# Rate enhancement of using silica gel as a practical, efficient grinding auxiliary to break $\pi$-$\pi$ stacking under mechanochemical conditions

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ABSTRACT

As a practical, efficient, easily accessible, low-cost grinding auxiliary, silica gel can break $\pi$-$\pi$ stacking under mechanochemical conditions. This effect could lead to significant rate enhancement and yield in multiple types of reactions which involve linear polyaromatic hydrocarbons. Additionally, in order to deeply understand how grinding auxiliaries behave under mechanochemical conditions, several particles were used in control reactions and different physical properties were determined. The control reactions and the physical properties revealed that the rate enhancement effect of silica gel appear to be based on a combination of surface charge, small particle size, acidity of silica gel and ability to absorb moisture. Among those factors, we think the most important factor is the strong surface charge of silica gel after grinding.

## 1. Introduction

Polyaromatic hydrocarbons (PAH) have been demonstrated to be important materials for a variety of applications [1–4]. However due to the limited solubility of many of these molecules the solution-based synthesis often utilizes large amounts of solvent, undesirable solvents or both. In the 90's Komatsu demonstrated the use of mechanochemistry to conduct chemical reactions of famously insoluble fullerenes and polyaromatic hydrocarbons [5,6]. Since then various other scientists have demonstrated the ability of mechanochemistry to be highly effective at facilitating the chemical reaction of highly insoluble molecules [7–11]. Previously we reported a solvent-free synthesis of a tetracene derivative under mechanochemical conditions [12]. Although the target product was obtained, we observed that the yield dropped rapidly as the linear aromatic structure increased. Surprisingly, the difficulty of oxidation of 2,3-bis(hydroxymethyl)anthracene was solved by adding silica gel to our mechanochemical conditions. It has been previously demonstrated that the addition of milling auxiliaries such as silica gel has been shown to provide significant rate enhancements of mechanochemical processes [13–17]. However, it is poorly understood how silica gel can speed up certain reactions and how to fully take advantage of this strategy in a mechanochemical reaction. There are possible reasons suggested, such as the acidity of silica gel [13,14], or silica gel's ability to alter the phase of the materials [15]. Other additives, such as NaCl, NaSO$_4$, CaCl$_2$, neutral and basic Al$_2$O$_3$, $\beta$-Dextrin and quartz sand are also, used but again how these agents work is still a mystery [16].

To address this gap, we would like to report a more detailed understanding of the rate enhancement of using silica gel under mechanochemical conditions. Given our previous experience, we directed our efforts towards the 2-iodooxy-benzoic acid (IBX) oxidation, Diels-Alder reaction, a nucleophilic addition reaction and a Wittig reaction, using anthracene or substituted anthracene as the starting material. Reaction rates and isolated yields were compared between the reaction with silica gel added and control reactions with no silica gel. Furthermore, other grinding auxiliaries were used for comparison and their physical properties were determined to better understand how grinding auxiliaries operate under mechanochemical conditions.

## 2. Results and discussion

In our previous report we observed our IBX oxidation gave 81% when oxidizing 2,3-bis(hydroxymethyl)naphthalene (1a) to naphthalene-2,3-dicarbaldehyde (1b). However, it only gave 8% when we tried the IBX oxidation with 2,3-bis(hydroxymethyl)anthracene (2a) to give anthracene-2,3-dicarbaldehyde (2b). We attempted to heat the reaction to see if that would lead to increase in reaction rates, but that proved to be unsuccessful suggesting the rate of reaction was not limited by the activation barrier, but rather the mixing of the
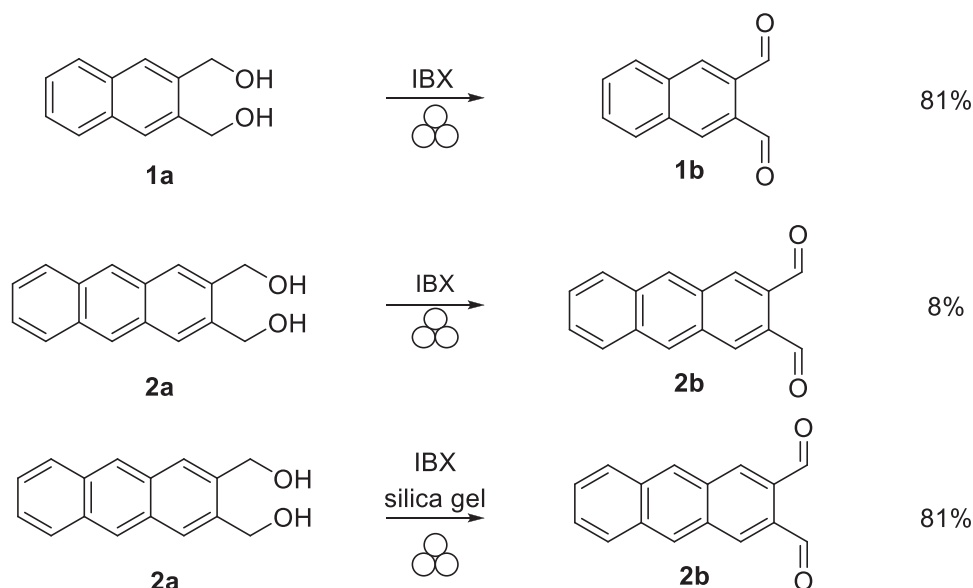
**Scheme 1.** Comparison of IBX oxidation of 2,3- bis(hydroxymethyl)napthalene, 2,3-bis(hydroxymethyl)anthracene and 2,3-bis(hydroxymethyl)anthracene with silica gel.
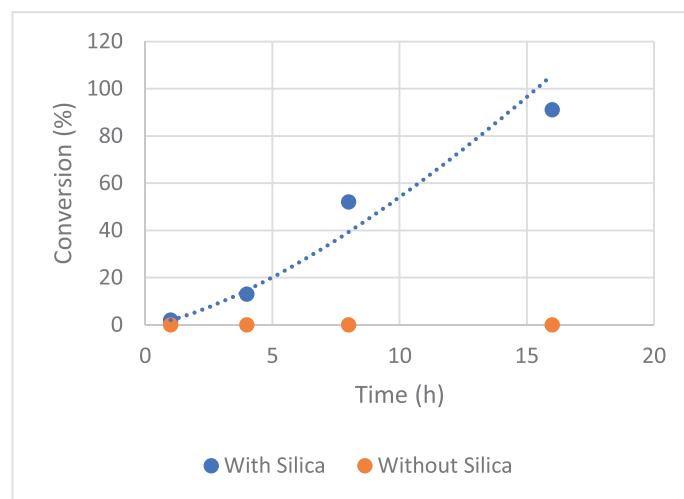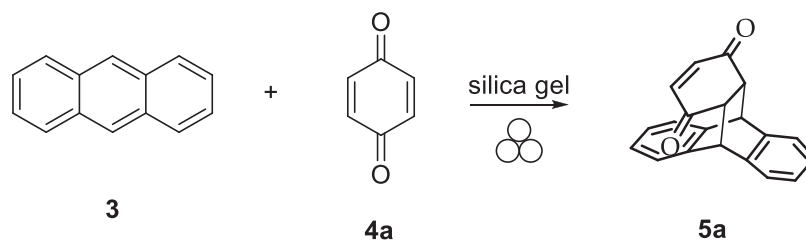




**Fig. 1.** Diels-Alder reaction of anthracene and benzoquinone. Reaction condition: 3 (1 mmol), 4a (2 mmol) and 0.5 g dry silica gel, 18 Hz, SS vial and one 1/4′ SS ball. Isolated yield after purified by column chromatography. Conversion determined by $^1$H NMR.

reagents. We next evaluated the melting points of the two starting materials. As we moved from 2,3-bis(hydroxymethyl)naphthalene (1a) to 2,3-bis(hydroxymethyl)anthracene (1b), the melting point increased about 80 °C, i.e. from 157 to 162 °C for the 2,3-bis(hydroxymethyl)naphthalene (1a) to 234–247 °C for the 2,3-bis(hydroxymethyl)anthracene (2a). The high melting point could imply stronger intermolecular forces presumably coming from increased $\pi$-$\pi$ stacking. That suggests a significant increase in the molecular packing, such that as we increase the size of the acene, mxing efficiency decreases, leading to a decrease in

reaction rate (Scheme 1). However, when silica gel was added, we observed an increase in reaction rate suggesting an increase in the mixing of reagents.

To further understand the efficiency of the silica gel and its application, more reactions involving insoluble reagents, were conducted under mechanochemical conditons with and without silica gel. In additon to the IBX oxidation, we tested the Diels-Alder reaction, nucleophilic substitution reactions and the Wittig reaction, each were found to have a rate enhancement by using dry silica gel as a grinding auxillary.
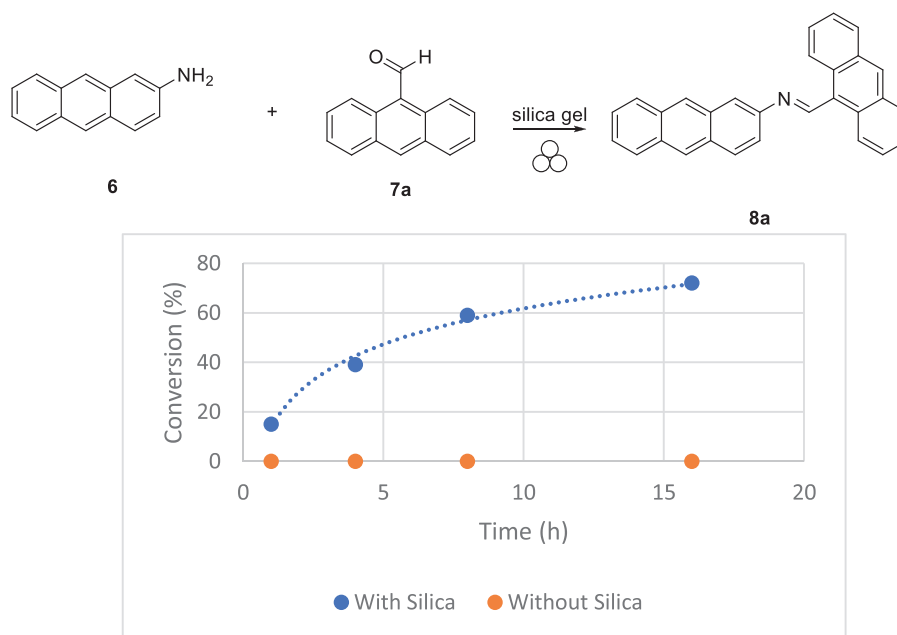
**Fig. 2.** Nucleophilic reaction of 2-aminoanthracene and 9-Anthraldehyde. Reaction condition: 6 (0.5 mmol), 7a (1 mmol) and 0.5 g dry silica gel, 18 Hz, SS vial and one 1/4′ SS ball. Isolated yield after purified by recrystallization. Conversion determined by $^1$H NMR.
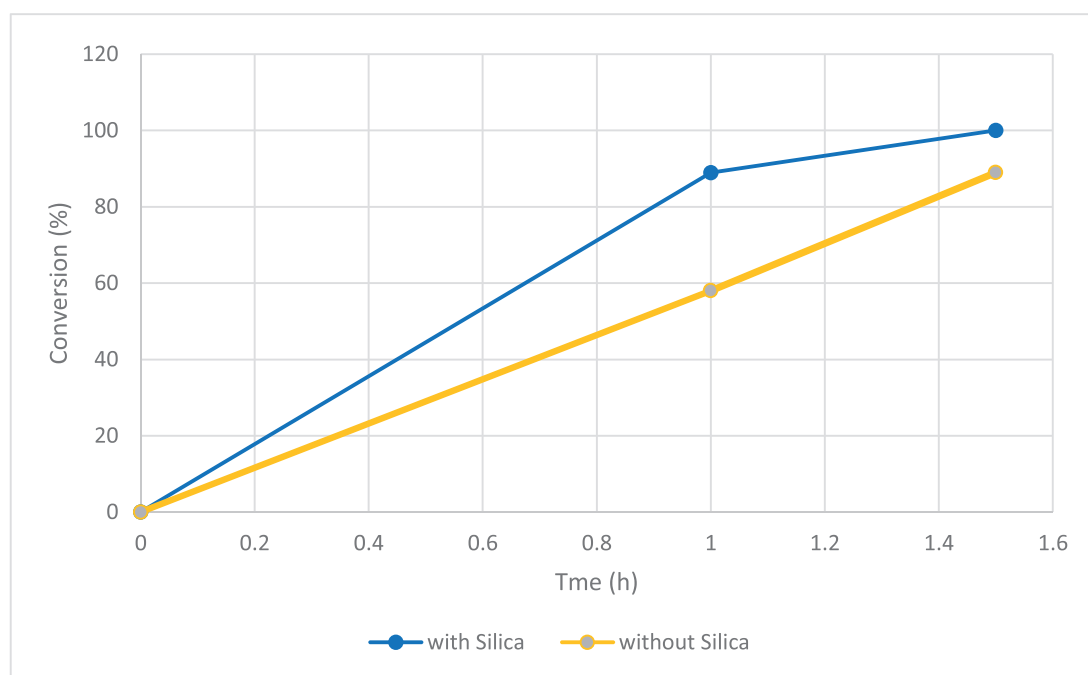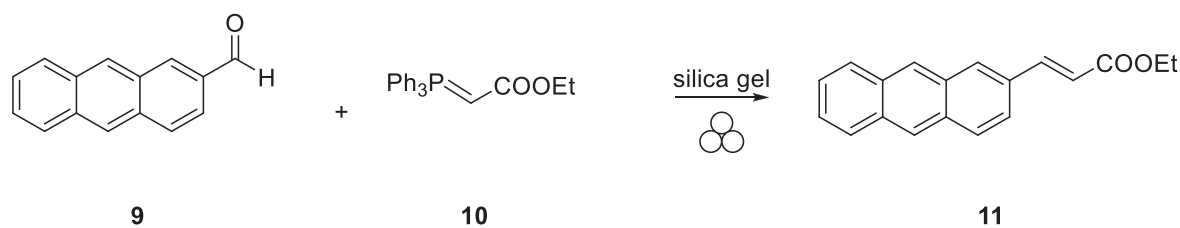


**Fig. 3.** Wittig reaction of 2-Anthracenecarbaldehyde (9) and (Carbethoxymethylene)triphenylphosphorane (10). Reaction condition: 9 (0.5 mmol), 10 (0.6 mmol) and 0.5 g dry silica gel, 18 Hz, SS vial and one 1/4′ SS ball. Isolated yield after purified by column chromatography. Conversion determined by $^1$H NMR.
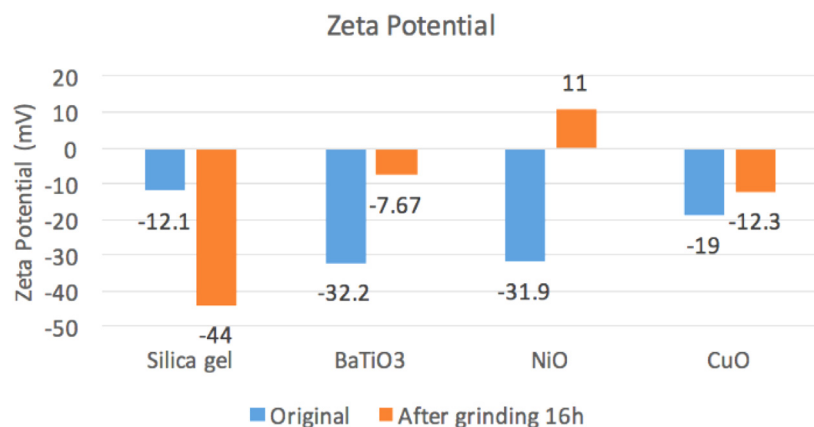
**Fig. 4.** Zeta-potential of several grinding assistant: before and after grinding for 16 h.

In addition to providing increased mixing, silica gel can also serve as a catalyst which can lower the activation barrier of various reactions. We have previoulsy demonstrated the Diels-Alder reaction between benzoquinone and anthracene give low yields over a long milling time [18], however this rate is significantly increased with the additon of silica gel (Fig. 1). Addtionally, we observed similar results with the reaction of 2-aminoanthracene and 9-Anthraldehyde to form (E)-N-(1-phenylethylidene)anthracene-2-amine (Fig. 2.)

In order to better understand how silica gel affects the Wittig reaction, we studied the reaction of 2-anthracenecarbaldehyde (9) and stable ylide (10). Similar to our previous results, the Wittig reaction showed a rate enhancement when silica gel is added under mechanochemical conditions (Fig. 3).

In order to further understand how silica gel maybe increasing mixing of these linear acenes and catalyzing these reactions, we thought to investigate the surface charge of various materials as a function of milling. If the surface charge is sufficiently high enough that could disrupt the $\pi$-$\pi$ stacking in addition to providing the catalytic activity observed. To test this thought we selected various grinding auxiliaries based on the consideration of size and surface charge. In addition to silica gel, we used nickel oxide, copper oxide and barium titanium oxide. Using the Diels-Alder reaction between maleic anhydride and anthracene as model, we compared the effect each of these grinding auxiliaries had on the reaction (Fig. 4.). We observed nickel oxide and coper oxide demonstrate a rate enhancement, while the barium titanium oxide decreased the reaction rate.

To further understand how the surface of the auxillaries affect on the rate of reaction, the zeta potential was determined for each auxillary (Fig. 4). Samples were compared with original additives and the additives after grinding for 16 h. Somewhat to our surprise the zeta potential of the silica gel greatly increased after milling. Similarly, the zeta potential of the barium titanium oxide, nickel oxide and copper oxide also showed a significant change in zeta potential, but in the opposite direction. However, only the barium titanium oxide gave a significant amount material that had zero zeta potential after milling, which may explain the difference in rate enhancement between the barium titanium oxide and the other materials (original zeta potential files can be found in supporting information). Therefore, we think the high absolute value of zeta potential is the main reason that why silica gel provides a significant rate enhancement for the reactions tested.

In addition to analyzing the surface charge, we also investigated particle size of the silica gel before and after milling. Although as expected particle size of silica gel is reduced upon prolonged milling, we did not observe a strong correlation between particle size and rate of reaction. This is somewhat surprising given the change in properties of silica at different particle sizes [19]. We also did not observe any significant change in rate if we treated the silica with triethyl amine, dried the silica beforehand in a vacuum oven or if we milled the reaction in a Teflon or stainless vial, suggesting the enhancement we observe is inherent to the silica itself. We also used silica gel from three different manufacturers as observed no difference in rate. we did notice the amount of silica used is important since there is a balance between the observed rate enhancement and using too much silica which could lead to lower dispersion concentration which may slow down the reaction rate in some cases [12].

## 3. Conclusions

In summary, four types of reactions, IBX oxidation, Diels-Alder reaction, nucleophilic reaction and Wittig reaction were conducted with and without silica gel. We observed a significant reaction rate when silica gel is used as a gringing auxillary specifically when used with long linear acenes. Since no solvent, heating/cooling or catalyst were needed, the reactions are safer, cheaper, greener and more worker-friendly. We think silica gel is a good grinding auxillary to break $\pi$-$\pi$ stacking in under mechanochemical conditions and it also could serve as catalyst. The rate enhancement effect of silica gel could be a combination of surface charge, small particle size, ability to absorb moisture and acidity of silica gel. However we believe the most important factor is the strong surface charge of silica gel after grinding.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jorganchem.2022.122430.

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