Challenges and Opportunities in the Production of Oxymethylene Dimethylether

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To reduce the NOx and soot emissions of conventional diesel fuels, different renewable alternatives are investigated. One example are oxymethylene ethers (OMEₙ) of different chain lengths, which are intended to be used as diesel blends. Especially OME₃–₅ show properties comparable to diesel. The key to producing longer chain OMEs is OME₁ as feedstock, which can react with formaldehyde to afford larger molecules. This article reviews different synthesis routes for OME₁, in order to elucidate energy-efficient methods.

Keywords: CO₂, Diesel alternative, Oxymethylene dimethylether

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1 Introduction

The increasing production of renewable energy is accompanied by the challenge of efficient storage and customized supply of the variable resources. An attractive option for storage of electrical energy on large scale and management of the fluctuations of solar and wind power generation is based on the production of liquid energy carriers. Tailored liquid energy carriers with adapted volumetric and gravimetric energy density represent a flexible element of future mobility, especially with regard to the transportation sectors. Currently, diesel fuel plays a major role in long distance transportation and 94 % of freight transportation relies on diesel engines. Moreover, modern diesel engines allow efficient propulsion with favorable CO and CO₂ emissions compared to gasoline engines. [1, 2] However, the combustion in diesel engines comes with problematic NOx and soot emissions, causing major challenges for after-gas treatment and motor management systems. [3] Accordingly, many existing diesel vehicles exceed the current limits for NOₓ and soot emission and require adapted solutions for future utilization within the legal regulations. [4–6]

The Kopernikus P2X project has accepted this challenge and targets the effective transformation of CO₂ with renewable energy to fuels and chemical products. In the initial phase of Kopernikus P2X, a focus was the development of oxygenate fuels, enabling the development of diesel engines with strongly reduced NOx and soot emissions. This approach was motivated by existing oxygen-containing liquids like ethanol, dimethyl ether, and dimethyl carbonate, already demonstrating a significant soot reduction in combustion processes. [7–9] The target structures of P2X were oxymethylene dimethylethers (OMEs), composed of oligomers with the repeating –(O-CH₂)n– unit and methyl/methoxy end capping groups (Scheme 1). The absence of C–C bonds in OMEs is the decisive element, allowing a combustion with decreased soot formation. [10–15]

![Scheme 1. Chemical structure of OMEs of different chain length n.](image)

Excitingly, previous engine studies already emphasized the significant potential of OMEs as fuel additives for reducing soot and NOₓ emissions. More specifically, an addition of 35 vol % of OMEs to standard diesel fuel reduces the soot formation by 90 %. [14] Interestingly, the soot reduction potential is not correlated to the chain length of the respective OMEs and physico-chemical properties like viscosity, cetane number, and flash point of OMEs with a chain length of 3–5 allow for the best fit to current diesel properties. [16]

The conventional production of OME₃–₅ proceeds by reacting methanol with a formaldehyde source (either trioxane or paraformaldehyde) for chain elongation. [17, 18] According to the chemical equilibrium, a large excess of formaldehyde units is required for significant chain growth while any water present in the system compromises chain elongation. In this manner, the production of paraformaldehyde and trioxane as "dry" formaldehyde sources is well investigated. [19–22] Alternatively, dimethoxymethane

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(DMM or OME₂) can serve as feedstock to be combined with a formaldehyde source to produce higher OMEs (OME₃–5) in an anhydrous approach. However, the development of novel production pathways to OME₁ and OME₃–5 is still of major importance, aiming for energy-efficient processes with reduced number of process steps (Fig. 1).

Starting from CO₂, methanol can first be formed by either electrochemical reduction or chemo-catalytic hydrogenation with hydrogen provided by water electrolysis. In the conventional process concept, one third of methanol is subsequently re-oxidized over an iron-molybdenum catalyst or dehydrogenated via a silver catalyst in a high temperature gas-phase reaction providing formaldehyde (FA). In the presence of an acid catalyst in a low-temperature liquid phase reaction, methanol from the main stream and formaldehyde react to OME₁ (Fig. 1, established route). Despite the undesirable energy and redox profile, the multi-step nature accompanied by several purification steps enhances production costs. OME₁ can also be synthesized by direct oxidation of methanol on a bifunctional catalyst, reducing the number of process steps, but still following the undesirable redox profile (Fig. 1, direct oxidation). Recently, the group of Klankermayer was able to use CO₂ instead of formaldehyde in the reductive route in the presence of methanol to form OME₁ (cf. Sect. 4). Here, re-oxidation of methanol is avoided, overcoming the undesirable methanol oxidation and further reducing the number of required unit operations. Theoretically possible but not demonstrated experimentally yet, the ideal route for OME₁ synthesis is via a one-step synthesis based solely on CO₂ and H₂ to yield formaldehyde and methanol within a single system which are combined to deliver OME₁ as the sole product.

The potential of these alternative process routes was also evaluated in a recent life-cycle assessment of OME₁, described by Deutz et al. Here, the authors confirmed that a mixture of 35 vol % OME₁ and 65 vol % diesel could not only reduce the impact of global warming, but also significantly reduce soot and NOₓ emissions (Fig. 2).

2 Indirect Synthesis of OME₁

Today, OME₁ synthesis proceeds via the indirect two-step production as described in the previous section. FA is either produced by methanol oxidation on an iron molybdate catalyst or dehydrogenation over a silver catalyst (Scheme 2, Eq. (1)). FA is stabilized in the presence of methanol via the formation of a methoxymethanol (MM) intermediate (Scheme 2, Eq. (2)). MM then condenses with methanol on an acid catalyst to OME₁ (Scheme 2, Eq. (3)). The latter reaction is reversible and hence, the yield is limited by chemical equilibrium. The equilibrium can be overcome by evaporating the low boiling OME₁ during the reaction.
tion [27, 29, 30]. Here, very good yields were achieved in a reactive distillation setup [31]. However, the separation is impeded by the formation of a low-boiling azeotrope of OME$_1$ and methanol with 92.2 wt % of OME$_1$. Pressure swing distillation allows increasing OME$_1$ purity up to 99.1 wt % [31–33].

OME$_1$ synthesis is well understood for soluble acid catalysts. H$_2$SO$_4$, HCl, p-TsOH as well as FeCl$_3$ were investigated and allowed an efficient production of OME$_1$ [34–37]. However, soluble acid catalysts bear a high corrosion potential, hamper product separation, and result in salt formation upon neutralization of the soluble acid. Consequently, solid acid catalysts, which overcome these challenges, have gained growing attention in recent years. [27, 30, 31, 38–41] The main groups considered in OME$_1$ synthesis are ion exchange resins, sulfonated tetrafluoroethylene resins, heteropoly acids, and zeolites. As the OME$_1$ synthesis is mainly limited by equilibrium, the catalysts are optimized based on engineering aspects like kinetic investigations, alternative formaldehyde sources, and demonstration in pilot plants. Kinetic investigations were demonstrated by the Hasse group for an Amberlyst 15 catalyst which fits well with experiments and clearly illustrates the limitation by chemical equilibrium. [30] Different sources of FA, comprising especially trioxane as FA trimer, were also investigated for the synthesis of OME$_1$. Zhang et al. demonstrated a reaction at 70°C, applying methanol and trioxane in the presence of Amberlyst 15. [40] Reactive distillation enabled nearly complete conversion of FA independently of the catalyst. A corresponding demonstration plant was presented by Zhang et al. [31] They showed a conversion of FA of 99.6 % and a purity of OME$_1$ of 92.1 %. For further purification, pressure swing distillation was applied.

### 3 OME$_1$ Production via the Oxidation of Methanol

The direct oxidation of methanol to OME$_1$ enables reduction of the process steps (Scheme 3). A solid bifunctional catalyst is located in the reactor in a fixed bed where vaporized methanol and oxygen react to OME$_1$ (Fig. 3). Here, FA is initially formed in situ by partial oxidation of methanol. The subsequent acetalization of FA in the presence of methanol then leads to the corresponding OME$_1$ product. As oxygen is involved in this reaction, the explosion risk can be excluded by restricting the amount of methanol to a regime below 7 % or over 36 %.

The bifunctional catalyst has to facilitate two different reactions in a well-adapted fashion. First, the catalyst needs a metal functionality allowing oxidation of methanol to formaldehyde. In a second step, acetalization proceeds on the acidic site of the catalyst in the presence of methanol and formaldehyde to form OME$_1$. Both functions must be aligned with regard to selectivity and reaction rate to suppress undesirable side reactions as well as enhance overall rate and selectivity of OME$_1$ production. [42] In the presence of rather strong oxidizing sites, side reactions can include the over-oxidation of methanol to CO$_2$, CO, or formic acid. The latter can react in the presence of methanol to methyl formate (MF). In addition, via the Tishchenko reaction, MF may arise from FA. [43] On the other side, if the strength of the acidic site is too high, the side product dimethyl ether (DME) can be produced by dehydration of methanol. Hence, an overall optimal strength of both active sites is indispensable to establish an efficient and highly selective reaction of methanol to OME$_1$. Noble and non-noble metal catalysts have shown their potential in OME$_1$ synthesis. The main category of noble catalysts comprises ruthenium-based and rhenium-based catalysts. On the other hand, molybdenum- and vanadium-based catalysts are potent non-noble alternatives.

**Scheme 3.** Direct synthesis of OME$_1$ starting from methanol.

\[
3 \text{CH}_3\text{OH} (g) + \frac{1}{2} \text{O}_2 (g) \rightarrow \text{H}_3\text{C} = \text{O} \text{C}_\text{O} \text{C}_\text{H}_3 (g) + 2 \text{H}_2\text{O} (g)
\]

Rhenium-based catalysts (ReO$_4$) were the first reported systems to catalyze the oxidation of methanol to OME$_1$. At a temperature of at least 240 to 300°C, Re-based catalysts showed a good performance in the OME$_1$ synthesis. Catalysts affording a selectivity of 90 % or higher towards OME$_1$ are stated in Tab. 1. The conversion employing these catalysts ranges from 5 % up to 50 %. It was found that rhenium can provide both functionalities of a bifunctional catalytic system. [44, 45] The bifunctional character is achieved by the presence of two oxidation states. Therein, Re$^{4+}$ species were proposed to facilitate the methanol oxidation step whereas its oxidized species Re$^{7+}$ (Re$^{4+}$ oxidizes in presence of oxygen) act as acidic sites catalyzing the acetalization step.

Non-noble catalysts play an important role in the sustainability of processes and, hence, products in chemical industries. Tab. 2 provides an overview of non-noble metal catalysts for the
direct OME\textsubscript{1} synthesis based on methanol oxidation. Vanadium and molybdenum oxides are promising candidates for non-noble metal catalysts in OME\textsubscript{1} production, facilitating superior performance to Re-based catalysts. At an optimum process temperature of about 140°C, above 90 % selectivity can be achieved (Tab. 2). In general, vanadium-based catalysts perform very well in methanol oxidation to OME\textsubscript{1}. They are mainly composed of vanadium pentoxide (V\textsubscript{2}O\textsubscript{5}) and well established in industrial oxidation processes. [43] The excellent oxidation properties of vanadium-based catalysts have to be combined with an acidic function, either by using an acidic support material or via the addition of acidic additives. The group of Shen inserted either Ti(SO\textsubscript{4})\textsubscript{2} or H\textsubscript{2}SO\textsubscript{4} on V\textsubscript{2}O\textsubscript{5}/TiO\textsubscript{2} by impregnation (entry 5 & 6). Both acids showed similar OME\textsubscript{1} selectivity of around 90 % and conversions between 41 % and 49 %. In another approach, V\textsubscript{2}O\textsubscript{5}/TiO\textsubscript{2} catalysts were modified with sulfur (VTiS), with rapid compression (RC) [47, 48], sol-gel (SG) [49, 50], and mechanical grinding (MG) [49] presenting the most efficient methodologies. More specifically, these catalysts afforded similar OME\textsubscript{1} selectivities; however, the conversion reached with these systems differed significantly ranging from 15 up to 49 %, respectively. Sina et al. protected VTiS by cetyltrimethylammonium bromide (CTAB) during the synthesis. Hence, nanoparticle of vanadium species and acidic sites were obtained by suppressing particle agglomeration. An increase in the activity was mainly observed at higher conversion (~54%, entry 10). Inspired by the small particle size and its good activity, TiO\textsubscript{2} nanotubes (TINT) where dispersed as monolayer on V\textsubscript{2}O\textsubscript{5}. [51, 52] Pure V\textsubscript{2}O\textsubscript{5} only showed a selectivity of 51 % towards OME\textsubscript{1}. Modifying the monolayer with H\textsubscript{2}SO\textsubscript{4} significantly improved the selectivity even at high conversion (58 %, entry 11). Another surface modification relies on the incorporation of metal oxides into the support material. The highest potential was shown for SiO\textsubscript{2} which was introduced in the TiO\textsubscript{2} structure to create more acidic sites (VTiSi, entry 13). Here, a selectivity of 99 % was achieved at 51 % conversion. [50] Another issue in the oxidation of methanol towards OME\textsubscript{1} is the reduction of the operating temperature of this reaction. Here, Meng et al. could show that V-based MO\textsubscript{3}/Al\textsubscript{2}O\textsubscript{3} decreases the reaction temperature to 120°C while keeping

### Table 1. Re-based catalyst for the OME\textsubscript{1} synthesis via methanol oxidation.

| Entry | Catalyst         | GHSV [L h\textsuperscript{-1} g\textsuperscript{-1}] | Conversion [%] | Selectivity [%] | Ref. |
|-------|------------------|-----------------------------------------------|----------------|-----------------|------|
|       |                  |                                               |                | OME\textsubscript{1} | FA | DME | MF | CO+CO\textsubscript{2} |      |
| 1     | SbRe\textsubscript{2}O\textsubscript{6} | 10                             | 6.5            | 92.5           | –   | 6.3 | 1.2 | – | [45] |
| 2     | 10%Re/V\textsubscript{2}O\textsubscript{5} | 40                             | 21.5           | 93.7           | –   | 4.3 | –   | 2 | [46] |
| 3     | 10%Re/α-Fe\textsubscript{2}O\textsubscript{3} | 40                             | 15.5           | 90.5           | 2   | 1   | 6   | 0.5 | [46] |
| 4     | 10%Re/γ-Fe\textsubscript{2}O\textsubscript{3} | 40                             | 48.4           | 91             | 2.4 | 1   | 4.6 | 1 | [46] |

n.a. = not available

### Table 2. Non-noble catalysts for the OME\textsubscript{1} synthesis via methanol oxidation.

| Entry | Catalyst         | GHSV [L h\textsuperscript{-1} g\textsuperscript{-1}] | Conversion [%] | Selectivity [%] | Ref. |
|-------|------------------|-----------------------------------------------|----------------|-----------------|------|
|       |                  |                                               |                | OME\textsubscript{1} | FA | DME | MF | CO+CO\textsubscript{2} |      |
| 5     | 5%V\textsubscript{2}O\textsubscript{5}/TiO\textsubscript{2}-H\textsubscript{2}SO\textsubscript{4} | 11.4                          | 48.2           | 91.6           | 0.1 | 2.4 | 6 | n.a. | [55] |
| 6     | 30%V\textsubscript{2}O\textsubscript{5}/TiO\textsubscript{2}-Ti(SO\textsubscript{4})\textsubscript{2} | 11.4                          | 41             | 90             | 0   | 1   | 9 | – | [56] |
| 7     | 11.7%VTiS-RC     | 5                             | 48.6           | 91.8           | 2   | 0.6 | 5.6 | 0.1 | [48] |
| 8     | 22.8%VTiS-SG     | 11.4                          | 33             | 93             | –   | 1   | 6 | – | [49] |
| 9     | 24.8%VTiS-MG     | 11.4                          | 15             | 90             | 2   | 7   | 1 | – | [49] |
| 10    | VTiS-CTAB        | 0.924                         | 53.4           | 92.8           | n.a. | n.a. | n.a. | n.a. | [57] |
| 11    | SVTiNT-673       | 11.4                          | 58             | 92             | 2   | –   | 6 | – | [52] |
| 12    | VTiS-673         | 11.4                          | 43             | 92             | 1   | 2   | 5 | – | [58] |
| 13    | VTiSi            | 12                             | 51             | 99             | –   | 1   | – | – | [50] |
| 14    | V\textsubscript{2}O\textsubscript{3}-MoO\textsubscript{3}/Al\textsubscript{2}O\textsubscript{3} | 4                             | 54.2           | 92.1           | –   | 5.6 | 2.3 | – | [53] |
| 15    | SbVO\textsubscript{x} | 80                             | 12             | 100            | –   | –   | – | – | [54] |
| 16    | NbO\textsubscript{x} | n.a                           | 58             | ~100           | –   | –   | – | – | [59] |

n.a. = not available; CTAB used as protective agent.
4 One Step Synthesis of OME<sub>1</sub> From the Direct Hydrogenation of CO<sub>2</sub> with H<sub>2</sub>

In comparison to the oxidative approach to produce OME<sub>1</sub> starting from methanol, the reductive approach comprises the direct hydrogenation of CO<sub>2</sub> with H<sub>2</sub> in presence of methanol in a multicomponent combination fashion to form OME<sub>1</sub> in only one step (Scheme 4, Eq.(5)). Although a detailed process design is not yet available, a simplified assessment analysis by Deutz et al. expected that the general demands of resources and energy for the direct route of OME<sub>1</sub> synthesis from CO<sub>2</sub> are relatively lower (economically beneficial) compared to the oxidative (formaldehyde) route, especially if H<sub>2</sub> is obtained from renewable resources. [25] In this manner, the need for an oxidative step to produce FA from methanol is eliminated and the use of CO<sub>2</sub>-based methanol is also feasible (Scheme 4, Eq.(6)), leading to a more sustainable synthetic pathway of OME<sub>1</sub> and addressing an overall reduction of hydrogen consumption as well as CO<sub>2</sub> emissions (Tab.3). [25]

The key step for this direct approach is the catalytic reduction of CO<sub>2</sub> to “FA reduction level”, which is thermodynamically not favored compared to the reduction of CO<sub>2</sub> to formic acid. Consequently, the reduction of CO<sub>2</sub> to formic acid and its subsequent esterification with methanol to a methyl formate (MF) intermediate would represent an alternative route to a favorable synthesis of OME<sub>1</sub> directly from CO<sub>2</sub> (Eq.(7)). In this manner, the subsequent hydrogenation of the MF intermediate to the corresponding methoxymethanol (MM) hemiacetal (possessing the FA-methylene) to afford OME<sub>1</sub> as a more stable product (Scheme 5). In accordance, the development and use of a multifunctional catalytic system catalyzing the different sequences (hydrogenation/esterification/acetalization) in a one-pot manner is an important, challenging, and highly recommended task. [60] This can be clearly reflected by the very few research reports published in the last few years and mainly describing the use of homogeneous catalytic systems employing defined molecular catalysts for the direct hydrogenation of CO<sub>2</sub> to OME<sub>1</sub>.

In 2016, the group of Klamkermayer reported the first catalytic hydrogenative approach to synthesizing OME<sub>1</sub> directly from CO<sub>2</sub>/H<sub>2</sub> as C<sub>1</sub> building block in the presence of methanol [61]. The developed multifunctional catalytic system described in this work comprises a ruthenium catalyst for the hydrogenation steps and an acidic co-catalyst for both activating the ruthenium catalyst as well as catalyzing the esterification/acetalization steps of the reaction sequence. More specifically, the catalytic system employed for this reaction was based on the [Ru(triphos)(tmm)] catalyst (triphos = (1,1,1-tri(diphenylphosphino)methyl) ethane, tmm = trimethylene methane) in combination with aluminum triflate (Al(OTf))<sub>3</sub> Lewis acid as co-catalyst (Scheme 6). The direct reaction of CO<sub>2</sub> to OME<sub>1</sub> was carried out with 20/60 bar of CO<sub>2</sub>/H<sub>2</sub> at a mild temperature of 80 °C to afford OME<sub>1</sub> in a TON (turnover number) of 214 whereas the expected MF intermediate was obtained with a TON of 104 at the end of the reaction. Further optimization of the reaction conditions resulted in the formation of OME<sub>1</sub> with up to 763 TON when 1,4-dioxane was used as a co-solvent of the reaction. [62] The multifunctionality of this catalyst system was proven to be crucial for the complex reaction sequence described in Scheme 5. This

![Scheme 5. Reaction pathway for the direct synthesis of OME<sub>1</sub> using CO<sub>2</sub>/H<sub>2</sub> and methanol.](image-url)
suggested sequence was further supported by performing a set of experiments employing non-labeled CO2/H2 in the presence of labeled methanol (13CD3OD), resulting in the formation of MF and MM intermediates as well as the OME1 product, in which the labeled atoms were tracked in the (13CD3O-) groups only (Scheme 7). These observations reveal that the final product OME1 incorporated only the methyl groups (CH3–) generated from the methanol substrate whereas the (–CH2–) units were generated solely from the CO2 and H2.

In 2017, a catalytic system for the direct hydrogenation of CO2 to OME1 based on a non-precious transition metal catalyst could be established. [63] In detail, various cobalt salts in combination with selected triphos ligands and acidic co-catalysts enabled a straightforward direct synthesis of OME1 via the formation of MF and MM intermediates. More specifically, Co(BF4)2·6H2O was employed as the most active cobalt precursor together with triphos ligand and Brønsted acid co-catalyst HNTf2 (bis(trifluoromethanesulfonyl)imide), leading to an active system for the formation of OME1 with a TON of 373 starting from MF as substrate, and with a TON of 92 starting from CO2 (Scheme 8). When compared to the ruthenium/triphos system, a higher temperature of 100°C was required for the cobalt/triphos system as well as the use of tetrahydrofuran (THF) as a co-solvent. Moreover, the investigation of the influence of a set of other triphos ligands (with variable ligand sphere induced by different sterically hindering functionalities) was reported and showed that the reactivity of the cobalt system could be enhanced. In particular, the use of triphosligand (1,1,1-tris(bis(4-methylphenylphosphino)methyl)ethane) for the synthesis of OME1 from CO2 enhanced the TON up to 157 (Scheme 8), yielding a comparable activity to the ruthenium/triphos precious-metal catalyst. [61]

In addition, the versatility of the novel ruthenium- and cobalt-catalyzed direct synthesis of OME1 from CO2/H2 and methanol was extended to the synthesis of dialkoxyethanes by replacing methanol with a variety of other alcohols. [61, 63] Interestingly, reacting CO2/H2 and ethanol resulted in diethoxymethane which is identified as a promising fuel candidate "bio-hybrid fuel" from a production perspective. [64, 65]

More recently, the group of Trapp used the developed catalyst lead structure and prepared catalysts derivatives (ruthenium/N-triphos/Al(OTf)3) in combination with consequent optimization of the reaction conditions for OME1 and MF synthesis from CO2/H2 and methanol. [66] The authors extensively investigated the effects of variations in the reaction conditions with respect to temperature, partial pressure of H2 and CO2, reaction time, and additive as well as catalyst and Lewis acid concentration. Consequently, the optimized conditions resulted in the formation of OME1 and MF in TONs of 786 and 533 (Scheme 9). Later, a multivariate optimization method was applied, finally leading to TONs of OME1 and MF up to 3874 and 1445. [67]

5 Conclusion

The established synthesis of OME1 is centered on the condensation of methanol and formaldehyde, including challenging separation steps on the pathway to the target product. However, the recent investigations on OME1 as effective fuel additive for diesel engines demand the development of sustainable and more energy-efficient production routes. Recent investigations in direct methanol oxidation towards OME1 enabled to decrease the number of process steps and increase efficiency and productivity. Consequently, high OME1 selectivity can be achieved at
medium to high methanol conversions with non-noble metal catalyst systems. The high conversion obtained in this reaction reduces recycling and purification procedures, makes vanadium-based catalysts attractive for industrial processes. Enforcing even higher sustainability, it was shown that CO₂ can be directly incorporated as a building block of OME₁ in a reductive approach using H₂ in the presence of methanol. When compared to the oxidative approach, the reductive method starting from CO₂/H₂ and methanol reduces the number of steps in the process, as re-oxidation of methanol to formaldehyde is eliminated. This direct hydrogenation of CO₂ to OME₁ is enabled with molecular catalyst systems and recent optimizations of the established lead structure allowed reaction with largely increased TONs. Consequently, tailoring of the catalyst system in combination with the development of adapted process concepts may in an interdisciplinary approach pave the way to a continuous OME₁ production based on renewable hydrogen and CO₂.

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Abbreviations

| Abbreviation | Definition |
|--------------|------------|
| CTAB         | cetyltrimethylammonium bromide |
| DME          | dimethyl ether |
| FA           | formaldehyde |
| MF           | methyl formate |
| MG           | mechanical grinding |
| MM           | methoxymethanol |
| OME₁         | dimethoxymethanol |
| RC           | rapid compression |
| SG           | sol-gel |
| THF          | tetrahydrofuran |
| TiNT         | TiO₂ nanotubes |
| VTiS         | sulfate-modified V₂O₅/TiO₂ |
| VTiSi        | silica-modified V₂O₅/TiO₂ |

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