

Review

Methanol-gasoline blends in spark-ignition engines: A review of research progress and application prospects

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Abstract: Spark-ignition engines remain widely used in passenger cars, motorcycles, hybrid vehicles, and light-duty transport, making fuel flexibility and emission reduction important during the transition to low-carbon mobility. Methanol-gasoline blends have attracted attention as alternative fuels because methanol has high oxygen content, high octane quality, strong charge-cooling capacity, and flexible production routes.

This review summarizes recent progress in methanol-gasoline blends for spark-ignition engines, covering fuel properties, blending ratios, combustion behavior, engine performance, regulated and unregulated emissions, life-cycle impacts, and application prospects. The literature shows that methanol addition can enhance knock resistance, promote oxygenated combustion, reduce soot-forming tendency, and support higher compression ratios, optimized ignition timing, and lean-burn operation. However, its lower energy density increases fuel consumption, while water affinity, phase separation, cold-start difficulty, corrosion, and material compatibility remain key barriers. Emission responses are strongly condition-dependent. CO and particulate emissions are often reduced, whereas HC and NO_x vary with operating condition, mixture preparation, injection strategy, and after-treatment performance. Formaldehyde, unburned methanol, and cold-start oxygenated emissions require further attention. Life-cycle benefits depend mainly on methanol production pathways. Low-level blends are more suitable for near-term use in existing engines, while higher blends require optimized engines, compatible fuel systems, green methanol supply, infrastructure readiness, and cost reduction.

Keywords: methanol-gasoline blends; spark-ignition engines; alternative fuels; methanol blending ratio; combustion behavior; exhaust emissions

Abbreviations

Abbreviation	Full name
AFDC	Alternative Fuels Data Center
AFR	Air-fuel ratio
ANN	Artificial neural network
BMEP	Brake mean effective pressure
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
CO	Carbon monoxide
CO ₂	Carbon dioxide
CR	Compression ratio
DISI	Direct-injection spark-ignition
EGR	Exhaust gas recirculation
EIA	U.S. Energy Information Administration
GDI	Gasoline direct injection
GHG	Greenhouse gas
HC	Hydrocarbons
LCA	Life-cycle assessment
LHV	Lower heating value
Mx	Methanol-gasoline blend containing $\times$ vol.% methanol
NEDC	New European Driving Cycle
NO _x	Nitrogen oxides
PM	Particulate matter
RON	Research octane number
RSM	Response surface methodology
SI	Spark ignition
THC	Total hydrocarbons
VOCs	Volatile organic compounds

1. Introduction

Energy-security concerns, petroleum dependence, and emission-reduction targets are driving the search for low-carbon alternative fuels for transportation. At the same time, despite the rapid development of vehicle electrification, spark-ignition engines remain widely used in passenger cars, motorcycles, hybrid vehicles, and light-duty transportation. Alcohol fuels have therefore attracted attention because of their oxygenated structure, high octane quality, and compatibility with gasoline engines [1]. Among them, methanol is particularly attractive because it combines high oxygen content, strong charge-cooling and anti-knock characteristics, and flexible production routes from coal, natural gas, biomass, municipal waste, industrial off-gas, and CO₂ hydrogenation [2,3]. When produced from

renewable resources or captured CO₂ with green hydrogen, methanol may further support life-cycle carbon reduction [4].

Methanol-gasoline blends offer both advantages and limitations. Methanol's high octane number can improve knock resistance and may allow higher compression ratios, advanced ignition timing, or more aggressive high-load operation [5]. Its oxygenated structure can promote more complete combustion and reduce carbon monoxide and particulate emissions under suitable conditions [6]. Its high latent heat of vaporization can cool the intake charge and suppress knock, especially under heavy-load conditions [7]. However, methanol has a much lower heating value than gasoline and is polar and hygroscopic, which may increase fuel consumption and cause phase separation, corrosion, cold-start difficulty, and material compatibility problems [8]. Alcohol-gasoline blend studies have also shown that fuel composition can change volatility, distillation behavior, evaporation, and mixture preparation [9]. These features indicate that methanol-gasoline blends should be evaluated as fuel-engine systems rather than simple drop-in gasoline substitutes.

The behavior of methanol-gasoline fuels is strongly affected by the blending ratio and engine calibration. Recent studies have shown that compression ratio and ignition timing influence combustion phasing and thermal efficiency [10–13], while lean combustion, stratified operation, and split injection affect mixture formation, combustion stability, and emissions [14–16]. Spray development and predictive modeling have also been investigated to support fuel-specific engine optimization [17,18]. In addition, optimized split injection in a methanol-fueled direct-injection spark-ignition engine shortened combustion duration and ignition delay while reducing formaldehyde and unburned methanol emissions [19]. These findings highlight the importance of fuel-engine co-optimization rather than fuel substitution alone.

Emission characteristics are central to the evaluation of methanol-gasoline blends. Studies on M15-fueled light-duty spark-ignition engines have examined regulated and unregulated emissions, particulate emissions, and catalytic converter efficiency [20]. Other work on alcohol-gasoline blends has shown that particulate composition, morphology, and characteristics may vary with fuel composition [21]. Methanol oxidation may also produce formaldehyde, acetaldehyde, and unburned methanol, especially during cold start or incomplete combustion, while vehicle-level studies have evaluated methanol application from both carbon-emission and pollutant-emission perspectives [22]. Thus, both regulated and unregulated emissions should be considered.

Recent research has further extended methanol-gasoline studies toward multi-fuel combustion, renewable fuels, modeling, and practical application issues. Hydrogen addition has been investigated as a method to improve combustion under different excess-air conditions [23]. Renewable methanol and hydrogen have also been connected with spark-ignition engine performance and emissions, suggesting the potential of multi-fuel low-carbon combustion strategies [24]. Artificial neural networks have been applied to predict engine performance and emissions using gasoline-methanol blends [25]. Noise, vibration, combustion stability, and engine operating quality should also be considered because methanol addition may affect engine drivability [26].

The bibliometric overview in Figure 1 presents the keyword co-occurrence patterns, country collaboration network, and annual publication output in methanol-gasoline blend research. The decrease in 2026 should be interpreted as a partial-year result rather than a decline in research activity. In addition, modern gasoline direct-injection engines already face challenges such as particulate emissions, wall wetting, and calibration complexity [27]. Existing reviews and experiments have shown that the effects of methanol addition depend strongly on engine type, blending ratio, operating

condition, and methanol fraction [28,29]. Low-temperature operation can worsen evaporation and cold-start performance, leading to higher hydrocarbon and unregulated emissions [30]. Recent experimental and artificial neural network–based studies further show that predictive tools can support the evaluation of methanol-gasoline engine behavior under different fuel and engine conditions [31].

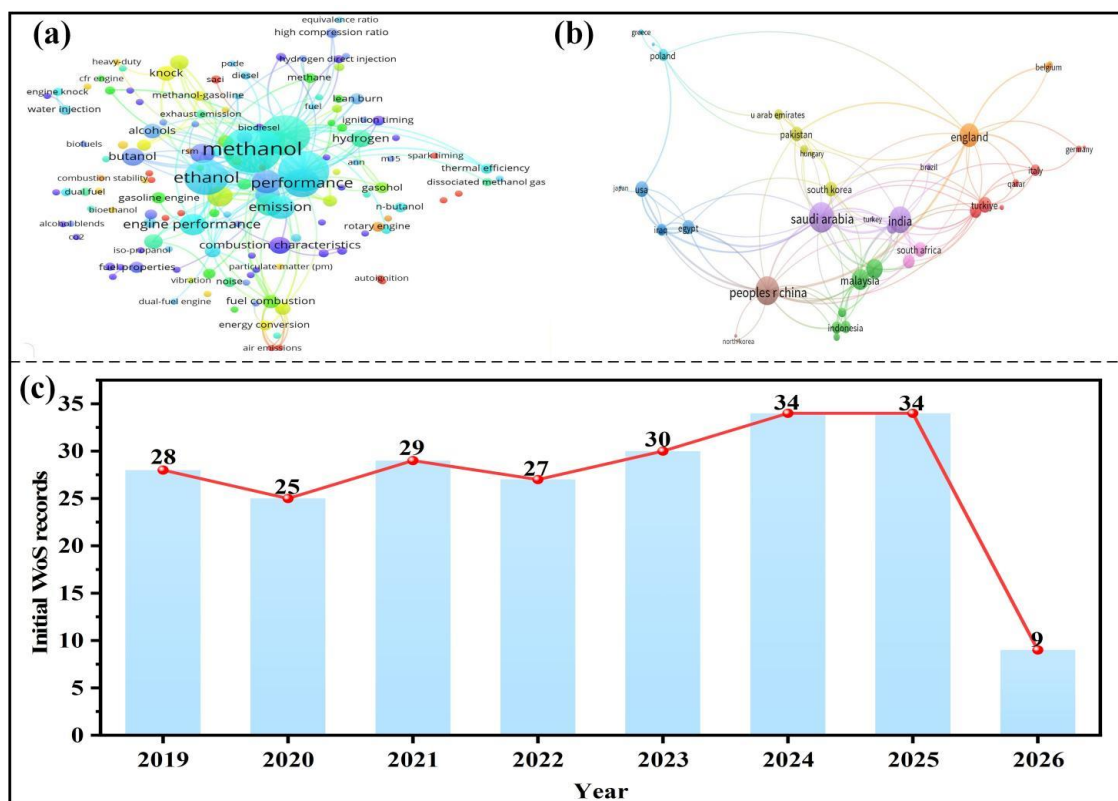


Figure 1. Bibliometric overview of methanol-gasoline blend research based on the Web of Science Core Collection: (a) keyword co-occurrence overlay visualization; (b) country collaboration network; and (c) annual publication output from 2019 to 2026.

To improve the transparency and reproducibility of this review, a structured, bibliometric-assisted narrative review method was adopted. The literature search was based mainly on the Web of Science Core Collection, and the search was conducted on 24 April 2026. The primary publication period was 2019–2026, with 2019 selected because the comprehensive review by Verhelst et al. [2] synthesized earlier research on methanol as an engine fuel and provided a suitable baseline for examining subsequent developments. Earlier key studies were retained when they provided fundamental information on methanol fuel properties, spark-ignition combustion, fuel and material compatibility, or life-cycle assessment. The search strategy was constructed around three groups of terms: fuel-related, engine-related, and environmental-assessment terms. The fuel-related terms included “methanol-gasoline blend”, “gasoline-methanol blend”, “M15”, “M30”, “M85”, “green methanol”, and “e-methanol”; the engine-related terms included “spark-ignition engine”, “SI engine”, “direct-injection spark-ignition engine”, “combustion”, “engine performance”, “regulated emissions”, “unregulated emissions”, “particulate matter”, and “formaldehyde”; and the environmental-assessment terms included “well-to-wheel”, “life-cycle assessment”, and “environmental impact”.

A total of 216 records were initially exported from the Web of Science Core Collection. The screening process was conducted in two stages. In the first stage, a preliminary relevance check was performed based on titles, abstracts, keywords, source information, and research scope. Studies were retained when they were related to methanol-gasoline blends, methanol as a spark-ignition engine fuel, combustion and engine performance, regulated or unregulated emissions, material compatibility, low-carbon methanol pathways, or environmental life-cycle assessment. Studies that were clearly outside the scope, such as those focusing only on unrelated fuels, non-SI combustion systems, non-engine applications, or topics without relevance to the methanol-gasoline blend application, were not selected for detailed screening. After this preliminary check, 179 records were retained for detailed screening and classification.

In the second stage, the 179 records were classified according to their relevance and function in this review. Category A included core studies directly related to methanol-gasoline blends, spark-ignition engines, combustion behavior, engine performance, emissions, fuel stability, material compatibility, or application challenges. Category B included studies used for comparison or supporting discussion, such as broader alcohol-gasoline fuel studies, modeling studies, low-carbon fuel studies, and related engine-control research. Category C included background references used mainly for general context, fuel-property explanation, or research-trend discussion. Category D included records excluded from the main review because their relevance to methanol-gasoline blends or spark-ignition engine application was insufficient. Based on this classification, 80 studies were identified as core references, 21 as comparative or supporting references, 8 as background references, and 70 as excluded records.

The retained studies were then synthesized using thematic classification rather than quantitative meta-analysis. This approach was adopted because the reviewed studies differed substantially in engine type, injection mode, blend ratio, operating condition, test cycle, emission-measurement method, and life-cycle system boundary. The main themes included fuel properties and blend stability, combustion and engine control, brake power and torque, brake-specific fuel consumption, brake thermal efficiency, regulated emissions, unregulated emissions, material compatibility, low-carbon methanol pathways, economic feasibility, and commercialization challenges. Where numerical data were available, representative values were extracted and compared. Because the reviewed studies differed substantially in engine configuration, injection mode, operating condition, and measurement method, absolute values from different studies were not treated as directly equivalent. Instead, performance and emission changes were preferentially expressed as relative variations from the gasoline baseline reported within each study. Where numerical normalization was not possible, the results were compared using directional trends, including increases, decreases, or negligible changes.

To provide a descriptive statistical synthesis, relative changes in brake thermal efficiency, brake-specific fuel consumption, CO, HC, NO_x, and particulate emissions were extracted when a gasoline baseline was available. The relative change in each indicator was calculated as $\Delta X = (X_{\text{blend}} - X_{\text{gasoline}}) / X_{\text{gasoline}} \times 100\%$. When multiple operating points were reported in the same study, the median within-study change was used so that each study contributed only one value per indicator. The number of studies, median, interquartile range, minimum-maximum range, and proportion of favorable responses were then calculated. Because of substantial heterogeneity in engine configuration, operating conditions, and measurement methods, no pooled effect size or inferential significance test was performed.

As shown in Figure 2, combustion and engine control, engine performance, and emissions are the

dominant themes in the retained literature. Because one study may involve more than one theme, the heatmap reflects multi-label thematic coding rather than mutually exclusive categories. Among the retained records, combustion and engine control appeared most frequently, with 101 coded occurrences from 2019 to 2026, followed by engine performance with 97 occurrences, and emissions with 89 occurrences. These three themes also show high values in recent years, especially in 2023–2025, indicating that current methanol-gasoline blend research remains strongly engine-oriented.

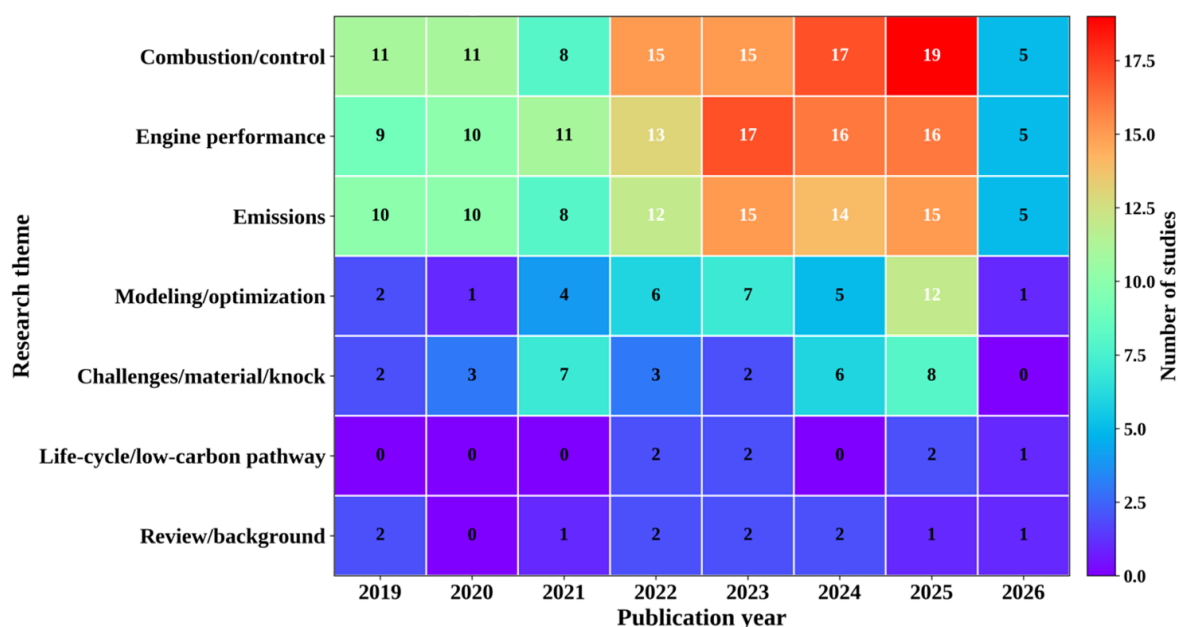


Figure 2. Heatmap of the thematic distribution of retained literature on methanol-gasoline blends based on the Web of Science Core Collection from 2019 to 2026.

Modeling/optimization and challenges related to materials, knock, and compatibility received less attention overall, with 38 and 31 coded occurrences, respectively, but both increased in the later part of the reviewed period. For example, modeling/optimization reached 12 occurrences in 2025, while challenges/material/knock reached 8 occurrences in the same year. In contrast, life-cycle/low-carbon pathway studies accounted for only 7 coded occurrences, mainly appearing after 2022. This indicates that life-cycle assessment and low-carbon fuel-supply pathways have not yet been systematically addressed in engine-oriented methanol-gasoline studies. Therefore, the following review is organized around fuel properties, combustion and performance, emissions, practical challenges, and future low-carbon assessment needs.

For the environmental life-cycle discussion, this review does not conduct a full life-cycle assessment or derive universal vehicle-level emission factors. Life-cycle issues are considered only as an important future assessment direction, because the environmental performance of methanol-gasoline blends cannot be determined from tailpipe emissions alone. Previous LCA and techno-economic studies are used only to support a qualitative discussion of potential influencing factors and future research needs. Overall, this review follows a structured literature search, relevance screening, thematic classification, and pathway-oriented synthesis method to evaluate methanol-gasoline blends from fuel, engine, emission, application, and future-development perspectives.

Table 1. Classification of selected studies on methanol-gasoline blends and related alcohol fuels.

Research focus	Representative studies	Main contribution	Remaining gap
General alcohol fuels in SI engines	[1–3]	Summarized combustion, performance, and emission characteristics of alcohol fuels	Methanol-gasoline blends are not always discussed separately
Methanol as SI engine fuel	[2,4]	Assessed methanol properties, combustion potential, and engine applicability	Limited integration with gasoline blending and commercialization
Fuel properties and blending stability	[8,9]	Discussed phase stability, volatility, and fuel formulation issues	Long-term storage and material compatibility still need further study
Knock resistance and high-load combustion	[5,7,10]	Demonstrated methanol's octane and charge-cooling advantages	Optimization depends on compression ratio and injection strategy
Engine performance	[11–13,29]	Evaluated power, torque, BSFC, BTE, and ignition timing effects	Results vary with engine type, blend ratio, and operating condition
Injection, spray, and mixture formation	[14–18]	Studied DISI combustion, lean burn, two-stage injection, spray, and control parameters	More real-engine validation is needed
Regulated and particulate emissions	[6,18,20,21]	Reported effects on CO, HC, NO _x , PM, and particle characteristics	Emission trends are not fully consistent across conditions
Unregulated emissions and after-treatment	[20,22–24]	Considered aldehydes, unburned methanol, catalyst efficiency, and multi-fuel strategies	More attention is needed for cold-start and real-driving emissions
Modeling and optimization	[12,25,31]	Applied 0D/1D modeling and ANN methods	Models need broader validation
Practical application challenges	[27–30]	Discussed GDI challenges, low-temperature emissions, and operational barriers	Infrastructure, standards, and green methanol supply remain key issues

The selected studies are classified in Table 1 according to research focus, representative studies, main contributions, and remaining gaps. This classification, together with the literature screening procedure described above, shows that current research on methanol-gasoline blends remains fragmented. Although many studies have investigated methanol fuel, alcohol-gasoline blends, combustion behavior, engine performance, emissions, spray behavior, modeling, and knock suppression, fuel properties, blending stability, engine calibration, regulated and unregulated emissions, material compatibility, and low-carbon methanol pathways are often discussed separately. Therefore, a comprehensive review is needed to evaluate methanol-gasoline blends as an integrated fuel-engine-carbon system.

To address this gap, the present review adopts a blend-ratio-centered fuel-engine-carbon perspective. Previous reviews have largely considered alcohol fuels as a broad category or focused on

individual topics such as methanol combustion, engine performance, and emissions [1–6,28]. In contrast, this review connects fuel formulation, engine calibration, emission control, material compatibility, and low-carbon methanol supply within a unified framework. The discussion covers five major aspects: fuel properties and production routes, combustion and engine performance, emission characteristics and environmental implications, technical and commercialization challenges, and future prospects. The overall framework is shown in Figure 3.

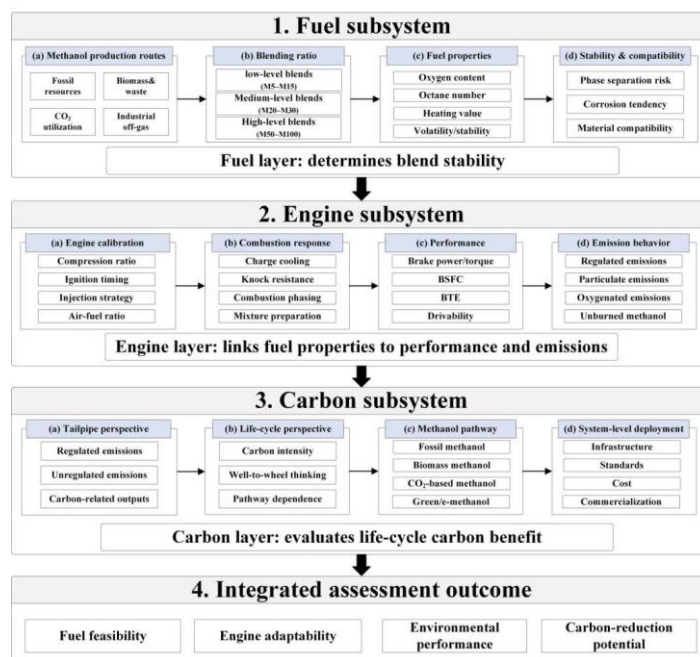


Figure 3. Integrated fuel-engine-carbon assessment framework for methanol-gasoline blends in spark-ignition engines.

Within this framework, the review examines how the methanol blending ratio changes fuel properties and mixture formation, how these changes interact with engine calibration to affect combustion, performance, and regulated and unregulated emissions, and how material compatibility, methanol production pathways, infrastructure, and cost influence practical deployment. This system-oriented assessment moves beyond a conventional engine-centered summary and distinguishes the near-term suitability of low-level blends from the technical requirements of medium- and high-level blends. It also identifies the main research priorities for the practical application of methanol-gasoline blends in low-carbon transportation.

2. Methanol-gasoline blends: properties, production, and fuel characteristics

Methanol-gasoline blends are affected by both upstream methanol production routes and downstream fuel-engine interactions. As shown in Figure 4, methanol can be produced from fossil resources, biomass and waste, CO₂ utilization, and industrial off-gas, and then blended with gasoline at different ratios for use in spark-ignition engines. The resulting blend properties, including oxygen content, octane quality, heating value, volatility, and stability, directly affect combustion behavior, engine performance, emissions, and practical application.

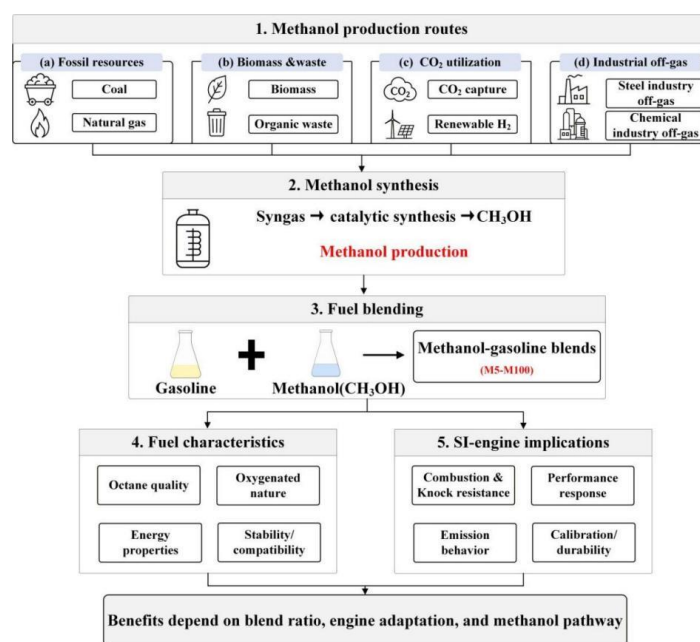


Figure 4. Production routes and fuel characteristics of methanol-gasoline blends.

2.1. Methanol as an alternative fuel component

Methanol has been widely investigated as an alternative fuel component for spark-ignition engines because it combines high oxygen content, high octane quality, strong charge-cooling potential, and flexible production routes. Oxygenated fuels can influence combustion efficiency, exhaust emissions, and thermal performance, although their effects depend strongly on engine type and operating conditions [32]. Compared with higher alcohols, methanol has a simpler molecular structure, higher oxygen content, and stronger evaporation-cooling potential, making it attractive for gasoline blending and high-load spark-ignition operation [33].

The high-octane quality of methanol is beneficial for knock resistance and may support higher compression ratios, optimized ignition timing, and high-load operation when suitable calibration is applied [34]. Methanol can also be produced from coal, natural gas, biomass, waste-derived resources, and CO₂ hydrogenation. Therefore, its practical value depends not only on engine performance but also on production pathway and carbon intensity. Fossil-based methanol mainly contributes to fuel diversification, whereas renewable or green methanol may provide greater life-cycle carbon reduction potential [35,36].

However, methanol also has important limitations as a gasoline blending component. Its lower heating value generally increases fuel consumption if the engine is not optimized, and experimental studies have shown that methanol addition can change both performance and emissions depending on methanol fraction and operating conditions [37]. In addition, methanol is polar and hygroscopic, which increases the risk of water absorption, phase separation, corrosion, and material compatibility problems. Co-solvents, surfactants, corrosion inhibitors, and compatible fuel-system materials have therefore been investigated to improve blend stability and durability [38,39]. Overall, methanol should be regarded as a functional blending component whose benefits depend on coordinated fuel formulation, engine calibration, and sustainable production.

2.2. Physicochemical properties of methanol-gasoline blends

The behavior of methanol-gasoline blends is closely related to their physicochemical properties. Methanol differs from gasoline in heating value, oxygen content, stoichiometric air-fuel ratio, latent heat of vaporization, volatility, polarity, and material compatibility. These differences explain why methanol addition can improve knock resistance and combustion cleanliness, while also causing higher fuel consumption, cold-start difficulty, volatility changes, and compatibility concerns.

Table 2. Physicochemical properties of gasoline, methanol, and their influence on methanol-gasoline blends.

Property	Gasoline	Methanol	Influence of methanol addition	Relevant standard	Ref.
Lower heating value	About 42–44 MJ/kg	About 19.9 MJ/kg	Lower energy content; higher fuel consumption	ASTM D4814/EN 228/GB 17930	[33,40]
Oxygen content	Nearly zero	About 50 wt.%	Better oxidation; lower CO/PM	ASTM D4814/EN 228/GB 17930	[33,42]
Research octane number	Usually 90–98	About 108–109	Higher knock resistance	ASTM D4814/EN 228/GB 17930	[33,41]
Stoichiometric air-fuel ratio	About 14.7	About 6.4	Injection/AFR adjustment required	ASTM D4814/EN 228/GB 17930	[33,40]
Latent heat of vaporization	Lower	Much higher	Charge cooling; cold-start penalty	ASTM D4814/EN 228/GB 17930	[33,43]
Boiling behavior	Wide distillation range	Single boiling point	Altered volatility and mixture formation	ASTM D4814/EN 228/GB 17930	[33,44]
Polarity	Non-polar	Polar	Higher water affinity; phase separation risk	GB/T 23510 /GB/T 23799	[38,44]
Material compatibility	Generally mature	More aggressive to some materials	Materials/additives required	GB/T 23799	[39,44]

The lower heating value of methanol decreases the energy content of the blend and usually increases volumetric fuel consumption, although this effect can be partly offset by optimized ignition timing, compression ratio, or injection strategy [40]. Its high research octane number improves knock

resistance and may allow more advanced combustion settings [41]. Its high oxygen content can promote local oxidation and reduce CO and particulate emissions under suitable conditions, but it also changes the stoichiometric air-fuel ratio and requires fuel-injection correction [42]. The high latent heat of vaporization provides charge cooling and knock suppression but may worsen cold-start performance at low temperatures [43]. In addition, methanol changes volatility and distillation behavior and increases the risk of water absorption and phase separation [44]. Long-term exposure may also affect metals, elastomers, plastics, seals, and other fuel-system materials [45]. These major properties and their expected influence are summarized in Table 2.

2.3. Influence of blending ratio

The blending ratio determines how far a methanol-gasoline fuel departs from conventional gasoline. Low-level blends such as M5–M15 usually retain gasoline-like characteristics and are more suitable for existing spark-ignition engines. However, even at low methanol contents, injection and ignition settings can affect regulated and particulate emissions, as shown in M15 direct-injection engine studies [46].

Medium-level blends such as M20–M30 show clearer changes in heating value, air-fuel ratio, and combustion behavior. Their higher oxygen content and octane quality may improve combustion and knock resistance, but greater fuel injection is needed to maintain the same energy input. Experimental work has shown that brake power, fuel consumption, and emissions vary with engine speed, load, and methanol content [47]. High-level blends such as M50–M85 are more suitable for flex-fuel or specially optimized engines. They can better use methanol's anti-knock and charge-cooling effects, but they also intensify problems related to fuel consumption, cold start, material compatibility, and fuel-system capacity [48,49].

Table 3. Influence of methanol blending ratio on fuel behavior and spark-ignition engine operation.

Blend range	Main characteristics	Engine requirement	Main limitation	References
M5–M15	Close to gasoline; slight increase in oxygen content	Usually compatible with existing SI engines	Limited efficiency and carbon reduction potential	[46]
M20–M30	Clearer changes in heating value, air-fuel ratio, and combustion behavior	Calibration of injection and ignition is recommended	Increased fuel consumption	[47]
M50–M85	Strong anti-knock and charge-cooling effects	Flex-fuel or optimized SI engine preferred	Cold start, material compatibility, and fuel-system demand	[48,49]
Advanced DI operation	Blend effect depends on spray and mixture preparation	Injection strategy optimization is needed	Greater control complexity	[50,51]

For direct-injection engines, blending ratio also affects spray behavior, evaporation, wall wetting, local equivalence ratio, and particulate formation. Recent studies on stratified lean burn and two-stage injection indicate that the blend ratio should be optimized together with the injection strategy rather

than treated as an isolated fuel parameter [50,51]. The main effects of different methanol blending ranges are summarized in Table 3.

2.4. Fuel stability and material compatibility

Fuel stability and material compatibility are key barriers to the practical use of methanol-gasoline blends. Because gasoline is mainly composed of non-polar hydrocarbons, whereas methanol is polar and hygroscopic, water contamination can cause a methanol-rich phase to separate from the gasoline-rich phase. This may lead to unstable fuel composition, poor startability, unstable combustion, and inconsistent emissions, especially at higher methanol contents or under humid storage conditions [52,53].

Methanol addition also changes the volatility and distillation behavior of gasoline, which may affect cold start, vapor formation, drivability, and mixture preparation [54]. Co-solvents and surfactants can improve water tolerance and help maintain a single liquid phase; Span 80 and Tween 80 have been investigated for gasoline-alcohol fuel stabilization [55]. However, additives may introduce additional issues such as dosage control, cost, long-term stability, deposit formation, and combustion influence.

Table 4. Main stability and material compatibility issues of methanol-gasoline blends.

Issue	Main cause	Possible influence	Possible solution	Ref.
Phase separation	Water absorption and polarity difference	Unstable fuel composition and poor startability	Co-solvents, surfactants, dry storage	[52,53,55]
Volatility change	Different evaporation behavior of methanol and gasoline	Cold-start and drivability problems	Volatility adjustment and optimized blending ratio	[54]
Water affinity	Hygroscopic nature of methanol	Phase instability and corrosion risk	Fuel quality control and sealed storage	[52,53]
Corrosion	Water, oxygen, impurities, and alcohol-metal interaction	Fuel-system degradation and leakage risk	Corrosion inhibitors and compatible materials	[53,56,57]
Polymer/elastomer compatibility	Interaction with seals, plastics, and coatings	Swelling, softening, mass change, degradation	Material screening and upgraded components	[56]
Additive dependence	Need for stabilizers or inhibitors	Higher cost and possible deposit concerns	Optimized additive package and durability testing	[55]

Material compatibility is another concern. Methanol may interact with metals, elastomers, plastics, coatings, tanks, pumps, seals, and injectors. Long-term exposure can cause swelling, softening, mass change, strength loss, or surface degradation in some materials [56]. For medium- and high-level blends, compatible materials, corrosion inhibitors, upgraded seals, and controlled storage conditions are therefore necessary [57]. The main stability and compatibility concerns, their causes, effects, and

possible mitigation measures are summarized in Table 4.

Overall, methanol-gasoline blends should be regarded as fuel formulations whose practical value depends on both fuel properties and application constraints. Low-level blends offer better compatibility with existing gasoline engines, whereas medium- and high-level blends provide stronger knock-resistance and low-carbon potential but require stricter control of fuel stability, water content, material compatibility, and volatility. Therefore, blend ratio, fuel quality control, and compatible fuel-system materials are key factors for the practical use of methanol-gasoline blends.

Fuel subsystem characteristics form the basis of the fuel-engine-carbon system. Upstream carbon intensity varies with the methanol production pathway, while the blending ratio determines energy density, oxygen content, volatility, phase stability, and material compatibility. These properties shape engine calibration, hardware requirements, and fuel consumption per unit brake work. A stable, engine-compatible blend is therefore not necessarily low-carbon unless its methanol component is supplied through a low-carbon production pathway.

3. Combustion behavior and engine performance

The combustion behavior of methanol-gasoline blends determines their influence on engine performance, fuel consumption, and emissions. In spark-ignition engines, methanol affects combustion mainly through oxygen content, octane quality, latent heat of vaporization, evaporation behavior, flame development, and mixture formation. Therefore, the effects of methanol addition should be interpreted together with compression ratio, ignition timing, injection strategy, air-fuel ratio, engine speed, and load.

3.1. Combustion behavior in spark-ignition engines

Methanol-gasoline blends influence spark-ignition combustion mainly through oxygenated combustion, knock resistance, and charge cooling. The oxygen contained in methanol can promote local oxidation and improve combustion completeness, while its high octane quality increases resistance to abnormal combustion. Its high latent heat of vaporization also lowers the intake or in-cylinder charge temperature during evaporation, which is beneficial for knock suppression under high-load operation [58,59].

The actual combustion response, however, depends strongly on engine calibration. The compression ratio is particularly important because methanol's anti-knock property allows operation under more severe conditions than conventional gasoline. Studies on methanol, gasoline, and methanol-gasoline blends have shown that compression ratio and fuel composition jointly affect combustion phasing, pressure development, heat release, and emission formation [60,61]. For example, a recent compression-ratio study covering $CR = 11 - 15$ reported that the effective expansion ratio and energy economy efficiency peaked at around $CR \approx 13$; at 2500–3500 r/min and $CR > 13$, methanol blends showed about 18%–23% higher efficiency than gasoline under these specific test conditions, although gasoline still produced higher full-load power at 3500 r/min [60]. Such gains arise mainly from compression-ratio and combustion-phasing optimization rather than simple fuel substitution. They should not be generalized across different engine types, injection strategies, loads, or ignition settings.

Ignition timing is another decisive factor. Since methanol changes flame development, charge temperature, and knock tendency, the optimum spark timing may differ from that of gasoline. Excessively advanced ignition timing may increase pressure rise and NO_x formation, whereas delayed

ignition may reduce thermal efficiency and combustion completeness [62]. Therefore, methanol-gasoline blends require coordinated optimization of spark timing, air-fuel ratio, and fuel injection quantity.

In direct-injection spark-ignition engines, mixture preparation becomes more sensitive to the methanol fraction. Methanol and gasoline differ in volatility, surface tension, evaporation rate, and latent heat of vaporization, so methanol addition changes spray development, wall wetting, and local equivalence-ratio distribution [63]. Direct methanol injection has also been investigated as a knock-suppression strategy, and injection timing has been shown to strongly affect the charge-cooling and knock-suppression effect [64]. Recent experimental and numerical studies further show that the methanol fraction affects injector flow, spray development, and evaporation in direct-injection systems [17,44,51]. Predictive spray models can therefore help connect blend properties with mixture preparation and guide injection-strategy selection, although validation across blend ratios and operating temperatures remains necessary.

Lean-burn, stratified combustion, and multi-stage injection strategies further influence methanol-gasoline combustion. Lean-burn studies showed that HC and particulate emissions could be minimized near $\lambda \approx 1.3$, while NO_x depended on lean-burn mode and excess-air ratio [65]. Stratified lean-burn operation and two-stage injection can improve mixture distribution, combustion stability, and particulate control, but their effects depend on methanol fraction and injection strategy [66,67]. The main fuel-property-driven combustion pathways and engine-level responses are illustrated in Figure 5.

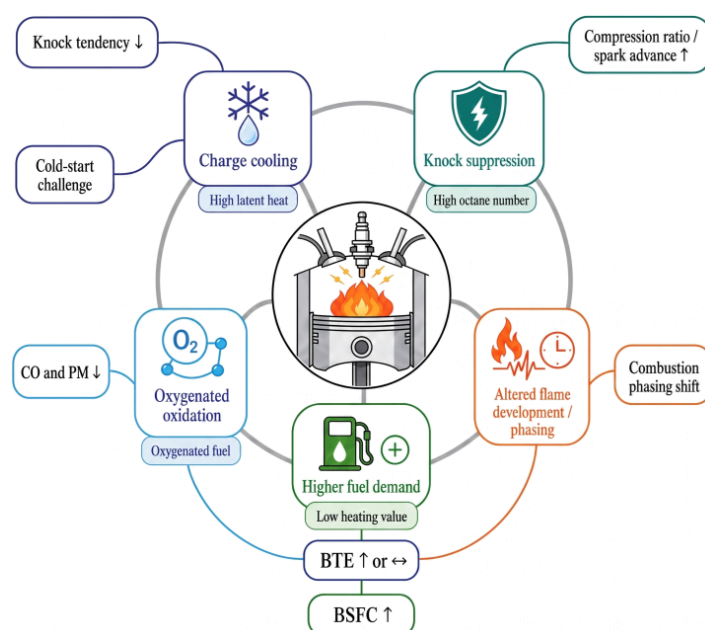


Figure 5. Fuel-property-driven combustion pathways and engine-level responses of methanol-gasoline blends in spark-ignition engines.

3.2. Brake power and torque

Brake power and torque are used to evaluate whether methanol-gasoline blends can maintain

useful engine output. Their response is not determined by methanol fraction alone but by fuel energy content, air-fuel ratio, charge cooling, knock resistance, combustion phasing, and engine calibration. Methanol has a lower heating value than gasoline, which tends to reduce the energy supplied per unit fuel mass or volume, but its high-octane quality and charge-cooling effect can support more favorable combustion when injection and ignition parameters are optimized.

For low- and medium-level blends, the influence on brake power and torque is usually moderate. An optimization study using methanol-gasoline blends identified M8 at 3400 r/min and high load as an optimized condition, giving a brake power of 2137.13 W and a torque of 6.08 N·m, together with a BSFC of 370 g/kWh and a BTE of 22.10% [68]. Tests on gasoline-methanol blends at different loads also showed that useful output depends strongly on engine load and fuel composition [69].

At higher methanol fractions or high-load operation, power and torque become more sensitive to engine design and calibration. The anti-knock advantage of methanol can allow more advanced spark timing or a higher compression ratio, which may improve indicated work under suitable conditions. High-compression-ratio methanol studies showed that engine response should be evaluated together with combustion phasing and thermal efficiency [70]. In a 1.5-L passenger-car SI engine, methanol direct injection was tested at 1.1 and 1.5 MPa BMEP with compression ratios of 11.5, 13.8, and 15.3, showing that high compression ratio and methanol injection can improve high-load efficiency, although output and efficiency gains remain limited by combustion duration and incomplete combustion at some conditions [71].

Engine speed also affects the output response. In an unmodified carbureted SI engine operated at wide-open throttle, M10 produced 2.450 kW of brake power and 4.62 N·m of torque at 2700 r/min, compared with 2.389 kW and 4.56 N·m for gasoline. At 3200 r/min, M10 produced 2.460 kW of brake power and 4.70 N·m of torque, compared with 2.440 kW and 4.66 N·m for gasoline. Accordingly, the brake-power advantage of M10 relative to gasoline decreased from 2.55% at 2700 r/min to 0.82% at 3200 r/min, while the torque advantage decreased from 1.32% to 0.86% [72]. Independent experiments with an M12 blend over 1300–3700 r/min and two load levels likewise reported higher brake power than gasoline; the maximum BTE of M12 was 23.69% at 2800 r/min under lower load [73]. These results show that the output benefit of methanol blending is condition-dependent rather than constant across the speed range.

Overall, methanol-gasoline blends do not produce a fixed increase or decrease in brake power and torque. Low-level blends can maintain output close to gasoline under suitable calibration, while medium- and high-level blends require optimized fuel injection, ignition timing, compression ratio, or flex-fuel control to fully use methanol's anti-knock and charge-cooling advantages. Therefore, brake power and torque should be interpreted together with BSFC and BTE rather than treated as isolated performance indicators.

3.3. Brake-specific fuel consumption

Brake-specific fuel consumption is one of the most sensitive performance indicators for methanol-gasoline blends. Since methanol has a much lower heating value than gasoline, about 19.9 MJ/kg compared with 42–44 MJ/kg for gasoline, more fuel is usually required to produce the same brake output when the methanol fraction increases [33,40]. Therefore, BSFC often increases after methanol addition, especially when the engine is operated without sufficient recalibration of fuel injection, ignition timing, or air-fuel ratio [74,75].

The increase in BSFC becomes more evident at medium and high methanol blending ratios because a larger injected fuel quantity is needed to maintain the required energy input. However, the trend is not governed by blend ratio alone. Energy and exergy studies, combustion-control-map development, and flex-fuel operation experiments show that BSFC is jointly affected by methanol fraction, speed, load, compression ratio, and calibration method [76,77]. For example, a methanol direct-injection control-map study reported the lowest BSFC of about 147 g/kWh for M0, whereas the highest BSFC reached 327 g/kWh for M30 across the tested operating map. Under optimized calibration, M30 also achieved the highest BTE of 30.76%, indicating that the higher fuel consumption associated with methanol-rich blends does not necessarily imply lower thermal efficiency [77]. Although these values represent the extrema across different operating points rather than a matched speed-and-load comparison, they show that BSFC and efficiency must be evaluated using fuel-specific control maps as methanol content changes. In an RSM-based study covering M0, M6, M12, and M18, BSFC ranged from 360 to 560 g/kWh across the tested speed-load-blend matrix. At low load, BSFC was 0.79% and 15.16% higher for M6 and M18 than for M0, respectively, whereas M12 was 1.10% lower. At high load, M6 and M12 showed 4.63% and 7.49% lower BSFC than M0, while M18 was 2.33% higher [68]. The multi-objective optimum was obtained for M8 at 3400 r/min and high load, with a BSFC of 370 g/kWh, brake power of 2137.13 W, and BTE of 22.10%.

Higher BSFC does not necessarily indicate poorer combustion. Methanol can improve knock resistance, promote more favorable combustion phasing, and provide charge cooling, which may partly compensate for its lower energy density when the engine is properly optimized. Nevertheless, additional control strategies may also introduce trade-offs. For instance, in an SI engine fueled with M15, water injection reduced some emissions but led to a 2.5% decrease in effective power and a 3.5% increase in specific fuel consumption compared with the standard M15 condition [78]. This shows that BSFC should be evaluated together with combustion stability, emissions, and BTE rather than as an isolated indicator.

Engine load and combustion mode further influence BSFC. At low load, incomplete evaporation, wall wetting, and unstable combustion may increase fuel consumption. At medium and high loads, methanol's anti-knock and charge-cooling effects become more useful, especially when injection timing, ignition timing, and compression ratio are optimized. Lean-burn or ultra-lean strategies may improve fuel economy, but their benefit depends on stable ignition and mixture preparation [79]. Therefore, minimizing BSFC requires coordinated optimization of fuel formulation and engine calibration.

3.4. Brake thermal efficiency

Brake thermal efficiency reflects how effectively the chemical energy of the fuel is converted into useful brake work. For methanol-gasoline blends, BTE is affected by two competing factors. On the one hand, methanol has a lower heating value than gasoline, which tends to increase fuel consumption. On the other hand, its high octane number, oxygen content, and charge-cooling effect can improve combustion phasing, suppress knock, and support more efficient operation when the engine is properly calibrated [80,81].

Under general operating conditions, low- and medium-level blends do not show a uniform increase in BTE; changes are usually modest and depend on engine type, load, and calibration. Higher BTE values reported in some studies were obtained under selected or optimized conditions. In an optimization study, a low-level methanol blend achieved a BTE of 22.10% under optimized conditions,

with a brake power of 2137.13 W and a BSFC of 370 g/kWh [68]. Other engine tests also reported that M15 and M20 could show higher BTE than gasoline under selected loads; for example, BTE improvements of about 14% and 4.9% were reported for M15 and M20 at 2.4 kW load, while the increases were about 7.91% and 3.55% at full load, respectively [80,81]. These values demonstrate condition-specific efficiency potential rather than a general trend of increasing efficiency with methanol content.

Compression ratio is another key factor. Studies on methanol, ethanol, and gasoline operation in spark-ignition engines have shown that alcohol fuels can better tolerate higher compression ratios because of their stronger knock resistance [82]. Similar findings have been reported for methanol-gasoline blends, where fuel composition and compression ratio jointly influence combustion phasing, heat release, and BTE [83]. Therefore, the efficiency advantage of methanol blends is more likely to appear when compression ratio, ignition timing, and fuel injection are adjusted together rather than when the engine is operated with unchanged gasoline calibration [84].

Lean-burn and stratified combustion strategies can further affect BTE. Methanol addition may support lean operation because of its oxygenated structure and high knock resistance, but excessive dilution or poor mixture preparation can reduce combustion stability. Direct-injection studies showed that the economic operating range depends on methanol fraction, excess-air ratio, and injection mode [85,86]. Therefore, the efficiency benefit of methanol blending is mainly realized through fuel-engine co-optimization rather than fuel substitution alone. The typical performance responses of brake power, torque, BSFC, and BTE are summarized in Figure 6.

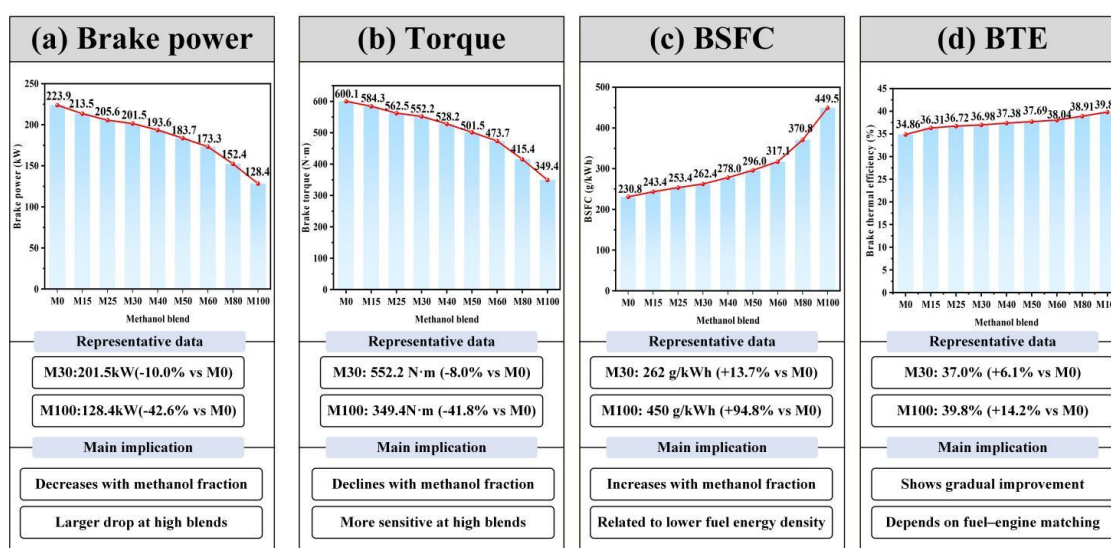


Figure 6. Representative engine performance responses of methanol-gasoline blends compared with gasoline.

To provide a clearer comparison across the reviewed studies, representative engine-performance data for methanol-gasoline blends are summarized in Table 5.

Table 5. Cross-study comparison of representative engine-performance results for methanol-gasoline fuels.

Ref.	Fuel	Engine and test condition	Key results
[60]	Methanol-gasoline blends	SI engine; CR 11–15; 2500–3500 r/min	Efficiency increased by 18%–23% at CR > 13; gasoline retained higher full-load power at 3500 r/min
[68]	M8	SI engine; 3400 r/min; high load	Power: 2.14 kW; torque: 6.08 N·m; BSFC: 370 g/kWh; BTE: 22.10%
[80]	M15	SI engine; 2.4 kW and full load	BTE increased by 14.0% and 7.91%, respectively
[81]	M20	SI engine; 2.4 kW and full load	BTE increased by 4.9% and 3.55%, respectively
[71]	Methanol DI	Passenger-car SI engine; BMEP 1.1–1.5 MPa; CR 11.5–15.3	Efficiency improved at optimized CR, but performance depended on combustion duration and completeness

The comparison shows that the efficiency benefit of methanol addition did not increase proportionally with the blending ratio. For example, the BTE improvements reported for M15 were greater than those for M20 under comparable load descriptions [80,81]. The results reported in studies [60] and [71] further indicate that the performance advantages of methanol-containing fuels were mainly obtained through compression-ratio and combustion-phasing optimization rather than fuel substitution alone. Meanwhile, the M8 case maintained acceptable power, torque, BSFC, and BTE under the optimized operating condition [68]. Overall, the reported performance differences were strongly affected by compression ratio, engine load, injection strategy, and combustion completeness.

3.5. Effects of engine operating conditions

The performance of methanol-gasoline blends is strongly affected by operating conditions. Even for the same blend ratio, different engine speed, load, compression ratio, ignition timing, injection strategy, and excess-air ratio may lead to different trends in brake power, torque, BSFC, BTE, and emissions. This explains why reported results are not always consistent across studies.

Engine load is one of the most important factors. At low load, low in-cylinder temperature and methanol's high latent heat of vaporization may worsen evaporation, mixture preparation, and combustion stability. At medium and high loads, the anti-knock and charge-cooling advantages of methanol become more useful, especially when ignition timing, air dilution, EGR strategy, or compression ratio is optimized [87,88]. Engine speed also affects performance because high-speed operation reduces the available time for evaporation, mixing, and combustion [89].

Compression ratio and ignition timing are closely linked to methanol's anti-knock characteristics. Methanol addition can relax knock limitations and allow more favorable combustion phasing, but excessive spark advance may increase pressure rise and NO_x formation [90,91]. Injection strategy is particularly important in direct-injection engines because methanol's evaporation behavior affects spray penetration, wall wetting, stratification, particulate formation, and combustion stability [92–94]. Low-temperature and cold-start operation can further worsen methanol evaporation, mixture

preparation, and catalyst light-off, increasing fuel consumption, HC emissions, unburned methanol, and formaldehyde emissions [95]. Therefore, methanol-gasoline blends are more likely to show performance benefits when blend ratio, load, speed, compression ratio, ignition timing, and injection strategy are optimized together. This operating-window interpretation is shown in Figure 7.

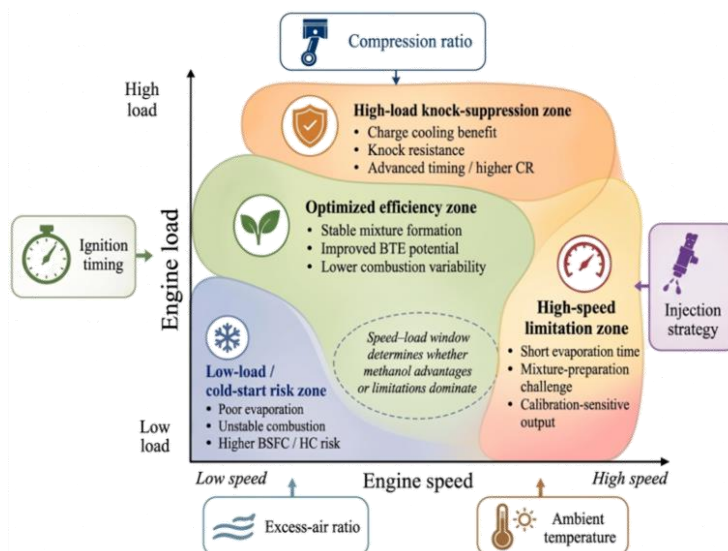


Figure 7. Operating-window interpretation of methanol-gasoline blend performance in spark-ignition engines.

Overall, the performance advantage of methanol-gasoline blends is not determined by methanol content alone. Methanol can improve knock resistance, charge cooling, and combustion phasing, but these benefits are released only when compression ratio, ignition timing, injection strategy, air-fuel ratio, engine speed, and load are properly matched. Future engine studies should therefore shift from single-factor blend comparison toward fuel-engine co-optimization.

Within this framework, the engine subsystem acts as the conversion link between fuel properties and environmental outcomes. Engine calibration determines whether methanol's octane and charge-cooling advantages are converted into higher efficiency or offset by incomplete evaporation, increased BSFC, and unstable combustion. Changes in BSFC and BTE also alter the amount of upstream fuel production required per unit brake work, while cold-start and mixture-formation behavior affect both regulated and unregulated emissions. Engine performance should therefore be evaluated together with tailpipe emissions and methanol production pathways rather than as an independent outcome.

4. Emission characteristics and environmental impacts

4.1. Regulated emissions

From a system perspective, the environmental performance of methanol-gasoline blends includes two connected levels: tailpipe pollutants generated during engine operation and fuel-cycle greenhouse-gas implications associated with methanol production and consumption. Tailpipe

emissions are influenced by blend properties, mixture preparation, combustion, and after-treatment, whereas fuel-cycle impacts depend on both engine fuel demand and the carbon intensity of the methanol pathway. Reductions in CO or particulate emissions therefore do not necessarily indicate a corresponding climate benefit, just as low-carbon methanol may not deliver its expected benefit if increased fuel consumption and cold-start penalties are ignored.

Regulated emissions are important indicators for evaluating the environmental performance of methanol-gasoline blends in spark-ignition engines. The main regulated pollutants usually include carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter. Compared with conventional gasoline, methanol-gasoline blends affect emission formation through fuel oxygen content, combustion temperature, air-fuel ratio, evaporation behavior, and after-treatment performance.

CO emissions are often reduced when methanol is blended with gasoline under suitable combustion conditions because the oxygenated structure of methanol promotes carbon oxidation. Previous reviews and vehicle-level studies have reported CO reduction with methanol-containing fuels, although the magnitude depends on blend ratio, engine load, air-fuel ratio, and combustion stability [6,22]. M15 direct-injection studies also show that engine control parameters strongly affect CO and HC emissions under light-load operation, while NO_x may increase slightly under some lean or high-temperature conditions [18]. For a BS-VI compliant light-duty spark-ignition engine, M15 reduced HC, CO, and particulate emissions, while NO_x remained comparable to gasoline [20].

HC and NO_x emissions show more variable trends. HC emissions may decrease because of improved oxidation, but poor evaporation, wall wetting, flame quenching, cold start, or insufficient calibration may increase HC emissions [30]. Low-temperature studies further showed that M10 reduced engine-out CO and HC by 44.8% and 25%, respectively, during the first 150 s after cold start, while NO emissions showed no significant fuel-dependent difference. Therefore, HC emissions cannot be predicted only from oxygen content; evaporation, combustion stability, and catalyst light-off must also be considered.

NO_x emissions are highly condition-dependent. Methanol's charge-cooling effect may reduce in-cylinder temperature and suppress thermal NO_x formation, especially under high-load operation. However, improved combustion completeness, advanced ignition timing, or leaner operation may increase local combustion temperature and oxygen availability, which can increase NO_x under some conditions. Studies on methanol-gasoline blends, lean-burn operation, and stratified combustion have shown that NO_x trends depend strongly on ignition timing, excess-air ratio, injection strategy, load, and combustion mode [85,86]. Vehicle-level results also confirm this sensitivity: methanol blending reduced NO_x, THC, and PM in the NEDC cycle, but CO increased by 24.1% for M30, indicating that transient operation may weaken CO oxidation even when other pollutants decrease [22].

CO₂ and particulate emissions should be interpreted carefully. Tailpipe CO₂ may decrease because methanol has a lower carbon-to-hydrogen ratio than gasoline, but its lower heating value may increase fuel consumption. Therefore, tailpipe CO₂ alone cannot represent the climate benefit of methanol-gasoline blends, which depends strongly on methanol production pathways [4,22,24]. Particulate emissions are often reduced because methanol contains oxygen and has no C-C bond, which suppresses soot precursor formation. M15 and other alcohol-gasoline blend studies reported reductions in particulate mass or particle number, although particle morphology and trace-metal characteristics may still change with fuel composition [20,21]. Overall, CO and particulate emissions often decrease under suitable conditions, whereas HC and NO_x remain more sensitive to combustion temperature, mixture preparation, ignition timing, load, and after-treatment performance.

To facilitate cross-study comparison, representative quantitative emission data for methanol-gasoline blends are summarized in Table 6.

Table 6. Cross-study comparison of representative emission data for methanol-gasoline blends.

Ref.	Fuel and test condition	Comparator	Reported emission result
[30]	M10; cold start, first 150 s	Gasoline	CO: −44.8%; HC: −25.0%; NO: no significant difference
[22]	M75; steady-state, 15 km/h	M0	CO ₂ : −9.6%; NO _x : −79.1%; CO: −70.2%
	M30; NEDC	M0	CO ₂ : −3.7%; NO _x : −19.3%; CO: 24.1%; THC: −10.9%
	M20; NEDC	M0	PM: −47.9%
[14]	M0–M40; HLB and SLB	Different λ values	Minimum HC and PM near $\lambda \approx 1.3$; M20 produced the highest PN
[15]	SISL and DISL	Same λ	PN concentration under SISL was at least 10 times that under DISL
[16]	M10/M20; 8:2 two-stage injection	Single-injection M0	PN: −21.4%/−19.7%, respectively

Table 6 shows that the emission response varied substantially among studies and operating conditions. During the first 150 s after cold start, M10 reduced CO and HC emissions by 44.8% and 25.0%, respectively [30]. At the vehicle level, M30 reduced CO₂, NO_x, and THC emissions by 3.7%, 19.3%, and 10.9%, respectively, under the NEDC, but increased CO emissions by 24.1% [22]. Injection strategy also had a pronounced effect on particulate emissions: the PN concentration under SISL was at least 10 times that under DISL [15], whereas an 8:2 two-stage injection strategy reduced PN by 21.4% for M10 and 19.7% for M20 relative to single-injection gasoline [16]. These comparisons indicate that emission behavior is governed not only by methanol content but also by cold-start conditions, driving cycle, mixture stratification, and injection strategy.

Based on the normalized data compiled from the reviewed studies, descriptive statistics for selected performance and emission indicators are presented in Table 7.

Table 7. Descriptive statistics of normalized changes in selected performance and emission indicators.

Indicator	Studies, n	Median change (%)	IQR (Q1–Q3, %)	Range (%)	Favorable responses (%)
BTE	4	3.24	−3.05 to 7.40	−12.39 to 10.40	75
BSFC	5	11.98	6.00 to 24.30	3.65 to 27.10	0
CO	6	−16.83	−39.36 to −9.86	−44.90 to −1.09	100
HC	5	−13.00	−21.90 to −6.18	−25.00 to 2.26	80
NO _x	4	−2.86	−21.17 to 12.09	−49.20 to 30.05	50
PM/PN	2	−34.23	−41.06 to −27.39	−47.90 to −20.55	100

Table 7 provides a descriptive statistical synthesis of the normalized performance and emission responses. The median BTE change was 3.24%, although the wide range from −12.39% to 10.40% indicates that efficiency improvement was strongly condition-dependent. In contrast, BSFC increased in all five included studies, with a median increase of 11.98%, reflecting the lower energy density of

methanol-containing fuels. CO exhibited the most consistent favorable response, decreasing in all included studies by a median of 16.83%. HC decreased in 80.0% of the studies, whereas NO_x showed only 50.0% favorable responses and the widest directional inconsistency. The available particulate data also indicated reductions, but the limited number of comparable PM and PN studies prevents a robust pooled interpretation.

4.2. Unregulated emissions

Unregulated emissions are important because alcohol-containing fuels can change oxygenated hydrocarbons, volatile organic compounds, unburned alcohols, and particulate-related species. Methanol contains no C-C bond and has a lower soot-formation tendency than gasoline, which can help reduce carbonaceous particles and soot precursors [6,21]. However, incomplete methanol oxidation may produce formaldehyde and unburned methanol, especially when evaporation, mixture preparation, or combustion completeness is insufficient [20,22]. These risks become more evident during cold start, low-temperature operation, low load, or delayed catalyst light-off [30,96].

Aldehyde emissions require particular attention. Formaldehyde is closely associated with methanol oxidation and is therefore a key unregulated species for methanol-containing fuels [6,22]. Acetaldehyde is more often related to ethanol-containing or mixed alcohol-gasoline fuels, but it may also appear in broader alcohol-blend emission studies [21]. For M15-fueled BS-VI compliant light-duty spark-ignition engines, several hydrocarbon and oxygenated trace species decreased compared with gasoline, while methanol and ethane trace emissions increased [20]. This indicates that alcohol slip should be evaluated separately from conventional HC emissions.

Unburned methanol is another concern. Because methanol has a high latent heat of vaporization, evaporation may be less favorable at low ambient temperature or during short cold-start operation [30]. Poor evaporation, wall wetting, and unstable early-cycle combustion can increase unburned fuel, HC, and oxygenated exhaust species [96]. M15 results showed that methanol trace emissions could increase even when several other unregulated components decreased [20]. Therefore, unburned methanol should be considered together with cold-start strategy, fuel injection control, catalyst light-off, and alcohol-specific after-treatment performance [20,30,96].

Particulate-related unregulated emissions should also be evaluated beyond total particle mass. The oxygenated structure of methanol can suppress locally rich combustion and reduce carbonaceous particle formation [6,21]. However, fuel composition can influence particle number, morphology, composition, and trace-metal characteristics. Studies on GM10, GE10, and GB10 showed that alcohol-gasoline blends emitted lower particulate mass and particle number than gasoline, while even 10% alcohol addition was sufficient to alter particle morphology [21]. This suggests that particle mass alone is not sufficient for evaluating the particulate impacts of methanol-gasoline blends.

For direct-injection spark-ignition engines, unregulated emissions are closely related to spray behavior and mixture formation. Methanol blending changes evaporation, local equivalence ratio distribution, and wall wetting because methanol and gasoline differ in volatility, surface tension, and latent heat of vaporization [17]. Light-load DISI, lean-burn, stratified combustion, and two-stage injection studies further show that injection and combustion strategies affect particulate formation and oxygenated exhaust species [18,65–67].

Methanol-gasoline blends may reduce soot-related emissions, but formaldehyde, unburned methanol, cold-start emissions, and particulate characteristics remain important concerns. These issues should be

included in future emission evaluations, especially for direct-injection engines and medium- or high-methanol blends. Figure 8 integrates the main pathways of regulated and unregulated emissions with quantitative NO_x results obtained under different methanol blending ratios and vehicle speeds.

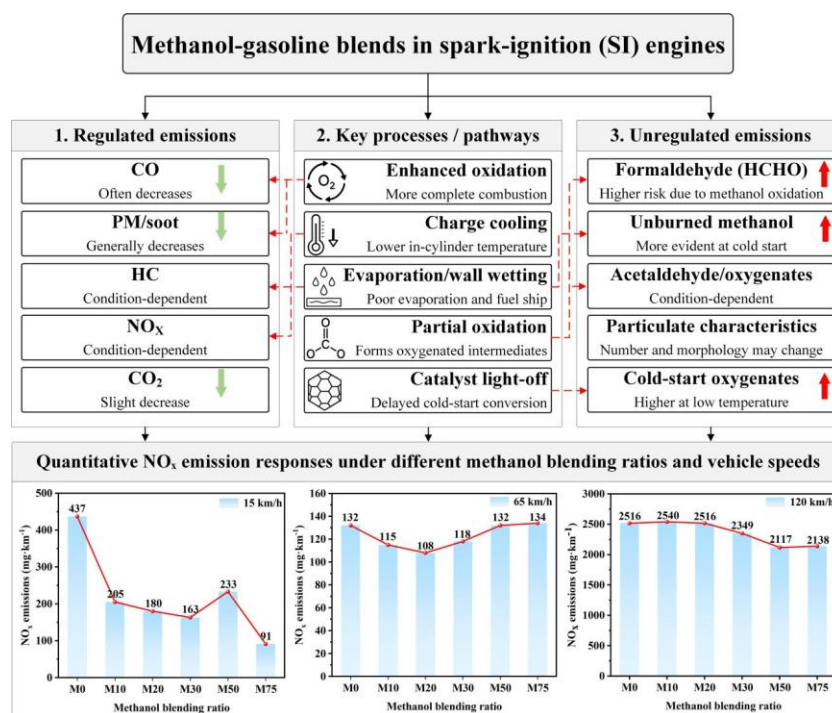


Figure 8. Emission pathways and quantitative NO_x responses of methanol-gasoline blends. Quantitative data were digitized and redrawn from [22].

The quantitative results in Figure 8, digitized and redrawn from [22], show that the effect of methanol blending ratio on NO_x emissions was strongly dependent on vehicle speed. At 15 km/h, NO_x emissions decreased from 437 mg km^{-1} for M0 to 91 mg km^{-1} for M75, corresponding to a reduction of approximately 79.1%, although a partial increase occurred at M50. At 65 km/h, the variation was comparatively small, with the minimum value of 108 mg km^{-1} observed for M20. At 120 km/h, M10 and M20 remained close to M0, whereas M30–M75 produced lower NO_x emissions, with the minimum value of 2117 mg km^{-1} obtained for M50. These results indicate that NO_x emissions varied non-monotonically with methanol content and were jointly affected by blending ratio and operating condition.

4.3. Emission mechanisms

The emission formation of methanol-gasoline blends is mainly controlled by fuel oxygen content, combustion temperature, local equivalence ratio, evaporation behavior, and after-treatment efficiency. Methanol contains oxygen and has no C-C bond, which can reduce soot precursor formation and particulate tendency compared with gasoline [6,21]. However, its high latent heat of vaporization and different volatility may affect spray evaporation, wall wetting, and local mixture distribution, especially in direct-injection spark-ignition engines [17,18].

CO emissions are mainly formed from incomplete oxidation. The oxygenated structure of

methanol can promote carbon oxidation and reduce CO under suitable combustion conditions [6,22]. However, low combustion temperature, poor mixture preparation, or insufficient catalyst activity may weaken this benefit, particularly during cold start or light-load operation [20,30].

HC, unburned methanol, and oxygenated hydrocarbons are closely related to evaporation, wall wetting, flame quenching, and incomplete combustion. Methanol's charge-cooling effect is useful for knock suppression, but poor evaporation at low temperature can increase unburned fuel and oxygenated exhaust species [7,30,96]. In DISI engines, injection timing and spray targeting further influence wall-film formation and local rich zones [17,18].

NO_x formation is governed by high-temperature reactions, oxygen availability, and residence time. Methanol's charge-cooling effect may reduce thermal NO_x formation, while advanced ignition timing, improved combustion completeness, or lean operation may increase local temperature and oxygen availability [65,66]. This explains why NO_x trends are often inconsistent across different studies.

Particulate emissions are generally suppressed by methanol's oxygen content and lack of C-C bonds, but particle number, morphology, and composition still depend on wall wetting, stratification, and injection strategy [20,21]. Formaldehyde is mainly associated with the partial oxidation of methanol, whereas acetaldehyde is more relevant to ethanol-containing or mixed alcohol fuels [6,21,22]. These mechanisms are summarized in Figure 9.

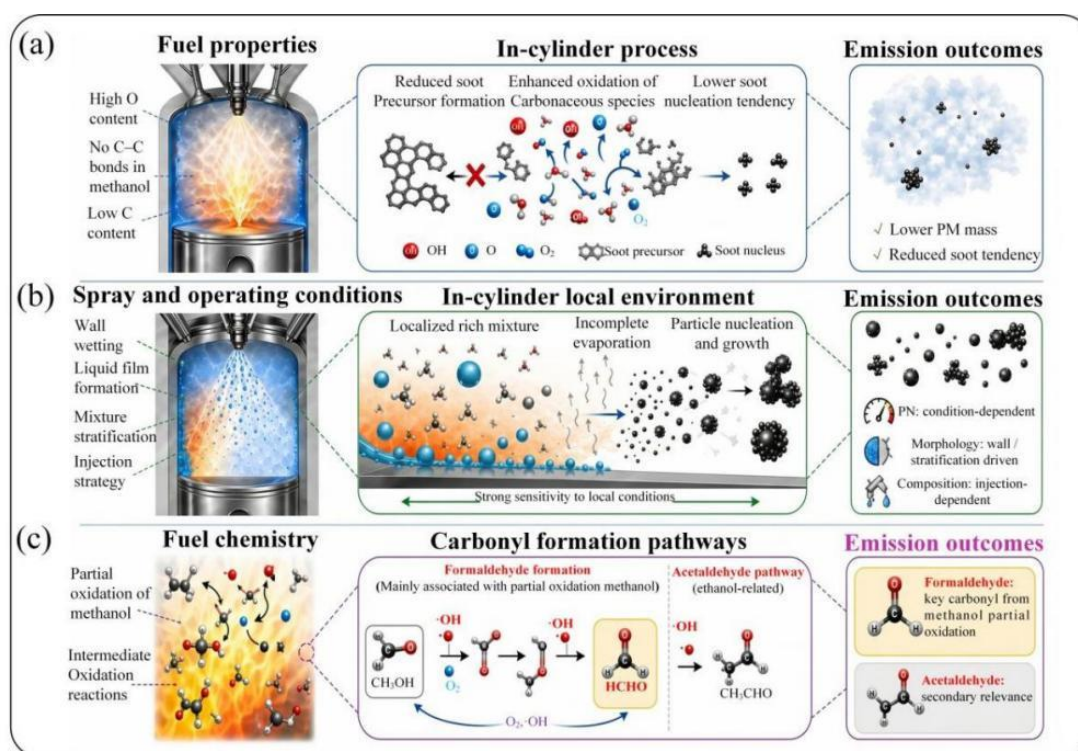


Figure 9. Particulate and carbonyl emission mechanisms in methanol-gasoline blends: (a) soot suppression by methanol properties; (b) particle dependence on wall wetting, stratification, and injection; (c) formaldehyde from methanol oxidation and acetaldehyde from mixed alcohol pathways.

4.4. Life-cycle implications and future assessment needs

Tailpipe emissions alone are not sufficient to evaluate the environmental value of methanol-gasoline blends. Engine tests can reveal changes in regulated and unregulated emissions, combustion behavior, and fuel consumption [6,20]. However, these results mainly describe the fuel-use stage and do not account for the energy consumption and emissions associated with feedstock acquisition, methanol production, fuel transport, and distribution. The GREET fuel-cycle framework demonstrates that these upstream stages and vehicle operation should be considered within a consistent system boundary [97]. Life-cycle thinking is therefore an important supplementary perspective when evaluating methanol-gasoline blends for spark-ignition engines.

Based on the reviewed literature, current studies remain concentrated on combustion and engine control, engine performance, and emission characteristics. Life-cycle implications and low-carbon fuel-supply issues have received less systematic attention, as also indicated by the thematic distribution in Figure 2. This imbalance leaves the environmental potential of methanol-gasoline blends beyond engine-level testing insufficiently understood. The present review does not perform a full life-cycle assessment; instead, it identifies the major pathway variables that should be quantified in future studies.

Available life-cycle studies demonstrate that the environmental performance of methanol is strongly dependent on its production pathway. Although Masum et al. examined marine rather than road-vehicle applications, their comparison of fossil-, biomass-, and waste-derived methanol showed that the upstream production route can substantially alter the life-cycle result [98]. For waste-derived renewable methanol, process integration and energy-recovery configuration also affect the environmental outcome [99]. The hydrogen production route introduces another important source of variation in methanol synthesis [100], while broader e-fuel research identifies the availability of low-carbon hydrogen as a central prerequisite for reducing upstream emissions [101]. Assessments of methanol synthesis from captured CO₂ further show that the CO₂ supply route and process configuration must be included in the evaluation boundary [102]. Renewable-resource availability and Power-to-X production costs also vary geographically, influencing where low-carbon e-methanol can be produced competitively [103]. More directly, Alhyari et al. found that Power-to-Liquid fuels provided environmental advantages over the fossil reference only in scenarios using renewable electricity [104]. Strategic assessments of e-fuel development in China further emphasize the importance of production capacity, low-carbon feedstock supply, and deployment conditions [105]. Consequently, reductions in tailpipe CO or particulate emissions [22] do not necessarily guarantee an overall environmental benefit. Because the existing studies differ in application, assumptions, functional units, and system boundaries, their results cannot be compared directly or used to derive universal vehicle-level emission factors.

Life-cycle assessment should therefore be regarded as an important direction for future research. Future assessments should couple blend-specific BSFC and tailpipe-emission data obtained from spark-ignition engine tests with pathway-specific carbon-intensity data under consistent functional units and system boundaries. Fossil-, biomass-, waste-, and electricity-based methanol routes should be evaluated separately. Sensitivity analysis should also consider the blending ratio, engine efficiency, electricity mix, hydrogen production route, CO₂ source, fuel transport, and production location. Such an approach would allow fuel production, blending, engine operation, and fuel consumption to be evaluated within the same framework, converting the present qualitative fuel-engine-carbon concept into a quantitative system-level assessment.

5. Recent advances, challenges, and future prospects

5.1. Advances in fuel formulation and engine optimization

Recent advances have shifted methanol-gasoline research from simple blending toward fuel-engine co-optimization. Methanol is increasingly considered not only as a gasoline additive but also as a functional component for knock suppression, charge cooling, lean operation, and particulate control.

Multiple-injection and combined fuel-injection strategies represent important directions for methanol-containing spark-ignition engines. Recent studies have shown that optimized injection scheduling can improve mixture preparation, lean-burn stability, combustion phasing, thermal efficiency, and emission control in high-compression-ratio methanol SI engines [106]. In fuel formulation, multi-alcohol blends have also received attention. Tests using methanol, ethanol, gasoline, E85, and GEM ternary mixtures under lean conditions showed that alcohol-containing fuels can affect combustion stability, efficiency, and emissions [107]. Bio-butanol-methanol-gasoline blends coupled with air dilution further influenced brake thermal efficiency, gaseous emissions, particulate emissions, and combustion stability [108].

Optimization methods are also becoming important because methanol-gasoline performance depends on several coupled variables, including blend ratio, engine speed, load, injection strategy, and ignition timing. Response surface methodology has been applied to optimize alcoholic fuel blends while considering performance, emissions, and lubricant-related responses [109]. These advances suggest that future applications will rely more on adaptive fuel delivery, calibrated engine control, and multi-objective optimization than on fixed blend ratios alone.

5.2. Green methanol and e-methanol pathways

Green methanol and e-methanol pathways are important because the environmental value of methanol-gasoline blends depends not only on tailpipe emissions but also on methanol production routes. Green methanol can be produced from biomass, waste-derived carbon, or renewable syngas, while e-methanol is commonly synthesized from captured CO₂ and green hydrogen. Global assessments show that e-methanol potential depends strongly on renewable electricity resources, CO₂ availability, and electrolysis cost [110]. Feasibility studies further indicate that both the carbon source and hydrogen pathway strongly affect production cost and life-cycle emissions [111].

CO₂ hydrogenation is one of the key routes for e-methanol production. Emerging technologies such as plasma-assisted CO₂ hydrogenation have been explored, although electricity cost remains a major barrier [112]. Captured CO₂ combined with low-carbon electricity or nuclear-powered electrolysis has also been assessed, showing that the electricity source is decisive for both economics and carbon intensity [113]. Recent reviews summarize multiple green methanol routes, including biomass conversion, renewable hydrogen-based synthesis, CO₂ utilization, and hybrid pathways [114]. Process simulation studies further show that hydrogen cost, carbon intensity, and system integration remain critical challenges [115]. Therefore, methanol-gasoline blends can contribute to low-carbon transportation only when methanol is supplied through scalable, low-carbon, and economically feasible pathways.

5.3. Technical and commercialization challenges

Despite their potential, methanol-gasoline blends still face several barriers to large-scale application. The first challenge is the availability of low-carbon methanol. Renewable methanol can be produced from biomass, waste carbon, captured CO₂, and green hydrogen, but its production cost, feedstock availability, and regional supply capacity remain uncertain [116]. If methanol is mainly produced from fossil resources, the life-cycle carbon benefit of methanol-gasoline blends will be limited.

Fuel handling and safety are also important. Methanol is toxic, corrosive to some materials, and more sensitive to water contamination than gasoline. These characteristics require compatible tanks, seals, pipelines, fuel pumps, and safety procedures [117]. Low-level blends are easier to introduce into existing gasoline infrastructure, while medium- and high-level blends require stricter control of material compatibility, water content, fuel quality, and cold-start performance.

Commercialization also depends on cost, infrastructure, standards, and market acceptance. Renewable methanol and e-methanol remain constrained by renewable electricity demand, CO₂ sourcing, production scale, and distribution infrastructure [118]. Policy support, carbon-intensity standards, certification systems, and long-term offtake agreements are also needed [119]. Based on the reviewed literature, the main barriers were grouped into technical, commercialization, and supply-side challenges, as summarized in Figure 10. The illustrative weights were derived by coding the reviewed studies based on the frequency with which each challenge was discussed. Each challenge mentioned in one study was counted once, and the frequencies were normalized within each challenge category. The percentages are intended to indicate relative discussion frequency within each category rather than absolute market shares or survey-based statistics.

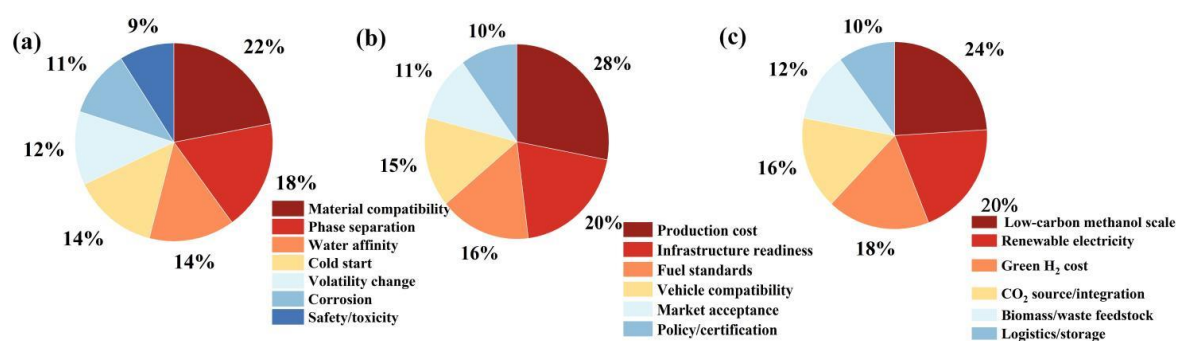


Figure 10. Relative frequency of reported challenges for methanol-gasoline blends: (a) technical barriers; (b) commercialization barriers; and (c) supply-side constraints.

As shown in Figure 10, the barriers to methanol-gasoline blend commercialization can be grouped into technical, commercialization, and supply-side challenges. In Figure 10(a), material compatibility (22%) and phase separation (18%) are the main technical barriers, followed by water affinity and cold-start issues (14% each). In Figure 10(b), production cost (28%) and infrastructure readiness (20%) are the dominant commercialization barriers. In Figure 10(c), low-carbon methanol scale (24%), renewable electricity (20%), and green H₂ cost (18%) are the major supply-side constraints. These results indicate that commercialization depends not only on fuel performance but also on fuel-system compatibility, supply-chain maturity, infrastructure readiness, and policy support.

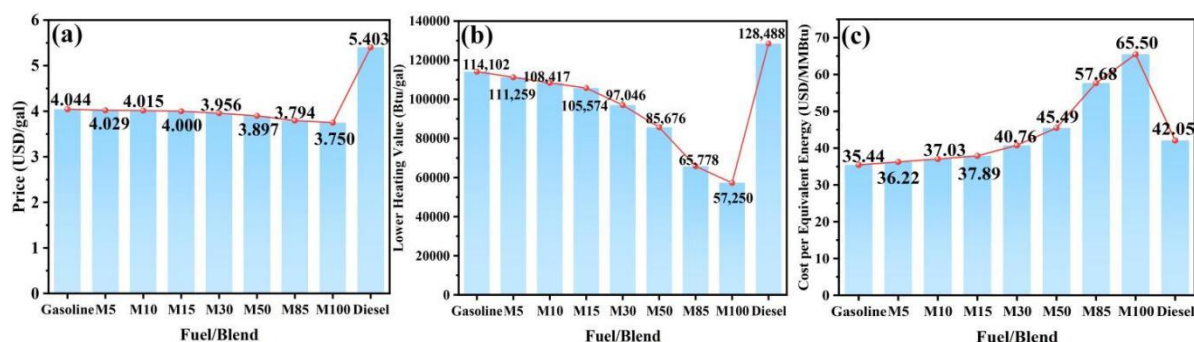


Figure 11. Comparison of fuel price, lower heating value, and energy-adjusted cost for methanol-gasoline blends, gasoline, and diesel. (a) Retail price per gallon; (b) lower heating value per gallon; (c) cost per equivalent energy.

To further evaluate economic feasibility, Figure 11 compares gasoline, diesel, and methanol-gasoline blends in terms of fuel price, lower heating value, and energy-adjusted cost. Gasoline and diesel prices were obtained from EIA, methanol price from Methanex, and lower heating values from AFDC [120–122]. The M5–M100 values were calculated using volume-based blending. As shown in Figure 11(a), fuel price decreases slightly with methanol content, from 4.044 USD/gal for gasoline to 3.750 USD/gal for M100, while diesel has the highest price at 5.403 USD/gal. However, Figure 11(b) shows that energy content falls sharply, from 114,102 Btu/gal for gasoline to 57,250 Btu/gal for M100, whereas diesel has the highest value at 128,488 Btu/gal. As a result, Figure 11(c) shows that the energy-adjusted cost increases with methanol content: M5–M15 remain close to gasoline, while M50, M85, and M100 rise to 45.49, 57.68, and 65.50 USD/MMBtu, respectively.

Therefore, high-methanol blends are not necessarily more economical despite their lower per-gallon price. This price comparison should be regarded as indicative because fuel prices vary with region, tax policy, market period, and supply contract.

5.4. Future research directions

Future research should move from isolated engine tests toward integrated evaluation of fuel formulation, engine calibration, emissions, economic feasibility, and carbon pathways. Near-term studies should focus on fuel standard compatibility, blend stability, cold-start performance, material compatibility, volatility control, injection strategy, and after-treatment matching. Low-level blends such as M5–M15 are more suitable for near-term application in existing spark-ignition engines, while medium-level blends such as M20–M30 require further calibration and fuel-system optimization. Therefore, the benefits of low-to-medium level methanol-gasoline blends depend on whether gasoline-like fuel behavior can be maintained while improving combustion and emission performance.

To further illustrate their relative position, Figure 12 presents a literature-based six-dimensional radar-chart comparison of low-to-medium level methanol-gasoline blends (M5–M30), pure gasoline, and diesel. The scores were derived from reported trends in fuel properties, engine performance, emissions, life-cycle assessment, fuel cost, and commercialization barriers [4,10–19,21,23,30,77].

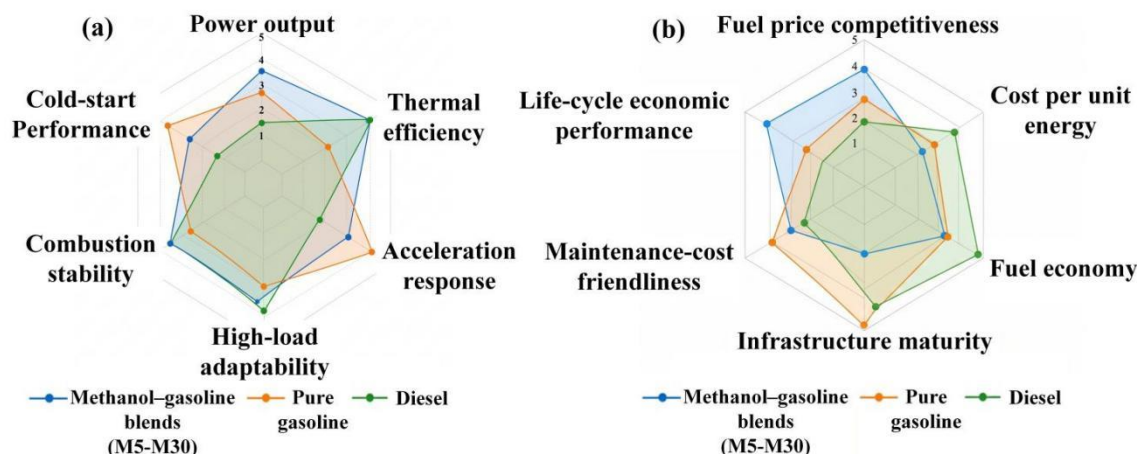


Figure 12. Literature-based hexagonal comparative assessment of methanol-gasoline blends, pure gasoline, and diesel: (a) engine performance; (b) economic feasibility.

These scores represent qualitative relative tendencies summarized from the reviewed literature rather than direct experimental measurements. Low-to-medium level methanol-gasoline blends show potential advantages in thermal efficiency under optimized conditions and in high-load adaptability, life-cycle potential, and future fuel competitiveness, but they are still limited by cold-start performance, fuel consumption, infrastructure maturity, and fuel-system compatibility. Pure gasoline remains advantageous in infrastructure and drivability, while diesel is strong in fuel economy but faces greater emissions and low-carbon transition pressure.

In the medium and long term, optimized engines and a low-carbon methanol supply should be developed together. Higher compression ratios, flexible injection systems, lean-burn operation, and improved catalysts can help use methanol's anti-knock and charge-cooling advantages. Green methanol and e-methanol deployment also depends on renewable electricity, sustainable carbon sources, certification systems, infrastructure support, and cost reduction [123]. Therefore, future studies should evaluate methanol-gasoline blends as an integrated fuel-engine-carbon system rather than only as gasoline substitutes.

Data-driven modeling can support this integrated development by reducing experimental and computational costs. Zhang et al. [124] used a Bayesian-optimized ANN to predict the macroscopic spray characteristics of typical alcohol fuels, achieving an $R^2 > 0.98$. Xi et al. [125] combined multi-physics simulation, LightGBM, and many-objective optimization for a methanol/diesel dual-fuel engine. Although the latter involved a different combustion system, these approaches provide transferable methods for spray prediction and multi-parameter optimization in methanol-gasoline SI engines.

6. Conclusions

This review examined methanol-gasoline blends as alternative fuels for spark-ignition engines from the perspectives of fuel properties, combustion and engine performance, emissions, environmental implications, application challenges, and future development. The main conclusions are as follows:

(1) Methanol-gasoline blends offer combustion and efficiency potential under matched operating conditions.

Methanol's high octane quality and charge-cooling capacity can support knock suppression and favorable combustion phasing. However, BTE does not increase uniformly under general operating conditions. The larger efficiency gains reported in the literature were obtained mainly at high compression ratios or selected loads with matched injection and ignition strategies. Methanol's lower heating value can also increase fuel demand. Efficiency improvements should therefore be regarded as condition-dependent rather than an inherent result of methanol addition.

(2) Methanol-gasoline blends generally reduce CO and particulate emissions, but emission responses remain condition-dependent.

The oxygenated structure and low soot-forming tendency of methanol help reduce CO and particulate emissions under suitable conditions. For example, M10 reduced engine-out CO and HC by 44.8% and 25% during the first 150 s after cold start, and M15 studies also reported reductions in HC, CO, and particulate emissions. However, HC and NO_x vary with mixture preparation, combustion temperature, injection strategy, load, and after-treatment performance. Formaldehyde, unburned methanol, oxygenated hydrocarbons, and cold-start emissions should therefore be included in future emission evaluations. Descriptive statistical synthesis further showed that CO emissions exhibited the most consistent favorable response, whereas BTE, HC, and NO_x presented wider variations across the reviewed studies because of differences in engine configuration, operating condition, and calibration strategy.

(3) Methanol-gasoline blends have comprehensive application value when fuel properties, engine adaptability, emissions, and low-carbon fuel supply are considered together.

The value of methanol-gasoline blends is not limited to a single performance or emission index. Methanol can improve knock resistance, provide oxygenated combustion, reduce soot-forming tendency, and support more flexible engine calibration. Low-level blends such as M5–M15 are more suitable for near-term use because they are relatively compatible with existing engines and infrastructure. Medium-level blends such as M20–M30 may provide stronger combustion and emission benefits but require calibration, volatility control, cold-start optimization, and material compatibility verification. Higher blends such as M50–M85 depend more strongly on optimized engines, dedicated fuel systems, infrastructure readiness, and stable low-carbon methanol supply. Therefore, methanol-gasoline blends are meaningful as a transitional liquid-fuel option for improving the fuel flexibility and emission performance of spark-ignition engines, especially when future methanol supply can be connected with lower-carbon production routes.

Despite this potential, increased fuel consumption, phase instability, corrosion, cold-start difficulty, and material compatibility remain major barriers. Addressing these issues requires coordinated advances in fuel formulation, engine adaptation, and low-carbon methanol supply, supported by pathway-specific life-cycle assessment.

Use of AI tools declaration

The authors used AI tools solely for improving grammar and language style. All intellectual content, analysis, and conclusions are the authors' own.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Z-H: Writing-review & editing, Writing-original draft, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. D-D: Writing-review & editing, Supervision, Methodology, Funding acquisition. X-B: Investigation, Formal analysis. Z-L: Writing-original draft. C-S: Investigation, Formal analysis. X-G: Methodology.

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