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Full Length Article

Emission control and carbon capture from diesel generators and engines: A decade-long perspective

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ABSTRACT

Diesel generators play a crucial role in providing electricity, particularly in less developed economies. As achieving Net Zero 2050 gains more traction, it is essential to address the environmental impacts and emission contributions of diesel generators. In this paper, we review the past decade of research into diesel generator emissions and discuss technologies available to mitigate their environmental effects. Starting with a description of the market importance and environmental problems caused by the release of chemicals like nitrogen oxides (NO_X), sulphur oxides (SO_X), carbon monoxide (CO), hydrocarbons (HC), and carbon dioxide (CO_2) as well as particulate matter (soot), the paper categorises and evaluates advanced mitigation systems. These systems include After-treatment Technologies, Engine Modification Technologies, and Fuel Modification Strategies. After-treatment systems such as Diesel Particulate Filters (DPF), Diesel Oxidation Catalysts (DOC), Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR) and their recent advancement are reviewed, followed by Engine Modification technologies, including Fuel Injection Strategies, Miller Cycle and In-cylinder Combustion Control. Then, we summarise the Fuel Modification Strategies and recent developments such as Blending Biodiesel and Diesel, Nanofuel Additives to Diesel, Metal-based Additives to Diesel and blending of Alcohol and Diesel. Furthermore, the potential for retrofitting CO_2 capture technologies to diesel generators is discussed as the topic that has received less attention compared to other areas mentioned above. CO_2 abatement methods, including absorption, adsorption, algae bio-fixation, and oxy-combustion techniques and their potential to be retrofitted for diesel generators, are also discussed. The paper concludes by reflecting on the importance that these technology developments play in the United Nations Sustainable Development Goals (SDGs), specifically in promoting good health, sustainable energy, innovation, and climate action. The work aims to contribute to addressing the significant gap in the decarbonisation of diesel generators by cohesively and systematically reviewing the research topics mentioned earlier. This gap is particularly evident in the application of CO_2 abatement technologies within the context of diesel generators, and this research strives to provide a foundation for further research in this critical area to meet Net Zero targets.

1. Introduction

1.1. Brief overview of the importance of emission control in diesel engines

Research indicates that the average global temperature could rise by 1.4–4.4 °C by 2100, leading to severe environmental impacts. To combat this, 196 nations, including the UK, committed to keeping global warming below 2 °C higher than pre-industrial levels and working toward reducing the temperature increase to 1.5 °C by the year 2100 at the 2015 United Nations Climate Change Conference (COP21) in Paris (Babamohammadi et al., 2023; Davies et al., 2024). By enacting the Net Zero Emission Law in 2019, the UK has set goals to achieve net-zero Carbon Dioxide (CO_2) emissions by 2050 to comply with this binding agreement (Masoudi Soltani et al., 2021), a target that since has been adopted by many other countries. Hence, significant reductions in CO_2 emissions from the power sectors are required to reach this target. Carbon capture can be done using different technologies, such as post-combustion, pre-combustion, direct air capture and oxy-combustion. In each of these technologies, different methods can be deployed, namely, absorption using solvent, adsorption using sorbent (solid materials), membrane, cryogenic, calcium and chemical looping (Borhani et al., 2024; Zhang et al., 2018).

A diesel generator is a device to generate electricity in many parts of the world, especially in developing countries. Many rural and remote areas rely on diesel generators for their electricity. The 2022 global market size for diesel generators reached USD 17.10 billion and is projected

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Nomenclature

Chemicals

DMEA	Dimethylethanolamine
NO_X	Nitrogen Oxides
SO_X	Sulphur Oxides
SO_2	Sulphur Dioxide
SO_3	Sulphur Trioxide
CO	Carbon Monoxide
HC	Hydrocarbons
MEA	Monoethanolamine
MDEA	Methyldiethanolamine
PZ	Piperazine
ZnO	Zinc Oxide

Abbreviations

BDC	Bottom Dead Centre
BET	Brunauer-Emmett-Teller Test
BioCCS/BECCS	Bioenergy with Carbon Capture and Storage
BTE	Brake Thermal Efficiency
BSFC	Brake-Specific Fuel Consumption
CAC	Conventional Air Combustion
CAGR	Compound Annual Growth Rate
CCD	Carbon Capture Device
CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CMO	Camphor Oil
COPD	Chronic Obstructive Pulmonary Disease
CRDI	Common Rail Direct Injection
CVRAS	Clean Vehicle Retrofit Accreditation Scheme
DDI	Diesel Direct Injection
DEF	Diesel Exhaust Fluid
DFE	Dual Fuel Engine
DPF	Diesel Particulate Filters
DOC	Diesel Oxidation Catalysts
EC	Elemental Carbon
EIVC	Early Intake Valve Closure
EGT	Exhaust Gas Temperature
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
GDI	Gasoline Direct Injection
HCCI	Homogeneous Charge Compression Ignition
HEI	Health Effects Institute
HPCR	High-Pressure Common Rail
ICRC	Internal Combustion Rankine Cycles
IEA	International Energy Agency
IMEP	Indicated Mean Effective Pressure
IMO	International Maritime Organisation
ISFC	Indicated Specific Fuel Consumption
IVC	Intake Valve Closure
LCA	Life Cycle Assessment
LIVC	Late Intake Valve Closure
LHR	Low Heat Rejection
LNT	Lean Nox Traps
LPO	Lemon Peel Oil
MFC	Microbial Fuel Cells
OBD	Onboard Diagnostic
OCC	Onboard Carbon Capture
OFC	Oxy-Fuel Combustion
PAHs	Polycyclic Aromatic Hydrocarbons
PBAU	Packed Bed Adsorption Unit
PBR	Photobioreactor
PFI	Port Fuel Injection
PM	Particulate Matter
PMFC	Photosynthetic Microbial Fuel Cells
PSA	Pressure Swing Adsorption
PSO	Particle Swarm Optimisation
RCCI	Reactivity Controlled Compression Ignition
RPB	Rotating Packed Bed
SCR	Selective Catalytic Reduction
SDG	Sustainable Development Goals
SEM	Scanning Electron Microscopy
SOI	Start of Injection
TEA	Technoeconomic Analyses
TSA	Temperature Swing Adsorption
VVA	Variable Valve Actuation
VCR	Variable Compression Ratio
XRD	X-Ray Diffraction

to witness a compound annual growth rate (CAGR) of 9.4% from 2023 to 2032 (Fig. 1).

The surge in global energy demand, driven by factors like ongoing population growth, infrastructure expansion, and rapid industrialisation in emerging economies, surpasses the available supply. Diesel generators, favoured for their low operating costs and superior fuel efficiency, are particularly popular in developing regions, notably the Asia Pacific. Despite their advantages, these generators face drawbacks, including noise pollution and the emission of hazardous gases (Grand View Research, 2024). It is estimated that there are around 82.6 million diesel generators in operation worldwide (Wonder, 2021). It's worth noting that this number is based on estimation, and disagreement exists among different references about the accurate number of diesel generators in the world.

1.2. Statement of the problem and the need for effective emission control technologies

Diesel engines, known for their high efficiency and low operating cost, are widely used in heavy-duty vehicles. However, their emissions contribute significantly to environmental pollution and pose health risks. In recent years, global efforts have focused on mitigating the negative effects of diesel engine emissions on human health and the environment. Considerable amounts of CO_2 and other harmful gases such as nitrogen oxide (NO_X), sulphur oxide (SO_X), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) are emitted by diesel generators (Jakhrani et al., 2012).

Emissions from diesel engines and diesel generators have several impacts on human health. Diesel engines emit CO, which impairs oxygen transport in the blood and leads to cardiovascular problems. Unburned hydrocarbons and fine particulates from diesel exhaust can penetrate deep into the lungs, causing respiratory diseases and exacerbating existing conditions. NO_X emissions contribute to smog formation and respiratory issues. Diesel emissions are associated with lung cancer, cardiovascular diseases, and premature mortality (Resitoglu et al., 2014; Wu et al., 2023). For such reasons, governments worldwide have imposed strict emission standards on diesel engines.

The CO_2 emission from a diesel generator depends on its fuel consumption. The analysis indicates that a diesel generator with a rated power of 2 kW and 5 kW will use 934.4 and 1485.5 L of diesel oil annually, respectively, while emitting 2800.0 and 4456.6 kg CO_2 per year. This is based on a load demand of 1.05 kW/hour (6.3 kW/day) (Jakhrani et al., 2012).

Diesel engines and generators contribute notably to global greenhouse gas emissions and air pollutants, such as NO_X, SO_X, CO, PM, and CO_2. These emissions worsen climate change and present serious health risks, including respiratory and cardiovascular problems. Despite advancements in emission mitigation technologies for diesel generators,

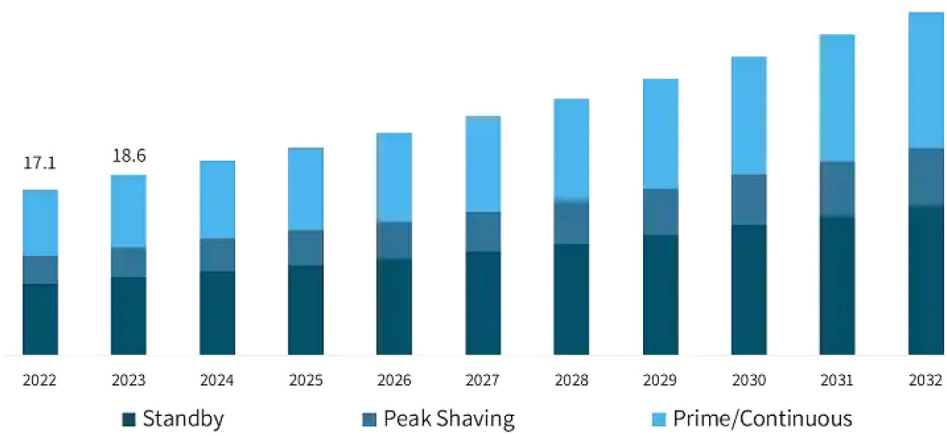


Fig. 1. Asia Pacific diesel generator market size (USD billion) (Global Market Insights, 2024).

significant research gaps remain, particularly in the integration of CO_2 capture systems. While after-treatment technologies and engine modifications address conventional pollutants, the challenge of reducing CO_2 emissions - a major contributor to global warming - has not been adequately explored in the context of diesel generators. The need for effective and scalable carbon capture solutions tailored to diesel engines is critical, given their widespread use in remote and industrial settings where renewable energy alternatives are not always feasible.

This is "why" authors in this review article aim to provide a comprehensive overview of emission mitigation technologies and CO_2 capture for diesel generators. This review aims to address this gap by systematically analysing existing emission control strategies and emphasising the potential for retrofitting CO_2 capture technologies in diesel generators. By identifying technical and practical barriers, this work provides a foundation for future research and innovation in achieving Net Zero targets for diesel-powered systems.

1.3. Motivation and roadmap of study

This study reviews various methods and technologies used to enhance the performance of diesel engines, with a particular focus on reducing pollutant emissions. To the best of our knowledge, no previous review paper has comprehensively addressed the removal of pollutants, including CO_2, from diesel engines. The introduction highlights the significance of diesel generators and the critical importance of mitigating pollutants in their exhaust gases. For instance, diesel engine generators often face challenges during cold starts or low-load operations, conditions under which incomplete combustion occurs more frequently. This results in increased emissions of polycyclic aromatic hydrocarbons (PAHs), a class of harmful hydrocarbons formed due to incomplete combustion. PAHs are not only toxic and carcinogenic but also contribute to secondary air pollution, such as smog formation, as discussed in Section 2.5. Additionally, prolonged low-load operation can lead to a condition known as 'wet stacking,' where unburned fuel and soot accumulate in the exhaust system. Wet stacking reduces engine efficiency, leads to higher emissions, and can cause long-term damage to the engine (Yilmaz and Donaldson, 2005).

Following this, the study examines the range of pollutants produced by diesel engines. It then explores technologies aimed at reducing emissions of NO_X, SO_X, CO, and particulate matter, including "After-treatment" technologies and strategies for fuel and engine modifications to lower these pollutants. After-treatment technologies tackle pollutants post-combustion, directly reducing the harmful components of exhaust gases. For instance, Selective Catalytic Reduction (SCR) converts NO_X into harmless nitrogen and water using a urea-based reductant, achieving up to 90% NO_X reduction. This is essential for meeting stringent emission standards like Euro 6. Another example is the Diesel Particulate Filter (DPF), which captures particulate matter, reducing PM emissions by over 90%. This is particularly crucial in urban areas with high population density. Fuel Modification Strategies such as Biodiesel Blends and Nanofuel Additives enhance combustion efficiency and reduce pollutant formation. Biodiesel, for instance, lowers CO and PM emissions due to its higher oxygen content compared to traditional diesel. Engine modification strategies focus on optimising the combustion process to lower peak temperatures, reducing NO_X formation. For example, the Miller Cycle adjusts valve timing to increase thermal efficiency while limiting NO_X emissions.

Furthermore, the review discusses various technologies for capturing CO_2 emissions from diesel generators and engines, covering post-combustion methods such as adsorption, absorption, and biological techniques, as well as oxy-combustion technologies. Post-combustion methods like absorption and adsorption, along with oxy-combustion techniques, enable the capture of CO_2 directly from exhaust gases. These technologies provide a pathway to achieving net-zero targets, particularly in industrial and maritime applications. Despite the advancements in emission control and CO_2 capture technologies, significant challenges remain, such as (a) Integration Feasibility: Retrofitting existing diesel generators with advanced systems can be cost-intensive and technically complex. (b) Efficiency Trade-Offs: Technologies like SCR and DPF may increase fuel consumption or operational costs. (c) Research Gaps in CO_2 Capture: Limited application of carbon capture technologies specifically tailored for diesel engines. Most studies focus on large-scale power plants or maritime engines.

Section 5 of the study evaluates the integration of these emission control and CO_2 capture technologies with Sustainable Development Goals (SDGs). Specifically, it examines how advancements in diesel engine emission control contribute to achieving SDG 3 (Good Health and Well-being) by mitigating the health impacts of harmful emissions like particulate matter PM and NO_X. It also addresses how these technologies align with SDG 7 (Affordable and Clean Energy) by supporting cleaner and more efficient diesel energy systems, particularly in remote and developing regions where diesel generators remain essential for energy access. The discussion extends to SDG 9 (Industry, Innovation, and Infrastructure), showcasing how innovations such as advanced catalytic materials foster sustainable industrial practices and create opportunities for green technology industries. In relation to SDG 11 (Sustainable Cities and Communities), the study highlights successful case studies of urban diesel emission reduction programs and their impact on air quality and public health in densely populated areas. For SDG 13 (Climate Action), the study emphasises the role of CO_2 capture technologies, alternative fuels like biodiesel and hydrogen, and hybrid systems in reducing greenhouse gas emissions, particularly from sectors heavily reliant on diesel engines, such as transportation and maritime industries. Finally, it reflects on SDG 17 (Partnerships for the Goals) by stressing the importance of global collaborations among academia, industry, and policymakers to develop and implement these emission control technologies at scale.

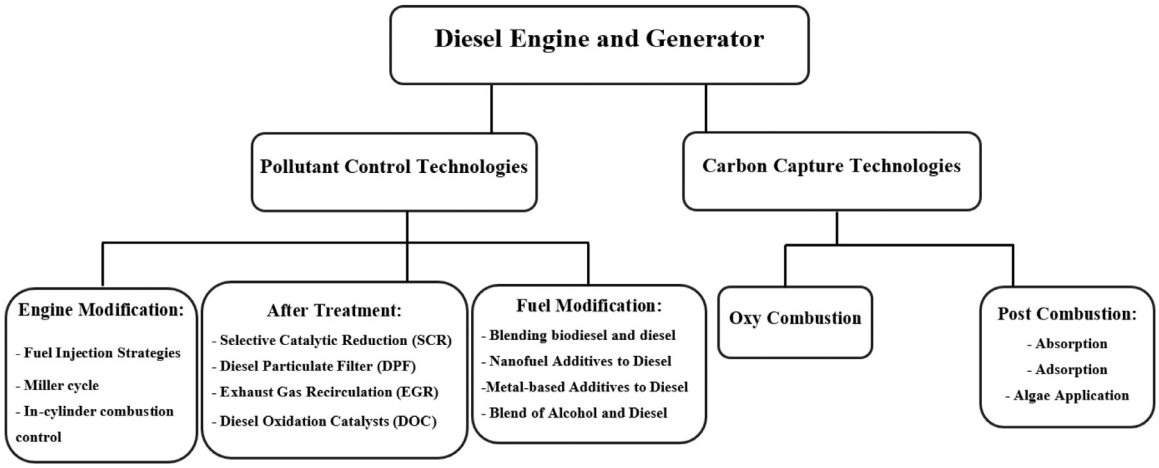
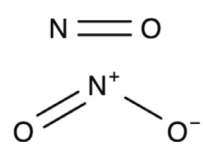
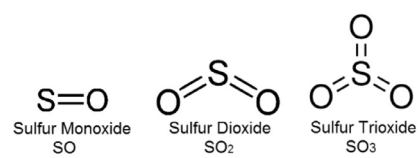
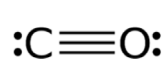
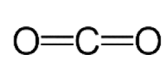


Fig. 2. Overview of pollutant control and carbon capture technologies used for diesel generators and engines.

Table 1
Typical emission values from an under 100 kW diesel generator.

Pollutant	Emission Range (g/kWh)	Description	Chemical Structure
PM	0.1 - 1.0	Including soot and fine particles, which harm health and the environment.	A mixture of many chemical species
NO_X	4 – 12	Contributing to smog, acid rain, and respiratory issues.	
SO_X	0.8 – 2.5	Contributing to acid rain, air pollution, soil degradation, and biodiversity loss.	 Sulfur Monoxide SO; Sulfur Dioxide SO_2; Sulfur Trioxide SO_3
CO	0.5 – 5	Toxic gas. It is harmful in small amounts.	
HC	0.1 – 1	Contributing to ground-level ozone formation (smog), some can be carcinogenic.	A mixture of hydrocarbons, formaldehyde and alkenes
CO_2	500 – 900	Greenhouse gas contributes to climate change.	

This integrated analysis provides a comprehensive framework for understanding the multifaceted benefits of advanced diesel emission control technologies and their alignment with global sustainability targets.

It concludes with recommendations for future research directions and policy measures to enhance the adoption and effectiveness of these technologies, ensuring their contribution to a more sustainable future. The overview of technologies reviewed and discussed in this study is presented in Fig. 2.

2. Overview of diesel generator emissions

As a result of diesel combustion, in addition to nitrogen and water, which are not harmful to the environment, several chemicals are generated and emitted to the atmosphere, such as CO, CO_2, NO_X, SO_X, PM and HC (Table 1). All these chemicals will be discussed in the following sub-sections. The general incomplete combustion happens as follows (R1):

$$C_{12}H_{26}\left(\text{or } C_{13}H_{28}\right) + O_2 \rightarrow CO_2 + H_2O + CO + NO_x + SO_x + HC + PM \quad \text{(R1)}$$

Table 1 represents the typical values for emissions from unregulated small diesel generators under 100 kW. Due to environmental controls, regulated generators usually emit much lower levels.

2.1. Particulate material

Diesel soot formation is of particular interest to environmental and health effects. Soot, or elemental carbon (EC), is a heterogeneous carbonaceous substance arising from the incomplete burning of organic matter in different forms (Moore et al., 2014). It forms a large part of tropospheric fine particulate matter and is notorious for its climate impacts (Xue et al., 2009). Soot particles are clusters of primary particles, and their characteristics, including mass-specific absorption coefficient and mass-mobility relationship, have attracted a lot of interest from optical and mass-based measurements (Cross et al., 2010). The primary components of diesel exhaust particles are ash and highly agglomerated solid carbonaceous material, together with sulphur and volatile organic chemicals (Kittelson, 1998). Fig. 3 illustrates the general structure of diesel exhaust particles. On the other hand, soot represents a composite material of thermally defined elemental carbon and organic carbon, as well as optically defined black carbon (Moore et al., 2014). Depending

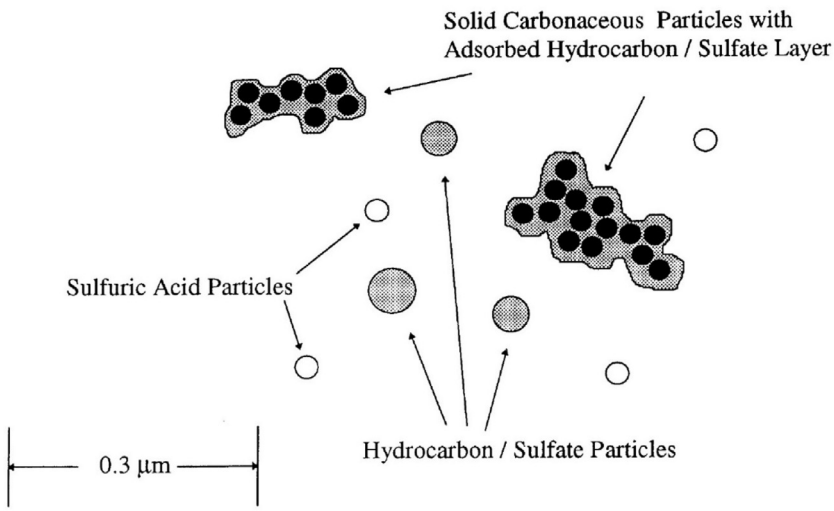


Fig. 3. Typical structure and composition of diesel exhaust particles (Kittelson, 1998).

on the specific conditions of combustion, soot may exhibit heterogeneous pore morphology and surface characteristics in addition to differing amounts of extractable organic compounds (Nguyen and Ball, 2006). Soot formation and evolution are complicated processes with numerous physical/chemical processes that take place, leading to important soot properties (e.g., surface functional groups, degree of graphitisation) which depend on the soot history and combustion conditions during its formation (Liu et al., 2017). Soot particles have been found to exhibit well-defined photoluminescence properties and behave as indirect band-gap materials due to their graphite structure (Sabbar et al., 2019). In addition, comprehensive modelling studies have been performed to gain insights on soot formation (inception, mass growth, and particle coagulation) (Xu et al., 2018). The soot particle was also investigated for its environmental influence, such as the mechanism of ice crystal nucleation and the impact on the atmospheric radiation budget (Panetta et al., 2016). A soot surface example seen in the atmosphere at different heights and locations has been highlighted based on their significant roles in promoting ice growth, as well as/or contributing to combustion aerosol properties (Longfellow et al., 1999).

In diesel engines, several factors such as combustion conditions, fuel properties, and engine design impact soot formation (Meloni and Palma, 2020). The microscopic characteristics of soot emissions from diesel engines have been extensively studied, highlighting the importance of understanding the composition and structure of soot particles (Likhanov and Anfilatov, 2020). The oxidation properties of soot in gasoline direct-injection (GDI) engines have been investigated, demonstrating variations in ash level and oxidation reactivity relative to typical diesel soot (Michelsen, 2017). Additionally, research has examined how fuel film affects soot generation in GDI engines, emphasising the variations in particulate matter between diesel and petrol engines (Ålander et al., 2004). Much research work focuses on the effects of fuel properties, such as sulphur content, with respect to soot formation in diesel engines, emphasising complex interactions between fuel composition and emissions of soot (Devetyarov, 2020). Mechanisms and numerical models have been developed to predict soot production and behaviour in diesel engines based on the studies carried out on soot formation and oxidation (Liang et al., 2021). The effect of in-cylinder flow structures on late-cycle soot oxidation in heavy-duty diesel engines has been studied, providing insight into the function of engine design in soot emissions. (Devetyarov, 2020). The soot propensity of petrol surrogates has also been evaluated to understand soot generation mechanisms and construct reliable models for simulating real fuel chemistry in petrol engine computational fluid dynamics simulations (Hua et al., 2018). In general, soot formation in diesel engines depends on modified factors such as engine design, combustion conditions, and fuel mix. Insights into the composition, structure, and behaviour of soot particulate matter emissions have been gained from research on soot formation and oxidation in diesel engines. This has helped to develop strategies and predictive models for reducing the environmental impact of soot emissions from diesel engines.

2.2. Nitrogen oxides

NO_X, or nitrogen oxides, are harmful pollutants that can negatively affect human health and the environment. When released into the atmosphere, NO_X can contribute to the formation of smog and acid rain. This can lead to respiratory problems in humans and damage to plant life, water bodies, and ecosystems (Cretescu et al., 2019). NO_X primarily consists of NO and NO_2, both of which are produced during high-temperature combustion processes. NO is a colourless gas that readily oxidises to form NO_2, a reddish-brown gas responsible for the characteristic colour of polluted air. The environmental impact of NO_X includes its role in forming ground-level ozone and fine particulate matter, which have adverse effects on respiratory health and contribute to environmental degradation.

The major sources of NO_X emissions include industrial activities such as metal smelting, combustion processes, and diesel engines. Diesel engines, particularly in heavy-duty applications like marine, highway use, and construction equipment, are major contributors to NO_X emissions globally. Forty per cent of the total PM and NO_X emissions globally are attributed to heavy-duty diesel engines in highway use, as reported by Wardana et al. (2020). In the UK, for example, NO_X emissions fell 78% from 1970 to 2022, reaching 643 thousand tonnes. The main factors driving this development were upgrading the road transport fleet and the decrease in coal consumption by power units. There was a 4% drop in NO_X emissions from 2021 to 2022 (See Fig. 4) (Department for Environment, 2024).

Satellite data has revealed a distinct weekly cycle in NO_x emissions, with reduced levels observed during weekends and rest days, indicating the significant impact of anthropogenic activities on these emissions (Stavrakou et al., 2020). NO_X emissions from diesel generators and engines are a significant concern due to their adverse environmental and health impacts. Studies have shown that NO_X emissions tend to increase with higher combustion temperatures, making diesel engines a notable source of NO_X due to their high combustion temperatures (Gopidesi and Premkartikkumar, 2018). The combustion characteristics of diesel engines, especially in terms of temperature and fuel types, play a crucial role in determining the amount of NO_X emitted (Modi and Patel, 2023).

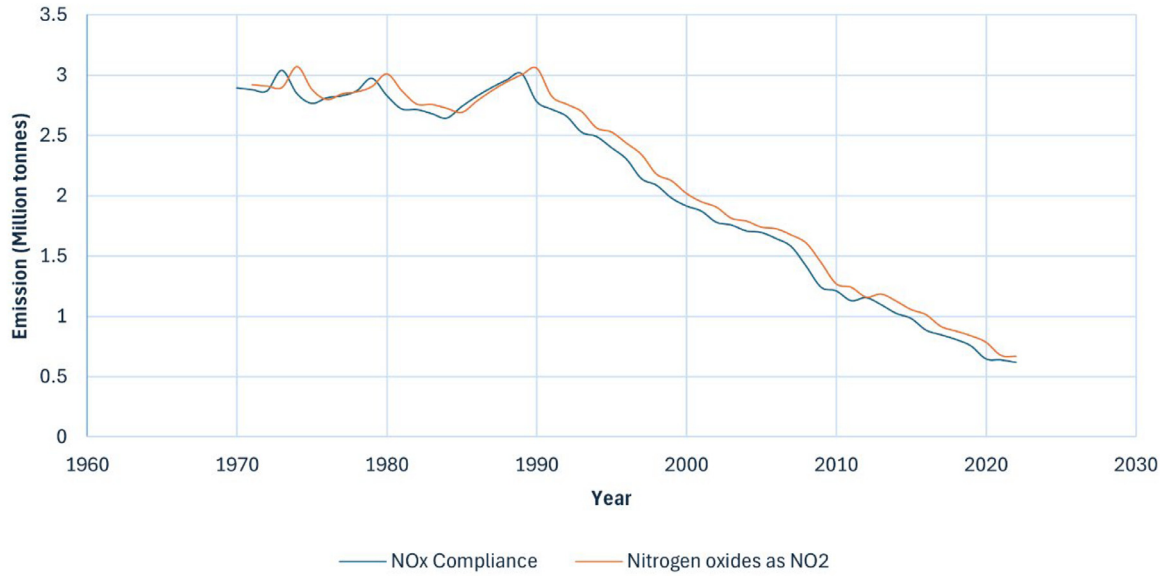


Fig. 4. Annual emissions of nitrogen oxides in the UK: 1970 – 2022 (Department for Environment, 2024).

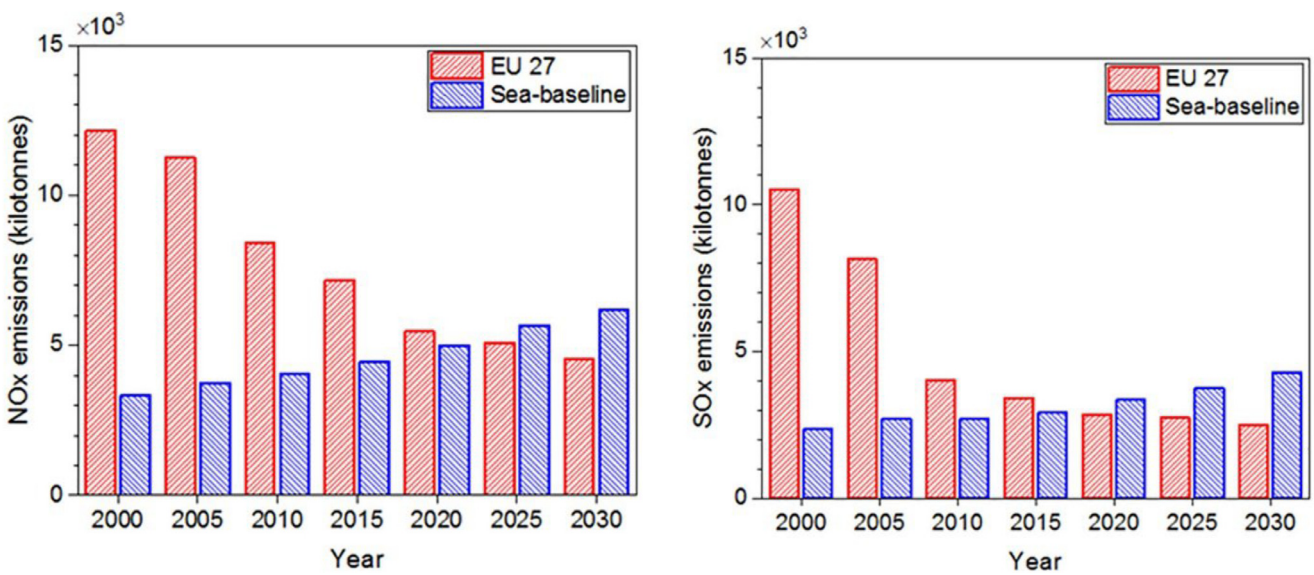


Fig. 5. Emissions trend of NO_X and SO_X in the 2000–2030 period (EU 27: land transportation emission according to a survey of 27 European countries. Sea-baseline: Marine emission) (Kamil et al., 2020).

2.3. Sulphur oxide

Burning fuels that include sulphur releases SO_X, another significant air pollutant, primarily in the form of sulphur dioxide (SO_2) and sulphur trioxide (SO_3), which are released into the atmosphere or flue gas at an average concentration of 10 mg/m^3 (Elsaid et al., 2021). Currently, marine diesel engines are the main SO_X emitters, while there were significant reductions in land transportation. As shown in Fig. 5, there is a 40% rise in NO_X and SO_2 emissions from ships between 2000 and 2020. NO_X emissions from ships are projected to rise 35% by 2030, while SO_2 emissions are forecast to rise 32% over the same period. On the other hand, tighter rules have led to a steady decline in NO_x and SO_2 emissions from vehicles. There will likely be a considerable decrease in maritime areas because of the new, more stringent rules (Deng et al., 2021).

Sulphur in the fuel can react with hydrogen and oxygen to form H_2S and SO_2. Further, available oxygen in the exhaust can lead to sulphur trioxide formation. SO_2 and SO_3 in the atmosphere are highly toxic, as they can react with water vapour in the atmosphere to form sulfuric acid. These acid substances again reach the surface of the Earth in the form of acid rain. Apart from this effect, SO_X in the atmosphere reacts with other substances to form solid particles. These solid particles further reduce visibility during fog. Higher concentrations of SO_X in the atmosphere damage plant growth and trees. Regarding the health effects of SO_X emissions, even exposure to SO_X in minor concentrations can affect the respiratory system, particularly in children and those with a poor respiratory background (Ashok et al., 2022).

2.4. Carbon monoxide

CO is a poisonous gas that has no discernible aroma, colour, taste, or irritant properties. It results from the partial oxidation of organic compounds during incomplete combustion in the absence of enough oxygen to create CO_2 (Bierhals, 2001). Exposure to CO has substantial dangers. Carboxyhaemoglobin (COHb) is a product of CO binding to haemoglobin in the blood. Tissue hypoxia and perhaps death result from this binding since it lowers the blood's oxygen-carrying capacity. Especially in organs

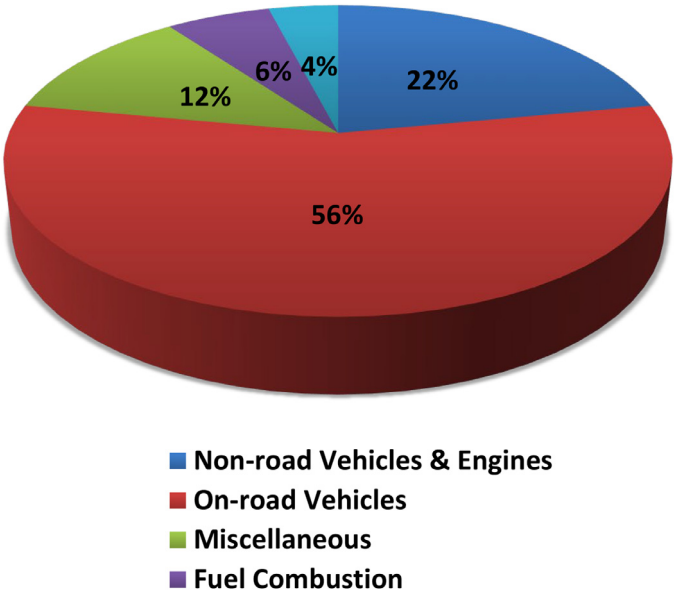


Fig. 6. Source of CO emission (Lee, 2011).

Table 2
Molecular mass and number of aromatic rings of main PAHs in diesel exhaust gas.

Component	Molecular Mass	Number of Aromatic Rings
Naphthalene - NAP	128	2
Phenanthrene - PHE	178	3
Pyrene - PYR	202	4
Fluorene - FLU	166	2
Acenaphthylene - ACY	152	2
Fluoranthene - FLT	202	3
Acenaphthene - ACE	154	2

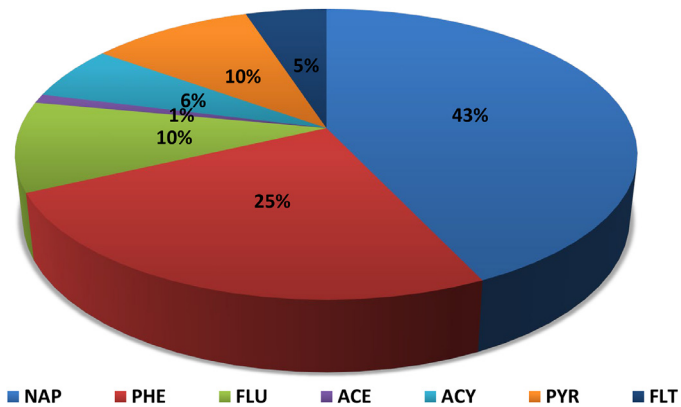


Fig. 7. PAH distribution in diesel exhaust (De Souza & Corrêa, 2016).

that are constantly working, like the heart and brain, this lack of oxygen may cause cell death or injury. There may be long-term brain abnormalities and problems due to the neurotoxic effects of CO, which may last for a long time after the first exposure (Wen et al., 2024). Headaches, vertigo, weakness, nausea, confusion, and even death in extreme instances can result from inhaling high concentrations (400 ppm or more) of CO gas in a short amount of time, typically within a few hours, depending on the individual's sensitivity and health status (Raub et al., 2000; Soria et al., 2008). The cardiovascular and central neurological systems may be affected by even low amounts of CO (50 to 300 ppm) when exposed to it for an extended period (Es et al., 2017; Soria et al., 2008). As a result, lowering CO emissions is essential for lowering the dangers to human health.

Along with other pollutants, including SO_X, NO_X, and PM, diesel engines are known to generate CO. Diesel engines, especially in heavily populated cities, are a major source of carbon monoxide emissions according to the US Environmental Protection Agency (EPA) (EPA, 2021). The primary source of CO is motor vehicle exhaust, including both on-road and off-road vehicles, which account for 85% of all CO emission sources. Fig. 6 illustrates the distribution of CO emissions by different sources (Lee, 2011).

Factors such as the combustion process and fuel mix may affect the quantity of CO that diesel engines emit (Zhang et al., 2021). Research has shown that, particularly when engine loads are greater, diesel usage might result in elevated CO emissions (Sutheerasak et al., 2018). Existing studies suggest that diesel engine CO emission rates may vary depending on engine type, operating circumstances, and fuel mix. For example, according to studies conducted by Mansor et al. (2018) compared to newer engines with better emissions controls, older diesel engines often release more carbon monoxide. In addition, research shows that diesel engines' CO emissions are increased during cold-start periods and while the engine is idling (Reiter and Kockelman, 2016). Diesel engines normally emit CO emissions between 100 and 500 ppm in exhaust gases, or 0.1 to 0.5 g/kWh of energy produced, depending on the operating circumstances and diesel fuel type (Jamali et al., 2019). Under typical operating settings, diesel engines have been shown to release CO amounts between 200 and 300 ppm. However, under certain conditions, the concentration of CO in the exhaust may increase as happens during idling or low-load situations (Sureshbabu and Ashokavarthanan, 2022). Also, it is worth noting that the engine speed affects CO emissions. Combustion is often more complete at higher engine speeds, leading to reduced CO emissions. As an example, CO emissions are normally reduced at speeds ranging from 2500 to 3500 rpm as compared to idle or low-speed operations (Ismail et al., 2018).

2.5. Hydrocarbons

The hydrocarbons (HC) emitted from diesel engines include unburned fuel, aldehydes, and polycyclic aromatic hydrocarbons (PAHs), which are of particular concern due to their potential health and environmental impacts. Formation of these hydrocarbons occurs through incomplete combustion processes, which can be exacerbated by factors such as fuel quality, engine design, and operating conditions (Sureshbabu and Ashokavarthanan, 2022). The emission of hydrocarbons from diesel engines is a critical issue because these compounds can contribute to the formation of ground-level ozone and smog, which pose significant health risks, including respiratory problems and cardiovascular diseases (Sureshbabu et al., 2023). Moreover, certain hydrocarbons, particularly PAHs, are known carcinogens, raising concerns about long-term exposure for populations living near high-traffic areas or industrial sites (Sureshbabu et al., 2023). The presence of these hydrocarbons in the atmosphere can also lead to the deposition of harmful substances in ecosystems, affecting both terrestrial and aquatic life (Shirneshan, 2014). PAHs are well-recognised for their possible mutagenic and carcinogenic properties. Table 2 presents the molecular mass and number of aromatic rings of the main PAHs in diesel exhaust gas (De Souza and Corrêa, 2016). Fig. 7 demonstrates the PAH distribution in diesel exhaust, as suggested by Souza et al. (De Souza and Corrêa, 2016) The study indicates that the collected results did not allow to determine the fractional contribution of petrogenic and pyrogenic PAHs.

One of the primary factors influencing hydrocarbon formation is the "fuel injection system." The timing, pressure, and fuel injection pattern are critical in determining how well the fuel mixes with air in the combustion chamber. A well-designed fuel injection system can enhance atomisation and promote better mixing, leading to more complete combustion and lower HC emissions. Conversely, poor injection timing or inadequate fuel atomisation can result in unburned fuel and increased

HC emissions (Nghia and Tuan, 2024). For instance, variations in injection pressure can significantly affect the spray characteristics and, consequently, the combustion efficiency (Park et al., 2010). Another significant factor is the "combustion chamber geometry." Flow dynamics and mixing of air and fuel are very depended on the shape and design of the combustion chamber. A combustion chamber that promotes effective swirl and turbulence can improve the mixing process, leading to more complete combustion and less HC emissions (Yan et al., 2020). Research has shown that well-designed and optimised combustion chamber geometry improves combustion and, therefore, can significantly reduce HC emissions (Zhang et al., 2011).

"Engine operating conditions" are also one of the most critical aspects in the formation of hydrocarbons. Parameters such as the load of an engine, its speed, and temperature can influence the combustion. For instance, at high loads, the engine might be unable to burn all the hydrocarbons in the required time and thus will exhaust more HC at the outlet (Venkatesan et al., 2023). Furthermore, cold start conditions may initially cause more HC emissions since the fuel is not entirely burned out during the warming up of the engine (Mendoza-Villafuerte et al., 2017). The temperature of the combustion chamber is one of the most crucial factors because a low temperature may cause incomplete combustion and, consequently, a higher amount of HC emissions (Wu et al., 2014).

Another critical factor in the formation of HC is the "fuel properties." Cetane number, viscosity, and volatility are examples of "fuel properties" that are important in forming HC. Higher cetane numbers in fuels improve combustion and, as a result, lower HC formation in engines (Venkatesan et al., 2023). Alternative fuel or the presence of additives in regular fuels can also reduce HC emissions. For example, biodiesel has been shown to reduce HC emissions compared to conventional diesel fuel, although the specific effects can vary depending on the blend and engine conditions (Mamilla et al., 2015).

2.6. Carbon dioxide

In addition to all these pollutants a diesel engine generates, CO_2 is also emitted. By considering the number of diesel engines around the world, this emission is significant, and it is required to consider solutions to mitigate this greenhouse gas. About 40 billion tons of CO_2 is emitted into the atmosphere every year, which is the main greenhouse responsible for global warming (Borhani et al., 2024). Section 4 is allocated to technologies to control CO_2 emissions.

3. Technologies for controlling diesel emissions

Several technologies and strategies have been developed to reduce and control emissions from diesel engines and generators effectively, each addressing various aspects of the combustion process and exhaust treatment. There are three major techniques for controlling emissions from diesel engines, which can be divided into three main categories: the first category includes after-treatment techniques, which involve the installation of systems to capture and convert harmful pollutants after combustion. The second encompasses fuel modification techniques, which aim to alter the chemical composition of the fuel to enhance combustion efficiency and reduce the formation of pollutants. The third involves engine structural modifications, which focus on redesigning engine components, such as optimising combustion chambers and improving injection systems, to promote cleaner and more efficient combustion processes. To reach near-zero emissions of these pollutants, it is necessary to apply each of these methods based on the conditions, application and feasibility.

3.1. After-treatment technologies

After-treatment technologies for diesel engines play a crucial role in reducing the harmful pollutants emitted by these engines. The term "after-treatment" refers to technologies or processes that are applied after combustion has occurred in a diesel engine. These technologies are designed to meet stringent emission standards and regulations governments set to protect the environment and public health. One major challenge diesel engines face is the production of CO, NO_X, and PM emissions. Until today, various after-treatment technologies have been developed to address these challenges, which are reviewed in the following subsections.

3.1.1. Selective catalytic reduction

One of the key technologies used for reducing NO_X emissions is selective catalytic reduction (SCR). Selective catalytic reduction is a technology that uses a catalyst, typically consisting of metal oxides, to convert nitrogen oxides into nitrogen and water vapour. This process involves injecting a urea-based solution, known as diesel exhaust fluid (DEF), into the exhaust stream. When the diesel exhaust fluid encounters the catalyst, it undergoes a chemical reaction that breaks down the nitrogen oxides into harmless components (see Fig. 8).

SCR systems utilise a catalyst and a reductant, typically NH_3 or urea, to convert NO_X into nitrogen and water. Recent studies indicate that SCR can achieve NO_X reductions of up to 90% when properly calibrated and integrated into the engine system (Chen et al., 2023).

The fundamental mechanism of SCR involves the injection of a reductant into the exhaust stream, where it reacts with NO_X over a catalyst. The most common catalysts in SCR systems include vanadium oxide (V_2O_5), tungsten oxide (WO_3), and metal-exchanged zeolites, particularly those containing copper (Cu) or iron (Fe) (Rauch et al., 2017). The reaction typically occurs in two main steps: the oxidation of NO to NO_2 and the subsequent reduction of NO_X by NH_3. The reactions can represent this process are summarised in Table 3.

These reactions highlight the efficiency of SCR in converting harmful pollutants into benign substances, thereby significantly reducing the environmental impact of combustion processes. The urea solution, often referred to as AdBlue, is injected into the exhaust gases before they enter the SCR catalyst. Precise control of urea injection is critical; improper dosing can lead to insufficient NO_X reduction or excessive ammonia slip, which can cause secondary pollution (Zhao et al., 2022). Research has shown that a model-based control strategy for urea injection can significantly enhance the efficiency of the SCR system, ensuring that the reductant is delivered in the correct quantity and at the right time to maximise NO_X conversion (Zhao et al., 2022).

The effectiveness of SCR systems in real-world applications has been demonstrated through numerous studies. For instance, evaluations of retrofitted buses equipped with SCR systems have shown significant reductions in NO_X emissions, achieving compliance with Euro 6 standards (Smit et al., 2019). Additionally, experimental studies on diesel engines using SCR technology have confirmed its capability to reduce NO_X emissions by over 90% under optimal conditions (Zhao et al., 2019). This level of efficiency is particularly important as it allows heavy-duty vehicles to meet increasingly stringent emissions regulations enforced across many regions (He et al., 2017).

SCR technology is not limited to automotive applications; it is also widely used in stationary sources, such as power plants and industrial facilities, where it helps to control NO_X emissions from combustion processes. In these settings, SCR systems are often integrated with other after-treatment technologies, such as diesel particulate filters (DPF), to achieve comprehensive emission control (Shan et al., 2014). The combination of SCR with DPF allows for the simultaneous reduction of particulate matter and NO_X, which is essential for meeting regulatory requirements in various industries (Thiruvengadam et al., 2015).

SCR technology has lately made great progress that increases its efficiency in lowering NO_X emissions from diesel engines. For instance, perovskite-based catalysts as alternatives to traditional vanadium-based catalysts demonstrate high activity and stability under various operating conditions, making them promising candidates for future SCR applications (Onrubia-Calvo et al., 2019). Incorporating nanomaterials,

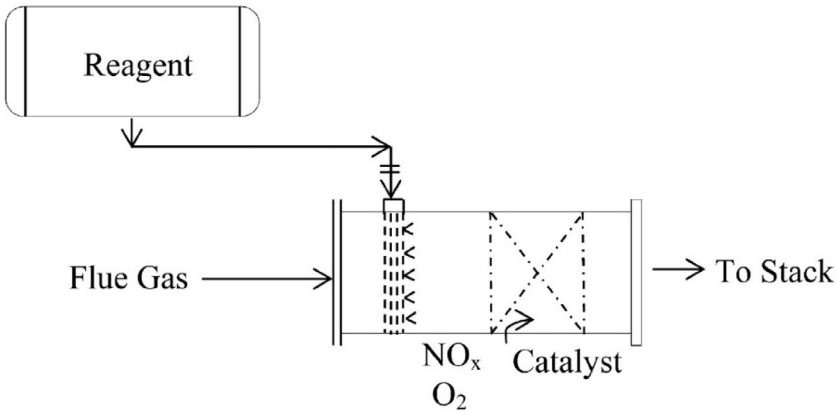


Fig. 8. The schematic diagram of a SCR (J. J. He et al., 2017).

Table 3
SCR series of reaction *via* NH_3.

Description	Reaction	No
Oxidation of Nitric Oxide (NO) to Nitrogen Dioxide (NO_2)	$2NO + O_2 \rightarrow 2NO_2$	(R2)
Reduction of Nitrogen Oxides by Ammonia when NO is reduced directly by NH_3 (Standard SCR Reaction)	$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$	(R3)
Reduction of Nitrogen Oxides by Ammonia when NO_2 is reduced directly by NH_3 (Fast SCR Reaction)	$4NH_3 + 2NO_2 + O_2 \rightarrow 3N_2 + 6H_2O$	(R4)
Reduction of Nitrogen Oxides by Ammonia when a mixture of NO and NO_2 is reduced by NH_3 (Optimal reaction mix for fast SCR)	$4NH_3 + NO + NO_2 \rightarrow 4N_2 + 6H_2O$	(R5)
Side Reactions in the presence of excess NH_3 could produce nitrogen gas and water	$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O$	(R6)
Side Reactions in the presence of excess O_2 could lead to Ammonia Oxidation	$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$	(R7)

such as $NiCO_2O_4$ nanoparticles, has shown potential in enhancing the catalytic performance of SCR systems, particularly at low temperatures (Aswin et al., 2022).

Another area of advancement is the optimisation of urea injection strategies. Research by Wardana and their team highlighted the importance of urea injector design and its impact on the uniformity of urea distribution in the exhaust stream (Wardana et al., 2020). Improved injector designs can lead to better mixing of urea with exhaust gases, enhancing the overall NO_X reduction efficiency of the SCR system. Furthermore, studies have shown that optimising the urea dosing rate can help mitigate issues such as ammonia slip, where excess ammonia escapes into the atmosphere (Mathavan et al., 2023). To address the challenges traditional SCR systems face in their performance at low exhaust temperatures, the use of non-thermal plasma-assisted SCR has been investigated to improve NO_X reduction efficiency at lower temperatures (Zhu et al., 2022). This approach can activate the SCR reaction even when exhaust temperatures are below the optimal range, making it suitable for various driving conditions.

Recent advances in computational modelling and simulation techniques have provided deeper insights into the SCR process. Kuternowski et al. (2020) utilised finite volume methods to model urea decomposition in SCR systems, allowing for better predictions of catalyst performance under various operating conditions. These models can help optimise SCR system design and operation, leading to improved emissions control.

Integrating after-treatment systems, such as DPF, DOC and SCR systems, has been emphasised to provide comprehensive solutions for reducing PM, CO, and NO_X emissions. This integrated approach not only enhances overall emission control but also improves the sustainability of diesel engines (Tan et al., 2023).

SCR systems are highly effective due to their ability to selectively target NO_X in exhaust gases, converting them into nitrogen and water through precise chemical reactions. The incorporation of urea as a reductant ensures high conversion rates, often exceeding 90%, under optimal conditions. Compared to alternatives such as Exhaust Gas Recirculation (EGR) and Lean NO_X Traps (LNT), SCR offers superior efficiency in NOx reduction, especially for high-load, high-temperature applications. While EGR reduces NO_X by recirculating exhaust gases to lower combustion temperatures, it can increase particulate matter and CO_2 emissions. LNT systems, though effective at lower temperatures, face challenges in maintaining efficiency during prolonged operation and require frequent regeneration. In contrast, SCR systems demonstrate consistent performance across a wide range of operating conditions and are compatible with other after-treatment systems like Diesel Particulate Filters (DPFs) to achieve comprehensive emission control. However, SCR systems involve higher initial costs and require careful maintenance to prevent issues like ammonia slip, making them most feasible for applications where stringent NO_X reduction is mandated. This balance of effectiveness and adaptability underscores SCR's pivotal role in modern emission control strategies.

3.1.2. Diesel particulate filter

Another technology used for reducing PM emissions from diesel engines is the diesel particulate filter (DPF) (Fig. 9). The diesel particulate filter is a device that captures and removes particulate matter, such as soot and ash, from the exhaust gases. The particulate matter is trapped in the filter and periodically burned off through a process called regeneration. During regeneration, the temperature of the exhaust gases increases, causing the trapped particles to burn and turn into ash.

DPF is one of the critical components in the emission control strategy for diesel engines. DPFs capture PM from the exhaust stream, including unburned HC. To a certain extent, DPFs trap the particles not only to decrease PM emissions but also to help lower HC emissions by prohibition of soot release that can contain hydrocarbons (Preble et al., 2019). The effectiveness of DPFs can be enhanced through various regeneration strategies, which periodically burn off the accumulated soot, thus maintaining filter efficiency (Preble et al., 2019).

DPFs operate through a process that involves a ceramic monolith that is a filter to trap the particulate matter from the exhaust gases. This particulate matter is then combusted during the regeneration cycle, thus effectively reducing PM emissions by over 90% (Papagianni et al., 2021). The integration of a catalysed DPF (c-DPF) enhances this process by utilising a catalyst to facilitate the oxidation of CO and HC alongside soot (Papadopoulou et al., 2022). This technology has been crucial in meeting stringent emission regulations, particularly in Europe, where Euro IV

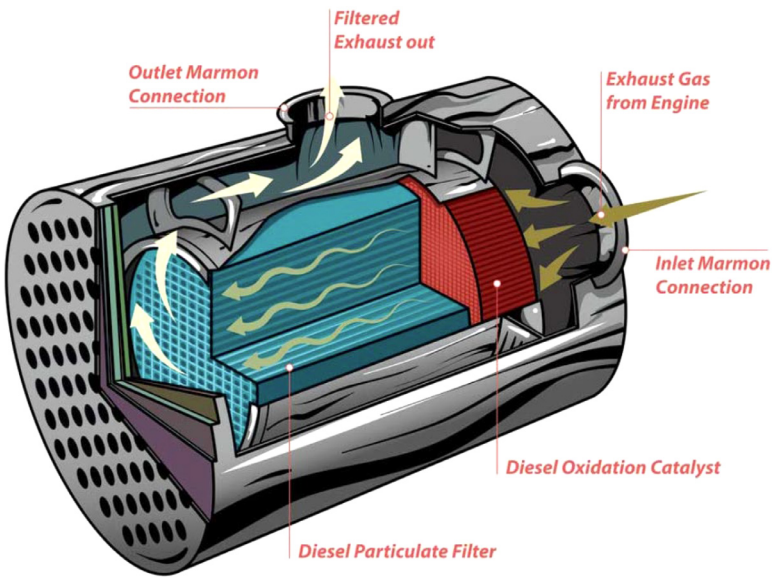


Fig. 9. A schematic figure of a DPF (DPF Fixer, 2024).

and subsequent standards mandate significant reductions in particulate emissions (Feulner et al., 2017).

Recent advances in DPF technology have focused on enhancing filtration efficiency, improving regeneration processes, and integrating diagnostic capabilities to ensure optimal performance in reducing diesel engine PM emissions. One significant advancement is the optimisation of DPF materials and structures. For instance, researchers have explored using novel catalytic coatings that enhance soot oxidation efficiency. A study demonstrated that doping catalysts with potassium ions can significantly improve soot oxidation rates within the DPF, thereby facilitating more effective regeneration and reducing the frequency of required maintenance (Li et al., 2022a). Additionally, the development of new filter designs, such as folding DPFs, has been proposed to enhance the surface area available for soot capture while minimising pressure drop, which is critical for maintaining engine performance (Guo et al., 2022).

Another area of innovation is the integration of onboard diagnostic (OBD) systems to monitor DPF performance in real time. Recent studies have focused on resistive PM sensors that can detect DPF failures and assess the filter's condition by measuring pressure differentials across the filter (Oh et al., 2022). This capability allows for proactive maintenance, ensuring that the DPF operates efficiently and reducing the risk of excessive PM emissions due to filter blockage.

Moreover, advancements in regeneration techniques have been explored to address the challenges associated with soot accumulation and ash loading in DPFs. For example, the use of reciprocating flow systems has been investigated to enhance the regeneration process by improving the distribution of exhaust gases within the filter, thereby promoting more uniform soot oxidation (Deng et al., 2019). Additionally, the implementation of advanced control algorithms, such as Kalman filters, has been proposed to optimise the regeneration cycles based on real-time soot-loading data, ensuring that the DPF operates within its optimal range (Singalandapuram Mahadevan et al., 2020).

Research has also highlighted the importance of understanding the effects of lubricant-derived ash on DPF performance. Lubricant additives can contribute to ash accumulation in the filter, which can adversely affect its filtration efficiency and lead to higher pressure drop (Zhang et al., 2021). Addressing these issues through better lubricant formulations or DPF designs that mitigate ash impact is an ongoing area of research.

3.1.3. Exhaust gas recirculation

In addition to selective catalytic reduction and diesel particulate filters, there are other emission control technologies that can be used for diesel engines, including exhaust gas recirculation (EGR). EGR is a well-established technique for reducing NO_X emissions in diesel engines. It recirculates a portion of the exhaust gases back into the combustion chamber, lowering the peak combustion temperature and, thus, NO_X formation. The concept of EGR dates to the 1970s when it was first introduced as a method to control NO_X emissions in gasoline engines. Initially, EGR systems were simple and primarily used in spark-ignition engines. Over the decades, advancements in technology and increasing environmental regulations have led to the evolution of EGR systems, particularly in diesel engines, where NO_X emissions are a significant concern. The introduction of high-pressure EGR systems in the 1990s marked a pivotal moment, allowing for more effective emissions control without requiring extensive after-treatment systems (Ladha, 2020).

EGR can be divided into two main types: Internal and External. Internal EGR utilises the natural flow of exhaust gases during the engine's operation. It occurs when the exhaust valves remain open during the intake stroke, mixing some exhaust gases with the incoming fresh air-fuel mixture. This approach is typically used in modern gasoline engines to improve thermal efficiency and reduce knock. In external EGR, exhaust gases are routed through an EGR cooler before reintroducing into the intake manifold. The cooling process reduces the temperature of the exhaust gases, further lowering the combustion temperature when mixed with fresh air. This method is commonly employed in diesel engines, where high combustion temperatures can lead to significant NO_X emissions (Chen et al., 2023b). The effectiveness of EGR is influenced by several factors, including the EGR rate (the proportion of exhaust gas recirculated), engine load, and operating conditions. Studies have shown that EGR rates between 5% and 20% can significantly reduce NO_X emissions while maintaining engine performance (Zhang et al., 2022). However, excessively high EGR rates can lead to increased soot formation and reduced engine efficiency, necessitating a careful balance in EGR system design (Ladha, 2020).

EGR is extensively employed in heavy-duty diesel engines, such as those used in trucks, buses, and industrial applications. The technology helps these engines meet stringent emissions standards while maintaining performance and fuel efficiency (Zhao et al., 2024). In spark-ignition engines, EGR is used to control NO_X emissions and improve fuel economy. The technology has been integrated into many modern gasoline engines, particularly in hybrid and fuel-efficient vehicles (Climent et al., 2022). Moreover, with increasing regulations on marine emissions, EGR systems have been adopted in marine diesel engines to reduce NO_X emissions and comply with international standards (Huang et al., 2022).

One form of EGR is the Dedicated EGR (D-EGR), which is a technology designed to improve fuel efficiency and reduce emissions in spark ignition engines. It uses a dedicated cylinder running on a fuel-rich mix-

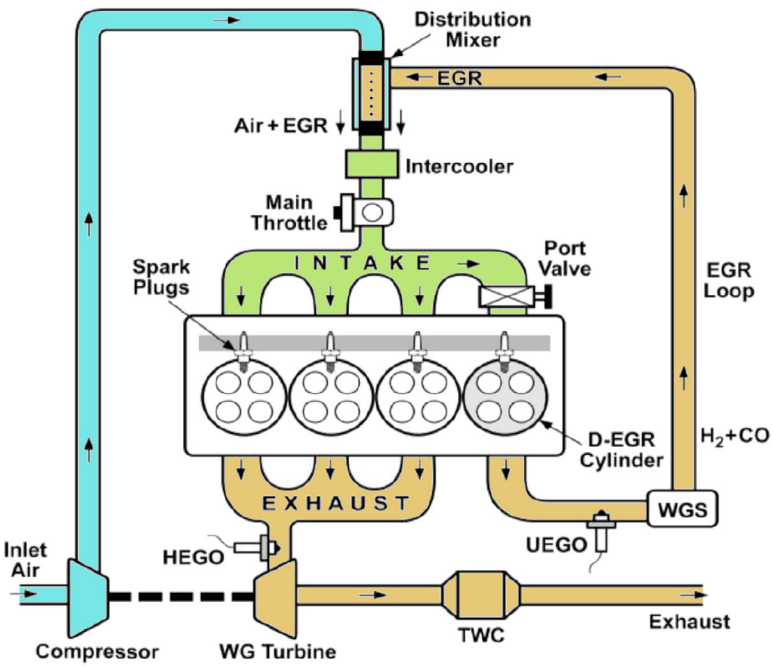


Fig. 10. A dedicated-EGR system (HEGO: heated exhaust gas oxygen sensor, UEGO: universal exhaust gas oxygen sensor, TWC: three-way catalyst, WG: waste-gate, WGS: water-gas shift catalyst (X-Engineer, 2016).

ture to produce hydrogen (H_2) and CO to be recirculated into the engine to enhance combustion stability and efficiency. This process reduces fuel consumption by up to 10% at light loads and significantly lowers HC and CO emissions while still keeping NO_X emissions low due to the high EGR rates (Fig. 10).

Recent advances in EGR technology have significantly evolved with various configurations and optimisations to improve its performance and efficiency. One notable advancement is the development of dual-loop EGR systems, which allow for more precise control over the amount of exhaust gas recirculated. This system can operate with both low-pressure and high-pressure EGR, providing flexibility in managing combustion conditions (Nyerges and Zöldy, 2023). The ability to switch between these modes enables better optimisation of engine performance and emissions under varying operational conditions.

Research has shown that integrating EGR with alternative fuels, such as biodiesel, can further enhance NOx reduction. For instance, a study indicated that using blended diesel-biodiesel fuel with varying EGR rates effectively reduced NO_X emissions while maintaining engine performance (Fayad et al., 2018; Sethin et al., 2024). Additionally, the incorporation of nano-additives, such as TiO_2, into biodiesel blends combined with high EGR rates has been shown to significantly reduce both soot and NO_X emissions in common rail direct injection (CRDI) diesel engines (Fayad et al., 2018).

The use of variable-nozzle turbochargers in conjunction with EGR systems has also emerged as a promising approach. This combination allows for improved engine thermal management and enhanced performance, particularly in heavy-duty applications. By optimising the turbocharger's operation alongside EGR, researchers have reported reductions in NO_X emissions while maintaining engine efficiency (Zhu et al., 2024).

Moreover, advancements in computational fluid dynamics modelling have facilitated a deeper understanding of EGR dynamics within engines. Studies utilising computational fluid dynamics (CFD) have explored the effects of EGR on combustion characteristics and emissions, enabling the design of more effective EGR systems (Agarwal and Batista, 2023). This modelling approach helps predict flow behaviour and thermal performance, which are critical for optimising EGR cooler designs to meet stringent emissions regulations (Agarwal and Batista, 2023). CFD has also been employed to analyse the impact of multiple injection strategies on combustion dynamics, ignition, and emissions (Martínez et al., 2022; Rajasegar et al., 2022). These studies help understand the complex interactions between fuel injection, combustion processes, and emissions, leading to more informed design choices for modern diesel engines.

Another significant development is the exploration of coupled internal and external EGR systems. This approach allows for better control of combustion timing and speed, improving emissions performance in homogeneous charge compression ignition (HCCI) engines (Zhang et al., 2022). By adjusting the timing of the exhaust valve closing and the amount of recirculated gas, researchers have found that it is possible to delay ignition timing and slow combustion speed, thereby reducing NO_X emissions.

3.1.4. Diesel oxidation catalysts

In addition to DPFs, the use of diesel oxidation catalysts (DOC) has been shown to mitigate pollutant emissions effectively. DOCs are essential components in the exhaust after-treatment systems of diesel engines, designed to reduce harmful emissions and enhance overall engine efficiency. The primary function of a DOC is to facilitate the oxidation of CO, HC, and PM in the exhaust gases produced by diesel engines. The combination of DPFs with DOCs has been shown to enhance the oxidation kinetics of HC species, allowing for effective emission control at lower temperatures (Fayad et al., 2018). The DOC's structure consists of four components: the shell, shock-absorbing layer, support, and catalytic coating. The schematic of the DOC structure is shown in Fig. 11. The catalyst, which is the core component of a catalytic converter and defines its primary performance index and conversion efficiency, consists of a mixture of catalytic active components and coating (Zhang et al., 2022b).

The operational mechanism of a DOC involves a catalytic reaction that converts CO and HC into less harmful substances such as CO_2 and water. The catalyst, typically composed of precious metals like platinum (Pt) and palladium (Pd), is coated onto a ceramic or metallic substrate, which provides a large surface area for the reactions to occur (Guardiola et al., 2017). The DOC is strategically placed upstream of other after-treatment devices, such as DPF and selective catalytic reduction (SCR) systems, to optimise the overall emission control process (Wu et al., 2019). The DOC also plays a critical role in the active regeneration of DPFs by raising the exhaust temperature through exothermic reactions, which is necessary to burn off accumulated soot (Yu et al.,

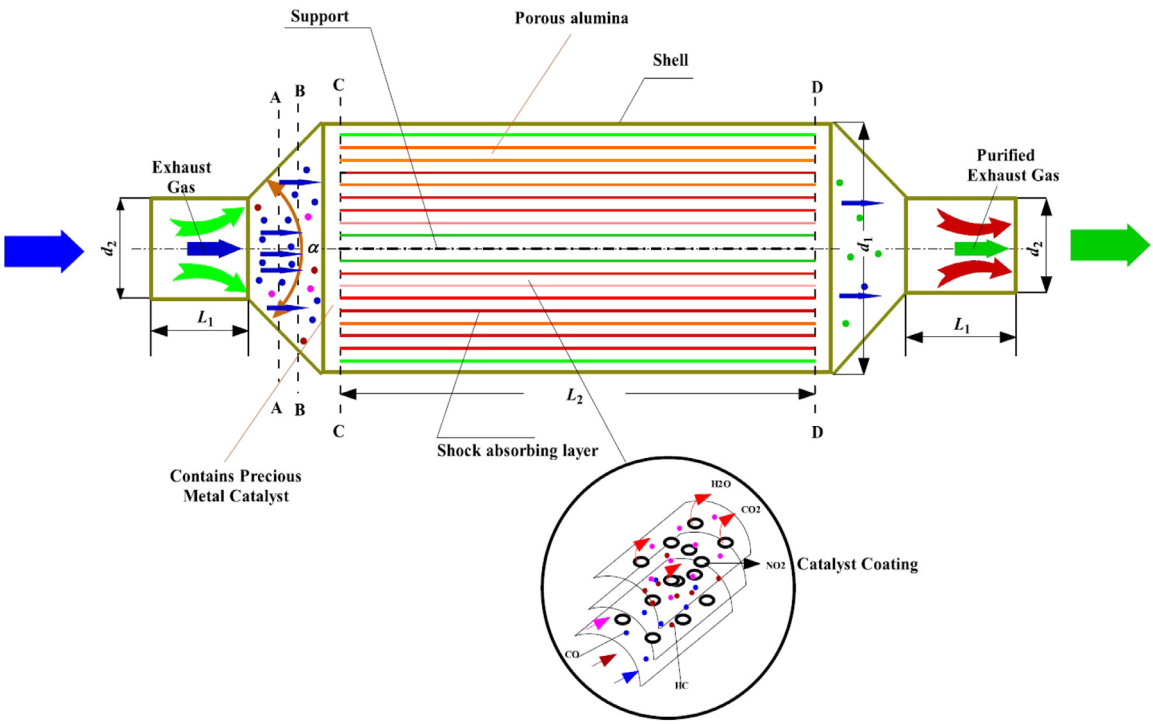


Fig. 11. Schematic diagram of DOC (Zhang et al., 2022b).

2024). When combined with DPFs, these systems can significantly lower the concentration of harmful particulate matter and associated toxic compounds, such as PAHs (Wu et al., 2022).

Recent advances in DOC have focused on enhancing their performance, stability, and efficiency in reducing harmful emissions from diesel engines. These advancements are crucial as stringent environmental regulations necessitate improved technologies to mitigate CO, HC, and PM. One significant development is the optimisation of perovskite-type catalysts, such as $BaMnO_3$, $BaMn_{1-x}Cu_xO_3$ and $BaFe_{1-x}Ni_xO_3$, which have shown promising results in NO_X-assisted diesel soot oxidation. Studies indicate that these catalysts exhibit high activity and stability, particularly $BaFe_{0.6}Ni_{0.4}O_3$, which combines effective NO oxidation capabilities with a high initial soot oxidation rate, minimising unreacted soot accumulation during reactions (Montilla-Verdú et al., 2023; Torregrosa-Rivero et al., 2022). The incorporation of transition metals into the perovskite structure has been a key strategy to enhance catalytic activity, as these metals can improve the oxidation processes essential for effective soot combustion.

Another innovative approach involves the use of multi-component catalysts, such as $Cs/Co/MNO_X$, which have demonstrated synergistic effects that significantly enhance soot oxidation activity. Research indicates that the presence of NO_2 in the reaction environment plays a critical role in promoting soot oxidation, making these multi-component systems particularly effective under real-world diesel engine conditions (Wang et al., 2021). This highlights the importance of understanding the interactions between different catalyst components and the composition of exhaust gas to optimise performance. The advancements in catalyst durability have been a focal point of research. The development of biphasic Janus particles has been explored to improve the self-healing properties of platinum-palladium (Pt-Pd) catalysts, which are commonly used in DOCs. These materials are designed to withstand the harsh conditions of high-temperature exhaust environments, thereby extending the operational lifespan of the catalysts (Porter et al., 2023). The US Drive initiative has established ageing protocols to simulate real-world conditions, ensuring that modern DOCs can maintain their effectiveness over time (Bergman et al., 2020; Porter et al., 2023).

Research into the effects of sulphur on catalyst performance has led to the development of strategies to mitigate catalyst poisoning, which is a significant challenge in maintaining DOC efficiency. Continuous regeneration technologies have been explored to enable soot combustion at lower temperatures, thereby addressing the issue of catalyst deactivation due to high sulphur content in diesel fuels (Liu et al., 2021).

In addition to these material advancements, innovative operational strategies have been proposed to enhance the efficiency of DOCs. For instance, the integration of DOCs with DPFs allows for active regeneration processes that require elevated temperatures. Recent studies have shown that injecting hydrocarbons at the end of the diesel engine cycle can facilitate this regeneration, effectively converting unburnt hydrocarbons into CO_2 and H_2O, thus improving overall emission control (Hamedi et al., 2021; Yu et al., 2024).

3.2. Engine modification technologies

While after-treatment technologies focus on mitigating emissions post-combustion, engine modifications aim to address the issue at its source by enhancing the combustion process itself. In this section, we review and investigate key methods such as fuel injection strategies, the Miller cycle, and in-cylinder combustion control, which together form a complementary approach to reducing pollutants from diesel engines and improving overall efficiency.

3.2.1. Fuel injection strategies

Advanced fuel injection strategies, such as multiple injection techniques and pilot injection, have been developed to optimise combustion. These strategies can improve fuel atomisation, reduce combustion temperatures, and minimise NO_X emissions. For instance, a pre-injection strategy can help control combustion, lowering peak temperatures and reducing NO_X (Anbalagan et al., 2024). These systems were primarily used in diesel engines, where the high compression ratios required precise fuel delivery for efficient combustion. The introduction of the common rail fuel injection system in the 1990s marked a significant advancement, allowing for multiple injections per cycle and greater con-

trol over injection timing and pressure (Liu et al., 2010). Fuel injection systems operate by delivering a precise amount of fuel into the combustion chamber at the right time and under the right conditions. The main types of fuel injection systems include Port Fuel Injection (PFI), Gasoline Direct Injection (GDI), Diesel Direct Injection (DDI), and Dual-Fuel Engine (DFE) and Reactivity Controlled Compression Ignition (RCCI) (see Fig. 12).

In PFI systems, fuel is injected into the intake manifold, where it mixes with air before entering the combustion chamber. This method is commonly used in gasoline engines. The advantages of PFI include better fuel atomisation and improved cold-start performance, as the fuel vaporises on the intake valves (Saliba et al., 2017). However, PFI systems can lead to carbon buildup on the intake valves over time due to fuel washing.

GDI systems inject fuel directly into the combustion chamber at high pressure, allowing for more precise control over the air-fuel mixture. This method improves fuel efficiency and power output while reducing emissions (Yamamoto and Toda, 2017). However, GDI engines tend to produce higher levels of PM compared to PFI engines, necessitating additional emission control measures (Saliba et al., 2017). Diesel engines utilise direct injection systems that inject fuel directly into the combustion chamber under high pressure. This method allows for better atomisation and mixing of fuel and air, leading to more efficient combustion and lower emissions. Advanced diesel injection systems often employ multiple injection strategies, including pilot, main, and post-injections, to optimise combustion and reduce NO_X and particulate emissions (Liu et al., 2010). RCCI involves injecting two different fuels into the combustion chamber, allowing for better control of the combustion process. RCCI, for example, uses a highly reactive fuel injected directly into the cylinder to ignite a less reactive fuel delivered *via* port injection. This method promotes efficient combustion and reduces emissions (Chojnowski and Karczewski, 2022).

Fuel injection strategies are employed in gasoline and diesel engines in passenger vehicles and commercial trucks to meet performance and emissions standards. The choice of injection strategy depends on the engine type, fuel used, and regulatory requirements (Lapuerta et al., 2021). Fuel injection technology is also used in marine diesel engines, where precise fuel delivery is essential for efficient operation and compliance with emissions standards (Huang et al., 2022).

An area of advancement is the "optimisation of injection timing and pressure". High-pressure common rail (HPCR) systems have become standard in diesel engines, allowing for precise control of fuel delivery. By adjusting the fuel injection advance angle and pressure, researchers have demonstrated significant emissions reductions and engine performance improvements (Niklawy et al., 2020). For instance, studies have shown that optimising the fuel injection advance angle can enhance the combustion process and reduce NO_X emissions by controlling the combustion timing (Yang et al., 2023). Additionally, varying the injection pressure has improved atomisation and fuel-air mixing, reduced emissions and enhanced efficiency (Niklawy et al., 2020).

Research on dual-fuel systems, such as diesel-natural gas and ammonia-diesel combinations, has gained traction. These systems often require specific adjustments to the fuel injection strategy to optimise performance and emissions (Jin et al., 2023; Lei et al., 2023). For example, some studies indicate that modifying the pilot injection timing in dual-fuel engines can improve thermal efficiency and reduce greenhouse gas emissions (Jin et al., 2023; Lei et al., 2023). The use of biofuels, such as biodiesel and vegetable oils, has also prompted investigations into how fuel injection strategies can be adapted to maintain performance while minimising emissions (Maldonado et al., 2024).

3.2.2. Miller cycle

Another engine modification technique is the Miller cycle. The Miller cycle involves modifying the valve timing in diesel engines to reduce exhaust temperature and NO_X emissions. This cycle has demonstrated significant reductions in NO_X compared to conventional diesel engine cycles (Yang and Wang, 2023). The Miller Cycle was first theorised by Ralph Miller in 1957. The concept emerged as engineers sought ways to enhance the efficiency of internal combustion engines while addressing the growing concerns over emissions (Oxenham and Wang, 2021). The cycle gained traction in the automotive industry, particularly with the introduction of Mazda's Miller Cycle engine in 1993, which showcased significant improvements in brake-specific fuel consumption (BSFC) and engine performance (Martins and Lanzanova, 2015). Over the years, the Miller Cycle has been increasingly integrated into various engine designs, especially in hybrid and high-efficiency vehicles, as manufacturers look for ways to meet stringent emissions regulations. In the Miller cycle, the intake valve closes either earlier or later than in a standard Otto cycle. This adjustment can be categorised into two main strategies: Early Intake Valve Closure (EIVC) and Late Intake Valve Closure (LIVC). In EIVC, the intake valve closes before the piston reaches the bottom dead centre (BDC) during the intake stroke. This reduces the effective compression ratio, which lowers the in-cylinder temperature and pressure during the compression stroke. As a result, the combustion process is more controlled, leading to lower NO_X emissions and improved fuel efficiency (Yang and Wang, 2023). Conversely, LIVC involves closing the intake valve after the piston has started its upward stroke. This allows for a longer expansion stroke, which enhances the work done by the expanding gases. The increased expansion ratio helps extract more energy from the combustion process, improving overall thermal efficiency (Pedrozo and Zhao, 2018).

Fig. 13 depicts the temperature–entropy (T–S) and pressure-volume (P–V) diagrams of an irreversible Miller cycle. The temperatures of the working material at state points 1, 2, 3, 4, and 5 are denoted by T1, T2, T3, T4, and T5, respectively. The process of compression is an isentropic process that goes from 1 to 2, the process of heat addition is an isochoric process that goes from 2 to 3, the process of expansion is an isentropic process that goes from 3 to 4, and the process of heat rejection is an isochoric process that goes from 4 to 5 and an isobaric process that goes from 5 to 1 (Ebrahimi, 2016).

Both strategies enable the Miller cycle to achieve a higher expansion ratio than the compression ratio, which is a key factor in enhancing engine efficiency. The cycle also benefits from the use of turbochargers, which can further optimise performance by increasing the intake air density (Oxenham and Wang, 2021).

The Miller Cycle also has advancements, such as adapting it to various fuel types and engine configurations. Recent studies have explored using "variable valve actuation" (VVA) to optimise the Miller Cycle's performance. By adjusting the timing of the intake valve closure (IVC), researchers have demonstrated that the Miller Cycle can achieve significant improvements in thermal efficiency. For instance, Guan et al. found that implementing VVA in a heavy-duty diesel engine allowed for a more advanced start of injection (SOI), which contributed to enhanced combustion control and emissions reduction (Guan et al., 2019). This flexibility in valve timing is crucial for adapting the Miller Cycle to different operating conditions and fuel types. The Miller Cycle has been increasingly applied to both gasoline and diesel engines, particularly in low-speed applications. Wang's research highlighted that the Miller Cycle effectively improves thermal efficiency by manipulating the IVC timing, which allows for a larger expansion ratio (Wang et al., 2023). This adjustment leads to better fuel economy and lower emissions, making it an attractive option for modern engine designs. Yang and Wang conducted experiments on a single-cylinder diesel engine utilising the Miller Cycle and found that it could effectively lower NO_X emissions by reducing exhaust temperatures (Yang and Wang, 2023). This finding aligns with other studies indicating that the Miller Cycle can lead to reductions in NO_X emissions by up to 17.5% when combined with EGR strategies (Guan et al., 2020). The ability to control combustion temperatures is critical for meeting stringent emissions regulations. Other studies indicate that using a turbocharger in conjunction with the Miller Cycle can enhance the engine's performance by improving air intake density and combustion efficiency. For instance, Liu et al. investigated

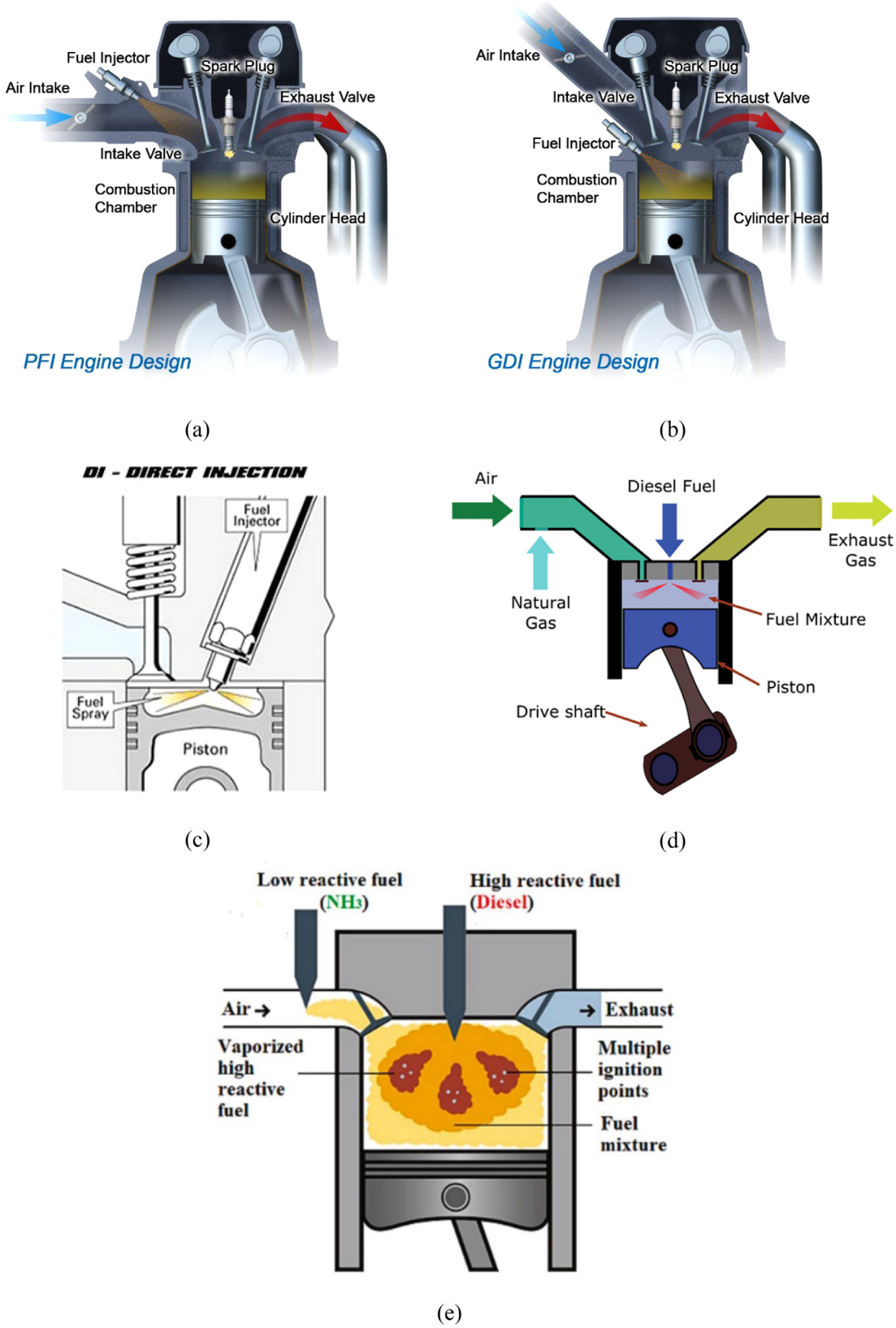


Fig. 12. Different fuel injection systems. (a) PFI (Afton Chemical, 2021), (b) GDI (Afton Chemical, 2021), (c) DDI (Diesel Hub, 2024), (d) DFE (LaFleur et al., 2016), (e) RCCI (Hossein Fakhari et al., 2024).

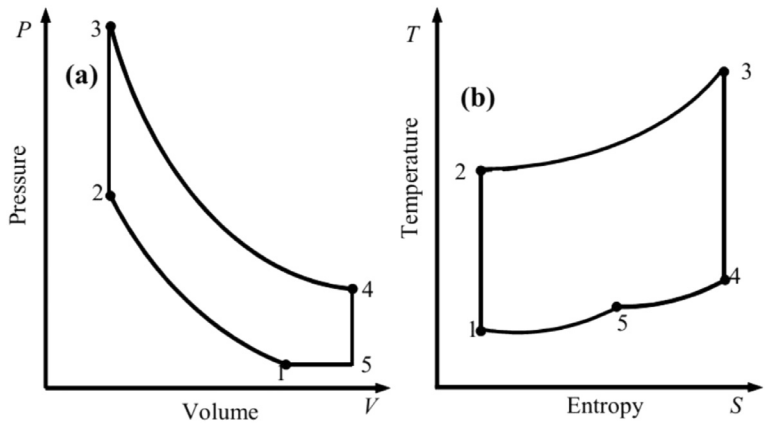


Fig. 13. Diagram for the air standard Miller cycle (a): P-V diagram and (b) T-S diagram (Ebrahimi, 2016).

a novel variable valve timing mechanism for a Miller Cycle diesel engine and found that turbocharging significantly improved the engine's overall performance (F. Liu et al., 2022). This combination allows for better power output while maintaining low emissions.

3.2.3. In-cylinder combustion control

In-cylinder combustion control techniques, such as post-injection, involve additional fuel injection after the main combustion event, which aids in oxidising soot particles and reducing soot formation. Optimising the timing and quantity of post-injection has been shown to significantly lower particulate emissions (Hardalupas et al., 2017). In addition, applying thermal barrier coatings to engine components like pistons and combustion chambers improves thermal efficiency, leading to lower HC emissions. Further design modifications, including increasing the compression ratio and adjusting fuel injection timing and pressure, can enhance combustion efficiency, reducing both CO and HC emissions (Suh, 2014b).

Fig. 14 shows how injection time affects engine emissions, emphasising the benefits of advanced injection techniques. Increasing injection time decreases soot, CO, and HC emissions, especially with dual pilot injection. Better air-fuel mixing and combustion efficiency account for this. Compared to delayed injection, advanced timing marginally increases NO_X emissions with twin pilot injection, although levels remain lower than with single or one pilot injection techniques. Twin pilot injection balances NO_X and soot emissions, whereas one pilot injection minimises CO and HC emissions efficiently. Injection timing optimisation and innovative methods reduce engine emissions dramatically (Suh, 2014b).

Engine modification strategies have undergone significant advancements over the years, leading to improved engine performance, efficiency, and emissions control. The choice of modification strategy depends on various factors, including engine type (application), fuel characteristics, and regulatory requirements, making it a critical aspect of modern engine design.

3.3. Fuel modification strategies

Although engine modifications can significantly improve combustion efficiency and reduce emissions, the type and composition of fuel used play an equally critical role. Fuel modification strategies provide an additional avenue to achieve cleaner and more efficient combustion by altering the fuel properties. Diesel fuels have played a crucial role in the industrial economy and transportation sector, particularly for diesel generators and engines. The first diesel engine was invented by Rudolf Diesel in 1892 (Kumar et al., 2023). Initially, the fuel for diesel engines was peanut oil. However, Diesel soon realised that vegetable oils could be a more viable fuel for his engine (Mukhopadhyay and Chakraborty, 2015). Over the years and decades, the development of fuels for diesel generators and engines has undergone significant advancements. In the early 20th century, there was a push to explore alternative fuel sources for diesel engines. Corn-based ethanol, promoted by Henry Ford in 1925, was one alternative fuel that gained attention (Geng et al., 2017). In the following decades, the focus shifted towards petroleum-based diesel fuels due to their high energy density and availability. These petroleum-based diesel fuels, also known as fossil fuels, became the standard fuel for diesel generators and engines. In the late 1970s and early 1980s, in response to concerns about energy security and the environmental impact of fossil fuels, the development of renewable fuels for diesel engines gained renewed interest (Ma and Hanna, 1999). This has led to the development of biofuels, such as biodiesel, which is made from recycled cooking oil, animal fats, or plant oils. These biofuels offer a more sustainable and environmentally friendly option as they reduce greenhouse gas emissions and are derived from renewable sources (Balat, 2008). Additionally, technological advancements have led to the development of synthetic diesel fuels, such as Fischer-Tropsch diesel, which is produced from coal or natural gas through a complex chemical process (Ajala et al., 2015). These synthetic diesel fuels have similar properties to petroleum-based diesel and can be used as a drop-in replacement in existing diesel engines without any modifications. Another important development in diesel fuels is the improvement of fuel efficiency and emission control. Through engine design and fuel formulation advancements, diesel fuels now have lower sulphur content and improved lubricity to enhance engine performance and reduce emissions (Mohd Noor et al., 2018).

Diesel generator emissions have been a subject of significant research interest in recent years, focusing on understanding the impact of various fuel blends and additives on emissions. The research on diesel generator emissions has highlighted the importance of exploring alternative fuel blends, additives, and combustion strategies to mitigate harmful emissions while maintaining or enhancing engine performance. Studies have explored the effects of biodiesel, alcohols, oxygenated additives, and rare earth fuel additives on diesel engine PM emissions (Junwu and Leyang, 2022; Verma et al., 2019; Wang et al., 2010).

3.3.1. Blending biodiesel and diesel

Wang et al. (2010) investigated the impact of biodiesel/diesel blends on engine performance, combustion, and emissions in a turbocharged, high-pressure common rail diesel engine. The study found that the use of biodiesel led to a reduction in PM, HC, and CO emissions, although there was a slight increase in NO_X emissions. Musa et al. (2016) and Ruina et al. Ruina et al. (2019) supported this by reporting a significant reduction in PM mass when using biodiesel blends in diesel. Junwu and Leyang (2022) investigated the emission reduction performance of two types of rare earth fuel additives (cerium carbonate as the inorganic acid rare earth and cerium stearate as the organic acid rare earth) in diesel engines, conducting tests on a twin-cylinder direct injection diesel en-

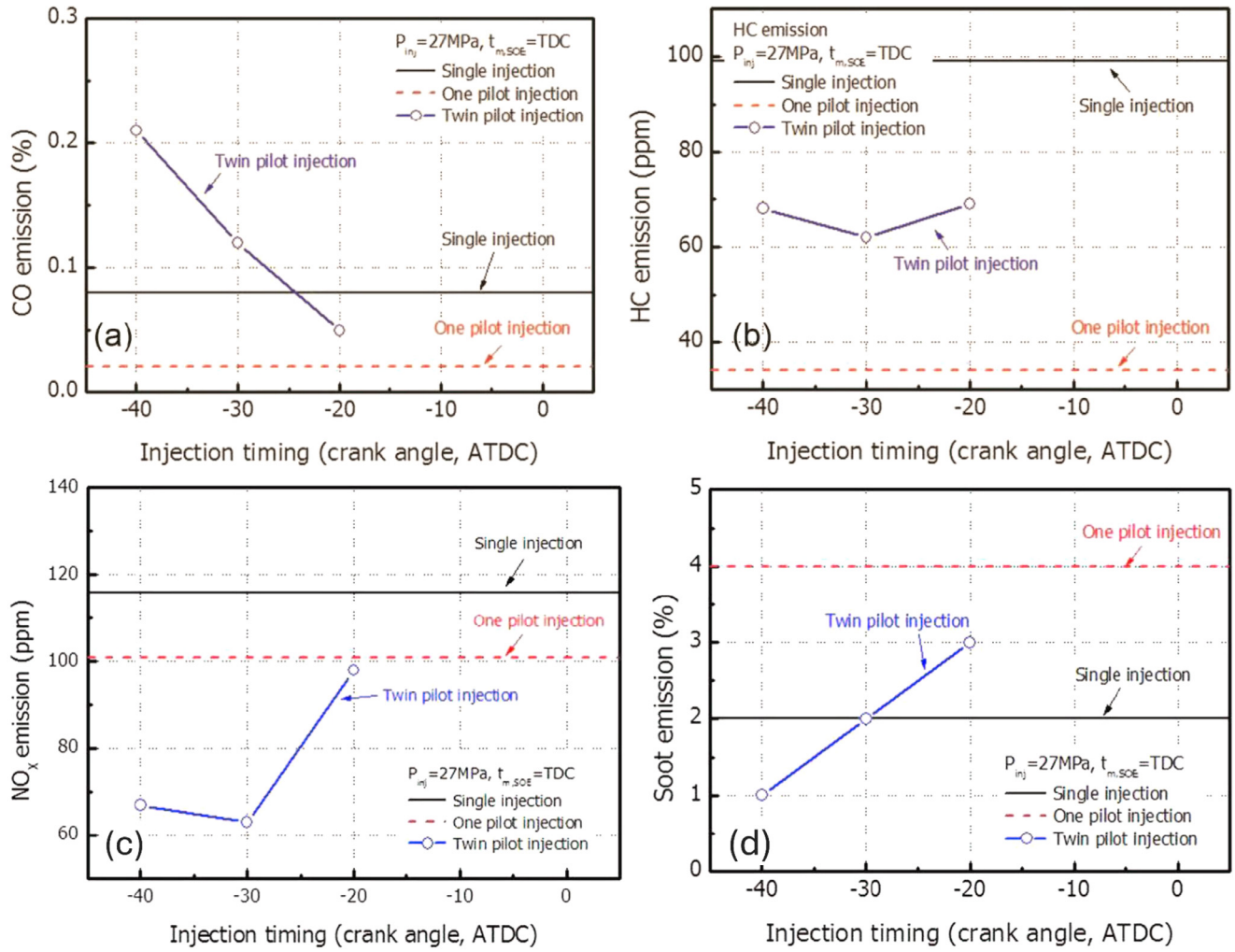


Fig. 14. Effect of injection strategies on emissions (TDC: top dead centre; ATDC: after top dead centre) (Suh, 2014b).

gine across five different rotational speeds to measure NO_X, CO, HC, and PM. They found that cerium carbonate showed a more significant reduction in emissions, with the maximum reduction rates for NO_X, CO, and HC being 11.37%, 14.63%, and 13.80%, respectively. To a lesser extent, Cerium stearate reduced emissions with maximum reduction rates for NO_X, CO, and HC at 10.19%, 12.15%, and 9.40%, respectively. Verma et al. (2019), in a comprehensive review, showed that alternative fuels such as biodiesel derived from various sources, alcohol fuels (e.g., ethanol, n-butanol, n-pentanol), and oxygenated additives could significantly affect the characteristics and quantity of PM emissions. Biodiesel, for instance, showed potential for PM reduction due to its oxygen content, leading to better combustion and reduced PM formation. Similarly, alcohol fuels contributed to lower PM emissions by enhancing fuel-air mixing and combustion efficiency. Venkateswara Rao and Ramesh (2016) conducted research on diesel engines, examining the effects of incorporating methanol into diesel-biodiesel blends to improve performance and reduce emissions. Their study focused on 50% diesel and 50% biodiesel blends with incremental methanol additions of 5%, 10%, and 15%. The findings revealed that methanol, thanks to its high oxygen content and evaporation heat, enhanced combustion efficiency, which significantly lowered exhaust gas temperatures and consequently reduced HC, NO_X emissions, and soot formation compared to engines running on pure diesel. This research underscores the potential of methanol as an effective additive in biodiesel-diesel blends for achieving cleaner and more efficient diesel engine operations.

3.3.2. Nanofuel additives to diesel

Recent studies have investigated the use of nanofuel additives in direct-injection diesel engines to improve performance and reduce emissions. For example, Gavhane et al. (2020) explored the effects of incorporating zinc oxide (ZnO) nanoparticles into soybean biodiesel (SBME25) on the performance and emissions of a variable compression ratio (VCR) diesel engine. Through the process of ultrasonication, ZnO nanoparticles were dispersed in biodiesel at varying concentrations, and the resultant nanofuel blends were tested under different engine loads and compression ratios. The study revealed that the SBME25-ZnO50 blend, particularly at a compression ratio of 21.5, significantly improved engine performance, evidenced by a 23.2% increase in brake thermal efficiency and a 26.66% decrease in brake-specific fuel consumption. HC, CO, soot, and CO_2 emissions were considerably reduced, though NO_X emissions rose due to higher oxygen levels and combustion chamber temperatures. Similarly, Rao et al. (2022) highlighted the potential of magnetite (Fe_3O_4) nanoparticles as an innovative nano-additive that can be easily recovered from exhaust gases using magnetic fields, thereby also mitigating environmental concerns. Through experimental analysis, they demonstrated that blending magnetite nanoparticles with biofuels reduced harmful emissions like PM, HC, and NO_X while improving fuel consumption and thermal efficiency. The study fills a gap in the current knowledge on the application of magnetite nanofuel in internal combustion engines, showing promising results for both engine efficiency and emission reduction.

3.3.3. Metal-based additives to diesel

Moreover, Resitoglu (2019) investigated the impact of metal-based additives, specifically Acetylferrocene and Ruthenium polypyridyl complex, on the performance and emission characteristics of a compression ignition (CI) diesel engine. These alternative metal additives were blended with diesel at 30 and 50 ppm concentrations and tested in a single-cylinder, direct-injection diesel engine to assess their effectiveness in enhancing engine performance and reducing emissions. The results demonstrated that both Acetylferrocene and Ruthenium polypyridyl complex effectively improved the emission characteristics of the diesel engine without causing performance degradation. Specifically, the additives reduced CO and soot emissions by up to 40% and 32%, respectively, while also improving the fuel consumption characteristic of the engine. Samuelraj et al. (2023) also found that combining oxygenated additives and carbon black bio-based nanofuels accelerated the combustion process in low heat rejection (LHR) engines. Chandrasekaran et al. (2021) demonstrate the potential of magnesia nanoflakes as an additive to improve the efficiency and environmental impact of diesel engines running on biodiesel-diesel blends. The study specifically focused on a blend of palm oil biodiesel and diesel (in a 1:4 ratio) dispersed with magnesia nanoflakes, compared to pure diesel with the same nanoparticle dispersion, regular diesel, and the biodiesel-diesel blend without nanoparticles. Emission analysis showed reductions in unburnt HC, CO, PM, and NO_x for fuels containing nanoparticles.

These studies collectively underscore the potential advantages of incorporating nanofuel additives in diesel engines, leading to improvements in combustion efficiency, reduced emissions, and enhanced engine performance. By integrating nanoparticles into fuel blends, researchers aim to optimise combustion processes, decrease ignition delays, and reduce harmful emissions, thereby promoting more efficient and environmentally friendly diesel engine operations.

3.3.4. Blend of hydrogen and ammonia with diesel

Integrating alternative fuels such as hydrogen and ammonia into diesel engines has emerged as a promising strategy to mitigate these issues. Research indicates that using hydrogen-diesel blends can enhance thermal efficiency and reduce emissions, as hydrogen (so-called E-fuels if the hydrogen is produced by splitting water molecules into hydrogen and oxygen using renewable electricity) combustion primarily produces water vapour, thus minimising the release of harmful pollutants (Zhang et al., 2024). Ammonia, recognised for its potential as a hydrogen carrier, has also been studied extensively in dual-fuel configurations with diesel. The optimisation of ammonia's energy ratio and injection timing has been shown to promote more complete combustion, thereby reducing unburned ammonia emissions (Chen et al., 2025). Furthermore, ammonia's role in SCR systems is notable, as it effectively reduces NO_X emissions when used as a reductant (Zhang et al., 2021). The combustion characteristics of these fuels differ from traditional diesel fuels and impact engine performance, necessitating careful management of injection strategies to ensure optimal performance. For example, hydrogen's rapid combustion can lead to higher peak cylinder pressures, which may enhance power output but also increase the risk of engine knock. In contrast, ammonia's slower combustion can result in lower power density and challenges in maintaining stable combustion across varying load conditions (Chen et al., 2025).

The trade-offs between hydrogen and ammonia blends with diesel fuel are multifaceted. Hydrogen's rapid flame speed can lead to improved combustion efficiency, but it also poses challenges such as premature ignition and backfire risks (Zhang et al., 2024). Conversely, ammonia's higher energy density and lower flammability can facilitate safer storage and handling, but its combustion can produce nitrogen oxides if not appropriately managed (Chen et al., 2025). Additionally, the physical properties of these fuels, including atomisation and combustion characteristics, differ significantly from conventional diesel, which can impact engine performance and emissions profiles. Research has shown that smaller nozzle diameters can enhance the atomisation of diesel fuel, leading to improved combustion efficiency and reduced emissions (Zhang et al., 2024).

3.3.5. Blend of alcohol and diesel

Alcohol blending with diesel or biodiesel in engines has been a subject of significant research interest in recent years. Studies have shown that alcohols can enhance combustion characteristics by increasing oxygen concentration, leading to reduced emissions such as soot and knock (Surakasi et al., 2023). Investigations have been carried out on the combustion characteristics of diesel engines fuelled with different blends, such as biodiesel-diesel-ethanol blends and methanol-diesel blends, to assess their impact on engine performance and emissions (Mofijur et al., 2015). The addition of higher alcohols to biodiesel has been found to improve ignition patterns, enhancing engine performance. For example, the use of propanol and sunflower biodiesel has been suggested to mitigate marine emissions (Nour et al., 2021). Furthermore, the use of alcohols like methanol, ethanol, and butanol has been shown to reduce carbon monoxide and hydrocarbon emissions, as well as fuel consumption in diesel engines. For instance, the experimental assessment of ternary fuel blends in a diesel engine indicated that heptanol-blended samples improved thermal efficiency with decreased specific fuel consumption (Khan et al., 2022).

Moreover, the utilisation of diesel/alcohol and diesel/biodiesel/alcohol blends has the potential to reduce PAHs and the phenomenon known as "wet stacking." Wet stacking occurs when a diesel engine operates at low loads for extended periods, leading to incomplete combustion and excessive soot formation, which can degrade engine performance and longevity. The integration of alcohols, such as n-propanol and n-butanol, into diesel blends has been shown to alter combustion characteristics, thereby influencing PAH emissions and mitigating wet stacking issues (Yilmaz et al., 2022, 2023).

Regarding the choice of alcohol for blending with diesel or biodiesel, various alcohols have been studied for their effects. For instance, the addition of n-butanol, n-heptanol, and n-octanol to biodiesel/diesel blends has been explored to improve engine performance, combustion, and emissions (Swarna et al., 2022).

These studies suggest that alcohol blending with diesel or biodiesel can have positive effects on engine performance and emissions. Different alcohols offer varying benefits, and the choice of alcohol for blending may depend on specific engine requirements and emission reduction goals. Further research is needed to optimise alcohol blends for different engine types and operating conditions.

Studies have been conducted to investigate the effects of emulsified fuels on NO_x and PM emissions from diesel engines. Ogunkoya et al. (2015) explored the performance, combustion, and emissions of a diesel engine using fuel-in-water emulsions based on lignin. They found that as the water content increased, brake specific fuel consumption (BSFC) increased at high engine speeds, while brake thermal efficiency (BTE) decreased, exhaust gas temperature (EGT) decreased, and NO_X emissions also decreased. In a study by Markov et al. (2021), the performances of a diesel engine operating on blended and emulsified biofuels from rapeseed oil were examined. The researchers noted that the content of rapeseed oil and water in the emulsified fuels had a comparable influence on reducing exhaust smoke. S. Park et al. (2016) focused on the effects of diesel-water emulsified fuel on NO_X and PM emissions from a diesel engine. Their study aimed to reduce NO_X and PM emissions by utilising diesel-water emulsified fuel, highlighting its potential application in conventional diesel engines.

In summary, the evolution of diesel fuels from their rudimentary beginnings to the sophisticated blends and additives of today showcases a relentless pursuit of efficiency and environmental stewardship. The journey from vegetable oils to advanced biofuels, synthetic diesel, and the exploration of nanotechnology and alcohol blending highlights a multifaceted approach to addressing the twin challenges of energy security and environmental sustainability. The breadth of research, ranging from the impact of biodiesel blends to the efficiency of nanotechnology

Table 4
Overview of fuel modification strategies for diesel engines.

Fuel Modification Area	Advantages	Disadvantages	Examples
Blending Biodiesel and Diesel	- Reduces emissions of PM, HC, and CO. - Derived from renewable sources. - Enhances combustion efficiency.	- Slight increase in NO_X emissions. - Performance variation depending on blend ratio.	- Biodiesel/diesel blends with rare earth additives (e.g., cerium carbonate). - Methanol addition to biodiesel blends.
Nanofuel Additives to Diesel	- Improves combustion efficiency. - Reduces emissions like CO, HC, and PM. - Enhances engine performance.	- Higher NO_X emissions due to increased combustion temperatures. - Complex production process.	- Zinc oxide nanoparticles in soybean biodiesel. - Magnetite nanoparticles in biofuels.
Metal-Based Additives to Diesel	- Reduces emissions (e.g., CO, soot). - Enhances fuel consumption efficiency. - Improves combustion.	- Potential for increased costs. - Environmental and health concerns with nanoparticle exposure.	- Acetylferrocene. - Ruthenium polypyridyl complex. - Magnesia nanoflakes in palm oil biodiesel-diesel blends.
Hydrogen and Ammonia Blends with Diesel	Hydrogen: - High thermal efficiency. - Zero carbon emissions (produces only water vapour). - Promotes cleaner combustion with reduced PM and CO emissions. Ammonia: - High energy density. - Acts as a hydrogen carrier. - Reduces NO_X emissions when used in SCR systems. - Low risk of ignition compared to hydrogen.	Hydrogen: - Risk of premature ignition and backfire. - Requires modifications for safe storage and handling. Ammonia: - Slow combustion rate leading to lower power density. - Risk of unburned ammonia emissions.	- Hydrogen-diesel blends (20% hydrogen with diesel). - Ammonia-diesel blends in dual-fuel configurations (70% diesel, 30% ammonia).
Blend Of Alcohol and Diesel	- Increases oxygen concentration, enhancing combustion. - Reduces emissions of HC, CO, and soot. - Improves thermal efficiency.	- Requires engine modifications. - Limited compatibility with some engine types.	- Methanol, ethanol, and butanol blends with diesel. - Propanol with sunflower biodiesel. - Heptanol-blended samples.

and the optimisation of alcohol fuel blends, illustrates a comprehensive effort to mitigate the environmental impact of diesel engines while harnessing the benefits of diverse fuel sources. These advancements are not only pivotal for the future of transportation and industrial power generation but also critical in the global quest for sustainable energy solutions. As the world moves towards a more sustainable and environmentally conscious future, the continued innovation and application of these fuel blends and additives will play a crucial role in shaping the next generation of diesel engine technology, paving the way for a cleaner, more efficient, and sustainable industrial economy. Table 4 summarises the four fuel modification areas discussed here, including their advantages and disadvantages.

4. CO_2 emission control technologies for diesel engines

While after-treatment systems and fuel and engine modifications target the reduction of harmful pollutants during combustion, carbon capture technologies address the challenge of CO_2 emissions directly by capturing and storing them after the combustion process. This approach is particularly vital for addressing greenhouse gas emissions and achieving Net Zero targets. The carbon capture from diesel engines or diesel generators can be classified based on the technology, namely post-combustion and oxy-combustion methods. In the post-combustion technology, different processes such as absorption and adsorption have been used (Balsamo et al., 2016; Pashaei et al., 2020) to capture CO_2 from flue gas produced from diesel generators. In the oxy-combustion, air is speared to nitrogen and oxygen and then only oxygen is sent to the combustion chamber, and the production of combustion is water and CO_2, where CO_2 can be collected by condensing the water (Li et al., 2020). It is worth mentioning that in recent years, more studies have focused on onboard carbon capture (OCC) in maritime and different ideas are being considered to decarbonise this transportation sector, which has a significant contribution to global greenhouse gas emissions.

4.1. Post-combustion carbon capture from diesel engine

4.1.1. Absorption

The absorption process is the most mature method for carbon capture in the world (Borhani and Wang, 2019). There are numerous studies on the CO_2 absorption process, and many researchers are working on this topic. The absorption process is also used for diesel engines and generators. A typical CO_2 absorption-desorption system using chemical solvents is shown in Fig. 15. Several types of columns can be used to perform the CO_2 absorption-desorption process. The most common ones are packed column, tray column, rotating packed bed (RPB), membrane contactor and bubble column (Table 5). In addition to unit operations, different types of chemical, physical and mixture of chemical and physical solvents also can be used to perform the absorption process (Babamohammadi et al., 2021; Borhani et al., 2022; Zhang et al., 2020).

One study elaborates on a carbon capture and storage (CCS) unit that is developed for a 3000-kW diesel engine on a ship (Long et al., 2021). The research evaluated several methods to improve the CO_2 capture in the absorber column. Methods such as using different mixtures of solvents, column intercooling, and multiple feeding to the system. The study also deployed heat integration for the desorber column to improve the efficiency of the regeneration unit. The work indicates that the design that combines the intercooler, numerous feeds, and heat integration along with the solvent methyldiethanolamine/piperazine (MDEA/PZ) seems to be the most beneficial, compared to other systems, for ship-based carbon capture (Long et al., 2021).

The effectiveness of chemical solvents in removing CO_2 from multi-pollutant diesel engine exhaust has also been the subject of experimental tests (Kumar et al., 2021). The studies suggest that the regeneration energy needed for the solvent's ammonia, dimethylethanolamine (DMEA), and monoethanolamine (MEA) is 1.1 kWh, 0.7 kWh, and 2.2 kWh, respectively. This is significantly less than the entire energy that exhaust gas can provide. According to experimental findings, the capture efficiencies of absorbents MEA, DMEA, and cooled ammonia at ambient circumstances are 90.95, 57.66, and 80.08, respectively (Kumar et al., 2021).

Exhaust gas recirculation (EGR) is a known method for controlling NO_X emissions, but it tends to increase CO_2 emissions. A theoretical design of a diesel engine equipped with devices for the simultaneous reduction of NO_X and CO_2 is presented (Kumar et al., 2022b). Simulations of the combustion process using ANSYS software revealed NO_2 reductions of 32.9%, 50.63%, and 54.43% with EGR ratios of 10%, 20%, and 30%, respectively, but also corresponding CO_2 increases of 4.76%, 9.52%, and 15.28%. To offset the rise in CO_2, experimental investiga-

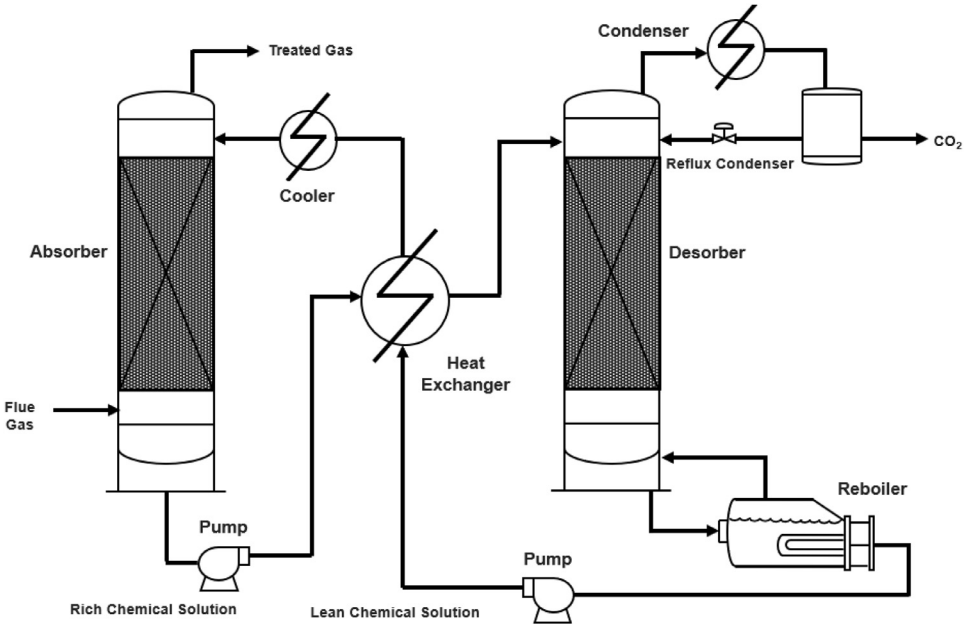


Fig. 15. A typical packed bed absorber and stripper columns to perform the CO_2 absorption process (Borhani et al., 2024).

Table 5
Comparison between different columns can be used in the CO_2 absorption process.

Technology	Advantages	Disadvantages	Key features
Packed Column	- High efficiency for large-scale operations. - Well-known and widely used.	- High-pressure drop. - Large size, prone to fouling.	-Low to moderate pressure and temperatures. -Well-established at the industrial scale, being common in CO_2 capture and other gas absorption processes
Tray Column	- Simple design. - Suitable for low to moderate gas flow rates.	- Lower efficiency at higher flow rates. - Large footprint.	-Low to moderate pressures. -Well-established at the industrial scale, being common in CO_2 capture and other gas absorption processes
RPB	- High mass transfer efficiency. - Compact design with low pressure drops.	- Complex sealing and rotating components. - Operational complexity.	-Efficient at both low and high pressures. -Progressing from pilot to industrial scale, as they offer high mass transfer rates in compact designs.
Membrane Contactor	- Very low pressure drop. - Compact and modular design.	- Membrane fouling. - High cost of membrane materials.	-Moderate pressure and temperature, limited by membrane durability. -Typically, at the pilot scale, but there is increasing research and interest for industrial applications.
Bubble Column	- Simple design. - Low maintenance and easily scalable.	- Moderate efficiency. - Requires large volume for high throughput.	-Low to moderate pressures; better at higher gas flow rates. -Used from lab scale to industrial scale, depending on the specific application, but are less efficient than packed or RPB systems for CO_2 capture.

tions were conducted using aqueous ammonia and monoethanolamine at various brake power settings. The results showed average carbon capture efficiencies of 91% with ammonia and 94% with MEA. Additionally, a blend of 67% ammonia and 33% MEA achieved a 95% carbon capture efficiency. This study expresses that combining EGR with a carbon capture unit can effectively reduce both NO_X and CO_2 emissions in diesel engines (Kumar et al., 2022a, 2022b).

CO_2 absorption from diesel generator using L-Alanine and L-Arginine amino acids solutions performed in a carbon capture device (CCD) (Manimaran et al., 2022). For L-Alanine and L-Arginine, the CO_2 emissions were reduced by 13.04% and 21.73%, respectively, at peak power output (5.2 kW). The authors also mentioned that comparing with no CCD operation, CO was reduced by 23.07% for L-Alanine and 38.46% for L-Arginine. However, the authors did not mention how they recovered the amino acid solutions and how much energy required to regenerate solvents which is the important part of CO_2 absorption process.

Some research has been performed on the exhaust of a direct injection diesel engine across five different brake powers using various absorbents for CO_2 capture, including blends of aqueous ammonia, MEA, DMEA, and the ionic liquid 1-ethyl-3-methylimidazolium tetrafluoroborate (C2mim BF4) (Kumar et al., 2022). The study found that the highest CO_2 absorption efficiency, nearly 97%, was achieved with a blend of 67% aqueous ammonia and 33% MEA. Additionally, a blend of MEA solution showed a 96% absorption efficiency, while a combination of aqueous MEA, DMEA, and C2mim BF4 demonstrated a 94% efficiency. However, the work did not specify the energy requirement for regeneration of the solvent (Kumar et al., 2022).

L-alanine, L-aspartic acid, and L-arginine were among the amino acids with five different molar concentrations, ranging from 0.1 to 0.5 are used (Muthiya et al., 2022). All these solutions were subjected to diesel exhaust to test their capacity to absorb CO_2. For this reason, a suitable CO_2 control system was created and put through testing. A single-cylinder, naturally aspirated diesel engine with a water-cooled system was used for the experiments. The findings demonstrated a noteworthy 90% reduction in CO_2 emissions in addition to concurrent drops in emissions of hydrocarbons (HC) and CO (Muthiya et al., 2022).

A spray tower using NaOH solution for the absorption of CO_2 from ship (Wang et al., 2022). Extensive experimental research was conducted to determine the impacts of varying engine exhaust gas temperature, concentration of NaOH solution, exhaust gas velocity, various load circumstances, and types of nozzles on CO_2 absorption efficiency. The study's findings demonstrated that ship emissions of CO_2 might be decreased by more than 20% by employing NaOH solution to absorb CO_2 from the exhaust. The discussion of chemical reactions between CO_2

Table 6
Comparison between different columns can be used for CO_2 adsorption.

Column Type	Used in PSA	Used in TSA	Key Features
Fixed Bed	Yes	Yes	Simple design, batch operation, well-suited for small to medium scales.
Moving Bed	Rarely	Yes	Continuous operation, good for large-scale TSA with constant adsorbent regeneration.
Fluidised Bed	Rarely	Yes	Excellent heat transfer, used in large-scale TSA with uniform temperature control.

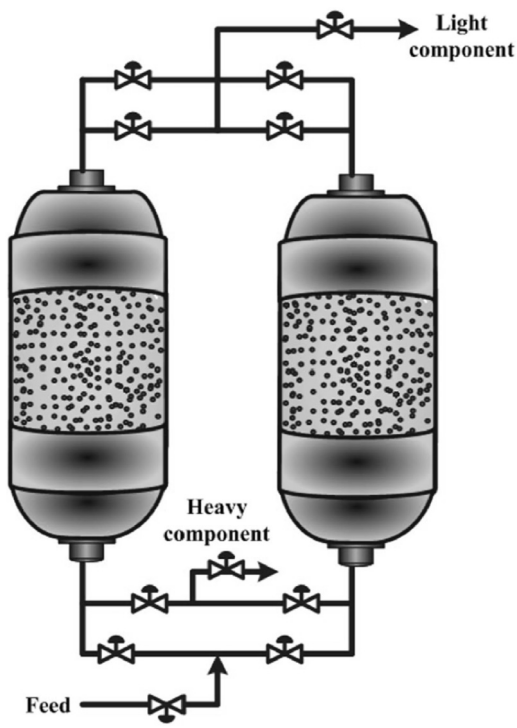


Fig. 16. A typical dual fixed bed reactor/column to perform the CO_2 adsorption process (Karimi et al., 2023).

and various solvents falls outside the scope of this study; readers are encouraged to see the relevant references for more details (Borhani and Wang, 2019).

4.1.2. Adsorption

The adsorption process is based on applying a solid sorbent to capture CO_2 in a fixed bed, fluidised beds or moving beds. A typical fixed bed column/reactor is shown in Fig. 16. In general, there are two different types of processes to perform CO_2 adsorption-desorption that are known as pressure swing adsorption (PSA) and temperature swing adsorption (TSA) (Dhoke et al., 2021). For PSA, the process alternates between high pressure (for adsorption) and low pressure (for desorption) without requiring a significant change in temperature. PSA is typically used when rapid adsorption/desorption cycles are needed and where CO_2 concentrations are relatively higher (James et al., 2021). PSA is suitable for high-pressure CO_2 streams, such as in natural gas processing or pre-combustion capture, and it will be used when sorbents selectively capture CO_2 at high pressure, such as in nitrogen-rich streams. TSA relies on temperature changes to adsorb CO_2 at low temperatures and desorb it at higher temperatures. TSA is typically used when the sorbents have high thermal stability and can handle repetitive heating. This method has longer cycle times than PSA since heating and cooling processes take longer than pressure changes (Raganati et al., 2021). TSA works efficiently in low-pressure environments with low CO_2 concentrations, such as flue gas from power plants. Hence, it is suitable for post-combustion CO2 capture, where gas streams are at lower pressures. Table 6 compares three types of columns/ reactors used in CO_2 adsorption.

An overview of CO_2 capture experiments on raw and alumina-supported potassium carbonate is presented (Balsamo et al., 2016), conducted in a fixed bed apparatus at temperatures (60–105 °C) and with a typical model marine diesel engine exhaust composition (CO_2 5%, H_2O 5%, N_2 90% by vol.).

The application of potassium carbonate supported onto porous alumina as sorbent for selective CO_2 capture in marine engines is investigated (Erto et al., 2018). With a model diesel engine exhaust (5% vol. CO_2, 5% vol. H_2O, balance N_2), carbonation tests were conducted in a fixed-bed column at temperatures between 60 and 105 °C, as those that often occur at the outlet of a scrubber and/or a waste heat recovery unit. Experimental data displayed a higher conversion degree and capture capacity compared with unsupported potassium carbonate, which is affected by significant intraparticle diffusion limitations. The results of steam regeneration tests on sorbent with 3.6% wt. potassium carbonate loading in a fixed-bed column showed that 120 °C ensures close to full recovery of collected CO_2 while maintaining the sorbent carbonation degree for ten consecutive carbonation/regeneration cycles (Erto et al., 2018).

The performance of a calcite/activated carbon-based post-combustion CO_2 capture system in reducing CO_2 emissions from a two-cylinder compression ignition (CI) engine fuelled with Calophyllum inophyllum biodiesel (B100) and diesel is tested (Subramanian et al., 2019). The results illustrated that B100 increased CO_2 emissions by 19% compared to diesel due to its higher fuel-bound oxygen and carbon content. Additionally, B100 combustion led to higher NO emissions and slightly reduced smoke opacity. The CO_2 capture system significantly reduced CO_2 emissions for both fuel types: by 11.5% for diesel with calcite and 7.3% with activated carbon, and by 15.8% and 10.5% for B100 with calcite and activated carbon, respectively. Both calcite and activated carbon effectively reduced NO emissions and smoke opacity due to their adsorption capabilities, with calcite proving more effective in reducing CO_2 emissions than activated carbon (Subramanian et al., 2019).

A truck delivery service is utilised as an illustration for the design of an on-board CO_2 capture and storage system (Sharma and Maréchal, 2019). Using the waste heat from the engine's exhaust gases, this system combines a temperature swing adsorption (TSA) system for CO_2 capture with a turbo-compressor system to compress and liquefy the CO_2 that has been captured. The authors concluded that an energy-free CO_2 capture system for a car, truck, bus, ship, or train can capture 90% of the CO_2 released by an engine exhaust stream (Sharma and Maréchal, 2019).

Mitigation of CO_2 emission from a diesel engine has been studied under different scenarios (Geo et al., 2021). (i) Lemon peel oil (LPO) and camphor oil (CMO) biofuels were combined with diesel. Only 20% of the biofuels were blended with diesel on a volumetric basis since adding more biofuels to the blend would have reduced engine efficiency. (ii) Hydrogen was introduced into the intake manifold to replace the mix. (iii) CO_2 were captured using an after-treatment system based on zeolite. All solutions together demonstrated a significant reduction in CO_2 and PM emissions. The other benefit of the zeolite-based after-treatment system was the decrease in NO emissions, which typically rise with the addition of hydrogen without significantly impacting engine performance (Geo et al., 2021).

Calcium and lithium hydroxides, which are cheap solid materials, were used as sorbents to adsorb CO_2 coming from an internal combustion engine (Costagliola et al., 2022). Each sorbent's carbonation capability was assessed for a range of sorbent granulometry (powder and pellets), temperatures (from room temperature to 300 °C), gas space velocity, moisture content, and the gaseous stream's chemical composition. The authors reported that the presence of sulphur dioxide and nitric oxide significantly reduced the carbonation ability of sorbents. Biomass-based sorbent is examined to adsorb CO_2 from the exhaust of a diesel engine (Ravi et al., 2022). An internal adsorption chamber that was connected to the exhaust of a single-cylinder, four-stroke engine held the adsorbent sample. According to the experimental findings, utilising a sorbent based on palm shells allowed for the average capture of between 30% of CO_2.

For onboard CCS, the viability of a novel hollow fibre carbon capture system impregnated with a carbon xerogel was evaluated. In a packed bed adsorption unit (PBAU), the working capacity of four carbon xerogels with different surface areas and surface groups was investigated throughout TSA cycles (Larkin et al., 2023). The best result showed 1.3 times higher than working capacity compared to the equivalent PBAU. A series of transition metal-modified CaO/Y_2O_3 sorbents were developed and used for CO_2 removal. The cyclic adsorption capacity test was done in a fixed-bed reactor. X-ray diffraction (XRD), scanning electron microscopy (SEM) and Brunauer-Emmett-Teller (BET) test used to characterise the adsorption properties of the samples. In the best result the initial adsorption capacity of Fe-CaY was 0.62 g/g at 650 °C and the adsorption capacity was 0.59 g/g at the 25th cycle, and the experimental calcination temperature was 750 °C (Zhang et al., 2023). In another study, the research group used adsorbents made of coconut shells, rice husks, and eucalyptus wood to adsorb CO_2 from the exhaust of the compression ignition (CI) (Ravi et al., 2024). At peak load, 2.4 kg of coconut shell, rice husk, and eucalyptus wood adsorbents reduce CO_2 emissions by approximately 36%, 25%, and 44%, respectively.

4.1.3. Algae application

Bioenergy with Carbon Capture and Storage (BioCCS/BECCS) gained traction in the 1990s, with the 1997 Kyoto Protocol marking a significant turning point. The Protocol allowed the use of "carbon sinks", formalising BioCCS methods (French, 1998). Following this, carbon trading became popular, with companies being able to offset their carbon emissions through afforestation (planting trees) and reforestation (restoring forests). This incentivised BioCCS, making it more cost-effective for companies as well as allowing nature-based solutions which are increasingly preferred. Forests and afforestation are commonly used BioCCS methods, also referred to as carbon sinks; trees absorb CO_2 and convert it into biomass, such as trunks and roots, where carbon is stored for centuries. Another form of carbon sink is soil sequestration, supported by regenerative farming. Examples of regenerative farming include no-till farming, cover cropping and rotational grazing, which all increase the soil carbon storage (Nunes et al., 2020). Limiting factors associated with many BioCCS methods include the limited land available, the slow and reversible storage and the vulnerability attached to the methods, such as deforestation and forest fires (Noble et al., 2012).

The use of microalgae for carbon capture sequestration works *via* the same mechanism as trees, recycling CO_2 into biomass *via* photosynthesis whilst tackling some of the previously mentioned issues with traditional BioCCS (Udaypal et al., 2024). There are two distinct types of algae, including micro and macro; this review will focus on microalgae as it is more commonly used in carbon capture applications due to the seasonality limitations of macroalgae. Microalgae often acts as an umbrella term for the prokaryotic blue-green algae, also known as cyanobacteria and eukaryotic green algae, red algae and diatoms (Singh and Dhar, 2019). Sequestration is the removal and storage of CO_2 from the environment or flue gases, the main biological sequestration techniques are forestation, ocean fertilisation and microalgae cultivation (Mallick et al., 2024). Photosynthesis is the mechanism responsible for the bioconversion of CO_2 into biomass, a well-known reaction summarised simply by Eq. (R8). Photosynthesis occurs in the chloroplasts of the cell and is the conversion of solar energy into chemical energy in the form of algal biomass (Alami et al., 2021).

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \; \textit{Photosynthesis reaction in the presence of light} \tag{R8}$$

The reaction can be separated into light-dependent reactions and light-independent reactions. The light-dependent reaction converts the captured solar energy into photonic energy using cyclic photophosphorylation to produce ATP and NADPH (Ma et al., 2022). The products of the light-dependent reactions are then used in the light-independent reactions, which utilise the fixated CO_2 in the Calvin-Benson cycle (Ma et al., 2022).

Microalgal carbon capture is both economically and environmentally beneficial. Their uncomplicated cell structure and rapid cell growth mean they can capture up to 100 times higher fold than terrestrial plants, this paired with their ability to flourish in extreme environments and simple nutrient ranks, means they surpass other biological feedstock options (Mallick et al., 2024; Singh and Dhar, 2019). Carbon capture can be measured directly, using the amount of carbon content in the biomass, or indirectly, based on the inlet and outlet CO_2 concentrations of the photobioreactor (Udaypal et al., 2024). The ability to grow in saline water sets microalgae aside from other plants and further reiterates the food security benefit of using microalgae over terrestrial plants. An obvious economic benefit of bio-fixation using microalgae is the simultaneous valorisation through the processing of algal biomass (Ma et al., 2022). Using microalgae as a method of carbon capture plays into a larger picture of a circular economy, working towards Net Zero, a milestone many countries, including the UK, the EU, the USA, China and India, all intend to meet by 2050. The biomass produced can be used to make many products ranging from low to high value, including biofuel, bioplastics, fertiliser, nutraceuticals and pharmaceuticals (Singh and Dhar, 2019).

Technoeconomic Analyses (TEAs) and Life Cycle Assessments (LCAs) show that for microalgal carbon capture to meet scale-up demands for widespread adoption, full use of biomass in an integrated biorefinery system is essential. This approach ensures every component is utilised, making the process more economically viable (Singh and Dhar, 2019). A well-designed biorefinery system circularises the process from start to finish and maximises the use of by-products. The exact process varies between algal strains, but typically, the products are lipids, proteins and carbohydrates. These components in the biomass can be further refined into value-added products such as pigments, antioxidants and omega fatty acids, creating multiple revenue streams and justifying the operational costs (Singh and Dhar, 2019). This is unique to microalgal carbon capture and adds many revenue streams to the process.

4.1.3.1. Associated challenges of microalgal carbon capture. Despite the potential of microalgae carbon capture, significant challenges are still faced when implementing these technologies on a commercial scale. The main hurdles include scalability, mass transfer requirements and complex cultivation methods. A key limitation preventing microalgal fixation from being used at a commercial scale is the upstream and downstream processing (Ma et al., 2022). Harvesting the microalgae alone can account for up to 40% of the capital costs, with the large-scale cultivation and nutrient supply creating a significant economic bottleneck (Singh and Dhar, 2019). For algal carbon capture to be commercialised, further work and research need to be done to optimise the technology.

Microalgae can be cultivated in different ways, predominantly using open pond methods such as raceway ponds, but more recently, vertical tubular bioreactors are emerging (Alami et al., 2021; Iglina et al., 2022). There are factors during cultivation that can influence CO_2 fixation efficiency, such as light intensity, nutrient availability and the strain used (Udaypal et al., 2024). Raceway ponds are often the cultivation method

of choice as they are relatively cheap, easy to clean and suitable for large-scale cultivation, but they do have drawbacks: there is little control over the conditions, the culture can be easily contaminated, and they require much space (Alami et al., 2021). The alternative option is photobioreactors (PBRs). These can be vertical, flat panel or tubular, and the main overarching benefits of PBRs as opposed to open ponds are increased control over conditions, including illumination, minimised contamination risk and much higher cell densities (Mallick et al., 2024). PBRs do have their own drawbacks, such as scalability issues, fouling and pH gradients (Alami et al., 2021). The type of PBR used for cultivation can influence the sequestration efficiency of the microalgae as well as the loss to the environment. Udaypal et al. (2024) found that to make large-scale cultivation economically possible, a novel PBR needs to be designed that focuses on optimising both the sequestration efficiency and the biorefinery aspect.

Fig. 17 is showing three algae systems. This figure shows that Vertical Tubular PBRs are closed systems arranged vertically to maximise sunlight exposure and minimise space requirements. They circulate the culture using a pump or gas sparging system (Fig. 17 (a)). Flat Panel PBRs (Fig. 17 (b)) have a high surface area to volume ratio, improving energy transfer rates and productivity. They are made of multiple layers of glass panes positioned vertically to increase the photosynthetic effect. In Fig. 17 (c) Tubular PBRs are serpentine-shaped to meet scaled-up production needs. It can operate at higher culture densities than conventional methods.

Mass transfer is a critical challenge in commercialising microalgal carbon capture. Inefficient CO_2 delivery, oxygen removal and nutrient transport are all significant bottlenecks when scaling up algal cultures. The mass transfer issues influence the efficiency of the CO_2 delivery to algae, which can be negatively impacted by the low solubility of CO_2 in water and the high density of algal cultures (Yang et al., 2024). These issues are more prominent on a large scale due to the decrease in the surface area-to-volume ratio and the increase in the diffusion path length. Insufficient mixing is a problem associated with mass transfer caused by a lack of distribution uniformity and associated energy costs (Yang et al., 2024). Oxygen accumulation occurs as the microalgae photosynthesise, and removing this oxygen becomes increasingly difficult on a large scale (Gilmour and Zimmerman, 2020). Research the use of microbubbles to overcome mass transfer problems in large-scale cultivation. Using microbubbles increases the surface area-to-volume ratio, increasing gas exchange and diffusion rates. Engineering the microbiome can further enhance the effectiveness of microbubbles by designing self-assembled artificial lichen that acts as scaffolding, thereby improving diffusion rates (Gilmour and Zimmerman, 2020). Fig. 18 illustrates the diverse designs of bioreactors employed in microalgal carbon capture, highlighting their integrated systems for efficient CO_2 introduction, which optimise algal growth and carbon sequestration efficiency.

While microalgal carbon capture holds significant promise for contributing to the fight against climate change, the current state of technology faces challenges. The high capital and operational costs associated with large-scale implementation, as well as the need for more efficient cultivation and harvesting techniques, remain key barriers. However, with continued advancements in genetic engineering, cultivation methods and biorefinery integration, there is growing potential for microalgae to play a large role in carbon capture. Fig. 19 presents a schematic representation of three distinct photobioreactor (PBR) designs utilised for carbon removal through algae, showcasing their structural variations and operational mechanisms to enhance CO_2 capture and algal productivity.

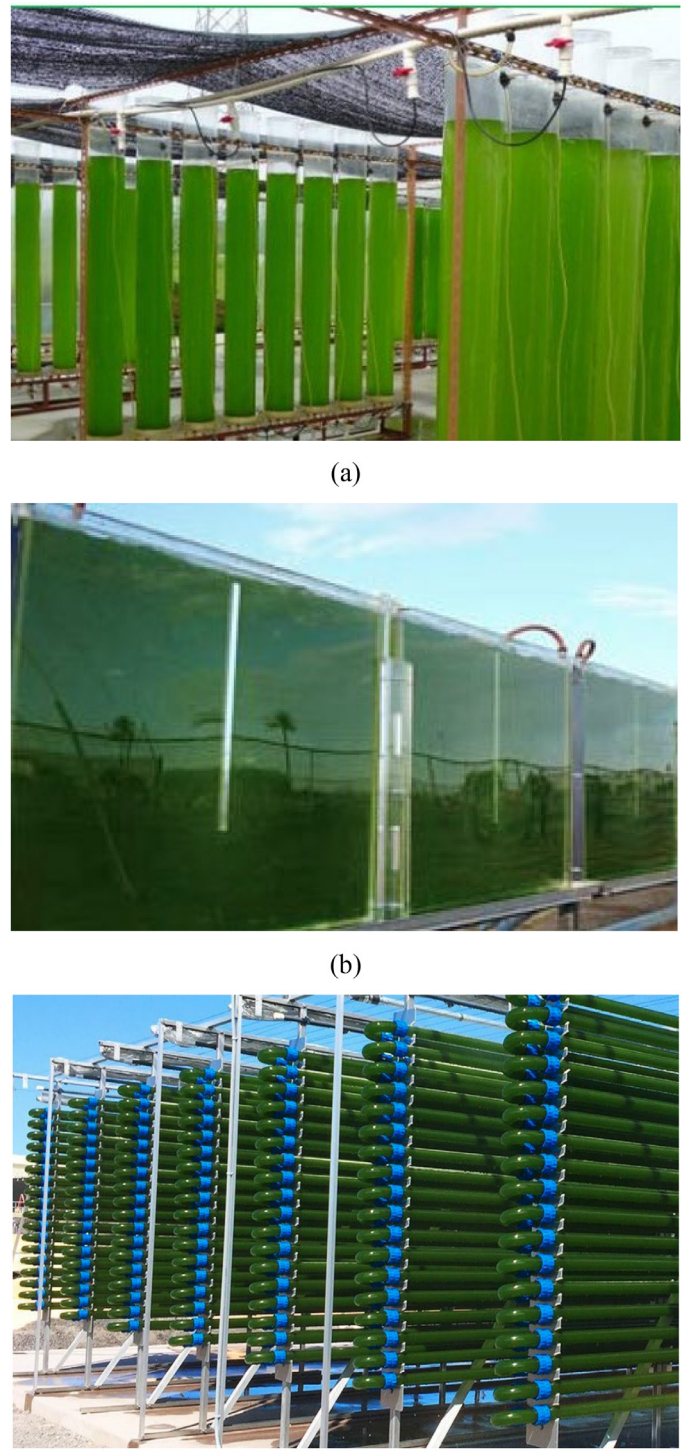


Fig. 17. (a) Vertical Tubular PBR (Alami et al., 2021), (b) Flat Panel PBR (Bitog et al., 2011), (c) Tubular PBR (Cheng et al., 2021).

4.1.3.2. Solutions and bioprospecting. A proposed approach is the development of a 'super-alga' - a genetically engineered strain that combines the desirable traits needed for efficient carbon capture and biomass production (Ma et al., 2022). Genetic modification is also suggested by Udaypal et al. (2024) with both papers suggesting the modifications could play a vital role in their carbon fixation ability, biomass productivity and in turn economic feasibility. This would likely involve altering pathways that regulate photosynthesis conditions, carbon uptake and biomass composition, creating strains that work more efficiently in a variety of conditions (Ma et al., 2022).

Advancements in cultivation methods could also drive progress. A promising option is the development of a hybrid cultivation system that combines the cost-effective large-scale cultivation of raceway ponds

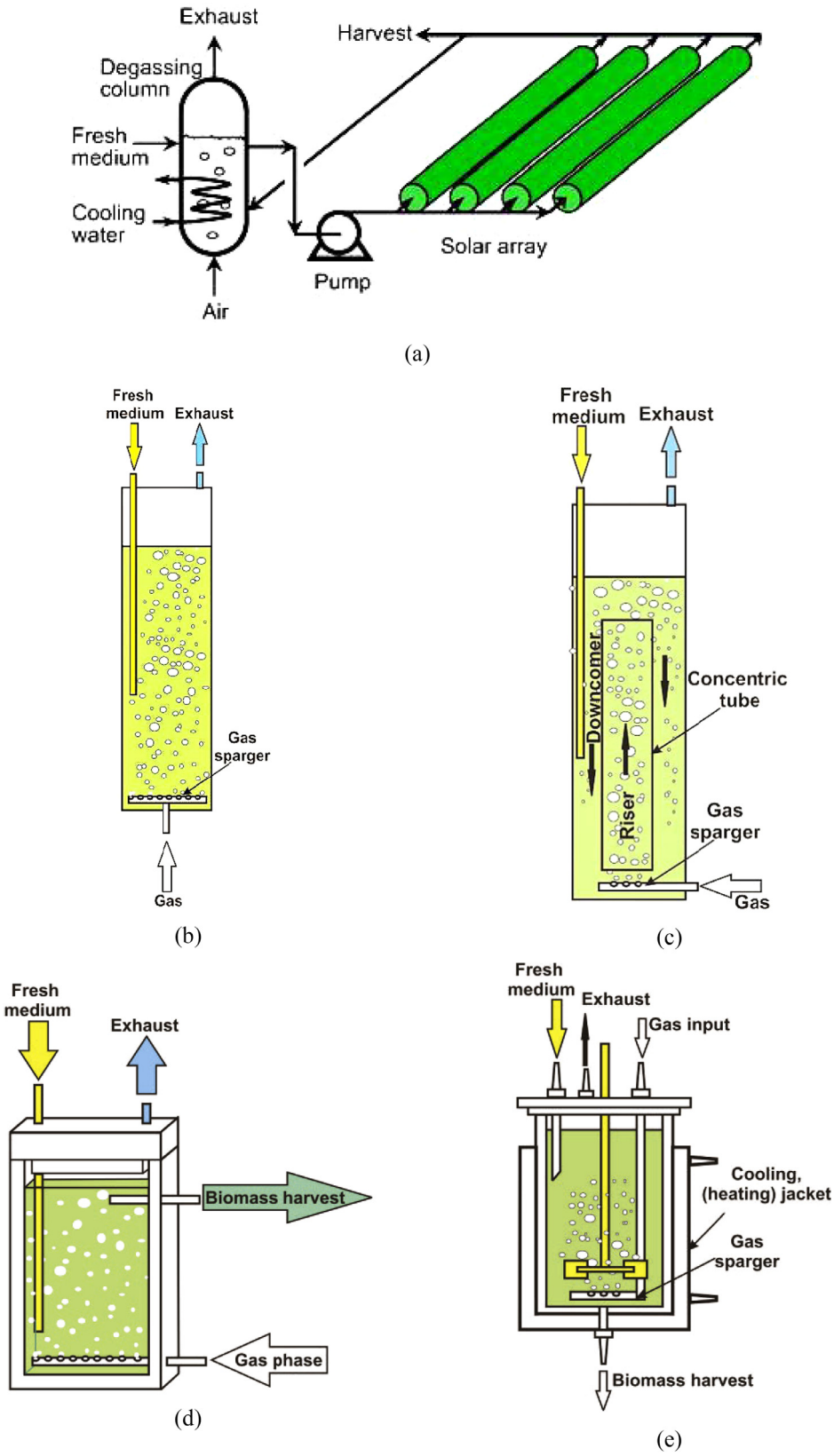


Fig. 18. Diagram of 5 different bioreactors used in microalgal carbon capture, which have integrated systems to introduce CO_2. a) Tubular PBR, b) Vertical Airlift PBR, c) Bubble Column, d) Flat Panel PBR and e) Stirred Tank PBR (Shareefdeen et al., 2023).

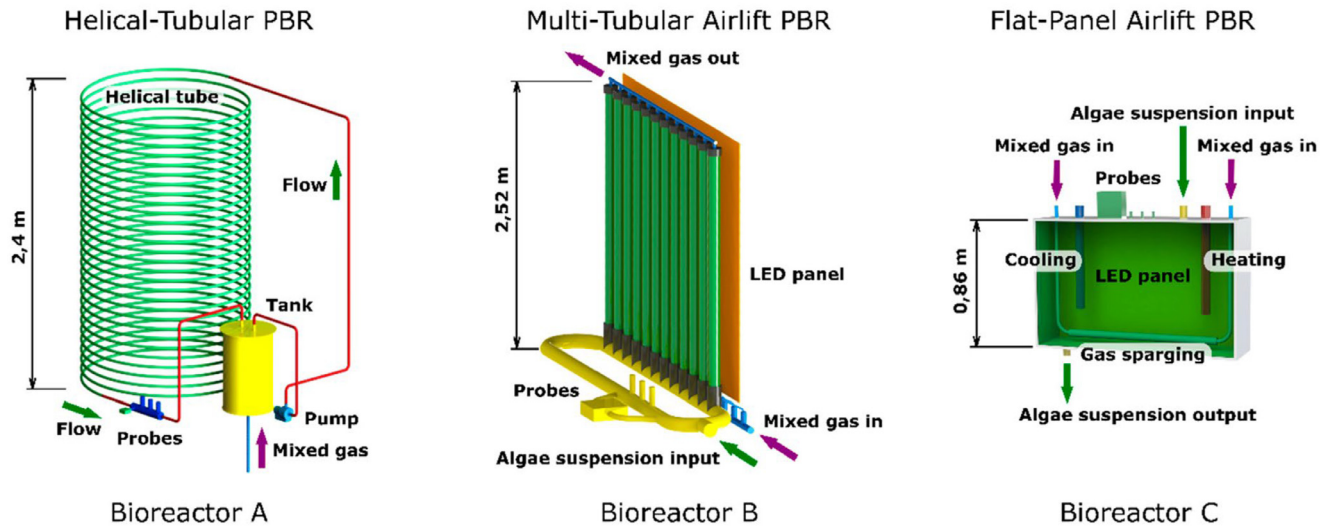


Fig. 19. Schematic of 3 different PBRs used for carbon removal using algae. Bioreactor A - Helical-Tubular PBR, Bioreactor B - Multi-tubular Airlift PBR and Bioreactor C - Flat-Panel Airlift PBR (Sukačová et al., 2021).

with the controlled environment of a PBR (Ma et al., 2022). This hybrid model could help balance scalability with control over environmental factors, such as light temperature and nutrient availability. A few key strategies include genetic engineering, structural improvements for cultivation, low-cost microbubble generation, hybrid absorption methods and ultraviolet spectrum conversion (French, 1998). Each of these has unique advantages; microbubble technology has been found to increase biomass productivity by increasing the surface area available for gas exchange between the algae and surrounding medium, thereby boosting carbon capture efficiency (Udaypal et al., 2024).

Phytohormones can be added to the growth medium to regulate cellular growth and metabolism. By influencing key enzymes, such as rubisco - an enzyme directly involved with carbon fixation - phytohormones have the potential to enhance algal productivity (French, 1998). Different phytohormones affect different metabolic pathways depending on what you want to change, whether it is improved growth rates, higher lipid production, or increased carbon capture efficiency (Udaypal et al., 2024).

The selection of optimal algal strains is crucial for enhancing biomass production and maximising carbon capture efficiency. Different strains of algae exhibit varying levels of tolerance to environmental stresses such as light intensity, salinity, temperature, and nutrient availability. Bioprospecting is a systematic and organised search for species that can be developed further based on their characteristics (Padma Nambisan, 2017). By bioprospecting, naturally tolerant strains can reduce the need for energy-intensive systems or genetic modification. Extremophilic microalgal strains may be tolerant to high salinity or temperature, making cultivation easier by reducing the costs associated with maintaining conditions.

4.1.3.3. Engine exhaust as a feedstock. One promising approach proposed is the integration of microbial fuel cells for indirect carbon capture, which is similar to Beltran et al. (2018)'s exploration of bicarbonate formation for algae-based carbon capture (Sharma et al., 2023). Both studies emphasise the role of algae in utilising CO_2 from flue gases though (Sharma et al., 2023) focus on microbial fuel cells (MFCs) for electricity generation whilst Beltran et al. (2018) concentrate on direct algal carbon capture using *Akistrodesmus falcatus* (Beltran et al., 2018; Sharma et al., 2023). The system described by Sharma et al. (2023) uses the ability of algae to thrive on the bicarbonates formed from the CO_2 in engine exhaust and flue gases, offering a potential simultaneous benefit of CO_2 sequestration and electricity generation. In this process, CO_2 from engine emissions is converted to bicarbonate, this not only minimises gaseous CO_2 losses but also creates a more stable form of carbon for the algae to utilise (Sharma et al., 2023). Beltran et al. (2018) explored the use of *Ankistrodesmus falcatus* for carbon capture from flue gases through bicarbonate formation, further supporting the effectiveness of this method in promoting algae growth and improving overall carbon fixation. This is a good example of how microalgae carbon capture can be used at a smaller scale, and using engine exhausts is promising for smaller, industrial uses such as those addressed in this review.

Research by Mallick et al. (2024) provides valuable insight into the carbon sequestration capabilities of *Chlorella vulgaris* when exposed to diesel engine exhausts. They identified several species, including *Chlorella sp.*, *Scenedesmus sp.*, *Nannochloropsis sp.* and *Botryococcus sp.*, as effective in capturing CO_2 from flue gases, though their study focuses on *Chlorella*. The findings reveal that microalgae not only sequester CO_2 but also benefit from it, showing more than a 44% increase in biomass productivity and a 36% increase in growth rate when exposed to exhaust emissions. In a glass column PBR, *Chlorella* was able to remove 24% of CO_2, while in a stirred-tank PBR, it achieved an annual sequestration of 2234 kg of CO_2 (Mallick et al., 2024).

Das et al. (2022) highlight the potential of photosynthetic microbial fuel cells (PMFC) for carbon capture, with Fig. 20 illustrating the operational mechanisms of these systems. One major limitation of traditional MFCs is the accumulation of CO_2 in the system, which reduces the overall efficiency. By introducing microalgae, this issue is minimised by the algae as they remove the CO_2 and, through photosynthesis, generate oxygen, which acts as a terminal electron acceptor. This integration not only enhances carbon capture but also improves the overall functionality of MFCs (Das et al., 2022).

Similarly, Udaypal et al. (2024), like A. Sharma et al. (2023) investigated hybrid systems that incorporate microalgae into industrial systems, aiming to optimise carbon capture. Although specific research on using engine exhaust specifically as a feedstock is limited, most studies focus on the broader use of flue gases. These preliminary findings indicate that algae-based systems, particularly in combination with innovative technologies like PMFCs, hold significant promise for capturing CO_2 from industrial sources.

A comparison of the carbon capture capabilities across various algal strains using flue gas as the feedstock is summarised in Table 7. These studies look at carbon capture across different scales and conditions, all of which can influence the capturing efficiency. Certain conditions, such as higher CO_2 concentrations and optimal temperature and pH, are critical for achieving maximum carbon capture efficiency, but this ranged widely across species. This table highlights distinct species-specific con-

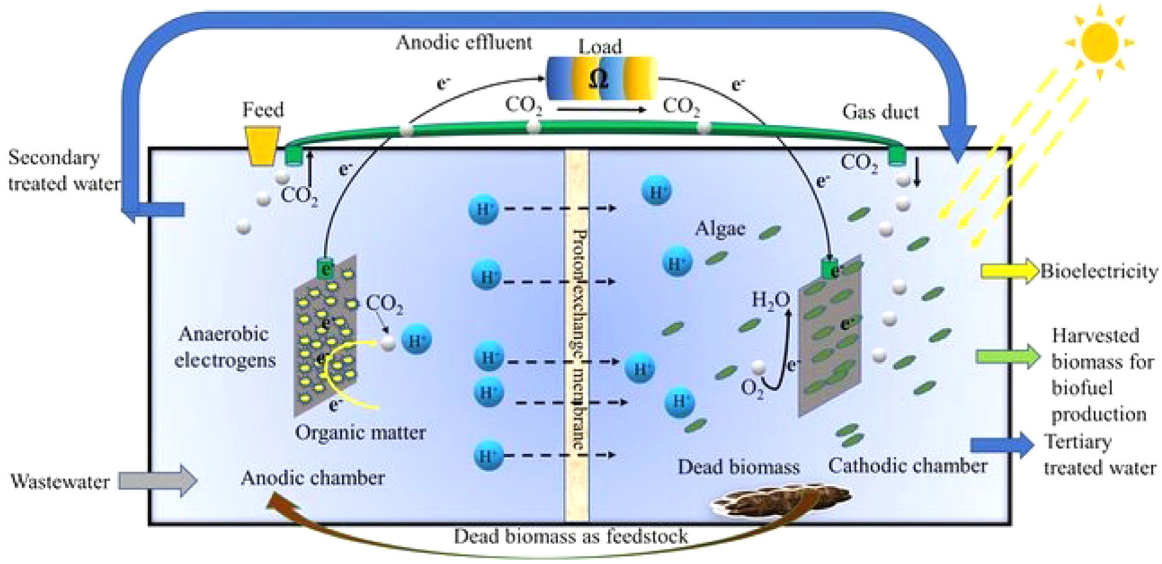


Fig. 20. Schematic of a Photosynthetic Microbial Fuel Cell: illustrating the process of converting wastewater and sunlight into bioelectricity and biofuel (Das et al., 2022).

Table 7
An analysis of various algae species across diverse circumstances and scales, along with their corresponding carbon capture potential.

Algae Species	Carbon Capture Ability	Operating Conditions	Scale	Reference
Chlorella sp.	CO_2 sequestration: 0.974 g/L	26–30 °C, pH 6.8, 12:12h light: dark period. 5% direct flue gas mixed with air was the most efficient.	500 ml Bubble Column PBR	(Yadav et al., 2015)
Nannochloropsis sp.	CO_2 sequestration: 1.23 g/L	22 °C, pH 6.3–8.8, artificial seawater, 12:12h light: dark cycle. Compressed synthetic flue gas (diesel engine exhaust, 11% CO_2)	1 L Bubble Column Bioreactor	(Banerjee et al., 2019)
Scenedesmus obliquus	0.97 g/L biomass, 67% CO_2 Removal Rate	26 °C, pH 7–8, 12–13k lux constant light, 12–14% CO_2	Pilot Scale (100L PBR)	(F. F. Li et al., 2011)
Spirulina platensis	CO_2 Sequestration: 0.45 g/L	32–37 °C, pH 9–11, natural daylight, Purified CO_2 from flue gas, 10% CO_{l8}	Large-Scale Open Raceway Ponds, 193,600L	(B. Zhu et al., 2020)

ditions and efficiencies. *Chlorella* and *Nannochlorpsis* are found to perform well in controlled, smaller-scale systems, whereas *spirulina* has been successfully used for sequestration at a large, open raceway pond scale. Sharma et al. (2023) outline a comprehensive table comparing the effects of flue gases and flue gas-derived bicarbonate on the algae biomass productivity. Other review papers give a broader overview of algal carbon capture capabilities, such as Yang et al. (2024) who provide a more comprehensive table of algal carbon capture capabilities based on objectives and using concentrated CO_2. Together, these insights underscore the potential of applying algal carbon capture at an industrial scale.

4.2. Oxy-combustion carbon capture from diesel engines

The oxyfuel combustion (OFC) technology was first proposed by Abraham et al. (1982) in 1982. This technology has emerged as a promising solution for reducing emissions from diesel engines, particularly in the transportation sector (Li et al., 2022b). In this approach, pure oxygen is used for combustion instead of air, resulting in exhaust gases primarily composed of CO_2 and water vapour, simplifying the CO_2 capture process (Ghiami et al., 2021; Luján et al., 2023). Recent studies have demonstrated the feasibility of implementing oxyfuel combustion in compression ignition engines, utilising oxygen separation membranes to enable CO_2 capture (Li et al., 2022b). This technology not only aims to achieve near-zero NO_X emissions but also facilitates efficient CO_2 capture for subsequent storage or utilisation (Serrano et al., 2023). The utilisation of pure oxygen also improves the efficiency of the combustion (Peng et al., 2022). Researchers have explored various aspects of oxyfuel combustion in diesel engines, including the design of carbon capture systems, the impact on engine performance, and the optimisation of combustion parameters (Li et al., 2022b). Some innovative approaches involve coupling oxygen generation cycles with oxyfuel combustion spark ignition engines to achieve zero NO_X emissions and effective carbon capture (Serrano et al., 2023). Integrating oxyfuel combustion technology with diesel engines presents unique challenges, such as managing combustion temperatures and adapting engine control systems. Still, it offers significant potential for reducing the carbon footprint of internal combustion engines in various applications, including maritime transport and heavy-duty vehicles (Li et al., 2022b). The other challenge and disadvantage is the necessity of providing pure oxygen for this process, which is costly. The design of a CCS unit for oxy-combustion also adds to the cost. The application of oxyfuel combustion for engines is an attractive idea, but the primary issues limiting this technology in practical engines are the cost of oxygen, the expense of CCS, the amount of space required for installing exhaust treatment equipment, and the onboard storage of CO_2 (Peng et al., 2022).

A typical concept of oxy-combustion application in an internal combustion (IC) engine is shown in Fig. 21. In addition to typical IC engines working based on oxy-combustion technology, there are diesel-based Internal Combustion Rankine Cycles (ICRCs) that integrate a diesel engine with a Rankine cycle to enhance thermal efficiency by recovering waste heat from the exhaust gases and cooling systems and are shown in Fig. 22. In this hybrid setup, the diesel engine generates primary power through internal combustion, while the heat from exhaust gases is used

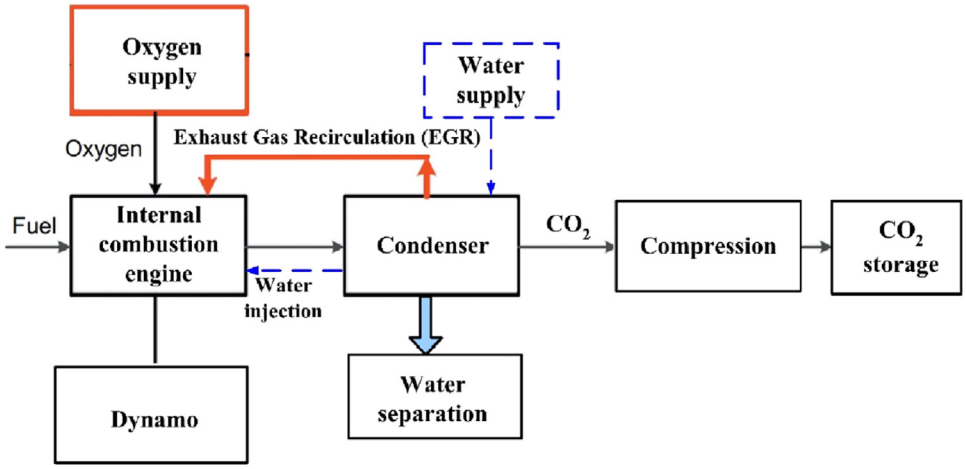


Fig. 21. A typical integration of IC engine running by oxy-combustion technology integrated to carbon compression and storage (Li et al., 2022b).

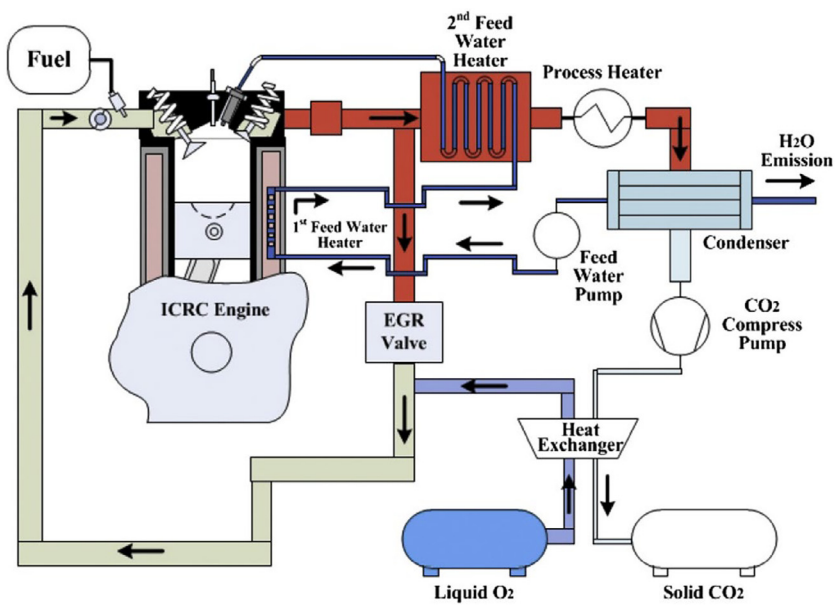


Fig. 22. Gasoline oxyfuel combustion engine (Wu et al., 2014a, 2014b).

to produce steam or drive a secondary working fluid in the Rankine cycle. This additional power generation significantly reduces energy losses and improves fuel utilisation. Diesel-based ICRCs are particularly attractive for heavy-duty applications and stationary power systems, offering a pathway to higher efficiency and lower emissions compared to standalone diesel engines.

More studies are available for oxy-combustion technology applications for engines. A study explores the performance of oxy-combustion systems for various fuels using a multifeatured combustion model validated against established software such as Chemical Equilibrium with Applications (CEA) and Gas Equilibrium (GASEQ). The study provides an in-depth exergy analysis of oxy-combustion at different oxygen fractions, equivalence ratios, and combustion chamber inlet temperatures. Key findings highlight that oxy-combustion reduces exergy destruction by approximately 1.5 times compared to conventional combustion, making it more efficient. Diesel was identified as the most advantageous fuel in terms of temperature ratios and exergy performance, while natural gas was found to be the best in minimising exergy destruction. The study underscores the potential of oxy-combustion systems in advancing cleaner and more efficient energy technologies (Ozsari and Ust, 2019).

Another study investigated the feasibility of implementing oxyfuel combustion in a practical diesel engine operating at economical oxygen-fuel ratios, using one-dimensional simulations (Li et al., 2020). The study explores various optimisation parameters, including fuel injection timing, intake charge temperature, intake composition, engine compression ratio, and water injection strategies, to recover engine power. Key achievements include demonstrating that OFC can achieve the same brake power as conventional air combustion (CAC) by increasing the oxygen-fuel ratio from 1.0 to 1.5. The findings show that optimising these parameters reduces the power losses initially observed in OFC, achieving a power output comparable to CAC while supporting carbon capture and storage (CCS). This work contributes to the development of zero-carbon solutions for inland waterway vessels (Li et al., 2020).

Another study explores the development and optimisation of an oxyfuel combustion system for compression-ignition (CI) engines, focusing on ultra-low emissions powerplants. Using computational fluid dynamics (CFD) and particle swarm optimisation (PSO), the research proposes an innovative design for the combustion system, including modifications to the piston bowl geometry, fuel injection parameters, and engine settings. The study successfully reduces soot emissions to near-zero levels while achieving significant reductions in carbon monoxide (CO) and unburned hydrocarbons. The optimised system demonstrates a 35.7% efficiency, improving from the baseline oxyfuel case while enabling the capture of high-purity CO_2 for carbon sequestration applications. This work highlights the potential of oxyfuel combustion as a pathway to cleaner, more sustainable engine technologies (Serrano et al., 2022).

In a diesel engine operating in the Homogeneous Charge Compression Ignition (HCCI) mode, the impact of intake charge temperature on OFC has been studied (Mobasheri et al., 2023). When the intake charge temperature is lower, combustion stability deteriorates and incomplete OFC results. With a higher intake charge temperature, combustion occurs earlier with shorter main stages, lowering the indicated mean effective pressure (IMEP) and increasing the indicated specific fuel consumption (ISFC).

5. Sustainable development goals and emission control in diesel engines

Throughout this review, we have explored various strategies to mitigate the environmental and health impacts of emissions from diesel generators, including pollutant emission control and potential carbon capture technologies for the diesel generator sector. Each of these approaches addresses different facets of the emission challenge, collectively contributing to a more comprehensive solution. Diesel generators, given their critical role in providing reliable energy in remote areas and under emergency conditions, remain indispensable in many regions, especially in developing countries where energy access is still limited.

By integrating advanced emission control technologies into diesel generator systems, we not only address pressing environmental challenges but also contribute to achieving the United Nations Sustainable Development Goals (SDGs). The United Nations' SDGs provide a blueprint for achieving a more sustainable future for all (Ingo et al., 2024). The research on emission control and CO_2 capture from diesel generators and engines has significant implications for several of these goals. This section explores how advancements in diesel engine technology and emission control contribute to global sustainable development efforts.

5.1. SDG 3: good health and well-being

Reducing harmful emissions from diesel engines directly contributes to SDG 3, which aims to ensure healthy lives and promote well-being. Diesel engine emissions, including PM, NO_X, CO, and HC, are associated with respiratory diseases, cardiovascular problems, and increased mortality rates, particularly in urban areas with high traffic density (Karimi et al., 2020).

Advanced emission control technologies, such as SCR and DPF, play a crucial role in mitigating these health risks. The research on alternative fuel blends and additives also shows promise in reducing emissions and their associated health impacts. Furthermore, CO_2 capture technologies for diesel engines contribute to preventing health issues related to climate change (Arya et al., 2022).

Recent studies highlight that reducing black carbon and NO_X emissions from diesel engines, including diesel generators used for power production, can significantly lower the prevalence of respiratory illnesses and reduce premature deaths associated with cardiovascular diseases. A study by the Health Effects Institute (HEI) reported that prolonged exposure to diesel exhaust particles from industrial and residential diesel generators increases the risk of chronic obstructive pulmonary disease (COPD) and lung cancer (Health Effects Institute, 2024). Moreover, implementing advanced DPFs in generators operating in enclosed or high-density environments has shown a significant reduction in fine particulate emissions, substantially improving air quality. Additionally, CO_2 capture technologies specifically designed for stationary diesel engines, such as adsorption-based systems, are increasingly being deployed, further mitigating the health impacts of emissions linked to climate change (McLaughlin et al., 2023).

5.2. SDG 7: affordable and clean energy

The development of cleaner diesel engine technologies supports SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all (Ingo et al., 2024). Diesel generators are crucial in providing electricity in many parts of the world, especially in developing countries and remote areas (IEA, 2024). Improving their efficiency and reducing emissions makes this energy production more sustainable.

Alternative fuels like biodiesel offer renewable alternatives to traditional diesel fuel. The implementation of CO_2 capture technologies also contributes to reducing the carbon footprint of diesel energy sources. These advancements can bridge the gap between current fossil fuel-based systems and future renewable energy systems, particularly in regions where an immediate transition to renewables is challenging (Ingo et al., 2024).

The trend in microgrid technologies, which integrate diesel generators with renewable sources like solar and wind, has enabled communities in remote areas to achieve stable and clean energy access. They indicate the potential of hybrid microgrids combining diesel and solar PV systems in providing reliable power in off-grid regions, reducing fuel consumption and emissions (Dei and Batjargal, 2022; Khamharnphol et al., 2023). For instance, hybrid systems combining biodiesel-powered generators with solar photovoltaics (PV) are being deployed in South Asia to reduce reliance on fossil fuels while maintaining energy affordability

5.3. SDG 9: industry, innovation, and infrastructure

Research in emission control and CO_2 capture technologies aligns with SDG 9, which aims to build resilient infrastructure, promote sustainable industrialisation, and foster innovation. The development of nanofuel additives, advanced emission control systems, and CO_2 capture technologies exemplifies the kind of research that SDG 9 seeks to promote (Gad et al., 2023). These innovations not only improve the environmental impact of diesel engines but also have the potential to create new industries and job opportunities in the green technology sector.

Emerging industries are focusing on producing advanced materials for emission control, such as porous ceramics for diesel particulate filters and catalytic coatings for SCR systems. A report by Grand View Research (Grand View Research, 2024) projects significant growth in the emission control technology market, driven by innovations in materials science. Moreover, international collaborations, such as those spearheaded by the International Energy Agency (IEA), are fostering innovation hubs to develop next-generation diesel emission solutions. The IEA's technology collaboration programme on Advanced Motor Fuels (AMF) facilitates global partnerships to advance cleaner diesel technologies (Schramm, 2023).

5.4. SDG 11: sustainable cities and communities

Advancements in emission control for diesel engines contribute to SDG 11, which aims to make cities inclusive, safe, resilient, and sustainable. Urban areas, where the concentration of diesel vehicles and generators is often high, benefit significantly from reduced emissions (World Health Organization, 2024). The use of biodiesel blends, nanofuel additives, and advanced emission control systems can help reduce urban air pollution, leading to improved quality of life and reduced incidence of respiratory diseases.

Several major cities have implemented successful programs to reduce diesel emissions in urban environments. A notable example is London's bus retrofit initiative, where SCR technology demonstrated approximately 90% reduction in NO_X emissions during trials. The effectiveness of this approach led to the establishment of the Clean Vehicle Retrofit Accreditation Scheme (CVRAS) in 2017, which accredits retrofit technologies capable of reducing NO_X emissions from existing buses to meet Euro VI standards. This urban transport emission reduction strategy exemplifies how technological solutions can be effectively implemented to improve air quality in densely populated areas (The Rt Hon Louise Haigh MP, 2024), which demonstrates the importance of addressing the diesel engine challenges for achieving SDG 11.

5.5. SDG 13: climate action

The most direct connection between this research and the SDGs is with SDG 13, which calls for urgent action to combat climate change. CO_2 capture technologies for diesel engines directly address this goal by reducing greenhouse gas emissions from a significant source (IPCC, 2023). The exploration of post-combustion and oxy-combustion methods for CO_2 capture represents an important step towards reducing the carbon footprint of diesel engines. Research into alternative fuels, particularly biofuels, also contributes to climate action by promoting renewable energy sources with lower net carbon emissions.

Recent advancements in alternative fuel technologies show promising results in climate change mitigation efforts. Studies on hydrogen-diesel dual-fuel systems have demonstrated significant CO_2 emissions in experimental conditions (Bakar et al., 2024). The maritime sector, which contributes approximately 3% of global GHG emissions, has begun implementing hybrid propulsion systems combining conventional marine engines with hydrogen technologies and advanced computational modelling has enhanced the optimisation of these systems. The implementation of these technologies is being accelerated through international maritime regulations, with the International Maritime Organisation (IMO)' strategy targeting at least a 40% reduction in carbon intensity by 2030 (International Maritime Organization, 2011).

5.6. SDG 17: partnerships for the goals

The research efforts described in this manuscript exemplify the global partnerships and collaboration that SDG 17 aims to strengthen. Advancing emission control and CO_2 capture technologies requires cooperation between academic institutions, industry partners, and governmental bodies across different countries. This collaboration can accelerate the adoption of cleaner diesel technologies worldwide and help in setting global standards for diesel engine emissions.

The research and development efforts in emission control and CO_2 capture for diesel engines, as discussed in our manuscript, have far-reaching implications for several of the UN's Sustainable Development Goals. By addressing issues of air pollution, climate change, energy access, and technological innovation, these efforts contribute to a more sustainable and equitable future.

As we continue to advance these technologies, it is crucial to keep the broader context of sustainable development in mind. The challenges we face in reducing emissions and capturing CO_2 from diesel engines are not isolated technical problems but part of a larger effort to create a more sustainable world. By aligning our research with the SDGs, we can ensure that our work contributes meaningfully to this global effort, creating technologies that not only solve immediate environmental problems but also support long-term sustainable development across various dimensions of human society and the natural environment.

6. Summary and future directions

6.1. Summary

This review paper provides a comprehensive analysis of emission control and carbon capture technologies for diesel generators and engines. Diesel generators provide energy in remote and developing regions, particularly areas with limited access to a power grid and essential and strategic areas such as airports, hospitals, and data centres. However, they significantly contribute to greenhouse gas emissions and air pollutants, such as NO_X, SO_X, CO, hydrocarbons, particulate matter, and CO_2. These emissions pose substantial environmental and health risks, necessitating the development and deployment of advanced mitigation strategies.

The review categorises pollutant emission control approaches into three main strategies: after-treatment technologies, engine modifications, and fuel modifications.

1. **After-treatment technologies** such as Selective Catalytic Reduction (SCR), Diesel Particulate Filters (DPF), Exhaust Gas Recirculation (EGR), and Diesel Oxidation Catalysts (DOC) were discussed in detail. These technologies address pollutants post-combustion and have demonstrated significant advancements, including improved catalyst materials, enhanced regeneration methods, and integration with diagnostic systems for real-time performance monitoring.
2. **Engine modifications** focus on optimising combustion processes to reduce emissions at the source. Techniques such as advanced fuel injection strategies, the Miller cycle, and in-cylinder combustion control were explored, showcasing their ability to improve combustion efficiency and reduce NO_X and particulate emissions.
3. **Fuel modification strategies** involve altering fuel properties to achieve cleaner combustion. Examples include biodiesel-diesel blends, alcohol-diesel blends, nanofuel additives, and the integration of hydrogen and ammonia. These alternatives improve combustion efficiency and reduce specific pollutants, such as particulate matter and polycyclic aromatic hydrocarbons (PAHs).

A significant portion of the review is dedicated to the potential of carbon capture technologies, including absorption, adsorption, algae bio-fixation, and oxy-combustion. These methods offer pathways to mitigate CO_2 emissions from diesel generators, aligning with global sustainability goals and Net Zero targets. Despite their promise, challenges such as scalability, cost, and integration feasibility remain critical areas for further research.

The paper also highlights the alignment of these emission control technologies with the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). By addressing the technological, environmental, and societal aspects of diesel emission control, this review provides a holistic perspective on the challenges and opportunities in achieving sustainable energy solutions.

6.2. Future directions

Future research in emission control and carbon capture technologies for diesel generators should prioritise the following areas to address existing gaps and advance sustainability goals:

1. **Integration of Advanced Carbon Capture Technologies:** While significant advancements have been made in CO_2 capture methods such as absorption, adsorption, algae bio-fixation, and oxy-combustion, their application to diesel generators remains under-explored. Future work should focus on designing scalable and cost-effective carbon capture solutions tailored explicitly for diesel engines. This includes developing compact and energy-efficient systems suitable for small and mobile diesel generators used in remote locations.
2. **Exploration of Novel Fuel Blends:** Research should continue investigating alternative fuel blends, such as hydrogen, ammonia, and alcohol-based fuels, to reduce emissions and enhance efficiency. Further optimisation of blending ratios, injection strategies, and combustion conditions is essential to address challenges like engine knock, NO_X formation, and fuel storage issues.
3. **Focus on Unregulated Pollutants:** Beyond regulated emissions like NO_X, SO_X, and PM, future studies should delve deeper into the characterisation and mitigation of unregulated pollutants, such as polycyclic aromatic hydrocarbons (PAHs) and secondary organic aerosols. Understanding the formation mechanisms of these pollutants under varying operating conditions, including cold starts and low loads, will be critical.
4. **Advancements in After-treatment Technologies:** Developing next-generation after-treatment systems, such as perovskite-based catalysts and non-thermal plasma-assisted technologies, holds

promise for achieving higher conversion efficiencies for NO_X and particulate matter. Research should explore integrating these advanced materials with existing systems to improve performance and reduce costs.

5. **Techno-Economic Analysis:** Comprehensive techno-economic assessments of emission control and carbon capture technologies are needed to evaluate their feasibility and scalability. These analyses should consider lifecycle costs, environmental benefits, and compatibility with existing infrastructure.
6. **Policy and Global Collaboration:** Stronger collaborations between academia, industry, and policymakers are essential to accelerate the adoption of these technologies. Initiatives should focus on developing global standards and frameworks to support widespread implementation, particularly in developing regions where diesel generators are crucial for energy access.
7. **Application in Hybrid and Renewable Systems:** Integrating diesel generators with renewable energy systems, such as solar or wind, and hybrid configurations could further reduce reliance on fossil fuels. Research should explore the compatibility of emission control technologies within these hybrid systems to optimise performance and sustainability.

By addressing these areas, future research can contribute to a more sustainable and efficient use of diesel generators, aligning with global climate and energy goals.

Declaration of competing Interest

The authors have declared no conflict of interest.

CRediT authorship contribution statement

Shervan Babamohammadi: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amy R Birss:** Writing – original draft. **Hamid Pouran:** Writing – original draft, Methodology. **Jagroop Pandhal:** Supervision. **Tohid N. Borhani:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

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