

Cite this: *Nanoscale Adv.*, 2025, 7, 5601

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

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Titanium dioxide (TiO<sub>2</sub>) 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 TiO<sub>2</sub>/graphitic carbon nitride (g-C<sub>3</sub>N<sub>4</sub>) nanocomposites in both powder and thin-film forms. The method takes advantage of the catalytic properties of TiO<sub>2</sub> to significantly lower the temperature required for the formation of g-C<sub>3</sub>N<sub>4</sub> 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 TiO<sub>2</sub> and TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> powders generate the hydroxyl radical, with lyophilization enhancing radical production fivefold. The lyophilized TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> nanocomposite exhibits 14% higher photocatalytic activity than its TiO<sub>2</sub> counterpart. In electrocatalytic studies, TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> thin films demonstrate a 70 mV lower overpotential for oxygen reduction compared to TiO<sub>2</sub> films. These results highlight the potential of the synthesized nanocomposites for environmental remediation and in energy-related applications such as fuel cell electrodes.

Received 14th May 2025

Accepted 30th July 2025

DOI: 10.1039/d5na00478k

rsc.li/nanoscale-advances

## 1 Introduction

Photocatalytic oxidation reactions that occur in semiconductor materials have attracted significant attention as an eco-friendly solution to environmental pollution.<sup>1</sup> The mechanism of photocatalytic oxidation typically involves the generation of reactive species, such as superoxide radical anion (<sup>•</sup>O<sub>2</sub><sup>-</sup>), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), singlet oxygen (<sup>1</sup>O<sub>2</sub>), and hydroxyl radical (<sup>•</sup>OH), which can efficiently mineralize organic pollutants.<sup>2-4</sup> Although numerous new photoactive materials have been reported, TiO<sub>2</sub> 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.<sup>5-10</sup> Although the photocatalytic activity of TiO<sub>2</sub> depends on various structural and surface characteristics,

titanium with a large surface area and a high degree of porosity is often required to achieve high efficiency in photocatalytic applications.<sup>11,12</sup> Mesoporous TiO<sub>2</sub> powders and films exhibit a high surface area and a narrow pore size distribution while retaining a crystalline framework.<sup>6-9,11,13-16</sup> 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.<sup>17,18</sup> Further research is still being conducted with the aim of identifying mesoporous catalytic materials with enhanced characteristics.

The activity of TiO<sub>2</sub> in photoreactions critically depends on the generation of the OH radical, one of the strongest oxidizing agents.<sup>19</sup> In particular, the generation of the free OH radical (<sup>•</sup>OH<sub>f</sub>) 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 <sup>•</sup>OH<sub>f</sub> by TiO<sub>2</sub> strongly depends on the kind of crystal polymorph. More specifically, anatase efficiently produces <sup>•</sup>OH<sub>f</sub>, while OH radicals generated by rutile mostly remain adsorbed on its surface.<sup>20,21</sup> The photocatalytic generation of <sup>•</sup>OH<sub>f</sub> by anatase can proceed *via* the reductive 3e<sup>-</sup> pathway (O<sub>2</sub> → <sup>•</sup>O<sub>2</sub><sup>-</sup> → H<sub>2</sub>O<sub>2</sub> → <sup>•</sup>OH<sub>f</sub>) or the oxidative process (OH<sup>-</sup> + h<sup>+</sup> → <sup>•</sup>OH<sub>f</sub>).<sup>20</sup> The

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reaction mechanism is still under debate and requires additional studies.<sup>21</sup>

To date, various strategies have been implemented to improve the performance of TiO<sub>2</sub> photocatalysts including doping with metal and non-metal elements, surface sensitization, the creation of semiconductor heterojunctions, *etc.*<sup>22,23</sup> Among these methods, heterostructuring TiO<sub>2</sub> with other semiconductor materials is one of the most effective methods to inhibit the fast electron-hole recombination in pure TiO<sub>2</sub>,<sup>24</sup> 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-C<sub>3</sub>N<sub>4</sub>), in particular, are frequently selected as the preferred materials for heterostructuring TiO<sub>2</sub>.<sup>25,26</sup> g-C<sub>3</sub>N<sub>4</sub> has been reported to be non-toxic, environmentally friendly, and stable.<sup>27,28</sup> It has been used for a variety of photocatalytic applications, including water splitting,<sup>29,30</sup> H<sub>2</sub> and O<sub>2</sub> evolution,<sup>31,32</sup> CO<sub>2</sub> reduction,<sup>29,30</sup> H<sub>2</sub>O<sub>2</sub> production,<sup>33,34</sup> pollutant degradation,<sup>30,31</sup> and selective oxidation of organic compounds.<sup>31</sup>

TiO<sub>2</sub> and g-C<sub>3</sub>N<sub>4</sub> are often chosen for the preparation of heterostructures, because the edges of both the valence and conduction bands of g-C<sub>3</sub>N<sub>4</sub> have higher energy values with respect to TiO<sub>2</sub>. Such an electronic structure of the resulting heterostructure is conducive of efficient charge separation, with the electrons preferably accumulating in the conduction band of TiO<sub>2</sub> and the holes favoring the valence band of g-C<sub>3</sub>N<sub>4</sub>. Indeed, in previous works, composites of carbon nitrides with TiO<sub>2</sub> were successfully applied as photocatalytic materials, *e.g.*, for CO<sub>2</sub> photoreduction,<sup>35</sup> photocatalytic decomposition of N<sub>2</sub>O,<sup>36</sup> NH<sub>3</sub> production,<sup>37</sup> H<sub>2</sub> evolution,<sup>38</sup> photocatalytic degradation of organic dyes,<sup>39</sup> and photocurrent generation.<sup>40</sup> In ref. 41, carbon nitride-TiO<sub>2</sub> hybrid was shown to outperform its components in several photo- and photoelectrocatalytic reactions while exhibiting enhanced activity in the visible range.<sup>41</sup> Enhanced generation of ·OH by carbon nitride-TiO<sub>2</sub> heterostructures can be expected as well.

A widely used approach to the synthesis of carbon nitride-TiO<sub>2</sub> hybrid materials is to prepare the two phases separately and then use them to create a composite.<sup>35,36,42-44</sup>

In this work, we prepare TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> powders and thin films from TiO<sub>2</sub> sol using a different procedure. A precursor of g-C<sub>3</sub>N<sub>4</sub> (urea or melamine) is added directly to TiO<sub>2</sub> sol prior to thermal treatment. The TiO<sub>2</sub> nanoparticles are shown to catalyze the polymerization of urea to g-C<sub>3</sub>N<sub>4</sub> 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-C<sub>3</sub>N<sub>4</sub> 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

TiCl<sub>4</sub> (99.9%), HCl (37%), HNO<sub>3</sub> (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 TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> nanocomposites

First, a concentrated TiO<sub>2</sub> 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 TiCl<sub>4</sub> 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 HNO<sub>3</sub> (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 TiO<sub>2</sub> 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% TiO<sub>2</sub> 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 TiO<sub>2</sub> nanoparticles in the formed sol were 3.1 ± 0.3 nm (Fig. 1).

In ref. 46, the properties of g-C<sub>3</sub>N<sub>4</sub> 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 TiO<sub>2</sub> nanoparticles to obtain the g-C<sub>3</sub>N<sub>4</sub> phase. 5 mL of the TiO<sub>2</sub> sol (corresponding to 0.6 g TiO<sub>2</sub>) 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 TiO<sub>2</sub> 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<sup>-1</sup>. The neat TiO<sub>2</sub> sol was also subjected to similar thermal treatment. The resulting powders were thoroughly milled with agate mortar and pestle.



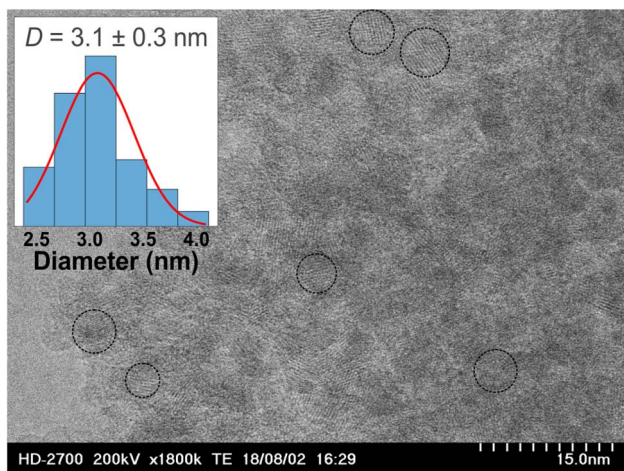


Fig. 1 TEM micrograph of TiO<sub>2</sub> nanoparticles drop-cast from the sol. Several typical particles are marked with dashed circles. The inset shows the corresponding size distribution (blue bars) and the fitting Gaussian function (red curve).

We also attempted to improve the synthetic procedure by including the lyophilization step. More precisely, 1.5 mL of the TiO<sub>2</sub> 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<sup>-1</sup>. The neat TiO<sub>2</sub> 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)-TiO<sub>2</sub>(/g-C<sub>3</sub>N<sub>4</sub>)-T, where “L” indicates that the sample was lyophilized prior to thermal treatment and T is the temperature of the synthesis. For instance, L-TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub>-300 refers to a TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> nano-composite that was lyophilized and then subjected to thermal treatment at 300 °C.

A similar procedure was also implemented to prepare thin films of TiO<sub>2</sub> and TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub>. 5 mL TiO<sub>2</sub> sol was mixed with 0.6 g urea, and the resulting mixture (as well as the neat TiO<sub>2</sub> 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<sup>-1</sup>.

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

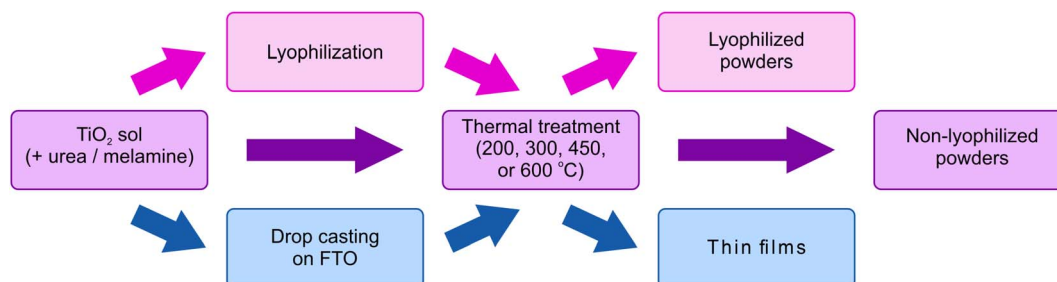


Fig. 2 The synthetic procedure for the preparation of TiO<sub>2</sub> and TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> in the form of non-lyophilized powders, lyophilized powders, and thin films.

Pure g-C<sub>3</sub>N<sub>4</sub> 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<sup>-1</sup>.

## 2.3 Characterization techniques

**2.3.1 X-ray diffraction.** XRD patterns were measured with a PANalytical Empyrean diffractometer using CuK $\alpha$ -radiation. The recording speed was 0.4° min<sup>-1</sup>. 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  $\theta$  is the glancing angle,  $n$  is the diffraction order, and  $\lambda = 1.54$  Å is the wavelength of CuK $\alpha$ -radiation. The mean crystallite size  $\tau$  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  $\beta$  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  $\mu$ m X-ray spot size (Al K $\alpha$ -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<sub>3/2</sub> 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 TiO<sub>2</sub> 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. N<sub>2</sub> gas physical adsorption was carried out at the temperature of liquified nitrogen. After physical adsorption of N<sub>2</sub> 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)<sup>47,48</sup> 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 cm<sup>2</sup>) 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<sup>-2</sup>. Prior to irradiation, the samples were bubbled with O<sub>2</sub> gas for 10 min. During irradiation, O<sub>2</sub> 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 TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> and TiO<sub>2</sub> powders were dispersed in the TA solution with sonication (5 min) at a concentration of 1 mg mL<sup>-1</sup> 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 TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> and TiO<sub>2</sub> 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<sup>-1</sup>. The measurements were conducted in a single-compartment glass cell equipped with three electrodes. The TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> or TiO<sub>2</sub> samples served as the working electrode. The area of the working electrode was 1 cm<sup>2</sup>. 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 O<sub>2</sub> gas for 1 h prior to the measurements.

# 3 Results and discussion

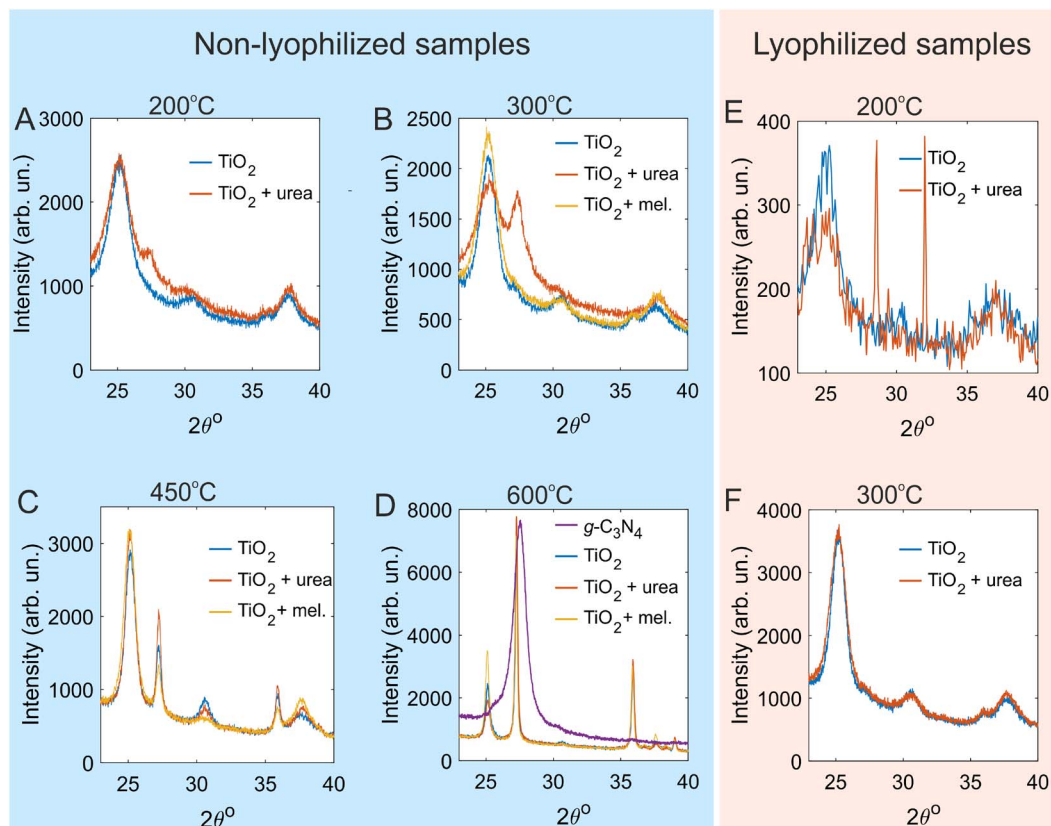
## 3.1 Characterization of TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> nanocomposites

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 TiO<sub>2</sub>, which exhibits superior catalytic activity compared to the rutile phase, particularly in the generation of hydroxyl radicals ( $\cdot$ OH<sub>f</sub>).<sup>20,21</sup> Second, to facilitate the conversion of precursor materials (melamine or urea) to the target g-C<sub>3</sub>N<sub>4</sub> phase.

The prepared materials were examined using XRD to establish the optimal parameters for synthesis. TiO<sub>2</sub> 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 TiO<sub>2</sub> annealed at 450 °C, the narrowing of the anatase reflexes and the appearance of rutile reflexes were evident (Fig. 3C). The XRD pattern for TiO<sub>2</sub> 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 TiO<sub>2</sub> 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.<sup>50</sup>

The influence of the temperature and the choice of the g-C<sub>3</sub>N<sub>4</sub> 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 TiO<sub>2</sub> sol mixed with urea and annealed at 200 °C contained a broad weak peak at 27.4° in addition to the TiO<sub>2</sub> reflexes (Fig. 3A). For the TiO<sub>2</sub> 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  $\text{TiO}_2$  and  $\text{TiO}_2/\text{g-C}_3\text{N}_4$ . (A)–(D). The  $\text{TiO}_2$  sol (blue curves), the  $\text{TiO}_2$  sol mixed with urea (red curves), and the  $\text{TiO}_2$  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  $\text{TiO}_2$  sol (blue curves) and the  $\text{TiO}_2$  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  $\text{g-C}_3\text{N}_4$ .<sup>46,51</sup> 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  $\text{TiO}_2$  sol after the introduction of melamine. The  $\text{TiO}_2$  sol mixed with urea or melamine and heated to 450 °C exhibited XRD patterns almost identical to that of the pure  $\text{TiO}_2$  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  $\text{g-C}_3\text{N}_4$ .<sup>46,51</sup> 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  $\text{g-C}_3\text{N}_4$ .<sup>46,51</sup> 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  $2\theta$  values and is substantially wider (Fig. 3D).

As follows from the XRD analysis of the prepared materials, the samples prepared from the  $\text{TiO}_2$  sol and urea at 200 °C and

300 °C had a two-phase composition of  $\text{TiO}_2$  (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  $\text{TiO}_2$  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  $\text{TiO}_2$  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  $\text{TiO}_2$  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  $\text{TiO}_2$  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  $\text{TiO}_2$  sol annealed at 200 or 300 °C (Fig. 3E and F) indicated that the samples consisted of anatase. For  $\text{TiO}_2$  that was mixed with urea, lyophilized, and then annealed at 200 °C (sample  $\text{L-TiO}_2/\text{g-C}_3\text{N}_4$ -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  $\text{TiO}_2$ ). 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.<sup>41</sup>

Elemental composition of all samples was determined using XPS (Table S1). XPS characterization was performed for the non-lyophilized  $\text{TiO}_2$  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<sub>3/2</sub> and Ti 2p<sub>1/2</sub>, respectively. These positions with the peak separation of 5.7 eV indicate octahedrally coordinated  $\text{Ti}^{4+}$  in  $\text{TiO}_2$ .<sup>52–54</sup> The O 1s peak located at 530.1 eV is assigned to lattice oxygen in  $\text{TiO}_2$ .<sup>36,42</sup> 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.<sup>55</sup>

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  $\text{sp}^2$  carbon, C–C/C=C, and COOH bands, respectively.<sup>36,56,57</sup> In the N 1s region, the main components were observed at 398.8 and 399.7 eV, corresponding to the  $\text{sp}^2$ -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.<sup>42,57,58</sup> The N 1s peak at 398.2 eV is related to weak C–N or N–N bonds linked to  $\text{sp}^2$  carbon.<sup>59</sup> The XPS data confirm the existence of graphite-like  $\text{sp}^2$  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  $\text{TiO}_2$  (ref. 60) (which are present due to nitric acid in the  $\text{TiO}_2$  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  $\text{sp}^3$  diamond bonds and does not belong to pure  $g\text{-C}_3\text{N}_4$ . It may be assigned to terminal C–NH<sub>x</sub> groups<sup>61</sup> or C–C/C=C bonds.<sup>62</sup> The C 1s signal at 289.2 eV can be attributed to the overlap of signals from  $\text{sp}^2$  carbon, carboxylic groups, and  $\text{sp}^2$  carbon in the aromatic ring attached to  $-\text{NH}_2$  groups.<sup>63,64</sup> In addition, a weak signal at 292.2 eV in the C 1s spectrum can be assigned to the  $\pi$  electron delocalization in  $g\text{-C}_3\text{N}_4$  heterocycles, confirming graphitic stacking of triazine- or heptazine-based layers.<sup>65</sup> The lowest energy contribution of the N 1s spectrum, 399.2 eV, is attributed to nitrogen

bonded with two carbon atoms in a graphitic  $\text{sp}^2$  network.<sup>66</sup> 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.<sup>63</sup> The presence of  $-\text{N}=\text{C}=\text{O}$  band was also identified in the N 1s spectrum (the peak at 401.5 eV).<sup>67</sup> The N 1s peak at 407.5 eV can be attributed to nitrate groups on the oxide surface.<sup>68</sup>

XPS analysis was also performed for the lyophilized  $\text{TiO}_2$  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 L- $\text{TiO}_2\text{-300}$  and L- $\text{TiO}_2/g\text{-C}_3\text{N}_4\text{-300}$  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  $\text{sp}^2$ -hybridized carbon in the triazine ring attached to  $\text{NH}_2$  species ( $\text{N}=\text{C}-\text{N}_2$ ), respectively.<sup>69–71</sup> 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  $\text{sp}^2$  carbon (289.2 eV) was the most intense band in the spectrum for the sample prepared at 300 °C. Although pure  $\text{TiO}_2$  and  $\text{TiO}_2/g\text{-C}_3\text{N}_4$  composites demonstrated similar C 1s peaks, the contribution from  $\text{sp}^2$ -hybridized carbon at 289.2 eV was higher for the composites (Fig. S4).

The N 1s spectrum for sample L- $\text{TiO}_2/g\text{-C}_3\text{N}_4\text{-300}$  revealed bands at 398.1 and 400.1 eV, which were assigned to  $\text{sp}^2$  nitrogen and tertiary nitrogen ( $\text{N}(\text{C})_3$ ), respectively. The N 1s spectrum for sample L- $\text{TiO}_2/g\text{-C}_3\text{N}_4\text{-200}$  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  $\text{sp}^2$ -hybridized imine groups (C–N=C) and surface functional amino groups ( $-\text{NH}_x$ ).<sup>72,73</sup> 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  $\text{TiO}_2$  (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  $\text{TiO}_2$  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 L- $\text{TiO}_2/g\text{-C}_3\text{N}_4$  composites suggest the formation of N-defective nanocrystalline  $g\text{-C}_3\text{N}_4$ .<sup>74</sup> 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  $\text{TiO}_2$  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 L- $\text{TiO}_2\text{-300}$  consisted of particles that were *ca.* 10 nm large, which is consistent with the particle size in



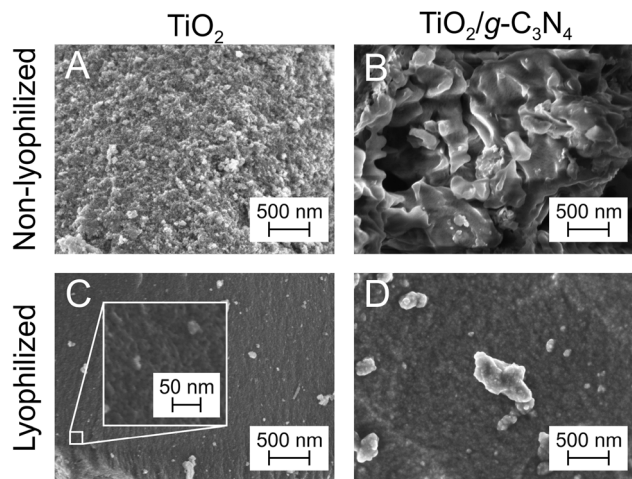


Fig. 4 SEM micrographs for  $\text{TiO}_2$  (A) and (C) and  $\text{TiO}_2/\text{g-C}_3\text{N}_4$  (B) and (D) samples not subjected (A) and (B) and subjected (C) and (D) to lyophilization before thermal treatment at 300 °C. The images were acquired at a magnification of 50k $\times$ . The inset in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

the  $\text{TiO}_2$  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,  $\text{TiO}_2$  nanoparticles in non-lyophilized samples were prone to sintering. Furthermore, adding urea to the  $\text{TiO}_2$  sol and subjecting this liquid mixture to thermal treatment seemed to promote the growth of the g- $\text{C}_3\text{N}_4$  crystalline phase on the surface of  $\text{TiO}_2$ . Lyophilization not only prevented the sintering of  $\text{TiO}_2$  nanoparticles but also inhibited the growth of large g- $\text{C}_3\text{N}_4$  crystals.

SEM data were further corroborated by  $\text{N}_2$  physisorption analysis. The lyophilized samples obtained at 200 and 300 °C exhibited different types of the  $\text{N}_2$  adsorption-desorption isotherms. As can be seen from Fig. S5, according to the IUPAC classification,<sup>75</sup> the type I isotherm is observed for the lyophilized samples annealed at 200 °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- $\text{TiO}_2$ -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.<sup>76</sup> The specific surface area was 108  $\text{m}^2 \text{g}^{-1}$  for L- $\text{TiO}_2$ -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  $\text{TiO}_2$ -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  $\text{TiO}_2$ -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  $\text{TiO}_2$ -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  $\text{TiO}_2$  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 °C was insufficient for the complete polymerization of urea, treatment at 300 °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 g- $\text{C}_3\text{N}_4$  and  $\text{TiO}_2$  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,<sup>19</sup> 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  $\text{TiO}_2$ .<sup>20,21</sup> Anatase was shown to exhibit superior activity compared to rutile in the generation of the free, non-adsorbed OH radical. Since  $\text{TiO}_2$  studied in this work consists of anatase, efficient  $\cdot\text{OH}$  production is expected. The presence of the g- $\text{C}_3\text{N}_4$  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  $\text{TiO}_2$  powders were compared with respect to

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

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



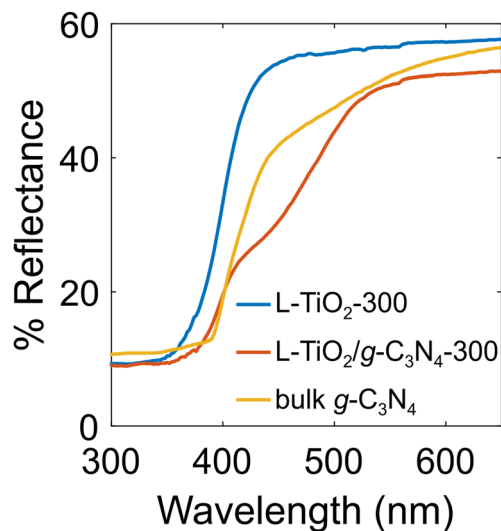


Fig. 5 Diffuse reflectance spectra for lyophilized  $\text{TiO}_2$  powder (blue curve) and  $\text{TiO}_2/\text{g-C}_3\text{N}_4$  nanocomposite (red curve) prepared at  $300^\circ\text{C}$  as well as for bulk  $\text{g-C}_3\text{N}_4$  prepared by polymerizing urea at  $600^\circ\text{C}$  (yellow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

the photocatalytic  $\cdot\text{OH}$  production upon activation with near-UV (385 nm) light. Both samples  $\text{TiO}_2$ -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- $\text{TiO}_2$ -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-

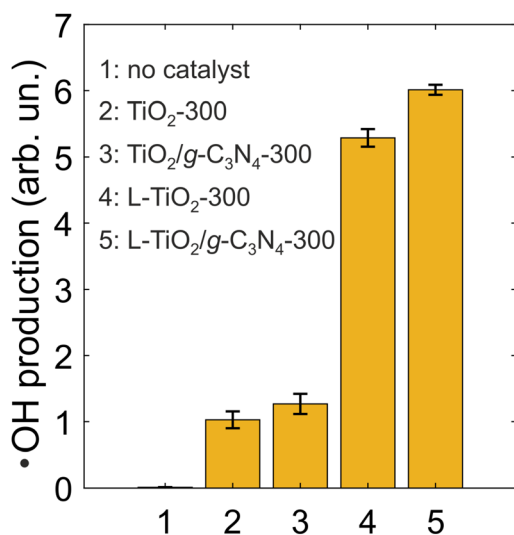


Fig. 6  $\cdot\text{OH}$  production (as HTA fluorescence intensity) without catalysts and in  $1\text{ mg mL}^{-1}$  suspensions of non-lyophilized and lyophilized  $\text{TiO}_2$  powders and  $\text{TiO}_2/\text{g-C}_3\text{N}_4$  composites annealed at  $300^\circ\text{C}$ . The photoactivation was performed with an LED peaking at 385 nm at a light dose density of  $36\text{ J cm}^{-2}$  ( $60\text{ mW cm}^{-2}$  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  $\text{TiO}_2$  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  $\text{TiO}_2$  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  $\text{TiO}_2$  film demonstrated two waves of oxygen electroreduction peaked at  $-0.74$  and  $-0.98\text{ V vs. Hg/HgO}$  (or  $0.15$  and  $-0.09\text{ V}$ , 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  $\text{C}_3\text{N}_5$  demonstrated a similar reduction in ORR overpotential with respect to bare nanospheres.<sup>77</sup> For comparison, loading  $\text{TiO}_2$ /carbon black composite with Pt nanoparticles resulted in a decrease in the ORR overpotential by *ca.* 200 mV.<sup>78</sup> 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  $\text{O}_2$

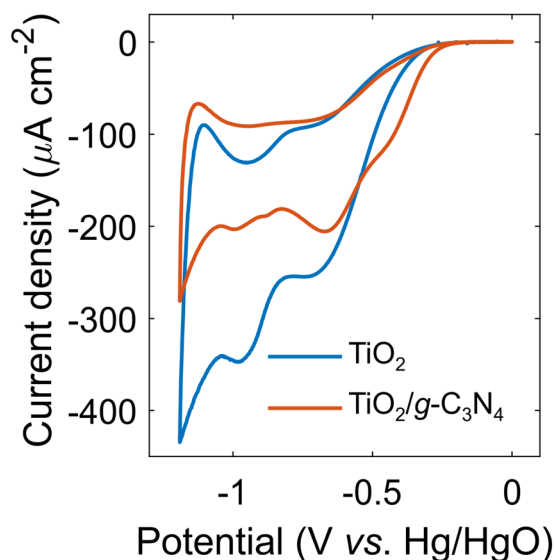


Fig. 7 Cyclic voltammograms for the ORR on the  $\text{TiO}_2$  (blue curve) and  $\text{TiO}_2/\text{g-C}_3\text{N}_4$  (red curve) thin films prepared on FTO at  $300^\circ\text{C}$ .



adsorption. In photocatalysis, the reduction of  $O_2$  by trapped electrons on  $TiO_2$  has been identified as the rate-limiting step in the oxidation of organic compounds,<sup>79,80</sup> whereas in electrocatalysis,  $O_2$  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,  $TiO_2/g-C_3N_4$  nanocomposites were prepared by polymerizing urea in the presence of  $TiO_2$ . Unlike urea, melamine was shown to be unsuitable as a precursor of  $g-C_3N_4$  formed in the presence of  $TiO_2$ . For non-lyophilized samples, the  $g-C_3N_4$  phase was formed after annealing at 200 or 300 °C. The lyophilization of the  $TiO_2$  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  $g-C_3N_4$  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  $TiO_2$  and  $TiO_2/g-C_3N_4$  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  $TiO_2/g-C_3N_4$  composite demonstrated a 14% increase in  $\cdot OH$  production in comparison to the lyophilized  $TiO_2$  powder. The  $TiO_2/g-C_3N_4$  thin film prepared at 300 °C showed a 70-mV reduction in the oxygen electroreduction overpotential compared to the bare  $TiO_2$  thin film.

The described synthetic approach differs from the previously reported procedures, which involved the preparation  $g-C_3N_4$  and  $TiO_2$  separately and then mixing them.<sup>35,36,42–44</sup> 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  $N_2$  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,  $N_2$  adsorption–desorption isotherms, and micropore size distributions. See DOI: <https://doi.org/10.1039/d5na00478k>.

## Acknowledgements

This work was supported by the Academy of Finland (Flagship Programme PREIN, decision 368653), the Horizon Europe MSCA FLORIN Project 101086142, MSCA YUFE4Postdocs Project 293210002415. The Pohjois-Savon Liitto DeepSurface projects (A78280 & A78303) support is acknowledged for XPS instrument acquisition and measurements.

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