

Copper Cocatalyst Modulated Radical Generation for Selective Heterogeneous Photosynthesis of α -Haloketones

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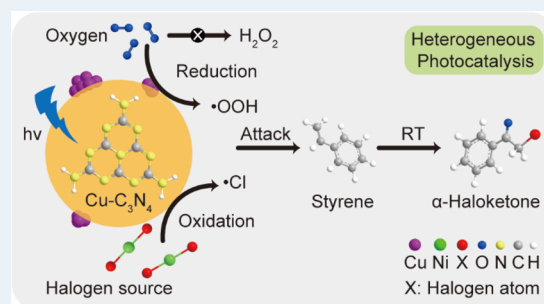
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Supporting Information

ABSTRACT: The α -haloketones are important precursors for synthetic chemistry and pharmaceutical applications; however, their production relies heavily on traditional synthetic methods via halogenation of ketones that are toxic and environmentally risky. Here, we report a heterogeneous photosynthetic strategy of α -haloketone production from aromatic olefins using copper-modified graphitic carbon nitride ($\text{Cu-C}_3\text{N}_4$) under mild reaction conditions. By employing NiX_2 ($\text{X} = \text{Cl}, \text{Br}$) as the halogen source, a series of α -haloketones can be synthesized using atmospheric air as the oxidant under visible-light irradiation. In comparison with pristine carbon nitride, the addition of Cu as a cocatalyst provides a moderate generation rate of halogen radicals and selective reduction of molecular oxygen into $\cdot\text{OOH}$ radicals, thus leading to a high selectivity to α -haloketones. The $\text{Cu-C}_3\text{N}_4$ also exhibits high stability and versatility, rendering it a promising candidate for solar-driven synthetic applications.

KEYWORDS: α -haloketones, heterogeneous photocatalysis, oxidative halogenation, oxygen radicals, halogen radicals



The α -haloketones are essential intermediates in synthetic chemistry and pharmaceutical manufacturing.^{1–3} Traditional synthesis of α -haloketones is realized by halogenation of the C–H bond of the corresponding ketones.⁴ These reactions exhibit high performance and decent selectivity; however, the need for harsh reaction conditions and toxic elemental halogens (i.e., Cl_2 , Br_2) or organic halogens (i.e., CH_2Cl_2 , *N*-bromosuccinimide (NBS), *N*-halosuccinimide (NCS)) as the halogen sources poses high demands toward the consideration of safety regulations and environmental protection.^{5–10} Direct conversion of olefins to the corresponding α -haloketones by employing oxidants and inorganic halogen salts is an eco-friendly, one-step process,¹¹ yet the challenges in choosing suitable precursors, selectivity control, and the limited substrate scope available through this route restrict its large-scale application. Additionally, the evolution of unwanted elemental halogens during the process is inevitable due to the use of strong oxidants (i.e., $\text{K}_2\text{S}_2\text{O}_8$).

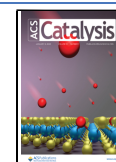
The synthesis of α -haloketones by photocatalytic oxidative halogenation of olefins is an alternative approach that has been developed in recent years.^{12–14} It possesses several advantages compared to conventional synthetic approaches. First, the electrons generated upon irradiation can activate molecular oxygen to oxidize the olefins into corresponding ketones, thus avoiding the use of strong oxidants. Second, the mild reaction conditions of photocatalysis render the conversion of olefins with susceptible functional groups applicable. Nevertheless, by tuning the oxidation power of the photocatalysts, it is possible

to achieve halogenation of the photogenerated ketones without the formation of elemental halogen during the whole reaction course, rendering it a mild process that is ideal for applications with a high demand of environmental preservation. Wang et al. report the synthesis of a series of α -haloketones from olefins under visible-light irradiation using $\text{Ru}(\text{bpy})_3\text{Cl}_2$ as the sensitizer, $\text{PhI}(\text{OAc})_2$ as the catalyst, and organic halides (CH_3X) as the halogen source.¹⁵ Meanwhile, the hazardous CH_3X halogen source can be replaced by inorganic salts (KBr and KCl) when catalyzed by metal halides (FeX_3) in the presence of *p*-toluenesulfonic acid (TsOH) under visible-light irradiation, though the need for an oxygen-rich atmosphere is a major setback.^{16,17} To date, homogeneous photocatalytic systems rely intensively on expensive catalysts, special additives, and complicated reaction conditions, limiting the photocatalytic approach for wide-scale application. Therefore, the development of a selective and efficient heterogeneous photocatalyst for the synthesis of α -haloketones using nontoxic inorganic halogen sources under ambient conditions is desirable.

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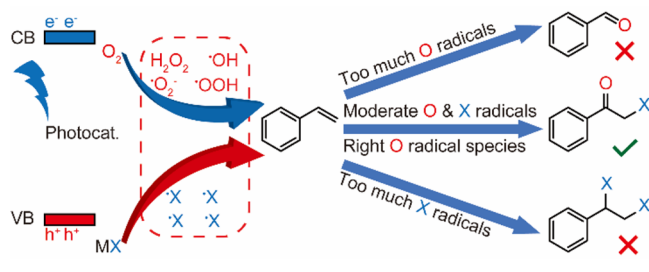
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Three criteria need to be considered to construct a promising heterogeneous photocatalyst from a catalytic perspective (Scheme 1). First, the photocatalyst should be

Scheme 1. Reaction Pathways of Photocatalytic Styrene Conversion Governed by Radical Species and Quantities



able to create suitable oxygen-based and halogen radical species with moderate kinetics to attack the olefins. However, a rapid formation rate of oxygen radical species will lead to unwanted dissociation of the reactant molecule and over oxidation of the α -haloketones to aldehydes, whereas too high a concentration of halogen radical species tends to produce dihalogenated compounds and the evolution of elemental halogen. Second, the reduction of molecular oxygen has often been ignored. The identity and kinetics of photogenerated oxygen radical species govern the overall rate and selectivity of the photocatalytic process. Here, the superoxide radical ($\cdot\text{OOH}$) is favored, as other oxygen radicals (i.e., $\cdot\text{OH}$) are associated with the formation of unwanted carbonyls.¹⁸ Lastly, the reduction product of O_2 (i.e., H_2O) needs to desorb from the surface of the photocatalyst rapidly to complete the catalytic cycle. A series of recent studies show that the aforementioned factors can be manipulated by employing metal cocatalysts supported on the photocatalysts,^{19–23} thus leading to efficient and selective photosynthesis,^{24–27} indicating that the selective oxidative halogenation of olefins may be achieved by such a strategy. The graphitic carbon nitride ($\text{g-C}_3\text{N}_4$) is the ideal photocatalyst support, owing to its suitable band positions and versatility for multiple organic transformations.²⁸

Herein, we report a facile synthesis of α -haloketones from oxidative halogenation of aromatic olefins by employing a copper-modified graphitic carbon nitride ($\text{Cu-C}_3\text{N}_4$) photocatalyst using NiCl_2 as the halogen source under visible-light irradiation and ambient conditions. The $\text{Cu-C}_3\text{N}_4$ photocatalyst presents an optimum formation of superoxide radicals ($\cdot\text{OOH}$), a moderate evolution of halogen radicals ($\cdot\text{X}$), and a weak adsorption of photogenerated water, thus resulting in an optimum selectivity to α -haloketones compared to other metal-decorated C_3N_4 . The potential of $\text{Cu-C}_3\text{N}_4$ for application in terms of stability and substrate scope is also discussed.

■ CATALYST CHARACTERIZATIONS

The pristine $\text{g-C}_3\text{N}_4$ photocatalyst is synthesized via pyrolysis of urea, and Cu is loaded on the $\text{g-C}_3\text{N}_4$ via a conventional photodeposition method in an isopropanol–water solution under deaerated conditions (Supporting Information Experimental Procedures and Figure S1). The inductively coupled plasma-atomic emission spectrometry (ICP-AES) analysis reveals that the loading of Cu is ~ 0.15 wt % (Table S1 in the Supporting Information). Transmission electron micros-

copy (TEM) imaging of a single Cu nanoparticle (NP) of the as-synthesized photocatalyst suggests that polycrystalline metallic copper with exposed (111) facets ($d = 2.01$ Å) is anchored on the edge of the $\text{g-C}_3\text{N}_4$ (Figure 1a). X-ray

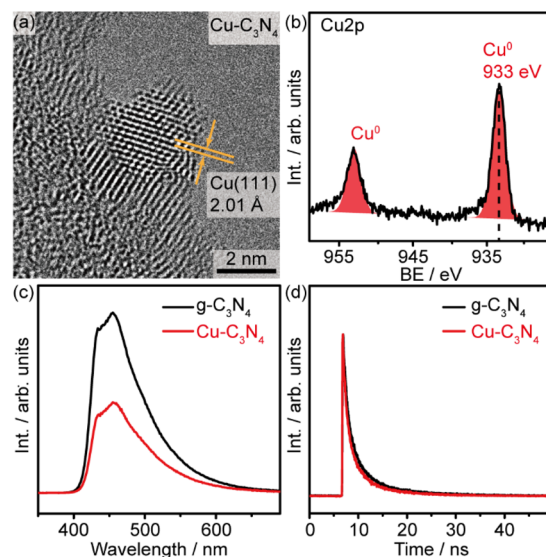


Figure 1. Characterization of the photocatalyst. (a) and (b) TEM image and Cu 2p XPS spectra of the $\text{Cu-C}_3\text{N}_4$. (c) and (d) Steady-state and transient fluorescence spectra of $\text{Cu-C}_3\text{N}_4$ and $\text{g-C}_3\text{N}_4$.

photoelectron spectroscopy (XPS) analysis of the pristine $\text{g-C}_3\text{N}_4$ and $\text{Cu-C}_3\text{N}_4$ confirms the purity of the catalyst (Figure S2 in the Supporting Information). The region-of-interest Cu 2p spectrum suggests that Cu is in its metallic state (narrow peak at 933 eV, Figure 1b). The absence of satellite features at ~ 943 – 945 eV indicates that no oxide species are present. The powder X-ray diffraction (PXRD) patterns of both pristine $\text{g-C}_3\text{N}_4$ and $\text{Cu-C}_3\text{N}_4$ are identical, displaying the characteristic diffraction peaks of (100) and (002) facets of $\text{g-C}_3\text{N}_4$, implying a negligible destruction of the nanocrystalline structure caused by the Cu loading (Figure S3 in the Supporting Information). The Cu (111) diffraction peak is nondetectable due to the low loading of Cu. Diffuse reflectance spectroscopy (DRS) shows that the pristine $\text{g-C}_3\text{N}_4$ and $\text{Cu-C}_3\text{N}_4$ exhibit a similar band gap (~ 2.8 eV) and light absorption properties (Figure S3 in the Supporting Information). The steady-state photoluminescence (PL) spectroscopy shows a characteristic asymmetric emission peak (~ 440 nm) for $\text{g-C}_3\text{N}_4$ (Figure 1c), confirming that the radiative recombination mainly takes place at trap states with energy levels close to the conduction band minimum (CBM) or the valence band maximum (VBM). The loading of Cu metal NPs only reduces the intensity of the emission peak, suggesting an enhanced charge separation without altering the electronic structure of the $\text{g-C}_3\text{N}_4$. However, time-resolved fluorescence spectroscopy suggests that the presence of Cu NPs does not influence the radiative recombination kinetics of photogenerated charge carriers (Figure 1d).²⁹

■ PERFORMANCE EVALUATION

Styrene (1a) is employed as the model compound to evaluate the photocatalytic performance of a series of metal-decorated $\text{g-C}_3\text{N}_4$ and the effect of metal chloride and solvent under 410 nm irradiation at room temperature (RT) and atmospheric

conditions (Table 1). The conversion and selectivity of the reaction were determined by gas chromatography (GC) and

Table 1. Screening of Catalysts and Reaction Conditions: Photosynthesis of 2-Chloroacetophenone from Styrene^a

Entry	Catalysts	Chloride	Solvent	Con./% ^b	Sel./% ^b
1	Cu-C ₃ N ₄	NiCl ₂ ·6H ₂ O	EtOAc- <i>i</i> PrOH ^c	99	80
2	g-C ₃ N ₄	NiCl ₂ ·6H ₂ O	EtOAc- <i>i</i> PrOH	99	52
3	Ag-C ₃ N ₄	NiCl ₂ ·6H ₂ O	EtOAc- <i>i</i> PrOH	83	58
4	Fe-C ₃ N ₄	NiCl ₂ ·6H ₂ O	EtOAc- <i>i</i> PrOH	99	47
5	Ni-C ₃ N ₄	NiCl ₂ ·6H ₂ O	EtOAc- <i>i</i> PrOH	88	57
6	Cu-C ₃ N ₄	NiCl ₂	EtOAc- <i>i</i> PrOH	77	69
7	Cu-C ₃ N ₄	FeCl ₃	EtOAc- <i>i</i> PrOH	22	11
8	Cu-C ₃ N ₄	NaCl	EtOAc- <i>i</i> PrOH	20	17
9	Cu-C ₃ N ₄	KCl	EtOAc- <i>i</i> PrOH	20	20
10	Cu-C ₃ N ₄	CuCl ₂	EtOAc- <i>i</i> PrOH	31	0
11	Cu-C ₃ N ₄	NiCl ₂ ·6H ₂ O	CH ₃ CN	99	57
12	Cu-C ₃ N ₄	NiCl ₂ ·6H ₂ O	EtOAc	99	49
13	Cu-C ₃ N ₄	NiCl ₂ ·6H ₂ O	1,4-Dioxane	69	52
14	Cu-C ₃ N ₄	NiCl ₂ ·6H ₂ O	THF	93	63
15	Cu-C ₃ N ₄	NiCl ₂ ·6H ₂ O	<i>i</i> PrOH	99	0
16	Cu-C ₃ N ₄	NiCl ₂ ·6H ₂ O	EtOH	81	0

^aReaction conditions: styrene (8 mM), catalyst (50 mg), chlorine source (0.2 mmol), solvent (10 mL), RT, 1 bar air, 410 nm LED (30 mW cm⁻²) irradiation for 12 h. ^bConversion (Con.) and selectivity (Sel.) are determined by GC and GC-MS. ^c1 mL of isopropanol in 9 mL of ethyl acetate.

gas chromatography–mass spectrometry (GC-MS) using standard compounds (see Experimental Procedures in the Supporting Information). The Cu-C₃N₄ photocatalyst fully converts styrene into 2-chloroacetophenone (2a) with high selectivity (80%) in an isopropanol–ethyl acetate solvent (1:9 v/v) with nickel chloride hexahydrate as the Cl source (Table 1, entry 1). In comparison, the pristine g-C₃N₄ and other metal (Ag, Fe, Ni)-decorated g-C₃N₄ show poor selectivity to 2a (Table 1, entries 2–5), indicating the essential role of Cu as the cocatalyst. GC-MS analysis reveals that the alternative g-C₃N₄ photocatalysts tend to produce 1,2-dichloroethylbenzene and 2-chloro-1-phenylethanol as byproducts (Figure S4 in the Supporting Information). Among the tested chlorine sources, nickel chloride hexahydrate outperforms the anhydrous nickel chloride (Table 1, entry 6) due to a better solubility in organic solvent. Interestingly, ferric chloride, sodium chloride, potassium chloride, and copper chloride all present poor performance in photocatalytic halogenative oxidation of styrene (Table 1, entries 7–10). This can be ascribed to the suitable redox potential of Ni²⁺/Ni⁰ (Ni²⁺/Ni = -0.257 V vs RHE) that allows its reduction by the conduction band electron of the excited g-C₃N₄. The solvent also significantly influences the selectivity of the reaction. A poor selectivity is observed in the absence of isopropanol due to the oxidative dissociation of 2a into benzaldehyde (Table 1, entry 11), indicating that isopropanol as a hydrogen donor can provide sufficient H atoms to avoid overoxidation of the generated 2a. No deuterated products are observed when CH₃CH₂OD was used as the hydrogen donor (Figure S5 in the Supporting Information), confirming that the abstracted D atoms convert into D₂O by reacting with molecular oxygen. A similar

phenomenon is observed when other aprotic solvents are used (Table 1, entries 12–14). Acetophenone becomes the dominant product in pure protic solvents due to the dehalogenation of photogenerated α -haloketones (isopropanol and ethanol, Table 1, entries 15 and 16). Additionally, control experiments show that the reaction is indeed a photocatalytic process (entry 4, Table S2 in the Supporting Information).

We have further investigated the heterogeneous photocatalytic oxidative addition of styrene employing Cu-C₃N₄ under optimized reaction conditions. A time-course analysis reveals that styrene is directly converted into 2-chloroacetophenone following pseudo-first-order kinetics ($k = 0.31 \text{ h}^{-1}$) within 12 h (Figure 2a). The selectivity to 2-chloroacetophe-

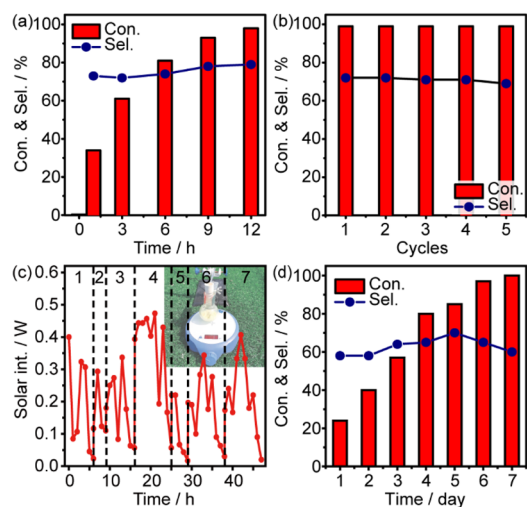


Figure 2. Photocatalytic performance. (a) Time-course study of photocatalytic styrene conversion to 2-chloroacetophenone using Cu-C₃N₄. Reaction conditions: 8 mM styrene, 50 mg of catalyst, 0.2 mmol of NiCl₂, and 1 mL of isopropanol in 9 mL of ethyl acetate under 1 bar air, irradiated under 410 nm LED (30 mW cm⁻²) at RT. (b) Stability of Cu-C₃N₄ in photocatalytic styrene conversion to 2-bromoacetophenone. Reaction conditions: 8 mM styrene, 10 mg of catalyst, 0.02 mmol of NiBr₂, and 0.1 mL of isopropanol in 1.9 mL of ethyl acetate under 1 bar air, irradiated under 410 nm LED (30 mW cm⁻²) at RT. Each cycle is irradiated for 2 h during the stability test. (c) and (d) Recorded solar intensity and solar-driven styrene conversion using Cu-C₃N₄. The reaction was performed in Suzhou, China, from July 1, 2021 to July 8, 2021.

none remains at ~80%, with benzaldehyde (~4%), acetophenone (~3%), 2-chloro-1-phenylethanol (~7%), and dichloroethylbenzene (~6%) as the major byproducts. A drop of the performance is observed with an increase of the styrene concentration, possibly due to its self-polymerization³⁰ and the dehalogenation of α -haloketones (Figure S6 in the Supporting Information). The stability of Cu-C₃N₄ has also been evaluated (Figure 2b). The Cu-C₃N₄ photocatalyst presents a stable performance for five cycles by simply applying a DI water washing and HCl (100 mM) washing after each cycle. Additionally, the Cu-C₃N₄ photocatalyst is capable of utilizing solar energy to fully convert styrene into 2-chloroacetophenone with a reasonable selectivity (>60%, Figures 2c and 2d). The drop of the selectivity may be associated to the higher energy of the photons in the UV region, resulting in the formation of unwanted radicals and the generation of complicated byproducts. Though the fluctuation of irradiation intensity and unoptimized bulk reactor limits the performance,

it still demonstrates the potential of solar photocatalysis for practical synthetic applications.

REACTION MECHANISMS

Since the photocatalytic oxidative halogenation of aromatic olefins involves the reduction of molecular oxygen and oxidation of a halogen anion, we have first examined the role of Cu NPs in the generation of reactive oxygen species (ROS) and halogen radicals using electron spin resonance (ESR).

This is achieved by using 5,5-dimethyl-1-pyrroline *N*-oxide (DMPO) and phenylbutylnitron (PBN) as spin traps under different reaction conditions (Figure 3 and Figure S7 in the

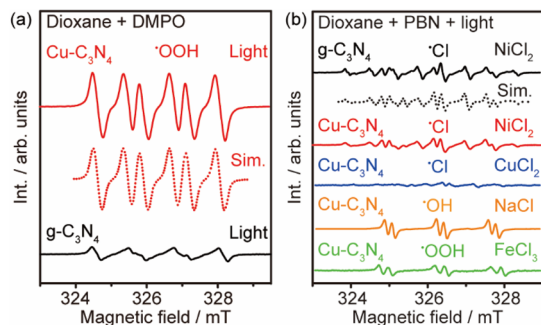


Figure 3. Cu-modulated evolution of radical species. (a) Evolution of oxygen radical species in the absence of metal chloride by Cu–C₃N₄ and g–C₃N₄ photocatalysts under irradiation using DMPO as the spin trap. Reaction conditions: 10 mg of catalyst and 20 mM DMPO in dioxane, irradiated at RT for 1.5 min. (b) Evolution of radical species with the presence of metal chloride by g–C₃N₄ and Cu–C₃N₄ photocatalysts under irradiation using PBN as the spin trap. Reaction conditions: 10 mg of catalyst, 0.02 mmol of metal chloride, and 20 mM PBN in dioxane, irradiated at RT for 1.5 min.

Supporting Information). In the absence of NiCl₂ (Figure 3a), both g–C₃N₄ and Cu–C₃N₄ generate oxygen radical species upon irradiation; however, the different spectra imply that distinct oxygen radical species are evolved in the presence of the different photocatalysts. The ESR spectrum recorded using the Cu–C₃N₄ photocatalyst contains only one component with relatively high intensity, assigned by simulation to the •OOH radical ($\alpha[{}^1\text{H}_\beta] = 24.96$, $\alpha[{}^1\text{H}_\gamma] = 3.37$, and $\alpha[{}^{14}\text{N}] = 38.15$ MHz). In contrast, the complicated ESR spectrum of pristine g–C₃N₄ suggests that multiple oxygen radical species beyond •OOH are evolved under irradiation. The weak intensity of the ESR spectrum indicates that either a slow generation or a rapid recombination kinetics of the oxygen radical species takes place on g–C₃N₄.

In the presence of NiCl₂, both pristine g–C₃N₄ and Cu–C₃N₄ photocatalysts produce •Cl radicals ($\alpha[{}^1\text{H}] = 2.19$, $\alpha[{}^{14}\text{N}] = 35.51$, and $\alpha[{}^{35}\text{Cl}] = 18.53$ MHz) upon irradiation (Figure 3b). Note that the pristine g–C₃N₄ shows a slightly higher ESR signal intensity due to a higher concentration of photogenerated chlorine radicals. However, this is not beneficial for the synthesis of α -haloketones, as a high concentration of •Cl radicals leads to the formation of dichloro-substituted compounds according to the product analysis (Figure S4 in the Supporting Information). Noticeably, the identity of the metal chloride is also a crucial parameter that influences the photocatalytic reaction. The addition of CuCl₂, NaCl, and FeCl₃ only produces a trace amount of •Cl radical in comparison with NiCl₂. Instead, a detectable amount of hydroxyl radicals (•OH) and superoxide

radicals (•OOH) are produced when NaCl and FeCl₃ are used as the chlorine source, respectively. These results are in line with the catalytic performance, revealing that NiCl₂ is the ideal chlorine source owing to its selective and mild generation of •Cl radicals.

We have further probed the evolution of H₂O₂ upon irradiation by UV–vis spectrometry titrated using a CuSO₄·2,9-dimethyl-1,10-phenanthroline (DMP) solution (Figure 4a).^{31,32} A gradual increase of the absorption peak at

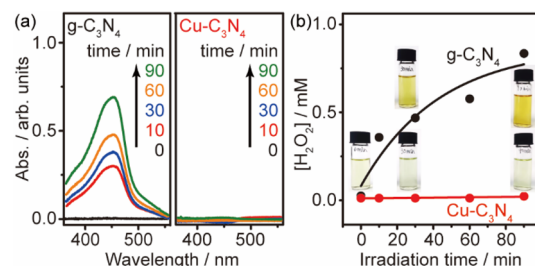


Figure 4. Cu-modulated evolution of H₂O₂. (a) UV–vis analysis of H₂O₂ formation using g–C₃N₄ and Cu–C₃N₄ under irradiation. (b) Kinetic analysis of H₂O₂ evolution. Reaction conditions: 50 mg of catalyst and 1 mL of isopropanol in 9 mL of ethyl acetate under ambient pressure, irradiated under 410 nm LED (30 mW cm^{−2}) at RT.

454 nm is observed for g–C₃N₄, implying the accumulation of photogenerated H₂O₂. Surprisingly, an absence of H₂O₂ is observed for Cu–C₃N₄ throughout the whole irradiation course. This is also evidenced by the color change of the solution (Figure S8 in the Supporting Information). Quantitative analysis further reveals that the formation of H₂O₂ on g–C₃N₄ follows pseudo first-order kinetics with a rate constant of 0.023 min^{−1}, whereas the Cu–C₃N₄ inhibits the H₂O₂ evolution completely (Figure 4b).

Interestingly, the pristine g–C₃N₄ exhibits a faster oxygen consumption rate (243 ppm·h^{−1}) than that of Cu–C₃N₄ (82 ppm·h^{−1}) under irradiation, as monitored using an oxygen sensor (Figure 5a and Figure S9 in the Supporting Information). This is in good agreement with the photocatalytic performance of pristine g–C₃N₄, which presents a fast conversion of styrene but a poor selectivity to **2a** compared to that of Cu–C₃N₄ under identical reaction conditions (Table 1, entry 2, and Figure S10 in the Supporting Information). In

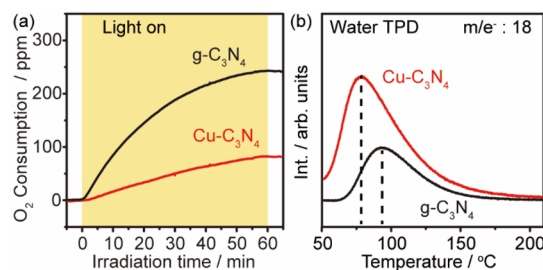


Figure 5. Cu-modulated O₂ reduction and H₂O desorption. (a) Oxygen consumption during photocatalytic conversion of styrene using g–C₃N₄ and Cu–C₃N₄. Reaction conditions: 15 mM styrene, 50 mg of catalyst, 0.2 mmol of NiCl₂·6H₂O, and 1 mL of isopropanol in 9 mL of ethyl acetate under 1 bar of atmosphere with 500 ppm of O₂, irradiated under 410 nm LED (30 mW cm^{−2}) at RT. (b) TPD of preadsorbed H₂O on g–C₃N₄ and Cu–C₃N₄.

connection with the product analysis in photocatalytic performance tests and previous investigations,^{33–35} we propose that the faster oxygen consumption rate observed for pristine g-C₃N₄ generates ROS in a nonselective fashion (H₂O₂ and •OOH), thus leading to the formation of unwanted by-products. In comparison, the presence of Cu on g-C₃N₄ regulates the dissociation path of molecular oxygen to produce solely the •OOH radical, thus resulting in a high selectivity to α -haloketones.

Additionally, the interaction of water (i.e., the final reduction product of O₂) with the photocatalyst has been evaluated by temperature-programmed desorption (TPD, Figure 5b). While a desorption peak of water is observed at 77 °C for the Cu–C₃N₄, the pristine g-C₃N₄ presents a relatively stronger interaction of water as characterized by a desorption peak located at a higher temperature of 91 °C. This suggests that the water molecules generated during the photocatalytic synthesis of α -haloketones only need to overcome a small barrier to desorb from the surface of the Cu–C₃N₄ under ambient conditions, which is crucial to complete the catalytic cycle.

A possible mechanism of the Cu–C₃N₄-promoted photocatalytic oxidative halogenation is proposed using styrene as the model compound and NiCl₂ as the chlorine source (Figure 6). First, •Cl radicals are created *via* the oxidation of chloride

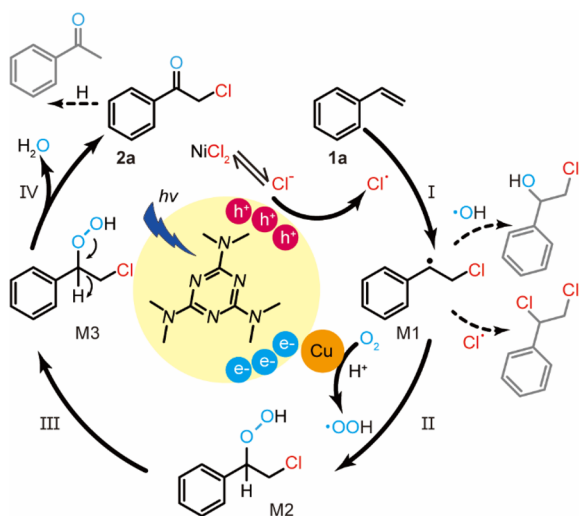


Figure 6. Proposed catalytic cycle and the role of Cu in modulating the generation of radical species. Side reactions and byproducts are indicated by the dashed lines and molecules in gray color.

ions by the photogenerated holes from the Cu–C₃N₄ photocatalyst upon irradiation. Then the •Cl radicals attack **1a** to generate the carbon-centered radical species (intermediate **M1**, step I). The **M1** intermediate is further attacked by the •OOH radical that is created *via* the reduction of molecular oxygen by the photogenerated electrons on the Cu cocatalyst to yield the intermediate **M2** (step II). In step III, the metastable **M2** is converted to intermediate **M3** *via* a molecular restabilization process. Finally, the **M3** releases a water molecule to generate **2a** (step IV).¹⁷ The byproducts, namely, 2-chlorophenylethanol and dichloroethylbenzene, are generated from •OH and •Cl radicals attacking the intermediate **M1**, respectively. The acetophenone is produced *via* the hydro-dechlorination of the photogenerated haloketone (**2a**) in the presence of isopropanol upon prolonged irradiation time.

SUBSTRATE SCOPE

The Cu–C₃N₄ displays high performance in the photosynthesis of a series of α -haloketones from the corresponding substrates under ambient conditions (Table 2). We have first

Table 2. Substrate Scope: Synthesis of α -Haloketones Catalyzed by Cu–C₃N₄ under Ambient Conditions^f

Synthesis of α -chloroketones ^a	
R = H 2a , Con. 99%; Sel. 80%	2j , Con. 99%; Sel. 71%
F 2b , Con. 99%; Sel. 77%	
Cl 2c , Con. 99%; Sel. 80%	
Br 2d , Con. 99%; Sel. 79%	
I 2e , Con. 99%; Sel. 67%	
CF ₃ 2f , Con. 99%; Sel. 82%	
Me 2g , Con. 99%; Sel. 58%	
MeO 2h , Con. 99%; Sel. 62%	
^t Bu 2i , Con. 99%; Sel. 60%	2k , Con. 99%; Sel. 79%
Con. 95%; Sel. 67%	Con. 99%; Sel. 70%
Con. 89%; Sel. 52%	
Synthesis of α -bromoketones ^c	
R = H 3a , Con. 93%; Sel. 76%	3j , Con. 97%; Sel. 67%
F 3b , Con. 95%; Sel. 74%	
Cl 3c , Con. 93%; Sel. 77%	
Br 3d , Con. 97%; Sel. 70%	
I 3e , Con. 93%; Sel. 70%	
CF ₃ 3f , Con. 97%; Sel. 81%	
Me 3g , Con. 96%; Sel. 60% ^d	
MeO 3h , Con. 94%; Sel. 60% ^e	
^t Bu 3i , Con. 93%; Sel. 51% ^e	3k , Con. 97%; Sel. 79%
Con. 93%; Sel. 71%	Con. 96%; Sel. 72%
Con. 99%; Sel. 57%	

^a1 mL of isopropanol in 9 mL of ethyl acetate. ^b1 mL of ethanol in 9 mL of ethyl acetate. ^c0.1 mL of isopropanol in 1.9 mL of ethyl acetate. ^d0.1 mL of ethanol in 1.9 mL of ethyl acetate. ^e0.1 mL of isopropanol in 1.9 mL of 1,4-dioxane. ^fReaction conditions: The conversion and selectivity are determined by GC-MS.

attempted the synthesis of α -chloroketones that are important precursors for pharmaceutical applications^{4,36} but kinetically challenging due to the low activity of chlorine radicals. For the synthesis of α -chloroketones (**2a–2n**), substrates with electron-withdrawing groups (EWG, **2b–2f**) show in general high yields toward the target products, as the EWG will stabilize the α -carbon radicals to facilitate the attack of photogenerated oxygen radicals. In comparison, though the presence of electron-donating groups (EDG, **2g–2i**) is unfavorable for the formation of α -carbon radicals, the target products can still be obtained with reasonable selectivities (~60%). Furthermore, substitution of the –Cl on the *ortho*- (**2j**) and *meta*- (**2k**) positions does not have a significant deleterious impact on the selectivity (>70%). Pleasingly,

styrene substituted with a vulnerable ester group (**2l**) attached on the aromatic ring can also be converted into the corresponding α -chloroketone with a decent selectivity. Furthermore, the successful synthesis of 2-vinylnaphthalene (**2m**) suggests that the steric effect barely influences such a photocatalytic process. The synthesis of **2l** and **2m** sheds light on the synthesis of more complicated α -chloroketones for pharmaceutical applications.^{37–40} However, it is noticed that the conversion of α -methylstyrene into 2-chloropropiophenone (**2n**) shows a reduced selectivity, indicating that the α -methyl group strongly influences the electronic properties of the α -carbon-centered radicals. Additionally, a series of α -bromoketones (**3a–3n**) have also been synthesized by employing NiBr₂ as the Br source. The impact of functional groups displays a similar trend observed in the synthesis of α -chloroketones, confirming a similar reaction mechanism. All bromination reactions complete in a much shorter reaction time (2 h) due to the higher activity of the bromine radicals.⁵

In summary, we have designed a facile heterogeneous photocatalytic system for the synthesis of α -haloketones from aromatic olefins under visible-light irradiation. By employing Cu–C₃N₄ as the photocatalyst and NiX₂ (X = Cl, Br) as the halogen source, a series of α -haloketones can be synthesized using atmosphere air as the oxidant. Mechanistic analysis reveals that the presence of Cu NPs as cocatalysts can optimize the formation kinetics of halogen radicals and the selective reduction of O₂ into [•]OOH radicals and promotes the desorption of generated H₂O molecules, thus avoiding the formation of unwanted byproducts. Additionally, its high stability, versatility in expanding substrates, and capability for solar-driven photosynthesis reflect great potential for wider synthetic applications.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acscatal.2c05189>.

Experimental details, material characterizations, and NMR data (PDF)

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Notes

The authors declare no competing financial interest.

Information on the data underpinning the results presented here, including how to access them, can be found in the Cardiff University data catalogue at <http://doi.org/10.17035/d.2022.0234944684>

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