Cleaner Engineering and Technology 14 (2023) 100639

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Assessing methanol potential as a cleaner marine fuel: An analysis of its implications on emissions and regulation compliance

Olakunle Oloruntobi [a], Lai Fatt Chuah [a,*], Kasypi Mokhtar [a], Adel Gohari [b], Vincent Onigbara [c], Jing Xiang Chung [d], Muhammad Mubashir [e], Saira Asif [f,**], Pau Loke Show [g], Ning Han [h]

[a] Faculty of Maritime Studies, Universiti Malaysia Terengganu, Terengganu, Malaysia
[b] Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Skudai, Malaysia
[c] Department of Welding and Fabrication Technology, Federal Polytechnic, Ilaro, Nigeria
[d] Faculty Science and Marine Environment, Universiti Malaysia Terengganu, Malaysia
[e] Physical Science and Engineering Division, Advanced Membranes and Porous Materials Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
[f] Faculty of Sciences, Department of Botany, PMAS Arid Agriculture University, Rawalpindi, Punjab, 46300, Pakistan
[g] Department of Chemical Engineering, Khalifa University, Shakhbout Bin Sultan St, Zone 1, Abu Dhabi, United Arab Emirates
[h] Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, Leuven, 3001, Belgium

ARTICLE INFO

Keywords:
Methanol
Marine fuel
Cleaner environment
Marine diesel engine

ABSTRACT

This article aims to fill a gap in existing studies by examining methanol's prospects as a cleaner marine vessel fuel and addressing the industry's challenges in reducing pollution from ship oil. The analysis focuses on methanol as a decarbonization fuel option, following its advantages compared to others through data triangulation that uses both bottom-up and top-down approaches to examine the safety concerns and environmental impacts of methanol. The findings support its use as a promising alternative to conventional marine fuels, considering regulations and safety codes related to low-flashpoint fuels and specifying key safety measures. Also, container vessels (6% of the global fleet) consume 23% of all annual bunker volume and require nearly two-thirds of the global bunker demand, along with liquid bulk tankers and dry bulk carriers. These findings, along with the current regulatory landscape and infrastructure requirements for methanol fuel distribution, pose the greatest challenges to its widespread adoption, despite successes by MAN and Wärtsilä engine manufacturers in offering high-pressure diesel combustion technology engines for burning methanol. This study provides insights that can help ASEAN adopt methanol fuel while complying with emission standards and reducing its environmental impacts.

1. Introduction

The maritime sector is facing heightened pressure to abide by stricter emissions regulations (Chuah et al., 2023a) that seek to curb GHG (Abbasi et al., 2023; Ahmad et al., 2023; Bokhari et al., 2020), NO_x (Ameen et al., 2023; Bokhari et al., 2019), PM (Arshad et al., 2023; Asif et al., 2021) and SO_x (Alsaiari et al., 2023; Bokhari et al., 2016) emissions released by ships. International authorities, such as the IMO, EU and US Environmental Protection Agency (EPA), introduced these regulations to address the environmental impact of shipping (Lin et al., 2021). These regulations have compelled national and local authorities globally to follow suit.

The Association of Southeast Asian Nations (ASEAN) reinstated its commitments to emissions reduction in ports and the shipping industry, prompting the regional maritime industry to widely explore alternative approaches that would reduce carbon emissions by 2030. This has included the potential use of alternative fuels (Cao et al., 2023; Cheah et al., 2016; Chuah et al., 2023b). The 19th ASEAN Port and Shipping 2022 Exhibition and Conference held in Kuala Lumpur, Malaysia, advanced the low-carbon shipping discourse ahead of 2030 (Halim et al., 2022). The conference amplified the call to weigh the possibility of using methanol as an alternative fuel for marine vessels that will help tackle compliance challenges related to emissions regulations. Industry experts classified the prospects of maritime fuel options for decarbonization in the ASEAN pathways to a sustainable shipping future.

---

* Corresponding author.
** Corresponding author
E-mail addresses: lfchuah@umt.edu.my (L.F. Chuah), sairaasif@uaar.edu.pk (S. Asif).

https://doi.org/10.1016/j.clet.2023.100639
Received 31 March 2023; Received in revised form 26 April 2023; Accepted 4 May 2023

SI units

°C	Temperature in degrees Celsius
h	Hours
M	Million
m^3	Cubic meter
mg/m^3	Milligrams per cubic meter
mL	Milliliters
ppm	Parts per million
t	Ton
T2	Temperature at Class 300 °C

Abbreviation

ABS	American Bureau of Shipping
AR-FFF	Alcohol Resistant Film Forming Foam
ASEAN	Association of Southeast Asian Nations
CDR	Carbon dioxide removal
C-level	CEOs, CFOs, CIOs, etc.
CO2	Carbon dioxide
EGR	Exhaust gas recirculation
EPA	United States Environmental Protection Agency
EU	European Union
FMEA	Failure modes and effects analysis
GHG	Greenhouse gas
HAZID	Hazard identification
HAZOP	Hazard and operability study
IBC Code	International Bulk Chemical Code
IDLH	Immediately Dangerous to Life or Health Concentrations
IGC Code	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels Code
IMO	International Maritime Organization
ISO	International Organization for Standardization
LCA	Life-cycle analysis
LFFS	Low-flashpoint fuel-burning ships
LNG	Liquefied Natural Gas
MAN	German manufacturer of large-bore diesel engines for marine
ME-LGI	Methanol and LPG
ME-LGIM	Dual-fuel engine that can run on methanol as well as conventional fuels
MGO	Marine gas oil
Mt	Million tons
MSC	Maritime Safety Committee
MVR	Rules for Building and Classing Marine Vessels
MW	Megawatt
NIOSH	US National Institute for Occupational Safety and Health
NOx	Nitrogen oxide
OSHA	Occupational Safety and Health Administration
OSV	Offshore Support Vessel
P/V	Pressure/vacuum
PEL	Permissible Exposure Limit
PM	Particulate Matter
PSV	Platform Supply Vessel
SCR	Selective Catalytic Reduction
SDS	Safety Data Sheets
SOx	Sulfur oxide
US	United States of America

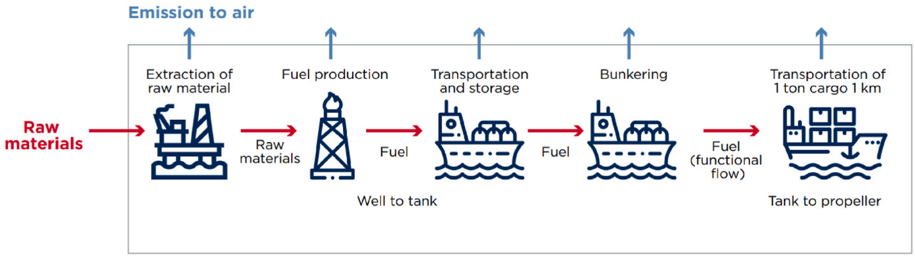

Fig. 1. Methanol fuel LCA from extraction to consumption.

Likewise, industry professionals and academic scientists have conducted studies that detailed specific decarbonization fuel options and greener technologies (Chuah et al., 2022a) that include methanol.

Methanol is widely available and has been used for decades; it is typically produced from natural gas. Also, it is produced from renewable resources (Chuah et al., 2022b), such as biomass (wood) (Mohd Shamsuddin et al., 2015; Chuah et al., 2022c), non-edible oil (Munir et al., 2023) or electrolysis powered by renewable energy, by utilizing carbon capture and utilization technology (Brynolf et al., 2014; Acha et al., 2021). The increasing use of renewable sources during methanol production has significantly reduced its CO_2 footprint (Chuah et al., 2022d), making it a desirable option for various types of vessels. This is due to its potential to reduce CO_2 emissions from marine fuels. Methanol is a colorless liquid that is easier to handle and store than other fuels like LNG, NH_3 and hydrogen, which has made it more suitable as a marine fuel (Bilgili, 2021). Methanol has a high hydrogen-to-carbon ratio, which could potentially lower CO_2 emissions from combustion compared to conventional fuels. It is also readily biodegradable, resulting in less environmental impact in the event of a spill (Vedachalam et al., 2022). Due to its lower specific energy, methanol requires about 2.54 times more storage volume for the same energy content compared to LNG (Chen et al., 2023). To accurately evaluate the volumetric density reduction of LNG, various factors like packaging, insulation and custody transfer losses should be taken into account when compared to methanol.

Brynolf et al. (2014) stressed the importance of life-cycle analysis (LCA) of methanol as a viable alternative maritime fuel, which could account for emissions from various stages of its production process, including raw methanol extraction, its fuel production and transportation, storage, onboard ship combustion and bunkering, as presented in Fig. 1. Energy- and carbon-intensive processes for its production may result in higher fuel prices because of proposed carbon levies and may also be subject to new regulations. Consequently, it is critical to evaluate the environmental impact of methanol production methods (from source to usage) to determine if it is a feasible and eco-friendly marine fuel.

Methanol as a potential marine fuel (Chuah et al., 2021a) can be produced from various feedstocks, such as natural gas and biomass

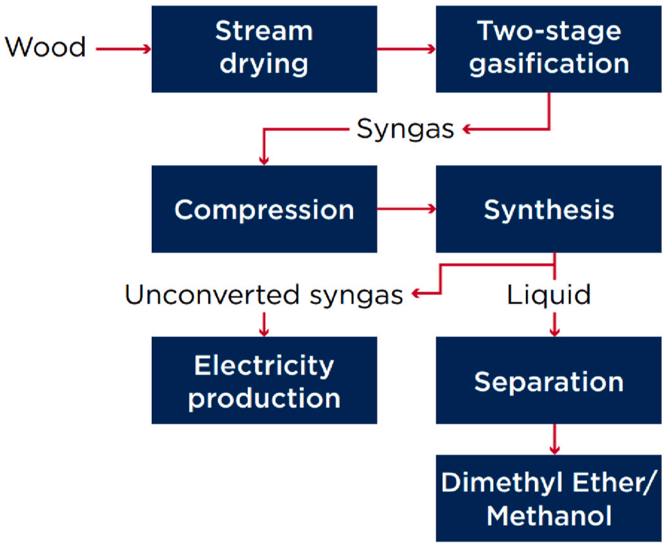

Fig. 2. Biomass (wood) to methanol process.

(Chuah et al., 2016; Karim et al., 2022). Li and Cheng (2020) study analyzed essential raw materials used as feedstock for reducing life-cycle GHG emissions. Production of natural gas-based methanol involves reforming and converting the gas into synthesis gas, followed by methanol synthesis and purification/distillation (Glaude et al., 2010). The distillation process then removes water, while excess heat from the reboiler is often used to generate electricity (Chen and Guan, 2021; Witthohn, 2022). Recent studies have shown that well-to-tank emissions of methanol produced from natural gas are higher than those of conventional fuels, resulting in marginally higher well-to-propeller emissions. Although Itskos et al. (2016) observed that utilizing feedstocks such as wood, biogas from landfills, municipal solid waste and wastewater treatment in methanol production can be deemed GHG-neutral. From the authors' evidence, it can be inferred that during production, the carbon emitted is equivalent to the same amount that plant matter absorbs during its lifespan. Energy generation for the process can still result in emissions. Fig. 2 further corroborates the eco-friendly process of converting biomass (wood) into methanol.

According toLi and Cheng (2020), the choice of energy source significantly impacts the life cycle of GHG emissions in production processes, with renewable energy sources reducing emissions. Methanol production using coal as a feedstock in China was found to have a detrimental effect on the environment, bordering on GHG emissions (Wang et al., 2023). Apart from biomass and fossil feedstocks, carbon dioxide recovery (CDR) technology can be used to produce low-carbon methanol by converting excess CO_2 generated from syngas into steam methane reforming. (Gray et al., 2021; Rim et al., 2023). Thepsithar et al. (2020) highlighted Gulf Petrochemical Industries in Oman, along with the Azerbaijan Methanol Corporation, Qatar Fuel Additives and the US South Louisiana Methanol Facility, as companies that use CDR technology. Renewable electricity sources like solar (Oloruntobi et al., 2023a), wind, geothermal, biodiesel (Chuah et al., 2017, 2021b) and hydropower can be employed to reduce the natural gas-based methanol plants' carbon footprint.

Methanol's clean-burning properties make it an attractive alternative fuel, as it lacks sulfur and carbon-to-carbon bonds, reducing SO_x and PM emissions, and its lower adiabatic flame temperature can limit NO_x formation during combustion (Glaude et al., 2010). As noted by Aabo (2020) and Korberg et al. (2021), MAN Energy Solutions research revealed that water addition to methanol can regulate NO_x formation during combustion, resulting in an engine that can meet Tier III NO_x regulations, eliminating the SCR or EGR requirement.

Several industry research has indicated that methanol exhibits lower life-cycle SO_x and NO_x emissions compared to conventional fuels. Specifically, Malmgren et al. (2020) revealed that methanol produces approximately 45% less NO_x emissions and 8% less SO_x emissions per unit of energy. The GHG emission performance of methanol is dependent on the feedstock and energy source used during production (Malmgren et al., 2021; Kountouris et al., 2023). While methanol is emerging as a promising marine fuel alternative, there is a knowledge gap in the research on its feasibility for compliance with emissions regulations in the maritime industry. The previous research in this area only focused on sustainability (Malik et al., 2019) and decarbonization fuel options and technologies. This study aims to comprehensively assess methanol's viability as a marine fuel for achieving emissions compliance in the maritime sector. Consequently, this research examines the potential of methanol through analyses conducted to determine its feasibility as a marine fuel option for the maritime industry in meeting more stringent emissions regulations, and in addressing challenges facing the industry, such as the need to reduce NO_x, SO_x, PM, GHG emissions and carbon from ships (Oloruntobi et al., 2023b). By assessing the suitability of methanol as a marine fuel, this study aims to contribute to the industry's efforts toward a cleaner and more sustainable environment. The study is based on proposals made at the 19th ASEAN Port and Shipping 2022 Exhibition and Conference. This research further touched on areas such as the potential of methanol as a decarbonization fuel option in comparison to other available maritime fuel options categorized in Gray et al. (2021) and Xing et al. (2021) publications.

This study resolves to answer four research questions related to the use of methanol as a marine fuel option, including (i) its advantages and disadvantages; (ii) its feasibility in addressing emissions regulations, (iii) its environmental impacts considering production process emissions; and (iv) the available feedstock options for methanol production and their impact on environmental and cost-effectiveness factors. This research article is synchronously organized to present the adopted

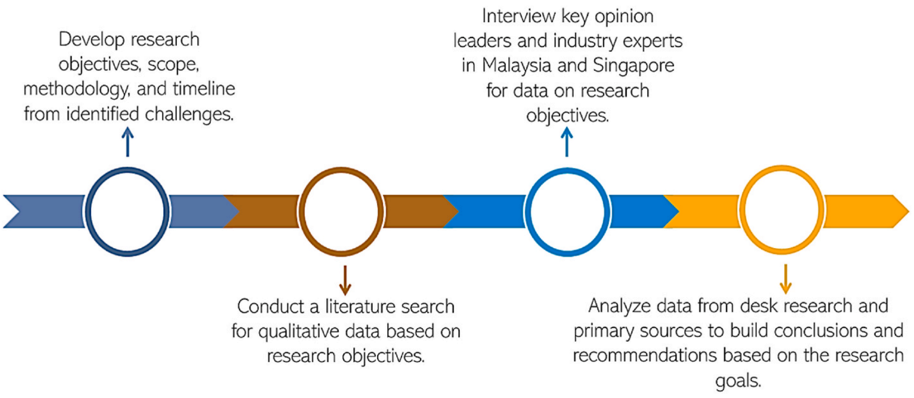

Fig. 3. Methodological process.

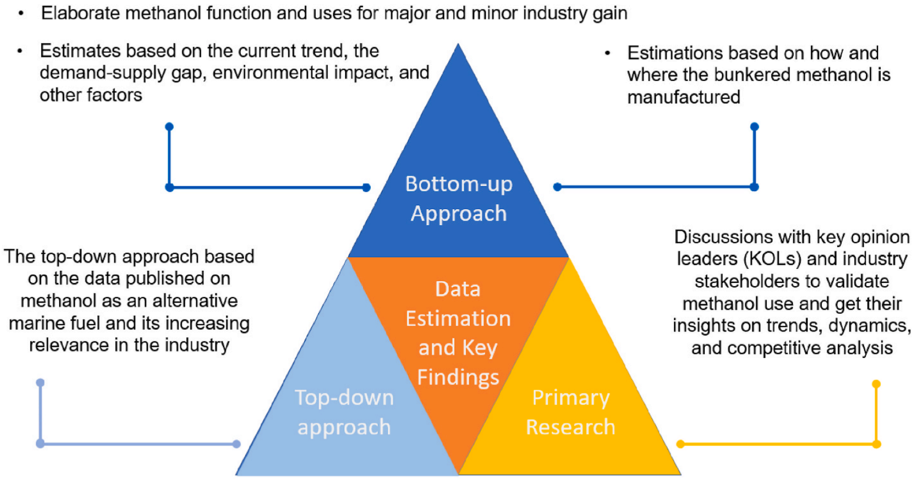

Fig. 4. Schematic diagram of research data triangulation.

methodology, which consists of three main steps in the next section. Section 3 provided answers to the research questions and discussed the findings in light of the actualization of the research objectives. The last section presents the conclusion and implications of this research.

2. Methodology

This research used a rigorous methodology that involved data triangulation using both top-down and bottom-up approaches. The assessment of methanol as a viable marine fuel option was validated through primary research. Since this study was determined to evaluate the feasibility of methanol as a marine fuel and forecast the maritime industry's compliance with emissions, useful information was gathered from the most credible published sources, and interviews were also conducted with maritime industry relevant stakeholders. Various factors that impact the global availability of methanol as a decarbonization fuel option, such as market drivers, industry challenges, environmental impact, technological developments and production and ecological cost implications, are considered when calculating the feasibility of using methanol in the maritime sector over a certain forecast period. The methodological process is summarized in Fig. 3. The growth in global advocacy for decarbonization fuel options and technologies incited this chosen method.

This study refers to the following secondary data sources:

- Recent data from reputable sources (i.e. the IMO Ship Fuel Oil Consumption data, American Bureau of Shipping (ABS) methanol/ethanol vessels fueled data and Methanol Institute data on marine fuel).
- Academic collaboration networks (i.e. ResearchGate, ScienceDirect and Academia).
- Industry journals.

A secondary research project was conducted that aimed at gathering information on methanol as a marine fuel option, including its applications, distribution channels and alternative strategies. This research is also intended to estimate the demand for methanol by region and country, as well as the average annual spending on producing methanol for seagoing vessels and related services. This research explored replacement demand and aftermarket services, as well as market dynamics such as drivers, restraints, trends and opportunities.

Interviews were conducted with key stakeholders, including shipping agencies, fleet managers, academic researchers and consultants from various end-use industries. These interviews included C-level executives, ship managers, vessel operation managers, marine engineers and vessel ship experts, among others. Key opinion leaders from relevant associations were also interviewed to gather their perspectives. This research also analyzed the methanol market and technological trends, new product developments, the product pipeline and other related topics. The methodology schematic for this study's triangulation approach is presented in Fig. 4.

The interviews conducted helped this study derive valuable information, which included insights from vessel fuel supply-side respondents in relation to methanol market size, demand estimates and market dynamics analysis. The information also includes insights from end-user respondents to assess expected consumption patterns and preferences, such as methanol value, alternative fuel offerings, benefits, cost implications, etc.

3. Results and discussion

3.1. Methanol as alternative marine fuel

An emerging concept in the maritime industry is the use of liquid low-flashpoint fuels in marine engines, such as methanol. According to Ampah et al. (2021), MAN's ME-LGI system, which was first implemented on methanol-burning Dual Fuel (DF) engines for various vessels, leverages high-pressure pumping and low fuel supply pressure but is confined in the injector. Methanol can be an easily available fuel that is supplied using existing liquid fuel infrastructure, like bunker vessels for maritime bunkering (Svanberg et al., 2018). Ellis and Tanneberger (2015) study further revealed that methanol has an advantage over LNG in terms of onboard containment as it is a liquid fuel, but it requires modifications to existing systems and an infrastructure upgrade to support regular marine fuel bunkering.

Since ASEAN is considering adopting methanol as a promising marine fuel, it is crucial to weigh the safety considerations such as tank location, inerting and venting, protection, fire detection, vapor, spill containment and firefighting. To that effect, Ampah et al. (2021) ratified MAN's ME-LGIM system, which delivers to the engine system a simplified methanol fuel supply as compared to LNG because it eliminates the need for cryogenic storage and handling and enables the use of a low-pressure system for fuel supply to the engine. According to a study by Dierickx et al. (2018), a retrofit conversion for engines was developed and installed on the RoPax ferry named Stena Germanica based on the Wartsila HP DF engine technology. These findings have proven that methanol adoption as a marine fuel option is a promising solution to address challenges faced by the maritime industry in complying with increasingly strict emissions regulations, and the development of advanced technology like the ME-LGI system and retrofit conversions is leading to a more sustainable and efficient shipping industry.

Table 1
Methanol fuel properties for marine vessel bunkering.

Methanol property	Value
Molecular weight (g/mol)	32.04
Heat of vaporization (kJ/kg)	1098
Adiabatic flame temperature at 1 bar (°C)	1980
Energy density (MJ/L)	15.7
Autoignition temperature (°C)	470
Liquid density (kg/m^3)	798
Boiling point @ 1 bar (°C)	65
Melting point (°C)	−97.8
Critical pressure (bar)	80.48
Critical temperature (°C)	239.4
Flammable range in dry air (%)	6–36.5
Flashpoint (°C)	12
Octane number	109
Cetane number	<5
Heavy fuel oil (HFO) equivalent volume	2.54

3.1.1. Risks and considerations of bunkering methanol

The chemical formula of methanol is CH_3OH, and the colorless liquid fuel properties summarized in Table 1 reveal a low flash point as a unique identity. Due to its low flash point, methanol is considered toxic and corrosive to some materials following several "Environmental Toxicology" studies. These studies further revealed that methanol poses a threat to the central nervous system and can lead to coma, death, or blindness even if ingested in large quantities. According to Van Hoecke et al. (2021), inhaling methanol vapor, which is denser than air, can pose a danger to crew members on board, potentially leading to asphyxiation in high concentrations. Due to its toxic nature, Gerba (2019) declared that methanol must be handled with care, particularly in confined spaces or on deck if spilled or leaked. Elsaid et al. (2021) also reported the Immediately Dangerous to Life or Health Concentrations (IDLH) value for methanol, which was set at 6000 ppm by the US National Institute for Occupational Safety and Health (NIOSH), while the Permissible Exposure Limit (PEL) was established at 200 ppm time-weighted average for methanol by the Occupational Safety and Health Administration (OSHA). The studies have clearly emphasized that methanol vapor tends to gather at lower region points, such as low pipe points or the bottom of tanks, which highlights the need for special attention in providing detection and ventilation systems in areas prone to leakage.

Recent studies on alternative fuel viability for marine vessel bunkering revealed that methanol produces particularly dangerous flames due to its low-temperature burning nature. Verhelst et al. (2019) reported that methanol produces a nearly invisible flame that is difficult to detect during daylight hours (h) and does not produce visible smoke. This characteristic makes the early detection of methanol flames challenging until they fully spread to nearby combustible materials that burn with visible light, thereby increasing the risk of accidents (Wei et al., 2022). Shamsul et al. (2014) findings have shown that the methanol vapor flammable range in the air is between 6 and 36.5%, creating a potential for an explosive or flammable environment that can pose a risk to crew members and the vessel. These findings further reinforced the seriousness of taking proper precautions when handling, storing and using methanol in operational vessels to prevent incidents and ensure the safety of onboard personnel.

The analysis based on the findings concluded that methanol can burn even when mixed with water in concentrations as low as 25%. This has implied that using specialized fire suppression methods, such as alcohol-resistant foams, is crucial when dealing with methanol fires. Since methanol is corrosive to some materials, choosing suitable ship fuel handling system pipes, tank coatings and fixtures is essential to help prevent issues like pipeline leaks or fuel contamination that could pose a risk to crew members, the environment and the vessel.

3.1.2. Methanol fuel toxicity, corrosion and compatibility

Evidence has shown that methanol has a lower impact on the environment when compared to conventional hydrocarbon fuels if spilled or leaked. Lin et al. (2021) asserted that methanol easily dissolves in water and would create lethal conditions when in high concentrations or having a significant effect on local marine life, apart from the carbon released into the marine ecosystem. While phytoplankton is famous for producing and releasing methanol into the ocean as a byproduct of their metabolic processes, certain bacteria consume methanol as a carbon and energy source. This natural occurrence of methanol in the ocean supports the marine food chain, which plays a key role in global carbon and energy cycling. Gerba (2019) further affirmed that methanol concentrations in the ocean vary widely depending on the location, season and biological activity, with concentrations ranging from trace levels up to several hundred nanomoles per liter. This evidence highlights the complex role of methanol in marine ecosystems and its importance in global biogeochemical cycles.

Meca et al. (2022) viewed methanol as a non-toxic substance and commonly transported chemical when shipped in accordance with the IBC Code. The Safety Data Sheets (SDS) classified liquid methanol as noxious when used onboard, as also reported by Vredeveldt et al. (2020) that it can cause skin irritation, cracking, dryness, inflammation, or burns. Pundir et al. (2021) reported that ingesting pure methanol, even as little as 10 mL, can cause the accumulation of hazardous levels of formic acid, which can result in a range of symptoms such as headache, nausea, vertigo, color perception changes, vomiting, inebriation, blurred vision, or eventual blindness. Besides, extended exposure can be harmful, with a median lethal dose of around 100 mL (Rim et al., 2023). Findings from Hobson and Márquez (2018) showed that acceptable levels of methanol exposure in the workplace can differ across countries. The standard set by SDS, which is commonly used, is 200 ppm (260 mg/m^3) limit for skin exposure. For brief periods of exposure, higher limits may be permissible.

To ensure the safe handling of methanol, crew members must be appropriately trained and aware of its hazards and characteristics, such as exposure, spills and leaks. The IMO Interim Guidelines for the Safety of Ships using Alcohol/Methyl/Ethyl as Fuel (MSC.1/Circ.1621) specify safety guidance for the onboard crew (Hughes, 2021). In any scenario involving a methanol spill, responders must have the appropriate equipment, including sorbent materials, a plastic shovel to disperse materials, caution tape, a waste container and emergency communication devices, as recommended by Vredeveldt et al. (2020) and Verhelst et al. (2019). Responders must also wear proper personal protective equipment, including face shields, chemical splash goggles, anti-static rubber gloves, nitrile or butyl gloves and chemical-resistant overalls, with fresh breathing air facet provided, as highlighted by Hughes (2021). Multiple fire extinguishers, eyewash stations, industrial first aid kits, water showers, drinking water and water for washing must be made available.

Many recent studies have shown that methanol can corrode some materials, which means that certain parts of combustion engines may need to be redesigned if must be used as marine fuel. Corrosion-resistant additives or unique coatings may be used to lessen methanol corrosion. Specific metallic materials, such as titanium alloys and aluminum, make methanol more corrosive by increasing its conductivity (Subedi et al., 2019). As a result, it is not recommended to use these materials for fittings or pipes meant for methanol blends or fuel. Methanol storage tanks must be constructed from a suitable grade of stainless steel or coated with a methanol-resistant material on the interior. When using coatings, it is essential to keep in mind that acidic impurities may harm the coating material, and prompt action must be taken to prevent accelerated corrosion, such as iron pick-up, pitting and additional methanol contamination. Fuel tanks and pipes should be made of non-metallic materials that are compatible with methanol, such as non-butyl rubber, neoprene, or nylon (Ghorbani et al., 2022).

3.1.3. Prevention, detection and fighting methanol fires

A study by Ellis and Bomanson (2018) reported that the wide adoption of methanol as an alternative marine engine fuel poses a fire hazard, requiring proper safety precautions to be taken to prevent and detect potential fires. Whereas the Methanol Institute Safe Handling Guide and Interim Guidelines for the Safety of Ships contain provisions for detecting and extinguishing methanol fires. Even though methanol liquid vaporizes more slowly than liquefied gas at normal temperature and pressure, as noted in Hughes (2021) findings, it can become flammable if methanol vapor concentrations between 6.5% and 36.5% are introduced to an ignition source, as was also revealed in Shamsul et al. (2014) study. It is important to prevent sparks or ignition sources from occurring in the methanol manifold, pressure/vacuum (P/V) relief valve, or ventilation system. This implied that if electrical equipment with an autoignition temperature of 450–470 °C is exposed to methanol gas, it must be protected with a T2 surface temperature class, while Ellis and Tanneberger (2015) recommend the use of inert gas to prevent explosive behavior in the methanol tank vapor space. The study also noted that CO_2 and wet or salty conditions can react with methanol to trigger corrosion; for this reason, inert gases containing carbon dioxide must be avoided. As a recommendation, using methanol blanketed with nitrogen gas to prevent fire hazards has some prospects. Methanol flames are difficult to detect due to their low light emission, low temperature and absence of soot.

Techniques such as the use of foam extinguishing systems, infrared (IR) cameras and stringent operational protocols can aid in detecting and preventing methanol fires (Evegren, 2017). Due to the low temperature of methanol flames, heat-based fire detection systems may be unreliable, and only flame detectors that operate by detecting radiation in the infrared light range are deemed effective for detecting methanol flames. Monitoring oxygen and CO_2 concentrations via vapor detection is a viable method for preventing leaks and fires (Solórzano et al., 2022). Gas detection systems should be installed in sensitive areas, such as near the ceiling and in low-lying regions, to detect flammable levels or toxic gases, while leak and overflow protection measures must be installed to prevent hazardous conditions near potential ignition sources. Hughes (2021) stated that the World Health Organization recommends adherence to the International Code for Fire Safety Systems guideline that CO_2 extinguishers or portable dry chemicals be used for minor methanol fires, while water extinguishers may be used for larger methanol volumes if the ratio of water to methanol pool is 4-to-1. For major methanol pool fires, Korzeniowski et al. (2018) recommend that foam-water measuring equipment with extinguishers made of Alcohol Resistant Film Forming Foam (AR-FFF) be used as the most effective option. It is essential to recognize that additional safety precautions for cofferdams on ships may be needed to avoid a probably hazardous methanol vapor or liquid buildup.

3.2. Standards and regulations for methanol as marine fuel

According to Ellis and Tanneberger (2015) and Hughes (2021), the IMO's Maritime Safety Committee (MSC) developed the interim guidelines for the safety of ships using Alcohol/Methyl/Ethyl as fuel, while several technical specifications and standards developed by the International Organization for Standardization (ISO) helped the marine industry facilitate wider adoption of low-flashpoint fuel engines. Dowling et al. (2022) and Rousseau and Tomdio (2023) reported that two IMO safety codes had been incorporated into the ABS Rules for Building and Classing Marine Vessels (MVR) for the handling and carriage of low-flashpoint fuels, including natural gas. Part 5C-8 of the MVR also incorporates the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) for specific vessel types, whereas Part 5C-13 incorporates the International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) for vessels using low-flashpoint fuels. In May 2018, the ISO was tasked by the IMO to develop standards for methyl/ethyl alcohol as fuel couplings and marine fuels.

The IGF-ready vessels, according to Rim et al. (2023), provide the 'Methanol Fuel Ready' notation, along with other notations, for existing and new vessels that can be converted to low-flashpoint fuels. These notations adhere to the existing classification requirements for conventional fuels while also allowing for conversion to specific low-flashpoint fuels. Cassar et al. (2021) noted that the IMO assigned notations "LFFS" for low-flashpoint fuel-burning ships that use low-flashpoint fuels except natural gas. Because the IGC and IGF codes are prescriptive and designed for natural gas, additional precautions are necessary for ships using other low-flashpoint fuels, as stated in both sections of the rules. Ampah et al. (2021) and Dierickx et al. (2018) concur that natural gas-specific classes and statutory requirements can aid in vessel designs for fuels with low flashpoints or natural gas. These specifications are cited in a number of widely accepted guidelines for gas and other low-flashpoint fuels.

Using low-flashpoint fuels in marine vessels requires risk assessments and engineering analyses. Such requirements are specified in the IGC and IGF codes, but as highlighted in Rousseau and Tomdio (2023) and Dowling et al. (2022), the Flag Administration must agree on the scope and approach for these evaluations. Established techniques such as hazard and operability study (HAZOP), hazard identification (HAZID) and failure modes and effects analysis (FMEA) should be used to conduct these assessments.

3.2.1. Considerations for methanol fuel bunkering

According to Etemad and Choi (2017) and Chen and Guan (2021), the IGC Code and IGF Code offer general safety guidelines for low-flashpoint fuels on marine vessels. These guidelines cover important safety measures like fuel tank protection, dual barriers on fuel supply lines, hazardous area classification, gas detection sensors, ventilation and explosion-proof materials for all low-flashpoint fuels. But the safety features required for individual fuels may vary based on their characteristics. Methanol produces denser vapors than air when it leaks, which makes it toxic and necessitates additional detectors.

Hughes (2021) and Dowling et al. (2022) also reported that the IMO's Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel provides a comprehensive reference for ship design and arrangement, pipe design, materials, fuel containment systems, fuel supply, bunkering, explosion mitigation, fire safety, ventilation, classified hazard areas, power generation, control systems, electrical systems and fixtures, crew competency, risk assessments and operations. According to Ellis and Tanneberger (2015), methanol, which is not cryogenic, is simpler to handle and transport than other fuels and is like conventional bunker vessels. The experience of the Platform Supply Vessel (PSV) and Offshore Support Vessel (OSV) fleets in handling methanol for the offshore industry, as reported by Le Fevre (2018) and Rousseau and Tomdio (2023), can serve as a guide for methanol endorsement as a widely bunkering fuel. It is important to always consider fuel characteristics in risk assessment analyses.

Methanol has a promising potential as a bunker fuel for ships due to its availability and global distribution. Ghorbani et al. (2022) described methanol as relatively efficient at storing energy by volume, despite its low energy content compared to other fuels. Short-sea vessels will most benefit from adopting methanol and other low-energy content fuels due to the limited trade distance and regulatory landscape. Since methanol requires more frequent bunkering, short-sea freight vessels can quickly adapt to this need.

The net carbon-neutral and low-carbon fuel usage for large ships seemed more complicated than it is for smaller vessels. Gray et al. (2021) argued that using fuels like methanol with low energy content would necessitate significant ship design changes since fuel tanks would require larger storage of sufficient energy for longer voyages. Despite methanol's greater versatility than other low-flashpoint fuels and its ability to be incorporated more readily into ship designs, industry studies (e.g., Pundir et al., 2021; Ellis and Bomanson, 2018) have raised

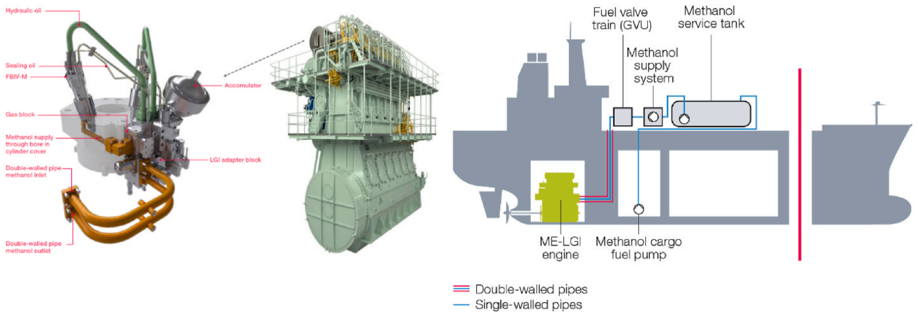

Fig. 5. MAN High-pressure liquid methanol-fuel injection ME-LGI engine.

concerns about its placement below the lowest possible waterline under MSC.1/Circ.1621 regulations. These studies indicate that methanol has the potential to decrease CO_2 emissions by approximately 10% as the primary marine fuel. Gray et al. (2021) further highlighted that if produced sustainably via biomass, biogas, or renewable electricity, it may become a carbon-neutral fuel in the future.

3.2.2. Challenges and opportunities for bunkering methanol fuel

Methanol is now considered a viable fuel option as engine manufacturers have successfully developed methanol-capable engine platforms. This development has raised the prospect of methanol contributing to meeting the carbon reduction goals set for 2030, thus paving the way for carbon-neutral propulsion systems. Vedachalam et al. (2022) have argued that methanol is costlier than low-sulfur marine gas oil (MGO), making it the least desirable option under existing regulations. Another insight is that the shipping industry is always susceptible to fuel price volatility. It is necessary to implement contractual measures to limit this volatility and ensure the supply of methanol.

All the literature sources reviewed pointed to the use of methanol as a marine fuel, but with complications. These challenges include supply, infrastructure and bunkering. Svanberg et al. (2018) and Vredeveldt et al. (2020) identified bunkering facilities, fuel supply systems, onboard containment systems and vessel engines as important areas requiring critical evaluation. Proper ventilation and an open deck location are essential for bunkering stations. Methanol is liquid, which makes it easy to store and available for bunkering. Van Hoecke et al. (2021) revealed that the current infrastructure built for the chemical industry can ensure adequate availability, but more terminals would be required for methanol's extensive use in maritime vessels. In contrast, Brynolf et al. (2014) suggested that methanol could be stored in conventional fuel tanks for onboard storage, which can be easy to use as liquid low-flashpoint fuels at ambient conditions and can be easily stored this way.

MAN and Wärtsilä propulsion engines for ships have been commended in several industry studies for possessing high capabilities for easily burning methanol. The ME-LGI engine from MAN uses high-pressure liquid fuel injection, like conventional oil fuel, through a dedicated liquid fuel injector and follows a dual-fuel combustion concept like the ME-GI engine as shown in Fig. 5. The Wärtsilä engine technology is built on their methanol common rail system and high-pressure natural gas injection mechanism that generates high pressure using a dedicated HP fuel supply pump. Giernalczyk (2019) and Güdden et al. (2021) affirmed that this technology has been developed for both offshore and land-based engine applications. The ME-LGI engine is designed to inject high-pressure liquid fuels (Zhu and Fan 2022).

3.3. Methanol-powered vessels: current research and future developments

Several advanced research and development projects in the maritime industry have successfully shown that methanol engines and fuel cells are technically possible. This study has analyzed the research and pilot projects that have used methanol as a reliable and potent marine fuel.

Table 2
Waterfront operational methanol-powered tankers fleet.

Vessel name	IMO number	Owner	Builder
Mari Jone	9725316	Marinvest	HMD
Mari Kokako	9848687	Marinvest	HMD
Mari Couva	9848584	Marinvest	HMD
Mari Boyle	9732979	Marinvest	HMD
Lindanger	9725299	Westfal-Larsen	HMD
Leikanger	9725304	Westfal-Larsen	HMD
Creole Sun	9850214	IINO LINES and Mitsui	HMD
Takaroa Sun	9850202	NYK	HMD
Cajun Sun	9724025	MOL Mitsui OSK	Minami Nippon
Taranaki Sun	9751406	MOL Mitsui OSK	Minami Nippon
Manchac Sun	9724013	MOL Mitsui OSK	Minami Nippon

The methanol-powered tanker fleet operated by Waterfront Shipping has demonstrated operational success. The Pu and Verhelst (2022) report revealed that the fleet consists of 11 ships that were delivered and began operation in October 2020. Waterfront Shipping Company is a subsidiary of Methanex, which is the world's largest methanol producer. Deep-sea commercial vessels run by Waterfront Shipping as summarized in Table 2 are the only vessels currently using methanol as fuel.

The industry research analyzed led to the findings that the successful use of methanol as a fuel source is fast growing. Laasma et al. (2022) validated that the Stena Germanica Ro-Pax ferry underwent a retrofit in 2015 to accommodate methanol combustion. The retrofitting aimed at a high-pressure pump room installation, ballast tanks converted for methanol storage, and safety features enabled double-wall fuel piping systems, as well as modifying engines for methanol use. In 2017, MS Innogy became Germany's first methanol-powered fuel cell vessel. The excursion vessel, according to Hobson and Márquez (2018), was designed to run on green methanol generated from the surrounding air, water and green electricity produced by the nearby Lake Baldeney hydroelectric plant. Witthohn (2022) reported the Alfred Wegener Institute's invention of the Uthörn, a 37.5 m methanol-powered research vessel, which was the first of its kind to be built in Germany in August 2020. The ship is currently operating in the North Sea, with operations centered on Germany's Heligoland Island station.

These recent developments have contributed to the increasing use of methanol as a fuel source in the maritime industry. The testing of methanol fuel cells on the AIDAnova cruise ship in 2021 was another turning point. Freudenberg Sealing Technologies designed and tested the fuel cells, which have a lifespan of up to 35,000 operating h (Elkafas et al., 2022). Tests were conducted to assess the efficiency, integration and operability of the fuel cell in comparison to other low-emission options such as LNG and batteries (Mallouppas and Yfantis, 2021). Proman Stena Bulk Ltd. commissioned two new tankers that have a deadweight capacity of 49,900 t and will run on methanol dual-fuel engines (Küfeoğlu, 2023). Shore-based research projects also focus on engines powered by pure methanol or a methanol blend. The

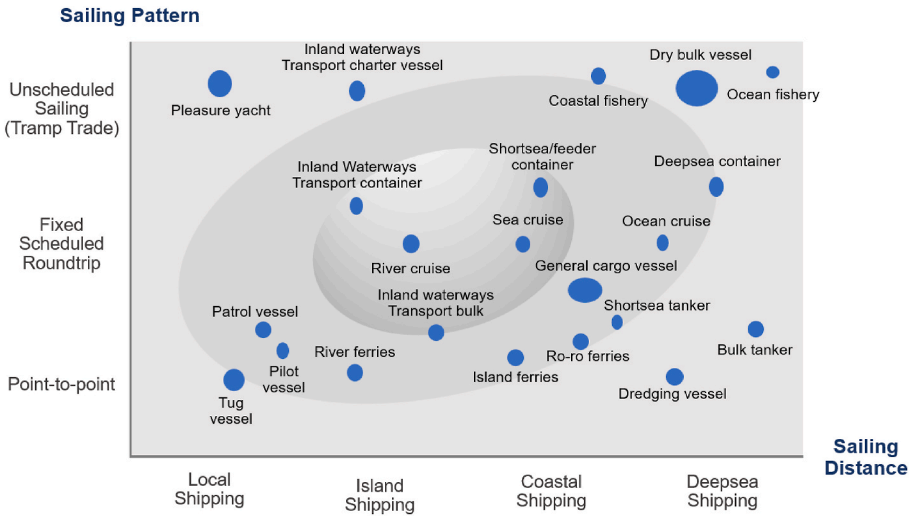

Fig. 6. Heatmap of shipping segments' methanol-applicability.

Table 3
Annual bunker demand estimate per vessel type.

Ship type	Fleet	GT capacity X (kt)	2014 Bunker volume (Mt)		Bunker per vessel
General cargo	16,061	57025	21700000	7%	1351
Oil & chemical tanker	11730	281072	57200000	19%	4876
Oil Tanker			39700000	13%	
Chemical tanker			17500000	6%	
Bulk carrier	9892	359521	53400000	18%	5398
Offshore	7002	27968	8600000	3%	1228
Cruise	6423	34892	11100000	4%	1541
Container vessel	4858	175627	66000000	23%	13586
RoRo	1470	44756	9300000	3%	6327
LNG tanker			15700000	5%	
Fishery			16100000	5%	
Ferry Ropax			9900000	3%	
Vehicle carrier			7900000	3%	
Other			23600000	7%	
Total	**79471**	**1048336**	**300500000**		

HyMethShip project is a 13-member European consortium that is developing a methanol ship that uses renewable energy (Malmgren et al., 2021). The Green Maritime Methanol Consortium is conducting engine testing programs using a retrofitted 3508 Caterpillar gas engine that runs completely on methanol. Fig. 6 provides the potential for attractive and feasible use of methanol in the shipping industry, based on vessel tank capacity, bunker needs and operational profiles. The analysis does not include the financial viability of adopting methanol as a marine fuel.

The US Navy, in collaboration with Alfa Lava, Aura Marine and Wärtsilä in Finland, is conducting tests on a dual-fuel methanol engine. The tests will use the Wärtsilä 32 (32 methanol) engine and two different fuel mixtures, one sustained by an emulsifier and the other hybrid mechanically (Wissner et al., 2023). The objective was to analyze the engine's performance with different fuel compositions and injection systems that meet the US Navy's maritime needs. Another research project by the Danish Energy Agency and the Danish Technological Institute is ongoing to optimize methanol additives, which could enable their use in conventional diesel engines with minimal modifications for carbon-neutral or zero-emissions applications (Kountouris et al., 2023). Several research and development projects are currently underway to increase the use of methanol as a fuel in various transportation sectors. Van Hoecke et al. (2021) listed some progress made in the development of methanol bunkering facilities and fuel supply systems to support marine vessels. A consortium led by AP Moller-Maersk and Ørsted, involving 25 other partners is scaling up the production of industrial hydrogen in Europe to produce sustainable fuel for marine vessels, aviation transport and road transportation by 2030 (Latapí et al., 2023). The project is expected to be powered by electrolyzers and renewable offshore wind energy. The plan is to raise electrolyzer output to 260 MW by 2027 and supply sustainable methanol to Maersk vessels using sustainably captured CO_2. The project is expected to reduce carbon emissions by 70% through sustainable fuels and changes to energy infrastructure.

The top-down and bottom-up methods were used to estimate global bunker demand, which was found to be approximately 300 Mt per year. This was based on IMO data and 7 equal sources. Container vessels, which make up only 6% of the global fleet, were found to consume 23% of the total annual bunker volume. When combined with dry bulk carriers and liquid bulk tankers, these vessels consume almost two-thirds of the global bunker demand. Table 3 demonstrates how this bunker demand is distributed throughout various shipping markets.

Based on global bunker demand, Shanghai Huayi Energy Chemical and Methanex collaborate with the Methanol Institute and the China Waterborne Transportation Research Institute to conduct advanced studies that explore methanol viability as a future maritime fuel (Wang et al., 2023). Since China is a major producer and consumer of methanol, the studies will consider China's current methanol availability and infrastructure, as well as its shipping sector. The outcome is predicted to provide a policy roadmap and guidance for the wider adoption of methanol for China vessels.

The ASEAN shipping industry is exploring methanol as a potential alternative fuel to reduce GHG emissions. The existing infrastructure to accommodate methanol and its trade will be critical to its availability and cost when compared to other alternative fuels. Vedachalam et al. (2022) predicted a possible surge in future demand for methanol in manufacturing and opined that financial incentives or synthetic methanol production may be necessary to meet the demand for global maritime use, which may result in additional costs. The Methanex Corporation and the Methanol Institute provide useful information on methanol prices, safe handling practices and supply infrastructure. Methanol has been used in power generation and propulsion in methanol carriers, and the development of reliable, efficient and dedicated propulsion mechanisms has driven an expansion in the building of new methanol-powered cargo vessels. Renewably produced methanol has a better prospect of reducing life-cycle emissions and improving the supply chain of renewable methanol fuel for other applications.

Data estimation and the key findings have shown an overall

Table 4
Projected models of future methanol market shares.

	High scenario %		Low scenario %	
	S/M share	L/VL share	S/M share	L/VL share
General cargo	50	10	25	0
Oil & chemical tanker	50	10	25	0
Bulk carriers	50	10	25	0
Offshore	50	20	10	0
Cruise	50	10	25	0
Container vessels	50	20	25	0
RoRo	50	20	10	0
LNG tanker	0	0	0	0
Fishery	50	10	10	0
Ferry Ropax	50	10	25	0
Vehicle carrier	50	20	25	0
Other	50	20	10	0

methanol market share of 5% in the low scenario and 23% in the high scenario. Applying this analysis technique to the expected bunker market in 2030, the results indicated that Malaysia would need between 0.6 and 2.6 M m^3 of methanol and that all of ASEAN will require between 1.1 and 5.0 M m^3. Table 4 demonstrates that future global methanol production capacity can easily meet ASEAN demand.

Research is underway to explore the potential of methanol as a dual-fuel marine engine that can facilitate the use of various alternative fuels in the future. Methanol has an advantage over LNG and other gas bunkers because of its liquid state, which makes it easier and more cost-effective to store and retrofit existing infrastructure. Although Chen et al. (2023) and Thepsithar et al. (2020) noted that one of the difficulties with using methanol in contrast to conventional fuel oils is its lower energy content. Converting tanks to hold larger volumes of methanol and scaling up production activities, storage and trade for further methanol applications in marine fuel can help address this challenge. Rapidly scaling up the methanol infrastructure globally and onboard applications to achieve the IMO 80% GHG emissions reduction targets by 2050 remains the focus of ongoing research. Fig. 7 represents the predicted production and use of methanol as a marine fuel before 2050, based on data analysis from Wissner et al. (2023) and Shamsul et al. (2014) studies.

An updated list of ASEAN methanol-fueled vessel fleets was not available during the study. But Japanese shipping fleets such as Mitsui OSK Lines, Tabuchi Kaiun, Niihama Kaiun and MOL Coastal Shipping are collaborating with Murakami Hide Shipbuilding and Hanshin Diesel Works to expand methanol-fueled vessel fleets in Asia. Methanol as a marine fuel is still in the early stages of development and implementation, and the number of methanol-fueled vessels in operation is relatively small. Notwithstanding, some notable developments in this area have occurred. For example, Methanex Corporation's subsidiary, Waterfront Shipping, ordered eight new methanol-fueled vessels to be delivered in 2021 and 2022, which are the first methanol-fueled vessels to be built in Asia.

The Maritime and Port Authority of Singapore has also been supporting methanol as a marine fuel, launching a pilot program to test its use on a small harbor craft in 2018. The program was successful, and the MPA has announced plans to expand the use of methanol as a marine fuel in Singapore. There is no comprehensive list of Asian methanol-fueled vessel fleets yet, but there is a growing interest in methanol as a marine fuel in the ASEAN region.

4. Conclusion

The benefits and drawbacks of methanol as an alternative fuel source, as well as its feasibility in meeting emission regulations, were carefully examined. In this study, the environmental implications of using methanol as fuel in marine vessels were analyzed, including its production process and comparison to other fuel alternatives. The impact of methanol on reducing greenhouse gas emissions, air pollution and the overall sustainability of the marine industry were also evaluated. The findings revealed the potential environmental impacts of increasing methanol production to meet the demand for marine fuel, including the potential for water contamination, land use change and other indirect effects. Ongoing research and industry projects related to feedstock options for methanol production are discussed in Section 3.

In terms of safety, the findings unveiled the ME-LGI concept by MAN, which safely uses liquid low-flashpoint fuels like methanol in marine engines. This success further indicates that methanol is easier to contain onboard than LNG and only minor modifications are required to the existing infrastructure. Although safety considerations such as tank location, protection, inerting, spill containment and fire-fighting must be considered. The findings further revealed that methanol is toxic and can pose a danger to human health if ingested, leading to blindness, coma and even death. It also produces a nearly invisible flame, making it challenging to detect until it has spread. The IMO interim guidelines for ships utilizing methyl/ethyl alcohol as fuel, in addition to those provided by the ISO, facilitate the use of low-flashpoint fuels in the

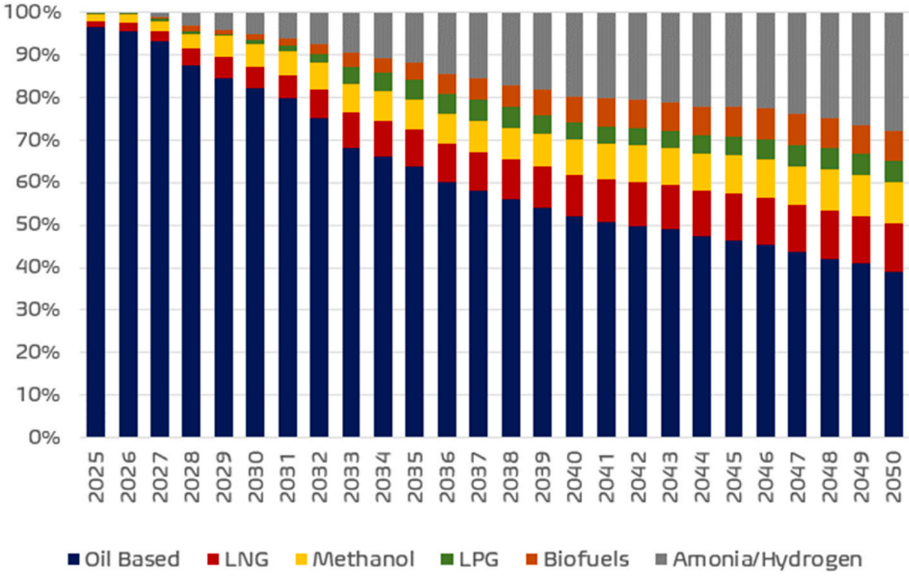

Fig. 7. Predicted methanol use as marine fuel before 2050.

maritime industry. These guidelines and standards have ensured the safe storage, handling and using methanol as well as other low-flashpoint fuels on board vessels. ABS also incorporated safety codes related to low-flashpoint fuels into their rules for marine vessels, requiring risk assessments and engineering analyses.

The analysis revealed that methanol is a promising alternative fuel source that can reduce carbon emissions, especially for short-sea vessels. Specific safety measures must always be taken due to methanol toxicity and additional detectors and ventilation systems are needed. Despite having a lower energy content than other fuels, methanol remains efficient at storing energy by volume. While methanol may be more expensive than low-sulfur MGO, the availability of engines capable of using methanol, coupled with existing distribution infrastructure, would make it a viable alternative sooner. Challenges such as fuel supply, infrastructure and bunkering must be addressed for widespread adoption. MAN and Wärtsilä have offered methanol-burning engines based on the high-pressure diesel combustion process and the ASEAN maritime industry can sufficiently benefit from this development.

This study suggests that methanol is a potential alternative marine fuel that can reduce greenhouse gas emissions and improve air quality in the shipping industry, but there are costs and challenges to consider, including initial costs, fuel costs, safety concerns, technical challenges, infrastructure challenges and regulatory challenges. Retrofitting ships to use methanol can be expensive and methanol is currently more expensive than traditional marine fuels. New infrastructure for methanol production, storage and distribution is needed. Further research is required to determine the full costs and benefits of implementing methanol as a marine fuel.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

The authors express gratitude to the Universiti Malaysia Terengganu (UMT) Library, the Faculty of Maritime Studies (FMS), SINODA Shipping Agency Pte. Ltd. Singapore, THOME Ship Management Pte. Ltd. Singapore, Tuck Sun Logistics Group Malaysia and TOG Shipping & Offshore Management Nigeria Ltd. for providing valuable insights for the successful completion of this research paper. Heartfelt appreciation to Prof. Dr. Wan Mohd Norsani Wan Nik, Nurul Akma Abdullah, Assoc. Prof. Dr. Noreha Hashim, Dr. Rudiah Md Hanafiah, Noorasiah Moidu, Suzana Shamsuddin, Nor Bahyah Mohamed, Nur Afiqah Wal' Affa Elmin, Muhammad Aiman Razali, Siti Nur Hazlinda Hasbu, Rohaida Ariffin, Nurul Atirah Zaidi, Siti Asmah Asmayudin, Dr. Loy Kak Choon, Dr. Chong Nyuk Sian, Mr. Moshood Olaniyan, Fiona Kerk Xiuzhen, Teh Bee Bee, Chew Kuan Lian, Loh Chong Hooi, Timmy Chuah Tim Mie and Ong Shying Weei for their support.

References

Aabo, K., 2020. Ammonia-fuelled MAN B&W 2-stroke dual-fuel engines. Mar. Eng. 55 (6), 737–744.

Acha, S., Sánchez-Silva, M., Galán-Martín, Á., García-Menéndez, L., 2021. Low carbon shipping: a systematic review of the literature. Energies 14 (9), 2489. https://doi.org/10.3390/en14092489.

Ampah, J.D., Yusuf, A.A., Afrane, S., Jin, C., Liu, H., 2021. Reviewing two decades of cleaner alternative marine fuels: towards IMO's decarbonization of the maritime transport sector. J. Clean. Prod. 320, 128871.

Abbasi, T.U., Ahmad, M., Asma, M., Rozina, Munir, M., Zafar, M., Katubi, K.M., Alsaiari, N.S., Yahya, A.E.M., Mubashir, M., Chuah, L.F., Bokhari, A., 2023. High efficient conversion of *Cannabis sativa L.* biomass into bioenergy by using green tungsten oxide nano-catalyst toward s carbon neutrality. Fuel, 126796. https://doi.org/10.1016/j.fuel.2022.126796.

Ahmad, T., Iqbal, J., Azmi Bustam, M., Babar, M., Tahir, M.B., Sagir, M., Irfan, M., Asgharf, H.M.A., Hassan, A., Riaz, A., Chuah, L.F., Bokhari, A., Mubashir, M., Show, P.L., 2023. Performance evaluation of phosphonium based deep eutectic solvents coated cerium oxide nanoparticles for CO_2 capture. Environ. Res. 222, 115314 https://doi.org/10.1016/j.envres.2023.115314.

Alsaiari, M., Bokhari, A., Chuah, L.F., Mubashir, M., Harraz, F.A., Almohana, A.I., Show, P.L., Awasthi, M.K., Rizk, M.A., 2023. Synthesis of methyl esters from *Hippophae rhamnoides* via pilot scale hydrodynamic cavitation intensification reactor. Renew. Energy 205, 238–247. https://doi.org/10.1016/j.renene.2023.01.072.

Ameen, M., Zafar, M., Ramadan, M.F., Ahmad, M., Makhkamov, T., Bokhari, A., Mubashir, M., Chuah, L.F., Show, P.L., 2023. Conversion of novel non-edible Bischofia javanica seed oil into methyl ester via recyclable zirconia-based phytonanocatalyst: a circular bioeconomy approach for eco-sustenance. Environ. Technol. Innov., 103101 https://doi.org/10.1016/j.eti.2023.103101.

Arshad, S., Ahmad, M., Munir, M., Sultana, S., Zafar, M., Dawood, S., Rozina, Alghamdi, A.M., Asif, S., Bokhari, A., Mubashir, M., Chuah, L.F., Show, P.L., 2023. Assessing the potential of green CdO_2 nano-catalyst for the synthesis of biodiesel using non-edible seed oil of Malabar Ebony. Fuel 333 (2), 126492. https://doi.org/10.1016/j.fuel.2022.126492.

Asif, S., Klemes, J.J., Mukhtar, A., Saqib, S., Chuah, L.F., Bokhari, A., 2021. Intensification of biodiesel synthesis in a cavitation system from *Xanthium Spinosum* oil. Chem. Eng. Transac. 86, 151–156. https://doi.org/10.3303/CET2186026.

Bilgili, L., 2021. Comparative assessment of alternative marine fuels in life cycle perspective. Renew. Sustain. Energy Rev. 144, 110985.

Bokhari, A., Yusup, S., Asif, S., Chuah, L.F., Michelle, L.Z.Y., 2020. Process intensification for the production of canola-based methyl ester via ultrasonic batch reactor: optimization and kinetic study. In: Singh, L., Yousuf, A., Mahapatra, D.M. (Eds.), Bioreactors Sustainable Design and Industrial Applications in Mitigation of GHG Emissions. Elsevier Inc, pp. 27–42. https://doi.org/10.1016/B978-0-12-821264-6.00003-6.

Bokhari, A., Chuah, L.F., Michelle, L.Z.Y., Asif, S., Shahbaz, M., Akbar, M.M., Inayat, A., Jamil, F., Naqvi, S.R., Yusup, S., 2019. Microwave enhanced catalytic conversion of canola-based methyl ester: optimization and parametric study. In: Azad, A.K., Rasul, M. (Eds.), Advanced Biofuels: Applications, Technologies and Environmental Sustainability. Woodhead Publishing Series in Energy, pp. 153–166. https://doi.org/10.1016/B978-0-08-102791-2.00006-4.

Bokhari, A., Yusup, S., Chuah, L.F., Kamil, R.N.M., 2016. Relative efficiency of esterified rubber seed oil in a hydrodynamic cavitation reactor and purification via distillation column. Chem. Eng. Transac. 52, 775–780. https://doi.org/10.3303/CET1652130.

Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95.

Cao, Y., Sun, Y., Han, N., Li, X., Wang, Q., Sun, K., Si, W., Wang, F., Zhao, X., Bokhari, A., Mubashir, M., Chuah, L.F., Show, P.L., 2023. Novel highly active and selective Co-NS-C efficient ORR catalyst derived from in-situ egg gel pyrolysis. Fuel 333 (1), 126432. https://doi.org/10.1016/j.fuel.2022.126432.

Cassar, M.P., Dalaklis, D., Ballini, F., Vakili, S., 2021. Liquefied natural gas as ship fuel: a Maltese regulatory gap analysis. Trans. Marit. Sci. 10 (1), 247–259.

Cheah, K.W., Yusup, S., Chuah, L.F., Bokhari, A., 2016. Physio-chemical studies of locally sourced non-edible oil: prospective feedstock for renewable diesel production in Malaysia. Procedia Eng. 148, 451–458. https://doi.org/10.1016/j.proeng.2016.06.460.

Chen, L., Guan, W., 2021. Safety design and engineering solution of fuel cell powered ship in inland waterway of China. World Electric Vehicle J. 12 (4), 202.

Chen, P.S.L., Fan, H., Enshaei, H., Zhang, W., Shi, W., Abdussamie, N., Yang, Z., 2023. A review on ports' readiness to facilitate international hydrogen trade. Int. J. Hydrogen Energy 1, 1–12.

Chuah, L.F., Mokhtar, K., Mhd Ruslan, S.M., Abu Bakar, A., Abdullah, M.A., Osman, N.H., Bokhari, A., Mubashir, M., Show, P.L., 2023a. Implementation of the energy efficiency existing ship index and carbon intensity indicator on domestic ship for marine environmental protection. Environ. Res. 222, 115348 https://doi.org/10.1016/j.envres.2023.115348.

Chuah, L.F., Mohd Rof'ie, N.R., Mohd Salleh, N.H., Abu Bakar, A., Oloruntobi, O., Othman, M.R., Mohamed Fazlee, U.S., Mubashir, M., Asif, S., 2023b. Analyzing the influencing factors of Port State Control for cleaner environment by using Bayesian Network model. Cleaner Engineering and Technology, 100636. https://doi.org/10.1016/j.clet.2023.100636.

Chuah, L.F., Chew, K.W., Bokhari, A., Mubashir, M., Show, P.L., 2022a. Biodegradation of crude oil in seawater by using a consortium of symbiotic bacteria. Environ. Res., 113721 https://doi.org/10.1016/j.envres.2022.113721.

Chuah, L.F., Mokhtar, K., Abu Bakar, A., Othman, M.R., Osman, N.H., Bokhari, A., Mubashir, M., Abdullah, M.A., Hasan, M., 2022b. Marine environment and maritime safety assessment using Port State Control database. Chemosphere 304, 135245. https://doi.org/10.1016/j.chemosphere.2022.135245.

Chuah, L.F., Bokhari, A., Asif, S., Klemeš, J.J., Dailin, D.J., Enshasy, H.E., Yusof, A.H.M., 2022c. A review of performance and emission characteristic of engine diesel fuelled by biodiesel. Chem. Eng. Transac. 94, 1099–1104. https://doi.org/10.3303/CET2294183.

Chuah, L.F., Klemeš, J.J., Bokhari, A., Asif, S., Cheng, Y.W., Chong, C.C., Show, P.L., 2022d. A review of intensification technologies for biodiesel production. In: Gutierrez-Antonio, C., Gomez Castro, F.I. (Eds.), Biofuels and Biorefining. Volume 2:

Intensification Processes and Biorefineries. Elsevier Inc, pp. 87–116. https://doi.org/10.1016/B978-0-12-824117-2.00009-0.

Chuah, L.F., Mohd Salleh, N.H., Osnin, N.A., Alcaide, J.I., Abdul Majid, M.H., Abdullah, A.A., Bokhari, A., Jalil, E.E.A., Klemes, J.J., 2021a. Profiling Malaysian ship registration and seafarers for streamlining future Malaysian shipping governance. Australia. J. Maritime Ocean Affair. 13 (4), 225–261. https://doi.org/10.1080/18366503.2021.1878981.

Chuah, L.F., Klemes, J.J., Bokhari, A., Asif, S., 2021b. A review of biodiesel production from renewable resources: chemical reactions. Chem. Eng. Transac. 88, 943–948. https://doi.org/10.3303/CET2188157.

Chuah, L.F., Bokhari, A., Yusup, S., Saminathan, S., 2017. Optimisation on pretreatment of kapok seed (Ceiba pentandra) oil via esterification reaction in an ultrasonic cavitation reactor. Biomass Convers. Biorefin. 7 (1), 91–99. https://doi.org/10.1007/s13399-016-0207-9.

Chuah, L.F., Abd Aziz, A.R., Yusup, S., Klemeš, J.J., Bokhari, A., 2016. Waste cooking oil biodiesel via hydrodynamic cavitation on a diesel engine performance and greenhouse gas footprint reduction. Chem. Eng. Transac. 50, 301–306. https://doi.org/10.3303/CET1650051.

Dierickx, J., Beyen, J., Block, R., Hamrouni, M., Huyskens, P., Meichelböck, C., Verhelst, S., 2018. Strategies for introducing methanol as an alternative fuel for shipping. In: 7th Transport Research Arena TRA 2018 (TRA 2018). Ghent University, pp. 1–10.

Dowling, M., Meyers, T., Carlucci, D., Delpizzo, R., 2022. Hydrogen for Marine Power and Propulsion: Regulatory and Classification Considerations. SNAME Maritime Convention, OnePetro.

Ellis, J., Bomanson, J., 2018. SUMMETH–Sustainable Marine Methanol Hazard Identification Study for the M/S Jupiter Methanol Conversion Design.

Ellis, J., Tanneberger, K., 2015. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. Eur. Marit. Saf. Agency 46, 1–38.

Elsaid, K., Abdelfatah, S., Elabsir, A.M.A., Hassiba, R.J., Ghouri, Z.K., Vechot, L., 2021. Direct alcohol fuel cells: assessment of the fuel's safety and health aspects. Int. J. Hydrogen Energy 46 (59), 30658–30668.

Etemad, H., Choi, J.H., 2017. Hazard identification (HAZID) of LNG dual-fueled ships operating between the Korean port of Busan and the Iranian port of Bandar Abbas. Journal of Advanced Marine Engineering and Technology (JAMET) 41 (5), 473–488.

Evegren, F., 2017. Safety & transport fire research. SP Rapp. 22.

Gerba, C.P., 2019. Environmental toxicology. In: Environmental and Pollution Science. Academic Press, pp. 511–540.

Ghorbani, B., Wang, W., Li, J., Jouybari, A.K., Saharkhiz, M.H.M., 2022. Solar energy exploitation and storage in a novel hybrid thermo-electrochemical process with net-zero carbon emissions. J. Energy Storage 52, 104935.

Giernalczyk, M., 2019. Analysis of the possibility of using low speed two-stroke dual-fuel engines for propulsion of sea-going vessels. J. KONES 26 (2), 45–52.

Glaude, P.A., Fournet, R., Bounaceur, R., Molière, M., 2010. Adiabatic flame temperature from biofuels and fossil fuels and derived effect on NOx emissions. Fuel Process. Technol. 91 (2), 229–235.

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., Murphy, J.D., 2021. Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Advan. Appl. Energy 1, 100008.

Güdden, A., Pischinger, S., Geiger, J., Heuser, B., Müther, M., 2021. An experimental study on methanol as a fuel in large bore high speed engine applications–Port fuel injected spark ignited combustion. Fuel 303, 121292.

Halim, M.K., Madzli, H., Yaakop, Y.A., Ahmad, Z., 2022. Malaysian role in port bilateral diplomacy towards Asean maritime working group for formulation of Malaysian & regional port strategic plan. Int. J. e-Navigat. Maritime Econ. 19, 48–65.

Hobson, C., Márquez, C., 2018. Renewable Methanol Report. Methanol Institute, Singapore.

Hughes, E., 2021. Fuel EU maritime–avoiding unintended consequences. In: Guidance on Regulations for the Transport of Infectious Substances 2019–2020: Applicable from 1 January 2019 (No. WHO/WHE/CPI/2019.20). World Health Organization.

Itskos, G., Nikolopoulos, N., Kourkoumpas, D.S., Koutsianos, A., Violidakis, I., Drosatos, P., Grammelis, P., 2016. Energy and the Environment. Environment and development, pp. 363–452.

Karim, S.S., Farrukh, S., Matsuura, T., Ahsan, M., Hussain, A., Shakir, S., Chuah, L.F., Hasan, M., Bokhari, A., 2022. Model analysis on effect of temperature on the solubility of recycling of Polyethylene Terephthalate (PET) plastic. Chemosphere 307, 136050. https://doi.org/10.1016/j.chemosphere.2022.136050.

Korberg, A.D., Brynolf, S., Grahn, M., Skov, I.R., 2021. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renew. Sustain. Energy Rev. 142, 110861.

Korzeniowski, S.H., Buck, R.C., Kempisty, D.M., Pabon, M., 2018. Fluoro surfactants in firefighting foams: past and present. In: Perfluoroalkyl Substances in the Environment. CRC Press, pp. 3–34.

Kountouris, I., Langer, L., Bramstoft, R., Münster, M., Keles, D., 2023. Power-to-X in energy hubs: a Danish case study of renewable fuel production. Energy Pol. 175, 113439.

Küfeoğlu, S., 2023. From Hydrogen Hype to Hydrogen Reality: a Horizon Scanning for the Business Opportunities.

Laasma, A., Otsason, R., Tapaninen, U., Hilmola, O.P., 2022. Evaluation of alternative fuels for coastal ferries. Sustainability 14 (24), 16841.

Latapí, M., Davíðsdóttir, B., Jóhannsdóttir, L., 2023. Drivers and barriers for the large-scale adoption of hydrogen fuel cells by Nordic shipping companies. Int. J. Hydrogen Energy 48 (15), 6099–6119.

Le Fevre, C.N., 2018. A Review of Demand Prospects for LNG as a Marine Fuel. The Oxford Institute for Energy Studies. https://doi.org/10.26889/9781784671143.

Li, J., Cheng, W., 2020. Comparative life cycle energy consumption, carbon emissions and economic costs of hydrogen production from coke oven gas and coal gasification. Int. J. Hydrogen Energy 45 (51), 27979–27993.

Lin, S., Chen, S., Henneman, L.R.F., St Martin, A., Russell, A.G., 2021. Assessing the impact of emissions control area designation on air quality and public health in the US Gulf Coast. Environ. Sci. Technol. 55 (1), 365–373. https://doi.org/10.1021/acs.est.0c04505.

Malik, S., Fatima, F., Imran, A., Chuah, L.F., Klemes, J.J., Khaliq, I.H., Asif, S., Aslam, M., Jamil, F., Durrani, A.K., Akbar, M.M., Shahbaz, M., Usman, M., Atabani, A.E., Naqvi, S.R., Yusup, S., Bokhari, A., 2019. Improved project control for sustainable development of construction sector to reduce environment risks. J. Clean. Prod. 240, 118–214. https://doi.org/10.1016/j.jclepro.2019.118214.

Mallouppas, G., Yfantis, E.A., 2021. Decarbonization in shipping industry: a review of research, technology development, and innovation proposals. J. Mar. Sci. Eng. 9 (4), 415.

Malmgren, E., Brynolf, S., Fridell, E., Grahn, M., Andersson, K., 2021. The environmental performance of a fossil-free ship propulsion system with onboard carbon capture–a life cycle assessment of the HyMethShip concept. Sustain. Energy Fuels 5 (10), 2753–2770.

Malmgren, E., Brynolf, S., Borgh, M., Ellis, J., Grahn, M., Wermuth, N., 2020. The HyMeth Ship Concept: an Investigation of System Design Choices and Vessel Operation Characteristics Influence on Life Cycle Performance. 8th transport research Arena, Helsinki, Finland.

Meca, V.L., d'Amore-Domenech, R., Crucelaegui, A., Leo, T.J., 2022. Large-scale maritime transport of hydrogen: economic comparison of liquid hydrogen and methanol. ACS Sustain. Chem. Eng. 10 (13), 4300–4311.

Mohd Shamsuddin, N.A., Yusup, S., Ibrahim, W.A., Bokhari1, A., Chuah, L.F., 2015. Oil extraction from Calophyllum inophyllum L. Via soxhlet extraction optimization using response surface methodology (RSM). In: A Paper Presented at the 10th Asian Control Conference (10th ASCC). IEEE Xplore, Sutera Harbour Resort, Kota Kinabalu, Sabah, Malaysia. https://doi.org/10.1109/ASCC.2015.7244791, 31 May -3 June, 2015 at.

Munir, M., Saeed, M., Ahmad, M., Waseem, A., Alsaady, M., Asif, S., Ahmed, A., Khan, M. S., Bokhari, A., Mubashir, M., Chuah, L.F., Show, P.L., 2023. Cleaner production of biodiesel from novel non-edible seed oil (*Carthamus lanatus L.*) via highly reactive and recyclable green nano $CoWO_3$@rGO composite in context of green energy adaptation. Fuel 332 (2), 126265. https://doi.org/10.1016/j.fuel.2022.126265.

Oloruntobi, O., Mokhtar, K., Mohd Roza, N., Gohari, A., Asif, S., Chuah, L.F., 2023a. Effective technologies and practices for reducing pollution in warehouses - a review. Cleaner Engineering and Technology, 100622. https://doi.org/10.1016/j.clet.2023.100622.

Oloruntobi, O., Mokhtar, K., Gohari, A., Asif, S., Chuah, L.F., 2023b. Sustainable transition towards greener and cleaner seaborne shipping industry: challenges and opportunities. Cleaner Engineering and Technology, 100628. https://doi.org/10.1016/j.clet.2023.100628.

Pu, Y.H., Verhelst, S., 2022. The FASTWATER demonstrator: retrofitting a pilot boat to methanol operation. In: Scaling Decarbonisation Solutions: Reducing Emissions by 2030. The royal institution of naval architects.

Pundir, S., Garg, P., Dviwedi, A., Ali, A., Kapoor, V.K., Kapoor, D., Negi, P., 2021. Ethnomedicinal uses, phytochemistry and dermatological effects of *Hippophae rhamnoides* L.: a review. J. Ethnopharmacol. 266, 113434.

Rim, R.B., Anh, D.P., Keun, K.H., 2023. A study on safety assessment for low-flashpoint and eco-friendly fueled ship. J. Navig. Port Res. 47 (1), 25–36.

Rousseau, J.H., Tomdio, J., 2023. Classification of single point moorings as offshore battery charging stations. In: SNAME 28th Offshore Symposium. OnePetro.

Shamsul, N.S., Kamarudin, S.K., Rahman, N.A., Kofli, N.T., 2014. An overview on the production of bio-methanol as potential renewable energy. Renew. Sustain. Energy Rev. 33, 578–588.

Solórzano, A., Eichmann, J., Fernández, L., Ziems, B., Jiménez-Soto, J.M., Marco, S., Fonollosa, J., 2022. Early fire detection based on gas sensor arrays: multivariate calibration and validation. Sensor. Actuator. B Chem. 352, 130961.

Subedi, B.N., Amgain, K., Joshi, S., Bhattarai, J., 2019. Green approach to corrosion inhibition effect of Vitex negundo leaf extract on aluminum and copper metals in biodiesel and its blend. Int. J. Corrosion and Scale Inhibit. 8 (3), 744–759.

Svanberg, M., Ellis, J., Lundgren, J., Landälv, I., 2018. Renewable methanol as a fuel for the shipping industry. Renew. Sustain. Energy Rev. 94, 1217–1228.

Thepsithar, P., Kiong, M.K.E., Piga, M.B., Zengqi, M.X., Yin, S.J., Ming, L., Rosario, M.M. K.P., 2020. Alternative Fuels for International Shipping. Maritime Energy & Sustainable Development (MESD) Centre of Excellence, Nanyang Technological University.

Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S.W., Lenaerts, S., 2021. Challenges in the use of hydrogen for maritime applications. Energy Environ. Sci. 14 (2), 815–843.

Vedachalam, S., Baquerizo, N., Dalai, A.K., 2022. Review on impacts of low sulfur regulations on marine fuels and compliance options. Fuel 310, 122243.

Verhelst, S., Turner, J.W., Sileghem, L., Vancoillie, J., 2019. Methanol as a fuel for internal combustion engines. Prog. Energy Combust. Sci. 70, 43–88.

Vredeveldt, A.W., van Dijk, T., van den Brink, A., Maritiem, C.T.K.I., 2020. Unconventional Bunker Fuels, a Safety Comparison.

Wang, X., Zhu, J., Han, M., 2023. Industrial development status and prospects of the marine fuel cell: a review. J. Mar. Sci. Eng. 11 (2), 238.

Wei, F., Wang, Y., Tian, H., Tian, J., Long, W., Dong, D., 2022. Visualization study on lean combustion characteristics of the premixed methanol by the jet ignition of an ignition chamber. Fuel 308, 122001.

Wissner, N., Healy, S., Cames, M., Sutter, J., 2023. Methanol as a Marine Fuel.

Witthohn, R., 2022. Offshore work. In: International Shipping: the Role of Sea Transport in the Global Economy. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 491–541.

Xing, H., Stuart, C., Spence, S., Chen, H., 2021. Alternative fuel options for low carbon maritime transportation: pathways to 2050. J. Clean. Prod. 297, 126651.

Zhu, Y., Fan, L., 2022. Fuel delivery system for alternative fuel engines: a review. Potent. Challenges Low Carbon Fuel Sustain. Transport 67–95.