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Editorial

Methane capture from atmosphere using direct air capture

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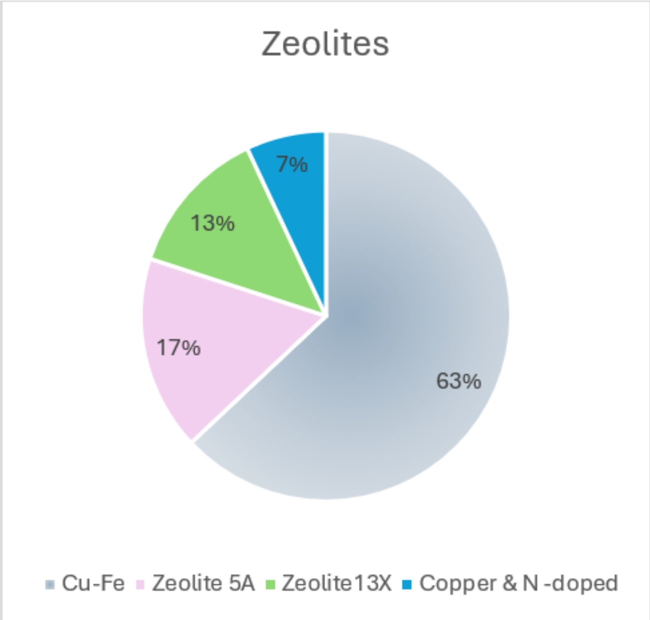
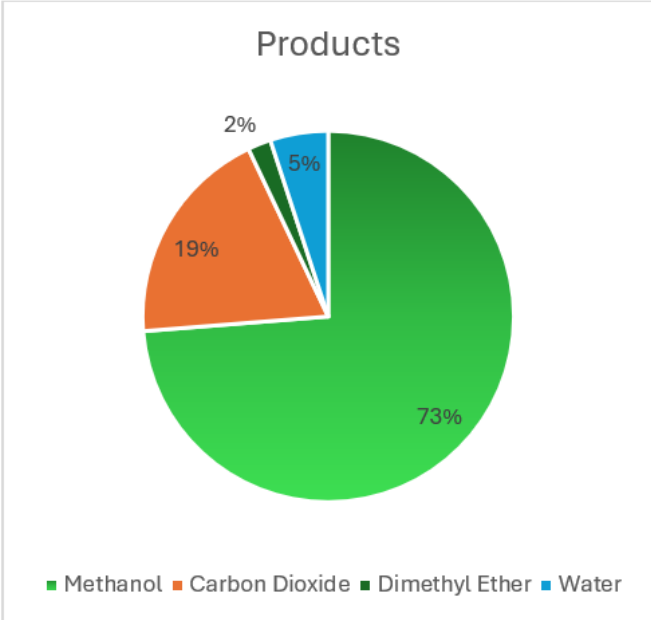
The current methane concentration in the atmosphere has tripled to 1.92 ppm (2024) compared to the preindustrial concentration of 0.7 ppm (1750), having 80–87 times more global warming potential than CO_2 over a 20-year span while it stays in the atmosphere for a decade. Various zeolites can be used to capture methane directly from the air and convert it into useful products (methanol, dimethyl ether).

A methane plume has been identified through satellite in Karachi, Pakistan, extending 4 kilometers from the landfill site, and another methane plume is southside of Midland (Permian Basin) from the oilfield [1]. With increased population, landfill (account for 10% of all CH_4 emissions) [2] sites are expected to increase with more methane release, which has caused heatwaves (America, Europe, South Asia, and China) and record high temperatures (53 °C in America, 52 °C in China, and 54 °C in the Middle East), extreme weather patterns, and record low temperatures (17 °C in Faisalabad, Pakistan) in summer; major floods (covering one third of Pakistan); glaciers and lakes melting; oceanic water pH variation; and droughts are the result of climate change caused by greenhouse gases. Reasons for climate change are increased industrialization, deforestation, increased personal vehicles and reduced use of local transport, expanding cities, forest fires, missing environmental impact assessment studies, lack of implementation of environmental remediation projects and policies, increased automation and electricity consumption, reduced tree plantation, and mismanagement of land use plans. Methane emissions are expected to increase due to urbanization and eutrophication, requiring its capture to control it [3]. A global sea level rise of 111 mm in 3 decades and its increased rate from ~2.1 mm/year (1993) to ~4.5 mm/year (2023) are clear signs of global warming [4], and atmospheric warming is proceeding towards 2.7 °C by 2100, exceeding the proposed 1.5 °C limit [5]. Thirty percent of global warming can be slowed down by controlling methane emissions, and direct air capture has the potential to capture methane, which can be converted into various useful products. Various zeolites are being used to capture atmospheric methane. Approximately 63% are Cu-Fe zeolites, 17% are zeolite 5A, 13% are zeolite 13x and 7% are copper & N-doped zeolites (**Figure 1a**). These zeolites capture methane, and the formed product most of the time is methanol (73%), carbon dioxide (19%), dimethyl ether (2%), and water (5%) (**Figure 1b**).





(a) **(b)**

Figure 1. Zeolites to capture methane and convert it into various products, **(a)** Zeolites used; **(b)** formed products.

Zeolites are naturally occurring or synthetic minerals composed of aluminosilicates, which is the combination of aluminum, oxygen, and silica. Its porous structure is good for gas absorption. They have small enough pores to trap gas molecules. Due to their thermal stability and resistance to degradation, zeolites can withstand high temperatures, making them highly durable for long-term applications in both industrial and environmental settings. One particularly promising type of zeolite for methane capture is copper-doped zeolites like copper mordenite. These zeolites are used in methane oxidation processes, where methane is chemically transformed into other products such as carbon dioxide or methanol. These copper-exchanged zeolites operate at relatively low temperatures (200–300 °C), making them energy-efficient solutions for methane abatement. Zeolites are pivotal materials in methane capture technologies, thanks to their porous structure, chemical stability, and versatility in catalysis. They offer a pathway for reducing methane's harmful environmental impact by converting it into less potent greenhouse gases (CO_2) or useful chemicals like methanol. Some other polymers also used methane to convert into carbon-based products. Many other zeolites (Fe-Cu, N-doped, NaX, etc.) are also being used for methane capture from different processes like biological conversion and chemical conversion.

Various processes for methane removal are explored in **Table 1**, including photocatalytic oxidation using nano-structured zinc oxide catalysts enhanced with silver decoration. This method demonstrated a high quantum yield of 8% under UV light, making it a promising low-temperature solution for atmospheric methane removal; furthermore, its application for hydrocarbons like ethane and propane. Additionally, research on methane removal through chlorine-mediated chemistry, biofilters, and zeolites is discussed, highlighting the effectiveness of these methods in high-methane environments such as landfills and fossil fuel sites. Methane emissions could rise between 9%–72% by 2100 without targeted policies. The importance of reducing methane emissions to meet the 1.5 °C global warming target is underscored, with strategies suggesting a reduction of up to 53% by 2050. Innovations in catalytic and photocatalytic methods are most required as an effective means of removing both methane and carbon dioxide from low-concentration emission sources. These catalysts demonstrated the potential to remove over 40% of anthropogenic methane. However, methane's non-polar nature challenges its selective capture, and future advancements in zeolite structures are required to overcome this hurdle. Additionally, the integration of methane removal with carbon dioxide capture technologies should be adopted as crucial for achieving energy-efficient solutions. Photocatalysis and thermal-catalytic oxidation, despite their energy requirements, are viable in methane-rich environments like oil fields, while zeolites and biofilters offer scalable solutions for agricultural and industrial methane capture. The research highlights the need for immediate, cost-effective measures across sectors to limit methane emissions and prevent further climate damage.

Table 1. Review matrix highlighting various processes to convert atmospheric methane into various products.

Publication		**Chemical conversion**			**Biological conversion**		**Brief remarks**
Author	**Year**	**Photocatalytic oxidation**	**Photochemical oxidation**	**Absorption oxidation**	**Biofilter**	**Soil amendment**	
Alonso et al.	2017			✔			The main focus is on nanoparticle-like zeolites that absorb methane and also on the cost of material.
Ishita Mundra, Andrew Lockley	2024	✔	✔	✔	✔		Mainly discussed the method of methane capturing and also discussed where methane is produced, like naturally or artificially.
Tingzhen Ming et al.	2022	✔	✔	✔	✔		Discussed method for methane removal and compare their efficiency which method is best regarding cost and stability.
Abernethy	2021		✔		✔	✔	Mainly discussed removal of methane and improvement of air.
R.B Jackson	2019			✔			Mainly discussed the methane effect on the environment and their solution.
Rebecca	2022			✔			Discussed oxidation of methane at low conditions.
Robert B. Jackson	2021	✔		✔		✔	Mainly discussed methane capturing from the atmosphere.
Jin Wang	2023	✔		✔			Mainly discussed methane capturing from the atmosphere.
Silvia	2017			✔			Mainly used porous 3D polymer for methane capturing and storage at high pressure and also focused on their efficiency.
Jihan Kim et al.	2013			✔			This article depicts the recent advancements like nanoporous zeolites and ionic liquids for more effective methane sorption and separation.
Qinyi Li et.al	2023		✔				This article depicts the role of chlorine-mediated chemistry in reducing atmospheric methane, suggesting that increasing chlorine emissions could significantly lower methane levels.

Table 1. (*Continued*).

Publication		**Chemical conversion**			**Biological conversion**		**Brief remarks**
Author	**Year**	**Photocatalytic oxidation**	**Photochemical oxidation**	**Absorption oxidation**	**Biofilter**	**Soil amendment**	
Shindell et al.	2024	✔	✔	✔	✔	✔	This article depicts the need to reverse methane growth & align methane and CO_2 emissions.
Shan Zhu et al.	2021	✔	✔				This article depicts the efficient photocatalytic oxidation of methane to liquid oxygenates using ZnO nanosheets under mild conditions to achieve high production rates and selectivity.
J. Jiang et al.	2024	✔	✔	✔	✔	✔	The article depicts the invention and diffusion of methane-targeted abatement technologies (MTATs) to effectively reduce methane emissions.
D.S	2023	✔	✔	✔			This article depicts the different approaches for co-removing methane and carbon dioxide using catalytic oxidation methods, using photocatalytic oxidation.
Klaus S. Lackner	2020			✔			It depicts the challenges of atmospheric methane removal as it will be easier to reduce methane emission as compared to methane capture.
Xuxing Chen et al.	2016	✔	✔				This article explores the photocatalytic oxidation of methane using silver-decorated zinc oxide nano-catalysts, highlighting their efficiency under sunlight. It presents promising results for methane and other hydrocarbon photo-oxidation at ambient conditions.
Peter B. R. Nisbet-Jones et al.	2021	✔	✔		✔		This article depicts an efficient photocatalytic oxidation of methane using silver-decorated zinc oxide nano-catalysts, achieving high quantum yields under sunlight.
Ilissa B. Ocko et al.	2021						This article emphasizes the urgency of implementing methane mitigation strategies to reduce near-term global warming. It advocates for rapid deployment of available technologies to cut methane emissions and highlights the potential benefits to slow climate change.
Nisbet et al.	2020	✔	✔	✔	✔	✔	This article depicts the various methane mitigation methods, emphasizing their effectiveness and potential for reducing emissions in line with climate goals.
Mathijs Harmsen et al.	2019						This article depicts methane emissions, their reduction strategies, and the implications for climate policy.
Qinyi Li et al.	2023		✔				This article depicts the methane role in climate change and its emission reduction potential.
Tomkins et al.	2017	✔	✔				The article depicts the various methods for the direct conversion of methane to methanol. It also includes the catalytic processes including Cu-zeolites and also depicts the alternatives for the oxidation methods & how to enhance the economic viability.

Future research should focus on porous 3D polymers which are better than MOFs, COFs and activated carbons [6]. Recently developed hyper-cross-linked polymers (HCPs) through mixed-solvent knitting show methane storage capacity of 0.429 g g^{-1}

at 273 K and have a high pore volume of 2.72 cm^3/g [7]. Another HCP has demonstrated a methane absorption capacity of 329 cm^3/g [8]. Microbubble-induced oxidation of methane has shown promising results with 171.5 ppm h^{-1} conversion rates [9]. Recently DAC plants are being installed for carbon capture and these technologies can be adopted for methane capture too [10,11].

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