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Sustainable Conversion of Palm Kernel Shell Biomass to Acid-Functionalized Graphene Oxide

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ABSTRACT

The development of sustainable carbon-based nanomaterials has stimulated increasing interest in the use of biomass-derived precursors for graphene oxide (GO) synthesis. However, studies utilizing palm kernel shell (PKS), an abundant agricultural by-product generated from palm oil processing, remain limited despite its high carbon content and availability, particularly in palm oil-producing regions like Malaysia. This study investigates the feasibility of synthesizing GO from PKS using Tour's method and explores its subsequent functionalization with varying concentrations of nitric acid (0.2 M to 1.0 M) to enhance acidity. The synthesized and functionalized GO were analyzed using Fourier-transform infrared spectroscopy (FTIR), UV–visible spectroscopy (UV–Vis), and thermogravimetric analysis (TGA) to characterize the oxidation level, functional groups, and thermal stability. FTIR analysis confirmed the introduction of oxygen-containing functional groups onto the GO surface, while UV-Vis spectroscopy revealed characteristic absorption peaks confirming successful oxidation and exfoliation of the carbonized PKS. TGA demonstrated reduced thermal stability of GO compared to carbonized PKS, consistent with the incorporation of thermally unstable oxygen functionalities. Functionalization with nitric acid resulted in a gradual decrease in pH from 2.06 (untreated GO) to 1.68 (GO functionalized with 1.0 M HNO_3), indicating improved surface acidity. This pH reduction followed a non-linear trend with a plateau beyond 0.8 M HNO_3, suggesting saturation of available reactive sites on the GO surface that limits further functionalization. The findings demonstrate that PKS is a viable and sustainable precursor for GO synthesis and that functionalization with nitric acid can effectively modulate its surface acidity for potential future applications.

Keywords: Graphene Oxide, Palm Kernel Shell, Tour's Method, Functionalization, Surface Acidity

INTRODUCTION

Graphene oxide (GO) is a two-dimensional carbon material derived from the oxidation of graphitic precursors, consisting of carbon, hydrogen, and oxygen atoms arranged in a hexagonal carbon lattice with various oxygen-containing functional groups attached to the basal planes and edges (Silva et al. 2024). Unlike pristine graphene, which is hydrophobic and chemically inert, GO exhibits hydrophilic character due to the presence of oxygen functionalities such as epoxy, hydroxyl, and carboxyl groups. These functional groups render GO highly dispersible in aqueous media and provide reactive sites for further chemical modification, making it an attractive platform for diverse applications (Heydari et al. 2020; Geetha Bai et al. 2021; Makhsin et al. 2021; Obayomi et al. 2022).

The unique structural and chemical properties of GO have stimulated extensive research interest across multiple disciplines. In catalysis, GO serves as a promising metal-free catalyst or catalyst support owing to its high specific surface area, tunable surface chemistry, and the presence of acidic functional groups that can participate in acid-catalyzed reactions (Heydari et al. 2020). In environmental remediation, GO-based materials have demonstrated exceptional adsorption capacity for various pollutants, including heavy metals, organic dyes, and emerging contaminants, due to their abundant active sites and π-π

interactions with aromatic compounds (Obayomi et al. 2022). Additionally, GO has found applications in energy storage devices, biomedical imaging, drug delivery, and sensor technologies, highlighting its versatility as an advanced functional material (Geetha Bai et al. 2021; Makhsin et al. 2021).

Conventional GO synthesis methods, such as Hummer's method, modified Hummer's method, Brodie's method, Staudenmaier's method, and Hoffman's method, have been extensively employed for GO production from graphite precursors (Yu et al. 2016; Miao et al. 2021). While these methods are effective in achieving high degrees of oxidation, they present significant limitations in terms of cost-effectiveness, scalability, environmental impact, and operational safety (Marcano et al. 2010). Most conventional approaches involve the use of concentrated strong acids and powerful oxidants under controlled conditions. Specifically, methods incorporating sodium nitrate ($NaNO_3$), such as Hummer's and modified Hummer's methods, generate toxic gaseous by-products including nitrogen dioxide (NO_2) and dinitrogen tetroxide (N_2O_4), which pose serious health and environmental hazards (Chasanah et al. 2022). These safety concerns, coupled with the challenges of waste disposal and energy-intensive reaction conditions, have motivated the search for greener and more sustainable synthesis routes.

In response to these limitations, Tour and colleagues developed an improved oxidation method that eliminates the use of $NaNO_3$ while maintaining high oxidation efficiency (Marcano et al. 2010). The Tour's method employs a 9:1 mixture of sulfuric acid (H_2SO_4) and phosphoric acid (H_3PO_4) as the reaction medium, with potassium permanganate ($KMnO_4$) as the primary oxidant. The exclusion of $NaNO_3$ not only prevents the generation of toxic NO_x gases but also enhances the oxidation efficiency, yielding GO with a more highly oxidized and regular structure compared to conventional Hummer's method (Kotsyubynsky et al. 2021; Adem et al. 2025).

Conventional GO synthesis has typically relied on graphite as the carbon precursor. However, increasing attention has been directed toward renewable biomass sources as sustainable and cost-effective alternatives. Agricultural residues such as rice husk (Ismail et al. 2019), coconut husk (Sahila & Littis 2020), and other lignocellulosic materials have been investigated as potential precursors for carbon nanomaterial production. These biomass-derived precursors offer several advantages: they are abundantly available, renewable, low-cost, and their utilization contributes to waste valorization and circular economy principles (Widyaningrum et al. 2021; Gozan et al. 2023).

Among various agricultural residues, palm kernel shell (PKS) stands out as a particularly attractive precursor for GO synthesis. PKS is a by-product of palm oil processing, generated in enormous quantities in palm oil-producing countries such as Malaysia, Indonesia, and Thailand. As a major global producer of palm oil, Malaysia generates approximately 168 million tonnes of palm oil biomass annually, including empty fruit bunches, mesocarp fiber, and PKS (Zamri et al. 2022). This massive waste stream often presents significant disposal challenges, with conventional practices such as landfilling or open burning contributing to environmental pollution and greenhouse gas emissions. Meanwhile, PKS possesses several intrinsic properties that make it advantageous for GO production. Compared to other biomass precursors, PKS exhibits higher fixed carbon content and lower ash content, resulting in more efficient conversion to graphitic structures upon carbonization (Widyaningrum et al. 2021). Therefore, converting PKS into value-added products such as GO provides an environmentally friendly waste valorization strategy while addressing the need for sustainable carbon precursors.

Although the synthesis of GO from PKS has been studied in previous research (Widyaningrum et al. 2021), systematic investigation of the functionalization of PKS-derived GO to enhance its surface properties remains limited. Enhancing the catalytic performance of GO often requires controlled modification to increase its surface acidity, as the density and strength of acidic sites directly influence catalytic activity in acid-catalyzed reactions. Strategies for increasing GO surface acidity include covalent and non-covalent functionalization, and heteroatom doping with elements such as nitrogen, sulfur, or phosphorus (Farooq et al. 2022).

Among various functionalization agents, nitric acid (HNO_3) has emerged as a particularly effective and accessible reagent for introducing oxygen-containing functional groups onto carbon surfaces. When applied to GO, nitric acid reacts with carbon atoms at defect sites and edges, leading to the formation of additional carboxyl, hydroxyl, and epoxy groups, thereby enhancing the overall surface acidity (Zhu et al. 2021; Tao et al. 2023). The degree of functionalization can be modulated by controlling reaction parameters such as acid concentration, temperature, and duration. However, a critical challenge lies in achieving significant acidity enhancement without compromising the structural integrity of GO, as overly aggressive acid treatment can lead to excessive oxidation, fragmentation, or degradation of the carbon lattice (Jankovský et al. 2017).

The present study addresses this challenge by investigating the effect of nitric acid concentration (0.2 M to 1.0 M) on the functionalization of GO derived from PKS via the greener Tour's method. The research focuses on characterizing changes in surface chemistry, thermal behavior, and acidity following treatment with varying

nitric acid concentrations. By establishing the relationship between acid concentration and surface acidity, this work aims to provide practical guidance for optimizing the functionalization of PKS-derived GO for potential future applications.

METHODOLOGY

MATERIALS

Palm kernel shell (PKS) was obtained from a local palm oil processing facility in Melaka, Malaysia. The raw PKS was thoroughly washed with distilled water to remove dirt, oil residues, and impurities, and was subsequently dried in an oven at 105°C for 24 hours to constant weight. Analytical-grade sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4), potassium permanganate ($KMnO_4$), hydrogen peroxide (H_2O_2, 30%), and nitric acid (HNO_3) were purchased from Sigma-Aldrich and used without further purification. All solutions were prepared using deionized water.

CARBONIZATION OF PALM KERNEL SHELL

The cleaned and dried PKS was crushed into smaller pieces using a mechanical grinder to facilitate uniform carbonization. The crushed PKS was placed in ceramic crucibles and subjected to carbonization in a muffle furnace under controlled atmosphere. The temperature was ramped from room temperature to 700°C at a heating rate of 10°C/min and maintained at 700°C for 3 hours to ensure complete carbonization and partial graphitization. After carbonization, the furnace was allowed to cool naturally to room temperature. The resulting carbonized PKS (CPKS) was collected and ground into a fine powder to ensure uniform particle size for subsequent oxidation.

SYNTHESIS OF GRAPHENE OXIDE USING TOUR'S METHOD

Graphene oxide was synthesized from CPKS following the Tour's method adapted from Marcano et al. (2010). A mixture of H_2SO_4 and H_3PO_4 was prepared in a volume ratio of 9:1 (360 mL H_2SO_4: 40 mL H_3PO_4) in a beaker immersed in an ice bath. The acid mixture was stirred continuously using a magnetic stirrer at 150 rpm for 30 minutes to ensure homogeneous mixing. Three grams of CPKS powder was slowly added to the acid mixture under constant stirring, followed by gradual addition of 1.8 g of $KMnO_4$. The addition of $KMnO_4$ was performed carefully over 30 minutes to prevent excessive heat generation and uncontrolled exothermic reaction. Throughout the addition process, the temperature was maintained below 50°C using the ice bath and monitored continuously using a thermometer. After complete addition of $KMnO_4$, the ice bath was removed, and the mixture was stirred continuously for 12 hours at room temperature. After 12 hours, 3 mL of 30% hydrogen peroxide (H_2O_2) was slowly added to eliminate excess potassium permanganate. The mixture was stirred for an additional 10 minutes to ensure complete reaction.

The resulting suspension was filtered under vacuum filtration, and the solid precipitate was washed with 200 mL of 30% HCl to remove metal ions and residual salts, followed by centrifugation at 5000 rpm for 10 minutes. The supernatant was discarded, and the washing procedure was repeated twice with fresh HCl. Subsequently, the solid was washed repeatedly with deionized water until the pH of the wash water reached approximately 6-7 (neutral). The washed product was dried in a vacuum oven at 90°C for 24 hours to obtain the final GO powder.

FUNCTIONALIZATION OF GRAPHENE OXIDE

Functionalization of the synthesized GO was performed using nitric acid (HNO_3) at varying concentrations to enhance surface acidity. A stock solution of GO was prepared (designated as 'solution A') by dispersing 500 mg of GO in 500 mL of deionized water to obtain a concentration of 1 mg/mL. The dispersion was sonicated using an ultrasonic bath at a fixed power output of 150 W for 1 hour to ensure homogeneous dispersion. Separately, five functionalization solutions (designated as 'solution B') were prepared by dissolving 4 mL of HNO_3 at different concentrations (0.2 M, 0.4 M, 0.6 M, 0.8 M, and 1.0 M) together with 6 g of NaOH in 200 mL of deionized water. The addition of NaOH serves to control the reaction medium and promote dispersion stability of GO during the functionalization process. The alkaline environment created by NaOH facilitates controlled oxidation while preventing excessive structural degradation that might occur under acidic conditions alone (Rochman et al. 2019).

For each functionalization experiment, 100 mL of solution A was slowly added to solution B while stirring constantly at 150 rpm using a magnetic stirrer for 1.5 hours at room temperature. After completion of the functionalization reaction, the resulting functionalized GO was collected by vacuum filtration and washed thoroughly with 500 mL of acetone to remove organic by-products, followed by extensive washing with deionized water until the wash water reached neutral pH. This extensive washing protocol ensures complete removal of any residual free acid or base, thereby confirming that the measured acidity

in the final product originates from surface-bound functional groups rather than unreacted reagents. The washed product was dried in an oven at 80°C for 24 hours. Samples were labelled as f-GO1 through f-GO5 corresponding to increasing HNO_3 concentrations from 0.2 M to 1.0 M, respectively.

CHARACTERIZATION TECHNIQUES

The GO samples were analyzed using FTIR, UV-Vis spectroscopy and thermogravimetric analysis (TGA). FTIR analysis was performed to identify the presence of functional groups in the GO samples. Samples were blended with potassium bromide (KBr), ground into a fine powder, and compressed into pellets. Spectra were recorded in the range of 400 to 4500 cm^{-1}. UV-Vis spectroscopy was employed to investigate the electronic transitions and degree of oxidation of the GO samples. Sample dispersions (25 mg of GO in 25 mL of deionized water, sonicated for 1 hour) was measured across a wavelength range from 220 nm to 700 nm. TGA was used to assess the thermal stability of GO by measuring weight changes as a function of temperature. Approximately 5 mg of GO samples were heated from 30°C to 700°C at a heating rate of 10°C/min under a nitrogen atmosphere.

ACIDITY MEASUREMENT

The total acidity of GO samples was determined using acid-base titration following established procedures for quantifying acidic functional groups on graphene oxide (Ederer et al. 2016). All GO samples were first dispersed in deionized water at identical concentrations (1 mg GO/mL deionized water) and sonicated for 30 minutes to ensure uniform dispersion. A 25 mL aliquot of GO dispersion was transferred into an Erlenmeyer flask, and phenolphthalein indicator was added. The sample was titrated with 0.1 M NaOH solution, which was slowly added from a burette until the endpoint, indicated by a faint pink color change, was reached. The volume of NaOH used was recorded. The molarity of GO (M_1) was calculated using Equation 1:

$$M_1V_1 = M_2V_2 \quad (1)$$

where M_1 is the molarity of the GO solution, V_1 is the volume of GO solution used, M_2 is the molarity of the NaOH solution, and V_2 is the volume of NaOH used. The molarity values (M_1) obtained were then used to determine apparent pH using Equation 2:

$$pH = -\log(M_1) \quad (2)$$

The pH values determined using Equation 2 provide an apparent acidity indicator for comparison across samples, assuming complete dissociation of acidic groups under titration conditions (Ederer et al. 2016).

RESULTS AND DISCUSSION

SYNTHESIS OF GRAPHENE OXIDE FROM PALM KERNEL SHELL

The synthesis of graphene oxide (GO) from palm kernel shell (PKS) was achieved using Tour's method, which is known for its strong oxidative capability and effectiveness in breaking down aromatic carbon structures. During the oxidation stage, the reaction mixture transitioned from a dark brown suspension to a thick paste with a greenish-black tint, as shown in Figure 1, suggesting significant oxidation of the carbonaceous structure (Widyaningrum et al. 2021).

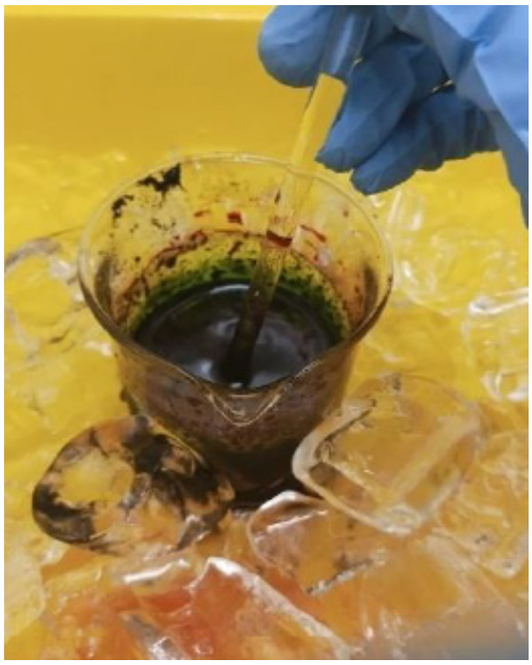

FIGURE 1. The dark green mixture produced during the synthesis of GO using Tour's method

The use of biomass-based precursors for GO synthesis has been reported in several studies involving materials such as rice husk (Ismail et al. 2019), coconut husks (Sahila & Littis, 2020), and cellulosic biomass (Ahmed-Haras et al. 2020). Each precursor presents unique characteristics that influence the properties of the resulting GO. Rice husk-derived GO, for instance, often contains significant silica residues that may require additional purification

steps. Coconut husk-derived materials have demonstrated good adsorption properties but may exhibit lower carbon yields.

Compared to these alternative biomass sources, PKS possesses distinct advantages for GO production. PKS typically exhibits higher fixed carbon content and lower ash content relative to other agricultural residues, making it uniquely advantageous for producing GO. The high carbon content ensures efficient conversion to graphitic structures during carbonization, while the low ash content minimizes interference from inorganic impurities that could affect oxidation efficiency (Widyaningrum et al. 2021). The observation of the expected color changes and phase transformations throughout the reaction, consistent with previous studies on GO synthesis from biomass precursors, supports the feasibility of PKS as a viable precursor for GO synthesis.

FTIR ANALYSIS

FTIR was employed to identify the functional groups present in the synthesized GO and to confirm successful oxidation of the carbonized PKS precursor. The FTIR spectrum of the synthesized GO (Figure 2) revealed several characteristic absorption bands that provide evidence for the introduction of oxygen-containing functional groups. A prominent peak observed at 1077.52 cm^{-1} is attributed to C-O stretching vibrations, indicating the presence of epoxy and alkoxy groups on the GO surface. These functional groups are crucial markers of GO formation, as they represent the primary oxygen functionalities introduced during the oxidation process (Marcano et al. 2010; Aliyev et al. 2019). These functional groups enhance the hydrophilicity and provide reactive sites for further chemical modifications. The peak at 1573.33 cm^{-1} corresponds to C=C stretching vibrations from unoxidized graphitic domains within the GO structure, reflecting the balance between oxidized and non-oxidized regions for structural integrity of GO while ensuring sufficient sites for functionalization (Kausar, 2021). The peak observed at 2356.35 cm^{-1} is attributed to adsorbed CO_2 on the porous GO structure, which is commonly observed in carbonaceous materials due to their high surface area and porosity (Gao et al. 2022; Roble et al. 2025). The peak at 2960.86 cm^{-1} corresponds to C-H stretching vibrations from alkyl groups, possibly originate from residual organic matters of the PKS precursor or synthesis solvents (Ismail et al. 2019). These groups can potentially be targeted in subsequent functionalization processes to further enhance acidity.

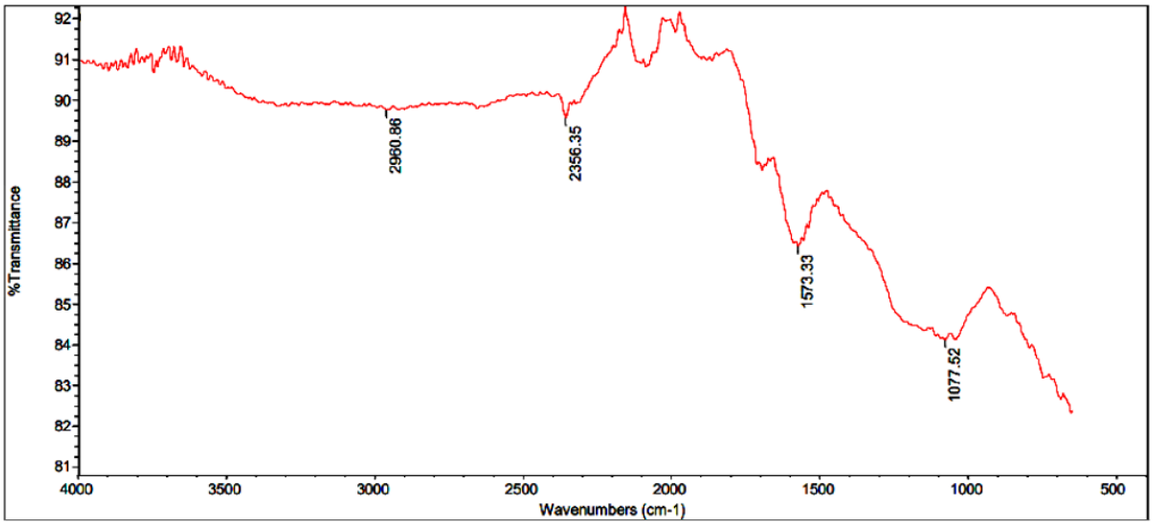

FIGURE 2. FTIR spectra of synthesized GO powder showing characteristic functional groups

UV-VIS SPECTROSCOPY ANALYSIS

UV–Vis spectroscopy was employed to investigate the electronic transitions associated with oxidation in GO synthesized from PKS. The UV-Vis spectra presented in Figure 3 compare the absorption characteristics of carbonized PKS (CPKS), synthesized GO, and commercial GO (CGO). The CPKS spectrum exhibited absorbance peaks between 243 nm and 286 nm, corresponding to $\pi-\pi*$ transitions of aromatic C=C bonds within the carbonized structure. These transitions are characteristic of conjugated carbon systems and indicate the presence of graphitic domains formed during the carbonization process (Makhsin et al. 2021). Upon oxidation, the main absorption peak of

the synthesized GO shifted from 260 nm (in CPKS) to 276 nm, suggesting an increase in degree of conjugation and successful exfoliation and oxidation of the PKS precursor (Geetha Bai et al. 2021).

A broad shoulder was observed in the synthesized GO spectrum at 309 nm, which was absent in the CPKS spectrum. This shoulder is assigned to n-π* electronic transitions associated with carbonyl (C=O) functional groups, confirming the introduction of oxygen-containing functional groups during the synthesis of GO from PKS using Tour's method (Saxena et al. 2011; Mahich et al. 2024). This feature is comparable to that of CGO, which exhibits a similar shoulder at around 311 nm, albeit with a slight wavelength shift. The minor shift observed in the synthesized GO may be associated with differences in the degree of oxidation and the distribution of oxygen functional groups (Lesiak et al. 2015).

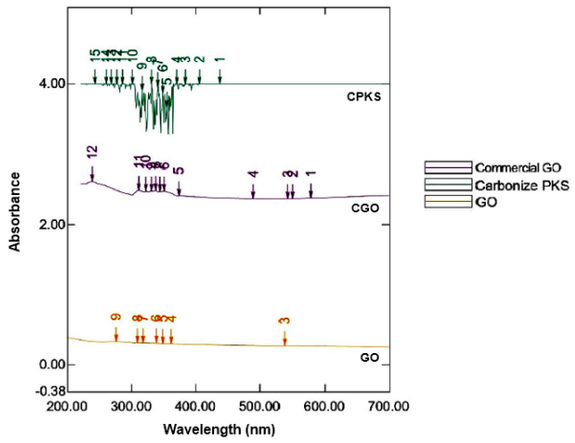

FIGURE 3. UV-Vis absorption spectra of carbonize PKS (CPKS), synthesized GO and commercial GO (CGO)

When comparing the overall absorption intensity, CGO (peak at 238 nm) showed significantly higher absorbance than synthesized GO (peak at 276 nm). This difference implies that CGO possesses a higher concentration of conjugated systems and potentially a higher degree of oxidation, with more homogeneous distribution of oxygen-containing functional groups. These differences are expected given that CGO is produced from high-purity graphite under optimized industrial conditions, whereas biomass-derived GO synthesis is still under development and subject to greater variability in precursor quality and reaction conditions (Aliyev et al. 2019; Kausar 2021).

The effect of nitric acid functionalization on the properties of GO was also examined, as shown in Figure 4. All functionalized samples (f-GO1 to f-GO5) showed shoulder peaks between 311 nm and 334 nm, corresponding to n-π* transitions of carbonyl groups. Sample f-GO5, treated with the highest nitric acid concentration (1.0 M), exhibited the highest absorbance in this region, indicating the greatest degree of oxidation among the functionalized samples, primarily due to increased carbonyl (C=O) groups. This trend shows that increasing nitric acid concentration enhances the incorporation of oxygen-containing functional groups into the GO structure (Andrade et al. 2013).

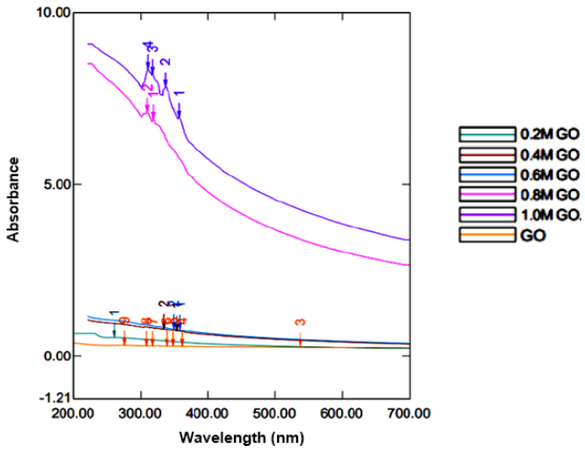

FIGURE 4. UV-vis absorption spectra of GO and functionalized GO (f-GO1 to f-GO5) treated with increasing HNO_3 concentrations (0.2 M to 1.0 M HNO_3)

THERMOGRAVIMETRIC ANALYSIS (TGA)

TGA analysis was conducted to evaluate the thermal stability of the synthesized GO and to provide complementary evidence for GO formation. Figure 5 presents the TGA thermograms of carbonized PKS (CPKS), synthesized GO, and commercial GO (CGO) over the temperature range of 30°C to 700°C under nitrogen atmosphere. The CPKS sample exhibited relatively high thermal stability, with gradual weight loss of approximately 10-15% over the entire temperature range. The high thermal stability of CPKS reflects its predominantly carbonaceous nature with relatively few thermally unstable functional groups. On the other hand, the synthesized GO sample displayed significantly lower thermal stability. The weight loss, amounting to approximately 20% of the initial mass, is attributed to the thermal decomposition of oxygen-containing functional groups, including hydroxyl, epoxy, and carboxyl groups (Li et al. 2021).

In contrast to synthesized GO and CPKS, CGO exhibited lower overall weight loss throughout the TGA analysis. While CPKS showed minimal weight loss due to its thermally stable carbonaceous structure and synthesized GO displayed significant decomposition, CGO demonstrated a comparatively smaller weight loss profile.

This lower weight loss may be due to differences in the carbon source or precursor material, as well as variations in synthesis conditions. CGO is typically produced from high-purity graphite under optimized and controlled processes, which may yield a more ordered structure with fewer thermally unstable defects compared to biomass-derived GO. Additionally, the synthesis conditions for CGO may involve milder oxidation, resulting in reduced incorporation of easily decomposable oxygen functionalities. These factors potentially contribute to the enhanced thermal stability observed for CGO relative to the synthesized GO and CPKS.

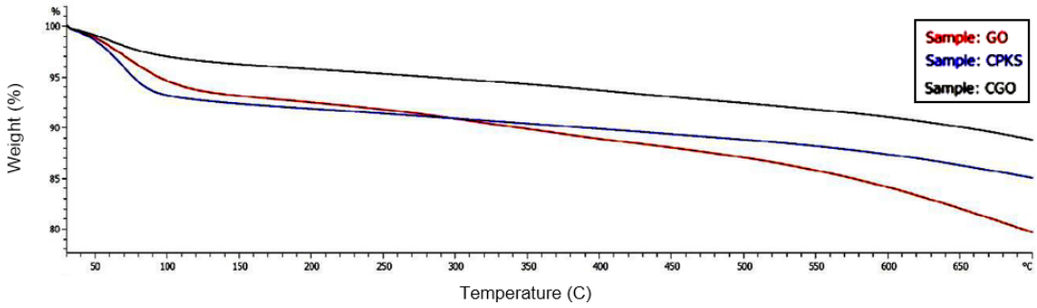

FIGURE 5. TGA thermograms for CPKS, synthesized GO and CGO showing thermal decomposition behavior

ACIDITY STUDY

The investigation into the effect of nitric acid concentration on the acidity of functionalized GO revealed a clear trend: as the concentration of nitric acid increased, the pH of the GO suspension progressively decreased, indicating the successful introduction of acidic functionalities onto the GO surface (Figure 6). The untreated GO synthesized from PKS exhibited a pH of 2.06, indicating intrinsic acidity arising from the oxygen-containing functional groups introduced during the Tour's method oxidation. This baseline acidity confirms that the synthesized GO possesses acidic surface character even without additional functionalization. Upon functionalization with 0.2 M HNO_3 (f-GO1), the pH decreased to 1.89, representing a measurable increase in acidity. Further increases in acid concentration led to progressive pH reduction: 0.4 M (f-GO2) to pH 1.77; 0.6 M (f-GO3) to pH 1.76; 0.8 M (f-GO4) to pH 1.70; and 1.0 M (f-GO5) to 1.68, confirming enhanced surface acidity upon nitric acid functionalization.

This pH decline is primarily attributed to the introduction of additional oxygen-containing functional groups, particularly carboxylic acid groups (-COOH), onto the GO surface during functionalization. These functional groups dissociate in aqueous media, releasing protons (H^+) into the solution and thereby increasing the acidity of the GO suspension (Tao et al. 2023). The pH values reported herein represent the apparent proton concentration in GO suspensions determined via acid-base titration, providing a practical measure of effective GO acidity in suspension rather than an absolute quantification of surface acid site density (Ederer et al. 2016).

Although the overall trend shows increasing acidity with higher nitric acid concentration, the pH decrease was not strictly linear. A plateau was observed beyond 0.8 M HNO_3, suggesting a saturation effect wherein the limited availability of reactive sites on the GO surface restricts further functionalization. (Jankovsky et al. 2017; Zhu et al. 2021).

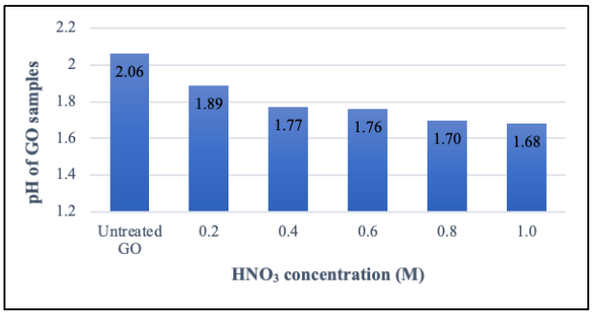

FIGURE 6. The trend of decreasing pH of GO samples with increasing nitric acid concentration used for functionalization

CONCLUSION

The results of this study confirm that PKS is a promising biomass precursor for the green synthesis of GO. The oxidation of carbonized PKS to GO was successfully executed using the Tour's method, which offers significant safety and environmental advantages over conventional Hummer's-type methods through its exclusion of $NaNO_3$ and consequent avoidance of toxic NO_x gas generation.

Characterization via FTIR, UV–Vis, and TGA confirmed the introduction of oxygen-containing functional groups and revealed changes in thermal behavior consistent with GO formation. Functionalization with nitric acid effectively enhanced the surface acidity of GO, as reflected by a progressive decrease in pH with increasing acid concentration. This pH reduction confirms the successful incorporation of additional acidic functional groups onto the GO surface.

While FTIR, UV–Vis, and TGA analyses provide useful evidence of chemical modification and thermal properties, they do not fully resolve structural parameters such as defect density, interlayer spacing, or crystallographic order. Advanced characterization methods such as Raman spectroscopy, X-ray diffraction, and electron microscopy techniques would be necessary to quantitatively assess structural changes following GO synthesis and the subsequent nitric acid functionalization. Therefore, the present study focuses primarily on chemical functionalization and surface acidity rather than on definitive structural characterization. Future work should incorporate these complementary techniques to provide a more complete understanding of structure-property relationships in PKS-derived GO.

Overall, the findings indicate that PKS-derived GO can be successfully synthesized and functionalized in alignment with green chemistry principles, supporting the valorization of agricultural waste into value-added materials. This study provides a foundation for further investigation ino the catalytic, electrochemical, and adsorptive applications of PKS-derived GO in chemical engineering fields.

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DECLARATION OF COMPETING INTEREST

None.

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