

# A Review of Feedstock Diversification for Methanol Production: from Fossil Fuels to Renewable Resources

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Methanol is a critical platform chemical and an increasingly important energy carrier. While global production is currently dominated by fossil-based pathways primarily natural gas (average 65%) and coal (average 35%), there is however an urgent industrial mandate to decarbonize the supply chain. This review provides a rigorous quantitative evaluation of conventional and emerging carbonaceous feedstocks, including biomass, agricultural residues, municipal solid waste, and captured carbon dioxide (CO<sub>2</sub>). Quantitative analysis reveals that while traditional biogas offers methane concentrations averaging 50–80%, emerging substrates can also provide superior methane yields. A significant contribution of this work is the integration of the latest 2025 findings on semolina processing waste, which demonstrates a high-hydrogen (H<sub>2</sub>) potential (average 23.0% H<sub>2</sub>) for bio-methanol synthesis. Furthermore, the paper delves into the relevance of process intensification, identifying membrane reactor technology as a primary solution to thermodynamic equilibrium constraints. By addressing critical technical hurdles such as membrane fouling often cited as a major barrier to the 0.2% renewable share in global supply. This review serves as a vital roadmap for industries aiming to transition toward carbon-negative methanol production and enhanced energy resilience.

## 1. Introduction

The compound methanol (CH<sub>3</sub>OH or MeOH) is the most fundamental organic chemical in the alcohol family because it is the simplest possible alcohol, acting as the foundational building block for a vast array of synthetic, industrial, and downstream chemicals (NCBI, 2026). Its discovery dates to 1661, when Irish chemist Robert Boyle first isolated it via the distillation of wood, leading to the historical common name, wood alcohol (New World Encyclopedia, 2022). Composed of one carbon, one oxygen, and four hydrogen atoms (Herdem et al., 2019), this compound exhibits a narrow liquid range, changing from solid to liquid at -93.9 °C and boiling at 64.96 °C (Majidov, 2023).

At room temperature, Methanol is a colourless liquid with a slightly sweet, pungent odor similar to ethanol (Majidov, 2023). However, it is a highly dangerous poison that can cause blindness or death if ingested (Nekoukar, 2021). Methanol is also highly volatile and flammable, with a low flash point of 12.2 °C (Elvers and Schütze, 2022). Its vapours are slightly denser than air, allowing them to travel along surfaces to a distant ignition source, often resulting in a dangerous flashback (Martinka et al., 2019; Majidov, 2023). Methanol is fully miscible with water and most organic solvents (Elvers and Schütze, 2022).

Methanol undergoes both complete and incomplete combustion reactions and exhibits a neutral pH due to its non-ionizing nature (PCC Group, 2022). Being less dense than water, it will float if spilled. However, methanol's complete miscibility in water allows for rapid dilution of spills. Crucially, when released into surface waters, it is quickly broken down via aerobic biodegradation, with microorganisms metabolizing it into formic acid, resulting in a short environmental half-life of 1-7 days (Andersson and Marquez Salazar, 2015).

## 2. Uses of methanol

Methanol is an exceptionally versatile chemical feedstock widely utilized to manufacture a large array of primary derivatives, including formaldehyde, acetic acid, methyl tert-butyl ether, methylamines, and dimethyl ether (Wang et al., 2021). These primary chemicals subsequently undergo secondary processing to yield indispensable commodities such as resins, paints, adhesives, silicones, and plastics (Malik et al., 2021). Furthermore, methanol is a crucial ingredient in the production of light olefins (ethylene and propylene), which serve as building blocks for manufacturing plastics (Mukherjee et al., 2024). In the agricultural sector, methanol is also incorporated into selective pesticides, herbicides, and manures, contributing to sustainable and eco-friendly practices (Reddy et al., 2023).

Methanol is gaining prominence as a direct fuel source for various applications. It is often blended with gasoline or diesel in ratios like M100 for use in flexible fuel vehicles (Mårald, 2010). Critically, methanol is widely adopted as a marine fuel due to its ability to comply with stringent sulfur and nitrogen oxide emission regulations (Reddy et al., 2023; Wissner et al., 2023). As a liquid at standard room temperature, methanol offers high-octane combustion properties, reliability, and superior biodegradability when compared to conventional petroleum fuels (Tabibian and Sharifzadeh, 2023). Its liquid state also makes it an efficient hydrogen carrier and energy storage medium (Methanol Institute, 2023; Reddy et al., 2023). Methanol requires only a quarter to a third of the storage capacity needed for the same energy output as hydrogen, simplifying logistics and enabling on-site conversion to clean energy via reformers for fuel cells and power generation (Singla et al., 2021; McKinlay et al., 2021). Beyond industrial use, methanol can serve as a cleaner domestic heating fuel for cooking (Reddy et al., 2023). Methanol presents a safer alternative to paraffin in impoverished households, which is known for emitting harmful gases and posing fire risks (Marebane, 2021). Methanol combustion is highly advantageous because it produces clear to blue flames with zero visible smoke or soot emissions (Hobson and Marques, 2018; Maurya et al., 2022). Although methanol still produces combustible gases, the negligible visible emissions offer a substantial environmental and health improvement over kerosene or paraffin.

## 3. Sources of feedstock for methanol production

Methanol production utilizes a broad array of carbonaceous feedstocks, ranging from conventional sources like natural gas and coal to sustainable options such as biomass (energy crops, forest waste, agricultural residue, and marine biomass), industrial byproducts, sewage, and captured CO<sub>2</sub> (Khalafalla et al., 2019; Li et al., 2021;). Despite this wide scope, global methanol production remains heavily dependent on fossil fuels: approximately 65% is derived from natural gas and 35% from coal, with only a minute 0.2% currently sourced from biomass and renewable streams (Methanol Institute, 2023).

### 3.1. Biomass and Renewable sources

Agricultural waste streams represent a major carbonaceous source for methanol production. Yoosefdoost et al. (2024) established that biogas, produced from the co-digestion of agricultural residues and biosolids, is a highly suitable feedstock. Composed primarily of CH<sub>4</sub> and CO<sub>2</sub>, this biogas can be derived from diverse sources including sugarcane bagasse, corn cob mix, and municipal solid waste (Lee, 2019). The methane yields from these substrates (Yoosefdoost et al., 2024) and their typical chemical compositions (Tables 1–2; Figure 1) underscore their potential as rich precursors for sustainable bio-methanol synthesis and hydrogen valorization.

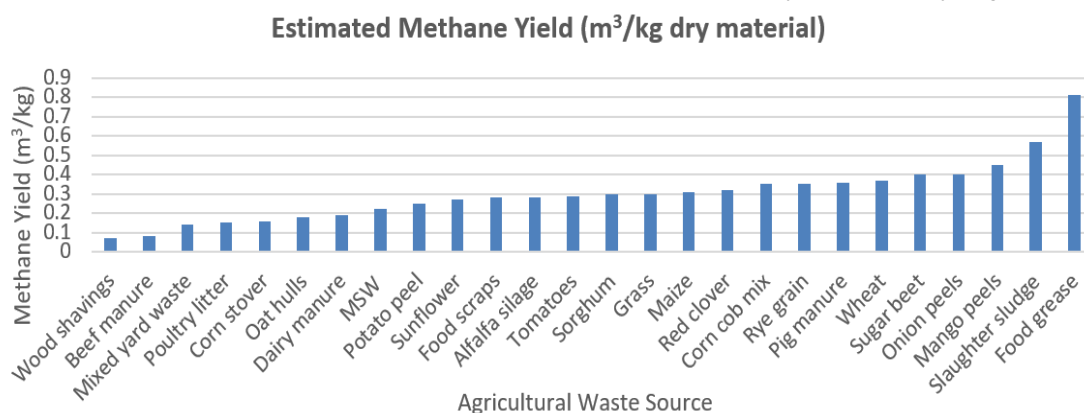


Figure 1: Schematic of methane yield (m<sup>3</sup>/kg dry material) from various sources of agricultural waste (Yoosefdoost et al., 2024).

Table 1: Composition of biogas from agricultural waste.

Substrate type	CH <sub>4</sub> (wt %)	CO <sub>2</sub> (wt %)	H <sub>2</sub> (wt %)	Reference
Mixed agricultural residue	50-80	20-80	-	Yoosefdoost et al. (2024)
Semolina Processing Waste	-	70 ± 6	23 ± 6.1	Marchetti et al. (2025)
Agriculture waste as is	44-67	30-44	-	Calbry-Muzyka et al. (2022)
Landfill agricultural waste	40-70	25-40	-	Calbry-Muzyka et al. (2022)
Raw and processed agricultural wastes	49.12-73.5	21.58-40.4	-	Onthong and Juntarachat (2017)

Table 2: Composition of compounds in various sources of biomass

Type of biomass	Carbon (wt %)	Oxygen (wt %)	Hydrogen (wt %)	Nitrogen (wt %)	Sulfur (wt %)	Reference
Pine	52.7	41.7	5.52	0.01	0.08	Puig-Gamero et al. (2018)
Straw	46.8	41.4	5.74	0.66	0.11	Yang et al. (2018)
Rice straw	41.96	29.11	4.72	0.57	0.09	Im-orb and Arpornwichanop (2020)
Corn cob	39.8	43.7	5.2	0.3	-	Brigagao et al. (2019)
Compost	37.1	31.4	5.1	3.7	0.5	AINouss et al. (2019)
Food waste	46.4	37.4	6.9	3.1	0.0	AINouss et al. (2019)

### 3.2. Coal, natural gas, and coke oven gas

Methanol production is geographically skewed, with China dominating both production and consumption, primarily relying on coal due to its widespread availability and cost-effectiveness (Wang et al., 2022; Methanol Institute, 2023). Conversely, the remaining continents overwhelmingly utilize natural gas for its similar economic advantages (Tabibian and Sharifzadeh, 2023). This reliance on fossil fuels viz. natural gas and coal is largely driven by cost efficiency (Liu et al., 2023). The environmental impact of hydrocarbon processing presents a unique opportunity for methanol feedstock diversification (Shahab-Deljoo et al., 2023; Salahudeen et al., 2022). Transforming this waste gas into methanol effectively resolves the flaring challenge and demonstrates significant success in waste valorization, converting a pollutant into a valuable commodity (Galli et al., 2021). Furthermore, industrial waste gases like coke oven gas (COG) offer a pathway to sustainable production by reducing reliance on conventional coal and natural gas feedstocks. While COG is traditionally used for iron production, its utilization for synthesizing methanol (and ethanol) offers a significantly more sustainable and energy-efficient solution compared to traditional methods that generate hefty CO<sub>2</sub> by-products (Park et al., 2021; Lee et al., 2019).

Table 3: Composition of various types of coal (Jithin et al., 2021)

Coal type	Hydrogen (mol %)	Carbon monoxide (mol %)	Methane (mol %)	Nitrogen (mol %)	CO <sub>2</sub> (mol %)
Brown coal	25	5	16	40	14
Bituminous	24.8	17.2	4.1	42.7	11
Lignite	12	22	1	55	10
Coke	15	29	3	50	3
Sub bituminous	17.3	14.7	3.3	51.6	12.4

Table 4: Composition of Coke Oven Gas and Natural gas

Coal type	Hydrogen (mol %)	Carbon monoxide (mol %)	Methane (mol %)	CO <sub>2</sub> (mol %)	Reference
Natural gas	No data	No data	70-90	30–80	Canete et al., 2018; Aregbe, 2017
COG	62	No data	>20	No data	Leonzio, 2018
COG	55–60	5-8	23–27	<3	Razzaq et al., 2013
COG	54-59	No data	24-28	No data	Xu et al., 2018

### 3.3 Alternative Systems for Methanol Production

The transition to sustainable methanol requires not only feedstock diversification but also the adoption of intensified reactor technologies. Traditional methanol synthesis is limited by thermodynamic equilibrium, requiring high pressures and multiple recycling loops. Membrane reactors offer a solution by simultaneously performing reaction and separation. As noted by Hamed et al. (2021), these systems can shift the equilibrium by removing water or methanol through the membrane wall, thereby increasing per-pass conversion. However, the primary hurdle for industrial adoption is membrane fouling. Fouling decreases the permeation flux and can lead to structural degradation of the membrane (Pulimeno, 2023). As a result, successful membrane integration requires robust fouling inhibition strategies, such as boundary layer control and periodic cleaning protocols, to maintain long-term operational stability in harsh chemical environments. Emerging biotechnological routes, such as guided fermentation of organic wastes, allow for the direct production of alcohols. Unlike thermochemical gasification, these biological pathways operate at ambient temperatures and pressures, potentially reducing the overall energy intensity of the production cycle (Dieterich et al., 2022).

## 4. Conclusion

Methanol remains an indispensable chemical, yet its production is currently locked into fossil-based pathways. This review has demonstrated that agricultural residues, biogas, and industrial waste gases like COG provide viable, low-carbon alternatives. The integration of 2025 data regarding semolina waste highlights the increasing relevance of high-hydrogen substrates for bio-methanol synthesis. However, technical challenges remain. The scaling of membrane reactor technology is promising for improving efficiency, but membrane fouling must be addressed through advanced material science and boundary layer engineering. Furthermore, the 0.2 % share of renewable methanol in the global market indicates that policy incentives and waste-to-chemical infrastructure investments are required. Future research should focus on the techno-economic optimization of modular, farm-scale methanol units that can utilize local biogas and organic residues, effectively decentralize the industry and enhance regional energy resilience.

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