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Eco-friendly preparation of titanium dioxide/ carbon nitride nanocomposites for photoelectrocatalytic applications

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Titanium dioxide (TiO₂) and its heterostructures are among the most extensively studied materials for photo- and electrocatalytic applications. Optimizing their synthesis remains crucial for enhancing performance and reducing production costs. In this work, we report a simple, eco-friendly method for preparing TiO₂/graphitic carbon nitride (g-C₃N₄) nanocomposites in both powder and thin-film forms. The method takes advantage of the catalytic properties of TiO₂ to significantly lower the temperature required for the formation of g-C₃N₄ from urea, from 600 °C to 300 °C. Incorporating lyophilization prior to thermal treatment results in a ca. 60% increase in the specific surface area. The materials were evaluated for their photo- and electrocatalytic performance. Upon photoactivation at 385 nm, both TiO₂ and TiO₂/g-C₃N₄ powders generate the hydroxyl radical, with lyophilization enhancing radical production fivefold. The lyophilized TiO₂/g-C₃N₄ nanocomposite exhibits 14% higher photocatalytic activity than its TiO₂ counterpart. In electrocatalytic studies, TiO₂/g-C₃N₄ thin films demonstrate a 70 mV lower overpotential for oxygen reduction compared to TiO₂ films. These results highlight the potential of the synthesized nanocomposites for environmental remediation and in energy-related applications such as fuel cell electrodes.

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1 Introduction

Photocatalytic oxidation reactions that occur in semiconductor materials have attracted significant attention as an eco-friendly solution to environmental pollution.¹ The mechanism of photocatalytic oxidation typically involves the generation of reactive species, such as superoxide radical anion ([•]O₂⁻), hydrogen peroxide (H₂O₂), singlet oxygen (¹O₂), and hydroxyl radical ([•]OH), which can efficiently mineralize organic pollutants.²⁻⁴ Although numerous new photoactive materials have been reported, TiO₂ has been considered as one of the most popular photocatalysts due to its chemical inertness, strong oxidizing power, nontoxicity, and long-term stability against photocorrosion.⁵⁻¹⁰ Although the photocatalytic activity of TiO₂ depends on various structural and surface characteristics,

titania with a large surface area and a high degree of porosity is often required to achieve high efficiency in photocatalytic applications.^{11,12} Mesoporous TiO₂ powders and films exhibit a high surface area and a narrow pore size distribution while retaining a crystalline framework.^{6-9,11,13-16} Furthermore, the mesoporous structure enhances the diffusion of reactants and products while also improving the access to the reactive sites on the surface of a photocatalyst.^{17,18} Further research is still being conducted with the aim of identifying mesoporous catalytic materials with enhanced characteristics.

The activity of TiO₂ in photoreactions critically depends on the generation of the OH radical, one of the strongest oxidizing agents.¹⁹ In particular, the generation of the free OH radical ([•]OH_f) and its subsequent diffusion from the surface of the catalyst are essential in achieving the decomposition of non-adsorbing substrates by extending the reaction from the surface to the solution bulk. The photocatalytic generation of [•]OH_f by TiO₂ strongly depends on the kind of crystal polymorph. More specifically, anatase efficiently produces [•]OH_f, while OH radicals generated by rutile mostly remain adsorbed on its surface.^{20,21} The photocatalytic generation of [•]OH_f by anatase can proceed *via* the reductive 3e⁻ pathway (O₂ → [•]O₂⁻ → H₂O₂ → [•]OH_f) or the oxidative process (OH⁻ + h⁺ → [•]OH_f).²⁰ The

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reaction mechanism is still under debate and requires additional studies.²¹

To date, various strategies have been implemented to improve the performance of TiO₂ photocatalysts including doping with metal and non-metal elements, surface sensitization, the creation of semiconductor heterojunctions, *etc.*^{22,23} Among these methods, heterostructuring TiO₂ with other semiconductor materials is one of the most effective methods to inhibit the fast electron-hole recombination in pure TiO₂,²⁴ thus enhancing the photocatalytic performance. Ideally, heterostructures should be designed in such a way as to tailor the generation of reactive intermediates and free radicals to a particular application.

Carbon nitrides, in general, and graphitic carbon nitride (g-C₃N₄), in particular, are frequently selected as the preferred materials for heterostructuring TiO₂.^{25,26} g-C₃N₄ has been reported to be non-toxic, environmentally friendly, and stable.^{27,28} It has been used for a variety of photocatalytic applications, including water splitting,^{29,30} H₂ and O₂ evolution,^{31,32} CO₂ reduction,^{29,30} H₂O₂ production,^{33,34} pollutant degradation,^{30,31} and selective oxidation of organic compounds.³¹

TiO₂ and g-C₃N₄ are often chosen for the preparation of heterostructures, because the edges of both the valence and conduction bands of g-C₃N₄ have higher energy values with respect to TiO₂. Such an electronic structure of the resulting heterostructure is conducive of efficient charge separation, with the electrons preferably accumulating in the conduction band of TiO₂ and the holes favoring the valence band of g-C₃N₄. Indeed, in previous works, composites of carbon nitrides with TiO₂ were successfully applied as photocatalytic materials, *e.g.*, for CO₂ photoreduction,³⁵ photocatalytic decomposition of N₂O,³⁶ NH₃ production,³⁷ H₂ evolution,³⁸ photocatalytic degradation of organic dyes,³⁹ and photocurrent generation.⁴⁰ In ref. 41, carbon nitride-TiO₂ hybrid was shown to outperform its components in several photo- and photoelectrocatalytic reactions while exhibiting enhanced activity in the visible range.⁴¹ Enhanced generation of ·OH by carbon nitride-TiO₂ heterostructures can be expected as well.

A widely used approach to the synthesis of carbon nitride-TiO₂ hybrid materials is to prepare the two phases separately and then use them to create a composite.^{35,36,42-44}

In this work, we prepare TiO₂/g-C₃N₄ powders and thin films from TiO₂ sol using a different procedure. A precursor of g-C₃N₄ (urea or melamine) is added directly to TiO₂ sol prior to thermal treatment. The TiO₂ nanoparticles are shown to catalyze the polymerization of urea to g-C₃N₄ at a much lower temperature (300 °C *vs.* 600 °C for pure urea) resulting in a simple and eco-friendly synthesis. We demonstrate the effect of the g-C₃N₄ precursor (urea *vs.* melamine), lyophilization, and the annealing temperature on the properties of the resulting materials. The prepared samples are characterized using X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and diffuse reflectance spectroscopy (DRS). The specific surface area and porosity of the prepared materials are measured. Finally, the photocatalytic activity in ·OH

production and the electrocatalytic activity in the oxygen reduction reaction (ORR) are tested.

2 Experimental

2.1 Materials

TiCl₄ (99.9%), HCl (37%), HNO₃ (70%), ammonia solution (25%), urea (>99.5%), KOH (>90%), and terephthalic acid (>98%) were purchased from Merck. Melamine (>98.5%) was purchased from Thermo Scientific. All solutions were prepared in deionized (DI) water.

2.2 Synthesis of TiO₂/g-C₃N₄ nanocomposites

First, a concentrated TiO₂ sol was prepared using the sol-gel technique. The following operations (up to centrifugation) were performed in an ice bath, and the reagents were cooled to 0 °C before use. To prepare the sol, 15 mL of TiCl₄ was added dropwise to 53 mL of 0.65 M aqueous HCl under vigorous stirring. The resulting clear yellowish solution was diluted to 250 mL with DI water and titrated with a 12% aqueous ammonia solution with vigorous stirring. As the pH reached 4–5, the suspension became viscous and the titration and stirring were stopped. The suspension was then centrifuged at 5000 rpm for 5 min. The supernatant was discarded, 250 mL DI water was added, and the precipitate was resuspended. Centrifugation and washing with DI water was repeated 4 times. The supernatant was discarded, and 1.6 mL concentrated HNO₃ (65 wt%) was added to the washed precipitate to promote peptization. The resulting suspension was sonicated for 10 min with an ultrasonic horn (22 kHz). As the suspension was heated by sonication, it became a transparent thick gel. The gel was cooled until it became liquid again. The steps of sonication and cooling of the suspension were repeated three times. Finally, the sol was centrifuged at 5000 rpm for 15 min, and the sediment was discarded. The TiO₂ content in the sol was determined by weight analysis after drying 3 mL of the sol at 800 °C. The resulting transparent opalescent sol contained 12 wt% TiO₂ and remained stable for several months at room temperature. A similar synthetic procedure was previously reported in ref. 45. As evidenced by TEM, the sizes of the TiO₂ nanoparticles in the formed sol were 3.1 ± 0.3 nm (Fig. 1).

In ref. 46, the properties of g-C₃N₄ were shown to depend on the choice of precursor (urea *vs.* melamine). Here, we attempted to polymerize both urea and melamine in the presence of the prepared TiO₂ nanoparticles to obtain the g-C₃N₄ phase. 5 mL of the TiO₂ sol (corresponding to 0.6 g TiO₂) was mixed with 0.6 g of urea or melamine. Note that mixing of the sol with melamine resulted in coagulation, while this effect was not observed with urea. The resulting suspensions containing TiO₂ nanoparticles and urea/melamine were placed in a ceramic crucible with a cover and subjected to thermal treatment at 200, 300, 450, or 600 °C for 2 h. The heating rate was 2 °C min⁻¹. The neat TiO₂ sol was also subjected to similar thermal treatment. The resulting powders were thoroughly milled with agate mortar and pestle.



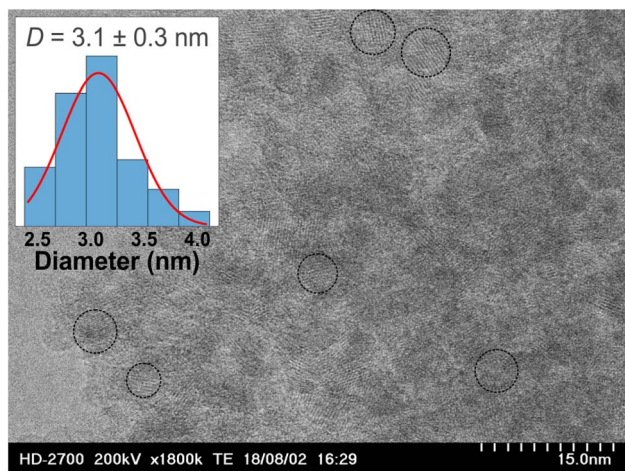


Fig. 1 TEM micrograph of TiO₂ nanoparticles drop-cast from the sol. Several typical particles are marked with dashed circles. The inset shows the corresponding size distribution (blue bars) and the fitting Gaussian function (red curve).

We also attempted to improve the synthetic procedure by including the lyophilization step. More precisely, 1.5 mL of the TiO₂ sol was mixed with 0.4 g urea, and the mixture was lyophilized. The resulting powder was then placed in a ceramic crucible with a cover and subjected to thermal treatment at 200 or 300 °C for 2 h. The heating rate was 2 °C min⁻¹. The neat TiO₂ sol was also subjected to similar processing. The resulting powders were thoroughly milled with agate mortar and pestle.

In the following, samples are denoted as (L)-TiO₂/(g-C₃N₄)-T, where “L” indicates that the sample was lyophilized prior to thermal treatment and T is the temperature of the synthesis. For instance, L-TiO₂/g-C₃N₄-300 refers to a TiO₂/g-C₃N₄ nanocomposite that was lyophilized and then subjected to thermal treatment at 300 °C.

A similar procedure was also implemented to prepare thin films of TiO₂ and TiO₂/g-C₃N₄. 5 mL TiO₂ sol was mixed with 0.6 g urea, and the resulting mixture (as well as the neat TiO₂ sol) was spin coated onto FTO-coated glass. The samples were then subjected to thermal treatment at 300 °C for 2 h. The heating rate was 2 °C min⁻¹.

The synthetic procedure described in this section is summarized in Fig. 2.

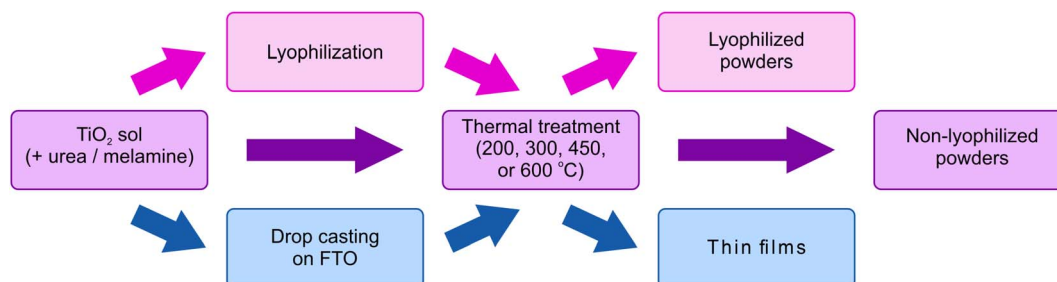


Fig. 2 The synthetic procedure for the preparation of TiO₂ and TiO₂/g-C₃N₄ in the form of non-lyophilized powders, lyophilized powders, and thin films.

Pure g-C₃N₄ was prepared by placing pure urea in a ceramic crucible with a cover and subjecting it to thermal treatment at 600 °C for 2 h. The heating rate was 2 °C min⁻¹.

2.3 Characterization techniques

2.3.1 X-ray diffraction. XRD patterns were measured with a PANalytical Empyrean diffractometer using CuK α -radiation. The recording speed was 0.4° min⁻¹. The interplanar distance d was calculated from the XRD peak positions using Bragg's law (eqn (1)):

$$2d \sin \theta = n\lambda, \quad (1)$$

where θ is the glancing angle, n is the diffraction order, and $\lambda = 1.54$ Å is the wavelength of CuK α -radiation. The mean crystallite size τ was estimated using Debye-Scherrer equation (eqn (2)):

$$\tau = \frac{k\lambda}{\beta \cos \theta}, \quad (2)$$

where $k = 0.9$ is the shape factor for spheroid particles and β is the full width at half maximum of the XRD peak used for the calculations.

2.3.2 X-ray photoelectron spectroscopy. The powdered samples were measured in a Cu powder holder using a Nexsa G2 spectrometer (ThermoFisher Scientific Inc.). The measurements were done with a 400 μ m X-ray spot size (Al K α -radiation) and concurrent use of an electron flood gun operating in charge compensation mode. The measurements were started with a 1-min delay to equilibrate possible transient effects. For all samples, low-resolution survey spectra were first collected (pass energy of 200 eV, step size of 1 eV, dwell time of 10 ms), followed by an automatic identification of the present elements. After that, the selected peaks were measured in high-resolution mode (pass energy of 50 eV, step size of 0.1 eV, dwell time of 50 ms). The high-resolution spectra were then used for elemental content analysis and peak fitting for chemical state analysis using Avantage v6.9 software (Thermo Fisher Scientific Inc.). For the analysis, the peaks were first aligned to Ti 2p_{3/2} of 458.8 eV since slight charging was observed despite the use of the flood gun. Peak fitting was performed using the smart background with varied peak components, each consisting of a Gaussian-Lorentzian product mixture (30% Lorentzian). Sensitivity factors accounting for variations in photoionization



cross-sections were automatically applied during elemental quantification, utilizing values retrieved from the Avantage software database.

2.3.3 Electron microscopy. The size of TiO₂ nanoparticles was determined using a Hitachi HD2700D transmission electron microscope. The morphology of the prepared samples was studied using a Zeiss LEO 1550 scanning electron microscope in the secondary electron detection mode. The accelerating voltage was 3 kV for the images acquired at a magnification of 50k \times and 10 kV for the high-resolution images acquired at a magnification of 500k \times .

2.3.4 Gas adsorption measurements. Specific surface area measurements were performed with a Microtrac Belsorp MAX X device. Before measurement, a sample was pretreated at 150 °C for 2 h. N₂ gas physical adsorption was carried out at the temperature of liquified nitrogen. After physical adsorption of N₂ gas, its desorption was recorded as well. Specific surface areas were obtained from the physical adsorption data by applying Brunauer–Emmett–Teller (BET) theory. To achieve average pore size distributions of the materials in the microporous range, the micropore analysis method (MP-method)^{47,48} was applied.

2.3.5 Diffuse reflectance spectroscopy. DRS spectra were measured using a PerkinElmer Lambda 1050 spectrophotometer equipped with a 150 mm InGaAs integrating sphere.

2.4 Photocatalytic activity

The photocatalytic activity of the prepared materials was studied using a light-emitting diode (LED) peaking at 385 nm with a bandwidth (FWHM) of 11 nm (CHROLIS, Thorlabs). The light was coupled into a 3 mm liquid light guide and passed through a collimating adapter (SLSLLG3, Thorlabs) to achieve a collimated light beam. The middle part of the light beam (1 \times 1 cm²) illuminated samples inside a 1 cm quartz cuvette at normal incidence. The injection current of the LED was adjusted so that the irradiance at the front face of the cuvette was 60 mW cm⁻². Prior to irradiation, the samples were bubbled with O₂ gas for 10 min. During irradiation, O₂ bubbling was continued accompanied by agitation with a magnetic stirrer.

\cdot OH production was registered using terephthalic acid (TA) as a fluorogenic probe. The method was adopted from ref. 49 with modifications. TA exhibits no fluorescence under 310 nm excitation. After oxidation by \cdot OH, 2-hydroxyterephthalic acid (HTA) is produced (Fig. S1). Under 310 nm excitation, HTA emits fluorescence peaked at 425 nm. The emission intensity at 425 nm was regarded as the parameter reflecting \cdot OH production. TA was dissolved in 0.1 M KOH and then diluted 10-fold with DI water resulting in a solution containing 3 mM TA and 10 mM KOH. The prepared TiO₂/g-C₃N₄ and TiO₂ powders were dispersed in the TA solution with sonication (5 min) at a concentration of 1 mg mL⁻¹ and were then agitated with a magnetic stirrer for 15 min prior to the irradiation. After irradiation, the samples were centrifuged at 14 000 rpm (19 000g) for 15 min. Finally, the supernatants were collected, and their fluorescence spectra were registered under 310 nm

excitation using an Edinburgh FLS1000 spectrofluorimeter (2 \times 1.5 nm excitation and emission slits).

2.5 Electrocatalytic activity

Electrocatalytic activity with respect to the oxygen reduction reaction (ORR) was examined using cyclic voltammetry for TiO₂/g-C₃N₄ and TiO₂ thin films prepared on FTO-coated glass slides. Cyclic voltammograms were acquired using an Autolab PGSTAT 302N potentiostat/galvanostat at a potential scan rate of 10 mV s⁻¹. The measurements were conducted in a single-compartment glass cell equipped with three electrodes. The TiO₂/g-C₃N₄ or TiO₂ samples served as the working electrode. The area of the working electrode was 1 cm². The reference electrode was an Hg/HgO electrode filled with 1 M KOH, and the counter electrode was a Pt foil. The potential of the reference electrode was 115 mV vs. a saturated calomel electrode. The supporting electrolyte was 0.1 M aqueous KOH (pH 13) saturated with O₂ gas for 1 h prior to the measurements.

3 Results and discussion

3.1 Characterization of TiO₂/g-C₃N₄ nanocomposites

The thermal treatment temperatures for the studied materials were selected to fulfill two primary objectives. First, to ensure the formation of the anatase phase of TiO₂, which exhibits superior catalytic activity compared to the rutile phase, particularly in the generation of hydroxyl radicals (\cdot OH_f).^{20,21} Second, to facilitate the conversion of precursor materials (melamine or urea) to the target g-C₃N₄ phase.

The prepared materials were examined using XRD to establish the optimal parameters for synthesis. TiO₂ powder subjected to thermal treatment at 200 or 300 °C consisted of anatase (JCPDS no. 21-1272) with a small admixture of brookite (JCPDS no. 29-1360) (Fig. 3A and B). The mean size of anatase crystallites calculated from the half-width of the (101) diffraction peak (25.5° (ref. 50)) using the Debye–Scherrer equation was 7 nm for the samples annealed at 200 °C and rose to 9 nm after annealing at 300 °C. In the XRD pattern for TiO₂ annealed at 450 °C, the narrowing of the anatase reflexes and the appearance of rutile reflexes were evident (Fig. 3C). The XRD pattern for TiO₂ annealed at 600 °C was dominated by narrow peaks of rutile (for instance, the (110) peak at 27.3° (ref. 50)), [JCPDS no. 21-1276], but weak and narrow anatase peaks were still present (Fig. 3D). According to the XRD data, thermal treatment of TiO₂ at 450 or 600 °C resulted in an increase in the crystallinity and the transformation of anatase to rutile. These observations are in line with previously reported data indicating that the anatase-to-rutile transformation occurs in the 400–1200 °C temperature range.⁵⁰

The influence of the temperature and the choice of the g-C₃N₄ precursor (urea vs. melamine) was then studied for the samples that were not subjected to lyophilization prior to thermal treatment. The XRD pattern for the TiO₂ sol mixed with urea and annealed at 200 °C contained a broad weak peak at 27.4° in addition to the TiO₂ reflexes (Fig. 3A). For the TiO₂ sol mixed with urea and annealed at 300 °C, a pronounced peak at



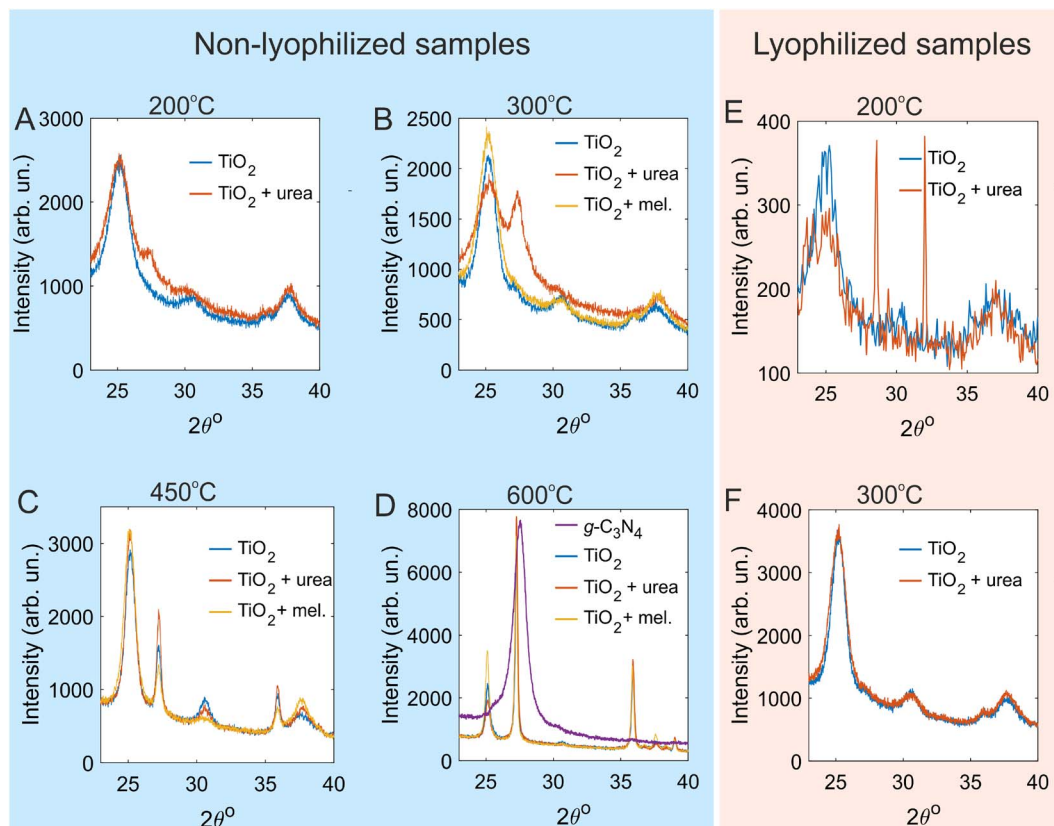


Fig. 3 XRD patterns for non-lyophilized (A)–(D) and lyophilized (E) and (F) samples of TiO_2 and $\text{TiO}_2/\text{g-C}_3\text{N}_4$. (A)–(D). The TiO_2 sol (blue curves), the TiO_2 sol mixed with urea (red curves), and the TiO_2 sol mixed with melamine (yellow curves) that were subjected to thermal treatment at 200 °C (A), 300 °C (B), 450 °C (C), and 600 °C (D). Panel D also shows the XRD pattern for pure urea polymerized at 600 °C to yield $\text{g-C}_3\text{N}_4$ (purple curve). (E) and (F). The TiO_2 sol (blue curves) and the TiO_2 sol mixed with urea (red curves) that were lyophilized and then subjected to thermal treatment at 200 °C (E) and 300 °C (F).

27.4° was observed (Fig. 3B). These peaks can be identified as the (002) reflex of $\text{g-C}_3\text{N}_4$.^{46,51} In contrast, when melamine was used instead of urea, no $\text{g-C}_3\text{N}_4$ phase was formed. This could be due to the coagulation of the TiO_2 sol after the introduction of melamine. The TiO_2 sol mixed with urea or melamine and heated to 450 °C exhibited XRD patterns almost identical to that of the pure TiO_2 sol subjected to the same treatment (Fig. 3C). This finding indicates that urea and melamine were completely decomposed, and $\text{g-C}_3\text{N}_4$ was not formed. Similarly, the $\text{g-C}_3\text{N}_4$ phase was not observed after annealing at 600 °C (Fig. 3D). For comparison, the polymerization of pure urea at 600 °C resulted in the formation of highly crystalline $\text{g-C}_3\text{N}_4$ (Fig. 3D). This is evidenced by the presence of a strong and narrow band peaked at 27.6° corresponding to the (002) reflex of tri-*s*-triazine based $\text{g-C}_3\text{N}_4$.^{46,51} The corresponding interplanar distance (calculated using Bragg's law) was found to be 0.33 nm, consistent with the interlayer spacing in tri-*s*-triazine based $\text{g-C}_3\text{N}_4$.^{46,51} Note that the (110) reflex of rutile and the (002) reflex of $\text{g-C}_3\text{N}_4$ have close peak positions (27.3° and 27.6°, respectively). They can still be distinguished as the (002) reflex of $\text{g-C}_3\text{N}_4$ is slightly shifted to larger 2θ values and is substantially wider (Fig. 3D).

As follows from the XRD analysis of the prepared materials, the samples prepared from the TiO_2 sol and urea at 200 °C and

300 °C had a two-phase composition of TiO_2 (anatase) and $\text{g-C}_3\text{N}_4$. For the sample prepared at 200 °C, the amount of the $\text{g-C}_3\text{N}_4$ phase was smaller and/or the $\text{g-C}_3\text{N}_4$ phase was poorly crystallized. Thermal treatment of urea in the presence of TiO_2 at 450 or 600 °C resulted in a complete decomposition of urea. The use of melamine did not allow for the formation of $\text{g-C}_3\text{N}_4$ at any temperature. The formation of $\text{g-C}_3\text{N}_4$ from pure urea was achieved only at 600 °C. These data seem to indicate that the TiO_2 nanoparticles efficiently catalyze the polymerization of urea and enable the synthesis of the $\text{g-C}_3\text{N}_4$ phase at substantially lower temperatures (200–300 °C). At higher temperatures, the presence of TiO_2 causes urea to decompose. Thus, further characterization is performed for samples $\text{TiO}_2/(\text{g-C}_3\text{N}_4)$ -200 and $\text{TiO}_2/(\text{g-C}_3\text{N}_4)$ -300 prepared from the TiO_2 sol and urea.

The influence of lyophilization on the crystallinity and the phase composition of the resulting materials was also studied. The XRD patterns for the lyophilized TiO_2 sol annealed at 200 or 300 °C (Fig. 3E and F) indicated that the samples consisted of anatase. For TiO_2 that was mixed with urea, lyophilized, and then annealed at 200 °C (sample L- $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -200), no reflexes of $\text{g-C}_3\text{N}_4$ were observed (Fig. 3E). Instead, narrow peaks at 16.8, 22.7, 28.6, 32.0, and 53.4° were present (see also Fig. S2). The peak at 22.7° can be identified as the most intense reflex of urea



(although slightly shifted, which could be due to low intensity and the influence of TiO_2). The rest of the peaks could be ascribed to the products of urea transformations. These data indicate that the thermal treatment of lyophilized powders at 200 °C was not sufficient to fully polymerize urea. After annealing at 300 °C (Fig. 3F), no residual XRD peaks of urea or intermediates were observed. Reflexes of $g\text{-C}_3\text{N}_4$ were not evident, too. The absence of reflexes of $g\text{-C}_3\text{N}_4$ in lyophilized samples might indicate that the crystallites were not sufficiently large to appear in XRD patterns or that the $g\text{-C}_3\text{N}_4$ phase formed was amorphous.⁴¹

Elemental composition of all samples was determined using XPS (Table S1). XPS characterization was performed for the non-lyophilized TiO_2 and $\text{TiO}_2/g\text{-C}_3\text{N}_4$ samples prepared at 200 and 300 °C to analyze their bonding configurations. As shown in Fig. S3, all samples showed the presence of carbon (C 1s), nitrogen (N 1s), titanium (Ti 2p) and oxygen (O 1s). The ratio of Ti and O abundances was very close to 1 : 2 for all samples, and the formation of composites did not seem to affect this ratio (Table S1). For sample $\text{TiO}_2/g\text{-C}_3\text{N}_4\text{-300}$, the ratio of C and N abundances was close to the expected stoichiometry of 3 : 4. The Ti 2p spectra of the $\text{TiO}_2/g\text{-C}_3\text{N}_4$ composites have two peaks at 458.8 and 464.5 eV, corresponding to Ti 2p_{3/2} and Ti 2p_{1/2}, respectively. These positions with the peak separation of 5.7 eV indicate octahedrally coordinated Ti^{4+} in TiO_2 .^{52–54} The O 1s peak located at 530.1 eV is assigned to lattice oxygen in TiO_2 .^{36,42} Samples $\text{TiO}_2/g\text{-C}_3\text{N}_4\text{-200}$ and $\text{TiO}_2/g\text{-C}_3\text{N}_4\text{-300}$ also exhibit a noticeable O 1s peak at 531–532 eV, which most likely belongs to the surface hydroxyl groups or organic C–O and C=O bonds formed during thermal polymerization of urea.⁵⁵

The C 1s spectrum for sample $\text{TiO}_2/g\text{-C}_3\text{N}_4\text{-300}$ was fitted with three peaks located at binding energies of 288.1, 285.5, and 289.4 eV, which correspond to sp^2 carbon, C–C/C=C, and COOH bands, respectively.^{36,56,57} In the N 1s region, the main components were observed at 398.8 and 399.7 eV, corresponding to the sp^2 -hybridized N atoms in the heptazine rings and tertiary N atoms bonded to carbon atoms in the form of $\text{N}(\text{C})_3$ or $\text{H-N}(\text{C})_2$, respectively.^{42,57,58} The N 1s peak at 398.2 eV is related to weak C–N or N–N bonds linked to sp^2 carbon.⁵⁹ The XPS data confirm the existence of graphite-like sp^2 bonded structure in graphitic carbon nitride. In addition to the three described N 1s peaks, the contribution at 406.4 eV can be assigned to the $-\text{NO}_2$ groups on the surface of TiO_2 (ref. 60) (which are present due to nitric acid in the TiO_2 sol).

The XPS spectra for sample $\text{TiO}_2/g\text{-C}_3\text{N}_4\text{-200}$ are presented in Fig. S3. The C 1s signal reveals three components, namely 285.9, 289.2, and 292.2 eV. The peak with the lowest binding energy is associated with C atoms with sp^3 diamond bonds and does not belong to pure $g\text{-C}_3\text{N}_4$. It may be assigned to terminal C– NH_x groups⁶¹ or C–C/C=C bonds.⁶² The C 1s signal at 289.2 eV can be attributed to the overlap of signals from sp^2 carbon, carboxylic groups, and sp^2 carbon in the aromatic ring attached to $-\text{NH}_2$ groups.^{63,64} In addition, a weak signal at 292.2 eV in the C 1s spectrum can be assigned to the π electron delocalization in $g\text{-C}_3\text{N}_4$ heterocycles, confirming graphitic stacking of triazine- or heptazine-based layers.⁶⁵ The lowest energy contribution of the N 1s spectrum, 399.2 eV, is attributed to nitrogen

bonded with two carbon atoms in a graphitic sp^2 network.⁶⁶ The peak at 400.4 eV corresponds to the overlap of signals from bridging nitrogen atoms, such as tertiary N ($\text{N}(\text{C})_3$), and amino groups ($-\text{NH}_x$), revealing the presence of tri-*s*-triazine rings.⁶³ The presence of $-\text{N}=\text{C}=\text{O}$ band was also identified in the N 1s spectrum (the peak at 401.5 eV).⁶⁷ The N 1s peak at 407.5 eV can be attributed to nitrate groups on the oxide surface.⁶⁸

XPS analysis was also performed for the lyophilized TiO_2 and $\text{TiO}_2/g\text{-C}_3\text{N}_4$ samples prepared at 200 and 300 °C (Fig. S4). All samples demonstrated Ti 2p and O 1s spectra similar to those of their non-lyophilized counterparts. The ratio of Ti and O abundances remained almost equal to 1 : 2 (Table S1). At the same time, the carbon content was similar for samples $\text{L-TiO}_2\text{-300}$ and $\text{L-TiO}_2/g\text{-C}_3\text{N}_4\text{-300}$ due to the presence of adventitious carbon. The C 1s spectra for all lyophilized samples demonstrated three bands peaking at 284.7, 286.5, and 289.2 eV, which were ascribed to C–C, C–N/C=C, and sp^2 -hybridized carbon in the triazine ring attached to NH_2 species ($\text{N}=\text{C}-\text{N}_2$), respectively.^{69–71} The spectrum for the sample prepared at 200 °C was dominated by the non-graphitic C–C bonds (284.7 eV), whereas, the contribution from sp^2 carbon (289.2 eV) was the most intense band in the spectrum for the sample prepared at 300 °C. Although pure TiO_2 and $\text{TiO}_2/g\text{-C}_3\text{N}_4$ composites demonstrated similar C 1s peaks, the contribution from sp^2 -hybridized carbon at 289.2 eV was higher for the composites (Fig. S4).

The N 1s spectrum for sample $\text{L-TiO}_2/g\text{-C}_3\text{N}_4\text{-300}$ revealed bands at 398.1 and 400.1 eV, which were assigned to sp^2 nitrogen and tertiary nitrogen ($\text{N}(\text{C})_3$), respectively. The N 1s spectrum for sample $\text{L-TiO}_2/g\text{-C}_3\text{N}_4\text{-200}$ was characterized by two components at 399.3 and 400.3 eV. The peak at 399.3 eV corresponded to the overlap of signals from sp^2 -hybridized imine groups (C–N=C) and surface functional amino groups ($-\text{NH}_x$).^{72,73} The highest energy contribution at 400.3 eV can be assigned to tertiary nitrogen groups ($\text{N}(\text{C})_3$). Abundance of N in the composites was substantially higher compared to pure TiO_2 (Table S1). Taken together, changes in the C 1s contributions and the increase in the abundance of N in the composites suggest that a small amount of the $g\text{-C}_3\text{N}_4$ phase was formed.

Based on the results of the XRD and XPS analyses, it was confirmed that the prepared composites (both non-lyophilized and lyophilized) annealed at 300 °C contained both the TiO_2 and $g\text{-C}_3\text{N}_4$ phases. At the same time, the composites prepared at 200 °C contained the anatase and $g\text{-C}_3\text{N}_4$ phases as well as urea residues and/or products of its thermal decomposition. The XPS data for $\text{L-TiO}_2/g\text{-C}_3\text{N}_4$ composites suggest the formation of N-defective nanocrystalline $g\text{-C}_3\text{N}_4$.⁷⁴ However, $g\text{-C}_3\text{N}_4$ in the sample prepared at 200 °C was poorly polymerized, and residual urea and intermediates were still present.

The morphology of non-lyophilized and lyophilized TiO_2 and $\text{TiO}_2/g\text{-C}_3\text{N}_4$ powders was studied using SEM (Fig. 4). Sample $\text{TiO}_2\text{-300}$ exhibited porous structure with a characteristic particle size of *ca.* 100 nm. For sample $\text{TiO}_2/g\text{-C}_3\text{N}_4\text{-300}$, much larger, micron-sized features were observed. These can be identified as $g\text{-C}_3\text{N}_4$ crystals, in line with XRD and XPS data discussed above. Sample $\text{L-TiO}_2\text{-300}$ consisted of particles that were *ca.* 10 nm large, which is consistent with the particle size in



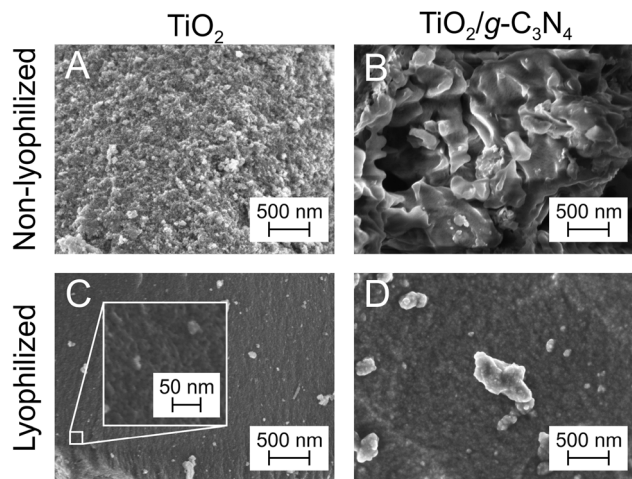


Fig. 4 SEM micrographs for TiO_2 (A) and (C) and $\text{TiO}_2/\text{g-C}_3\text{N}_4$ (B) and (D) samples not subjected (A) and (B) and subjected (C) and (D) to lyophilization before thermal treatment at $300\text{ }^\circ\text{C}$. The images were acquired at a magnification of $50\text{k}\times$. The inset in panel C shows a high-resolution image acquired at a magnification of $500\text{k}\times$ to resolve the nanoporous structure of this sample.

the TiO_2 sol as determined by TEM (Fig. 1). Sample L- $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300 was characterized by a slightly larger particle size. Thus, TiO_2 nanoparticles in non-lyophilized samples were prone to sintering. Furthermore, adding urea to the TiO_2 sol and subjecting this liquid mixture to thermal treatment seemed to promote the growth of the $\text{g-C}_3\text{N}_4$ crystalline phase on the surface of TiO_2 . Lyophilization not only prevented the sintering of TiO_2 nanoparticles but also inhibited the growth of large $\text{g-C}_3\text{N}_4$ crystals.

SEM data were further corroborated by N_2 physisorption analysis. The lyophilized samples obtained at 200 and $300\text{ }^\circ\text{C}$ exhibited different types of the N_2 adsorption-desorption isotherms. As can be seen from Fig. S5, according to the IUPAC classification,⁷⁵ the type I isotherm is observed for the lyophilized samples annealed at $200\text{ }^\circ\text{C}$. This type of isotherm represents the physical adsorption process on microporous adsorbents. However, there are differences in BET surface areas and micropore size distributions—urea modification decreased both. The specific surface area, as calculated by the multi-point BET method, was found to be 185 and $137\text{ m}^2\text{ g}^{-1}$, respectively. The decrease in the specific surface area for L- $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -200 can be explained by pore-blocking caused by products of poor

polymerization of urea. Samples L- TiO_2 -300 and L- $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300 exhibited the type IV isotherm with an H2a hysteresis loop at P/P_0 of 0.4 – 0.7 (Fig. S6), which is characteristic of mesoporous solids having pores with a uniform size distribution.⁷⁶ The specific surface area was $108\text{ m}^2\text{ g}^{-1}$ for L- TiO_2 -300 sample, which increased up to $231\text{ m}^2\text{ g}^{-1}$ for L- $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300 sample, and pore size in the microporous area increased from 1.2 to 1.4 nm after the addition of urea. The non-lyophilized TiO_2 -300 and $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300 samples had a mesoporous structure (type IV isotherm, H2b hysteresis) with a wide range of sizes in pore restrictions or pore entrances. (Fig. S7). In addition to meso- and micropores, the sample contained a certain amount of macropores, as evidenced by the rise of the isotherm at $P/P_0 > 0.9$. The BET surface area was $132\text{ m}^2\text{ g}^{-1}$ for sample TiO_2 -300 and $140\text{ m}^2\text{ g}^{-1}$ for sample $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300. The pore sizes of both samples in the microporous range were *ca.* 1.5 nm , although for sample TiO_2 -300, the pore determination was not so clear because the graph has more than one maximum point.

Characterization data for the prepared $\text{TiO}_2/\text{g-C}_3\text{N}_4$ composites and pure TiO_2 powders are summarized in Table 1.

By using lyophilization and changing the annealing temperature, $\text{TiO}_2/\text{g-C}_3\text{N}_4$ composites with different characteristics can be prepared. Based on BET analysis, the non-lyophilized samples exhibited smaller specific surface area. Since annealing at $200\text{ }^\circ\text{C}$ was insufficient for the complete polymerization of urea, treatment at $300\text{ }^\circ\text{C}$ should be chosen.

The optical response of the prepared materials was studied using DRS (Fig. 5). A diffuse reflectance spectrum for the L- $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300 nanocomposite seems to be a combination of the spectra for the pure $\text{g-C}_3\text{N}_4$ and TiO_2 phases.

3.2 Photo- and electrocatalytic activity of $\text{TiO}_2/\text{g-C}_3\text{N}_4$ nanocomposites

The production of the OH radical, one of the strongest oxidizing agents,¹⁹ is a key parameter of a photocatalyst used for the degradation of chemically resistant organic compounds, including environmental pollutants. Several works explored the photocatalytic $\cdot\text{OH}$ production by TiO_2 .^{20,21} Anatase was shown to exhibit superior activity compared to rutile in the generation of the free, non-adsorbed OH radical. Since TiO_2 studied in this work consists of anatase, efficient $\cdot\text{OH}$ production is expected. The presence of the $\text{g-C}_3\text{N}_4$ phase could further improve the yield of the OH radical.

Thus, non-lyophilized and lyophilized $\text{TiO}_2/\text{g-C}_3\text{N}_4$ nanocomposites and TiO_2 powders were compared with respect to

Table 1 Specific surface area and phase composition of the prepared materials

Sample	Specific surface area ($\text{m}^2\text{ g}^{-1}$)	$\text{g-C}_3\text{N}_4$ state
TiO_2 -300	132	–
$\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300	140	+
L- TiO_2 -200	185	–
L- $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -200	137	+(as well as urea and intermediates)
L- TiO_2 -300	108	–
L- $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300	231	+(nanocrystalline)



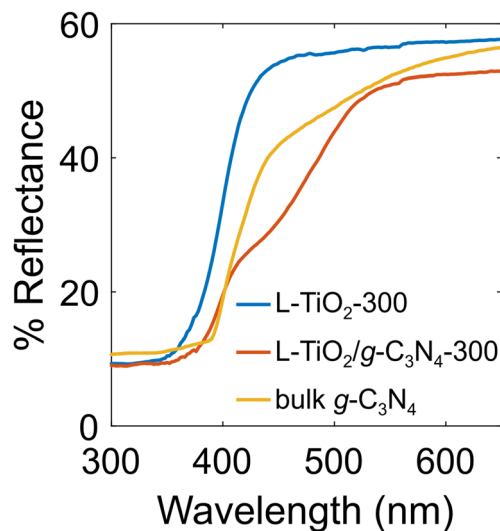


Fig. 5 Diffuse reflectance spectra for lyophilized TiO_2 powder (blue curve) and $\text{TiO}_2/\text{g-C}_3\text{N}_4$ nanocomposite (red curve) prepared at 300°C as well as for bulk $\text{g-C}_3\text{N}_4$ prepared by polymerizing urea at 600°C (yellow curve).

the photocatalytic $\cdot\text{OH}$ production upon activation with near-UV (385 nm) light. Both samples TiO_2 -300 and $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300 generated the OH radical, with the nanocomposite being slightly more efficient (Fig. 6). The lyophilized samples L- TiO_2 -300 and L- $\text{TiO}_2/\text{g-C}_3\text{N}_4$ -300 demonstrated a drastic 5-fold improvement in $\cdot\text{OH}$ production compared to their non-lyophilized counterparts. Between the two lyophilized samples, the nanocomposite containing the $\text{g-C}_3\text{N}_4$ phase was more efficient by 14% with respect to $\cdot\text{OH}$ production. The diminished photocatalytic activity observed in the non-

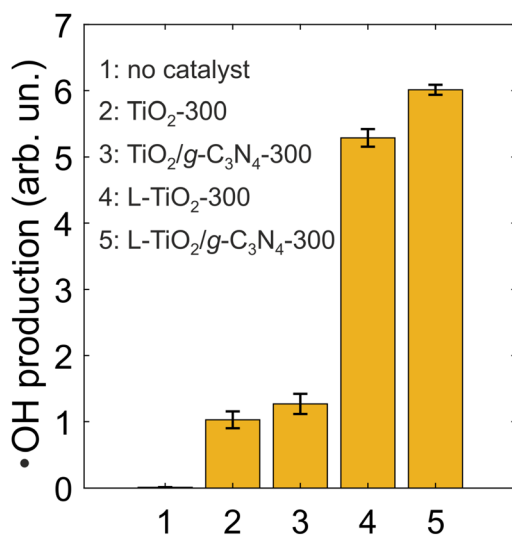


Fig. 6 $\cdot\text{OH}$ production (as HTA fluorescence intensity) without catalysts and in 1 mg mL^{-1} suspensions of non-lyophilized and lyophilized TiO_2 powders and $\text{TiO}_2/\text{g-C}_3\text{N}_4$ composites annealed at 300°C . The photoactivation was performed with an LED peaking at 385 nm at a light dose density of 36 J cm^{-2} (60 mW cm^{-2} for 10 min).

lyophilized samples is likely attributable to sintering during thermal treatment and the resulting poor dispersibility in aqueous media. The enhanced $\cdot\text{OH}$ generation upon incorporation of the $\text{g-C}_3\text{N}_4$ phase can be ascribed to improved charge separation, facilitated by the favorable alignment of the valence and conduction band edges of the TiO_2 and $\text{g-C}_3\text{N}_4$ components.

Improving the performance of electrode materials with respect to the ORR is important for the development of more cost-efficient fuel cells. The electrocatalytic activity of TiO_2 and $\text{TiO}_2/\text{g-C}_3\text{N}_4$ thin films in the ORR was studied (Fig. 7). The cyclic voltammogram for the TiO_2 film demonstrated two waves of oxygen electroreduction peaked at -0.74 and $-0.98\text{ V vs. Hg/HgO}$ (or 0.15 and -0.09 V , respectively, vs. reversible hydrogen electrode). For the $\text{TiO}_2/\text{g-C}_3\text{N}_4$ film, the onset of oxygen electroreduction occurred at a more positive potential. At the current density of $-100\text{ }\mu\text{A cm}^{-2}$, the reduction in the ORR overpotential amounted to 70 mV. Heterostructures of hollow carbon nanospheres and graphitic C_3N_5 demonstrated a similar reduction in ORR overpotential with respect to bare nanospheres.⁷⁷ For comparison, loading TiO_2 /carbon black composite with Pt nanoparticles resulted in a decrease in the ORR overpotential by *ca.* 200 mV.⁷⁸ As anticipated, the $\text{TiO}_2/\text{g-C}_3\text{N}_4$ composite did not match the electrocatalytic performance of platinum-based materials, which serve as standard benchmarks for the ORR. However, reducing reliance on precious metals aligns with the principles of sustainable development. The electrocatalytic activity of $\text{TiO}_2/\text{g-C}_3\text{N}_4$ can be further enhanced through careful optimization of synthesis parameters or loading it with noble-metal nanoparticles.

Photocatalytic and electrocatalytic properties for the studied materials demonstrate similar improvements due to the introduction of the $\text{g-C}_3\text{N}_4$ phase. Photocatalytic $\cdot\text{OH}$ production and electrocatalytic oxygen reduction share certain material-dependent characteristics, particularly the critical role of O_2

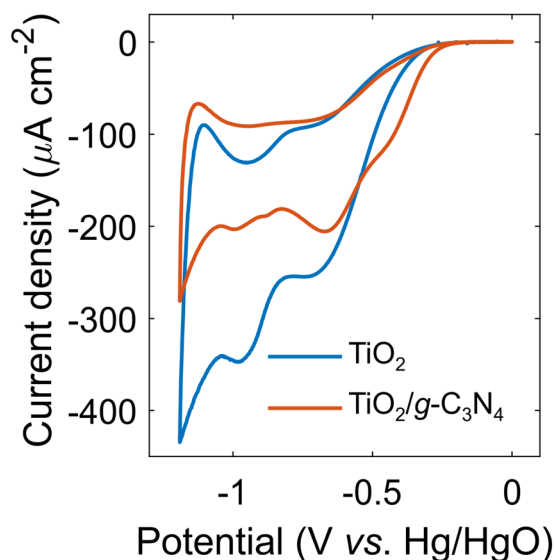


Fig. 7 Cyclic voltammograms for the ORR on the TiO_2 (blue curve) and $\text{TiO}_2/\text{g-C}_3\text{N}_4$ (red curve) thin films prepared on FTO at 300°C .



adsorption. In photocatalysis, the reduction of O₂ by trapped electrons on TiO₂ has been identified as the rate-limiting step in the oxidation of organic compounds,^{79,80} whereas in electrocatalysis, O₂ adsorption significantly influences the overpotential. Despite these similarities, the two processes differ in other performance-determining factors. Enhanced photocatalytic activity can be attributed to improved dispersibility achieved through lyophilization and favorable band alignment that promotes charge separation. In contrast, the reduced overpotential observed in oxygen electroreduction is more likely due to increased electrical conductivity and the greater availability of active sites.

Conclusions

In this work, TiO₂/g-C₃N₄ nanocomposites were prepared by polymerizing urea in the presence of TiO₂. Unlike urea, melamine was shown to be unsuitable as a precursor of g-C₃N₄ formed in the presence of TiO₂. For non-lyophilized samples, the g-C₃N₄ phase was formed after annealing at 200 or 300 °C. The lyophilization of the TiO₂ sol or the mixture of the sol with urea prior to annealing resulted in materials with substantially larger specific surface areas. After lyophilization, annealing at 300 °C was required for a complete polymerization of urea. Thus, the material with optimal characteristics was obtained when using urea as the g-C₃N₄ precursor, implementing lyophilization, and performing thermal treatment at 300 °C.

Overall, the higher sample processing temperature increased the pore size diameter of the samples and increased the number of mesopores. Urea addition decreased both BET surface area and pore size diameter when temperature of 200 °C was applied while processing temperature of 300 °C increased both BET surface area and pore size diameter. Lyophilization treatment increased BET surface area only if urea was added together with higher processing temperature (300 °C).

Lyophilized TiO₂ and TiO₂/g-C₃N₄ samples prepared at 300 °C generated the hydroxyl radical 5 times more efficiently compared to their non-lyophilized counterparts upon photoactivation in the near-UV range. Furthermore, the lyophilized TiO₂/g-C₃N₄ composite demonstrated a 14% increase in ·OH production in comparison to the lyophilized TiO₂ powder. The TiO₂/g-C₃N₄ thin film prepared at 300 °C showed a 70-mV reduction in the oxygen electroreduction overpotential compared to the bare TiO₂ thin film.

The described synthetic approach differs from the previously reported procedures, which involved the preparation g-C₃N₄ and TiO₂ separately and then mixing them.^{35,36,42–44} The synthetic procedure described here results in materials with lowered crystallinity of the phases (especially, when lyophilization is implemented), but a substantially larger specific surface area.

The low-temperature conditions required for synthesizing the composites enhance both cost and energy efficiency. Moreover, the process eliminates the need for surfactants, which can be non-biodegradable and potentially harmful to the environment. This eco-friendly synthesis approach aligns with

the principles of sustainable materials development while yielding composites with good catalytic performance.

Author contributions

Hanna Maltnava: conceptualization, data curation, investigation, methodology, visualization, writing – original draft. Nikita Belko: conceptualization, data curation, investigation, methodology, visualization, writing – original draft. Konstantin Tamarov: data curation, investigation, methodology, visualization, writing – review & editing. Niko M. Kinnunen: data curation, investigation, methodology, visualization, writing – original draft. Pauliina Nevalainen: data curation, investigation, methodology, visualization, writing – original draft. Martynas Zalieckas: data curation, investigation, methodology. Renata Karpicz: conceptualization, supervision, writing – review & editing. Igor Koshevoy: funding acquisition, methodology, supervision. Dmitry Semenov: methodology, investigation, supervision. Sari Suvanto: investigation, methodology, resources, supervision. Sergei Malykhin: investigation, methodology. Vesa-Pekka Lehto: funding acquisition, resources, supervision. Polina Kuzhir: conceptualization, funding acquisition, methodology, resources, supervision, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data for this article, including XRD patterns, XPS spectra, DRS spectra, SEM images, cyclic voltammograms, and N₂ adsorption–desorption isotherms are available at Zenodo at <https://doi.org/10.5281/zenodo.15267936>.

Scheme of the oxidation of terephthalic acid, additional XRD curves, element abundances, XPS spectra, N₂ adsorption–desorption isotherms, and micropore size distributions. See DOI: <https://doi.org/10.1039/d5na00478k>.

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Notes and references

- 1 A. Chakravorty and S. Roy, *Sust. Chem. Environ.*, 2024, 100155.
- 2 M. M. Khin, A. S. Nair, V. J. Babu, R. Murugan and S. Ramakrishna, *Energy Environ. Sci.*, 2012, 5, 8075–8109.



- 3 J. Y. Hwang, G.-h. Moon, B. Kim, T. Tachikawa, T. Majima, S. Hong, K. Cho, W. Kim and W. Choi, *Appl. Cat. B Environ.*, 2021, **286**, 119905.
- 4 B. C. Hodges, E. L. Cates and J.-H. Kim, *Nat. Nanotechnol.*, 2018, **13**, 642–650.
- 5 T. Ochiai and A. Fujishima, *J. Photochem. Photobiol. C Photochem. Rev.*, 2012, **13**, 247–262.
- 6 A. L. Linsebigler, G. Lu and J. T. Yates Jr, *Chem. Rev.*, 1995, **95**, 735–758.
- 7 K. Nakata and A. Fujishima, *J. Photochem. Photobiol. C Photochem. Rev.*, 2012, **13**, 169–189.
- 8 J. Schneider, M. Matsuoka, M. Takeuchi, J. Zhang, Y. Horiuchi, M. Anpo and D. W. Bahnemann, *Chem. Rev.*, 2014, **114**, 9919–9986.
- 9 B. O'Regan and M. Grätzel, *Nature*, 1991, **353**, 737–740.
- 10 M. Zhou, J. Yu, B. Cheng and H. Yu, *Mater. Chem. Phys.*, 2005, **93**, 159–163.
- 11 W. Zhou and H. Fu, *ChemCatChem*, 2013, **5**, 885–894.
- 12 B. Niu, X. Wang, K. Wu, X. He and R. Zhang, *Mater*, 2018, **11**, 1910.
- 13 A. Fujishima, T. N. Rao and D. A. Tryk, *J. Photochem. Photobiol. C Photochem. Rev.*, 2000, **1**, 1–21.
- 14 M. A. Fox and M. T. Dulay, *Chem. Rev.*, 1993, **93**, 341–357.
- 15 J.-M. Herrmann, *Cat. Today*, 1999, **53**, 115–129.
- 16 M. Ni, M. K. Leung, D. Y. Leung and K. Sumathy, *Renew. Sustain. Energy Rev.*, 2007, **11**, 401–425.
- 17 P. Yang, D. Zhao, D. I. Margolese, B. F. Chmelka and G. D. Stucky, *Nature*, 1998, **396**, 152–155.
- 18 L. Robben, A. A. Ismail, S. J. Lohmeier, A. Feldhoff, D. W. Bahnemann and J.-C. Buhl, *Chem. Mater.*, 2012, **24**, 1268–1275.
- 19 S. Gligorovski, R. Strekowski, S. Barbati and D. Vione, *Chem. Rev.*, 2015, **115**, 13051–13092.
- 20 W. Kim, T. Tachikawa, G.-h. Moon, T. Majima and W. Choi, *Angew. Chem.*, 2014, **126**, 14260–14265.
- 21 Y. Nosaka and A. Nosaka, *ACS Energy Lett.*, 2016, **1**, 356–359.
- 22 P. S. Basavarajappa, S. B. Patil, N. Ganganagappa, K. R. Reddy, A. V. Raghu and C. V. Reddy, *Int. J. Hydrogen Energy*, 2020, **45**, 7764–7778.
- 23 S. G. Kumar and L. G. Devi, *J. Phys. Chem. A*, 2011, **115**, 13211–13241.
- 24 T. Ishaq, Z. Ehsan, A. Qayyum, Y. Abbas, A. Irfan, S. A. Al-Hussain, M. A. Irshad and M. E. Zaki, *Catalysts*, 2024, **14**, 674.
- 25 R. Acharya and K. Parida, *J. Environ. Chem. Eng.*, 2020, **8**, 103896.
- 26 J. Lei, Y. Chen, F. Shen, L. Wang, Y. Liu and J. Zhang, *J. Alloys Compounds*, 2015, **631**, 328–334.
- 27 D. Bhandari, P. Lakhani and C. K. Modi, *RSC Sustainability*, 2024, 265–287.
- 28 J. Wen, J. Xie, X. Chen and X. Li, *Appl. Surf. Sci.*, 2017, **391**, 72–123.
- 29 S. Cao, J. Low, J. Yu and M. Jaroniec, *Adv. Mater.*, 2015, **27**, 2150–2176.
- 30 K. Qi, S.-y. Liu and A. Zada, *J. Taiwan Inst. Chem. Eng.*, 2020, **109**, 111–123.
- 31 L. Wang, K. Wang, T. He, Y. Zhao, H. Song and H. Wang, *ACS Sust. Chem. Eng.*, 2020, **8**, 16048–16085.
- 32 A. B. Jorge, D. J. Martin, M. T. Dhanoa, A. S. Rahman, N. Makwana, J. Tang, A. Sella, F. Corà, S. Firth, J. A. Darr, et al., *J. Phys. Chem. C*, 2013, **117**, 7178–7185.
- 33 S. Deng, W.-P. Xiong, G.-X. Zhang, G.-F. Wang, Y.-X. Chen, W.-J. Xiao, Q.-K. Shi, A. Chen, H.-Y. Kang, M. Cheng, et al., *Adv. Energy Mater.*, 2024, **14**, 2401768.
- 34 L. Sun, P. Li, Z. Shen, Y. Pang, X. Ma, D. Qu, L. An and Z. Sun, *Adv. Energy Sust. Res.*, 2023, **4**, 2300090.
- 35 A. Crake, K. C. Christoforidis, R. Godin, B. Moss, A. Kafizas, S. Zafeiratos, J. R. Durrant and C. Petit, *Appl. Cat. B Environ.*, 2019, **242**, 369–378.
- 36 K. Kočí, M. Reli, I. Troppová, M. Šihor, J. Kupková, P. Kustrowski and P. Praus, *Appl. Surf. Sci.*, 2017, **396**, 1685–1695.
- 37 S. Wu, C. He, L. Wang and J. Zhang, *Chem. Eng. J.*, 2022, **443**, 136425.
- 38 S. Higashimoto, K. Hikita, M. Azuma, M. Yamamoto, M. Takahashi, Y. Sakata, M. Matsuoka and H. Kobayashi, *Chin. J. Chem.*, 2017, **35**, 165–172.
- 39 M. Azami, K. Ismail, M. Ishak, A. Zuliahani, S. Hamzah and W. Nawawi, *J. Water Proc. Eng.*, 2020, **35**, 101209.
- 40 M. Sun, Y. Fang, Y. Kong, S. Sun, Z. Yu and A. Umar, *Dalton Trans.*, 2016, **45**, 12702–12709.
- 41 I. F. Silva, C. Pulignani, J. Odutola, A. Galushchinskiy, I. F. Teixeira, M. Isaacs, C. A. Mesa, E. Scoppola, A. These, B. Badamdorj, et al., *J. Colloid Interface Sci.*, 2025, **678**, 518–533.
- 42 S. Gong, Z. Jiang, S. Zhu, J. Fan, Q. Xu and Y. Min, *J. Nanopart. Res.*, 2018, **20**, 1–13.
- 43 L. Jing, W.-J. Ong, R. Zhang, E. Pickwell-MacPherson and J. C. Yu, *Cat. Today*, 2018, **315**, 103–109.
- 44 S. Pareek and J. K. Quamara, *J. Mater. Sci.*, 2018, **53**, 604–612.
- 45 S. Poznyak, A. Kokorin and A. Kulak, *J. Electroanal. Chem.*, 1998, **442**, 99–105.
- 46 Y. Zheng, Z. Zhang and C. Li, *J. Photochem. Photobiol. A Chem.*, 2017, **332**, 32–44.
- 47 R. S. Mikhail, S. Brunauer and E. Bodor, *J. Colloid Interface Sci.*, 1968, **26**, 45–53.
- 48 J. De Boer, B. Lippens, B. Linsen, J. Broekhoff, A. Van den Heuvel and T. J. Osinga, *J. Colloid Interface Sci.*, 1966, **21**, 405–414.
- 49 J. Liu, T. An, Z. Chen, Z. Wang, H. Zhou, T. Fan, D. Zhang and M. Antonietti, *J. Mater. Chem. A*, 2017, **5**, 8933–8938.
- 50 D. A. Hanaor and C. C. Sorrell, *J. Mater. Sci.*, 2011, **46**, 855–874.
- 51 F. Fina, S. K. Callear, G. M. Carins and J. T. Irvine, *Chem. Mater.*, 2015, **27**, 2612–2618.
- 52 Y. Lai, L. Sun, Y. Chen, H. Zhuang, C. Lin and J. W. Chin, *J. Electrochem. Soc.*, 2006, **153**, D123.
- 53 B. M. Reddy, K. N. Rao, G. K. Reddy and P. Bharali, *J. Mol. Cat. A Chem.*, 2006, **253**, 44–51.
- 54 D. Gonbeau, C. Guimon, G. Pfister-Guillouzo, A. Levasseur, G. Meunier and R. Dormoy, *Surf. Sci.*, 1991, **254**, 81–89.
- 55 Y. Zhang, Z. Chen, J. Li, Z. Lu and X. Wang, *J. Energy Chem.*, 2021, **54**, 36–44.



- 56 H. Yu, R. Shi, Y. Zhao, T. Bian, Y. Zhao, C. Zhou, G. I. Waterhouse, L.-Z. Wu, C.-H. Tung and T. Zhang, *Adv. Mater.*, 2017, **29**, 1605148.
- 57 A. Nasri, B. Jaleh, Z. Nezafat, M. Nasrollahzadeh, S. Azizian, H. W. Jang and M. Shokouhimehr, *Ceram. Int.*, 2021, **47**, 3565–3572.
- 58 M. Benedet, A. Gasparotto, G. A. Rizzi, D. Barreca and C. Maccato, *Surf. Sci. Spectra*, 2022, **29**(024001).
- 59 O. Auciello, J.-F. Veyan and M. J. Arellano-Jimenez, *Front. Carbon*, 2023, **2**, 1279356.
- 60 M. Zhao, *Appl. Sci.*, 2018, **8**, 1303.
- 61 A. Torres-Pinto, A. M. Díez, C. G. Silva, J. L. Faria, M. Á. Sanromán, A. M. Silva and M. Pazos, *Fuel*, 2024, **360**, 130575.
- 62 J. Liu, T. Zhang, Z. Wang, G. Dawson and W. Chen, *J. Mater. Chem.*, 2011, **21**, 14398–14401.
- 63 G. P. Mane, S. N. Talapaneni, K. S. Lakhi, H. Ilbeygi, U. Ravon, K. Al-Bahily, T. Mori, D.-H. Park and A. Vinu, *Angew. Chem., Int. Ed.*, 2017, **56**, 8481–8485.
- 64 W. Xia, Y. Wang, R. Bergsträßer, S. Kundu and M. Muhler, *Appl. Surf. Sci.*, 2007, **254**, 247–250.
- 65 Q. Guo, Y. Xie, X. Wang, S. Zhang, T. Hou and S. Lv, *Chem. Commun.*, 2004, 26–27.
- 66 W. Gammon, O. Kraft, A. Reilly and B. Holloway, *Carbon*, 2003, **41**, 1917–1923.
- 67 W. M. Silva, H. Ribeiro, L. M. Seara, H. D. Calado, A. S. Ferlauto, R. M. Paniago, C. F. Leite, G. G. Silva and J. Brazil, *Chem. Soc.*, 2012, **23**, 1078–1086.
- 68 J. Baltrusaitis, P. M. Jayaweera and V. H. Grassian, *Phys. Chem. Chem. Phys.*, 2009, **11**, 8295–8305.
- 69 A. M. Sadanandan, M. Fawaz, N. P. Dharmarajan, M. Huš, G. Singh, C. Sathish, B. Likozar, Z. Li, A. M. Ruban, C.-H. Jeon, et al., *Appl. Cat. B Environ. Energy*, 2025, **362**, 124701.
- 70 H. Xu, Z. Wu, Y. Wang and C. Lin, *J. Mater. Sci.*, 2017, **52**, 9477–9490.
- 71 T. Wang, M. Huang, X. Liu, Z. Zhang, Y. Liu, W. Tang, S. Bao and T. Fang, *RSC Adv.*, 2019, **9**, 29109–29119.
- 72 P. Kyriakos, E. Hristoforou and G. V. Belessiotis, *Energies*, 2024, **17**, 3159.
- 73 I. Y. Kim, S. Kim, X. Jin, S. Premkumar, G. Chandra, N.-S. Lee, G. P. Mane, S.-J. Hwang, S. Umopathy and A. Vinu, *Angew. Chem.*, 2018, **130**, 17381–17386.
- 74 X. Yang, L. Zhang, D. Wang, Q. Zhang, J. Zeng and R. Zhang, *RSC Adv.*, 2021, **11**, 30503–30509.
- 75 M. Kruk and M. Jaroniec, *Chem. Mater.*, 2001, **13**, 3169–3183.
- 76 K. S. Sing, *Pure Appl. Chem.*, 1985, **57**, 603–619.
- 77 Q. Li, S. Song, Z. Mo, L. Zhang, Y. Qian and C. Ge, *Appl. Surf. Sci.*, 2022, **579**, 152006.
- 78 Z. Wang, X. Jin, F. Chen, X. Kuang, J. Min, H. Duan, J. Li and J. Chen, *J. Colloid Interface Sci.*, 2023, **650**, 901–912.
- 79 H. Gerischer, *Electrochim. Acta*, 1993, **38**, 3–9.
- 80 C. M. Wang, A. Heller and H. Gerischer, *J. Am. Chem. Soc.*, 1992, **114**, 5230–5234.

