African Journal of Inter/Multidisciplinary Studies (AJIMS)
Volume 8, Issue 1, pp. 1-16
e-ISSN: 2663-4589

The Socio-Economic Effects of Biofuels in Maritime Transport: A Case Study of a South African Port

Laura Novienyo Abla Amoah,† Okuhle Mbangwa,† Felix Kwabena Donkor†

[1]Department of Development Studies, Nelson Mandela University, Gqeberha, South Africa

Abstract: The adoption of biofuels in maritime transport has garnered increasing interest as a potential strategy for enhancing sustainability in the shipping sector. This study examines the socio-economic and environmental implications of biofuel use at a South African port through a qualitative case study approach. Following an interpretivist paradigm, the research utilises semi-structured interviews with key stakeholders, including port officials, shipping operators, and environmental practitioners, to explore their perceptions, experiences, and expectations regarding the adoption of biofuels. The findings reveal that stakeholders generally view biofuels as beneficial for environmental stewardship, particularly in reducing air pollution and aligning with global decarbonization targets. However, they also expressed concerns about cost implications, infrastructural readiness, and the long-term viability of biofuels in the maritime sector. This study highlights the tensions between environmental aspirations and socio-economic realities, illustrating how stakeholder perspectives shape the discourse surrounding alternative fuels. Overall, this research contributes to ongoing discussions about sustainable energy transitions in maritime transport and provides insights that are relevant to policymakers, industry leaders, and port authorities in South Africa and beyond.

Keywords: biofuels; environmental sustainability; maritime transport; renewable energy; socio-economic impact

CORRESPONDENCE

Email: laura.amoah@mandela.ac.za

EDITORIAL DATES

Received: 21 August 2025
Revised: 20 March 2026
Accepted: 23 March 2026
Published: 21 June 2026

DOI: https://doi.org/10.51415/ajims.v8i1.3355

Introduction and background

Maritime transport is a crucial component of the global economy, facilitating the movement of over 80% of international trade by volume across oceans, seas, and inland waterways (UNCTAD, 2023). Its ability to efficiently transport large volumes of diverse cargo, ranging from bulk commodities to manufactured goods, makes it indispensable to global supply chains and economic development (Notteboom et al., 2021). Various specialised vessels, including container ships, tankers, Roll-on/Roll-off (RO-RO) ships, refrigerated carriers, and liquefied natural gas (LNG) vessels, enable the sector to meet complex logistical demands across continents.

Despite its operational efficiencies, the maritime sector significantly contributes to environmental degradation and climate change. Shipping is responsible for approximately 2–3 % of global anthropogenic carbon dioxide (CO_2) emissions, along with considerable releases of nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter, and other pollutants that negatively impact marine and coastal environments (International Maritime Organization, 2020; Xiang et al. 2023). These emissions contribute to ocean acidification, biodiversity loss, and deteriorating air quality, which can lead to adverse public health effects, such as respiratory diseases among populations living near ports and coastal areas (Woods Hole Oceanographic Institution, 2021; Queensland Government, 2013). Furthermore, environmental challenges are exacerbated by ballast water discharges and toxic antifouling paints, which pose additional threats to marine biodiversity and water quality (Xiang et al., 2023).

In response to these issues, the International Maritime Organisation (IMO) has implemented strict regulatory measures to mitigate environmental impacts. One important measure is the sulphur cap, which limits the sulphur content in marine fuels to 0.5%, significantly reducing sulphur oxide emissions (International Maritime Organization, 2020). Additionally, the IMO's Initial Greenhouse Gas Strategy aims to halve carbon intensity by 2050 compared to 2008 levels, signalling a clear policy shift towards decarbonization and the adoption of alternative fuels and energy technologies. These regulations have spurred innovation and investment in sustainable maritime fuels, including liquefied natural gas (LNG), hydrogen, ammonia, and biofuels.

Biofuels have garnered particular interest due to their renewable nature, compatibility with existing marine engines, and potential for substantial reductions in greenhouse gas emissions (DNV, 2023; International Energy Agency, 2024). These fuels are produced from biological feedstocks such as algae, agricultural residues, plant oils, and organic waste, providing a renewable alternative to traditional fossil-based bunker fuels (FAO, 2019). While first-generation biofuels, derived from edible crops like maize and sugarcane, have faced criticism for competing with food production and raising land-use concerns, second- and third-generation biofuels, produced from lignocellulosic biomass, non-edible crops, and microalgae, offer more sustainable and environmentally sound options (FAO, 2019; International Energy Agency, 2024). These advanced biofuels demonstrate significant life-cycle reductions in carbon emissions and can be used with minimal engine modifications, making their integration into maritime fuel supply chains more feasible and less disruptive (El-Araby, 2024).

Despite notable progress in Europe and Asia, where several ports have piloted biofuel usage with measurable improvements in air quality and emissions profiles (DNV, 2023), Africa's maritime sector has yet to fully harness the potential of biofuels, largely due to structural constraints including limited domestic production capacity, weak policy incentives, inadequate infrastructure, and fragmented coordination among stakeholders (DoE, 2021). In South Africa, however, a more enabling policy environment is emerging. National initiatives such as the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) and the National Biofuels Industrial Strategy offer frameworks to advance renewable energy adoption and sustainable transport. Despite these developments, significant gaps remain in policy enforcement, alignment with maritime regulations, and the implementation of comprehensive strategies necessary to drive effective biofuel uptake within the shipping industry (DoE, 2021; Global Energy Monitor, n.d.).

The Port of Ngqura, located within the Coega Industrial Development Zone (IDZ) in the Eastern Cape province, is well-positioned to lead in biofuel innovation and deployment. Since its commissioning in 2009, the port has developed into a modern deep-water facility, serving as a vital transshipment hub for regional and international trade (Africa Ports, 2022). Its proximity to agricultural and biomass resources, combined with its status as part of an IDZ designed to attract industrial investment and stimulate regional economic development, provides unique advantages for biofuel production, storage, and export logistics (Coega Development Corporation, 2023). Moreover, the Port of Ngqura's designation as South Africa's only "green port" highlights its commitment to environmentally sustainable operations, aligning with both national and international sustainability priorities (Transnet National Ports Authority, n.d.).

The Port of Ngqura provides a strategic context to investigate the socio-economic and environmental dimensions of biofuel adoption in maritime transport. This study focuses on three questions: (1) What environmental gains can biofuels deliver in the South African maritime sector? (2) What are the socio-economic implications for port communities and the wider economy? (3) What mechanisms can enable effective biofuel integration in maritime operations?

Drawing on qualitative data from stakeholder interviews and a critical analysis of existing literature and policy frameworks, the research aims to bridge knowledge gaps, inform evidence-based policy, and guide industry practices in advancing Africa's transition toward sustainable maritime energy systems.

Literature review

Maritime transport is a cornerstone of global trade, accounting for approximately 80% of international cargo volume (UNCTAD, 2023). However, the sector's heavy reliance on fossil fuels, particularly heavy fuel oil, has made it a significant driver of environmental degradation, climate change, and localised pollution. In response, the ecological footprint of maritime operations has increasingly come under scrutiny, fostering a growing body of research focused on emission reduction strategies and sustainable shipping practices (Zhou et al., 2023).

African scholarship on renewable energy transitions and energy justice emphasises that decarbonisation processes are influenced by historical inequalities, uneven investments in infrastructure, and the priorities of developmental states. In the context of South Africa, maritime energy transitions must balance environmental objectives with the need for job creation, food security, and industrial localisation. By incorporating these perspectives, we can gain a clearer understanding of the adoption of biofuels within African port systems (Radtke & Renn, 2025; Tsoeu-Ntokoane et al., 2024).

Environmental impacts and regulatory context

Maritime vessels emit large volumes of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter, contributing to global warming, acid rain, and adverse respiratory health outcomes (International Maritime Organization, 2020). Beyond air emissions, ballast water discharge, and the application of antifouling agents pose significant threats to marine biodiversity, highlighting the need for effective regulatory frameworks and sustainable operational practices (Xiang et al., 2023).

In response to these environmental challenges, the International Maritime Organisation (IMO) has set ambitious targets through its Initial GHG Strategy, aiming for at least a 50% reduction in greenhouse gas emissions from ships by 2050 (International Maritime Organization, 2020). The implementation of the sulphur cap, which reduced the allowable sulphur content in marine fuels from 3.5%–0.5 %, has further incentivised the adoption of cleaner fuels and technologies (International Maritime Organization, 2020). Despite these regulatory advances, significant obstacles remain. The capital-intensive nature of the shipping industry and the scale of operations complicate rapid fuel transitions, while alternative fuels such as liquefied natural gas (LNG) and hydrogen face technological and infrastructure constraints (Global Maritime Forum, 2023). Biofuels, by contrast, have emerged as a promising solution, offering compatibility with existing engine systems alongside the potential for substantial decarbonization of the maritime sector (DNV, 2023).

Generations of biofuels: Sustainability potential and challenges

Biofuels are categorised into four generations according to feedstock types and production technologies (Afolalu et al. 2021; Khan et al. 2021; Rai et al., 2022). First-generation biofuels are derived from food-based feedstocks such as sugarcane, maize, vegetable oils, and animal fats (Kant et al. 2025). Although technologically mature and widely deployed, their production raises concerns over competition with food crops and increased land-use pressures, potentially undermining food security (FAO, 2019).

Second-generation biofuels, by contrast, are produced from lignocellulosic biomass and non-edible crops, reducing reliance on arable land and mitigating some food security risks (Kant and Kanda 2019). Third-generation biofuels are generated from microalgae and specialised bacterial strains, notable for their high biomass productivity, minimal freshwater requirements, limited land footprint, and carbon dioxide sequestration during cultivation. However, their commercial adoption remains constrained by technological and economic challenges (International Energy Agency, 2024). Fourth-generation biofuels are still largely experimental, leveraging synthetic biology and genetic engineering to enhance fuel yields and carbon capture, offering significant potential for deep decarbonisation in hard-to-abate sectors such as maritime transport (Afolalu et al., 2021).

Table 1 summarises the four generations of biofuels, highlighting their feedstocks, benefits, and associated challenges. This concise format enables readers to quickly compare technological maturity, environmental advantages, and limitations, providing valuable guidance for maritime stakeholders evaluating which biofuel types best fit their operational, environmental, and economic priorities.

The adoption of biofuels in maritime vessels can cut sulphur emissions by up to 90% and carbon dioxide emissions by around 70% (Mahapatra et al., 2021). Additionally, biofuels are generally less toxic and pose fewer hazards than petroleum diesel, improving environmental safety (Mahapatra et al., 2021). However, choosing

Table 1. Generations of Biofuels and Their Maritime Applicability

Generation	Feedstock Examples	Advantages	Disadvantages	Maritime Applicability
First Generation	Sugarcane, maize, soybean	Mature technology, readily available feedstock	Competes with food crops, potential land use change impacts	Limited use in the maritime sector due to the food *vs*. fuel debate
Second Generation	Agricultural residues, forestry waste, non-food crops ((*e.g.*) jatropha)	Reduced food competition, better GHG performance	Higher production costs require advanced processing	Suitable for blending with marine diesel; promising for reducing emissions
Third Generation	Algae, other aquatic biomass	High yield per hectare, non-arable land use, CO_2 sequestration potential	High capital investment, technology is still maturing	Strong potential for long-term maritime fuel transition
Fourth Generation	Genetically engineered algae and microbes	Enhanced efficiency, integrated carbon capture	Not yet commercially viable, regulatory uncertainty	Potential game-changer for carbon-neutral shipping

the most suitable biofuel involves balancing environmental benefits with socio-economic considerations, as no single biofuel can address all the challenges faced by the shipping industry (Holden & Gilpin, 2013). Production costs remain high, and concerns linger about potential deforestation and disruptions to food supplies linked to certain feedstocks (Yacout et al., 2024). Despite these issues, biofuels are widely seen as a proactive short- to medium-term solution for reducing greenhouse gas emissions in maritime transport (Jeswani et al., 2020).

Socio-economic impacts of biofuels

Beyond environmental gains, the social sustainability of biofuels involves significant socio-economic implications, particularly in regions where feedstocks are cultivated. Biofuel industries can create employment across agriculture, logistics, processing, and research sectors, thereby supporting rural development and poverty alleviation (FAO, 2019). Uzorka et al. (2023) highlight the importance of community involvement in renewable energy projects, noting that such engagement fosters skills development, education, and technology transfer, thus promoting social inclusion and empowerment within local communities.

Expanding biofuel use offers considerable potential for sustainable energy transitions, but it must be managed carefully to prevent negative social effects, including land-use conflicts, loss of food production capacity, and unequal economic benefits. To address these risks, inclusive policy frameworks are essential, prioritising food security, land rights protection, and fair access to new opportunities within the biofuel sector (FAO, 2019). A core element of these frameworks should be participatory approaches that involve government, industry, and local communities in decision-making processes. Such approaches have proved to strengthen both the social legitimacy and operational success of biofuel projects. For instance, the Roundtable on Sustainable Biomaterials requires transparent, consultative, and inclusive procedures for planning and monitoring projects (RSB, 2008).

Evidence from wider energy transition research supports that participatory governance enhances legitimacy and policy flexibility (Radtke & Renn, 2025), while co-designed, community-led projects tend to achieve fairer benefits, greater acceptance, and longer-term sustainability (Tsoeu-Ntokoane et al., 2024).

Biofuel adoption in African maritime contexts

While biofuel deployment has gained traction in Europe and Asia, African maritime sectors have lagged, impeded by infrastructural deficits, policy inconsistencies, and limited investments (Hlungwani et al., 2025). South Africa stands out with a comparatively progressive renewable energy policy environment, anchored by initiatives such as the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) and the National Biofuels Industrial Strategy (Department of Minerals and Energy 2021). Yet, integration of biofuels specifically into maritime transport remains embryonic due to regulatory fragmentation and infrastructural gaps (DoE, 2021).

Industrial Development Zones (IDZs), including the Coega IDZ, offer strategic advantages for scaling biofuel production and distribution. The Port of Ngqura, situated within this IDZ, benefits from advanced infrastructure, policy incentives, and proximity to biomass feedstocks, positioning it as a potential biofuel production and export hub (Coega Development Corporation, 2023). However, realising these potential demands requires coordinated investment, policy harmonisation, and capacity-building to overcome economic and logistical barriers. Song et al. (n.d.) highlight that fiscal competition among subnational governments can divert resources away from strategic innovation investments, potentially limiting long-term knowledge-driven growth. Complementing this, the OECD (2023) emphasises that integrated approaches, including coordinated policy frameworks and investment strategies, are essential to address structural and logistical challenges effectively. Together, these perspectives underscore the critical role of governance, strategic planning, and policy alignment in enabling sustainable biofuel development and distribution.

Case study: The port of Ngqura

The Port of Ngqura, located in South Africa's Eastern Cape province, commenced operations in 2009 as a modern deep-water facility serving regional and international shipping (Africa Ports, 2022). It functions as a pivotal transshipment hub and is integrally linked to the Coega Special Economic Zone (SEZ), a regional industrial and logistics cluster focused on stimulating economic development, industrialisation, and job creation (Global Energy Monitor, n.d.). Figure 1 below shows the location of the study sites in the Eastern Cape Province.

The Port of Ngqura's designation as a "green port" reflects its alignment with both national and global sustainability agendas, incorporating energy efficiency and environmental management practices (Transnet, n.d.). Its considerable energy demands, interface with global shipping routes, and advanced infrastructure render it a compelling site to examine the socio-economic and environmental dimensions of maritime biofuel adoption. Transitioning the port's operations and supply chains towards biofuels is not only technologically feasible but also crucial for supporting South Africa's maritime decarbonisation objectives (Olojede, 2021). As such, the Port of Ngqura serves as a practical lens to explore the opportunities and constraints of sustainable fuel adoption in African port systems.

Data and methodology

This study employs a qualitative case study approach to explore the socio-economic and environmental implications of biofuel adoption in maritime transport, with a particular focus on the Port of Ngqura. Qualitative methods were selected to gain an in-depth understanding of the complex, context-dependent, and multi-dimensional nature of sustainability transitions in the maritime sector (Creswell, 2014). The case study design is appropriate for addressing 'how' and 'why' questions in real-life contexts where the boundaries between phenomenon and context are blurred (Yin, 2018).

Research philosophy and paradigm, sampling strategy and population

The research is underpinned by an interpretivist philosophy, which prioritises subjective experiences, meanings, and contextual realities as central to knowledge creation (Saunders et al., 2012). An interpretivist paradigm was adopted to examine how expert stakeholders construct meaning around biofuel adoption, policy uncertainty, and socio-economic trade-offs within the maritime sector. This approach is appropriate for addressing the study's research questions, which seek to understand perceptions, interpretations, and governance dynamics rather than to measure causal impacts.

While pragmatic or critical realist approaches may support outcome evaluation, interpretivism enables deeper insight into values, assumptions, and power relations that shape policy feasibility and implementation. Such understanding is essential for developing context-sensitive and actionable policy recommendations in complex governance environments such as maritime transport.

Interpretivism facilitates exploration of stakeholders' lived experiences, perceptions, and motivations regarding biofuel adoption in maritime transport, enabling rich, contextually grounded insights (Alharahsheh & Pius, 2020). This approach supports generating nuanced recommendations tailored to the socio-economic and environmental complexities of the Port of Ngqura setting.

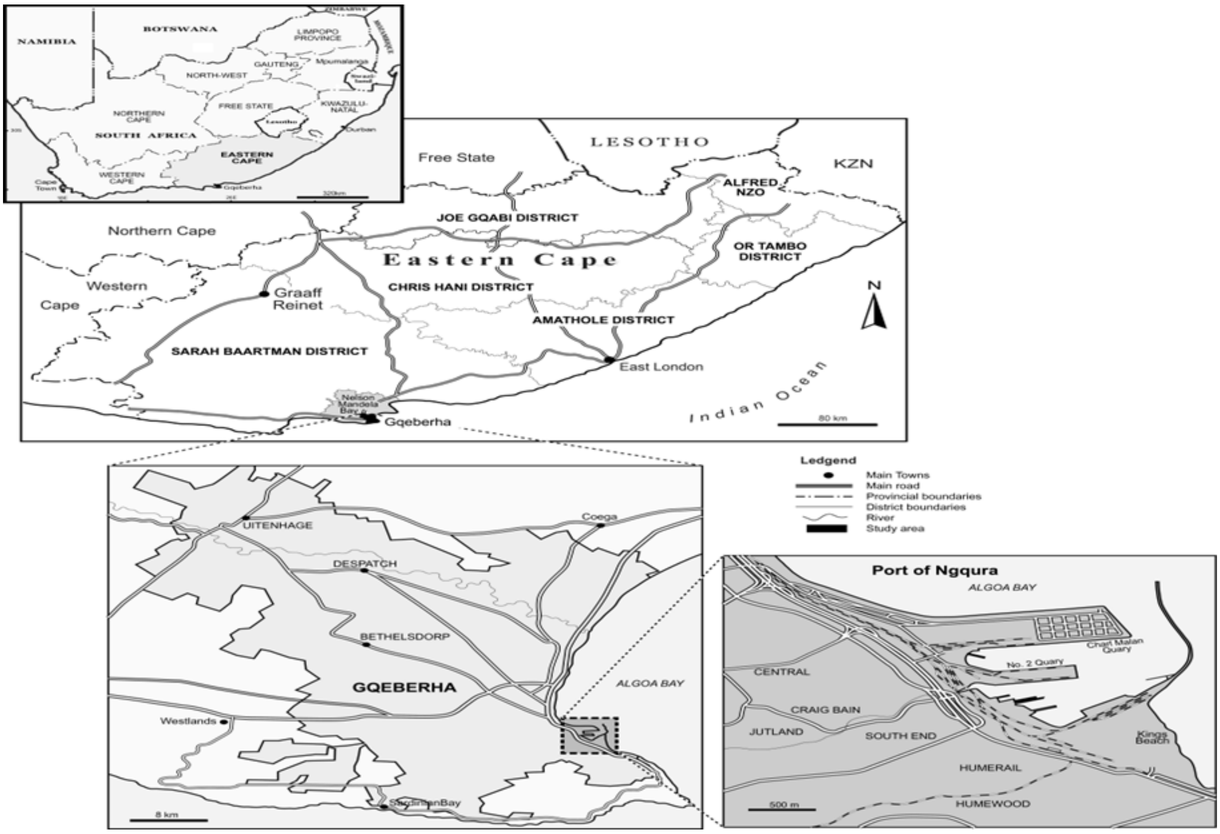

Figure 1. Location of study sites in Eastern Cape Province.
Source: Cartographic Unit, University of the Witwatersrand 2025

A purposive, non-probabilistic sampling strategy was adopted to select 12 expert participants whose knowledge and experience were directly relevant to the research objectives (Matthews & Ross, 2010; Saunders et al., 2009). This sample size aligns with qualitative research norms where depth of data is prioritised over breadth, and is supported by Guest et al. (2006) finding that saturation typically occurs within 12–15 interviews among homogeneous expert groups.

Participants were drawn from key sectors, including government departments (Department of Transport and Department of Mineral Resources and Energy), marine environmental science, renewable energy, and academia. Inclusion criteria required at least seven years of professional experience, advanced academic qualifications (Honours to PhD), and demonstrable expertise in maritime transport, renewable energy, or environmental management. This ensured the collection of authoritative and relevant data. Individuals not meeting these criteria or lacking direct connection to the maritime biofuel domain were excluded to preserve data integrity and thematic coherence (Styks et al. 2025).

While purposive expert sampling enabled in-depth insight into governance, regulatory, and strategic dimensions of maritime biofuel adoption, the absence of shipping company executives, port labour representatives, fuel suppliers, and local community members limits the breadth of socio-economic perspectives captured. Accordingly, the findings are interpreted as reflecting institutional and policy-level understandings rather than lived community or labour experiences. This limitation is acknowledged, and future research is encouraged to adopt participatory and multi-stakeholder approaches to capture these perspectives more fully.

Data collection and secondary data selection

Primary data were gathered through semi-structured interviews conducted with the 12 purposively sampled experts. Participants were assigned codes (P1–P12) to maintain anonymity. Interviews, lasting 45 to 60 min, were conducted face-to-face or via secure video conferencing platforms based on participant availability. All sessions were audio-recorded with informed consent and transcribed verbatim to ensure accuracy (Kallio et al., 2016). In addition to primary data, relevant secondary sources published between 2008 and 2024 were analysed, including policy documents, regulatory frameworks, industry reports, and peer-reviewed literature. Selection was based on relevance to biofuels, maritime transport, sustainability, and the Port of Ngqura context, ensuring coverage of contemporary policy and technological developments (DoE, 2021; International Maritime Organization, 2020). Outdated materials, non-peer-reviewed sources (except official policies and credible industry reports), and documents lacking direct relevance were excluded (Fusch et al., 2018). This triangulation of primary and secondary data strengthened the validity and robustness of the study's findings.

Data analysis

Thematic analysis, a qualitative method for examining textual data (Matthews & Ross, 2010), was applied to both primary and secondary sources to identify patterns, correlations, and contrasts relevant to the research question and sub-questions. Semi-structured interview responses were audio-recorded, transcribed, and systematically coded using Atlas. ti, which facilitated thematic categorisation, data organisation, and visualisation (NYU Libraries, 2025). Emerging themes from the interviews guided the document analysis, ensuring alignment between primary and secondary data and supporting a comprehensive understanding of the study objectives.

Validity, reliability, and ethical considerations

Data saturation was achieved after the tenth interview, as no new significant codes or themes emerged during the additional data collection. The final two interviews confirmed the stability of the themes, indicating that we had gathered enough depth and coverage of stakeholder perspectives. To ensure accuracy and credibility, we conducted member checking by sharing a summary of the preliminary themes with selected participants. Their feedback helped refine our interpretations related to policy uncertainty and infrastructure readiness (Guest et al., 2006; Birt et al., 2016).

Validity was enhanced through member checking, whereby preliminary findings were shared with selected participants for feedback on accuracy and interpretation (Birt et al., 2016). Peer debriefing and maintenance of audit trails documented research decisions and enhanced transparency. Reliability was supported by rigorous documentation of the research process, consistent use of interview protocols, and reflexive journaling by the researchers to identify and mitigate potential biases (Creswell & Poth, 2018). Ethical clearance was granted by Nelson Mandela University's Research Ethics Committee. Participants were provided informed consent and were assured of confidentiality and anonymity. Data were securely stored, and participants retained the right to withdraw without penalty at any stage.

The researchers recognise their roles as academics involved in sustainability and policy-oriented research, which may favour institutional viewpoints. To reduce interpretive bias, they employed reflexive journaling and conducted peer debriefing throughout the research process. Additionally, they used triangulation by analysing policy documents, regulatory texts, and industry reports alongside interview data, which enhanced the validity of the study.

Results and discussion

The analysis of interviews and literature review revealed three dominant themes: socio-economic benefits, environmental benefits, and challenges associated with the adoption of biofuels in maritime transport in South Africa. The case study of the Port of Ngqura provided context-specific insights that align with global discourse on sustainable marine fuels. The Drivers-Pressures-State-Impact-Response (DPSIR) framework offers a comprehensive lens through which to analyse the complex dynamics shaping biofuel adoption and its outcomes in this context.

Discussion of themes

Socio-economic benefits of biofuels in maritime transport

Participants identified several socio-economic benefits related to the adoption of biofuels in maritime transport. These benefits include job creation, the stimulation of rural economies through biomass supply, and opportunities for local value addition, particularly in the context of the Port of Ngqura. Similar socio-economic expectations have been noted in other African and Global South energy transition studies, highlighting the potential of bioenergy value chains to support rural livelihoods and industrial development, provided they are governed effectively (FAO, 2019; Hlungwani et al., 2025; Radtke & Renn, 2025).

However, these benefits are not automatic or uniformly distributed. They are consistently framed as dependent on factors such as governance arrangements, investment patterns, and the localisation of processing activities. For example, Participant 1 (see Table 2) explicitly linked employment gains to local processing and value addition rather than solely to the transportation or export of biofuel feedstocks. This perspective aligns with political economy analyses of renewable energy transitions in Africa, which caution that externally focused value chains often limit domestic employment opportunities and local economic benefits (OECD, 2023; Tsoeu-Ntokoane et al., 2024).

Table 2. Key Findings from Interviews – Themes, Participant Quotes, and Implications (*Longer quotations are selectively included to illustrate stakeholder reasoning and areas of tension, while shorter excerpts are used where perspectives were widely shared across participants*)

Theme	Sub-theme / Focus	Participant Quote (Verbatim)	Implication/ Interpretation
Socio-Economic Benefits	Job creation & local economy	*"Biofuels can open new jobs in communities around the port, but this really depends on whether processing happens locally. If feedstocks are just transported out, then the employment benefits are limited and short-lived." (P1*)	This highlights conditional socio-economic benefits, showing that employment gains depend on local beneficiation rather than fuel substitution alone.
	Skills development	*"Training programmes linked to biofuels give young people technical skills, but they need to be sustained. Short-term training without long-term projects doesn't translate into real career paths." (P4*)	These demonstrate that capacity-building must be embedded in long-term industrial strategies to produce lasting socio-economic impact.
	Business opportunities	*"There is potential for small suppliers to enter the value chain, especially around biomass supply and logistics, but access to information and finance remains a major barrier." (P6*)	These indicate opportunities for inclusive growth while exposing structural barriers that limit participation by smaller actors.
Environmental Benefits	Emissions reduction	*"If vessels switch to biofuels, sulphur emissions drop significantly. You notice the difference around the port, but only if uptake is consistent and not just at pilot scale." (P3*)	These suggest that environmental benefits are real but contingent on scale and sustained adoption rather than isolated trials.
	Sustainable resource use	*"Using algae or waste biomass feels more sustainable because it doesn't compete directly with food crops, but the technology and costs still need to come down." (P7*)	This reflects stakeholder awareness of food–fuel trade-offs and technological constraints shaping fuel choices.
Challenges	Policy & regulatory barriers	*"Policies are fragmented, and it's unclear how to comply with everything. One department promotes decarbonisation, another*	This reveals governance fragmentation and policy incoherence as key deterrents to private-sector investment.

(*Continued*)

Table 2. (Continued)

Theme	Sub-theme / Focus	Participant Quote (Verbatim)	Implication/ Interpretation
		focuses on cost control, and there is no clear maritime biofuel framework. That uncertainty makes investors hesitant." (P2)	
	Information access & inclusion	*"Information about biofuel opportunities doesn't always reach local operators or smaller businesses. Decisions tend to happen at higher levels, and communities are informed later." (P5*)	These highlight to power asymmetries and communication gaps that undermine inclusive participation in energy transitions.
	Technical & infrastructure issues	*"The port is not fully equipped for large-scale biofuel storage and handling. Retrofitting infrastructure is expensive, and without incentives, it's hard to justify the investment." (P9*)	This illustrates the interaction between technical constraints and economic risk in shaping adoption decisions.

The socio-economic potential of biofuel expansion in South Africa is underscored by national estimates suggesting that the sector could create thousands of direct and indirect jobs, especially in rural agricultural areas where biomass feedstocks are sourced (Department of Mineral Resources and Energy 2021). For ports like Ngqura, situated within the Coega Industrial Development Zone, integrating biofuel processing, storage, and bunkering facilities could diversify the regional economy, promote industrial localisation, and decrease reliance on imported petroleum products. Similar findings in maritime decarbonization research indicate that ports located within special economic or industrial zones are more likely to benefit from transitions to alternative fuels (Notteboom et al., 2021; DNV, 2023).

Participants also noted skills development and enterprise formation as potential co-benefits, particularly for youth and small-scale suppliers. However, concerns were raised that short-term training initiatives and limited access to financing could hinder these gains. This reflects broader discussions in energy justice literature, which argue that employment benefits only materialise when capacity-building and enterprise support are sustained and integrated into long-term industrial strategies (Radtke & Renn, 2025; Uzorka et al. 2026).

Table 2 summarises these socio-economic insights along with environmental benefits and challenges to adoption, drawing directly on participant narratives to illustrate how empirical evidence supports the thematic analysis.

Environmental benefits of biofuels in maritime transport

Respondents frequently emphasised the environmental advantages of biofuels, particularly in relation to reduced greenhouse gas emissions and improved air quality in port environments. These benefits were viewed as especially relevant for densely populated coastal cities, where shipping emissions contribute to both climate change and localised public health impacts (International Maritime Organization, 2020; Woods Hole Oceanographic Institution, 2021).

Stakeholder perspectives revealed a nuanced understanding of environmental sustainability that extended beyond emission reductions alone. As Participant 7 noted (Table 2), waste-based and algae-derived biofuels were perceived as more sustainable due to their lower competition with food crops, yet their adoption remains constrained by technological maturity and cost considerations. Similar concerns have been widely documented in recent biofuel sustainability assessments, which highlight that second- and third-generation biofuels offer superior environmental performance but face commercialisation barriers (International Energy Agency, 2024; El-Araby, 2024).

These stakeholder perceptions align with findings from the International Maritime Organisation (International Maritime Organization, 2020) and DNV (2023), which indicate that advanced biofuels can reduce carbon dioxide emissions by up to 70–86 %, sulphur oxides by over 95%, and nitrogen oxides by approximately 10–20 %, depending on feedstock and production pathways. At the Port of Ngqura, reduced sulphur emissions would be particularly significant given prevailing wind patterns that transport pollutants toward urban areas in Nelson Mandela Bay, amplifying public health benefits (Queensland Government 2013; Surname et al. 2021).

Environmental benefits were also discussed in relation to regulatory compliance and international obligations. Biofuel adoption was perceived as a viable pathway for meeting IMO MARPOL Annex VI requirements and contributing to South Africa's commitments under the Paris Agreement and the Just Energy Transition Investment Plan. Table 1 contextualises these benefits by illustrating the differing environmental profiles, risks, and maritime applicability of biofuel generations, reinforcing evidence that sustainability outcomes depend strongly on feedstock choice and governance context (FAO, 2019; Jeswani et al., 2020).

Challenges to biofuel adoption in the maritime sector

Despite the recognised socio-economic and environmental benefits of biofuels, participants consistently identified significant barriers to their large-scale adoption. These barriers included uncertainties in the supply chain, high infrastructure and fuel costs, and fragmented policy and regulatory frameworks. Similar challenges have been noted in emerging maritime economies, where alternative fuels are competing with established fossil fuel systems amid conditions of limited policy certainty (Global Maritime Forum, 2023; Zhou et al., 2023).

One particularly significant concern that emerged was policy incoherence. As noted by Participant 2 (Table 2), conflicting mandates across government departments between decarbonization objectives and cost-containment priorities create regulatory uncertainty, which discourages long-term investment. This policy uncertainty has consistently been identified as a major deterrent to private investment in alternative maritime fuels, especially in capital-intensive contexts such as ports and shipping (DNV, 2023; OECD, 2023).

Further analysis revealed notable tensions between different stakeholder groups, shaped by their institutional roles and risk exposure. Participants involved in regional development and environmental planning emphasised long-term socio-economic benefits, such as job creation and local value addition. Conversely, stakeholders closer to shipping operations and investment decision-making highlighted short-term financial risks, including fuel price volatility, infrastructure retrofitting costs, and a lack of risk-sharing mechanisms. These differing perspectives reflect findings from international maritime governance studies, which illustrate how power dynamics, capital exposure, and institutional positioning influence energy transition pathways (Notteboom et al., 2021; Song and Panayides 2021).

From a technical perspective, blending biofuels with conventional marine diesel requires compatibility testing for engines, modifications to storage, and ongoing performance monitoring. Economically, biofuels remain more expensive than heavy fuel oil, and without targeted subsidies, carbon pricing, or fiscal incentives, their adoption is likely to remain limited (International Energy Agency, 2024; Global Maritime Forum, 2023). Institutionally, South Africa's renewable energy incentives have primarily focused on the electricity sector, leaving maritime transport comparably neglected.

While many early-stage challenges have been experienced in Brazil, the European Union, and the United States, a key distinction lies in the certainty of policies. Initiatives such as the EU's FuelEU Maritime framework and the US Renewable Fuel Standard provide clear compliance pathways and investment signals. In contrast, South Africa's policy landscape lacks specific guidance for the maritime sector. Table 3 illustrates this misalignment by comparing national frameworks to the requirements of IMO MARPOL Annex VI.

The persistence of these policy gaps reflects deeper political and economic dynamics within South Africa's energy governance system. Institutional fragmentation has hindered interdepartmental coordination, and the prioritisation of decarbonization in the electricity sector has limited policy harmonisation. These power asymmetries determine which sectors receive regulatory focus, financial incentives, and infrastructure investment, thereby impeding the integration of biofuels into maritime operations (OECD, 2023; Song et al. n.d.).

Rather than functioning as a descriptive inventory, Table 3 is used as an analytical tool to highlight structural misalignments between international maritime decarbonisation requirements and South Africa's sectorally fragmented energy policy framework.

Table 3. Analytical assessment of alignment between South African maritime biofuel policies and IMO MARPOL Annex VI, including underlying governance and political–economic drivers of identified policy gaps.

Policy Dimension	IMO MARPOL Annex VI Requirements	South African Policy Position	Identified Gap	Underlying Cause (Why the Gap Persists)	Implications for Biofuel Adoption at Ngqura
Emission reduction targets	Progressive reduction of GHG emissions from shipping, aligned with IMO decarbonisation timelines	No maritime-specific emission reduction targets for shipping fuels	Absence of binding maritime decarbonisation targets	Prioritisation of electricity-sector decarbonisation; lack of cross-sector policy coordination	Weak regulatory pressure on ship operators to transition to biofuels
Sulphur limits (SOx)	Global sulphur cap of 0.5% m/m; stricter controls in Emission Control Areas	Compliance via fuel import standards, not alternative fuels	No incentive to use low-sulphur biofuels	Compliance framed as a fuel-quality issue rather than a transition opportunity	Continued reliance on low-sulphur fossil fuels rather than renewable alternatives
Fuel standards and certification	Encourages certified low-carbon fuels with lifecycle emissions accounting	No maritime biofuel sustainability or certification framework	Lack of lifecycle assessment standards for maritime biofuels	Institutional gap between energy, transport, and environmental authorities	Uncertainty for investors regarding acceptable fuel types and compliance
Policy certainty and investment signals	Predictable regulatory frameworks to encourage long-term investment	Fragmented policy signals across departments	High regulatory uncertainty	Competing departmental mandates and absence of a lead maritime decarbonisation authority	Investment hesitation and delayed infrastructure development
Port infrastructure and bunkering	Support for alternative fuel bunkering infrastructure	No mandated support for biofuel bunkering at ports	Infrastructure development left to market forces	Limited public-sector financing mechanisms for maritime fuels	Limited availability of biofuels for vessels calling at Ngqura
Economic incentives	Market-based mechanisms (carbon pricing, subsidies, credits)	Incentives focused on electricity and road transport biofuels	Maritime sector excluded from incentive schemes	Sectoral bias in renewable energy policy design	Biofuels remain cost-uncompetitive with conventional marine fuels
Stakeholder coordination	Emphasis on multi-stakeholder engagement	No formal maritime biofuel coordination platform	Weak stakeholder integration	Institutional silos and limited participatory governance	Misalignment between port authorities, ship operators, and fuel suppliers
Monitoring and compliance	Transparent reporting and compliance mechanisms	No maritime biofuel reporting framework	Lack of monitoring mechanisms	Regulatory capacity constraints	Difficulty tracking progress toward decarbonisation goals

Integrated analysis and policy implications

The findings reveal that the socio-economic and environmental benefits of adopting biofuels in maritime transport are closely interlinked and mutually reinforcing. Job creation, skills development, and business opportunities rely not only on fuel substitution but also on enabling policy frameworks, access to timely information, and appropriate technical infrastructure. Similar interdependencies have been identified in studies on maritime decarbonization, which show that environmental gains are maximised when socio-economic objectives are explicitly integrated into transition strategies (Notteboom et al., 2021; DNV, 2023).

Environmental benefits, such as emission reductions and improved air quality, are further enhanced by stakeholder engagement and local awareness. However, these benefits are often constrained by policy incoherence and infrastructural limitations. This aligns with broader research on energy transitions, which indicates that stakeholder participation enhances legitimacy and adoption but cannot compensate for weak institutional support (Radtke & Renn, 2025; OECD, 2023).

In this study, the Drivers–Pressures–State–Impact–Response (DPSIR) framework is used as a heuristic synthesis tool rather than as a prescriptive analytical model. Its purpose is to integrate and organise thematic findings across environmental, socio-economic, and governance dimensions without replacing or duplicating qualitative thematic analysis. This approach is consistent with prior applications of DPSIR in complex socio-environmental systems, where it enhances conceptual coherence instead of dictating research design (Nordstrom et al., 2015; Maxim et al., 2009).

The DPSIR framework illustrates how Drivers, such as maritime trade growth, port expansion, and international environmental regulations, interact with Pressures, including greenhouse gas emissions and fossil fuel dependency, when applied to the Port of Ngqura. These pressures influence the State of port operations, infrastructure readiness, and resource availability. The resulting Impacts, both socio-economic (employment potential and skills development) and environmental (emissions reduction and improvements in air quality), are shaped by Responses such as biofuel adoption, workforce training initiatives, and policy interventions. This synthesis emphasises the need for integrated strategies that simultaneously address environmental objectives, economic feasibility, and coordinated governance (International Energy Agency, 2024; Notteboom et al., 2021).

Policy gaps and strategic alignment

The analysis of South African maritime biofuel policies reveals significant gaps when compared to the International Maritime Organisation's (IMO) MARPOL Annex VI requirements. Existing instruments, such as the Surname et al. n.d. and the Department of Minerals and Energy, Republic of South Africa 2020, primarily promote renewable energy production in agriculture and electricity generation but do not specifically address maritime fuel use. As a result, vessel operators and port authorities lack clear regulatory guidance, a challenge also noted in other emerging maritime economies (Global Maritime Forum, 2023; OECD, 2023).

Using the DPSIR (Drivers, Pressures, State, Impacts, Responses) framework, these gaps can be understood as a misalignment between Drivers and Responses. While Drivers, such as port growth, international decarbonization commitments, and expanding maritime trade, increase the demand for cleaner fuels, the lack of maritime-specific biofuel policies hinders effective Responses. Consequently, Pressures including greenhouse gas emissions, fuel dependency, and local air pollution continue, resulting in a State of port operations characterised by a reliance on diesel and insufficient alternative fuel infrastructure.

These circumstances lead to under-realised socio-economic and environmental Impacts, such as missed opportunities for job creation, skills development, and emissions reduction. Current legislation weakly supports or outright lacks essential Responses, such as fuel blending mandates, port-based biofuel bunkering infrastructure, financial incentives, and structured capacity-building programs.

This persistence of gaps reflects deeper political and economic dynamics within South Africa's energy governance framework. Issues such as institutional fragmentation, limited interdepartmental coordination, and a focus on electricity-sector decarbonization have hampered policy harmonisation across sectors. Similar dynamics have been observed in energy transitions across other African nations, where sectoral silos and competing mandates impede integrated responses (Tsoeu-Ntokoane et al., 2024; Song et al. 2025).

To address these gaps, it is essential to integrate maritime-specific provisions into national energy and transport policies. These provisions should include clear emission reduction targets aligned with IMO timelines, operational standards for biofuel use in shipping, and mechanisms for monitoring and compliance. Financial incentives, such as tax exemptions, subsidies, or grant schemes, are needed to lower economic barriers and encourage early adoption, in line with international best practices (DNV, 2023; International Energy Agency, 2024).

Port authorities should receive support in developing biofuel bunkering infrastructure and supply chains to ensure reliable access to low-carbon fuels. Additionally, capacity-building initiatives are necessary to equip maritime personnel with the technical and operational skills required to effectively implement these strategies.

By aligning South African maritime policies with international requirements and embedding these measures within an integrated DPSIR framework, ports such as Ngqura can facilitate more effective Responses, reduce environmental Pressures, and maximise socio-economic and environmental Impacts. This approach positions the port as a potential green maritime hub and a reference case for other African ports facing similar decarbonization challenges.

Conclusion and recommendations

This study has critically examined the socio-economic and environmental implications of biofuel adoption in maritime transport, using the Port of Ngqura as a case study. The findings indicate that biofuels represent a viable pathway for maritime decarbonisation, offering substantial reductions in greenhouse gas and sulphur emissions while supporting job creation, rural economic development, and improved energy security. The Port of Ngqura's location within an Industrial Development Zone positions it strategically to capture these benefits through industrial localisation and innovation (Notteboom et al., 2021; DNV, 2023).

However, the transition to biofuels remains complex and constrained by high infrastructure costs, limited feedstock availability, and fragmented policy frameworks. Achieving equitable and sustainable biofuel adoption requires careful land-use management, explicit consideration of food security risks, and sustained stakeholder engagement, consistent with energy justice principles (FAO, 2019; Radtke & Renn, 2025).

To enhance operational relevance, recommendations are structured across short-, medium-, and long-term timeframes. In the short term (1–3 years), policy clarity and pilot-scale biofuel blending using waste-based feedstocks should be prioritised to reduce investment uncertainty and minimise food security risks. Medium-term interventions (3–5 years) focus on infrastructure development, skills training, and public–private partnerships. Long-term strategies involve integrating advanced biofuels into South Africa's Just Energy Transition financing mechanisms and aligning maritime policy with IMO decarbonisation timelines (International Energy Agency, 2024; Department of Mineral Resources and Energy 2021).

These phased recommendations explicitly acknowledge trade-offs between environmental benefits, economic costs, and land-use pressures. Complementary measures, including tax incentives, subsidies, and targeted grants, would further reduce barriers to entry and enhance the feasibility of investment.

Together, these actions present a coherent pathway for the Port of Ngqura to emerge as a green maritime hub. The insights generated offer transferable lessons for other African ports seeking to integrate biofuels into maritime energy systems amid institutional complexity and resource constraints.

Declarations

Interdisciplinary Scope: This study is explicitly interdisciplinary, drawing on Development Studies, Environmental Studies, and Maritime Transport and Energy Policy to examine the socio-economic and environmental implications of biofuel adoption in maritime transport. By integrating sustainability transitions theory, socio-economic development perspectives, and maritime environmental governance, the research provides a holistic analysis of biofuels within an African port context. This interdisciplinary approach enables a nuanced understanding of how environmental objectives, policy frameworks, and socio-economic realities intersect in South Africa's maritime sector.

Author Contributions: Amoah conceptualised the study, analysed the data, drafted the manuscript, and undertook the revision, interpretation of the findings and critical review of the article. Mbangwa conducted the data collection, interview transcription, and analysis of the findings. Donkor reviewed the manuscript and contributed to the theoretical framing. All authors read and approved the final version of the manuscript.

Conflict of Interest: The authors declare that there is no conflict of interest regarding the publication of this article.

Funding: This work is based on an MPhil treatise, and financial support was received from the Department of Transport, but not towards the publication.

Availability of Data: All relevant data are included in the article.

References

(2021). Woods Hole Oceanographic Institution. https://www.whoi.edu/know-your-ocean/ocean-topics/climate-weather/ocean-warming

Department of Mineral Resources and Energy, Department of Trade Industry and Competition, and Department of Science and Innovation. 2023. (n.d.). *Renewable Energy and Minerals Masterplan, Available*. https://greencape.co.za/assets/SAREM-Draft-March-2022.pdf

Afolalu, S. A., Yusuf, O. O., Abioye, A. A., Emetere, M. E., Ongbali, S. A., & Samuel, O. D. (2021). Biofuel production and sustainability perspectives. *IOP Conference Series: Earth and Environmental Science*, *665*, 012040. https://doi.org/10.1088/1755-1315/665/1/012040

Africa Ports. (2022). *Port performance and infrastructure developments in Africa*. Africa Ports & Harbours. https://www.africaports.co.za

Alharahsheh, H., & Pius, A. (2020). A review of key paradigms: Positivism vs interpretivism. *Global Academic Journal of Humanities and Social Sciences*, *2*(3), 39–43. https://doi.org/10.36348/gajhss.2020.v02i03.001

Birt, L., Scott, S., Cavers, D., Campbell, C., & Walter, F. (2016). Member checking: A tool to enhance trustworthiness or merely a nod to validation? *Qualitative Health Research*, *26*(13), 1802–1811. https://doi.org/10.1177/1049732316654870

Cartographic Unit, University of the Witwatersrand. (2025). *Study site locations: Eastern Cape Province*. University of the Witwatersrand.

Coega Development Corporation. (2023). *Industrial development zone and port of Ngqura profile*. https://www.coega.co.za

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches*. (4th ed.). Sage.

Creswell, J. W., & Poth, C. N. (2018). *Qualitative inquiry and research design: Choosing among five approaches*. (4th ed.). Sage.

Department of Mineral Resources and Energy. (2021). *Renewable energy employment and socio-economic impact report*. Republic of South Africa. https://www.energy.gov.za

Department of Minerals and Energy. (2021). *National biofuels industrial strategy and renewable energy framework*. Republic of South Africa. https://www.energy.gov.za

Department of Minerals and Energy, Republic of South Africa. (2020). *Biofuel incentive scheme*. Government Gazette. https://www.gov.za/documents

DNV. (2023). *Maritime biofuels: Pathways to decarbonisation*. DNV Maritime Services. https://www.dnv.com

El-Araby, R. (2024). Biofuel production: Exploring renewable energy solutions for a greener future. *Biotechnology for Biofuels and Bioproducts*, *17*(1), 129. https://doi.org/10.1186/s13068-024-02571-9

Food and Agriculture Organization of the United Nations. (2019a). *The state of the world's biodiversity for food and agriculture*. FAO. https://www.fao.org/3/CA3129EN/CA3129EN.pdf

Food and Agriculture Organization of the United Nations. (2019b). *The role of biofuels in sustainable rural development and food security*. FAO. https://www.fao.org

Fusch, P., Fusch, G. E., & Ness, L. R. (2018). Revisiting triangulation in qualitative research. *Journal of Social Change*, *10*, 19–32. https://doi.org/10.5590/JOSC.2018.10.1.02

Global Energy Monitor. (n.d.). *Coega Special Economic Zone and Port of Ngqura overview*. https://www.globalenergymonitor.org

Global Maritime Forum. (2023). *Alternative Fuels in Shipping: Barriers and Opportunities*. https://www.globalmaritimeforum.org

Guest, G., Bunce, A., & Johnson, L. (2006). How many interviews are enough? *Field Methods*, *18*(1), 59–82. https://doi.org/10.1177/1525822X05279903

Hlungwani, L., Venter, M., Grundling, J., & de Bruyn, C. (2025). Enhancing local economic development through biofuel production in Limpopo, South Africa. *Journal of Infrastructure Policy and Development*, *9*(2), 10410. https://doi.org/10.24294/jipd10410

Holden, E., & Gilpin, G. (2013). Biofuels and sustainable transport: A conceptual discussion. *Sustainability*, *5*(7), 3129–3149. https://doi.org/10.3390/su5073129

International Energy Agency. (2024). *Renewables 2023*. IEA. https://www.iea.org/reports/renewables-2023

International Maritime Organization. (2017). *Energy efficiency and the reduction of GHG emissions from ships*. https://www.imo.org

International Maritime Organization. (2020). *MARPOL Annex VI: Regulations for the prevention of air pollution from ships*. IMO.

Jeswani, H. K., Chilvers, A., & Azapagic, A. (2020). Environmental sustainability of biofuels: A review. *Proceedings of the Royal Society A*, *476*(2243), 20200351. https://doi.org/10.1098/rspa.2020.0351

Kallio, H., Pietilä, A.-M., Johnson, M., & Kangasniemi, M. (2016). Developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, *72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Kant, M., & Kanda, W. (2019). Innovation intermediaries: What does it take to survive over time. *Journal of Cleaner Production*, *229*, 911–930. https://doi.org/?

Kant, G., Hasan, A., Yadav, P., Pandey, A., & Srivastava, S. (2025). The generational shift in biofuels. *Biomass & Bioenergy*, *196*, 107757. https://doi.org/10.1016/j.biombioe.2025.107757

Khan, N., Sudhakar, K., & Mamat, R. (2021). Role of biofuels in energy transition. *Sustainability*, *13*(22), 12374. https://doi.org/10.3390/su132212374

Mahapatra, S., Kumar, D., Singh, B., & Sachan, P. (2021). Biofuels and their sources of production. *Energy Nexus*, *4*, 100036. https://doi.org/10.1016/j.nexus.2021.100036

Matthews, B., & Ross, L. (2010). *Research methods: A practical guide for the social sciences*. (2nd ed.). Pearson.

Maxim, L., Spangenberg, J. H., & O'Connor, M. (2009). An analysis of risks for biodiversity under the DPSIR framework. *Ecological Economics*, *69*(1), 12–23. https://doi.org/10.1016/j.ecolecon.2009.03.017

Nordstrom, K. F., Armaroli, C., Jackson, N. L., & Ciavola, P. (2015). Managed retreat on exposed sandy shores. *Ocean & Coastal Management*, *104*, 11–21. https://doi.org/10.1016/j.ocecoaman.2014.11.010

Notteboom, T., Pallis, A., & Rodrigue, J.-P. (2021). *Port economics, management and policy*. Routledge. https://doi.org/10.4324/9780429318184

OECD. (2023). *Sustainable investment policy perspectives in the Southern African Development Community* OECD Publishing. https://doi.org/10.1787/02c9ef1d-en

Olojede, O. (2021). Transport decarbonisation in South Africa. *Scientific Journal of Silesian University of Technology: Transport*, *110*, 125–142. https://doi.org/10.20858/sjsutst.2021.110.11

Queensland Government. (2013). Nitrogen Oxides. Retrieved 10 C.E., from https://www.qld.gov.au/environment/management/monitoring/air/air-pollution/pollutants/nitrogen-oxides. Accessed

Radtke, J., & Renn, O. (2025). Participation in energy transitions. *Energy, Sustainability and Society*, *14*(1), 21. https://doi.org/10.1002/eet.2158

Song, D. W., & Panayides, P. (2021). *Maritime Logistics: A Guide to Contemporary Shipping and Port Management*. (3rd ed.). Kogan Page Publishers.

Song, C., Zhao, X., Shi, Z., & Li, L. (2025). Potential of Microalgae for Biodiesel Production and Carbon Capture in Wastewater. https://doi.org/10.2139/ssrn.5823425

Song, C., Zhao, X., Shi, Z., & Li, L. (n.d.). *Potential of microalgae for biodiesel production and carbon capture in wastewater*.

Styks, J., Wróbel, M., & Francik, S. (2025). Production of Compacted Biofuels in Terms of Their Quality—Current State of Research. *Energies*, *18*(13), 3468. https://doi.org/10.3390/en18133468

Tsoeu-Ntokoane, S., Mosabala, T. D., Kali, M., & Lemaire, X. (2024). Community imaginaries and renewable energy acceptance. *Cogent Social Sciences*, *10*(1). https://doi.org/10.1080/23311886.2023.2292755

UNCTAD. (2023). *Review of maritime transport 2023*. United Nations Conference on Trade and Development. https://unctad.org

Uzorka, A., Kibirige, D., & Makumbi, D. (2026). Smart renewable energy systems: the role of artificial intelligence in enhancing efficiency and reliability. *Sustainable Energy Res*. https://doi.org/10.1186/s40807-026-00253-8

Xiang, X., Zhou, N., Ma, M., Feng, W., & Yan, R. (2023). Global transition of operational carbon in residential buildings since the millennium. *Advances in Applied Energy*, *11*, 100145. https://doi.org/10.1016/j.adapen.2023.100145

Yin, R. K. (2018). *Case study research and applications: Design and methods*. (6th ed.). Sage.

Zhou, Y., Li, X., & Yuen, K. F. (2023). Sustainable shipping: A critical review. *Marine Policy*, *148*, 105478. https://doi.org/10.1016/j.marpol.2023.105478