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Characterization of Green-Synthesized Reduced Graphene Oxide using *Aloe vera* Extract and Its Application for Surface Water Treatment

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Abstract: Reduced graphene oxide (rGO) is a carbon-based material with high surface area and chemical stability, making it an effective adsorbent for water purification. This study investigates the green synthesis of rGO using *Aloe vera* extract as a natural reducing agent and its application in treating surface water from the Kapuas River, Indonesia. Graphene oxide was reduced with *Aloe vera* extract under varying time conditions, and the resulting rGO samples were characterized to confirm the reduction process. The structural and compositional analyses revealed that increasing reduction time enhanced oxygen removal and improved surface morphology. The application tests showed that rGO substantially improved water quality: color decreased from 225 to 95 PCU (57.8% reduction), turbidity dropped from 16.2 NTU to 1.2 NTU (92.4% removal), and dissolved iron concentration decreased from 0.65 ppm to 0.37 ppm (43.07% removal), with pH remaining stable near 6.5. Among all samples, rGO reduced for 120 minutes achieved the highest purification efficiency. These findings demonstrate the feasibility of *Aloe vera*-reduced rGO as a sustainable adsorbent for surface water purification.

Keywords: Adsorption; *Aloe vera* Extract; Green synthesis; Reduced graphene oxide; Surface water treatment

Introduction

The growing concerns over freshwater scarcity and declining surface water quality have prompted an urgent need for effective, low-cost, and sustainable water purification technologies. Rivers are among the most critical surface water sources for the support of a variety of daily necessities, including domestic, agricultural, fisheries, and industrial activities. Nevertheless, the quality of river water has substantially declined as a result of the escalating anthropogenic activities in the river basin, which have rendered rivers as locations for waste disposal (Yanti et al., 2022). In West Kalimantan, the Kapuas River has a crucial role as the main source of raw water for the local community. Dissolved iron (Fe), which contributes to increased turbidity and a brownish color of the water, is one of the primary issues indicating the deterioration of the water quality of the Kapuas River. High levels of turbidity and color not only reduce the aesthetic quality of river water but also disrupt the habitat of aquatic organisms. Therefore, a water treatment process is needed to enhance the water quality of the Kapuas River.

Among the various methods available for improving water quality, adsorption has emerged as one of the most versatile and efficient techniques for pollutant removal (Albatrni et al., 2021). Adsorption is the process of attaching an adsorbate onto the surface of an adsorbent when it comes into contact. However, the performance of adsorption-based purification systems is primarily determined by the surface area characteristics

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of the adsorbent material. For example, conventional adsorbents such as activated carbon derived from biomass can improve water quality and reduce pollutants, but they require more than one hour of contact time (Andrio et al., 2024; Harmawanda et al., 2023; Sumila et al., 2023; Wahyuni et al., 2022). This performance is insufficient for rapid water treatment because the adsorption capacity often remains limited due the small surface area of the adsorbent. As a result, current research efforts have shifted toward developing new classes of carbon-based nanomaterials with tunable surface functionality, higher surface area, and enhanced reactivity to improve adsorption efficiency.

One of the adsorbents that has gained significant attention as an advanced adsorbent and functional material for environmental remediation is reduced graphene oxide (rGO) which is a reduced derivative of graphene oxide (GO) (Soffian et al., 2022; Tuan et al., 2024; Yang et al., 2021). Its two-dimensional structure, large specific surface area (up to 2600 m^2/g), and abundance of reactive sites enable strong interactions with both metal ions and organic molecules (Pei & Cheng, 2012). As a result, the oxidized graphene sheets in GO are partially restored to a structure resembling pristine graphene, characterized by a significantly lower concentration of oxygen functionalities (Razaq et al., 2022). These improvements make rGO an excellent candidate for applications such as sensors (Lee et al., 2019), supercapacitors (Doloksaribu et al., 2025), and adsorbents for water purification (Gupta & Khatri, 2017). Nevertheless, most rGO synthesis routes employ chemical reductants, such as Zn, which pose environmental and safety concerns due to toxicity, high cost, and the potential for secondary contamination (Kusrini et al., 2019; Wahyuni et al., 2025). The drive toward more sustainable materials has thus accelerated interest in green synthesis approaches using natural reducing agents.

Green synthesis methods represent a sustainable alternative that utilizes plant extracts, microorganisms, or biopolymers as reducing and stabilizing agents in nanomaterial fabrication (Saini et al., 2024; Tewatia et al., 2020; Utkan et al., 2023). Plant extracts contain bioactive compounds, such as flavonoids, polyphenols, saponins, terpenoids, and reducing sugars, that can donate electrons to metal ions or oxidized carbon species, thereby converting GO to rGO without the need for harsh chemical reductants (Bhattacharya et al., 2017). *Aloe vera* extract has been identified as a promising green reducing agent due to its richness in phytochemicals that exhibit effective oxygen-scavenging capability, which facilitates the removal of oxygen functional groups from GO (Ramanathan et al., 2017). Moreover, *Aloe vera* is inexpensive, renewable, and abundantly available in tropical regions such as Indonesia, making it an ideal candidate for sustainable nanomaterial production.

Although rGO that is reduced using *Aloe vera* has demonstrated a high adsorption capacity, achieving 98% removal of methylene blue dye (Bhattacharya et al., 2017) and hazardous organic dyes (Parthipan et al., 2021), the material was used in controlled environments. Real surface waters, such as rivers, present a much more complex matrix of organic matter, colloidal particles, and dissolved ions, all of which can interact competitively with adsorbent surfaces. To date, there has been a scarcity of studies that directly apply *Aloe vera*-reduced rGO to natural river water systems, leaving a significant gap in understanding the effectiveness of green synthesized rGO under realistic conditions.

Another key factor that remains underexplored is the effect of reduction time on the physicochemical properties and performance of *Aloe vera*-reduced rGO. Reduction duration can critically influence the removal of oxygen functionalities, crystallite size, and surface morphology, which in turn affect adsorption behavior and selectivity (Das et al., 2024; Lesiak et al., 2021). Thus, an optimal balance between reduction completeness and surface functionality is essential to optimize the performance of rGO. Nevertheless, existing studies on green-synthesized rGO predominantly focus on the type and concentration of plant extract or the reduction temperature, while the temporal evolution of the reduction process has received minimal attention. In this context, the present study introduces a novel approach by systematically varying the reduction time in the green synthesis of rGO using *Aloe vera* extract as a natural reducing agent. This investigation aims to elucidate how different reduction durations influence the degree of deoxygenation, defect restoration, and the formation of surface-active sites in *Aloe vera*–mediated rGO.

The novelty of this research lies in addressing these gaps by exploring the green synthesis of rGO using *Aloe vera* extract as a natural reducing agent under sonication-assisted conditions and evaluating how reduction time influences the structural and adsorption characteristics of the resulting material using real surface water samples from the Kapuas River, focusing on key parameters including turbidity, color, and iron content. The approach not only minimizes environmental impact during synthesis but also offers a sustainable and scalable pathway for producing functional nanomaterials from locally available biological resources. Furthermore, by systematically varying the reduction time, this work elucidates the interplay between reduction kinetics, structural order, and adsorption capacity to determine the optimal synthesis and application performance.

Method

Materials

The materials used in this study were graphene oxide (GO, $C_{140}H_{42}O_{20}$) produced by the NRE Laboratory, with a stated purity of 99% with 6 - 7 layers. Fresh *Aloe vera* (*Aloevera aloesinensies*) was purchased from the *Aloe vera* Center in Pontianak, Indonesia. Kapuas River water, representing a real contaminated surface water matrix, was collected directly from the riverbank in Pontianak (0°02'31.8"S 109°21'16.3"E) using sterilized glass bottles and stored at 4°C until use. All other reagents were of analytical grade and used as received without further purification.

Preparation of Aloe vera Extract Solution

The *Aloe vera* extract was prepared by collecting mature leaves, washing them thoroughly to remove surface contaminants, first with tap water then with aquadest. After that, the spiny margins were removed and the outer green layer was peeled off, then the clear inner gel was separated. To prepare the *Aloe vera* gel as reduction agent, we homogenized 7.5 g of *Aloe vera* gel in 10 mL of deionized water using a magnetic stirrer at room temperature for 10 minutes to ensure uniform dispersion of phytochemicals (Bhattacharya et al., 2017).

Green Synthesis of rGO

The synthesis process, described in Figure 1, began by weighing 0.04 grams of GO flakes and mixing them with 70 mL of distilled water in a beaker. The mixture was stirred using a magnetic stirrer for 30 minutes to ensure homogeneity and to disperse the GO flakes effectively (Bhattacharya et al., 2017). Following the stirring step, we added the 10 mL of *Aloe vera* solution into the mixture and underwent sonication for varying durations of 60, 90, and 120 minutes, indicated as rGO-60, rGO-90, and rGO-120, respectively, with the aim of reducing the oxygen-containing functional groups on the GO structure, thereby enhancing its properties as an adsorbent (Das et al., 2024). The sonication process in the presence of *Aloe vera* extract activates its bioactive compounds, which interact with GO, preventing phase separation and allowing the composite to remain well-dispersed in the solution. After that, the solution was centrifuged to obtain the rGO powder. The successful reduction of GO was visually indicated by a color change of the mixture to blackish, signifying the removal of oxygen groups. The mixture was washed and dried in an air oven at 110°C to remove residual water and obtain solid rGO powder. The dried rGO samples were ground and stored in airtight containers for further characterization and adsorption experiments.

Figure 1. Synthesis stage of rGO using *Aloe vera* extract

Characterization of rGO

A scanning electron microscopy combined with energy dispersive X-ray (SEM-EDX, Tescan Vega 4 LMH) was used to characterize rGO. The surface morphology was examined via SEM at 10 kV. EDX analysis was simultaneously used to evaluate the elemental composition, with particular focus on the carbon-to-oxygen (C/O) atomic ratio as an indicator of reduction success. Functional groups present in the synthesized rGO samples were identified using Fourier-transform infrared spectroscopy (FTIR, Bruker Alpha II) in the range of 400-4000 cm^{-1}. The spectra were used to assess the degree of oxygen group removal and evaluate the presence of key bonds such as C=O, C–O, O–H, and

C=C. The diffraction patterns corresponding to the transformation of GO into rGO were observed using a Panalytical Aeris X-ray diffractometer operated with Cu-Kα radiation (λ = 1.54 Å). Diffraction patterns were collected over a 2θ up to 90°, and peak shifts were interpreted to determine the extent of reduction and structural restoration of rGO. The interlayer spacing of GO and rGO from the XRD results was also calculated using Bragg's law, as shown in Equation (1).

$$d = \frac{n\lambda}{2\,\mathrm{Sin}\theta} \quad (1)$$

where d is the interlayer spacing, λ is the wavelength of the X-ray used (1.54 Å for the Cu-Kα source), and θ is the diffraction angle obtained from the XRD pattern.

Adsorption Experiments with Kapuas River Water

The adsorption performance of the green synthesized rGO was evaluated using raw water samples from the Kapuas River. The initial water quality measurements indicated a color value of 225 PCU and an iron (Fe) concentration of 0.65 ppm, determined using a color checker and iron checker (HANNA Instruments). In addition, the turbidity and pH were measured at 16.23 NTU and 6.73, respectively, employing a turbidity meter and pH meter (PCE Instruments). Batch experiments were conducted in 250 mL beaker glass, each containing 200 mL of river water and 0.08 g of rGO. The suspensions were stirred magnetically at 150 rpm for 30 minutes at room temperature to ensure uniform dispersion of rGO throughout the solution. The contact time was set to 1 hour then measure some parameters, which are color, turbidity, iron concentration, and pH of the treated river water wheremeasured. The obtained data were used to calculate the removal efficiency of Fe, turbidity, and color using Equation (2).

$$\text{Degradation (\%)} = \frac{(C_i - C_t)}{C_i} \times 100 \quad (2)$$

where C_i represent the initial concentration of the tested parameter, and C_t denotes the concentration of the parameter after treatment.

Result and Discussion

FTIR Analysis of Synthesized rGO

The FTIR analysis results of rGO are presented in Figure 2. FTIR characterization was performed to identify the chemical functional groups present in the rGO sample, particularly the oxygen-containing groups remaining after the reduction process. The transmittance spectrum was recorded over an infrared wavenumber range of 400–4000 cm^{-1}. Typically, the functional groups found in rGO include C=C, C–O, C=O, and O–H bonds (Hidayat et al., 2019). These functional groups are interconnected, forming a hexagonal carbon atom structure with covalent bonds, predominantly involving C=C linkages.

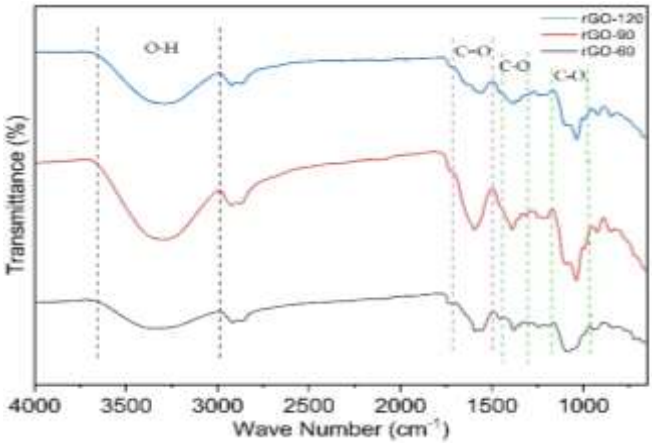

Figure 2. FTIR spectra of rGO with variations of reduction times

FTIR characterization in Figure 2 indicates the presence of O–H functional groups in the wavenumber range of 3200–3350 cm^{-1}, while C=O and C–O functional groups were detected in the range of 1600–1700 cm^{-1} and 1000–1300 cm^{-1}, respectively. The O–H band indicates the presence of hydroxyl groups, typically associated with residual water molecules or surface-bound OH groups (Putri et al., 2023). For rGO-90, the O–H stretching vibrations band appeared with relatively high intensity, signifying that significant hydroxyl functionality remained. These hydroxyls may stem from incomplete reduction or the adsorption of water molecules via hydrogen bonding to oxygenated sites on the graphene sheet. The C=O stretching band is commonly attributed to carbonyl groups, which are abundant in GO and are reduced during the synthesis of rGO. In our data, the intensity of this band decreased as the reduction time increased. This reduction suggests the successful transformation of part of the carbonyl species. Meanwhile, the C–O stretching bands are associated with epoxy and alkoxy groups on the basal plane and edges of GO sheets. The presence of these peaks in all samples indicates that not all epoxide or alkoxy groups were removed. This is consistent with prior studies that suggest green reductants like plant extracts may only partially remove oxygen functionalities due to their moderate redox potential (Parthipan et al., 2021).

In addition, the samples also show N–H bonds (1580–1640 cm^{-1}), which may originate from amine groups derived from residual solvents or reagents used during the rGO synthesis process, as well as N=O bonds (920–950 cm^{-1}) associated with nitro groups from nitrogen-containing compounds. However, in this

study, C=C functional groups were not clearly observed in any of the samples, indicating that the reduction of GO to rGO was incomplete and may affect the material's structural integrity and adsorption performance. Nevertheless, it was observed that as the sonication time increased, the intensity of oxygen-related peaks (O–H, C=O, C–O) decreased. This indicates that sonication time affects the degree of reduction, with longer times favoring more complete deoxygenation. This phenomenon is consistent with the findings of Bhattacharya et al. (2017), which states that the sono-chemical process promotes better interaction between the phytochemicals in *Aloe vera* (e.g., flavonoids, tannins, saponins) and the GO surface, enhancing electron transfer and chemical conversion of oxidized groups.

XRD Analysis of Synthesized rGO

X-ray Diffraction (XRD) analysis was performed to investigate the structural changes in GO reduced using Aloe vera extract to form rGO. The structural transformation from GO to rGO is typically accompanied by a shift in diffraction peaks, which can be interpreted as evidence of oxygen group removal. The diffraction patterns presented in Figure 3 display characteristic peaks corresponding to both GO and rGO. The XRD patterns of rGO-60, rGO-90, and rGO-120 show a systematic structural evolution consistent with progressive reduction and partial restoration of the graphitic framework.

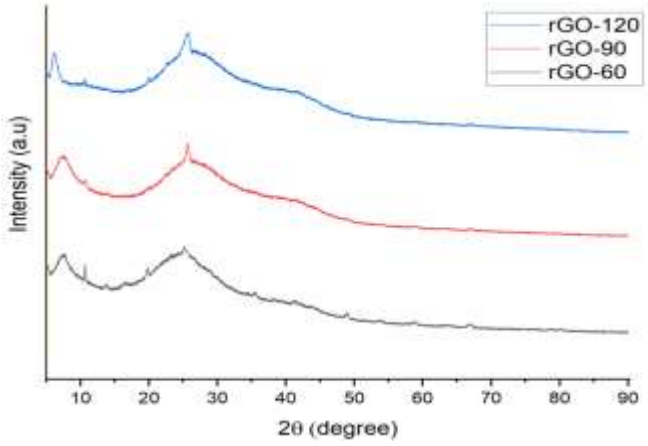

Figure 3. XRD patterns of rGO with different reduction times

The initial diffraction peaks of GO identified in each variation were observed at 2θ values of 7.61°, 7.53°, and 6.28°, for rGO-60, rGO-90, and rGO-120, respectively. These results are consistent with previous studies reporting GO diffraction peaks within a similar range (Hidayah et al., 2017). This peak is indicative of the oxidized form of graphene with expanded interlayer spacing due to the presence of oxygen-containing groups. In addition to this, a low-angle hump near 2θ values of 10.65 to 10.66° is visible in rGO-60 and rGO-90 but is substantially attenuated in rGO-120. The diffraction peaks of GO have also been reported to appear within the 2θ range of 10–12°, and are attributed to the (001) reflection plane (Jiao et al., 2017). This residual GO-type reflection indicates the presence of remnant oxidized regions or incomplete exfoliation in the less reduced samples. Its disappearance in rGO-120 further supports a higher reduction efficiency for this sample, as further evidenced by the appearance of a sharper rGO peak in the same sample. Nevertheless, the incomplete reduction of oxygen functional groups during the sonication-assisted *Aloe vera* proces led to an imperfect rGO structure, as indicated by the residual oxygen detected in the samples, potentially limiting the maximum adsorption capacity of the material. Therefore, future research is recommended to optimize the reduction parameters to achieve more complete oxygen removal.

Following the reduction process, new diffraction peaks corresponding to rGO emerged at 2θ of 23.8° to 25.7°, which are associated with a decreased interlayer spacing (*d*-spacing) from GO to rGO due to the removal of oxygen functional groups (Saron et al., 2025). As shown in Table 1, the interlayer spacing decreases from 8.30 to 8.27 Å in GO and 3.72 to 3.42 Å in rGO. This gradual reduction in interlayer distance with increasing reducing time indicates the progressive restoration of the crystalline carbon framework, suggesting that prolonged reduction promotes a more ordered and crystalline structure, as evidenced by the decrease in interplanar distance (Kristanti et al., 2024). The interlayer spacing in these results is also consistent with previous findings, which reported an interlayer spacing of approximately 8.8 Å for GO and 3.7 Å for rGO synthesized using *Citrus aurantifolia* extract (Akbar & Hasby, 2023). The rGO samples display a primary (002) peak position that shifts monotonically to higher 2θ values from rGO-60 to rGO-120, corresponding to a continuous contraction of the interlayer spacing. This contraction is characteristic of deoxygenation and de-intercalation during reduction, whereby oxygen-containing functional groups and intercalated water are removed. rGO samples yield apparent crystallite sizes of approximately 20.28 Å, 25.43 Å, and 30.15 Å for rGO-60, rGO-90, and rGO-120, respectively. The relative increase confirms that longer or more aggressive reduction conditions promote the growth of larger graphitic-like domains.

Table 1. Interlayer spacing of GO and rGO samples with corresponding crystallite size

Variation	GO		rGO		Crystallite
(min)	2θ	d-spacing (Å)	2θ	d-spacing (Å)	Size (Å)
60	10.65	8.30	23.86	3.72	20.28
90	10.66	8.29	24.62	3.62	25.43
120	10.69	8.27	25.66	3.47	30.15

The presence of these rGO peaks confirms that *Aloe vera* extract can be used as a natural reducing agent, with its active compounds such as polyphenols and flavonoids playing a role in the reduction of oxygen functionalities from GO. It is worth noting that while chemical reduction often leads to the disappearance of the GO peak and the emergence of a sharp rGO peak near 26°, plant extract-based reductions typically result in broader and less intense peaks due to partial reduction and structural disorder. The application of sonication served as an assisting physical process in the green reduction using Aloe vera, further enhancing the crystalline structure of the rGO material, as evidenced by the crystallinity percentages of 39.52%, 39.80%, and 41.70% for the rGO-60, rGO-90, and rGO-120 samples, respectively. Similarly, previous studies have reported that the incorporation of additional physical reduction methods, such as microwave irradiation alongside green synthesis, can also improve the crystalline structure of rGO (Hikmah et al., 2024). In the current study, the rGO peaks observed were characteristically broad and asymmetric. This observation is consistent with Ramanathan et al. (2017), who reported similar XRD patterns when *Aloe vera* extract was used to reduce GO under mild heating.

SEM-EDX Analysis of Synthesized rGO

SEM characterization was conducted to analyze the surface morphology of rGO, while EDX was employed to identify and determine the elemental composition of the synthesized rGO.

The morphological features of the rGO surface at a magnification of 500×, are presented in Figure 4. According to the morphological observations in Figures 4, the three samples exhibit similar surface morphologies. The surfaces of the rGO samples appear wrinkled, which can be attributed to the removal of oxygen functional groups from GO during the reduction process (Fauzi & Dwandaru, 2021). The SEM micrograph of rGO-60 (Figure 4(a)) reveals a heterogeneous surface morphology characterized by agglomerated flakes of rGO in irregular clusters (indicated by red circles). The surface exhibits stacked regions, with certain areas displaying prominent wrinkles and folds. These wrinkles are indicative of structural distortions introduced during the reduction process, which induce lattice distortions and partial sheet collapse due to van der Waals interactions between adjacent layers (Pei & Cheng, 2012; Putri & Supardi, 2023). The observed aggregation in rGO-60 suggests incomplete exfoliation, consistent with the corresponding XRD characterization, which indicates a higher residual oxygen content. Nevertheless, the agglomeration in this variation remains relatively thick, indicating that the oxygen functional groups are less reduced, as also supported by the EDX results showing that this sample possesses the highest oxygen percentage.

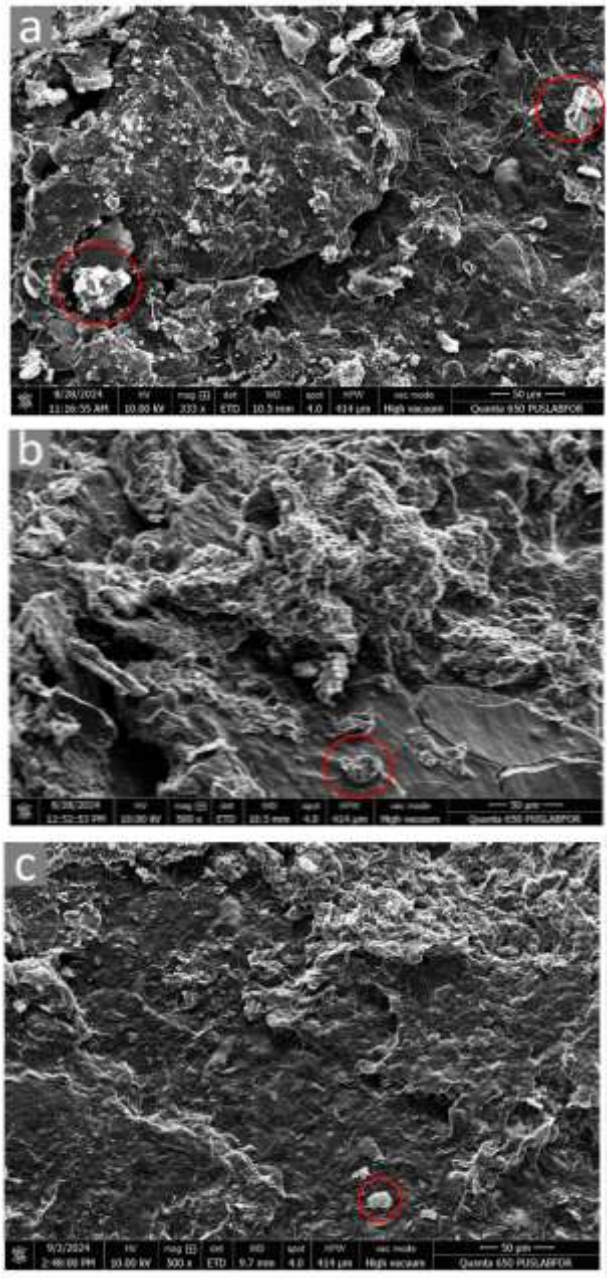

Figure 4. Morphological features of rGO observed at 500× magnification for various reduction times: (a) 60 minutes, (b) 90 minutes, and (c) 120 minutes

The rGO-120 (Figure 4(c)) sample exhibits the most developed morphology among the three, characterized by thin, wrinkled graphene layers with pronounced sheet separation. The wrinkles are finer and more frequent, which indicates more extensive oxygen removal (Bhattacharya et al., 2017; Shalaby et al., 2015). This well-exfoliated morphology aligns with the observed peak in XRD, indicating improved crystallite alignment. However, rGO-120 shows excessive sheet re-stacking, with thicker and denser regions observed throughout the surface. This is attributed to the prolonged sonication and reduction, which, although beneficial for removing oxygen functionalities, also decreases surface hydrophilicity. Such dense morphological features can hinder water diffusion into internal pores and reduce the accessibility of adsorption sites.

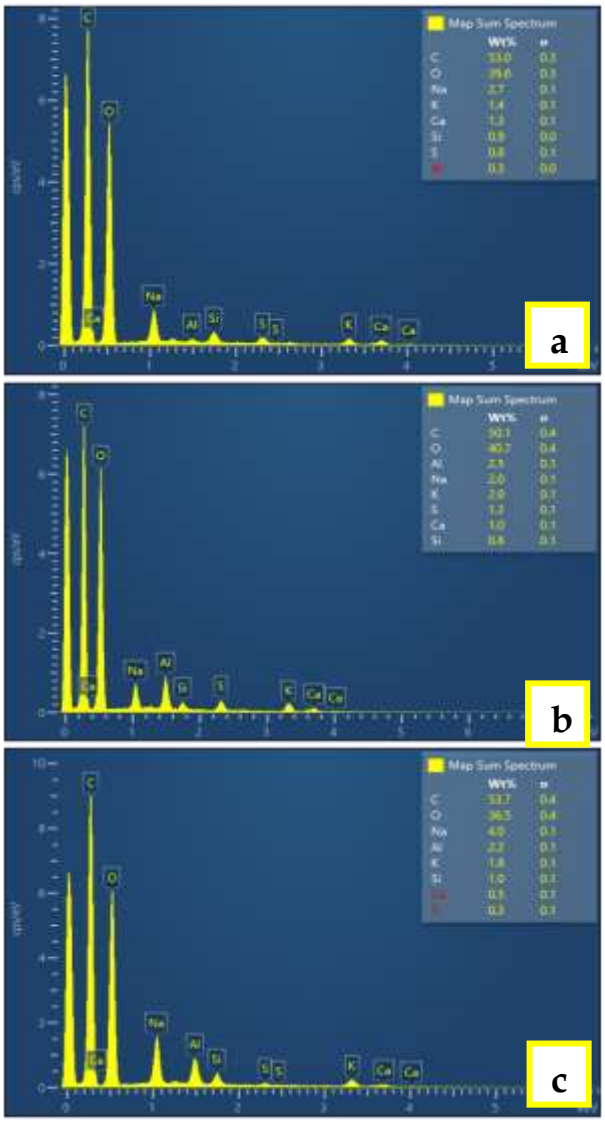

Figure 5. EDX spectrum of rGO: (a) 60 minutes, (b) 90 minutes, and (c) 120 minutes

Using the EDX characterization of the rGO samples, as displayed in Figure 5, it was confirmed that carbon (C) and oxygen (O) peaks dominated the EDX spectra, indicating that these two elements are the main constituents of the rGO material. However, trace amounts of other elements such as sodium (Na), potassium (K), calcium (Ca), silicon (Si), sulfur (S), and aluminum (Al) were also detected. These minor elements are likely derived from the natural composition of the *Aloe vera* extract used as a reducing agent, while elements such as Al and Si may have originated from external contamination during the rGO reduction process. The sonication-assisted reduction process using *Aloe vera* extract was intended to reduce the oxygen content in GO by removing oxygen-containing functional groups from its structure (Parthipan et al., 2021).

The C/O ratio is widely recognized as a critical indicator of the degree of reduction in graphene oxide, where higher values reflect a greater removal of oxygen-containing functional groups. Among the three samples, rGO-120 exhibited the lowest oxygen percentage, resulting in the highest C/O ratio, followed by rGO-60 and rGO-90. This progressive increase in C/O ratio with longer reduction times indicates more effective deoxygenation and structural ordering (Lesiak et al., 2021).

Adsorption Batch Analysis

The evaluation of the synthesized rGO samples for water treatment applications necessitates a comprehensive understanding of how reduction time influences their performance in removing various contaminants in surface water. Table 2 presents the measurement data showing changes in color, turbidity, iron concentration, and pH over a 1-hour treatment period for the variation of reduction time of rGO samples.

Table 2. Measurement of surface water qualities

Variation (min)	Initial	After treatment	Initial	After treatment
	Color (PCU)		Turbidity (NTU)	
60		135		3.95
90	225	115	16.23	4.75
120		95		1.23
	Iron content (ppm)		pH	
60		0.36		6.18
90	0.65	0.49	6.73	6.40
120		0.37		6.57

The removal efficiency of color, turbidity, and iron was found to be directly associated with surface morphology and oxygen functionality. As confirmed by FTIR (Figure 2), the intensity of oxygen-related bands

(O–H, C=O, and C–O) decreased significantly with longer reduction time, indicating progressive deoxygenation. Quantitatively, the transmittance intensity of the C=O band decreased by approximately 52.23% from rGO-90 to rGO-120, while the O–H peak reduced by 46.45%, suggesting more complete removal of oxygenated species in the latter. This is supported by the EDX results, where the enhanced carbon content in rGO-120 signifies improved graphitic character and reduced hydrophilicity, consistent with XRD data showing a shift of the (002) peak from 2θ = 23.8 to 25.7°, corresponding to an interlayer contraction from 3.72 to 3.47 Å (Saron et al., 2025).

The data show a reduction in color across all rGO samples after 1-hour of treatment. The larger reduction in color by rGO-120 (57.8% reduction) versus rGO-60 (40.0%) indicates more effective removal of dye compounds. Color removal is generally attributed hydrophobic interactions between aromatic dye-like species on rGO surfaces (Natasha et al., 2024; Yang et al., 2022). In other words, the rGO-120 sample, which has higher C/O ratios and fewer oxygen functionalities, typically shows stronger stacking and hydrophobic adsorption of organic dyes. In the color reduction of surface water, the adsorbent mass is a parameter that significantly affects the efficiency of color removal, allowing for more optimal decolorization (Kalsum et al., 2024). Therefore, this is an important recommendation to be considered in future studies involving rGO. The turbidity removal data present an interesting non-monotonic trend. Turbidity is primarily caused by suspended colloidal particles, which can be removed through adsorption mechanisms. In the case of rGO, this depends on the nature of the surface area (Roy et al., 2023). Although all samples exhibited a significant reduction in turbidity, the slightly better performance of rGO-60 compared to rGO-90 can be attributed to differences in morphology and the relatively higher content of oxygen functional groups in the rGO-90 sample. The SEM data (Figure 4) show that rGO-90, with a turbidity removal efficiency of 70.73%, exhibits greater aggregation, which limits the accessibility of suspended colloidal particles. In contrast, rGO-60 presents a more porous and dispersed structure, corresponding to a turbidity removal efficiency of 75.66%. This observation is further supported by the EDX results shown in Figure 5, where rGO-90 contains 40.7 wt% oxygen, while rGO-60 contains 39.6 wt%. Oxygen functional groups are known to significantly influence the adsorption capacity of graphene-based materials, as they can alter surface polarity, hydrophilicity, and the availability of active sites for interaction with adsorbates (Zhang et al., 2020). Meanwhile, the rGO-120 sample, which has the lowest oxygen content of 36.5 wt%, demonstrated the most optimal turbidity removal, reaching up to 92.4%. The particular state of aggregation (dense morphology) observed in rGO-120 might create a less favorable environment for turbidity removal.

Similar to turbidity, iron removal is not simply monotonic with reduction. This again highlights that a longer reduction time does not necessarily translate to improved performance for all parameters. Iron removal by rGO is primarily an adsorption process, where metal ions bind to the surface of the rGO sheets. Iron removal by rGO can proceed by adsorption onto oxygen functional groups (complexation with -COOH, -OH). Interestingly, oxygen-containing functionalities are often the active adsorption sites for metal ions (Wahyuni et al., 2025; Yang et al., 2025). A rGO-90, exhibiting the highest oxygen content according to EDX analysis (40.7 wt%), demonstrated a relatively low adsorption capacity for iron ions, at only 24.61%. The presence of oxygen-containing functional groups plays a crucial role in determining the adsorption performance of graphene-based materials, by affecting surface polarity, hydrophilicity, and the accessibility of active sites for adsorbate binding (Zhang et al., 2020). This observation is further supported by SEM images (Figure 4(b)), which reveal that aggregation in the rGO-90 sample reduces the availability of active sites, thereby limiting Fe ion interaction with the surface. In contrast, the rGO-60 sample achieved the highest Fe removal efficiency of 44.61%, indicating that although it possesses a higher oxygen content (39.6 wt%) compared to rGO-120 (36.5 wt%), its more open and porous surface (Figure 4(a)) significantly enhances Fe ion adsorption. These findings are consistent with previous studies reporting that carbon materials with a porous structure and larger pore sizes exhibit greater metal ion adsorption capacities than those with smooth or dense surfaces (Chen et al., 2016). Nevertheless, the observed difference was minimal, with Fe removal decreasing to 0.36 for rGO-60 and 0.37 for rGO-120, suggesting that this difference is not practically significant. Meanwhile, throughout the adsorption process, the pH remained relatively stable at around 6, showing only slight decreases to final values of 6.18, 6.40, and 6.57 for rGO-60, rGO-90, and rGO-120, respectively. This indicates that, although the adsorption of Fe^{3+} ions involves the release of H^+ ions via an ion exchange mechanism—which would normally cause water acidification—the overall impact on pH was negligible. This minimal change is likely due to the relatively low concentration of Fe ions in the Kapuas River water, as well as the natural buffering capacity of the water matrix.

Conclusion

The rGO synthesized using *Aloe vera* extract assisted by sonication confirms the feasibility of a green synthesis

approach, highlighting *Aloe vera* as a natural and environmental friendly reducing agent for rGO production. By giving different durations of sonication, rGO samples exhibited distinct structural, morphological, and compositional characteristics. FTIR and XRD analyses confirmed the formation of rGO through the presence of its characteristic functional groups and the emergence of new diffraction peaks observed in all reduction time variations. SEM-EDX results revealed an increasing C/O ratio, with rGO-120 exhibiting the highest value. With its optimal properties, rGO-120 demonstrated the highest removal efficiency for improving surface water quality, achieving 57.8% color reduction, 92.4% turbidity removal, and 43.07% dissolved iron removal, while maintaining a stable pH of around 6.57. These findings suggest that Aloe vera–mediated synthesis of rGO provides a sustainable and efficient approach for developing functional materials applicable to surface water purification, with 120 minutes of sonication identified as the optimal reduction condition. Furthermore, the study underscores the potential of integrating green material synthesis with practical environmental applications for improving surface water quality.

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Author Contributions

The conceptualization, characterization of samples, visualization, writing—original draft preparation, funding acquisition, D.W.; methodology, M.N.; prepared the samples, M.A.; investigation of the application, Y.M.A.; analysis, writing—review and editing, D.W. and Y.M.A.; supervision, D.W. and M.N.; project administration, M.N. and M.A. All authors have read and approved the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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