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Effect of Vacuum Treatment Temperature on the Structure, Morphology, and Porous Characteristics of Reduced Graphene Oxide

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The effect of thermal reduction temperature on the structural, morphological, and porous characteristics of graphene oxide-derived materials was investigated. Graphene oxide films were thermally treated in vacuum at temperatures from 200 to 600°C, and the resulting materials were characterized by XRD, FTIR, SEM, and low-temperature nitrogen adsorption–desorption measurements with BET, NLDFT, and FHH analyses. The results showed that vacuum heat treatment induces a gradual transformation of graphene oxide into a disordered turbostratic reduced graphene oxide structure. Increasing treatment temperature is accompanied by progressive deoxygenation, morphological evolution from fragmented lamellar films to open frameworks of thin weakly stacked sheets, and pronounced development of porosity. The BET specific surface area increases from 61 m² g^{−1} for the material obtained at 200°C to 112, 197, 276, and 331 m² g^{−1} for the materials obtained at 300, 400, 500, and 600°C, respectively. It was demonstrated that thermal treatment temperature is a key parameter controlling the transformation of GO into porous turbostratic rGO.

Keywords: graphene oxide; reduced graphene oxide; thermal reduction; turbostratic structure; porosity; pore size distribution.

Received 19 April 2026; Accepted 17 August 2026; Published 21 August 2026.

Introduction

The reduction of graphene oxide (GO) into reduced graphene oxide (rGO) is a critical step in tailoring its structure and functional properties for applications in energy storage, catalysis, and electronic devices [1]. A variety of reduction strategies have been developed, including chemical [2], thermal [3], electrochemical [4] methods, each offering distinct advantages and limitations in terms of efficiency, scalability, environmental impact, and control the resulting material structure [5].

Chemical reduction, employing agents such as hydrazine or ascorbic acid, enables relatively low-temperature

processing and good restoration of electrical conductivity [6]. However, it is often associated with incomplete removal of oxygen functional groups, incorporation of residual impurities, and challenges related to toxicity and post-treatment purification. Electrochemical and hydrothermal approaches provide improved control over reduction pathways and defect engineering but are typically limited by processing complexity and difficulties in large-scale implementation [7].

Thermal reduction represents a particularly promising route for the scalable production of rGO. This method relies on rapid decomposition of oxygen-containing functional groups at elevated temperatures, resulting in

efficient exfoliation, significant restoration of the sp^2 carbon network, and the formation of highly porous structures. In contrast to conventional chemical reduction, thermal treatment does not require hydrazine or other solution-phase reductants, thereby avoiding reagent residues in the product and reducing the burden associated with washing, purification, and chemical waste management [8]. A key technological advantage of thermal reduction is its compatibility with large-scale processing. Thermal exfoliation has been described as a rapid and efficient route for producing graphene-based materials in large quantities, and recent process-oriented studies continue to emphasize its suitability for scalable manufacturing. This is particularly important for electrode materials, conductive additives, sorbents, and composite fillers, where reproducibility and throughput are more critical than atomically perfect graphene [9].

Another important benefit is that thermal reduction often generates a porous, low-density, expanded structure. Because oxygen functionalities decompose with gas release, the process can create interlayer voids and prevent dense restacking, which is advantageous for ion transport, electrolyte accessibility, and high specific surface area. Experimental studies have reported layered porous morphologies after thermal exfoliation, while more recent work shows that thermally processed rGO films can achieve mesoporosity and high surface area together with restored conductivity [10]. These features are especially valuable in supercapacitors, catalysis, adsorption, and other interfacial applications. Thus, the main strength of thermal reduction is not that it always yields the most structurally perfect graphene, but that it offers the best compromise between deoxygenation efficiency, pore generation, process speed, and scalability for many practical applications.

Detailed understanding of how thermal-treatment parameters govern the structure and properties of the resulting rGO is essential for both fundamental interpretation and process optimization. In particular, the reduction temperature and heating rate can substantially influence the extent of deoxygenation, defect formation, interlayer expansion, pore development, and restoration of electrical pathways. The establishing structure-processing relationships is necessary to identify the conditions that provide the most favorable balance between conductivity, porosity, and structural integrity. For this reason, the present study is focused on the influence of thermal-treatment conditions on the physicochemical properties of graphene oxide-derived materials and on determining the processing conditions most suitable for their targeted practical application.

I. Materials and Methods

Graphene oxide (GO) was synthesized using a modified Tour method in accordance with previously reported procedures [11]. Synthetic graphite powder (Aldrich, #282863, CAS 7782-42-5) with a particle size $<20\ \mu\text{m}$ was used as the starting material. The structural ordering of the initial graphite was confirmed by X-ray diffraction (XRD), which exhibited (002) reflection at $2\theta=26.65^\circ$ and a less intense peak at $2\theta=54.85^\circ$, while the

absence of a reflection near $2\theta \approx 43^\circ$ indicated its high crystallinity. Graphite powder was added to a pre-cooled acid mixture in a 1500 mL conical flask under continuous stirring in an ice bath ($2-5^\circ\text{C}$). The suspension was maintained at 0°C for 3 h to ensure homogeneous intercalation. Potassium permanganate (KMnO_4 , 36 g) was added at 5°C , followed by stirring for 30 min. The reaction mixture was heated to 40°C and maintained at this temperature for 1.5 h to promote oxidation. Distilled water (270 mL) was added dropwise under stirring, while maintaining the temperature below $60-65^\circ\text{C}$. The reaction was terminated by the addition of 30% hydrogen peroxide (H_2O_2 , 30 mL), resulting in a color change from dark brown to yellow. The system was diluted with 250 mL of water, yielding a light-yellow colloidal dispersion with $\text{pH} \approx 2$.

The dispersion was subjected to ultrasonic treatment (22 kHz, 50-55 W) for 30 min (six cycles of 5 min). The resulting suspension was centrifuged at 1000 rpm; supernatant was washed until $\text{pH}\ 5.0-5.5$ was achieved. The purified GO dispersion was dried at room temperature (sample marked as Initial) or in air at 100°C (sample marked as G100), yielding light-yellow films with a thickness of 0.5-0.7 mm. Thermal reduction of GO was carried out by rapid heating of the obtained films under controlled conditions. Thermal reduction was performed using G100 sample. The films were placed in a quartz ampoule evacuated with a rotary forevacuum pump to a residual pressure of about 10 Pa and heated in a tubular furnace at a rate of $25^\circ\text{C}\ \text{min}^{-1}$ to the target temperature of 200, 300, 400, 500, or 600°C . The samples were held at the target temperature for 30 min, after which the ampoule was removed from the furnace and cooled to room temperature outside the heating zone. An increase in the heat-treatment temperature led to a rise in the dispersion of the materials. The most pronounced morphological changes were observed in the $200-300^\circ\text{C}$ temperature range, indicating structural rearrangement already at the initial stage of thermal reduction. The obtained materials were marked G200-G600 according to the thermal reduction temperature. The sample prepared at 200°C (G200) still preserved the features of a fragmented film, whereas the samples obtained at higher temperatures appeared as dispersed powders. The degree of agglomeration decreased with increasing heat-treatment temperature.

The obtained materials were characterized by X-ray diffraction (XRD) using a Shimadzu XRD-7000 diffractometer with $\text{Cu}\ K\alpha$ radiation ($\lambda = 1.5406\ \text{\AA}$), operated at 40 kV and 30 mA. The diffraction patterns were recorded in the 2θ range of $5-80^\circ$ with a step size of 0.02° . The average crystallite size (stacking thickness) was calculated from the XRD peak broadening using the Scherrer equation, $D = \frac{K\lambda}{\beta \cos \theta}$, where D is the crystallite size, $K=0.89$ is the shape factor, λ is the X-ray wavelength, β is the full width at half maximum of the diffraction peak, and θ is the Bragg angle.

Fourier-transform infrared (FTIR) spectra of the obtained materials were recorded using a Shimadzu IRXcross spectrometer in the wavenumber range of $4000-500\ \text{cm}^{-1}$ with a resolution of $2\ \text{cm}^{-1}$. The FTIR measurements were performed to determine the presence

of oxygen-containing functional groups and to evaluate the evolution of the surface chemical structure during the thermal reduction of graphene oxide.

The porous structure of the obtained materials was studied by low-temperature nitrogen adsorption-desorption measurements using a Quantachrome Nova 2200e porosimeter at 77 K. The samples were degassed under mild conditions at 100°C for 3 h in order to minimize the possible influence of thermal pretreatment on the structure. The specific surface area was calculated using the Brunauer-Emmett-Teller (BET) method. The pore size distribution was determined from the adsorption branch of the isotherms using the non-local density functional theory (NLDFT) approach.

The morphology of the obtained materials was studied by scanning electron microscopy (SEM) using a Sigma 360 VP microscope (Zeiss Gemini 1 column). The images were acquired under high-vacuum conditions ($>10^{-6}$ Pa) using a secondary electron detector at an accelerating voltage of 5 kV. SEM analysis was employed to examine the changes of surface morphology induced by thermal reduction at different temperatures.

II. Results and Discussion

The XRD patterns (Fig.1) of the G100 and G200 samples were analysed by deconvolution into Lorentzian components. In both cases, the low-angle peak centered at 11.70° for G100 and 12.13° for G200 was assigned to the (001) reflection of graphene oxide, indicating the preservation of the layered structure. At the same time, a second broad peak located at 23.56° for G100 and 24.16° for G200 was attributed to a graphitic-type (002) reflection associated with disordered turbostratic carbon domains or partially restored stacked graphene layers. The pronounced width of this component indicates a low degree of structural ordering and a small thickness of coherent scattering regions along the stacking direction. A comparison of the two samples shows that the transition from G100 to G200 is accompanied by a shift of the (001) peak toward higher angles, which corresponds to a decrease in the interlayer spacing of the GO phase, as well as by an increase in the area and height of the broad graphitic-type component. This behavior suggests that heat treatment at 200°C already induces partial deoxygenation and structural rearrangement of the layered system, leading to the formation of a larger fraction of graphene-like domains with short-range interlayer ordering. G200 retains the features of graphene oxide, but already exhibits signs of the onset of thermal reduction and transformation toward a more disordered rGO structure.

The interlayer spacing corresponding to the (001) reflection decreased from 0.756 nm for G100 to 0.729 nm for G200, while the broad graphitic-type peak corresponded to d-values of 0.377 and 0.368 nm, respectively. The average crystallite thickness estimated from the Scherrer equation was 3.62 nm for the (001) GO phase in G100 and 2.68 nm in G200 that are within the range reported for GO in the literature [12, 13].

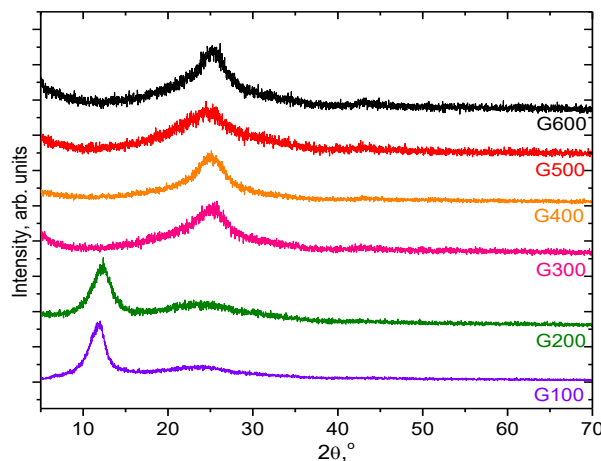


Fig. 1. XRD patterns of graphene oxide film (G100) and materials obtained by vacuum thermal treatment of this sample at 200°C (G200), 300°C (G300), 400°C (G400), 500°C (G500) and 600°C (G600).

In contrast, the broad graphitic-type component near 24° yielded lower apparent values, 0.65 and 0.58 nm, respectively, reflecting the highly disordered character and very short-range stacking of the partially restored carbon layers. The XRD patterns for the G300-G600 samples could be fitted with a single Lorentzian, indicating the disappearance of the low-angle (001) reflection characteristic of graphene oxide and, consequently, the loss of the regular oxidized layered structure. The only broad diffraction maximum was observed at 24.72° (G300), 24.83° (G400), 24.72° (G500), 24.92° (G600) and was assigned to the graphitic-type (002) reflection of disordered turbostratic carbon. The corresponding interlayer spacing, calculated from Bragg's law, was 0.360 nm for G300, 0.358 nm for G400, 0.360 nm for G500, and 0.357 nm for G600, which is noticeably smaller than that of the GO phase and approaches the values typical of reduced graphene oxide. At the same time, the substantial width of this reflection indicates that the stacking order remains limited. According to the Scherrer equation, the coherent scattering region thickness associated with this graphitic-type phase was 1.09 nm for G300, 1.43 nm for G400, 0.89 nm for G500, and 1.21 nm for G600. These results show that after heat treatment at 300°C and above, the oxidized layered GO structure is no longer detected by XRD, while the material is dominated by poorly ordered graphene-like domains with short-range interlayer stacking. The rGO crystallite thickness did not exhibit a monotonic dependence on the reduction temperature. Thus, although increasing temperature promotes deoxygenation and local structural rearrangement, the applied treatment conditions remain insufficient for the development of extended graphitic stacking order.

SEM reveals temperature-driven evolution from dense GO film to open turbostratic rGO framework (Fig.2). The initial GO sample exhibits a compact lamellar film-like morphology formed by overlapped sheets, whereas after treatment at 100°C the film becomes fragmented into aggregates with a more heterogeneous surface. This indicates that even mild heating is sufficient to disrupt the integrity of the dried GO film, although the oxidized layered structure is still preserved according to XRD.

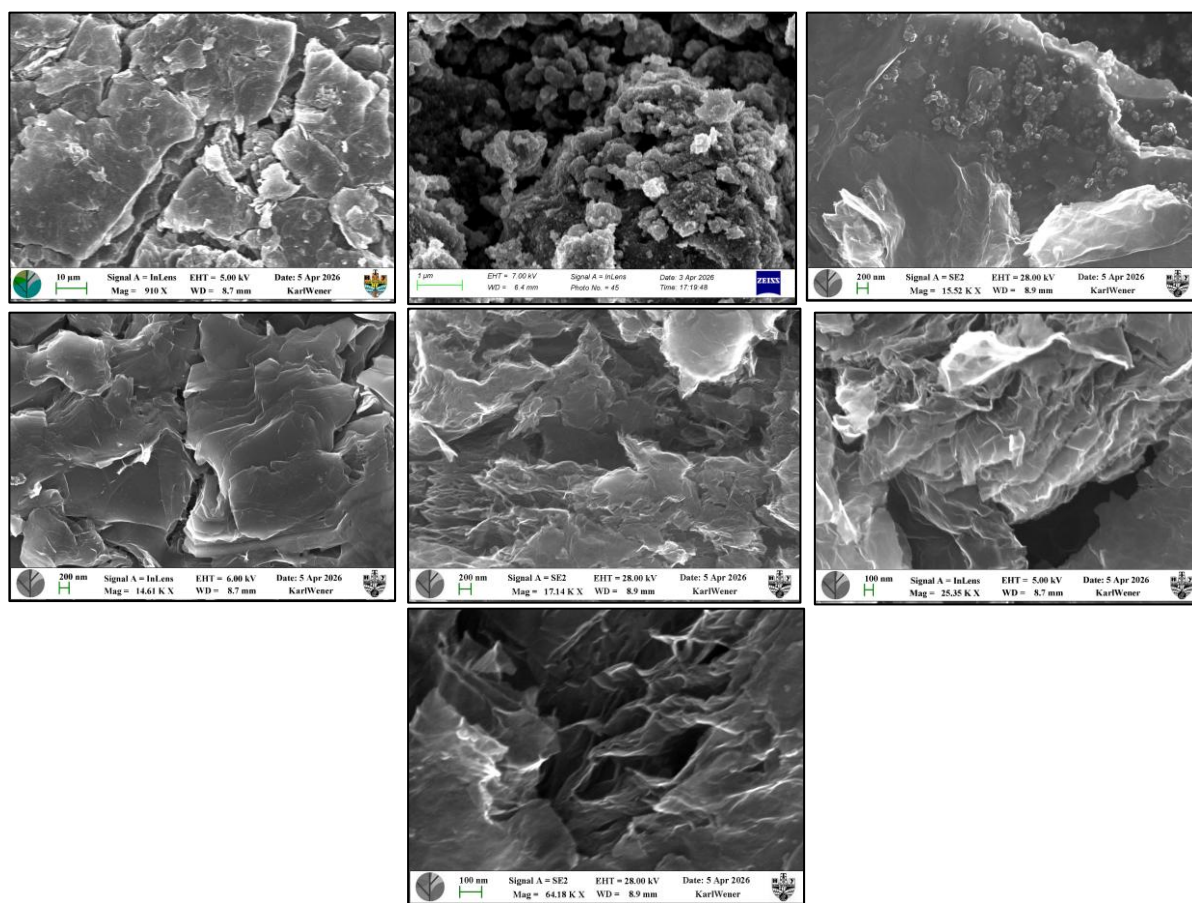


Fig. 2. SEM images of GO films dried at room temperature (initial) and at 100°C as well as for materials obtained by vacuum thermal treatment of graphene oxide film (G100) at 200°C (G200), 300°C (G300), 400°C (G400), 500°C (G500) and 600°C (G600).

The G200 sample retains a fragmented lamellar morphology, but already shows partial delamination, pronounced folding and wrinkling, local separation of adjacent layers, and the onset of pore formation, consistent with the coexistence of residual GO and turbostratic rGO domains. In G300, the morphology changes to irregular flake-like aggregates composed of folded and partially exfoliated sheets with slit-like voids, in agreement with the disappearance of the GO-related (001) reflection and the increase in accessible surface area. Samples G400–G600 are characterized by progressively more open rGO frameworks built of thin, weakly stacked graphene-like sheets. In G400 exfoliation and the formation of slit-shaped intersheet voids are evident. G500 exhibits a more corrugated and texturally heterogeneous morphology, reflecting the coexistence of exfoliation and local restacking. G600 shows the open-textured structure, with thin, crumpled lamellae, intersheet voids, and minimal packing density.

The FTIR spectrum of the initial GO film dried at room temperature is typical of highly oxidized graphene oxide (Fig.3). The broad band centered at 3264 cm^{-1} can be attributed to O–H stretching vibrations of hydroxyl functionalities and hydrogen-bonded adsorbed water, in agreement with the typical spectra reported for graphene oxide materials [14]. The band at 1715 cm^{-1} is assigned to the stretching vibration of carbonyl groups, mainly carboxylic/carbonyl functionalities, whereas the absorption near 1625 cm^{-1} is commonly associated with the skeletal vibration of sp^2 carbon domains, often with a

contribution from the bending vibration of adsorbed water [15]. An increase in the treatment temperature led to the attenuation and eventual disappearance of the bands at 950, 1053, 1239, 1392, 1625, and 1715 cm^{-1} , indicating removal of oxygen-containing functional groups and destruction of the oxidized GO structure. The bands at 1053 and 1239 cm^{-1} are associated with C–O and epoxy-related vibrations [16]. The band near 1392 cm^{-1} can be assigned to C–OH/O–H deformation vibrations; however, a contribution from sulfate-related species cannot be excluded for GO samples prepared in strongly acidic sulfate-containing media [17, 18]. The absorption at 1715 cm^{-1} is attributed to the C=O stretching vibration of carboxyl and other carbonyl-containing groups in graphene oxide [17]. Their weakening with increasing temperature is consistent with the thermal reduction pathway of GO, in which intercalated water and oxygen functionalities are eliminated, while the carbon framework undergoes deoxygenation and partial restoration of conjugation.

For the samples obtained at $\geq 300^\circ\text{C}$ the spectrum is consisting of broad bands at about 1566 and 1173 cm^{-1} . The broad mode near 1566 cm^{-1} can be assigned to the skeletal C=C stretching vibration of the restored sp^2 -conjugated carbon network [19]. The broad band around 1173 cm^{-1} can be attributed to residual C–O-containing functionalities (epoxy groups) that remain after thermal reduction [20].

The nitrogen adsorption-desorption isotherms of G200 and G300 provide additional evidence for the trans-

formation of GO into a porous disordered rGO structure (Fig.4).

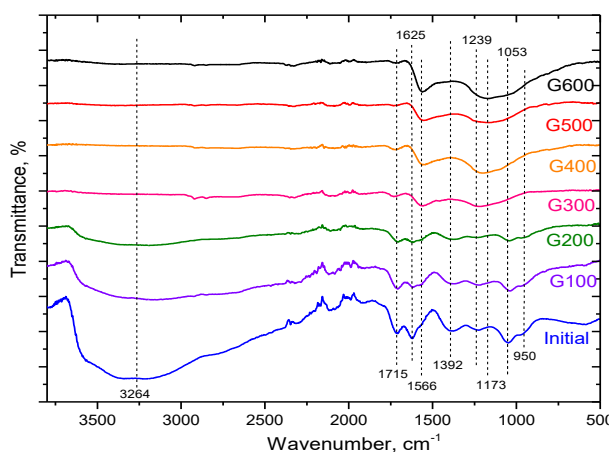


Fig. 3. FTIR spectra of GO films dried at room temperature (initial) and at 100°C as well as for materials obtained by vacuum thermal treatment of graphene oxide film (G100) at 200°C (G200), 300°C (G300), 400°C (G400), 500°C (G500) and 600°C (G600).

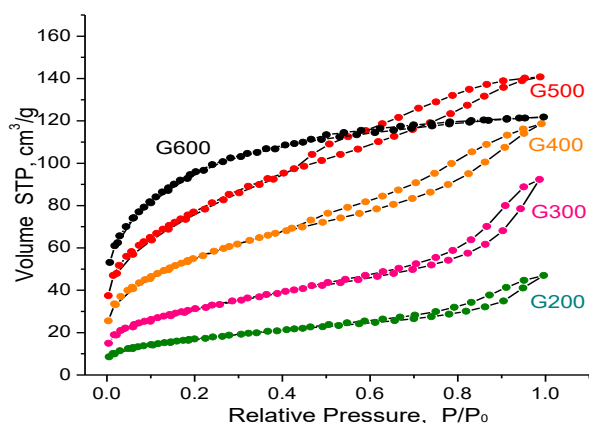


Fig.4. Nitrogen adsorption/desorption isotherm of materials obtained by vacuum thermal treatment of graphene oxide film (G100) at 200°C (G200), 300°C (G300), 400°C (G400), 500°C (G500) and 600°C (G600).

In the case of G200, the isotherm shows a moderate nitrogen uptake at low and intermediate relative pressures together with a pronounced increase in adsorption at high P/P_0 , accompanied by a hysteresis loop. That indicates the presence of mesoporosity, while the still limited adsorption in the low-pressure region suggests that the material retains a relatively compact character. Such textural features are consistent with the XRD data, according to which G200 still preserves the (001) reflection of GO and therefore contains a fraction of the oxidized layered phase, although the simultaneous appearance of the broad graphitic-type (002) component confirms the onset of thermal reduction and partial structural rearrangement. The G300 isotherm is characterized by a higher adsorption capacity over the whole pressure range and a developed hysteresis loop, indicating an increase in accessible surface area and mesopore volume. This change correlates with the XRD data, where the disappearance of the GO-related (001) reflection and the presence of only a broad turbostratic (002) peak demonstrate the loss of the regular oxidized

layered structure. The transition from G200 to G300 reflects not only further deoxygenation, but also a development of porosity caused by exfoliation of stacked GO layers and the formation of poorly ordered graphene-like domains separated by slit-shaped pores. The BET specific surface areas of G200 and G300 samples are 61 and 112 $\text{m}^2\cdot\text{g}^{-1}$, respectively. The nitrogen adsorption-desorption isotherms of G400, G500, and G600 reveal the development of a porous rGO framework with increasing reduction temperature. The G400 and G500s samples exhibit a pronounced adsorption in the low-pressure region combined with a broad hysteresis loop at intermediate and high relative pressures, which is typical of mesoporous carbon materials with slit-shaped pores. An increase in the overall nitrogen uptake is observed from G400 to G500, reflecting progressive exfoliation and deoxygenation. Correspondingly, the BET specific surface area increases from 197 $\text{m}^2\cdot\text{g}^{-1}$ for G400 to 276 $\text{m}^2\cdot\text{g}^{-1}$ for G500. The G500 sample shows the highest adsorbed volume near saturation, indicating the largest total pore volume within this part of the series and suggesting a particularly well-developed system of larger mesopores and interparticle voids. In contrast, G600 exhibits a lower total nitrogen uptake at high P/P_0 than G500, but a steeper adsorption at low and intermediate pressures and a higher BET surface area (331 $\text{m}^2\cdot\text{g}^{-1}$). This combination suggests that heat treatment at 600°C leads to a redistribution of the porous structure toward a larger contribution of smaller, more surface-efficient pores, while the fraction of larger mesopores decreases. Thus, in agreement with XRD data, the transition from G300 to G600 does not involve the formation of ordered graphite-like stacks, but rather a gradual densification and textural refinement of the turbostratic rGO structure, accompanied by an increase in accessible surface area and a non-monotonic evolution of total pore volume.

The NLDFT pore size distributions (Fig.5) of G200 and G300 reveal the predominance of narrow mesopores-micropores and confirm the temperature-induced development of the porous structure. For G200, the main contribution is centered at about 1.15 nm, accompanied by a broad tail toward larger pore diameters, indicating a heterogeneous system of slit-shaped pores and interaggregate voids. For G300, the distribution becomes more intense and better resolved, with characteristic maxima at approximately 1.54 and 3.30 nm, evidencing the formation of a more developed mesoporous framework. The NLDFT pore size distributions of G400, G500, and G600 reveal a progressive temperature-induced redistribution of pore volume toward the low-diameter region. G400 is characterized by a major maximum at 1.15 nm and a secondary contribution at 3.30 nm, reflecting a heterogeneous micro/mesoporous structure. G500 exhibits a more complex multimodal distribution with peaks at 1.00, 1.66, and 3.30 nm, indicating further differentiation of the fine pore system. In contrast, G600 is dominated by a sharp peak at 1.30 nm with only a weak secondary feature at 3.66 nm, demonstrating that the porous framework becomes increasingly governed by micropores and very narrow mesopores at the highest reduction temperature. These results confirm that the increase in temperature from 400 to 600 °C leads to textural refinement of the turbostratic rGO structure and

the predominance of small slit-like pores responsible for the high accessible surface area.

The fractal dimensions were calculated from the nitrogen adsorption isotherms using the Frenkel-Halsey-Hill (FHH) method [21]. The FHH approach is employed for porous carbon materials and rGO to characterize surface roughness and pore heterogeneity on the basis of gas adsorption data [22]. Reports on GO nanosheets and graphene-oxide-containing porous carbons further support the use of this method for GO/rGO-derived materials. In the present work, the FHH fractal dimension was used as an additional descriptor of the structural heterogeneity developed during thermal reduction [23]. The FHH representations (Fig.6) of G200 and G300 exhibit two

distinct linear regions, evidencing bimodal fractal behavior and, therefore, a structurally heterogeneous porous framework. For G200, the fractal dimensions were estimated as 2.54 and 2.79 for the two regions, while for G300 the corresponding values were 2.52 and 2.77. In both samples the higher fractal dimension is associated with the region related to finer pore structure, indicating a greater degree of surface and pore irregularity at smaller length scales. The close similarity of the obtained values suggests that thermal treatment from 200 to 300°C preserves the fractal character of the GO-derived carbon framework, while promoting further opening of the porous structure. The FHH plots of G400, G500, and G600 reveal bimodal fractal behavior with two linear regions,

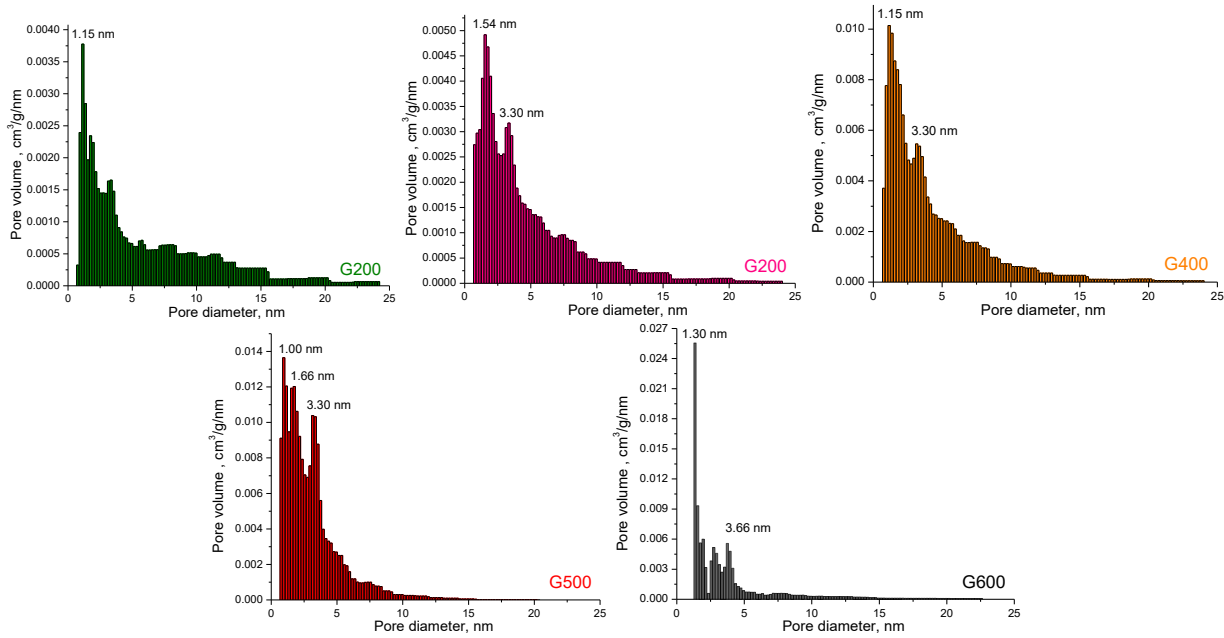


Fig. 5. NL-DFT pore size distributions for materials obtained by vacuum thermal treatment of graphene oxide film at 200°C (G200), 300°C (G300), 400°C (G400), 500°C (G500) and 600°C (G600).

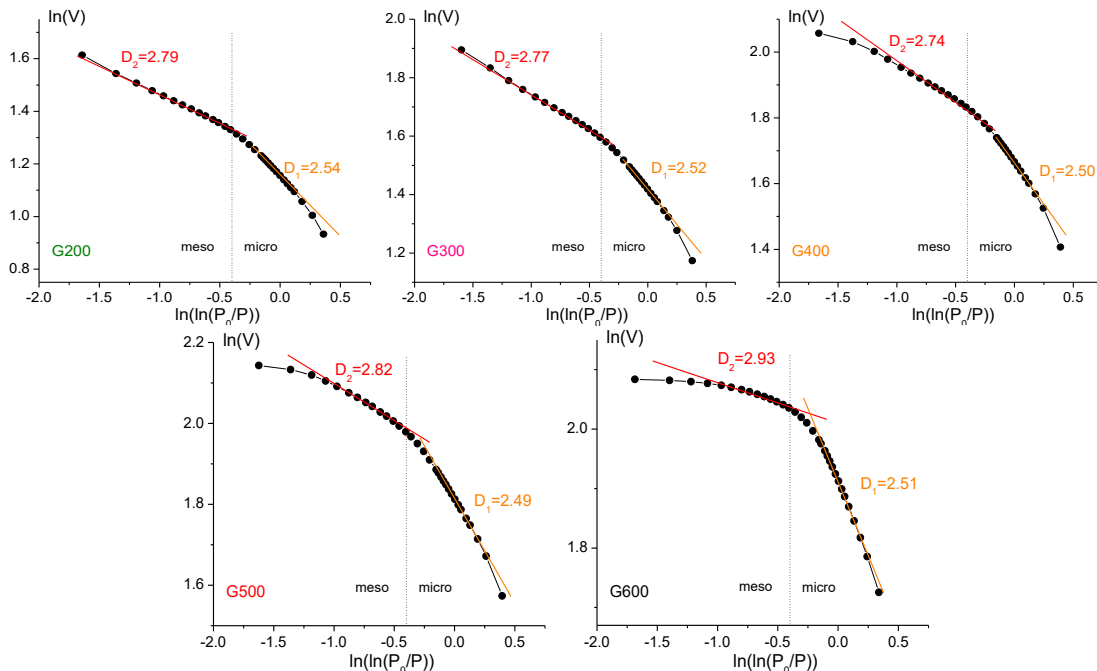


Fig. 6. FHH plots for materials obtained by vacuum thermal treatment of graphene oxide film at 200°C (G200), 300°C (G300), 400°C (G400), 500°C (G500) and 600°C (G600).

confirming the hierarchical nature of the porous structure. The calculated fractal dimensions are 2.50 and 2.74 for G400, 2.49 and 2.82 for G500, and 2.51 and 2.93 for G600. While the first fractal dimension remains nearly constant, the second increases systematically with increasing reduction temperature, indicating that the smaller-scale pore domain becomes progressively more irregular and complex. This trend is consistent with the adsorption and NLDFT results, which point to the formation of an increasingly fine-porous and surface-developed rGO structure at higher temperatures. The G600 sample is characterized by a flattened first FHH region and the highest value of the second fractal dimension ($D=2.93$), suggesting that high-temperature reduction produces a particularly heterogeneous fine-pore structure with highly rough internal surfaces.

Conclusions

The effect of thermal reduction temperature on the structural, morphological, and porous characteristics of graphene oxide-derived materials was investigated. It was shown that vacuum heat treatment induces a gradual transformation of GO into a disordered turbostratic rGO structure. At 200°C, the material still retains residual GO features, whereas from 300°C the structure corresponds to rGO. The increase in treatment temperature is accompanied by progressive deoxygenation,

morphological evolution from fragmented lamellar films to open frameworks of thin weakly stacked sheets, and pronounced development of porosity. The BET specific surface area increases from 61 m² g⁻¹ for the material obtained at 200 °C to 112, 197, 276, and 331 m² g⁻¹ for the materials obtained at 300, 400, 500, and 600°C, respectively. NLDFT and FHH analyses further indicate a redistribution of porosity toward micropores and narrow mesopores together with increasing structural heterogeneity, most pronounced for the material obtained at 600°C. These results provide a basis for rational selection of thermal-treatment conditions for the preparation of rGO materials intended for applications requiring high surface area and developed fine porosity, including adsorption, catalysis, electrochemical energy storage, and functional carbon-based composites.

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Вплив температури вакуумної термообробки на структуру, морфологію та пористість відновленого оксиду графену

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Досліджено вплив температури термічного відновлення на структурні і морфологічні характеристики матеріалів, отриманих на основі оксиду графену. Плівки оксиду графену піддавали термообробці у вакуумі в інтервалі температур 200–600°C, а отримані матеріали характеризували методами XRD, FTIR, SEM та низькотемпературної адсорбції–десорбції азоту із застосуванням аналізів BET, NLDFT і FHH. Показано, що вакуумна термообробка зумовлює поступову трансформацію оксиду графену в неупорядковану турбостратну структуру відновленого оксиду графену. Підвищення температури обробки супроводжується прогресуючою деоксигенацією, морфологічною еволюцією від фрагментованих плівок до відкритих каркасів із слабко зв'язаних ламелярних частинок, а також вираженим розвитком пористості. Питомою площею поверхні BET зростає від 61 м²/г для матеріалу, отриманого при 200 °C, до 112, 197, 276 і 331 м²/г для матеріалів, отриманих при 300, 400, 500 і 600°C відповідно. Показано, що температура термообробки є ключовим параметром, який визначає трансформацію GO у пористий турбостратний rGO.

Ключові слова: оксид графену; відновлений оксид графену; термічне відновлення; турбостратна структура; пористість; розподіл пор за розмірами.