature

Readiness Level	Commercially mature globally	(E10 blends)	(CNG vehicles)	in developed markets	globally

Sources: Kesieme et al., 2019; Khan et al., 2015; Kolodziejski & Michalska-Pozoga, 2023; Corvus Energy, 2022a; Yeh, 2007

4.2 Environmental Performance

Table 2 summarises relative emissions performance normalised to a diesel baseline (100%), drawn from lifecycle analysis literature and contextualised for Nigeria's energy system characteristics, particularly the grid carbon intensity of approximately 450–550 gCO_2/kWh from Nigeria's gas-heavy electricity generation mix.

Table 2: Comparative Emissions Performance Relative to Diesel Baseline (Diesel = 100%)

Pollutant	Biodiesel (B20-B100)	Bioethanol (E10-E85)	Biogas / Bio-CNG	Battery-Electric (Grid)	Battery-Electric (Renewable)
CO_2 (lifecycle)	22–78% reduction*	20–90% reduction*	80–100% reduction	20–40% reduction**	Near-zero (residual: battery manufacture)***
CO_2 (tailpipe only)	10–50% reduction	10–30% reduction	23–35% reduction	Zero at point of use	Zero
Carbon monoxide (CO)	10–50% reduction	10–30% reduction	30–70% reduction	Zero at point of use	Zero
Nitrogen oxides (NO_x)	0–10% increase	0–15% increase	50–70% reduction	Zero at point of use	Zero
Particulate matter (PM)	20–50% reduction	50–80% reduction	Around 95% reduction	Zero at point of use	Zero
Sulfur dioxide (SO_2)	Eliminated (sulfur-free)	Eliminated (sulfur-free)	Eliminated (post-H_2S scrub)	Zero at point of use	Zero
Unburned hydrocarbons	20–40% reduction	15–30% reduction	50–80% reduction	Zero at point of use	Zero

**Feedstock and land-use change dependent; waste feedstocks achieve upper bound. **Nigeria grid ~450–550 gCO_2/kWh (gas-heavy). ***Residual manufacturing ~50–100 gCO_2/kWh lifecycle*

Sources: Hagos & Ahlgren, 2017; Banković-Ilić et al., 2012; European Maritime Safety Agency, 2020; Sofiev et al., 2018; Karmakar et al., 2018; Franziska et al., 2017; Atelge et al., 2020

For Nigeria's waterfront communities, CNG/biogas and electric propulsion deliver the most meaningful local air quality improvements through near-complete elimination of particulate matter and NO_x which are the pollutants most acutely linked to respiratory disease and cardiovascular mortality. Biodiesel's water pollution profile is substantially safer than petroleum diesel, exhibiting 85–88% biodegradability within 28 days versus less than 20% for diesel, which is critical in the ecologically sensitive Niger Delta where aquatic ecosystems underpin artisanal fishing livelihoods for millions of people.

4.3 Economic Analysis

Table 3 presents a comparative economic analysis covering capital cost premiums, fuel cost differentials, maintenance savings, and estimated payback periods. Estimates are contextualised for Nigerian market conditions, including current fuel prices, available financing structures, and local labour costs.

Table 3: Comparative Economic Estimates of Alternative Fuel Pathways (Reference Vessel: 75 kW Propulsion, 20-Passenger Ferry)

Economic Parameter	Biodiesel	Bioethanol	Biogas / Bio-CNG	Battery-Electric	Hybrid-Electric
Propulsion system capital premium vs. diesel	~0% (blending only)	~0% (for E10–E20)	~100% (cylinders + conversion)	~225% (battery pack + motor)	~195% (battery + generator)
Onboard storage cost premium	Negligible	Negligible	$5,000–$12,000 (HP cylinders)	$15,000–$45,000 (150 kWh LFP)	$10,000–$25,000 (75 kWh LFP)
Shore infrastructure (amortised / vessel)	~$0	~$0	$20,000–$50,000	$15,000–$30,000 (solar)	$15,000–$25,000
Fuel / energy cost vs. diesel	±10–30% (scale-dependent)	+10–30% vs. petrol (E85)	62–77% cheaper than diesel	30–60% cheaper**	30–50% cheaper
Maintenance cost change	Similar to diesel	Similar to petrol	15–30% reduction	50–70% reduction	20–40% reduction

***Savings diminish with Nigeria's grid tariff; improved significantly with integrated solar charging. Sources: Khan et al., 2015; Mongird et al., 2020; Ubani & Ikpaisong, 2018; Kersey et al., 2022; Igbojionu et al., 2019; 2024 industry estimates*

Liquid biofuels demonstrate near-zero capital cost premium, enabling adoption without financial barriers beyond fuel supply chain establishment. Bio-CNG requires a ~100% capital premium primarily from high-pressure storage cylinders and refuelling infrastructure, offset by dramatic fuel cost savings. Battery-electric systems command a ~225% capital premium from battery pack costs, though rapidly declining battery prices and 50–70% maintenance cost reductions progressively improve the economic case.

4.4 Infrastructure and Implementation Readiness

Biodiesel's principal strength in the Nigerian context is minimal infrastructure disruption: existing fuel distribution networks, storage tanks, and vessel fuel systems require only modest blending-level modifications for B20 deployment, enabling near-term rollout without capital-intensive infrastructure development. The main bottleneck lies in commercial-scale biodiesel production capacity which is essentially nonexistent in Nigeria, with estimated development timelines of 5–8 years to establish production at commercial scale. Bioethanol infrastructure readiness holds similarities to that of biodiesel, although ethanol has attained wider use in Nigeria mostly from imports. Bio-CNG requires focused infrastructure investment in compressor stations, high-pressure dispensing equipment, and onboard cylinder systems. Electric propulsion's viability is most tightly coupled to grid reliability; however, solar PV integrated charging stations (potentially complemented by floating solar arrays on river terminal rooftops) represent a viable off-grid pathway uniquely suited to Nigeria's solar resource endowment.

From a regulatory perspective, Nigeria lacks marine-specific fuel quality standards for biodiesel, bioethanol, or CNG, and has not domestically implemented IMO or DNV battery system safety rules for electric vessels. Nigeria's technical workforce limitations represent a cross-cutting constraint: CNG high-pressure system inspection, lithium-ion battery management, and power electronics maintenance require specialised skills largely absent from the current marine workforce, whereas biodiesel's maintenance profile closely resembles conventional diesel, minimising training requirements and supporting near-term deployment.

4.5 Multi-Criteria Technology Assessment

Table 4 presents a weighted multi-criteria assessment scoring each technology and the diesel baseline across seven evaluation criteria (scale: 1 = Poor to 5 = Excellent). Criteria weights reflect the relative importance of each dimension in the Nigerian small-scale marine context, with operating cost and GHG emissions weighted highest given the dual imperatives of economic viability and environmental improvement.

Table 4: Multi-Criteria Technology Assessment Matrix (Score: 1 = Poor → 5 = Excellent)

Criterion	Weight	Diesel	Biodiesel	Bioethanol	Bio-CNG	Battery-Electric	Hybrid-Electric
Capital Cost	15%	5	5	5	3	2	3
Operating Cost	20%	3	2	2	3	4	4
GHG Emissions	20%	1	4	4	4	5	4
Local Air Quality	15%	1	3	3	3	5	4
Infrastructure Readiness	15%	5	2	2	3	1	2
Range/Flexibility	10%	5	5	4	3	2	4
Technology Maturity	5%	5	4	4	4	3	3
WEIGHTED SCORE	**5 (100%)**	**3.20**	**3.40**	**3.30**	**3.25**	**3.35**	**3.5**

No single technology dominates across all criteria. Biodiesel and hybrid-electric configurations achieve highest overall scores through balanced performance across multiple dimensions. Battery-electric scores are suppressed by capital cost and infrastructure barriers despite excellent operational performance. Bioethanol marginally outperforms diesel overall but range limitations and lower adaptability to conventional compression-ignition engines suppresses score. Bio-CNG demonstrates improving infrastructure readiness (mainly for road vehicles) but faces cost complications and storage complexity due to its lower energy density as a fuel.

4.6 Vessel-Technology Matching Matrix

Table 5: Technology-Vessel Matching Matrix for Nigerian Small-Scale Marine Applications

Vessel Type	Route Profile	1st Choice	2nd Choice	Rationale
Short-route urban ferry (30–100 pax)	Fixed, 10–25 km, high frequency	Battery-Electric	Hybrid-Electric	Zero emissions in populated areas; predictable routes enable charging optimisation; suitable for solar terminal charging
Creek passenger boat (15–30 pax)	Variable routes, 15–40 km	Biodiesel (B20–B50)	Hybrid-Electric	Infrastructure limitations favour drop-in liquid fuel; hybrid viable near urban grid access
Artisanal fishing boat (<12 m)	20–50 km to grounds, 4–8 hr operation	Hybrid-Electric	Biodiesel / Bioethanol	Hybrid system utilizes both diesel (for transit to fishing area) and electric power (which enables quieter fishing)
River cargo vessel (<50 tons)	30–80 km, irregular schedule	Biodiesel	Diesel (transition)	Range and payload requirements favour liquid fuel; biodiesel provides drop-in emissions improvement
High-speed intercity ferry (50+ pax)	25–60 km intercity routes	Biodiesel	Hybrid-Electric	High power demands challenge battery capacity; liquid fuel maintains full performance range
Harbor tug	Short-distance, intermittent high power	Hybrid-Electric	Battery-Electric	Intermittent high-power demands suit peak-shaving; extended idle periods benefit from electric mode
Naval / Government patrol craft	Variable, extended range potential	Hybrid-Electric (biofuel)	Biodiesel / Bioethanol	Operational flexibility essential; biofuel hybrid provides backup, stealth in electric mode
Oil-field support vessel	Niger Delta, near-shore operations	Bio-CNG (dual-fuel) / Biodiesel	Hybrid-Electric	Gas infrastructure available in Niger Delta; backup fuel critical for offshore safety requirements

5. Strategic Implementation Roadmap

5.1 Near-Term (0–5 Years): Biodiesel Deployment and Pilot Projects

Biodiesel emerges as the most immediately deployable alternative fuel pathway, given its drop-in compatibility with the existing fleet, minimal vessel infrastructure requirements, and established technology maturity at TRL 9. Priority actions include: (1) establishing pilot biodiesel production facilities from used cooking oil and palm oil processing residues at 5–10 million litres/year scale, targeting government demonstration fleets; (2) conducting fleet demonstration projects on 20–30 government-owned vessels (Lagos State Waterways Authority ferries, Rivers State transport services), systematically documenting fuel consumption, maintenance, and emissions performance to build the operational evidence base; (3) adopting and enforcing ASTM D6751 biodiesel quality standards through NIMASA and the DPR, creating the regulatory framework for broader private sector supply; (4) developing blending infrastructure at major fuel depots in Lagos, Port Harcourt, Warri, and Calabar, enabling B5–B20 supply through existing distribution networks; and (5) commissioning 3–5 battery-electric pilot vessels on short-route urban ferry services (e.g., Lagos Waterfront to Lagos Island) with dedicated solar PV charging infrastructure, generating critical operational data under Nigerian grid and climate conditions.

5.2 Medium-Term (5–10 Years): Infrastructure Development and Market Expansion

As biodiesel production scales and electric pilot results mature: (1) expand grid-connected and solar charging infrastructure at major river ports where electricity reliability permits, prioritising routes where electric ferries have demonstrated viability in the pilot phase; (2) scale commercial biodiesel production to 50–100 million litres/year from second-generation feedstocks, including Jatropha cultivation on identified marginal land tracts and industrial-scale used cooking oil collection systems; (3) introduce subsidised financing instruments for hybrid-electric conversion targeting high-utilisation ferry and fishing fleets, potentially structured as green shipping loans through the Bank of Industry or development finance partners; and (5) establish marine CNG and electric system maintenance certification programmes through the National Maritime University and NIMASA-approved technical institutes.

5.3 Long-Term (10–20 Years): System Transformation and Renewable Integration

With infrastructure maturity and demonstrated viability: (1) integrate renewable electricity (solar PV and hydroelectric capacity) for zero-carbon vessel charging, aligned with Nigeria's broader energy transition goals; (2) develop anaerobic digestion infrastructure producing compressed biomethane from municipal solid waste and agricultural residues at major river cities (Onitsha, Lokoja, Yola); (3) advance third-generation biodiesel production from algae and lignocellulosic feedstocks as technology matures globally and domestically; (4) establish new vessel construction requirements favouring battery-electric or hybrid-electric propulsion for eligible route types through NIMASA vessel registration policy; and (5) build a circular economy framework incorporating battery recycling partnerships, used cooking oil collection networks at fish markets and food processing clusters, and integrated waste-to-biofuel value chains serving both stationary and marine energy markets.

6. Conclusion

This review has demonstrated that no single alternative fuel pathway optimally serves all vessel types and operational contexts within Nigeria's diverse small-scale marine transport sector. Rather, an optimised, portfolio-based transition strategy, matching technologies to specific vessel types, operational profiles, and regional infrastructure conditions, represents the most pragmatic and resilient pathway toward decarbonisation.

Biodiesel emerges as the near-term workhorse technology, offering immediate deployment potential with minimal infrastructure investment and vessel modification, leveraging Nigeria's exceptional agricultural biomass endowment while delivering meaningful emissions improvements, particularly for NO_x, CO, and particulate matter. Its drop-in compatibility with the existing diesel fleet is an unmatched advantage in a sector characterised by limited capital access and conservative technology adoption patterns. Battery-electric propulsion represents the superior long-term solution for short-range, high-frequency urban ferry services, delivering zero operational emissions, dramatically reduced maintenance costs, and significant noise reduction, contingent upon electricity grid reliability improvements and renewable energy integration that extend beyond the marine sector alone. Hybrid-electric configurations emerge as the optimal transitional technology for mixed-profile vessels, decoupling electric operation from grid dependency through on-board biofuel generation and providing the operational flexibility essential for Nigeria's variable waterway conditions. Bioethanol and biogas, while offering genuine benefits, are secondary priorities in the near term given bioethanol's limited marine engine compatibility and biogas's requirement for substantial new production infrastructure.

The multi-criteria analysis reveals that the current diesel-dependent status quo is not only the most environmentally costly option but also increasingly economically suboptimal as oil price volatility intensifies and alternative fuel competitiveness improves. The transition timeline proposed herein is ambitious but achievable through coordinated public-private action: near-term biodiesel deployment establishes an alternative fuel market and operational precedent; medium-term infrastructure development enables CNG and electric propulsion adoption; and long-term system transformation achieves substantive decarbonisation aligned with IMO 2050 net-zero targets. Ultimately, success depends not only on technology selection but on institutional development, regulatory clarity, financing innovation, and sustained political commitment; challenges that are social and institutional as much as they are technical.

This review is subject to several limitations that should be acknowledged. First, quantitative economic estimates, including fuel cost savings, payback periods, and capital cost premiums, are derived from literature spanning different time periods, national contexts, and market conditions. Nigerian market conditions, including exchange rate volatility, irregular subsidy regimes, and informally structured supply chains, introduce uncertainty into cost projections that should be treated as indicative rather than precise. Second, the review does not include primary data collection from vessel operators, government agencies, or fuel suppliers in Nigeria; field-based studies capturing operator behaviour, real-world maintenance outcomes, and actual fuel consumption under tropical waterway conditions would substantially strengthen the evidence base. Third, lifecycle emissions data for biofuels are highly sensitive to feedstock assumptions, land-use change accounting, and supply chain methane leakage rates, parameters that are poorly characterised for Nigerian-specific feedstock systems.

Several directions for future research are identified. Techno-economic feasibility studies for specific Nigerian waterway corridors, such as the Lagos Lagoon ferry network, the Onitsha–Lokoja Niger River route, and the Trans-Forcados creek system in Delta State, would provide the route-specific data needed for investment decision-making. Laboratory and pilot-scale testing of biodiesel produced from Nigerian-sourced feedstocks (palm kernel oil, Jatropha, used cooking oil) in representative marine engine configurations would validate fuel quality and performance under local conditions. Life cycle assessment studies calibrated to Nigerian agricultural systems, grid carbon intensity, and waste management infrastructure would yield more precise GHG reduction estimates than currently available from international literature analogies. Finally, socio-economic impact assessments of alternative fuel transition on artisanal fishing communities, river transport operators, and waterfront fuel vendors (who represent substantial informal employment) are essential to designing equitable transition policies that do not inadvertently harm the most economically vulnerable stakeholders in Nigeria's maritime economy.

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