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Catalytic conversion of CO₂ to chemicals and fuels: the collective thermocatalytic/photocatalytic/electrocatalytic approach with graphitic carbon nitride

Subhajyoti Samanta * and Rajendra Srivastava *

Rapid industrial development and the excessive use of fossil fuels have produced a significantly large volume of CO₂ in the atmosphere. The efficient conversion of CO₂ to useful chemicals and fuels is an important step towards reducing the concentration of CO₂. To overcome the thermodynamic and kinetic barriers involved in CO₂ activation and conversion, an effective heterogeneous catalyst and a suitable form of energy, such as thermal, photochemical, and electrochemical, are necessary. Considering a wide variety of catalytic materials for CO₂ conversion using all forms of energy resources discussed above, earth-abundant carbon materials have exhibited the capability to catalyze the thermal, photo-assisted, and electrochemically mediated conversion of CO₂. Among carbon-based materials, graphitic carbon nitride (g-C₃N₄) is an inexpensive and sustainable catalyst that can be effectively used for CO₂ conversion. The chemical reactivity and optoelectronic properties of g-C₃N₄ can be finely tailored for its use as a conventional catalyst or photocatalyst or photoelectrocatalyst. This article aims to summarize the synthetic strategies to prepare various types of g-C₃N₄ materials as conventional catalysts/photocatalysts/electrocatalysts for the improved conversion of CO₂ to chemicals and fuels. This article reviews the utilization of CO₂ as a feedstock for chemical and fuel synthesis *via* insertion, carboxylation, and reduction reactions. Further, an in-depth understanding of the catalytic mechanism of various reactions discussed in this article will help in the design of a new generation of heterogeneous catalysts for CO₂ conversion. Special emphasis is placed on the various parameters influencing the photocatalytic and electrocatalytic CO₂ reduction. Finally, the underlying challenges and outlook for the future development of catalysts for CO₂ conversion to specialty chemicals and fuels are discussed.

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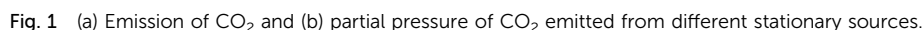
1. Introduction

CO₂ is one of the major variable components in the troposphere that significantly influence human life.¹ A large amount of CO₂ is present in the soil as CaCO₃. However, only gaseous CO₂ present in the troposphere is responsible for global warming. The effect of carbon dioxide on Earth is being discussed at every forum and international meeting.^{2,3} A closer look reveals that several activities by millions of living entities (plants, animals, and human beings) have raised the CO₂ level in the atmosphere by 280 ppm in the last few centuries. However, after the industrial revolution, the CO₂ level in the atmosphere has risen from 280 ppm to 400 ppm and it is expected to reach up to 500 ppm by the 22nd century, which would raise the mean

temperature of the Earth by 1.9 °C.⁴ Today, each and every second of our life is dependent on energy resources. The energy dependency can be taken care of with the use of renewable and alternative resources such as wind, water, radioactive, and solar energy, which do not increase the CO₂ level in the atmosphere and provide a CO₂ emission-free environment.⁵ In recent times, several alternative energy generation systems, such as fuel cells, are being developed which do not emit CO₂.⁷ However, the H₂ required in fuel cells is produced by steam reforming, which produces a large amount of CO₂ in the atmosphere.⁶ Future energy demands and current technologies suggest that it is a long journey and by that time a significant amount of CO₂ will be released into the atmosphere. If the CO₂ concentration increases beyond 600 ppm it would be difficult for human beings to breathe because it is difficult for the human respiratory system to operate in the presence of a greater concentration of CO₂ even though an excess of O₂ is present in the atmosphere. Thus, there is a high priority in developing strategies to reduce the CO₂ concentration in the environment. This can be achieved *via* two

Catalysis Research Laboratory, Department of Chemistry, Indian Institute of Technology Ropar, Rupnagar, Punjab-140001, India.
E-mail: subhajyoti.samanta@iitrpr.ac.in, rajendra@iitrpr.ac.in;
Tel: +91-1881-242175





or houses where the concentration ranges fall at the ppm level.⁸ Besides being the most desirable task, direct CO₂ capture and storage are undoubtedly challenging.^{9,10} In general, liquid CO₂ scrubbers and metal oxides are used to absorb CO₂ from flue gases.^{11–20} Aqueous amine based liquid CO₂ scrubbers are commonly used but their associated energy consumption and cost remain a constraint for further development.⁹ Similarly, solid materials such as alkali metal oxides, layered double hydroxides, solid amines, *etc.* are widely explored materials for CO₂ adsorption.¹⁴ However, CO₂ absorption using the CO₂

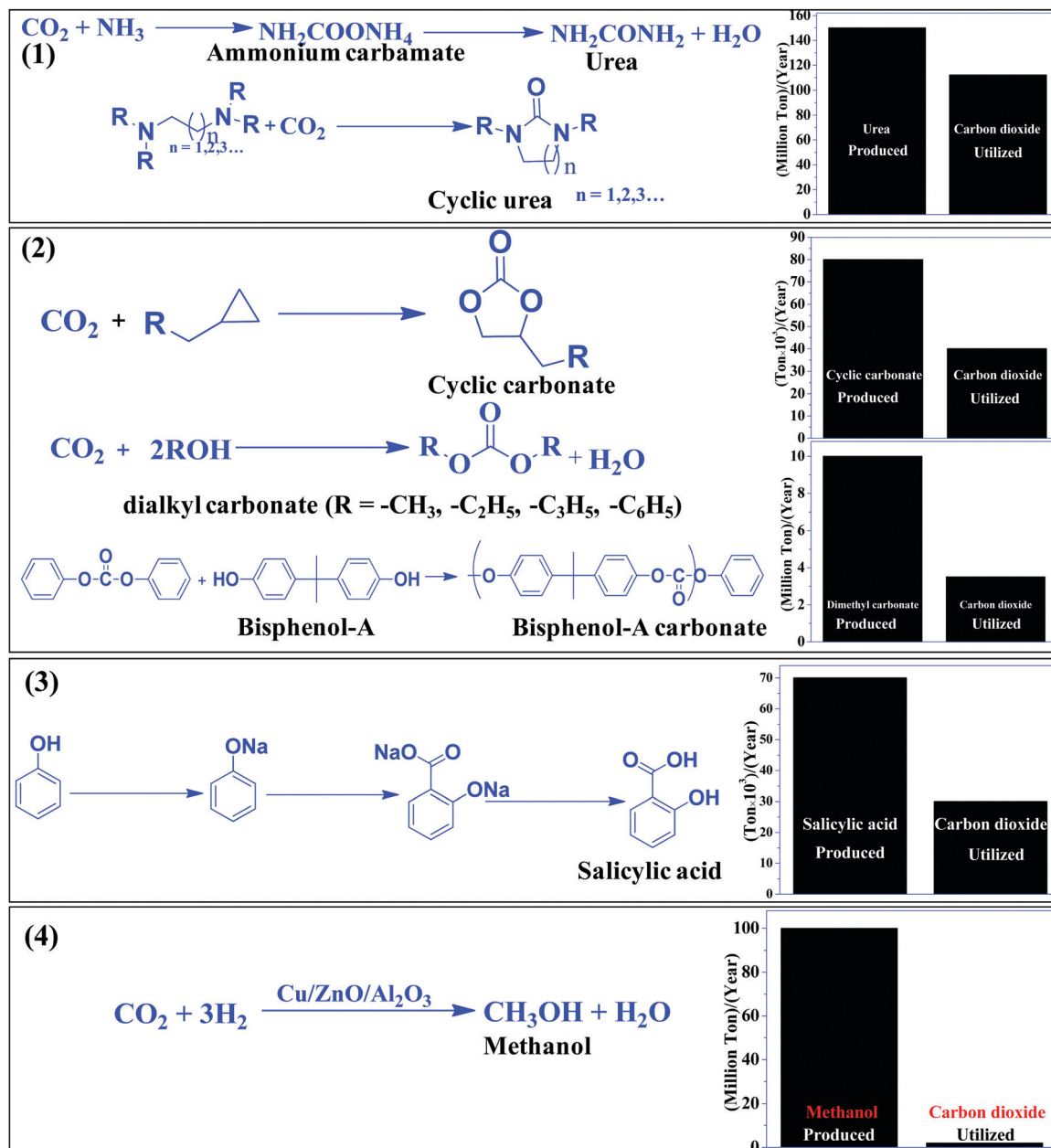


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The most efficient strategy to reduce the concentration of CO_2 in the atmosphere is to convert CO_2 to useful chemicals and fuels. CO_2 is a thermodynamically inert molecule with a high $\text{C}=\text{O}$ bond dissociation energy of 750 kJ mol^{-1} which is much higher than the $\text{C}-\text{O}$ bond (327 kJ mol^{-1}) and even higher than the $\text{C}-\text{C}$ (336 kJ mol^{-1}) and $\text{C}-\text{H}$ (441 kJ mol^{-1}) bonds.²⁵ Due to such high stability, it is difficult to transform CO_2 into useful chemicals. The energy gap between its highest occupied molecular orbital and lowest unoccupied molecular orbital is 13.7 eV and the electron affinity of CO_2 is $(-0.6 \pm 0.2 \text{ eV})$, which leads to a very negative redox potential for one-electron transfer $\text{CO}_2 + \text{e}^- \rightarrow \text{CO}_2^-$ ($E_{\text{redox}}^0 = -1.90 \text{ eV vs. NHE}$).^{26,27} Such a high energy requirement for electron transfer to generate active species for CO_2 conversion makes photocatalytic and electrocatalytic processes highly challenging tasks. Due to such a high energy requirement, only a few chemicals have been commercialized, which utilizes a large amount of CO_2 to give useful chemicals such as urea, methanol, salicylic acid, cyclic carbonates, and dimethyl carbonate (Scheme 1). Synthesis of urea and cyclic urea is not a 100% atom economic process because water is formed as a by-product. In an atom economic process, the total number of atoms present in the reactants is incorporated into the product. Synthesis of cyclic carbonates takes place by an insertion reaction in which CO_2 is inserted into a three-membered epoxide ring to produce a five-membered cyclic carbonate *via* a 100% atom economic process.^{28,29} Dimethyl carbonate (DMC), a solvent, can be produced by the reaction of methanol and CO_2 .^{30,31} DMC reacts with phenol using a $\text{Pb}(\text{OPh})_2$ catalyst to produce diphenyl carbonate (DPC). Then DPC reacts with bisphenol-A to produce a polycarbonate *via* a melt polymerization method (Scheme 1).³² Salicylic acid is manufactured

This focused review aims to concisely cover almost all the important points, starting from the requirements of CO₂ conversion, fundamentals of CO₂ activation, strategies adopted for g-C₃N₄ preparation for improved CO₂ conversion, structure elucidation of g-C₃N₄, and structure–activity relationship, followed by critical operational parameters for collective ‘thermo-photo-electro’-chemical CO₂ conversion focusing on the g-C₃N₄ catalyst,



Scheme 1 CO₂ based commercial processes and amount of CO₂ utilized vs. product formed in the given process.

which is not available in a single article hitherto reported in the literature.

2. Carbon nitride, a versatile material for CO₂ adsorption and conversion: structural elucidation for catalysis

Among porous materials, carbon materials have a high surface area, tunable porosity, hydrophobicity for CO₂ adsorption under hydrated conditions, high thermal and chemical stability, and functional ability.^{35–37} Activated carbon is the most economical and widely available carbon material having micropores,

mesopores, and macropores.³⁸ Due to the porous architecture and high surface area, it can significantly adsorb large amounts of CO₂ by the physisorption process but it finds difficulty in the activation and utilization of CO₂ in chemical synthesis due to the inability to chemisorb and activate CO₂.³⁹ Biomass pyrolysis and KOH activation can produce high surface area activated carbon, suitable for CO₂ physisorption.⁴⁰ N-Doped microporous carbon prepared with coconut shell and urea has exhibited high CO₂ adsorption and CO₂/N₂ selectivity at 1 bar, confirming that N-doping has improved the CO₂ adsorption.⁴¹ Similar to inorganic porous materials, sol-gel methods have been applied for the synthesis of porous carbon materials in water and/or ethanol medium followed by acid activation



in the presence and absence of metal catalysts. Due to the high surface area and surface to volume ratio, these materials can be easily functionalized using various amines for the efficient adsorption of CO₂.^{50,51} These porous carbons have varied surface area, morphology, and porosity and, thus, the extent of CO₂ adsorption over these materials varies depending on their tunable textural properties. However, the adsorption and chemisorption capability improves if nitrogen-doped or nitrogen-containing carbon materials are considered. Nitrogen-containing carbon materials induce interactive forces between CO₂ and nitrogen groups present in the material. CO₂ is a weak Lewis acidic molecule because the carbon atom in CO₂ is electron-deficient. Nitrogen-doped carbon atoms are negatively charged and nitrogen sites act as electron donors and behave like a Lewis base; therefore, nitrogen-containing carbon materials have acid–base interactions through which CO₂ molecules are chemisorbed. The strong dipolar C=O bond generates an electric quadrupole moment in the CO₂ molecule, whereas nitrogen doping induces local polarization in the porous carbon matrix.⁵² Notably, N₂ has a lower electric dipole moment than CO₂. Hence, the interaction between the CO₂ molecular quadrupole moment and high electrostatic potential of N-doped carbons enhances the CO₂ adsorption energy, leading to selective and higher CO₂ adsorption from flue gases. Experimental and computational studies have shown that surface hydroxyl

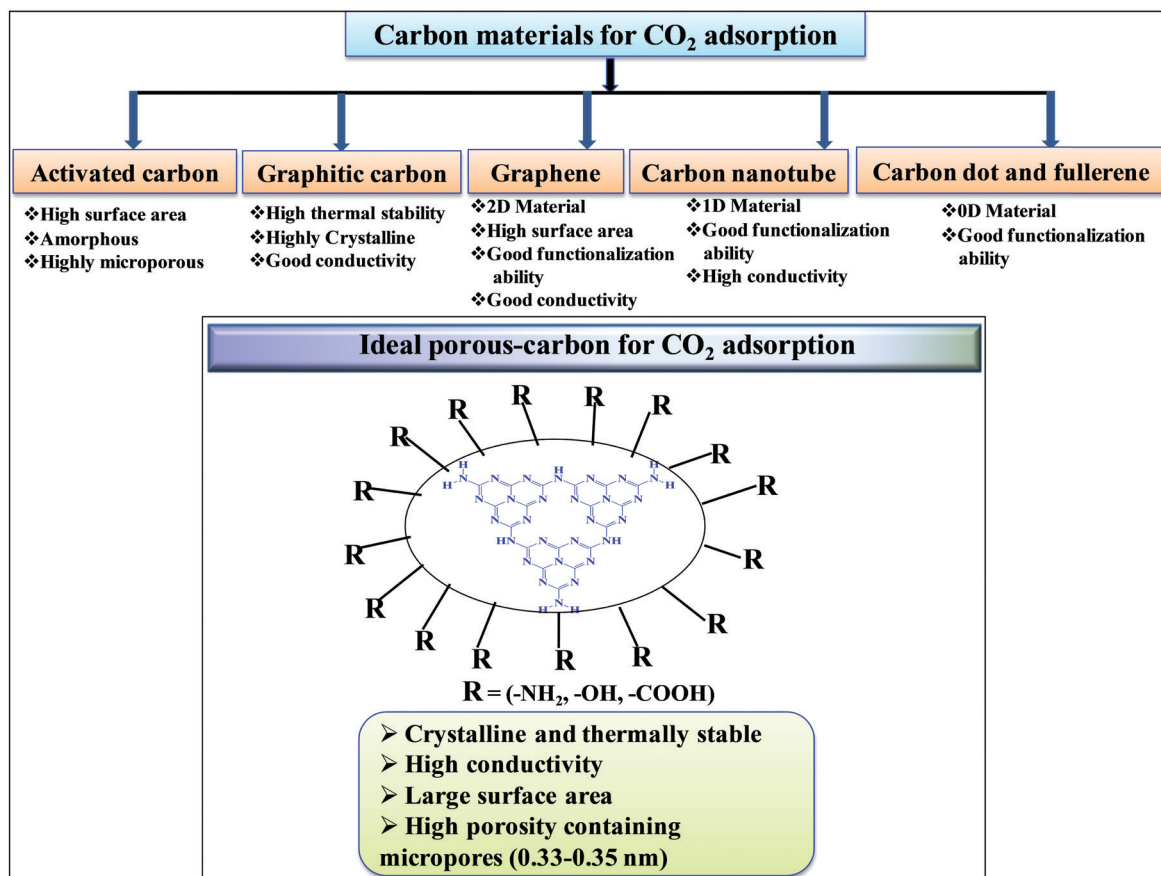


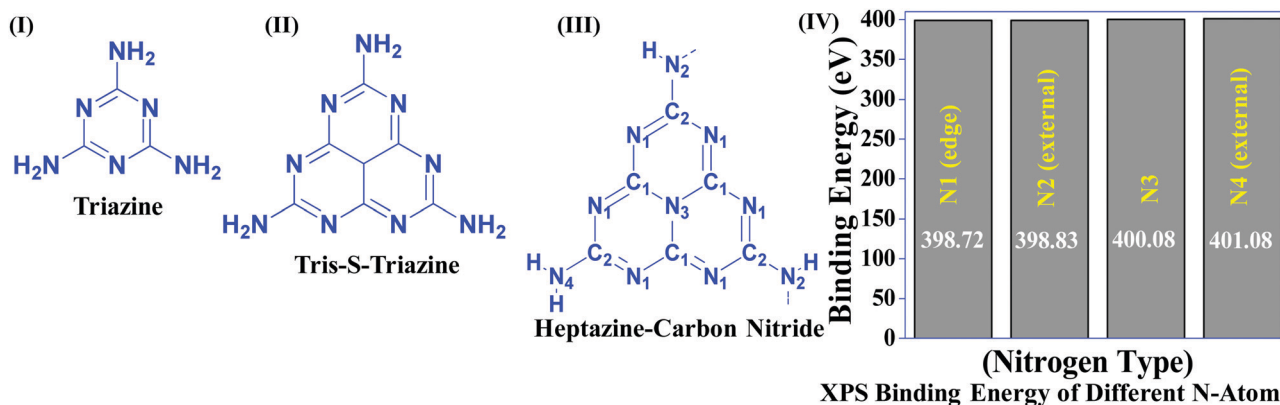
Table 1 Nitrogen-containing carbon materials and their CO₂ uptake capacity⁴⁴

E. no.	Material	S_{BET} (m ² g ⁻¹)	Nitrogen content (%)	CO ₂ uptake mmol ⁻¹ g ⁻¹ (298 K)
1	NMC-600	272	6.33	3.90
2	NMC-700	518	6.06	3.60
3	AC-600-0.5	508	6.70	3.00
4	AC-600-2	966	4.50	3.64
5	AC-800-2	2448	3.90	3.00
6	Sk-0.5-700	1060	0.48	4.24
7	SK-4-700	2792	0.18	3.05
8	PGC-K	1143	8.30	4.00
9	FCP-1-KC	800	0.60	5.20

groups present in the N-doped carbon skeleton enhance the interaction between –OH and –NH functionalities leading to high CO₂ adsorption in N-doped carbon materials.⁵³ Nitrogen doping and surface functionalized amines have different types of interaction. Surface functionalized amines interact with electropositive carbon of CO₂ and form ammonium carbamate leading to high CO₂ adsorption on the surface.⁵⁴ However, surface and pore blockage and thermal instability of functionalized amines are some of the demerits of surface amine-functionalized carbon materials; therefore, nitrogen-doped carbon is superior over amine-functionalized carbon materials. Based on the varied textural properties and chemical properties (due to N doping and amine functionalization), it can be concluded that high surface area and high nitrogen contents both are important factors contributing to high CO₂ adsorption (Table 1).⁴⁴ Moreover, when CO₂ activation and utilization for chemical synthesis are considered both these factors play important roles.

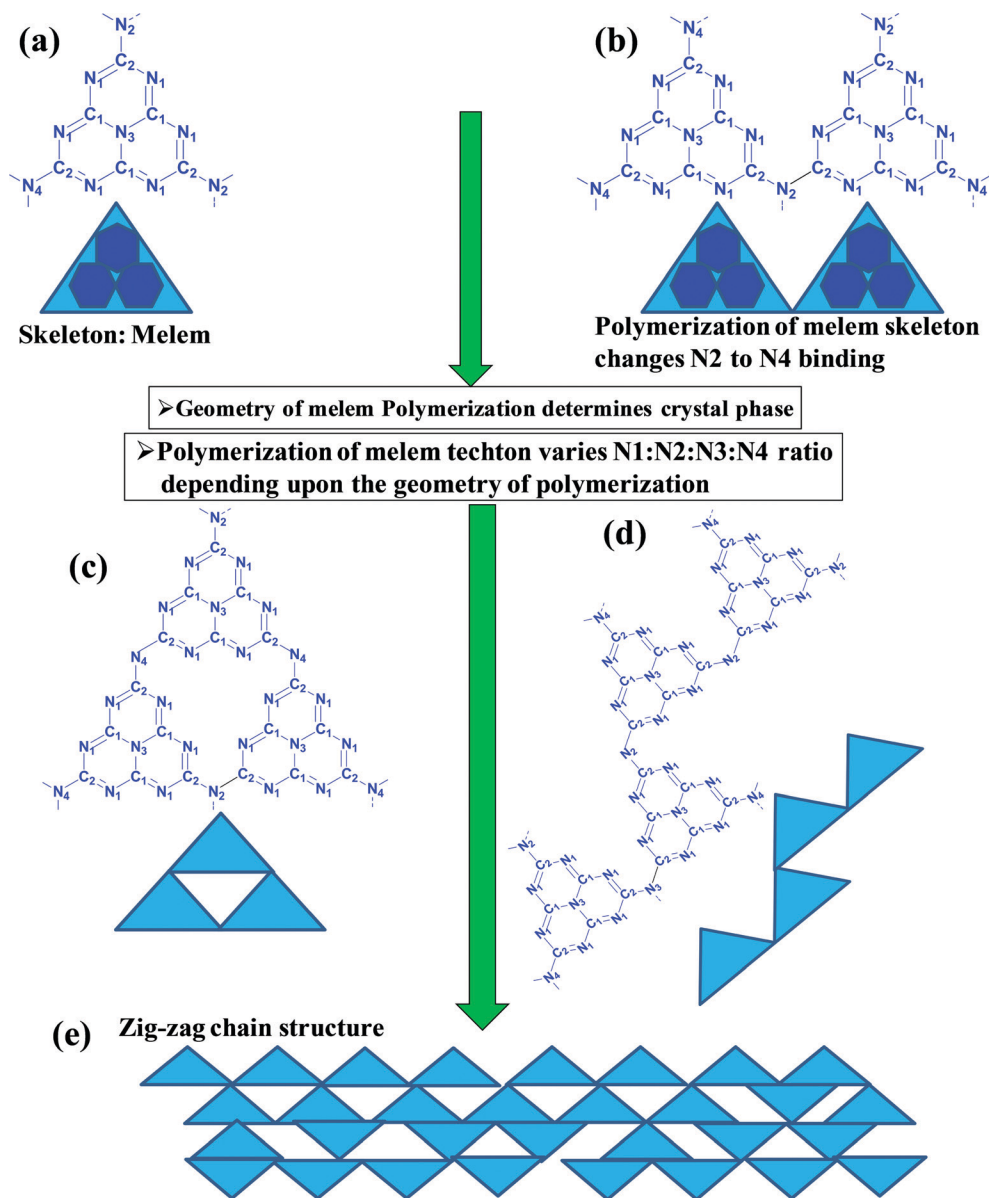
Table 1 suggests that a large number of framework substituted N atoms in a carbon matrix is required for high CO₂ adsorption. The graphitic carbon framework provides high thermal stability and conductivity, which would be good for photocatalysis and electrocatalysis. An ideal porous carbon material and its properties are listed in Scheme 2. Based on these characteristic features, a unique carbonaceous material known as graphitic carbon nitride (g-C₃N₄) can best serve this purpose. When a simple nitrogen-rich organic compound (such as urea, melamine, cyanamide, dicyandiamide, *etc.*) is thermally-

polymerized in the temperature range of 500–700 °C, it produces carbon nitride. This material was synthesized way back in 1834 by Berzelius;⁵⁵ however its potential as a catalyst⁵⁶ and photocatalyst⁵⁷ was realized in 2006 and 2009, respectively. This crystalline material exists in seven allotropes: α -C₃N₄, β -C₃N₄, cubic C₃N₄, pseudocubic C₃N₄, *g-h*-triazine, *g-o*-triazine, and *g-h*-heptazine with bandgaps of 5.49, 4.85, 4.30, 4.13, 2.97, 0.93, and 2.88 eV, respectively.⁵⁸ These allotropes vary in their nitrogen environment and nitrogen contents. Theoretically, carbon nitride is predicted to have a C/N ratio of 0.75 without any surface functional groups and hydrogen content but the reality is far from this prediction. Carbon nitrides have been actually obtained with varied C/N ratios using different nitrogen-containing organic compounds at varied reaction temperature. It is possible to synthesize carbon nitrides such as C₃N, C₃N₂, C₁₀N₃, C₅N, C₃N₅, C₃N₆, C₃N₇, *etc.*, having different nitrogen contents than the theoretically predicted ideal C₃N₄ and those are termed as nitrogen-rich (C/N < 0.75) and nitrogen lean (C/N > 0.75) C₃N₄.⁵⁹ Whenever a six-membered conducting atomic-scaffold is envisaged, structures such as those of benzene or borazine pop-up in our minds. Based on this perception, the triazine-like structure of C₃N₄ can be predicted (Scheme 3(I)). But it has been found that triazine or tri-*s*-triazine units (Scheme 3(II)) (also known as tectonic units) propagate in three dimensions to produce allotropes of g-C₃N₄ (Scheme 3). Computational studies based on Density Functional Theory (DFT) suggest that the tri-*s*-triazine unit is more stable than the triazine unit by 30 J mol⁻¹.⁶⁰ Later, 2,5,8-triamine, tri-*s*-triazine (C₆N₁₀H₆) has been isolated, which confirms the building units of g-C₃N₄.⁶¹ Theoretical g-C₃N₄ should have an ideal C/N ratio of 0.75 and should not possess any H or O atoms; however, XPS and elemental analysis suggest that it has H and O atoms in small quantities in addition to C and N. Notably, H and O atoms are observed due to terminal amine groups and surface adsorbed water and (C=O), (O–N), and (C–OH) groups, for which the details are provided in Scheme 3. Various types of C and N are designated in one pictorial representation of a terminal tri-*s*-triazine unit of g-C₃N₄ (Scheme 3). The structure clearly shows that it has two different types of C represented as C1 and C2 (Scheme 3(III)). Similarly, four different types of

**Scheme 3** Chemical structure of (I) triazine, (II) tris-*s*-triazine, and (III) heptazine units of carbon nitride, and (IV) various N types and their binding energies.

nitrogen atoms are designated as N1 (pyridinic), N2, N3 (graphitic-N), and N4 (Scheme 3(III)). They can be easily distinguished from XPS analysis due to different electronic environments that provide different binding energies (Scheme 3(IV)).⁶²

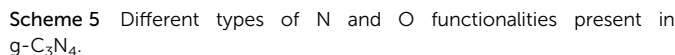
In a true heptazine building unit (also known as melem), N2 is absent and N1:N3:N4 should be present in the ratio 6:1:3 (Scheme 4a). When the melem monomer polymerizes, the N4-type of nitrogens are converted to the N2-type (Scheme 4b).



Sl. No.	N1	N2	N3	N4	N1 %	N2 %	N3 %	N4 %
Dimer	12	1	2	4	63.16	5.26	10.52	21.05
Tetramer	12	1	2	3	66.66	5.55	11.11	16.67
Octamer	12	1	2	2.5	68.85	5.71	11.43	14.28
Infinite chain	12	1	2	2	70.58	5.88	11.76	11.76

Scheme 4 Evolution of different geometry and N types present in C_3N_4 based on the variation of the linkages of melem units.⁵³

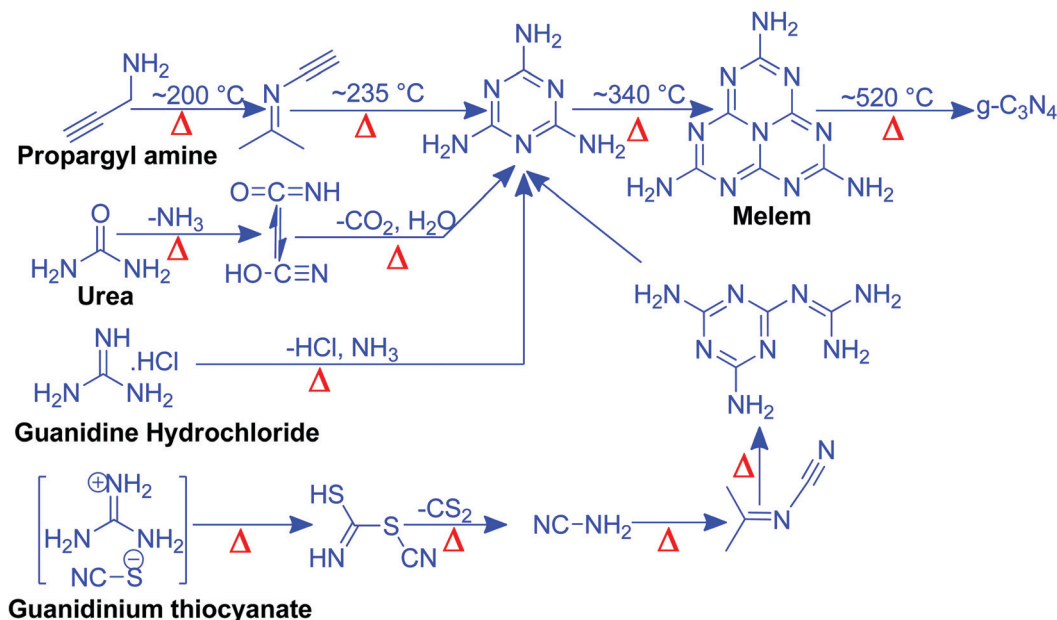




Pyridinic-N with a higher negative charge in the 2-D plane retains a lone pair of electrons that can bind CO₂ more efficiently than other types of N moieties.^{65,66} Quaternary graphitic nitrogen exhibits Lewis acidity.^{67,68} Electrons are mostly present in the π^* -antibonding orbital in graphitic-N and thus are less accessible to CO₂ for binding.⁶⁵⁻⁶⁷ Pyridinic-N and graphitic-N can be easily presented in the melem units; however, other types of N-species are formed during un-controlled thermal polymerization in an oxygen lean environment leading to partial terminal uncondensed amines, N-oxide, and pyrrolic N species as shown in Scheme 5. The various N-species discussed above have the ability to impart tunable basicity, H-bonding, and Lewis acidity (frustrated Lewis acid-base pairs) and are thus suitable for various types of catalytic reactions involving CO₂ as a reactant.

Based on the discussion so far we have understood that suitable micropores, high surface area, and pyridinic rich N sites are required for high CO₂ adsorption. CO₂ adsorption alone is not sufficient to catalyze various types of CO₂ based reactions because reactive partners also need to be efficiently adsorbed and suitably activated to synthesize various CO₂ derived chemicals. Further, bandgap and band edge positions can be finely tuned depending on the doping and crystallinity for light-induced CO₂ conversion. Thus, synthetic strategies, types of precursors, the temperature for synthesis along with the environment, and other parameters influence the physicochemical properties of g-C₃N₄. The following section describes the various synthesis strategies reported for the preparation of g-C₃N₄ for improved CO₂ activation.

Nitrogen-rich organic compounds such as melamine, cyanamide, and dicyandiamide are heated in semi-closed systems in oxygen-lean conditions to form $g\text{-C}_3\text{N}_4$ (Scheme 6). $g\text{-C}_3\text{N}_4$ is formed by various condensation steps in which the first melamine is formed at lower temperatures ($<350\text{ }^{\circ}\text{C}$) followed by removal of NH_3 leading to tris-*s*-triazine at a temperature around $400\text{ }^{\circ}\text{C}$. The polymerization of tris-*s*-triazine takes place at around $520\text{ }^{\circ}\text{C}$ to form $g\text{-C}_3\text{N}_4$ (Scheme 6).⁶⁹ TGA investigation reveals that this framework is stable up to $550\text{ }^{\circ}\text{C}$. Even oxygen-containing precursors such as urea also follow the same sequence and form $g\text{-C}_3\text{N}_4$ *via* a melamine intermediate (Scheme 6). The nitrogen content and surface area of $g\text{-C}_3\text{N}_4$ depend upon the precursor and the pyrolysis temperature. With the increase in the pyrolysis temperature, the C/N ratio increases whereas the bandgap decreases.⁷⁰ During the polymerization process, the amine groups of tris-*s*-triazine don't condense completely, which results in the formation of uncondensed amine group-containing $g\text{-C}_3\text{N}_4$ with about 2% H content with a C/N ratio less than 0.75. Such a structural defect is important for the adsorption of reactant molecules, which is good for catalytic reactions.⁷¹ It may be noted that if the uncondensed groups (discussed above) are present in higher numbers then it might be good for conventional catalysis but is definitely not suitable for photocatalysis due to the less efficient charge transportation and separation of charge carriers. High-temperature polymerization leads to the formation of crystalline $g\text{-C}_3\text{N}_4$, which is better for charge carrier separation and a higher degree of π -conjugation and thus good for photocatalysis.⁷² Moreover, with the increase in the pyrolysis temperature, aggregated bulk $g\text{-C}_3\text{N}_4$ changes to a nanosheet and nanoflake like morphology with improved surface area.^{73,74} Also, urea and thiourea derived $g\text{-C}_3\text{N}_4$ exhibit better surface area due to the removal of CO_2 at higher temperatures, leading to high porosity and improved surface area when compared to the cyanamide precursor.



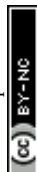
Scheme 6 Synthesis of g-C₃N₄ via the melem unit using different precursors.

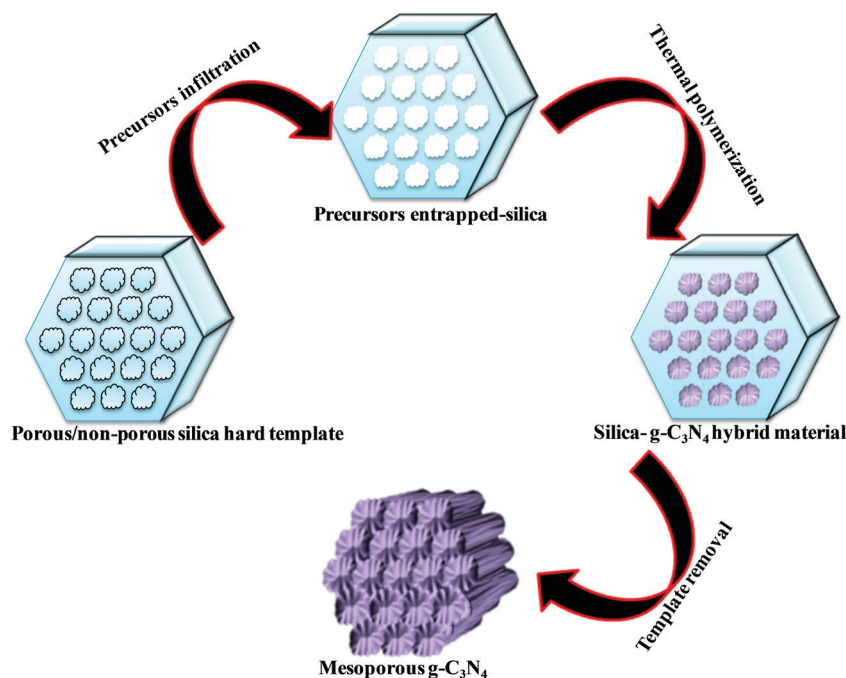
Further, the surface area of urea derived g-C₃N₄ is improved if the pyrolysis is carried out for a longer time.⁷⁴ During such prolonged heating the layered structure of g-C₃N₄ is exfoliated and splitting takes place to produce low yield g-C₃N₄ with better surface area and photocatalytic activity.⁷⁵ Inspired by the synthetic paradigm of g-C₃N₄ from urea which has resulted in higher surface area due to the liberation of CO₂ during urea pyrolysis, sucrose and melamine have been pyrolyzed together. The reason for selecting sucrose is that it will generate a large amount of CO₂ during pyrolysis and produce g-C₃N₄ with N-deficiency and improved surface area (6 fold higher) and porosity.⁷⁶ The type of N species and surface area can be tailored by selecting different precursors. For example, guanidine hydrochloride or guanidine thiocyanate pyrolysis results in g-C₃N₄ via a melem intermediate and produced materials with high surface area and enhanced photocatalytic activity (Scheme 6).⁷⁷ The bandgap of g-C₃N₄ can be reduced and mid-gap creation is possible if a nitrogen-vacancy is created in the material. Nitrogen deficiency in g-C₃N₄ leaves additional electrons and creates nitrogen-vacancy related C³⁺ states leading to a reduced bandgap material. This can be easily achieved by heating the material in an H₂ atmosphere. H₂, being a small molecule, can easily penetrate and diffuse to the interior lattice sites and reduce the lattice N sites and liberate NH₃ and create an N vacancy. In this process, the terminal N sites are more prone to reduction due to the lowest change in the energy of the molecule. Such an N vacancy in the system reduces the bandgap by downshifting of the CB and up-shifting of the VB position. Another situation can also arise in which new C and N sites are generated, which increases the H contents in the material and alters the bandgap of the material. Experimental analysis suggests that a three coordinated N-vacancy and H-substitution at the N sites decrease the bandgap by 0.2 and 0.55 eV.⁷⁸ This lowering in the bandgap is due to the formation

of additional band states below the CB by the defect C sites leading to lowering the bandgap values. The N-vacancy moves the VB energy to more negative values and H-substitution lowers the CB to more positive values and improves the visible light absorption capacity. The surface area of g-C₃N₄ can be improved by exfoliating bulk g-C₃N₄ in different solvent media such as water, ethanol, acetone, IPA, and NMP. Among these solvents, NMP has been found to be the best choice.⁷⁹ However, it is difficult to remove NMP from the exfoliated g-C₃N₄. Thus IPA has been explored as the next most desirable solvent to exfoliate bulk g-C₃N₄, so as to produce high surface area g-C₃N₄ of the order of 300–400 m² g^{−1}. For exfoliation of bulk g-C₃N₄, aqueous alkaline and acidic solutions have also been explored with the aim of obtaining higher surface area.^{80,81} Although an improvement in the surface area is observed by varying the precursors, reaction temperatures, and pyrolysis environment, however, the materials still remain nonporous in nature. In order to introduce porosity in the material, template-assisted synthetic strategies have also been adopted as discussed below.

3.2 Template-mediated synthesis strategy to produce g-C₃N₄ with high surface area and porosity for improved CO₂ adsorption

Various hard template-mediated synthetic strategies utilize silica-based mesoporous materials (SBA-15, SBA-16, KIT-6, MCM-41, and MCM-48) as the template (Scheme 7). Nitrogen-containing organic precursors or carbon and nitrogen precursors are infiltrated into the porous architecture of silica materials via the incipient wet impregnation or wet impregnation method followed by pyrolysis, which results in the formation of g-C₃N₄/silica hybrid materials. Finally, the silica template is removed by chemical etching using various etching agents, for example, NaOH, HF, and NH₄HF₂. The final material has the same architecture as that of the original silica material.⁸²





Scheme 7 Hard template mediated synthesis of mesoporous q-C₃N₄.

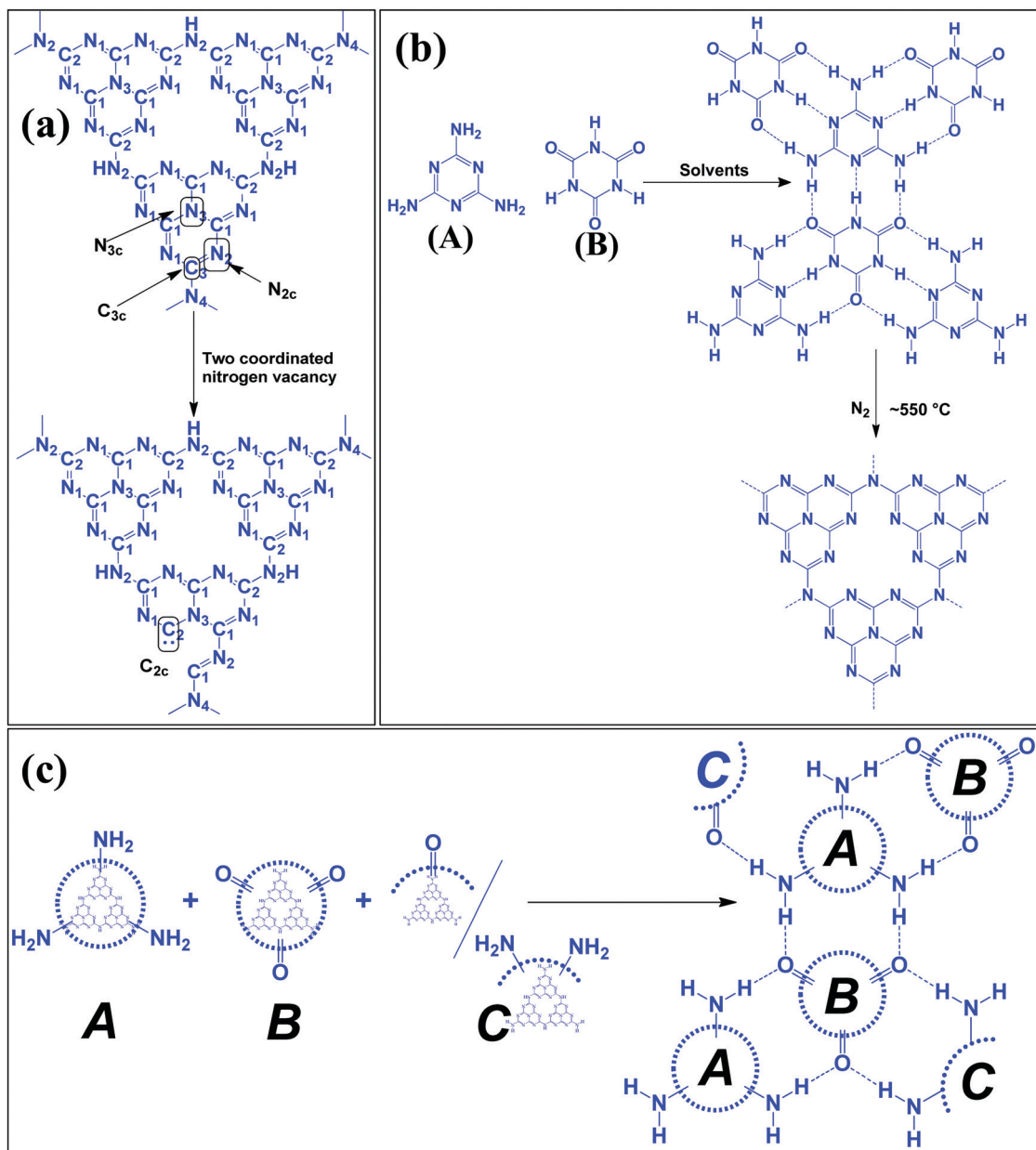
Even silica nanoparticles have produced porous g-C₃N₄ with an average pore diameter of 12 nm, which is equivalent to the original silica nanoparticles.⁸³ In general, the pore diameter of the resulting material is smaller than the porous silica materials due to volume shrinkage of g-C₃N₄ filled inside the pores during the condensation.⁸⁴ The surface area and porosity significantly depend on the Si/precursor, hard template, and etching agent. The surface area can be further improved if the original silica material is treated with acid to enhance the surface reactivity, which allows a large number of organic precursors to in-filter, which improves the surface area of the resultant material.⁸⁵ This synthetic strategy produces a low yield of g-C₃N₄ and, therefore, is difficult for application in the large scale synthesis of mesoporous g-C₃N₄. Further, hazardous and costly HF and NH₄HF₂ limit its industrial-scale production.⁸⁶ To overcome this problem, CaCO₃ has been used as a hard template in which the template is removed with dilute HCl after polymerization, leading to the formation of high surface area g-C₃N₄ with improved photocatalytic activity.⁸⁷

Large scale synthesis of mesoporous g-C₃N₄ can be achieved using the soft template method. Since the soft template is a carbon-based compound, therefore g-C₃N₄ with higher C/N is formed with diverse functionality. Ionic liquids and block copolymer-based soft templates have been widely used to prepare mesoporous g-C₃N₄. Among the soft templates, only a few templates such as Triton-100 and ionic liquids have produced g-C₃N₄ with large surface area and porosity.^{87–89} Ionic liquids act as soft modifiers for the thermal polymerization, leading to tunable textural properties, morphology, and reactivity. Anions of the ionic liquids participate in the growth process *via* C–N condensation.⁹⁰ Dual templating methods and cooperative assembly of two surfactants lead to formation of a

mesophas, which results in the formation of nanostructured materials. A similar strategy can be applied to synthesize mesoporous g-C₃N₄. Cooperative supramolecular assembly of surfactants, or a reactant and a surfactant, or reactants induced by hydrogen bonding and other weak electrostatic forces can act as a template to form mesoporous g-C₃N₄. Nitrogen-rich organic precursors can easily form hydrogen bonding with “O” containing organic compounds to form self-assembled porous g-C₃N₄. For example, melamine can form hydrogen bonding with cyanuric acid in DMSO and form stable aggregates that easily precipitate out (Scheme 8). Such precipitates can be thermally polymerized to form mesoporous g-C₃N₄.⁹¹ In fact, supramolecular aggregates can be formed by the hydrogen bonding between three reactants such as melamine, cyanuric acid with urea/barbituric acid/cafeine, *etc.* in a different solvent medium, which results in different morphology of mesoporous g-C₃N₄ on thermal polymerization with different textural properties and photophysical characteristics (Scheme 8).^{92–94} Template mediated synthesis strategies can provide materials with high surface area and porosity but it is difficult to tune the N contents and type of nitrogen due to the specific use of a suitable template and nitrogen precursor. Thus more work is needed to develop soft-template mediated synthesis recipes with variable N contents and functional amine sites using a diverse range of C and N containing precursors for the appointed applications.

3.3 Strategies to functionalize and dope elements to improve catalytic activities and light absorption properties

Template-mediated synthetic strategies can improve the surface area and porosity. However, for tuning the catalytic activities relating to the efficient adsorption of reactants and



Scheme 8 Supramolecular assembly of precursors leading to formation of mesoporous g-C₃N₄.

light absorption, suitable doping and functionalization are required. By varying the nitrogen precursors, the C/N ratio can be tailored, but for doping other elements such as O and S, suitable precursors containing O and S should be used during the synthesis of g-C₃N₄. Just by H₂O₂ treatment, O doped g-C₃N₄ with high surface area is obtained, which exhibits efficient charge carrier separation, and a red-shift in the absorption spectra.⁹⁵ An oxygen group containing melamine precursor also produces O doped g-C₃N₄.⁹⁶ Organic surfactant mediated synthesis produces C doped g-C₃N₄.⁹⁷ Diammonium hydrogen phosphate, hexachloro-cyclotriphosphazene, 2-aminoethylphosphonic acid, *etc.* have been used as a P source to dope P into the g-C₃N₄ framework.^{98–100} H₂S treatment, thiourea, and

tri-thiocyanic acid precursors are known to dope S in the g-C₃N₄ framework.^{101–103} B-Doped g-C₃N₄ has been prepared by heating melamine and B₂O₃ above 520 °C to introduce B into the g-C₃N₄ framework.¹⁰⁴ BH₃NH₃ and sodium-tetraphenyl boron have been used as precursors to prepare B-doped g-C₃N₄.^{105,106} Recently, it has been reported that exfoliation of g-C₃N₄ (prepared by urea and thiourea) with concentrated H₂SO₄ aqueous solution at 80 °C has produced –SO₃H functionalized g-C₃N₄.¹⁰⁷ Furthermore, it has been found that a small quantity of 2-methyl imidazole can be treated with urea-thiourea to produce O and C co-doped g-C₃N₄.¹⁰⁸ Thus, the choice of precursor and the treatment conditions can introduce desired elements and functionality in g-C₃N₄ to impart the desired catalytic activity.



4. Synthesis of chemicals and fuels from CO₂ using g-C₃N₄ as a catalyst in the conventional thermal catalytic process

Several recent review articles have been published, even using carbon nitrides as catalysts and photocatalysts.^{109–111} In this section, the role of CO₂ as a C₁ source to produce chemicals and fuels is described (Scheme 9). CO₂ can also act as an “O” source and can be utilized as an oxidant. CO₂ can be efficiently reduced to provide various chemicals and fuels. All these processes are non-atom efficient processes. CO₂ can be inserted in organic compounds like epoxides, amines, and alkynyl acids to produce organic carbonate and carbamate in a highly atom efficient process.

4.1 Role of CO₂ as a soft oxidant or promoter in the oxidation reaction

The oxidizing ability of various gases in coke oxidation follows the order: O₂ (105) > H₂O (3) > CO₂ (1), and thus CO₂ can act as a soft oxidant.¹¹² Such a weak oxidation ability is suitable in the oxidative dehydrogenation reaction. Oxidative dehydrogenation in the presence of oxygen leads to the generation of a large amount of CO₂ as a by-product due to the strong oxidizing ability of O₂.¹¹³ CO₂ is a weaker oxidant and, therefore, it requires activation energy. In general, this activation can be achieved with alkali metals such as Li, K, Na, Ba, Ca, and Cs, which activate CO₂ to form MCO₂.¹¹⁴ The activity of Li is higher among the above-mentioned metals due to the CO₂–M valence bond angle, which is favorable for efficient CO₂ activation and utilization. In this dehydrogenation reaction, CO₂ facilitates the abstraction of hydrogen from hydrocarbons (alkanes, alkenes, alcohols, and alkyl aromatics) *via* catalytic activation to form CO and O species and suppress the total oxidation.¹¹⁵

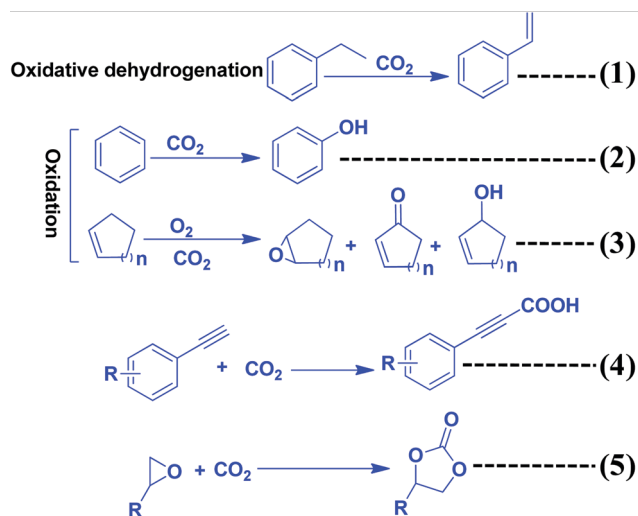
g-C₃N₄ has been reported for the oxidation of benzene to phenol using CO₂ as a mild oxidant.¹¹⁶ CO₂ is activated *via* the secondary amine and pyridinic N of g-C₃N₄. Benzene is adsorbed weakly on g-C₃N₄. CO₂ splits into an $\ddot{O}$ diradical, followed by its reaction with weakly adsorbing benzene to form the desired phenol as a product (Scheme 10). CO is eliminated after the reaction to regenerate the active sites for further CO₂ adsorption.¹¹⁶ CO₂ acts as a promoter in the cycloalkene oxidation using O₂ as an oxidant over a g-C₃N₄ catalyst (eqn (3), Scheme 9).¹¹⁷ CO₂ is efficiently adsorbed on g-C₃N₄ to form surface O species and produce CO (confirmed from the FT-IR study). Such surface O assists in the oxidation of cyclic olefins.¹¹⁶

4.2 Carboxylation of terminal alkynes with CO₂

Alkynylcarboxylic acid is an important synthetic intermediate for several important compounds. For this reaction to proceed, both the alkyne and CO₂ need to be activated (Scheme 9, eqn (4)). CO₂ can be activated with g-C₃N₄ but for the efficient adsorption and activation of an alkyne, highly disperse active metals such as Cu or Ag are required. Ag NP decorated g-C₃N₄ has been reported for this reaction.¹¹⁸ This reaction follows the Langmuir–Hinshelwood mechanism in which CO₂ is absorbed and activated by g-C₃N₄ and the alkyne is adsorbed and activated by Ag NPs supported on g-C₃N₄. Alkyne acidic hydrogen is activated by the Ag NPs and forms silver acetylide and then this reactive intermediate reacts with activated CO₂ to produce silver carboxylate, which can be easily converted into cesium carboxylate with the help of Cs₂CO₃ *via* a transmetalation step. Finally, by workup with an acidified solution, it forms the desired alkynyl carboxylic acid.

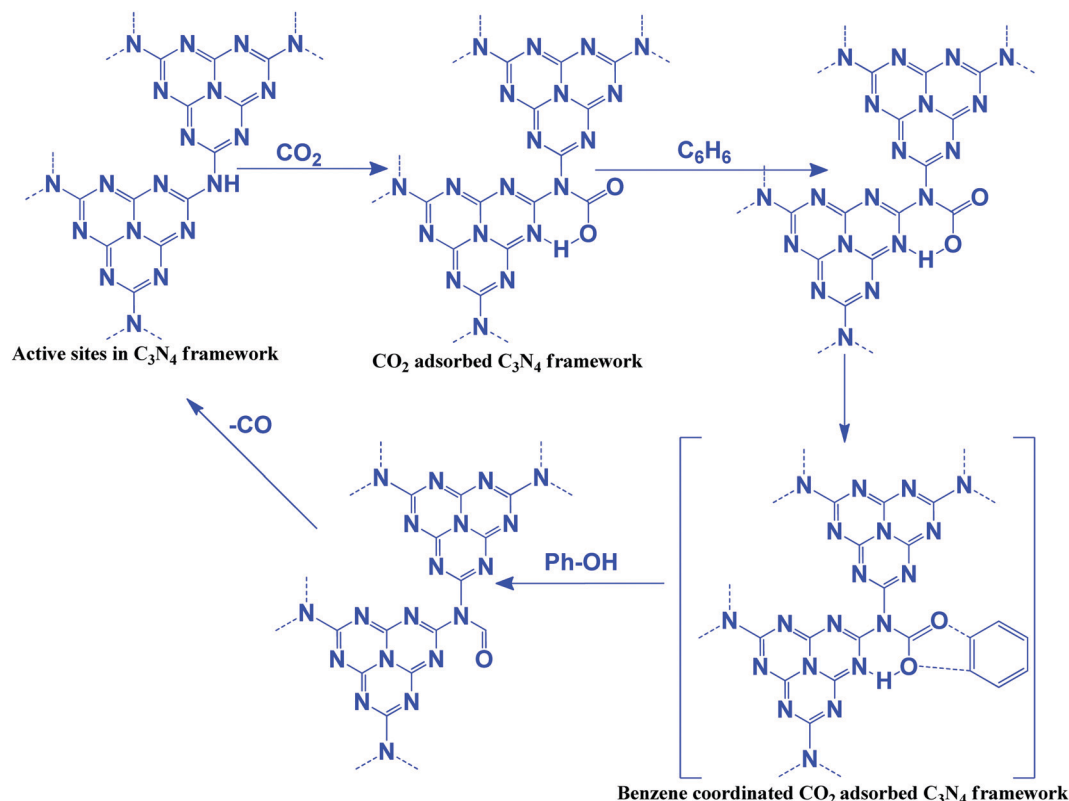
4.3 Insertion of CO₂ into epoxides to form cyclic carbonates

The synthesis of cyclic carbonates by the reaction of CO₂ and epoxides is one of the most widely investigated reactions for CO₂ utilization because it is a 100% atom economic process. The cyclic carbonate product can be used as an intermediate for the production of value-added compounds such as Bisphenol-A carbonate (a synthetic polymer used in the packaging industry) and dimethyl carbonate (a methylating agent and a green solvent), the latter being a good fuel additive and a precursor for various other industrially important chemical transformations. CO₂ can be inserted in the epoxide ring *via* a non-concerted process to produce the cyclic carbonate. For this reaction, generally, a catalyst should contain a Lewis basic site, which acts as a nucleophile to activate the ‘C=O’ bond of the CO₂ molecule, while a Lewis acidic site acts as an electrophile for activating the epoxide ring.¹¹⁹ The Lewis acidic site polarizes the epoxide ring and forms an epoxide anion and then it acts as a nucleophile and attacks the CO₂ molecule, leading to the formation of a carbonate anion intermediate. The next step is either a ring-closing process for the formation of the cyclic carbonate or insertion of one or more epoxides and CO₂ molecules into the intermediate, which produces a polycarbonate.¹¹⁹ g-C₃N₄ has surface/edge located free –NH₂ groups which serve as Lewis basic sites and act as the



Scheme 9 Synthesis of organic compounds using CO₂ as a reactant or oxidant or promoter and C₃N₄ as a catalyst.





Scheme 10 Oxidation of benzene to phenol using CO₂ as an oxidant and g-C₃N₄ as a catalyst.

nucleophile to activate CO₂. However, a Lewis acid site is absent to activate the epoxide. The weak activity of g-C₃N₄ towards this reaction is due to surface -OH sites which have the ability to weakly activate the epoxide and produce a very low yield of the product. For this reaction to proceed efficiently, a co-catalyst such as tetra butyl ammonium bromide (TBAB) is used. However, suitable metal-free bi-functional g-C₃N₄ is reported to effectively catalyze this reaction.¹⁰⁷ Production of cyclic carbonates using different g-C₃N₄ based catalysts is summarized in Table 2. Conventional g-C₃N₄ exhibits very low activity (Table 2, entry 1).¹²⁰ Mesoporous g-C₃N₄ (prepared with different precursors) has exhibited better activity than conventional g-C₃N₄. Among the prepared materials, mesoporous g-C₃N₄ prepared with melamine exhibits 34% propylene oxide conversion, and 90% propylene carbonate selectivity with a TOF of 3.4 h⁻¹ at moderate reaction conditions in DMF (Table 2, entries 2–4).¹²¹ A mixture of gas (50% O₂ and 50% CO₂) is used during this reaction and it has been proposed that O₂ plays a promotional role for the activation of the epoxide by supplying additional oxygen during the course of the reaction.¹²⁰ Further, to improve the surface area and dispersed active sites, SBA-15 supported g-C₃N₄ is employed for propylene carbonate synthesis under solvent-free conditions in the presence of doped metal ions, which act as Lewis acid sites. Among metal salts, Zn²⁺ exhibits the highest conversion and selectivity of 98.3% and >99%, respectively (Table 2, entries 5–8).¹²² The activity of doped Zn²⁺ is better than the supported ZnCl₂ catalyst (Table 2, entry 9).¹²³ It is proposed that the C₃N₄ nanosphere inside the mesopore

channel of silica supplies the activated CO₂ to the epoxide through a transfer mechanism and facilitates cyclic carbonate synthesis *via* Zn²⁺ activated epoxide species. Porous and amino rich g-C₃N₄ is prepared without using any hard template using urea as a precursor to form defective and edge enriched C₃N₄. The urea derived C₃N₄ produces a wide variety of cyclic carbonates in the absence of any co-catalyst under solvent-free conditions (Table 2, entries 10–13).¹²⁴ It is suggested that the edge defects contain both primary amines (-NH₂) and secondary amine groups (-C-NH-C) and therefore they are able to activate CO₂. The epoxide is activated by the defective C₃N₄ edge containing -OH groups. Further, it has been revealed that urea derived C₃N₄ exhibits relatively higher surface area (41 m² g⁻¹) than dicyandiamide derived C₃N₄ and a porous nature, and the existence of macropores facilitates mass transfer and enhances the catalytic activity. *n*-Bromobutane grafted mesoporous g-C₃N₄ exhibits better catalytic activity for solvent-free propylene carbonate synthesis with 88% conversion and 98% selectivity (Table 2, entry 14).¹²⁵ In this process, the *in situ* depleted Br⁻ acts as the electrophile which activates the epoxide ring, while the defect rich edge positioned -NH₂ polarizes the CO₂ molecule leading to the bi-functional nature. Butane in conjugation with halides have been evaluated and it has been found that bromide exhibits the best activity because of its better leaving group ability. The better catalytic activity is attributed to the mesoporous nature (15 nm), high surface area (241 m² g⁻¹), and coexistence of terminal -NH₂ groups in g-C₃N₄ and X⁻ groups, which is even far better than the

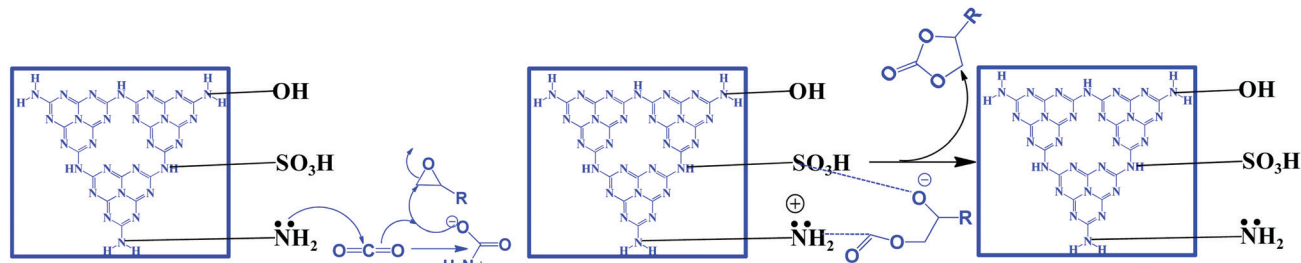


Table 2 Comparative catalytic activity of various g-C₃N₄ based catalysts in the synthesis of cyclic carbonates

E. no.	Catalyst	S_{BET} (m ² g ⁻¹)	Co-catalyst	Reaction conditions	Conv. (%)	Select. (%)	TOF (h ⁻¹)	Ref.
1.	g-C ₃ N ₄ (prepared with melamine)	64	—	ECH (5 mL), catalyst (50 mg), temp. (150 °C), press. (3.5 MPa), time (2 h)	5.6	96.7	3.3	120
2.	Mesoporous-C ₃ N ₄ (prepared with melamine-2D mesoporous silica)	—	—	PO (1.5 mL), catalyst (20 mg), DMF (10), temp. (100 °C), press. (0.55 MPa), time (10 h)	34.0	90	—	121
3.	Mesoporous-C ₃ N ₄ (prepared with urea-formaldehyde-2D mesoporous silica)	—	—	PO (1.5 mL), catalyst (20 mg), DMF (10), temp. (100 °C), press. (0.55 MPa), time (10 h)	28.0	92	—	121
4.	MS-C ₃ N ₄ (prepared with melamine-glyoxal-2D mesoporous silica)	—	—	PO (1.5 mL), catalyst (20 mg), DMF (10), temp. (100 °C), press. (0.55 MPa), time (10 h)	25.0	98	—	121
5.	Mesoporous-C ₃ N ₄ (prepared with dicyandiamide-SBA-15)	586	—	SO (3 mL), catalyst (100 mg), temp. (150 °C), press. (3.5 MPa), time (1.5 h)	28.8	99	4.8	122
6.	Mesoporous-C ₃ N ₄ (prepared with dicyandiamide-SBA-15)	585	Zn ²⁺ (0.8 wt%)	SO (3 mL), catalyst (100 mg), temp. (150 °C), press. (3.5 MPa), time (1.5 h)	94.5	99	15.8	122
7.	Mesoporous-C ₃ N ₄ (prepared with dicyandiamide-SBA-15)	585	Zn ²⁺ (0.8 wt%)	PO (3 mL), catalyst (100 mg), temp. (150 °C), press. (3.5 MPa), time (1.5 h)	97.1	99	16.2	122
8.	Mesoporous-C ₃ N ₄ (prepared with dicyandiamide-SBA-15)	585	Zn ²⁺ (0.8 wt%)	EO (3 mL), catalyst (100 mg), temp. (150 °C), press. (3.5 MPa), time (1.5 h)	98.3	99	16.4	122
9.	10%ZnCl ₂ /mesoporous C ₃ N ₄	206	Zn ²⁺	EO (7 mL), DMF (3 mL), catalyst (200 mg), temp. (140 °C), press. (2.5 MPa), time (6 h)	73.0	99.4	5.6	123
10.	g-C ₃ N ₄ (prepared with urea and heated at 480 °C)	40.8	—	ECH (21.5 mmol), catalyst (100 mg), temp. (130 °C), press. (3.5 MPa), time (4 h)	99.6	96.4	—	124
11.	g-C ₃ N ₄ (prepared with urea and heated at 480 °C)	40.8	—	EO (21.5 mmol), catalyst (100 mg), temp. (130 °C), press. (3.5 MPa), time (4 h)	91.7	99.3	—	124
12.	g-C ₃ N ₄ (prepared with urea and heated at 480 °C)	40.8	—	SO (21.5 mmol), catalyst (100 mg), temp. (130 °C), press. (3.5 MPa), time (4 h)	98.0	99.8	—	124
13.	g-C ₃ N ₄ (prepared with urea and heated at 480 °C)	40.8	—	PO (21.5 mmol), catalyst (100 mg), temp. (130 °C), press. (3.5 MPa), time (24 h)	99.3	99.6	—	124
14.	<i>n</i> -ButBr doped mesoporous C ₃ N ₄ (prepared with cyanamide and 12 nm silica spheres)	248	Br ⁻	PO (10 mL), catalyst (200 mg), temp. (140 °C), press. (2.5 MPa), time (6 h)	88.0	99.7	9.6	125
15.	H ₂ SO ₄ treated g-C ₃ N ₄ (prepared with melamine)	32	—	ECH (5 mL), catalyst (50 mg), temp. (130 °C), press. (3.5 MPa), time (2 h)	99.1	99.5	58.1	120
16.	H ₂ SO ₄ treated g-C ₃ N ₄ (prepared with urea-thiourea)	10	—	ECH (63 mmol), catalyst (50 mg), Temp. (100 °C), press. (1.0 MPa), time (4 h)	93.5	99	—	107
17.	P-Doped g-C ₃ N ₄ (prepared with melamine-hexachloro-triposphazene)	—	Bu ₄ NBr	PO (28.6 mmol), catalyst (150 mg), Bu ₄ NBr (2.4 mol%), temp. (100 °C), press. (2.0 MPa), time (4 h)	99.8	99.9	—	126
18.	B-Doped g-C ₃ N ₄ (prepared with melamine-BmimBF ₄)	11.1	—	ECH (14.3 mmol), catalyst (50 mg), temp. (130 °C), press. (2.8 MPa), time (6 h)	89.0	98.0	5.8	127
19.	B-Doped g-C ₃ N ₄ (prepared with melamine-BmimBF ₄)	11.1	—	PO (14.3 mmol), catalyst (50 mg), temp. (130 °C), press. (2.8 MPa), time (6 h)	31.0	99.9	1.5	127
20.	B-Doped mesoporous g-C ₃ N ₄ (prepared with dicyandiamide-B(OH) ₃ -SBA-15)	123	—	SO (1 mL), catalyst (30 mg), temp. (130 °C), press. (3.0 MPa), time (24 h)	97.8	96.8	—	129
21.	g-C ₃ N ₄ (prepared with melamine)	—	Bu ₄ NBr	Light assisted method, ECH/SO (13.7 mmol), catalyst (50 mg), Bu ₄ NBr (1.8 mol%) temp. (105 °C), press. (1 atm, balloon), time (20 h)	100	100	—	130

ECH = epichlorohydrin, PO = propylene oxide, SO = styrene oxide, TOF = turnover frequency, conv. = epoxide conversion, selec. = cyclic carbonate selectivity, S_{BET} = surface area.





Scheme 11 Synthesis of cyclic carbonates using bi-functional g-C₃N₄, reproduced with permission, Copyright Royal Society of Chemistry, ref. 107.

externally induced *n*-bromobutane to carbon nitride during the course of the reaction (Table 1, entry 14).¹²⁵ Huang *et al.* have reported H₂SO₄ treated, protonated acidic functionality containing carbon nitride, which has been investigated for the solvent-free cycloaddition of CO₂ with epichlorohydrin for the synthesis of the corresponding carbonate (Table 2, entry 15).¹²⁶ This protonation process has altered the electronic and textural properties and surface chemistry, which results in the incorporation of hydroxyl groups and amine groups into the bulk urea derived carbon nitride, which provides 17 fold higher catalytic activity. Surface hydroxyl groups (–OH) and amine groups (–NH₂) are responsible for this improved reactivity. Inspired by this work, Samanta *et al.* have synthesized urea and thiourea derived carbon nitride CN-(UTU), which exhibits moderate catalytic activity better than the counterparts urea/thiourea under solvent-free cyclic carbonate synthesis from epichlorohydrin without any co-catalyst (Table 2, entry 16) (Scheme 11).¹⁰⁷ Further, to improve the catalytic activity, the resultant materials have been chemically exfoliated with H₂SO₄, which results in the simultaneous incorporation of –SO₃H and –NH₂ groups into the melem framework (Scheme 11).

The bi-functional catalyst (which is ideal for the CO₂ activation reaction) has been investigated in the CO₂ insertion reaction by varying the epoxide under very mild conditions (100 °C and 1 MPa). Excellent conversion and selectivity are achieved over this bi-functional CN-(UTU) catalyst. The simultaneous introduction of –NH₂ groups (that act as basic sites for activating CO₂) and –SO₃H groups (that polarize the epoxide ring) has been confirmed from CO₂/NH₃-TPD. The synergistic participation of –NH₂ and –SO₃H groups during the reaction is the main reason for obtaining the excellent product yield. Moreover, doping with non-metals (such as P and B) over g-C₃N₄ is also reported for the synthesis of cyclic carbonates, which is found to be very effective for this reaction.^{126–129} The –B(OH) and –P(OH) groups are found to be responsible for the catalytic activity enhancement (Table 2, entries 19–20). All the reactions discussed above require CO₂ pressure higher than one atmosphere. Only one report is available in which a cyclic carbonate is synthesized at 1 atm pressure under solvent-free conditions but in the presence of external co-catalyst (1.8%) TBAB (Table 2, entry 22).¹³⁰ Therefore, more work should be carried out to synthesize efficient catalysts that can catalyze this reaction under solvent-free conditions at atmospheric pressure.

5. Photocatalytic CO₂ reduction reaction (CO₂ photoreduction)

Photocatalytic CO₂ reduction is a surface catalytic reaction which employs light-induced holes and electrons generated over the surface of the catalyst and protons from the reaction medium. In ideal conditions, CO₂ reduction follows some fundamental steps, like other light assisted reactions such as water splitting, N₂ reduction, and organic transformations.^{131–140} The basic operating steps involved in the photocatalytic CO₂ reduction reaction are summarized in two categories, namely optoelectronic and physicochemical steps, that are complementary to each other:

(A) Optoelectronic steps (Scheme 12A):

- (1) Creation of charge carriers (e[–]–h⁺) on the semiconductor surface by illumination with light having energy greater than the bandgap: $E_{hv} \geq E_g$.
- (2) Light-induced charge carrier dissociation and migration on the catalytic surface.
- (3) Charge-carrier recombination followed by the dissipation of energy in the form of heat.
- (4) The transported electrons participate in CO₂ reduction whereas holes participate in the oxidation of H₂O to O₂, and H⁺ or any other reducing agents to their corresponding oxidized products.

(B) Physicochemical steps (Scheme 12B):

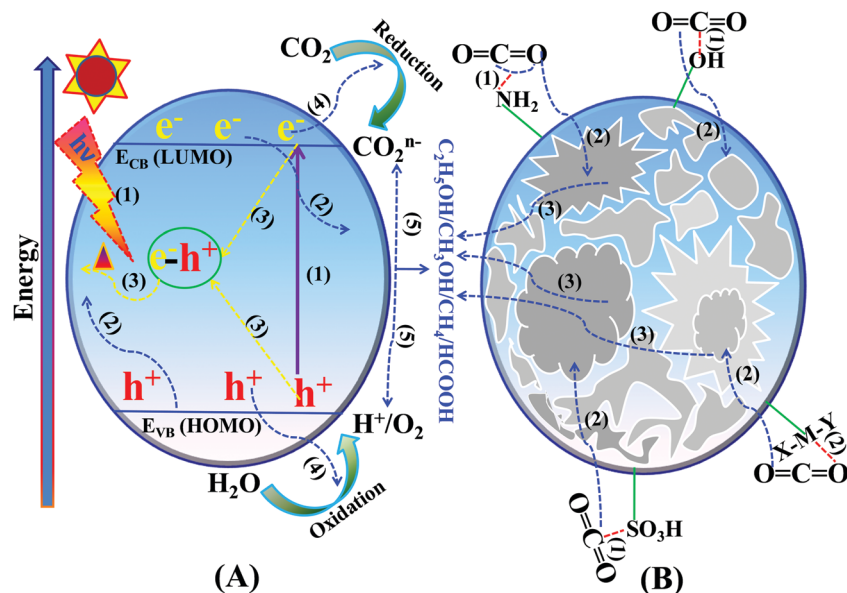
- (1) Adsorption of CO₂ on the catalyst surface.
- (2) CO₂ activation by the inherent functional groups of the catalyst.
- (3) Intermediate species adsorption and desorption of the products from the catalytically active sites during the reduction reaction.

5.1 Factors and parameters governing the mechanism of CO₂ photoreduction

Carbon dioxide is the most stable and inert oxidized product, while methane is a completely reduced form of carbon (Scheme 13a). The light-induced conversion of CO₂ to hydrocarbons and oxygenated hydrocarbons depends on various factors and parameters. These factors determine the fate of the reaction as well as the CO₂ conversion and product distribution. Various factors influencing CO₂ reduction, especially with graphitic carbon nitride as a photocatalyst, are discussed in this section.

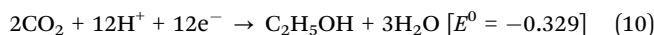
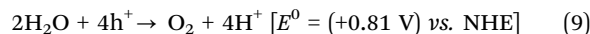
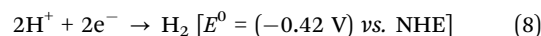
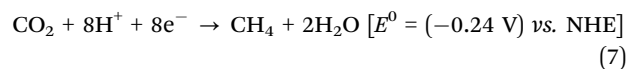
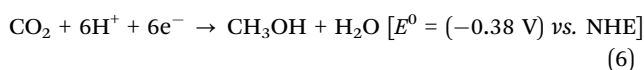
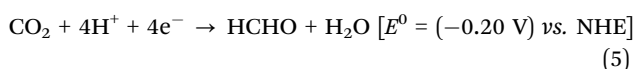
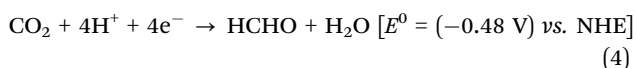
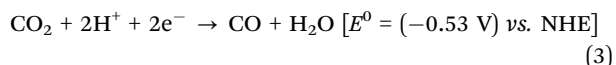
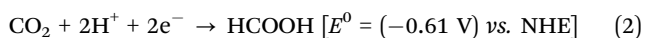
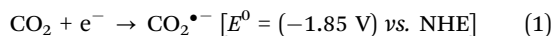
5.1.1 Thermodynamic factors. CO₂ conversion is a thermodynamically uphill energy process that requires a tremendous





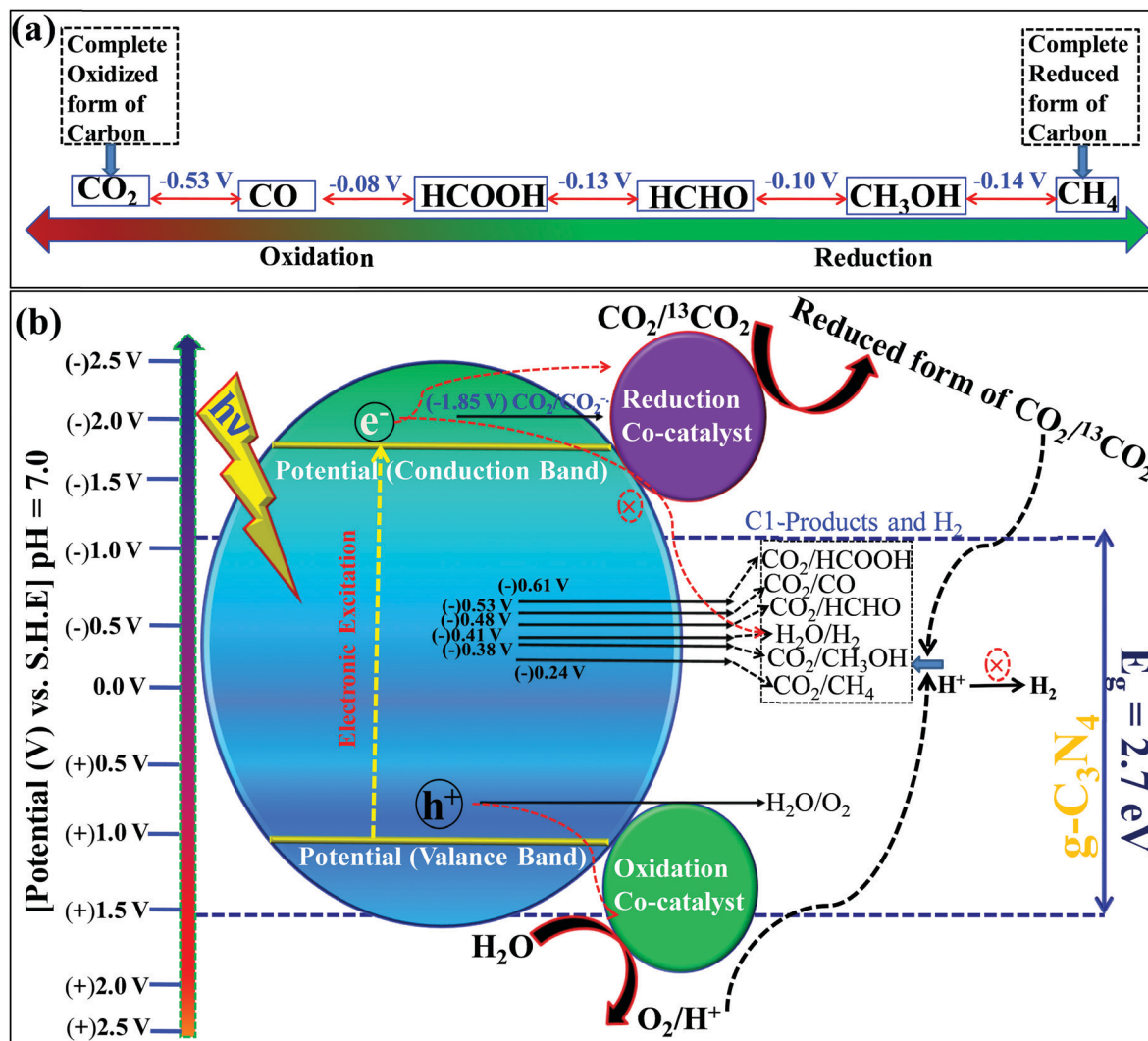
Scheme 12 Basic mechanism of the photocatalytic process: (A) optoelectronic steps and (B) physicochemical steps involved in the CO₂ reduction reaction.

energy input because of its stable and inert nature. An energy of 750 kJ mol⁻¹ is required for the splitting of one 'C=O' bond in the CO₂ molecule. CO₂ has a low electron affinity and a high energy gap of 13.7 eV between its lowest unoccupied molecular orbital (LUMO) and highest occupied molecular orbital (HOMO).¹³⁷ CO₂ is a linear molecule and electronic accumulation in the empty LUMO (antibonding Π^* orbital) facilitates the transformation of a linear to a bent geometry over the catalyst surface, which in turn expedites the kinetic barrier and enables its smooth conversion to appropriate products. The band edge position of any photocatalyst decides this electron accumulation and, accordingly, the product distributions occur. Particularly, the valence band edge must be positioned at a more negative electrode potential than the standard reduction potential of CO₂ to any other products otherwise the process is not thermodynamically feasible (Scheme 13b). Based on the standard reduction potential,¹³⁸ the reduced products are given below, which must be considered to analyze the reaction products after the reaction to establish the plausible mechanism of the reaction (Scheme 13b).



Among these reactions, eqn (1) is the most unfavorable one and, thus, the proton-coupled electron transfer process always occurs on the catalyst surface with the production of different products.

5.1.2 Reaction mechanism and selectivity control. CO₂ reduction occurs sequentially involving multiple electrons and protons. Also, it requires the splitting of highly stable 'C=O' bonds and the creation of C-H bonds. The complete reduction occurs *via* the formation of several radical intermediates, which also tend to recombine at different stages during the course of a reaction.¹³⁹ The product distribution depends upon the specific set of reaction conditions. The simultaneous and competitive photo-oxidation and reduction reactions bring complexity to CO₂ photoreduction. The most important parameters influencing these reactions include the type of photocatalyst, band edge potentials and bandgap, reaction conditions and medium, co-catalyst, *etc.*, which are briefly described here. The first study reported for CO₂ photoreduction involves TiO₂ powder under photo-electrochemical conditions.¹⁴⁰ Based on the mechanistic investigation reported in the literature, three possible pathways have been proposed, (I) the formaldehyde pathway forming CO₂ → CH₄ (fast hydrogenation pathway), (II) the carbene pathway forming CO₂ → CH₄ (fast deoxygenation pathway), and (III) the glyoxal pathway (Scheme 14I–III).^{131,141} It may be noted that at some stage of the reaction, all the suggested



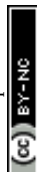
Scheme 13 (a) The different states of carbon with the potential difference, and (b) photocatalytic CO_2 reduction with respect to the standard redox potential of different products and band straddling.

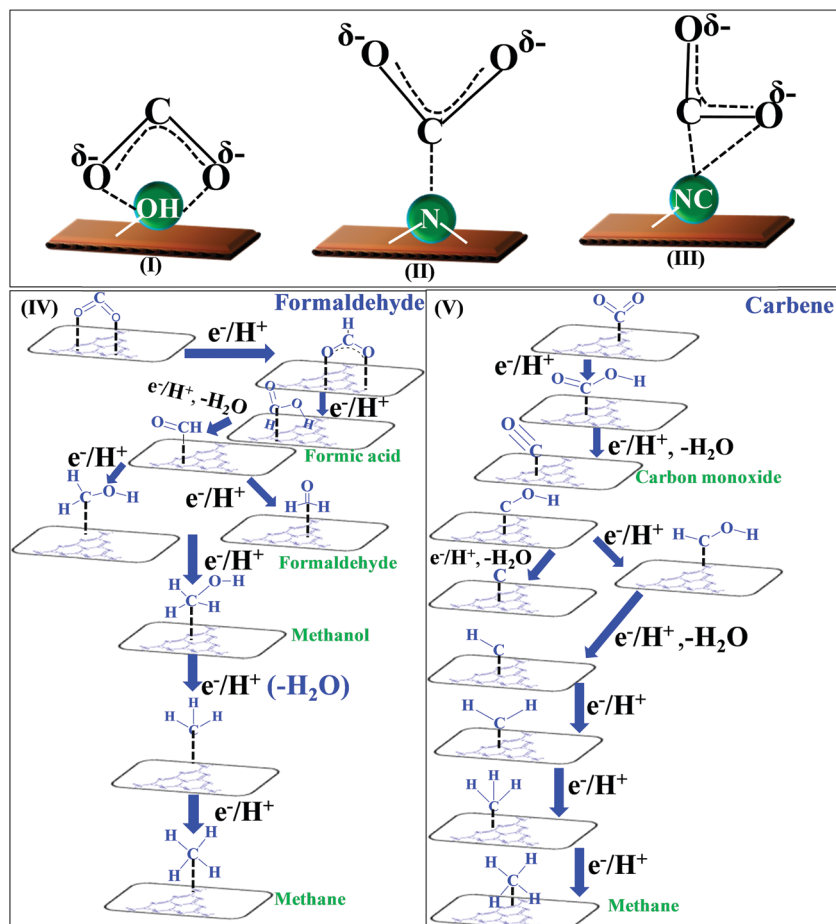
pathways can equally dominate. The elementary steps based on the specific reaction conditions need more work to establish the possible involvement of several radical species. The above-mentioned pathways are specifically discussed here.

The conversion of CO_2 through the formaldehyde pathway involves multiple electrons and protons, which leads to the formation of several products such as HCHO , HCOOH and CH_3OH , and finally the deoxygenated product CH_4 . Starting from CO_2 involving $2e^-/2\text{H}^+$, it first produces HCOOH (oxyhydrogenation), followed by involving $2e^-/2\text{H}^+$ again in the next step, which produces HCHO (reductive dehydrogenation).¹⁴² These two species formed during the reaction are intermediates and not side products. They can proceed to form unstable and reactive intermediates like $(^*\text{CHO})/(^*\text{COOH})$, which in the next step takes up $2e^-/2\text{H}^+$ to produce CH_3OH . CH_3OH can split to form $(^*\text{CH}_3)$ and $(^*\text{OH})$ radicals. $(^*\text{CH}_3)$ can take one $(^*\text{H})$ produced from the cleavage of HCHO to form CH_4 at the end. The formation of $\text{CH}_3\text{OH}/\text{HCHO}$ also depends on the adsorption and desorption energy over the catalyst surface. If the

coordination is strong enough and the desorption process is not facile, then $\text{CH}_3\text{OH}/\text{HCHO}$ will be the main product (Scheme 14(IV)). However, a weak binding energy allows this intermediate to produce the completely reduced CH_4 .¹⁴¹ Depending upon the intermediate binding energy, the yields and selectivity are regulated.

If the conversion process of $\text{CO}_2 \rightarrow \text{CH}_4/\text{CH}_3\text{OH}$ follows the carbene pathway, then several reactive intermediates can form *via* de-oxygenation followed by hydrogenation elementary steps. It can propagate like $\text{CO}_2 \rightarrow \text{CO} \rightarrow (^*\text{C}) \rightarrow (^*\text{CH}_3) \rightarrow \text{CH}_3\text{OH}/\text{CH}_4$. Thus this suggests the following: (1) CO formation and radical formation of $(^*\text{C})$ and $(^*\text{CH}_3)$. (2) In the second step, the competitive reduction tendency between $(^*\text{CH}_3/^*\text{C})$ and $(^*\text{OH}/^*\text{H})$ often determines the product selectivity. In the first step, CO_2 is adsorbed on the catalyst surface through carbon co-ordination by the $1e^-/1\text{H}^+$ attachment to form the carboxyl radical $(^*\text{COOH})$. After coupling with several e^-/H^+ , this can undergo decarboxylation to produce the formyl radical $(^*\text{CHO})$. In the next step, it can break into $(^*\text{C})$ and also can take three protons





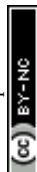
Scheme 14 Co-ordination geometry of CO₂ over the catalyst surface (I–III), and plausible reaction mechanism of CO₂ reduction: formaldehyde pathway (IV), carbene pathway (V).

to produce the ([•]CH₃) radical intermediate. In the final state, it couples with one H⁺ or ([•]OH) to form CH₃OH or CH₄ as the end product (Scheme 14(V)).¹⁴³ The adsorption strength of CO on the catalyst surface also influences the product selectivity. If the CO absorption is very strong then it could lead to the formation of several interim products and, consequently, desorption as different products. But if the absorption is weaker, then the easy desorption produces CO as an exclusive reduced product. In this process, the formation of radical species ([•]CH₃) and ([•]C) has been postulated and therefore electron paramagnetic resonance (EPR) measurements are very crucial to obtain a clear understanding of the reaction mechanism.

In the glyoxal mechanism, the first step is the formation of the one-electron reduction of (CO₂^{•-}), which takes 1e⁻/1H⁺ to form the formyl radical ([•]CHO). This further undergoes dimerization to form the glyoxal product. The complete sequence of the elementary steps involves oxidation and reduction reactions as follows: (CO₂ → CO₂^{•-}) → ([•]CHO) → CHO-CHO → CH₂OH-CHO → ([•]CH₂-CHO) → CHO-CH₃ → (CH₃OC[•]) → ([•]CH₃) → CH₄/CH₃OH. However, this process is less explored and not completely understood yet.¹⁴⁴ Various C₂ products such as C₂H₅OH or CH₃COOH *etc.* are believed to proceed through this pathway.

Based on the experimental observation and radical trapping/detection experiments, mechanistic routes are postulated, which requires further exploration. However, recent theoretical calculations suggest that defects and preferable coordination such as oxygen or carbon binding of the reactant, CO₂, over the catalyst frequently determine the selectivity of the obtained product. A defect-less catalyst surface produces CH₄ only, while oxygen defect containing g-C₃N₄ catalysts simultaneously form CH₃OH/CH₄.^{145,146} This is an interesting observation and more detailed work is required.

5.1.3 Light-harvesting capacity and band straddling. Apparently, 40% is visible radiation within the spectral range of 0.4 to 0.7 μm, 51% is infrared radiation in the spectral region of 0.7 to 4 μm and 4% is UV radiation of the solar radiation received on the Earth's surface on a sunny day.¹⁴⁷ The total radiation energy emitted by the Sun in unit time remains practically constant. A blue shift of the light-harvesting domain also changes the thermal energy associated with the phonons. However, in a lab-scale reaction system, the most widely used 1.5 AM G light source provides energy equivalent to the energy of 1 Sun, which is 100 mW cm⁻².¹⁴⁸ The focus should be on developing materials that absorb in a wide area of the light spectrum and have a bandgap of 1.23 eV or higher so that the kinetic



5.1.5 CO₂-Philicity. CO₂ adsorption on the photocatalyst surface is the very first and crucial step. Higher CO₂ philicity

5.1.6 Effect of the reaction medium. CO₂ photoreduction can be carried out in two different reaction conditions, liquid phase suspension and solid-gas interaction.¹⁵³ In the suspension medium, the photocatalyst is dispersed in water medium. In the second one the photocatalyst is immobilized on a solid substrate and then water vapor is introduced through the reactor. In the first case, sometimes a CO₂ miscibility agent like acetonitrile or DMF is used, which is not an ideal reaction condition. The catalyst at the periphery of the reactor would get less light illumination and thus uniform light absorption may not be achieved. Moreover, the symmetrical photocatalyst particle distribution also depends upon mechanical stirring and those particles in the close vicinity of water molecules would contribute more to the resultant catalytic activity. The mixing of acetonitrile or DMF into water raises a question about the actual source of carbon during the CO₂ photoreduction reaction. So in ideal reaction conditions, a solid photocatalyst dispersed in CO₂ gas purge-pure water must be considered when performing this reaction to avoid any unwanted products. Besides, in the gas-solid medium, the gaseous CO₂ is allowed to react with the immobilized solid catalyst and H₂O vapor, which itself is in the gaseous phase. Considering the two states of H₂O and its ease of oxidation either in the liquid state or in the vapor phase, the activity and selectivity are greatly affected. Moreover, in this case, uniform light illumination is reached over the photocatalyst surface. Therefore, the total photons available in the solid-gas interaction are always more than in the case of the liquid-suspension medium. Additionally, the vapor phase of

on the area of illumination and not on the amount of catalyst. Similarly, in the second case, the catalyst at the bottom will get less light exposure and so its activity will be different from the catalyst placed at the top of the reactor. It is not possible to exactly propose the selectivity of the CO₂ photo-reduction products exactly based on the applied reactor. For example, the pressure sustaining reactor allows CO to stay inside the reactor, which may further undergo hydrogenation, leading to the formation of multiple products. On the contrary, in the continuous flow process, lower numbers of reduced products are achieved as it allows the reactant to spend less time inside the reactor.

5.1.9 Effect of sacrificial agents. Ideal CO_2 photoreduction uses water as the medium, where it acts as a sacrificial hole scavenging agent. But this fact totally depends upon the valence band edge position of the catalyst. If the valence band edge potential is more positive than the standard $E^0(\text{H}_2\text{O}/\text{O}_2)$, then it can exhibit sacrificial hole scavenging behavior. For the oxidation of one $\text{H}_2\text{O} \rightarrow \text{O}_2$, four holes are required and the produced O_2 can act as an oxidizing agent, which has an adverse impact on the CO_2 reduction reaction.^{141,153} But in several cases, additional sacrificial electron donors like triethanolamine (TEOA), *etc.* are used to facilitate the hole scavenging process, which makes the electrons free to reduce the CO_2 molecule. The hole induced oxidation of TEOA can also produce CO_2 and thus creates a disturbance in the operating reaction conditions. Therefore, the actual source of carbon in the reduced products it inevitably in doubt. Thus, a $^{13}\text{CO}_2$ isotope tracing experiment is also important in those cases where TEOA is used as a sacrificial electron donor. In some cases, H_2 gas is used as proton and electron sources respectively. But it is imperative to state that a true CO_2 photoreduction reaction involves H_2O only as a sacrificial electron donor.

5.1.10 Effect of a co-catalyst. Noble metal-based co-catalysts such as Pt, Ag, and Au are widely used over a solid catalyst to add extra momentum to the overall thermodynamics of the CO₂ photoreduction reaction.^{157,158} This has a severe influence on both the performance and product selectivity of the CO₂ photoreduction process. It is well documented that when noble metals like Au, Pt, and Pd are decorated over a photocatalyst, a Schottky barrier is created at the junction. At this interface, the metal nanoparticles act as electron traps and prohibit the recombination of the photo-generated charge carriers. Additionally, plasmonic nanoparticles, specifically Au and Ag, facilitate photocatalysts to harness an extended range of visible light and enhance their photocatalytic performance. Also, the localized surface plasmon resonance induces the injection of hot electrons into the conduction band of the appointed photocatalyst and therefore electron accumulation enhances the CO₂ reduction tendency. These exciting features of noble metal co-catalysts are applicable to provide additional benefits in the CO₂ photocatalytic reaction. At the same time, they also enhance the competitive H₂ reduction tendency, which prohibits the CO₂ reduction reaction. But the overall bandgap, as well as the band edge positions, is altered, which provides opportunities to produce different CO₂ photo-reduction products

if it is the case of *ex situ* decoration of noble metals. Another distinctive point to be noted here is that the different affinity towards different interim species over different noble metal nanoparticles truly regulates the product distribution. Since noble metals are costly, their application as a co-catalyst is rather discouraging in ideal reaction conditions. But to obtain better activity and desired selectivity, one can employ such a co-catalyst.

5.1.11 Stoichiometric ratio of reaction consumed electrons and holes against the yield of the products. The stoichiometric involvement of electrons and holes in CO₂ reduction and H₂O oxidation is another important parameter because this will definitely influence the rate of formation of different products after the reaction. For example, the rate of total reactant conversion can be correlated with the rate of the different products formed and the numbers of electrons and holes consumed. For the reduction of 2 CO₂ molecules to produce 2CH₃OH molecules, 12 electrons are required and, at the same instance, 12 holes must be consumed by the water molecules to produce 6O₂ molecules. This is also a feasible thermodynamic concern in the CO₂ photo-reduction reaction, which can provide a meaningful idea about the photo-reduction and light-induced charge consumption during the reaction.

5.2 Graphitic carbon nitride as a CO₂ reduction photocatalyst

The basic phenomenon of CO₂ photo-reduction, especially with respect to heterogeneous catalysis, have already been addressed through several critical, tutorial, perspective, and edge articles by eminent researchers across the globe.^{159–165} Most importantly, CO₂ photoreduction over g-C₃N₄ has also been reviewed recently.^{153–165} Still, various aspects of this material and its further manipulation for CO₂ photoreduction catalytic efficiency improvement remain uncovered.

It is pertinent to mention that g-C₃N₄ has been continuously investigated in different photocatalytic applications since its application as a semiconductor HER photocatalyst by Wang *et al.* in 2009. However, among the seven different types of polymorphic phases (all are semiconductors), only the *g-h*-heptazine and *g-h*-triazine phases possess appropriate bandgaps and band straddling to catalyze various photocatalytic reactions. But, a close look at the valence band edge potential and theoretical calculations confirm that only *g-h*-heptazine fulfills the thermodynamic requirements for water oxidation.⁶² Notably, the *g-h*-heptazine based polymorphic g-C₃N₄ material has been most widely investigated as a photocatalyst with a bandgap of 2.7 eV where the conduction band is situated at (−1.2 V vs. NHE) and the valence band is positioned at (+1.5 V vs. NHE) at pH = 7. The CB and VB indicate that it is capable of reducing the CO₂ molecule and also can oxidize H₂O to produce O₂ and H⁺ required for the production of hydrocarbons/oxygenated hydrocarbons in CO₂ photoreduction. Thus various nanostructured carbon nitrides with diverse morphologies such as nanosheets, microspheres, nanotubes, *etc.* are proven to be efficient catalysts for CO₂ photoreduction. Thermodynamic constraints and optoelectronic limitations are the main bottlenecks of this catalyst for CO₂ photoreduction as simultaneous CO₂ and H₂ reduction tendencies are observed for this particular catalyst.

Also, the rapid charge recombination and low active surface area are other shortcomings that significantly hamper the efficiency of this catalyst. Strategic improvement of the physico-chemical and optoelectronic properties is a pragmatic approach to overcome the poor CO₂ conversion efficiency of pristine g-C₃N₄. In the forthcoming sections, a concise summary of the recent literature reports dealing with CO₂ photoreduction efficiency improvement is compiled to give a clear understanding to researchers actively working in this area.

Dong *et al.* demonstrated, for the first time, CO₂ photo-reduction involving porous carbon nitride (PCN) as a catalyst in 2012.¹⁶⁶ In this study, the authors propose that the porosity is introduced in bulk g-C₃N₄ by changing the precursors from melamine to melamine hydrochloride, which exhibits selective CO production of 4.5 mM in 11 h during CO₂ photoreduction. However, on the contrary, the activity of bulk g-C₃N₄ is shown to be better (20.6 mM in 11 h) than porous g-C₃N₄ and this is attributed to the presence of predominant inherent defect sites in PCN compared to bulk g-C₃N₄ that act as charge carrier recombination sites (Table 3, entry 1).¹⁶⁶ However, this adverse trend in the catalytic activity is unfortunately not fully understandable due to inadequate experimental evidence. Micro-structure dependent CO₂ reduction activity has been reported by Mao *et al.* The authors have observed that urea derived, mesoporous, flake-like g-C₃N₄ has produced a mixture of oxygenated hydrocarbons (C₂H₅OH and CH₃OH), while melamine derived, non-porous, flaky C₃N₄ has produced CO and CH₄ as products. The varied product selectivity is correlated to the reaction medium NaHCO₃ and CO₂ gas, where CO₂ is available in the activated form (HCO₃[−]), which is more accessible to the catalyst. In this process, O₂ is obtained as a side product and it is established that the holes and electrons are consumed in a close ratio of ~1 during the reaction with an apparent quantum efficiency (A.Q.E.) of 0.18% at 420 nm (Table 3, entry 2).¹⁶⁷ The fine-tuning of the product selectivity is also reported in different studies, in which g-C₃N₄ nanosheets produce CH₄ as a selective product, while the bulk g-C₃N₄ produces CH₃CHO. This change in the product selectivity is proposed due to the switching of band edge potentials and also due to the different bandgap values. g-C₃N₄ nanosheets exhibit bandgap enlargement by 0.2 eV, which leads to a more positive valence band edge by 80 meV and a negative shift of the conduction band potential by 120 meV, which are the key reasons behind the different activity and selectivity as compared to bulk g-C₃N₄ (Table 3, entry 3).¹⁶⁸ Thermal polymerization of pre-synthesized urea derived C₃N₄ and red phosphorous (P) has formed a heterojunction and, with the aid of Pt as a co-catalyst, the optimized catalyst (PCN-30) has converted CO₂ to CH₄ with a rate of 295 μmol h^{−1} g^{−1} in the suspension medium. The authors have proposed that the interfacial heterojunction has transferred the electrons from the high position g-C₃N₄ conduction band to a relatively lower position red P conduction band and the holes have been transferred in the reverse direction, which effectively reduces CO₂ to CH₄ and oxidizes OH to the (OH•) radical, respectively. However, the authors have not emphasized the exact role of Pt involved in the reaction as a co-catalyst





Table 3 Photocatalytic CO₂ reduction reaction over g-C₃N₄ based photocatalysts

E. Catalyst/ no. amount	S _{BET} (m ² g ⁻¹)/ precursors and process	Co-catalyst	Reaction conditions and (CO ₂ source)	Light source	Products/rate	Time (h)	¹³ C isotope CO ₂ tracing pressure	Q.E.	Bandgap and band straddling	CO ₂ adsorption	Ref.
1. g-C ₃ N ₄ (100 mg)	—	None	CO ₂ gas + H ₂ O	300 W Xe lamp	20.6 mM CO in 11 h	11	No	—	—	—	166
2. g-C ₃ N ₄ (200 mg)	39.5	—	Supercritical fluid grade-CO ₂ + NaOH solution	300 W Xe lamp	15.1 μmol CH ₃ OH + 10.8 μmol C ₂ H ₅ OH + 51.2 μmol O ₂	12	—	0.18% At 420 λ ≥ nm	2.78 eV (E _{cb} = -1.23 eV, E _{vb} not defined)	—	167
3. g-C ₃ N ₄ nano- sheet (100 mg)	(306) dicyandia- mide in thermal oxidation in air	—	CO ₂ + H ₂ O	300 W Xe lamp	~0.12 μmol CH ₄ and ~0.25 μmol CH ₃ CHO	5	No	0.06 MPa	E _g = 2.97 eV; E _{cb} = (+1.85 eV), E _{vb} not defined	—	168
4. Red P doped g-C ₃ N ₄ PCN-30 (20 mg)	(Not provided) urea derived C ₃ N ₄ combined pyrolysis of red P	0.5 wt% Pt	CO ₂ gas + H ₂ O	500 W Xe lamp	295 μmol h ⁻¹ g ⁻¹	—	No	—	Not mentioned	—	169
5. CN-12-1.5 (8 mg)	(240) (silica hard template/ cyanamide)	Ru co-catalyst (3.9 μmol g ⁻¹)	CO ₂ gas + (H ₂ O + TEOA) solution	400 W high- pressure Hg lamp	1854 nmol HCOOH	5	Yes	—	E _g and E _{vb} not mentioned; E _{cb} = (-1.29 V) vs. Ag/ AgCl at pH 6.6	—	170
6. g-C ₃ N ₄ nano- sheet CNU-BA _{0.03} (30 mg)	(54) thermal polymerization of (urea and barbituric acid)	(CoCl ₂ + 2,2'- bipyridine) as an electron donor	CO ₂ + H ₂ O + (TEOA as electron donor)	300 W Xe lamp	56.3 μmol CO	4	Yes	1 atm	No data available	Isotherm provided, binding energy did not mention	171
7. S-Doped g-C ₃ N ₄ (TCN) (100 mg)	(4,4) thermal poly- merization of thiourea at 520 °C in an ambient environment	1 wt% Pt	(120 mg NaHCO ₃ + 0.25 mL 4 M HCl) → (CO ₂ + H ₂ O) vapour	Simulated xenon lamp	Yield 1.12 CH ₃ OH μmole g ⁻¹	3	No	1 atm	E _g = 2.63 eV, no data available for band edge potentials	—	172
8. O-Doped g-C ₃ N ₄ tube (50 mg)	(36) melamine in two-step heating in air and N ₂	—	NaHCO ₃ + H ₂ SO ₄	Not mentioned (420 nm)	2.6 μmol CH ₃ OH	3	No	—	E _g = 2.97 eV; E _{vb} = not mentioned, E _{cb} = -0.87 eV vs. Ag/ AgCl at pH = 7	0.045 mmol g ⁻¹	173
9. P-Doped g-C ₃ N ₄ nanotube (50 mg)	(13.4) melamine and sodium hypo- phosphite mono- hydrate in 550 °C 4 h ⁻¹	—	NaHCO ₃ + H ₂ SO ₄	A high- pressure xenon lamp (300 W)	9.48 μmol CO and 7.24 μmol CH ₄	4	No	1 atm	(E _g = 2.97 eV, E _{cb} = -0.90 eV vs. E _{NHE} at pH = 7), E _{vb} = not mentioned,	0.39 mmol g ⁻¹	174
10. Phenyl grafted g-C ₃ N ₄ (100 mg)	(94.7) thermal polymerization of urea and phenyl urea at 550 °C for 2 h	—	DMF + TEOA + H ₂ O + CO ₂	No informa- tion available	0.907 μmol CH ₄ + 450 micromole CH ₃ OH + 5 μmol HCOOH	24	No	—	0.96% using 20 W LED bulb	—	175
11. C ₂ O co-doped g-C ₃ N ₄ (100 mg)	(50) thermal co- polymerization of (urea + thouria + 2-methyl imidazole)	—	(CO ₂ + H ₂ O) + (TEOA acts as a sacrificial electron donor)	Xenon lamp (300 W)	4.18 mmol g ⁻¹ CH ₃ OH	6	No	1 atm	E _g = 2.97 eV, E _{cb} = -1.01 eV, E _{vb} = +1.65 calculated from Kulbeka monk plot	0.69 mmol g ⁻¹	110

Table 3 (continued)

E. Catalyst/ no. amount	S_{BET} ($\text{m}^2 \text{g}^{-1}$)/ precursors and process	Co-catalyst	Reaction conditions and (CO ₂ source)	Light source	Products/rate	Time (h)	¹³ C isotope CO ₂ tracing pressure	Q.E.	Bandgap and band straddling	CO ₂ adsorption	Ref.
12. mp-g-CN _x (2 mg)	(104) cyandiamide and <i>in situ</i> synthesized cobalt phthalocyanine	CoPpC	CO ₂ -Saturated (4 : 1) MeCN/TEOA	Xenon lamp, 100 mW cm ⁻² , AM 1.5G, $\lambda > 400 \text{ nm}$	455 $\mu\text{mol g}^{-1} \text{CO}$	24	Yes	(EQE) for CO: 0.11% and 0.03% at $\lambda_{\text{ex}} = 360$ and 400 nm	$E_g = 2.82 \text{ eV}$, $E_{\text{cb}} = -1.10 \text{ eV}$ vs. E_{NHE}^0 , $E_{\text{vb}} =$ $+1.60 \text{ eV}$	—	176
13. DCN-0.05 (not mentioned)	(29.5) one step thermal polymerization of cyandiamide and tartaric acid	Bi-pyridine + CoCl ₂	CO ₂ gas saturated in 5 mL solution (4 mL lamp ACN + 1 mL of TEOA) containing aq. bi-pyridine (10 mmol L ⁻¹ + 25 mL of 20 mmol L ⁻¹ CoCl ₂)	300 W xenon lamp (420 nm cut off filter)	284.7 $\mu\text{mol g}^{-1} \text{CO}$ and 51.6 $\mu\text{mol g}^{-1} \text{H}_2$	15	No	—	$E_g = 2.49 \text{ eV}$, $E_{\text{cb}} = -0.83 \text{ eV}$ vs. E_{RHE}^0 , $E_{\text{vb}} =$ $+1.66 \text{ eV}$	—	177
14. BA20-CNS-PDA15 nanosphere (not mentioned)	(95) silica template (barbituric acid + polydopamine)	Co(bpy) ₃ ²⁺ (150 mg 2,2- bipyridine, +10 μmol CoCl ₂)	CO ₂ gas purged in 50 mL suspension (30 mL ACN + 10 mL TEOA + 10 mL H ₂ O)	300 W xenon lamp (420 nm cut off filter)	158 $\mu\text{mol CO} + 26$ $\mu\text{mol H}_2$ (86% selectivity)	4	No	—	$E_g = 2.63 \text{ eV}$	Isotherm provided, binding energy did not mention	178
15. CN-ATZ-NaK (50 mg)	(15) (5-amino- tetrazole in a or NaCl/KCl eutectic mixture)	—	(0.084 g NaHCO ₃) + 350 W Xe lamp (0.3 mL 2 M H ₂ SO ₄) with an AM1.5 filter	350 W Xe lamp with an AM1.5 filter	14 $\mu\text{mol g}^{-1} \text{h}^{-1} \text{CO}$ Not mentioned CH ₄ + <1 $\mu\text{mol g}^{-1}$ h ⁻¹ CH ₃ OH	12	No	—	$E_g = 2.53 \text{ eV}$, $E_{\text{cb}} = (+1.87 \text{ eV})$, $E_{\text{vb}} = (-0.66 \text{ eV})$	No data available	179
16. O,C co-doped C ₃ N ₄ (MG ₃) (30 mg)	(10.8) (melamine + glucose) water dispersion flowed by heating	—	CO ₂ gas purged in (ACN+ TEOA + H ₂ O)	300 W Xe lamp with a UV cut- off filter >420 nm	55.2 $\mu\text{mol CO g}^{-1}$	12	No	—	$E_g = 2.66 \text{ eV}$, $E_{\text{cb}} = (+1.38)$, $E_{\text{vb}} = (-1.28 \text{ eV})$	—	180
17. Nitrogen defect- modified g-C ₃ N ₄ and atomic layers: (CN ₅₅₀) (amount not mentioned)	(103.1) (melamine and NH ₄ Cl) heating at different temperature	—	Catalyst coated on a graphite rod + H ₂ O + arc lamp CO ₂ gas	500 W xenon assembled with a UV cut-off filter ($\lambda > 400 \text{ nm}$)	9.28 $\mu\text{mol g}^{-1} \text{CH}_4$	8	No	0.089%	$E_g = 2.72 \text{ eV}$, $E_{\text{cb}} = (+2.17)$, $E_{\text{vb}} = (-0.55 \text{ eV})$	—	181
18. 1%B/g-C ₃ N ₄ (amount not mentioned)	(62.5) one-step calcination boric acid + urea	—	CO ₂ and H ₂ O vapor = (H ₂ SO ₄ solution + NaHCO ₃ powder)	300 W Xe lamp with a UV/ visible cut-off filter ($\lambda > 400 \text{ nm}$)	0.32 $\mu\text{mol g}^{-1} \text{CH}_4$ + 3 0.45 $\mu\text{mol g}^{-1} \text{CO}$	3	Yes	—	Not provided	—	182
19. CNU-TM-13.0 (30 mg)	(109.1) (urea + trimesic acid)	Co(bpy) ₃ ²⁺ ; 1 μmol of cobalt chlor- ide (CoCl ₂) + (15 mg of 2,2- bipyridine)	CO ₂ gas purged in 5 mL solution (1 mL TEOA + H ₂ O)	Visible light ($\lambda > 420 \text{ nm}$) filter	70.63 $\mu\text{mol of CO}$ and 14.99 $\mu\text{mol of H}_2$	4	Yes	1 bar	Not provided	Isotherm provided, binding energy did not mention	183
20. B,K-Doped C ₃ N ₄ (100 mg)	5.3 (di-cyandia- mide + KBH ₄) in H ₂ thermal etching	—	H ₂ O + CO ₂ gas	300 W Xe lamp	5.93 $\mu\text{mol g}^{-1} \text{CH}_4$ + 5 3.16 $\mu\text{mol g}^{-1} \text{CO}$	5	No	2 bar	$E_g = 2.35 \text{ eV}$, $E_{\text{cb}} = (+1.45)$, $E_{\text{vb}} = (-0.90 \text{ eV})$	—	184
21. Tubular yolk- shell g-C ₃ N ₄ (100 mg)	(75) (urea + melamine + DI H ₂ O) hydrothermal treatment at 180 °C for 24 h	—	supercritical fluid- grade CO ₂ gas + H ₂ O	300 W Xe lamp	40.3 $\mu\text{mol g}^{-1} \text{CO}$	4	Yes	—	$E_g = 2.72 \text{ eV}$, edge potential not mentioned	Isotherm provided, binding energy did not mention	185





Table 3 (continued)

E. Catalyst/ no. amount	S_{BET} ($\text{m}^2 \text{g}^{-1}$)/ precursors and process	Co-catalyst	Reaction conditions and (CO_2 source)	Light source	Products/rate	Time (h)	^{13}C isotope CO_2 tracing pressure	Bandgap and band straddling CO_2 adsorption	Ref.
22. Nitrogen vacancy containing C_3N_4 (CN-550)	(89.5) thermal combustion of melamine in air followed by H_2 atmosphere	—	(High-purity CO_2 gas + H_2O)	300 W xenon lamp equipped with a 420 nm cut-off filter	6.21 $\mu\text{mol h}^{-1} \text{CO}$	Not mentioned	No	$E_g = 2.77 \text{ eV}$, $E_{\text{vb}} = (+1.67)$, $E_{\text{cb}} = (-1.07 \text{ eV})$ vs. NHE	146
23. Cyano and P-doped $\text{g-C}_3\text{N}_4$ ($\text{g-C}_3\text{N}_4$ -425) (100 mg)	(31.1) urea derived C_3N_4 mixed with Na_2HPO_4 followed by heat treatment	1 wt% Au	1 M 100 mL NaHCO_3 + CO_2 gas	300 W xenon lamp equipped with a ($\lambda = 420 \text{ nm}$) cut-off filter	1.135 $\mu\text{mol g}^{-1} \text{CO}$	3	Yes	$E_g = 2.77 \text{ eV}$, $E_{\text{vb}} = (+1.68)$, $E_{\text{cb}} = (-0.54 \text{ eV})$ vs. NHE	186
24. CNX_i (30 mg)	(29.4) (melamine + HX) (X = Cl, Br, I) hydrothermal followed by carbonization in N_2	—	CO_2 gas purged in (ACN + TEOA + H_2O)	300 W xenon lamp with a UV-cut filter ($\lambda = 420 \text{ nm}$)	34.14 $\text{CO } \mu\text{mol g}^{-1}$, 10.42 $\mu\text{mol g}^{-1} \text{H}_2$, 1.99 $\mu\text{mol g}^{-1} \text{CH}_4$	12	No	$E_g = 2.83 \text{ eV}$, $E_{\text{cb}} = (-1.13 \text{ eV})$ vs. NHE, E_{vb} not defined	187
25. Pyrene- functionalized polymeric carbon nitride (10% Py-PCN)10 mg	(2.11) cyanuric chloride (CC) + cyanamide (CA) + acetonitrile (ACN) hydrothermal treatment followed by rehydrothermal treatment with 1-(4,6-dichloro- 1,3,5-triazin-2- yl)pyrene (PyCC)	3 wt% Pt	Biphasic (1 mL 3 M aqueous solution of NaHCO_3) (3 M) and 9 mL cyclohexene (or 9 mL toluene containing 2 mmol of 2-methyl-2- butene)	300 W xenon lamp	$\sim 0.7 \mu\text{mol CO}$ (using NaHCO_3 + cyclohexane); ~ 0.15 $\mu\text{mol CO}$ and ~ 0.23 $\mu\text{mol CH}_4$ (using NaHCO_3 + 2-methyl- 2-butene in toluene)	4	No	$E_g = 2.31 \text{ eV}$; E_{vb} $= (+1.15)$, $E_{\text{cb}} =$ (-1.16 eV) vs. NHE	188
26. $\text{g-C}_3\text{N}_4$ (catalyst amount not mentioned)	(SA analysis not measured) thermal polymerization of melamine	—	H_2O vapour + CO_2 gas	100 W xenon lamp	$\sim 20 \text{ ppm CO}$	5	No	$E_g = 2.8 \text{ eV}$, band edge potential not mentioned	62
Metal modified/doped $\text{g-C}_3\text{N}_4$ for CO_2 reduction									
27. Se-Modified poly- meric carbon nitride nano- sheets (m-CNNSS 0.08) 50 mg	(133) urea derived CN mixed in an ethanolic solution of diphenyl diselenide (DDS) followed by calcination	(15 mg; 2,2- bipyridine, 1 $\mu\text{mol CoCl}_2$)	1 mL TEOA in 5 mL solvent (ACN: 3 mL; H_2O , 2 mL), 40 °C	300 W xenon lamp ($\lambda > 420 \text{ nm}$)	$\sim 10 \mu\text{mol CO}$, $\sim 1.42 \mu\text{mol H}_2$	1	No	No information available	189
28. Mg-Doped $\text{g-C}_3\text{N}_4$ Mg/ PCN-20% (50 mg)	(59.9) urea derived $\text{g-C}_3\text{N}_4$ mixed in an ethanolic solution of Mg (NO_3) $_2$ ·6 H_2O followed by hydro- thermal treatment	—	(100 mL H_2O + CO_2 gas)	300 W xenon lamp	CH_4 17.09 $\mu\text{mol g}^{-1}$, CO 4.13 $\mu\text{mol g}^{-1}$	6	No	$E_g = 2.54 \text{ eV}$, no information available about $\text{g-C}_3\text{N}_4$	No informa- tion available 190
29. CN1/Pd nano- tetrahedron (NT) (50 mg of the catalyst was suspended in 6 mL of DI water in a glass reactor)	Urea derived $\text{g-C}_3\text{N}_4$ followed by seed-mediated polyol-assisted reduction of Na_2PdCl_4	Pd	(CO_2 and H_2O vapor) 0.084 g of NaHCO_3 + 0.3 mL of 2 M H_2SO_4 solution	300 W Xe arc lamp	2.13 $\mu\text{mol h}^{-1} \text{g}^{-1}$ CH_4 -production rate of 0.58 $\mu\text{mol h}^{-1} \text{g}^{-1}$ available	No information	No	$E_g = 2.75 \text{ eV}$ Theoretical CO_2 adsorp- tion energy ($E_{\text{ads}} =$ -0.0083 eV) at the 100 surfaces of Pd NT	191

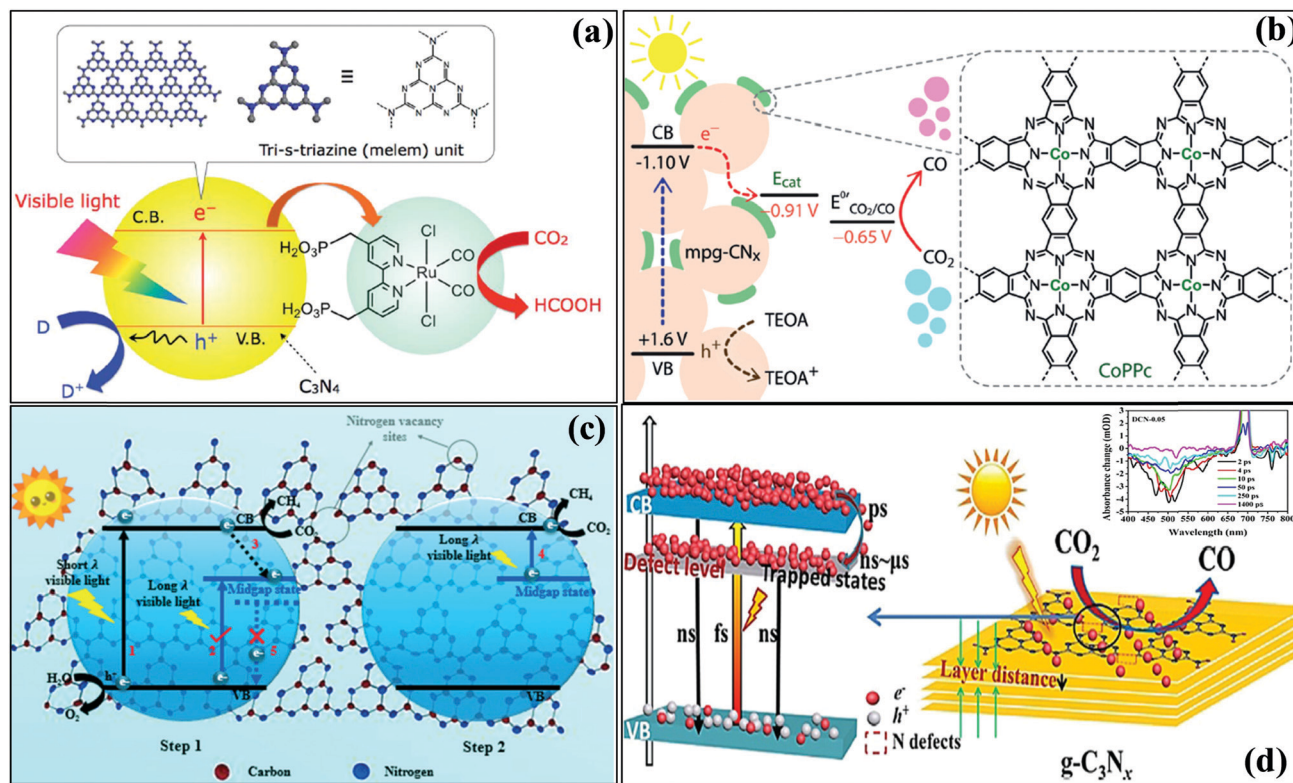
Table 3 (continued)

E. Catalyst/ no. amount	S_{BET} ($\text{m}^2 \text{g}^{-1}$)/ precursors and process	Co-catalyst	Reaction conditions and (CO_2 source)	Light source	Products/rate	Time (h)	^{13}C isotope CO_2 tracing pressure	Q.E.	Bandgap and band straddling	CO_2 adsorption	Ref.
30. Au/P-Doped $\text{g-C}_3\text{N}_4$ (200 mg of the sample was dispersed in 3 mL H_2O)	[Ionic liquid 1-butyl-3-methyl imidazoliumhexa- fluorophosphate (BmimPF ₆) + dicyandiamide (DCDA)] thermal annealing followed by <i>in situ</i> photo- reduction of HAuCl_4	Au	(H_2O + CO_2) gas	300 W xe-lamp	24 $\mu\text{mol CH}_4$	5	No	$\text{CH}_4 \sim$ 2.83%, respectively at $\lambda =$ 420 nm	$E_g = 2.38 \text{ eV}$, $E_{\text{vb}} = (+1.4 \text{ eV})$, respectively $E_{\text{cb}} = (-0.98 \text{ eV})$	—	192
31. Pt/ $\text{g-C}_3\text{N}_4$	(The surface area was not men- tioned) urea derived $\text{g-C}_3\text{N}_4$ followed by polyol- assisted reduction of H_2PtCl_6	2 wt% Pt	(H_2O + CO_2) gas	15 W bulb, the average intensity at the reactor 8.5 mW cm^{-2}	13.02 $\mu\text{mol g}^{-1}$	10	No	—	$E_g = 2.8 \text{ eV}$, No information available about E_{cb} and E_{bv}	—	193

(Table 3, entry 4).¹⁶⁹ K. Maeda *et al.* have synthesized high surface area mesoporous $\text{g-C}_3\text{N}_4$ using SiO_2 as a hard template and dicyanamide as a precursor by varying the silica/precursor ratio.¹⁷⁰ The dependency of the pore wall geometry on the CO_2 photoreduction activity has been uncovered in this study. Furthermore, the resulting mesoporous C_3N_4 has been grafted with a Ru complex *trans* (Cl)-[Ru{4,4'-($\text{CH}_2\text{PO}_3\text{H}_2$)₂-2,2'-bipyridine}(CO)₂Cl₂], where the electrons from the conduction band of $\text{g-C}_3\text{N}_4$ are transferred to the Ru and the bare holes in the valence band of $\text{g-C}_3\text{N}_4$ are engaged in the oxidation of water/triethanolamine, thus completing the total redox cycle (Scheme 15a).¹⁷⁰ The best catalyst of this study exhibits the selective formation of 1854 nmol HCOOH in 5 h by involving (H_2O + TEOA + CO_2) in the catalytic system under visible light illumination. The most fascinating outcome of this work is that high surface area is not always beneficial, rather the average surface area ($240 \text{ m}^2 \text{g}^{-1}$) with higher pore volume ($0.74 \text{ cm}^3 \text{g}^{-1}$) has minimized the charge carrier recombination and has shortened the electron-hole diffusion to the reactive sites (Table 3, entry 5).¹⁷⁰ J. Qin *et al.* have investigated the co-polymerization effect of monomer burbutyric acid with urea to synthesize $\text{g-C}_3\text{N}_4$, which eventually extends the pi-conjugated network, engineers the molecular hetero-interface and tailors the optical, surface area and nanostructural properties of $\text{g-C}_3\text{N}_4$ semiconductors for CO_2 reduction with the involvement of $\text{Co}(\text{bpy})_3^{2+}$ as a co-catalyst and acetonitrile containing triethanolamine solution as a sacrificial electron donor, and CO_2 gas.¹⁷¹ In this study, 56.3 μmol selective CO gas production is achieved in 4 h. ^{13}C isotope tracing measurements have confirmed that the CO_2 gas is the sole source of carbon, and, in fact, the control experiment has proved that all the components are essential for triggering CO_2 photoreduction (Table 3, entry 6).¹⁷¹ K. Wang *et al.* have reported S-doped $\text{g-C}_3\text{N}_4$ (TCN) which has been prepared *via* a simple heat combustion method and first-principles calculations suggest that some of the bi-dentate N atoms of the tris-triazine melem framework are replaced by sulfur during this process, having a narrow gap energy ($E_g = 2.63 \text{ eV}$) as compared to the melamine derived bulk $\text{g-C}_3\text{N}_4$ (2.7 eV). The CO_2 photoreduction result demonstrates the selective production of methanol with a yield of $1.25 \mu\text{mol g}^{-1}$ in 3 h from the (NaHCO_3 + HCl) induced (CO_2 + H_2O) vapor medium and Pt co-catalyst (Table 3, entry 7).¹⁷² J. Fu *et al.* have reported O-doped C_3N_4 nanotubes from controlled thermal oxidation etching which exhibit selective CH_3OH production with a yield of 2.6 μmol in 3 h from a (NaHCO_3 + H_2SO_4) mixture as CO_2 and proton sources, respectively. The oxygen doping causes a lowering of the conduction band by 0.16 eV by substituting the nitrogen atom of the melem unit, as evidenced by theoretical calculations, which is the prime reason for this selectivity control. Moreover, the higher CO_2 affinity and CO_2 uptake are also supported by CO_2 -TPD and CO_2 -adsorption analysis. The mechanism of methanol formation has also been confirmed by *in situ* FTIR and GC analysis (Table 3, entry 8).¹⁷³ B. Liu *et al.* have synthesized phosphorus-doped $\text{g-C}_3\text{N}_4$ nanotubes through a one-step thermal condensation between melamine and sodium hypophosphite monohydrate, which simultaneously dopes P and introduces surface amino groups. These modifications have led to higher



are demonstrated with transient absorption spectroscopy (Table 3, entry 13) (Scheme 15d).¹⁷⁹ M. Li *et al.* have synthesized polydopamine and barbituric acid co-modified carbon nitride nanospheres through thermal silica template-polymerization followed by a post-modification method, which has produced 158 $\mu\text{mol g}^{-1}$ CO and 28 $\mu\text{mol H}_2$ from CO_2 gas dissolved in aqueous (TEOA + ACN) solution and $\text{Co}(\text{bpy})_3^{2+}$ as a co-catalyst in 4 h using a 300 W xenon lamp (visible light). The co-modification tunes the band edge potentials and favors CO_2 -adsorption, which are the key factors for the activity improvement (Table 3, entry 14).¹⁸⁰ J. Zhang *et al.* have synthesized grain boundary controlled carbon nitride using 5-amino tetrazole as a high nitrogen-containing organic compound and NaCl/KCl. The synthesized catalyst (CN-ATZ-NaK) exhibits 14 $\mu\text{mol g}^{-1} \text{ h}^{-1}$ CO, 1.2 $\mu\text{mol g}^{-1} \text{ h}^{-1}$ CH_4 , and $<1 \mu\text{mol g}^{-1} \text{ h}^{-1}$ CH_3OH production rates from an activated CO_2 source (NaHCO_3) and H_2SO_4 as a proton donor. The grain boundary tailoring is the main reason for this impressive catalytic activity (Table 3, entry 15).¹⁸¹ Another carbon and oxygen co-doped g- C_3N_4 has been achieved by aqueous dispersion of glucose with melamine followed by thermal treatment. The resultant optimized material has produced 55.2 $\mu\text{mol CO g}^{-1}$ with nominal amounts of CH_4 and CH_3OH under visible light from CO_2 dissolved in a (TEOA + ACN + TEOA) reaction mixture in 12 h. Simultaneous co-doping has improved the visible light absorption and given fast electron extraction, which are responsible for this activity enhancement (Table 3, entry 16).¹⁸² Very recently J.-Y. Tiang *et al.* have synthesized nitrogen-vacancy enriched carbon nitride by two-step thermal copolymerization between NH_4Cl and melamine in a controlled environment, which induces mid-gap band state dangling between the conduction and valence band edge positions. The material has produced 9.28 $\mu\text{mol g}^{-1}$ CO in 8 h in the presence of a catalyst-coated graphite rod and ($\text{CO}_2 + \text{H}_2\text{O}$) vapors under visible light illumination. The main reasons underlying this enhanced CO_2 reduction activity are the introduction of dense nitrogen vacancies, extended light absorptivity of visible light leading to a wide range of light wavelength due to the strategic mid-gap arising, and prolonged lifetime of the charge carriers trapped inside the midgap. The obtained apparent quantum efficiency is calculated to be 0.089% (Table 3, entry 17) (Scheme 15c).¹⁸³ J. Fu *et al.* have reported boron as a dopant that induces charge localization inside the cavity of tris tri-azine by the interaction with the two co-ordinated $-(\text{N})_2$ at the interstitial position. This claim is also justified by DFT calculations. The resulting 1%B/ C_3N_4 has produced 0.32 $\mu\text{mol g}^{-1}$ $\text{CH}_4 + 0.45 \mu\text{mol g}^{-1}$ CO from ($\text{CO}_2 + \text{H}_2\text{O}$) vapor under visible light irradiation in 3 h. A ^{13}C isotope tracing experiment has supported the CO intermediate end product CH_4 formation (Table 3, entry 18) (J. Fu *et al.*, 2019).¹⁸⁴ Trimesic acid-modified g- C_3N_4 (CNU-TMU-13) has been synthesized *via* a thermal combustion method which produces 70.63 μmol of CO and 14.99 μmol of H_2 in 5 h from aqueous TEOA saturated with CO_2 gas and $\text{Co}(\text{bpy})_3^{2+}$ as a co-catalyst. The origin of the carbon in the produced carbon is analyzed by a ^{13}C isotope experiment and high CO_2 uptake is also in favor of the surface modification



Scheme 15 (a) CO₂ photoreduction over (a) Ru-complex grafted g-C₃N₄, reprinted with permission, Copyright Royal Society of Chemistry, ref. 172; (b) Co(bpy)₃²⁺/g-C₃N₄, reprinted with permission, Copyright John Wiley and Sons, ref. 178; (c) N-vacancy containing g-C₃N₄ with a midgap state, reprinted with permission, Copyright Royal Society of Chemistry, ref. 183; and (d) defect and trap state containing g-C₃N₄, reprinted with permission, Copyright John Wiley and Sons, ref. 179.

by trimesic acid, leading to high catalytic activity (Table 3, entry 19).¹⁸⁵ Simultaneous B, K co-doped g-C₃N₄ has been synthesized using dicyandiamide and KBH₄ under an H₂ thermal etching process, which has accelerated the CO₂ reduction activity with the formation of 5.93 μmol g⁻¹ CH₄ and 3.16 μmol g⁻¹ CO from CO₂ dissolved in H₂O in the absence of any co-catalyst, electron donor, or CO₂ miscibility agent like DMF or acetonitrile in 5 h under visible light. This is also ascribed to the creation of nitrogen-vacancies and the incorporation of B and C together according to the reported theoretical simulation (Table 3, entry 20).¹⁸⁶ The morphology also has a great impact on photocatalytic CO₂ reduction. Tubular yolk-shell g-C₃N₄ has been hydrothermally synthesized from melamine and urea at 200 °C. The material has produced 40.3 μmol g⁻¹ CO in 4 h from super-critical grade CO₂ and H₂O. The formation of CO is also analyzed by a ¹³C isotopic experiment. This catalytic improvement is correlated to the higher CO₂ uptake as evident by the CO₂-uptake profile and also due to the obtained tubular morphology (Table 3, entry 21).¹⁸⁷ Another study reports the synthesis of nitrogen-vacancy containing C₃N₄ through the controlled polymerization of melamine in different atmospheres, which selectively produces 6.21 μmol h⁻¹ CO from the catalyst suspension medium of CO₂ and H₂O under visible light illumination (Table 3, entry 22).¹⁴⁶ The replacement of nitrogen has profoundly controlled selective CO production, which is established *via* DFT calculations

(Table 3, entry 22).¹⁴⁶ In a very strategic approach, X. Liu *et al.* have synthesized cyano-groups and phosphorus-doped C₃N₄ by treating pre-synthesized carbon nitride with NaH₂PO₂ under an argon atmosphere at different temperatures. The authors have proposed and proved that the thermal decomposition of NaH₂PO₂ produced PH₃ gas, which itself was doped as phosphorus and was also accountable for the conversion of the terminal, uncondensed =C-NH₂ to -CN groups during the synthesis process. In fact, the attachment of -CN groups served as electron-withdrawing groups over the carbon nitride surface, which benefited CO₂ activation. The phosphorus doping has enlarged the light absorption and has inhibited photogenerated charge recombination. The active material (g-C₃N₄-425) has converted NaHCO₃ saturated CO₂ gas to CO with a yield of ~1.14 μmol g⁻¹ in 3 h using 1 wt% Au as a co-catalyst under a 300 W xenon lamp (Table 3, entry 23).¹⁸⁸ S. Wan *et al.* have prepared hexagonal tubular carbon nitride by the heat treatment of the supra-molecular organization of the *in situ* hydrogen-bonded melamine cyanuric acid assembly under hydrothermal conditions. Hydrogen fluoride is found to be the best suitable haloic acid (H-X; X = F, Cl, Br, I) that promotes the dissolution of melamine, which eventually facilitated the pi-pi stacking as evidenced by the intense EPR spectra. The light absorption has been blue-shifted and charge separation is maximized with HF. The best active catalyst has produced 34.14 CO μmol g⁻¹, 10.42 μmol g⁻¹ H₂, and 1.99 μmol g⁻¹ CH₄ in 12 h under



visible light from 0.8 bar CO₂ gas pressure dissolved in a mixture solution of (acetonitrile + TEOA + H₂) (Table 3, entry 24).¹⁸⁹ The authors have also calculated the average electron consumption rate (R_{electron}) during the CO₂ reduction reaction as equal to 8.96 mol g⁻¹ h⁻¹ on the basis of the equation $R_E = (2R_{\text{H}_2}) + (2R_{\text{CO}}) + (8R_{\text{CH}_4})$, where R is the rate, expressed in $\mu\text{mol g}^{-1} \text{h}^{-1}$ (Table 3, entry 24).¹⁸⁹ For the first time ever, the stability aspect of g-C₃N₄ in the CO₂ photoreduction reaction has been investigated in-depth by F. R. Poimilla *et al.*, in which the authors provide insights about the stability of the melem framework before and after catalytic activity evaluation (Table 3, entry 25).⁶² They have synthesized g-C₃N₄ by following a two-step thermal polymerization of melamine. For comparison purposes, they have also synthesized O-doped g-C₃N₄ by treating carbon nitride with H₂O₂. They observed a marginal difference in the catalytic activity after repetitive cycles. In gas phase CO₂ reduction, the catalyst exhibits 20 ppm selective CO in 5 h under 100 W xenon light (Table 3, entry 25).⁶² But, surprisingly, CO is obtained even in the absence of CO₂ gas under light illumination, which raised the question about the origin of carbon from the graphitic carbon nitride photocatalyst. In association with detailed optoelectronic and physicochemical measurements and also with controlled analysis, the authors concluded that the photo-corrosion rather than the thermal decomposition of melamine is responsible for this unexpected behavior of the catalyst under their experimental conditions. In another breakthrough, X. Gong *et al.* have synthesized pyrene functionalized graphitic carbon nitride, which endows biphasic CO₂ reduction combining CO₂ reduction by the electrons in the aqueous phase and hole generated (OH) radical-induced olefin oxidation in the organic phase. The process of accessibility of the organic olefin into the aqueous system is facilitated by the increased lipophilicity of the grafted pyrene-functionality over g-C₃N₄. The authors have achieved $\sim 0.7 \mu\text{mol CO}$ from (NaHCO₃ + cyclohexane) and ($\sim 0.15 \mu\text{mol CO} + \sim 0.23 \mu\text{mol CH}_4$) from (NaHCO₃ + 2-methyl-2-butene in toluene) under 300 W xenon light illumination in 4 h (Table 3, entry 26).¹⁹⁰

Various noble and non-noble metal modified carbon nitrides also exhibited profound CO₂ reduction catalytic activity. H. Ou *et al.* have prepared selenium modified thin g-C₃N₄ porous nanosheets (m-CNNS_s) using pre-synthesized g-C₃N₄ in an ethanolic solution of diphenyl diselenide (DDS) followed by thermal polymerization. The evolution of $\sim 10 \mu\text{mol CO}$ and $\sim 1.42 \mu\text{mol H}_2$ is obtained over this catalyst from a reaction mixture containing (TEOA + acetonitrile + H₂O) at 40 °C in 1 h using 420 nm light irradiation using Co(bpy)₃²⁺ as a co-catalyst (Table 3, entry 27).¹⁹¹ The role of selenium is investigated with density of state calculations, which evidences that selenium has narrowed the conduction band by creating an electronic distribution with the conduction band of CN. But it has not hampered the conduction and valence band composition as its Fermi level exists in the middle of the CB and VB level of g-C₃N₄. J. Tang *et al.* have synthesized Mg-doped g-C₃N₄ considering the high CO₂ philicity of MgO and the light-harnessing capacity of the Mg²⁺ ions in natural chlorophyll. The synthesized material has produced $17.09 \mu\text{mol g}^{-1} \text{CH}_4$ and $4.13 \mu\text{mol g}^{-1}$

CO from CO₂ gas saturated H₂O under a 300 W xenon lamp in 6 h (Table 3, entry 28).¹⁹² Though the light-harvesting capacity is enhanced, they did not emphasize the CO₂ uptake phenomenon with any experimental evidence. S. Cao *et al.* have prepared Pd nano-tetrahedron doped g-C₃N₄ from urea derived g-C₃N₄ followed by seed-mediated polyol-assisted reduction of Na₂PdCl₄. They focused on the facet dependent CO₂ reduction catalytic activity of Pd NT/g-C₃N₄, which exhibits a CH₃OH and CH₄ production rate of $2.13 \mu\text{mol h}^{-1} \text{g}^{-1}$ and $0.58 \mu\text{mol h}^{-1} \text{g}^{-1}$, respectively, from activated (CO₂ + H₂O) vapor under 300 W visible light illumination (Table 3, entry 29).¹⁹³ Furthermore, DFT calculations confirm that the Pd(100) facet over g-C₃N₄ exhibits high CO₂ uptake and high CO₂ binding energy and thus facilitates CH₃OH desorption. M. Humayun *et al.* have synthesized Au NP loaded P-doped g-C₃N₄ in ionic liquid followed by thermal annealing of a mixture of [1-butyl-3-methyl imidazoliumhexafluorophosphate (BmimPF₆) + dicyandiamide (DCDA)] and then finally the *in situ* photoreduction of HAuCl₄ for the decoration of Au NPs. The catalyst exhibits selective CH₄ evolution of $24 \mu\text{mol}$ in 5 h from CO₂ gas saturated H₂O under 300 W visible light (Table 3, entry 30).¹⁹⁴ The calculated quantum efficiency for CH₄ formation at 420 nm is $\sim 2.83\%$. The impressive catalytic activity is ascribed to the extended visible-light absorption along with the improved charge carrier separation *via* the phosphorus induced surface states and the Au nanoparticle decoration. The impact of Pt on the CO₂ reduction over g-C₃N₄ is revealed by W.-J. Ong *et al.*, using 2 wt% Pt loaded g-C₃N₄ nanocomposites. The catalyst exhibits the highest CH₄ yield of $13.02 \mu\text{mol g}^{-1} \text{catalyst}^{-1}$ after 10 h of light irradiation, which is 5.1-fold higher in comparison with pure g-C₃N₄ ($2.55 \mu\text{mol g}^{-1} \text{catalyst}^{-1}$), from CO₂ gas dissolved in H₂O under a 300 W xenon lamp (Table 3, entry 31).¹⁹⁵ The enhancement in the photocatalytic activity of the Pt/g-C₃N₄ nanocomposite for CO₂ photo-reduction CH₄ production can be attributed to the enhanced visible light absorption and smooth interfacial photogenerated electron transfer from g-C₃N₄ to Pt by lowering the Fermi level of Pt in the Pt/g-C₃N₄ hybrid as evidenced by the UV-vis and photoluminescence studies. The accumulated electron density on Pt facilitates the reduction of CO₂ to CH₄ *via* a multi-electron transfer process.

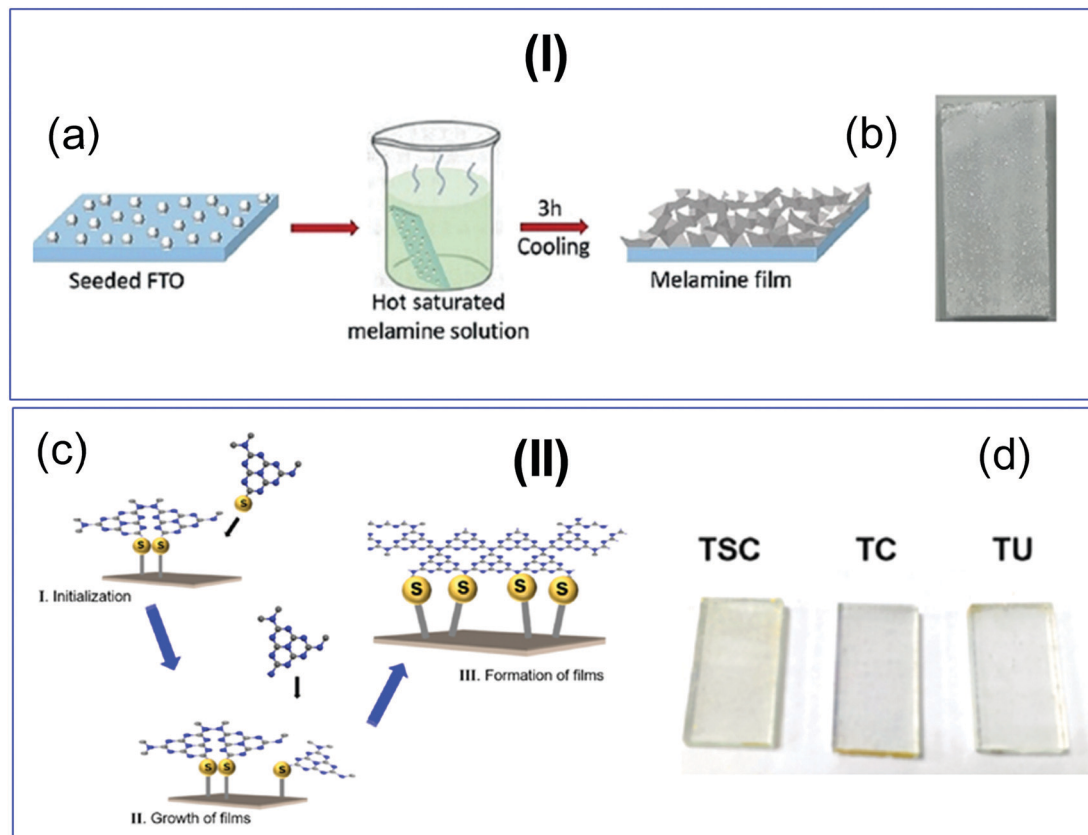
5.3 Critical factors regarding catalytic activity assessment and result presentation

Amidst the CO₂ photoreduction reports published in several journals, there is great concern regarding the precise catalytic activity evaluation, supportive characterization, and data presentation. Despite addressing this matter in several perspectives, edge articles, and editorials, this problem still persists.^{196–200} Although the intention is not to indicate or draw attention to any inappropriateness about the results reported on g-C₃N₄ for CO₂ photoreduction, the aim is to emphasize and regulate the standard requirements for a particular report that can be followed precisely by the readers. The following points may be considered during an experiment and result presentation. If g-C₃N₄ is the appointed photocatalyst, the abundance or source of carbon in the resultant product may be ensured with



6. Electrocatalytic CO₂ reduction reaction (e-CO₂RR)

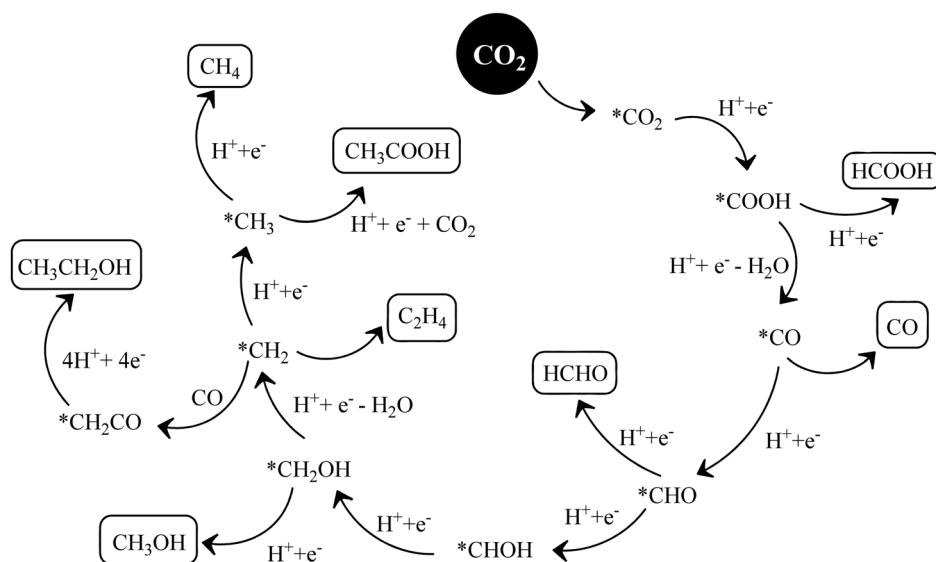
The electrocatalytic reduction of carbon dioxide into clean fuels is not fairly straightforward. In the last two decades, several research groups have studied purely metallic electrodes for this purpose and have segregated them based on the products that are obtained during the electrocatalytic CO₂ reduction reaction (e-CO₂RR) and the photoelectrocatalytic CO₂ reduction reaction (pe-CO₂RR). There are three major steps involved during the heterogeneous catalytic conversion of CO₂ on the electrode surface: (i) adsorption of the originally linear CO₂ molecule



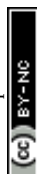
Scheme 16 (I) (a) Fabrication of a crystalline carbon nitride based-PEC device, and (b) the resultant FTO based device, reprinted with permission, Copyright John Wiley and Sons, ref. 201; and (II) (c) a polymeric carbon nitride-based adhesive connected-PEC device, and (d) corresponding images of the FTO coated PEC devices synthesized from different precursors: TSC-thiosemicarbazide, TC-tri-thiocyanuric acid, TU-thiourea and urea, respectively, reprinted with permission, Copyright American Chemical Society, ref. 204.

on an electrode material with the loss of its absolute linearity; (ii) cleavage of the C–O bonds to form C–H bonds by electron transfer and/or proton migration processes; and (iii) desorption of the product preceded by configurational rearrangement and

followed by diffusion into the electrolyte.²⁰⁷ Further, it is found that both the e-CO₂RR and pe-CO₂RR involve multiple steps with overall two-, four-, six-, or eight-electron transfer processes (Scheme 17).²⁰⁸ Naturally, the range of products that form



Scheme 17 Various products formed due to multi-step processes during electrochemical CO₂ reduction.



chromatograms obtained from GC (gas chromatography) and/or HPLC (high-performance liquid chromatography) of the product mixtures. A bulk-electrolysis experiment should be carried out for about an hour to obtain products that are enough for further analysis.²¹² It is wise to carry out experiments under potentiostatic conditions to avoid deviations from the product selectivity. Galvanostatic experiments are likely to generate potentials that are not suitable for the e-CO₂RR, or can generate a variety of products. However, the latter may be preferred only under certain special conditions where the working electrode is studied well in advance and the applied current is precise for scaling up e-CO₂RR processes.²⁰⁹ The complexity of e-CO₂RR experiments, therefore, lies in the varied physical states of the products that are generated in the reaction medium. In the separate evaluation of the FE for various products, the faradaic selectivity or faradaic yield, defined as the fraction of the FE for a given product with respect to the total FE for all products, should also be calculated and reported. For the analysis of the H₂ gas which is invariably evolved during e-CO₂RR experiments due to very close potentials, the evolving gases should be directly delivered to the sampling loop of an online gas chromatograph equipped with a thermal conductivity detector (TCD) using argon as the inert carrier gas. Besides, a flame ionization detector (FID) should be used to analyze the possible carbon-containing gaseous products such as CO, CH₄, C₂H₄, and C₂H₆ as described in the mechanistic pathway (Scheme 17). On identification of the constituents present in the liquid (*e.g.*, HCOOH, CH₃OH, and C₂H₅OH) and gaseous mixtures, the selectivity of the product can be evaluated. Relevantly, nuclear magnetic resonance (NMR) spectroscopy and mass spectroscopy (MS) are often used to confirm the associated products. However, to minimize interfering proton signals arising from the aqueous electrolyte, a solvent-suppression method (suppresses the solvent peak, such as water) and deuterium locking (usually done to every NMR sample before acquisition of the spectra) should be necessarily adopted during NMR measurements.²⁰⁹ As the mechanistic pathway involved in the catalysis over a given heterogeneous surface may be completely changed with the change in the nanoarchitecture of various carbon-based electrodes, structural characterizations of the electrode materials are also important. These include Fourier transform-infrared (FT-IR) spectroscopy, Raman spectroscopy, X-ray diffraction measurements (XRD), X-ray photoelectron spectroscopy (XPS), X-ray absorption near-edge spectroscopy (XANES), X-ray absorption fine structure (XAFS), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and aberration-corrected-scanning transmission electron microscopy (AC-STEM). Even when coupled with active metallic catalyst nanoparticles, various carbon materials may often be seen generating very different products than what can be expected from the purely metallic catalysts. Hence, it is important to understand the structure–activity relationships of the active catalysts with the reactant and product molecules. For detailed analyses of these processes, *in situ* techniques are often used. To understand the source of CO₂ especially with carbon-based electrocatalysts or

Based on the mechanistic pathways of the abovementioned processes, electrocatalysts can be tailored for efficient performance and high selectivity. The performance of various electrocatalysts can be judged by electrochemical techniques such as linear sweep voltammetry (LSV), cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS). While the overpotentials can be calculated for different products at various current densities directly from the LSV and CV profiles, the kinetics can be understood using the Tafel slopes that can be derived from the relevant voltammograms and/or the impedance spectra. All experiments should be performed using a two-compartment H-shaped electrochemical cell separating the cathode and the anode. This separation can be achieved using a thin frit glass membrane or a semi-permeable conducting membrane such as that of Nafion. A detailed gas-leak-proof setup design has been proposed by Pander *et al.*²⁰⁹ Since e-CO₂RR involves the reduction of CO₂, the working electrode is always a cathode which is capable of reducing other gaseous contaminants such as O₂ and N₂. Therefore, the e-CO₂RR process should be preceded by the removal of air from the cathodic chamber. Subsequently, to accurately determine the products formed during the e-CO₂RR, it is inevitable to saturate the cathodic chamber with high purity CO₂. The electrolyte is generally KHCO₃ and the counter-electrode (anode in this case) is graphite or a carbon electrode. In several cases, researchers have demonstrated the e-CO₂RR in KOH medium in order to elevate the pH, and, thereby, suppress the reduction of protons/water (hydrogen evolution). However, saturation of the KOH electrolyte with CO₂ reduces its pH due to the spontaneous formation of K₂CO₃ and KHCO₃. Although the pH is maintained between 6.8 and 7.5 under normal conditions, the exact pH of the medium should be monitored to correctly convert the potential vs. reference electrode (commonly, a pre-calibrated Ag/AgCl or SCE) to the potential vs. reversible hydrogen electrode (RHE). The reference electrode is placed in the cathode chamber of the H-cell. The working electrode should be kept protected from metal impurities present in the electrolyte, such as that of Fe and Zn, in order to avoid poisoning and severe deterioration of the catalytic performance. For this, the aqueous electrolyte can be pre-electrolyzed so as to eradicate the contaminants by depositing them on a sacrificial cathode.²¹⁰ Chelex is another option to prevent metal ion deposition due to its chelating action. The current densities that are reported for electrochemical experiments such as CV, LSV *etc.* should be normalized with respect to the electrochemical surface area (ECSA), which can be calculated as per an earlier report.²¹¹ To evaluate the faradaic efficiencies (FE) of various electrocatalysts, the aforesaid electrochemical measurements are generally correlated with the

E. no.	Electrocatalyst	Electrolyte	Major product (F.E.%, optimal potential)	Onset potential	Ref.
1.	2D-pg-C ₃ N ₄	2 M NaHCO ₃	CO (~ 80%, -0.35 V vs. RHE)	-0.13 V (vs. RHE)	214
2.	Au-BCN _{3.0} (gold decorated boron-doped carbon nitride)	0.5 M NaHCO ₃	Ethanol (78%)	0.15 V (vs. Ag/AgCl)	215
3.	BCN _{3.0} (boron-doped carbon nitride)	0.5 M NaHCO ₃	Ethanol (47%)	0.15 V (vs. Ag/AgCl)	217
4.	g-C ₃ N ₄ /MWCNT	0.5 M NaHCO ₃	CO (~ 60%, -0.75 V vs. RHE)	—	217
5.	Cu-C ₃ N ₄	0.1 M KHCO ₃	—	—	219
6.	Au/C ₃ N ₄	0.5 M KHCO ₃	CO (90%, -0.45 V vs. RHE)		220
7.	Au-CDot-C ₃ N ₄	0.5 M KHCO ₃	CO (79.8%)	-0.3 V	221
8.	OA-PCN (hydroxyl and amino functionalized polymeric carbon nitride)	0.5 M NaHCO ₃	CO (40.1%)	-0.56 V	222

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(Table 4, entry 8).²²² From the perspective of consistency, reproducibility and ease of synthesis, C₃N₄-based materials should, therefore, be advocated as efficient potential electrocatalysts for CO₂ reduction.

In summary, this article covered three important CO₂ conversion processes, thermal CO₂ activation, photocatalytic CO₂ conversion, and electrochemical CO₂ reduction, focused on the rising star carbonaceous material ‘g-C₃N₄’. A summary indicating the general characteristics, advantages, and disadvantages of the thermocatalytic/photocatalytic/electrocatalytic CO₂ conversion process is provided in Table 5.

Some of the demerits of g-C₃N₄ are: (a) It is thermally stable, but it is prone to light-induced framework oxidation/decomposition. If CO₂ is a reactant, then it requires deep investigation because the framework oxidation/decomposition product and CO₂ derived product could give misleading information. Therefore, integrating g-C₃N₄ with another semiconductor is necessary to stop its framework degradation caused by light absorption. (b) It contains less oxygen in the form of hydroxyl groups, which is not enough to make it a steam reforming chemical looping catalyst. (c) It has low electrochemical conductivity and thus exhibits inferior activity for electrocatalytic CO₂ reduction. Moreover, in the absence of an

Table 5 Summary of the thermocatalytic/photocatalytic/electrocatalytic CO₂ conversion process

Process	General characteristics	Advantages	Disadvantages
Thermocatalytic	(1) Thermal energy is the driving force to disrupt the stable atomic and molecular bonds of CO₂ and other reactants over a bi-functional catalyst to produce various platform chemicals and fuels. (2) Industrially available high-pressure liquid phase and gas phase reactors can be employed to convert CO₂ to important feedstock chemicals and fuels under the influence of mild to high CO₂ pressure (1–500 bar or so). (3) Catalysts can be easily designed for the appointed applications.	(1) Easy to implement in large scale production. (2) A variety of chemicals and building blocks can be produced. (3) Catalyst recovery is easy. (4) More than 90% of CO₂ is converted <i>via</i> this process. (5) Can be applied in a broad range of pressure (1–500 bar or so). (6) Thermodynamic and kinetic parameters can be easily tuned.	(1) Not sustainable due to the involvement of a non-renewable energy source. (2) The trade-off between conversion and energy efficiency is very low. (3) The requirement of high pressure and temperature. (4) Pure CO₂ gas is required. (5) Atmospheric CO₂ gas cannot be converted.
Photocatalytic	(1) The driving force is light-energy under ambient conditions to bring down the thermodynamic constraint of stable CO₂ molecules over a semiconductor photocatalyst having efficient photon capturing ability. (2) It depends on the chemisorption magnitude of CO₂ at $[P/P_0 = 1]$. (3) The design of a photocatalyst is more-challenging than the thermocatalytic process.	(1) Light energy is available abundantly. (2) Eco-friendly and sustainable process. (3) A selective product can be achieved since one-pot CO₂ reduction and H₂O oxidation takes place. (4) The source of CO₂ can be varied and, accordingly, different products can be achieved. (5) Recyclability is high if a powder suspension system is employed.	(1) A custom-made catalytic reactor coupled with a suitable light source makes the process less user-friendly. (2) Low light-harnessing and quick charge carrier recombination of the photocatalyst are a major drawback. (3) Product isolation and separation are comparatively tough. (4) Mechanistic investigation is somewhat difficult. (5) The competitive reduction tendency between CO₂ and H⁺ by the light-induced electrons suppresses the overall activity. (6) Large-scale implementation and night time operation are not possible due to the absence of sunlight. (7) Only low CO₂ pressure can be employed (<10 bar). (8) Atmospheric CO₂ gas cannot be converted.
Electrocatalytic	(1) A suitable external potential is a driving force (under ambient conditions) to bring down the thermodynamic constraint of a stable CO₂ molecule over a highly electrochemically conductive electrocatalyst. (2) Mainly carried out under alkaline solution as a CO₂ source. (3) Electrolyte and potential bias both play a key role. (4) The design of an electrocatalyst is highly challenging.	(1) Easy to operate. (2) Eco-friendly and sustainable process. (3) Highly economic. (4) The trade-off between conversion and energy efficiency is very high. (5) Product selectivity can be finely tuned. (6) Less dependent on the CO₂ chemisorption process. (7) The liquid phase reaction medium is primarily followed. (8) High turnover number (TON) and turnover frequency (TOF).	(1) It is extremely difficult to design the electrocatalytic reactor. (2) An appropriate membrane is difficult to synthesize. (3) A redox-active metal is required owing to its inherent redox properties. (4) Catalyst recovery is very difficult if a thin-film is used. (5) Product quantification from a basic medium by GC, GC-MS, and HPLC leads to low yield. (6) Only low CO₂ pressure can be employed (<10 bar). (7) Atmospheric CO₂ gas cannot be converted. (8) Mechanistic investigation is difficult.



active metal, it exhibits limited redox activity in electrochemical CO₂ reduction. Other carbonaceous materials, primarily N-doped carbons, are more suitable for electrochemical CO₂ reduction owing to their superior electronic conductivity. (d) Porous carbon can be derived from any natural resources, but specific carbon and nitrogen-containing precursors are required for g-C₃N₄ synthesis. Moreover, it is a visible light active catalyst and cannot cover the UV and NIR regions of the solar spectrum, which is also a drawback for its limited photocatalytic CO₂ reduction activity.

The most crucial feature of g-C₃N₄ is its facile synthesis, which can be performed without any complex synthesis setup. But plenty of research is required to improve its catalytic CO₂ conversion efficiency. g-C₃N₄ exhibited activity in all these three processes but with limited efficiency. For example, thermal CO₂ activation needs high temperature and pressure, which is not sustainable. Moreover, the involvement of an added co-catalyst raises the question of its effectiveness. Integrating an alkali metal oxide with the g-C₃N₄ framework can enhance CO₂ adsorption and activation. Therefore, further improvement of g-C₃N₄ based catalysts is required for CO₂ ambient condition activation and utilization. Since g-C₃N₄ does not have enough oxygen content, integrating it with transition metal oxides like CeO₂ and MnO₂, or spinel based oxides like NiCo₂O₄ with high oxygen exchange capacity can make it an active catalyst for steam reforming of methane coupled with the CO₂ splitting reaction. In the case of photocatalytic CO₂ reduction, the target of mole scale product yield is not yet achieved. Moreover, selectivity control and inclusion of additional organic additives like acetonitrile and dimethylformamide, and sacrificial agents like triethanolamine along with a co-catalyst are the serious drawbacks of this photocatalytic process. It is noteworthy that an ideal CO₂ photoreduction system involves a light-harvesting material, CO₂ gas, and H₂O only. But very rarely has this target been served by this catalyst to date. Another controversial aspect is the source of carbon in the converted product during CO₂ photo-reduction, especially when the catalyst itself is a carbon-based material. Utilization of suitable precursors during thermal polymerization (or other synthesis strategies) can incorporate required C, N, O, or S functionalities that have the capability to alter its solar light harnessing capability and can improve the charge carrier separation suitable for high photocatalytic CO₂ reduction reaction activity. Another vital area is the configuration of thin-film based-device fabrication for practical CO₂ photoreduction. g-C₃N₄ has a triazine skeleton, and therefore single-metal-atoms can be entrapped in the framework *via* wet impregnation followed by thermal annealing in a reducing environment. It will minimize attrition and deactivation, which are advantages for catalyst long term stability. High overpotential, low current densities, and limited redox-tunability are the shortcomings in its electrochemical CO₂ reduction application. Therefore these concerns should be carefully considered for its further efficiency improvement. Carbon nitride-based single-atom-catalysts can be a viable solution to improve photocatalytic, electrocatalytic, or photoelectrocatalytic CO₂ reduction.

We have concisely covered almost all the parameters starting from the synthesis of materials to fundamentals of CO₂

activation, followed by critical operational parameters for collective 'thermo-photo-electro'-chemical CO₂ conversion focusing on the g-C₃N₄ catalyst. The conclusion section has provided the details of the merits and demerits of g-C₃N₄ along with a concise perspective on the application of carbon nitride for CO₂ conversion. We envisage that this review will be helpful for beginners in their early stage of research on heterogeneous CO₂ conversion reactions for further technological advancement in the 21st century.

Author contributions

The theme of the review article was proposed by SS and RS jointly. The manuscript was co-written by S. S. and R. S. The authors thank Mr Aniruddha Mukherjee for the preparation of some figures and helpful discussion and drafting the electrochemical section. All the authors proofread and approved the final version of the manuscript.

Conflicts of interest

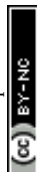
The authors state that no competitive and non-competitive conflicts of interest exist to declare. The authors also declare that some of the figures included in this manuscript have been prepared by themselves with the appropriate citations wherever it is applicable. Copyright permission has been obtained for the required figures of this manuscript.

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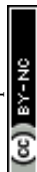
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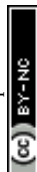
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