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COMMUNICATION

Graphitic carbon nitride catalysed photoacetalization of aldehyde/ketones under ambient conditions

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Graphitic-C₃N₄ is shown for the first time to catalyse photoacetalization of aldehydes/ketones with alcohols to acetals at high yields using visible light under ambient conditions: transient charge separation over the material is effective to catalyse the reaction in absence of Lewis or Brønsted acids, giving a new green alternative catalyst.

Acetalization reactions of aldehydes and ketones with alcohols is one key reaction step to protect or/and introduce chemical functionalities in carbonyl compounds during multistep organic synthesis.¹ Although many reported methods have been employed for this conversion, most of them are using acid catalysts which also often involve the use of toxic and corrosive reagents.^{2–5} Acidic environment is unsuitable when acid sensitive moiety groups of the substrates (e.g., carrying silyl groups or unsaturation)¹ are involved. Acetals are also highly unstable for reversible reactions to hemiacetals and starting substrates in acidic conditions but are stable in basic or neutral pH.^{6,7} Besides, during acetalization reaction, by-product, water is produced that requires additional physical and chemical means for its removal in order to avoid equilibrium shifting back to reactants.¹ Acetalization reactions are traditionally catalysed by Lewis or Brønsted acids in aqueous medium. However, only few exceptions are acetalizations in the presence of homogeneous examples in organic solvents such as LiBF₄,⁴ thiourea,⁶ ionic liquids,⁷ NBS,^{8,9} *N,N'*-bis[3,5-bis(trifluoromethyl)phenyl] and TBATB¹⁰. Apart from separation problems incurred to these systems some of them are toxic, costly and they suffer from a lack of generality. Solid catalytic systems are deemed to be relatively less deleterious to environment.^{11–18} It would thus be highly desirable to develop a general acid-free, non-transition metal containing solid catalyst so that a wide range of substrates can

also be acetalized in environmental friendly manner. Since such a method does not exist, we therefore set out to develop this route in this work.

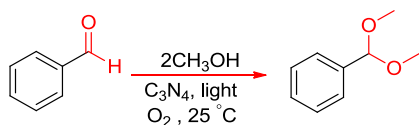
One exciting approach is to employ energetic light to polarize a semiconducting material to generate excitons under transient conditions (positive hole and electron). The excitons can then activate organic molecules for their conversion to products (most of the organic molecules do not absorb visible light) before they are self-recombined. Recently semiconducting carbon nitrides consisting of earth abundant elements of carbon and nitrogen have attracted a lot of attention due to their ability to capture light efficiently without any use of transition metal. In reported works, thermal polycondensation of common organic monomers to synthesize graphitic carbon nitrides (g-C₃N₄) with tunable band positions.^{19–22} The graphitic planes are derived from tri-s-triazine units inter-connected by planar amino groups with a band gap of about 2.7 eV (see Fig. S1 of ESI). Their HOMO and LUMO band positions are placed in such a way that the band gap energy is capable of activating molecular O₂ from air by photoelectron to generate mild and selective [•]O₂ radicals for organic transformations using visible light but the production of nonselective [•]OH radicals are thermodynamically prohibited.^{23,24} Using the transient [•]O₂ radicals, recent reports on selective oxidations of alcohols to aldehydes, C-H²⁵, O-H^{23,24} and N-H²⁶ oxidations over these materials have been claimed but the kinetics are yet to be improved. Such studies prompted us to employ this system for the acetalization reactions of carbonyl compounds.

In this work, we report the photocatalytic acetalization of aldehyde/ketones over g-C₃N₄ in molecular oxygen and visible light under ambient conditions. It is found that the conversion of benzaldehyde **2** with excess methanol to corresponding acetal is > 97 % and with selectivity > 98 % in absence of any acid additive. As far as we are aware, this is the first example of heterogeneous photoacetalization of aldehyde/ketones in alcohol over g-C₃N₄ at room temperature and oxygen pressure of 1 bar using visible light in environmental friendly manner (Scheme 1). It also appears that this material can act as generic

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catalyst which catalyses photoacetalization over a wide range of aldehydes and alcohols at high yields. Notice that acetals formation in aqueous acid medium at ambient conditions are thermodynamic limited because of their relatively low equilibrium constants ($K \sim 0.01\text{--}0.05 \text{ mol}^{-1}$) and with a loss in entropy when two or three molecules of starting materials (aldehyde or ketone plus alcohol) condense to hemiacetal/acetal products. Thus, separation and purification of products is necessary.¹ The presently observed high yields from a single pot reaction are attributed to the preferential strong adsorption of polar organic substrates and oxygen and water molecules on confined surface, which enable photoacetalization reactions to take place favourably by pre-concentrated substrates over this solid material surface under transient charge (excitons) separation upon light excitation.



Scheme 1. Photoacetalization of benzaldehyde with methanol

First, the time course for acetalization reaction of benzaldehyde **2** with methanol was monitored and results are shown in the Figure 1a. Under visible light irradiation, reaction proceeded at a steady rate and reached completion at about 6 h, giving the final high conversion and selectivity for the acetal formation. The acetal remained to be the main product with traces of formaldehyde, ester and acid (<1%) were also detected. To ascertain $g\text{-C}_3\text{N}_4$ is required to catalyse the reaction, control experiment without $g\text{-C}_3\text{N}_4$ addition was conducted. No acetal was found from benzaldehyde under irradiation of light and oxygen pressure of 1 bar. Under same conditions in the dark with $g\text{-C}_3\text{N}_4$, negligible product was also detected over prolong period (48 h).

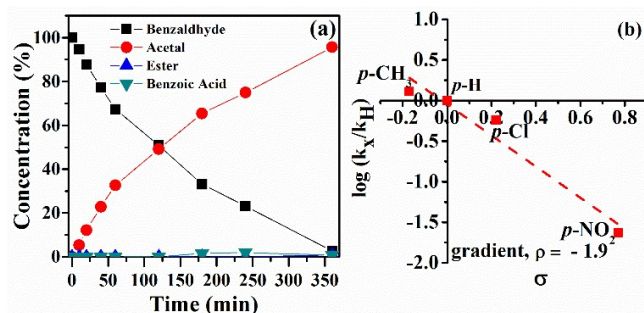


Fig. 1a Acetalization of benzaldehyde catalysed over $g\text{-C}_3\text{N}_4$ and **b.** the Hammett plot of para substituted benzaldehyde.

To gauge the role of oxygen, the reaction was carried out in argon atmosphere instead of using molecular oxygen. Complex condensation products but with poor selectivity to acetal (10 %) at relatively low conversion (35 %) were observed. These tests confirm that reaction clearly requires heterogeneous nitride surface whereby O_2 , light and substrates are essential ingredients for the cooperative catalysis. It was found that the catalytic application is also wide ranging and the $g\text{-C}_3\text{N}_4$ system appears to work well with a variation of aromatic, alicyclic aldehydes and ketones under ambient conditions using visible light.

Table 1. Photoacetalization of aldehyde/ketones over $g\text{-C}_3\text{N}_4$

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No	R ₁	R ₂	T / h	Conv. / %	Sel. / %
1	C ₃ H ₇	H	20	93.35	91.90
2	C ₆ H ₅	H	6	97.33	98.30
3	<i>p</i> -(CH ₃)C ₆ H ₄	H	4	87.44	97.44
4	<i>p</i> -(CH ₃ O)C ₆ H ₄	H	3	83.65	98.20
5	<i>p</i> -(HO)C ₆ H ₄	H	6	0	0
6	<i>p</i> -(Cl)C ₆ H ₄	H	6	69.76	98.85
7	<i>p</i> -(HOOC)C ₆ H ₄	H	10	96.72	97.48
8	<i>p</i> -(NO ₂)C ₆ H ₄	H	6	53.91	94.94
9	<i>p</i> -(NO ₂)C ₆ H ₄	H	6	6.50	85.00
10	C ₆ H ₅	CH ₃	24	25.35	66.25
11	C ₆ H ₅ CH=CH	H	24	21.22	70.94
12	C ₃ H ₇	CH ₃	3	84.48	86.53
13	*C ₅ H ₁₀	CH ₃	24	42.72	93.43
14	*C ₅ H ₁₀	—	24	84.68	90.85

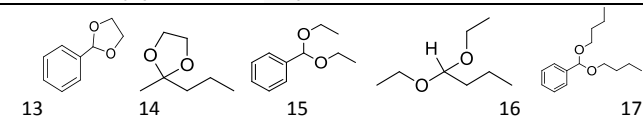
Substrate (1mM); C_3N_4 (25mg); methanol (5 mL); 1bar (O_2); visible light; conversion and selectivity were determined by GC. *Cyclohexanone

A moderate increase in reactivity for electron donating ($-\text{CH}_3$ and $-\text{OCH}_3$) groups **3–4** at para position of substituted benzaldehyde was observed whereas electron withdrawing ($-\text{Cl}$ and $-\text{NO}_2$) analogues **6–8** underwent acetalization considerably at a slower rate, however all still displayed high selectivity. As expected, steric hindered acetophenone **9** although gives high electron density at the carbonyl carbon which exhibited sluggish acetalization response, but the failure of 4-Hydroxybenzaldehyde **5** to yield any product, notwithstanding the electron donating nature of the OH group, is surprising and not understood. It could be due to strong inter H-bonding formed between the molecules which prohibit the photoacetalization on surface. In case of α, β unsaturated cinnamaldehyde **10**, corresponding acetal was obtained with good yield and selectivity, while the double bond remained intact. This clearly demonstrates the synthetic usefulness to sensitive unsaturation moiety groups of this photocatalytic system. The reactions of butyraldehyde **1**, 2-pentaneone **11**, and cyclohexanone **12** without conjugated stabilization to the carbonyl group were also successful without requiring the general use of high temperatures. Thus, the versatility of the catalytic system to efficiently drive the photoacetalization in the absence of acid catalysts is evident. The extension of substrate scope for the catalytic system beyond the reaction with methanol was realized by performing reactions with ethanol and rather difficult but more desirable ethylene glycol (biomass derivative)^{5,27} (Table 2). The reaction of benzaldehyde **13** with ethylene glycol, whose nucleophilicity is reduced due to mutual inductive withdrawal with the proximal oxygen atoms, to produce more stable cyclic acetal still proceeded with high conversion and selectivity. Similarly the reaction of butyraldehyde **14** with ethylene glycol also furnished five-member cyclic 1, 3-dioxolane product with 78 % selectivity and 70 % conversion. Under same conditions, the reaction with ethanol **15** afforded corresponding acetals with good selectivity nonetheless low yield. This suggests the kinetics of the reaction is slower than the reaction with methanol. The low selectivity of **16** is probably due to observed polymerization products. A challenging reaction²⁸ with alcohol larger than C_3 **17** (butanol) was also successful showing moderate conversion and selectivity for the corresponding acetal product.

These results extend the range and flexibility of the catalytic system to catalyse substrates for targeted acetals using light excitation.

Table 2. Photoacetalization of selected aldehydes with different alcohols over g-C₃N₄.

No	Substrate	Alcohol	T / h	Conv. / %	Sel. / %
13	C ₆ H ₅ CHO	†C ₂ H ₆ O ₂	6	90.85	87.13
14	C ₃ H ₇ CHO	†C ₂ H ₆ O ₂	6	70.88	78.42
15	C ₆ H ₅ CHO	C ₂ H ₅ OH	6	38.94	91.12
16	*C ₄ H ₉ CHO	C ₂ H ₅ OH	6	32.45	11.37
17	C ₆ H ₅ CHO	C ₄ H ₉ OH	12	43.49	55.73



Substrate (1mM); C₃N₄ (25mg); alcohol (5 mL); 1bar (O₂); visible light; conversion and selectivity were determined by GC. †Ethylene glycol, *Butyraldehyde

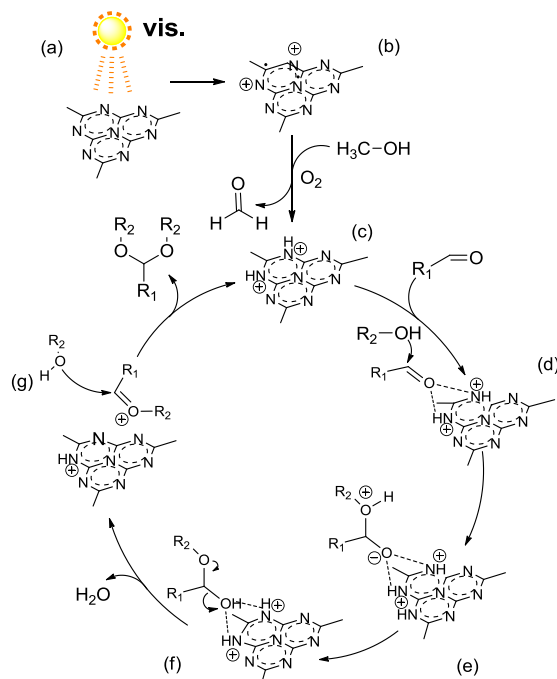
To elucidate the origins of the observed catalysis, kinetics data were collected at different reaction times using benzaldehyde derivatives with some selected para-substituted electron donating and electron withdrawing groups of substituted benzaldehyde with methanol, the results are shown in Figure S2 of ESI. It is revealed that the rates of electron donating substituents are significantly faster than those of electron withdrawing groups in comparison to benzaldehyde. Following the kinetics at progressive increasing conversions, the derived reaction rates follow a trend of CH₃>H>Cl>NO₂ (Table S1 of ESI). This distinctive change in reactivity of reacting substrates suggests the possible involvement of electron deficient charged intermediate during the photochemical transformation. In addition, the plots of log (k_x/k_H) obtained from kinetic data of the *para* substituted benzaldehyde against the Hammett substitution constant (σ) showed a linear correlation (Figure 1b) and the gradient of this fitted line gave the moderate negative Hammett reaction constant (ρ) value of -1.9.

We considered the mechanism for this new but efficient light-induced heterogeneous catalysis reaction and the particular high yield of acetal under ambient conditions. Static and time-resolved photo-luminescence (PL) spectroscopy was thus employed on a g-C₃N₄ film. In static PL, (Fig. S3a of ESI) the observed peak around 500 nm is associated to n-π* manifold of conjugated heptazine units suggesting a charge transfer from nitrogen (+ve hole) to conjugated carbon (-ve electron) under the photo-excitation.²⁹ This matches with previous theoretical HOMO and LUMO calculations.³⁰ It is interesting to note from Figure S3b that an interesting but rather long luminescence time-decay curve of g-C₃N₄ with an average exciton lifetime of 6.43ns, which is within the typical timescale to initiate chemical reactions (10⁻¹⁰-10⁻⁵ s).³¹ Clearly the semiconducting carbon nitride upon visible light excitation (λ >420nm) can generate long-lived excitons (charge separation) where the excited photogenerated electron takes residence in conduction band (CB) and positively hole on valence band (VB) to catalyse the photoacetalization.^{23,29,32,33} It has been reported that CB of this material at -1.3 V possess a large thermodynamic driving force with a long live photoelectron to reduce molecular O₂ to form [•]O₂⁻ (E° O₂/[•]O₂⁻ = -0.16 V) but the potential of the photogenerated hole in the VB at 1.4 V is inadequate to oxidize -OH to hydroxyl radicals [•]OH (E° [•]OH/[•]OH = 2.4V).^{30,34} Despite the possible existence

of [•]O₂⁻ we did not see any typical unselective radical reactions giving a wide range of different products. Instead, we observed the ultra-high selectivity towards acetal and the negative Hammett constant clearly reflecting an ionic mechanism. In addition, we neither observed a significant conversion of alcohol substrate to corresponding aldehyde in **2** at ambient temperature in contrast to those previously studies due to the [•]O₂⁻ catalytic role generated by g-C₃N₄ under light irradiation at elevated temperature (in our case, trace of formaldehyde was only observed). On addition of more reactive H₂O₂ (radicals promoter) to the catalytic system **2**, poor conversion and selectivity were noted. Importantly, by blending benzoquinone, a superoxide radical scavenger, into the reaction **2**, we did not detect much of its effect to alter the intrinsic high conversion and selectivity of the reaction **2** (Table S2 of ESI). We therefore argue that [•]O₂⁻ is likely retained on the carbon nitride surface as electron trap unless elevated temperature is used to release it into solution phase. Thus, we conclude that [•]O₂⁻ does not play a significant role in the charge-sensitive photoacetalization reaction. The surprisingly high yield for photoacetalization at ambient temperature also suggests a clear 'pre-concentration effect' for the polar substrates on confined surface sites presumably due to the characteristic transient charge separation of this material. We believe that the polar organic substrates, O₂ and water could strongly bind on this material surface during the light illumination. Despite the fact that the activation is momentarily conducted under the light irradiation before the recombination of exciton, the local strong field intensity and high charge density (+ve nitrogen in close proximity to -ve carbon in carbon nitride surface) will facilitate the remarkable catalytic performance for the forward reaction especially in the absence of solvent, additive or diluent. Notice that our GC-MS clearly indicated preferential binding of polar substrates than the less polar product on catalyst when the reaction was continuously monitored hence reversible reaction with no acidic protons in solution phase was not facilitated. H₂O¹⁸ was still the product from the reaction of O¹⁸ labelled benzaldehyde and dried methanol, however, it did not seem to evolve quantitatively from the material. Thus, the mesoporous nature of the g-C₃N₄ reflected by morphological and surface characterization (Figs. S4 and S5 of ESI) could have also trapped the by-product water dragging the equilibrium further. In addition the material showed excellent stability over repeated catalytic cycles (Fig. S6).

Although more detailed studies are needed to elucidate the mechanism, a simplified pathway for photoacetalization is summarized in Scheme 2. From this Scheme, visible light impinging on g-C₃N₄ can generate surface charge separation of [•]N and [•]O₂⁻ which may help to deprotonate alcohol to form adsorbed protons on the surface initially. Such transient surface charge species will also induce fast acetalization from polar aldehyde and alcohol by ionic mechanism on the material surface. This may involve the formation of oxonium ion (**g**) as reflected by the negative value of the Hammett study (ρ = -1.9) to form acetal. We anticipate that it is stabilized by carbon nitride surface presumably through cation-π interactions.³⁵ Such transition state specie is known to exist in the rate determining step in solution phase in the presence of acid

catalysts. But, in our case, there is no need to add aqueous acid catalysts as the surface protons can be quickly regenerated from the reaction cycle on confined surface with high affinity for the polar terminal oxygen group of substrates under transient conditions. It is interesting to note that, for substrates with β -hydrogens, the photoacetalization reaction may also undergo vinyl ether intermediate (Scheme S1 of ESI), which upon the addition of alcohol to C=C bond will produce acetal.^{28,36} Indeed, we observed trace of vinyl ether species for **11**, **12** to corresponding acetals.²⁸



Scheme 2. Proposed pathway for photoacetalization

In conclusion, we have demonstrated efficient photoacetalization of aldehydes and ketones with alcohols using g-C₃N₄ as photocatalyst, which gives impressive selectivity and conversion in high rate and yield at ambient conditions. The reaction takes place at room temperature in oxygen atmosphere involving substrates and acid-free solid catalyst without adding solvent and hence is clearly a new green synthesis method. The broad reaction scope and remarkable versatility of this catalytic system could enable us to tackle a wide spectrum of aldehyde/ ketones /alcohols of interests for specific acetals production with favoured equilibrium.

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