PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–09
https://doi.org/10.14719/pst.5499

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Synthesis and characterization of groundnut shell carbon nanosheets for treating greywater: A step towards a circular economy

Prabu Padanillay Chidambaram[1], Kumaraperumal Ramalingam[2*], Rakesh SS[3], Raja K[4], Ramesh PT[3], Prabakaran C[3] & Muppidi Teja[3]

[1]Centre for Water and Geospatial Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Remote Sensing and Geographic Information System, Tamil Nadu Agricultural University, Coimbatore 641 003, TamilNadu, India

[3]Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[4]Centre for Nano Science and Technology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: kumaraperumal.r@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 03 October 2024
Accepted: 05 December 2024
Available online
Version 1.0 : 31 December 2024
Version 2.0: 27 August 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Chidambaram PP, Ramalingam K, Rakesh SS, Raja K, Ramesh PT, Prabakaran C, Teja M. Synthesis and characterization of groundnut shell carbon nanosheets for treating greywater: A step towards a circular economy. Plant Science Today.2024'11 (sp4):01-09. https://doi.org/10.14719/pst.5499

Abstract

Carbon nanostructured materials, such as nanosheets, can be synthetically produced from various natural waste sources through carbonization and activation. Potassium hydroxide (KOH) is a well-known agent for creating porous structures and refining the micro or nanostructure of carbon. This study explores the effect of KOH, in both its solute and solid forms, on the production of carbon from groundnut shells. Using KOH activation and thermal treatment, carbon nanosheets were synthesized from groundnut shells. The surface microstructure and individual carbon nanosheets showed significant changes when treated with solute KOH compared to solid KOH. This highlights that treatment with solute KOH is an efficient and cost-effective method for carbon nanosheet production. A column study revealed that using groundnut shell carbon nanosheets (GSCNS) to treat sewage wastewater resulted in a reduction in BOD (biochemical oxygen demand) from 393 mg L^{-1} to 112.23 mg L^{-1} (71.5%) and COD (chemical oxygen demand) from 512.70 mg L^{-1} to 125 mg L^{-1} (75.6%). Additionally, groundnut shell-derived carbon nanosheets (GSCN) treatment led to a 40-60% reduction in the cations and anions in sewage wastewater. This study emphasizes the effective utilization of groundnut shell-derived carbon nanosheets as an eco-friendly and cost-effective solution for wastewater treatment, addressing the environmental challenges of untreated sewage discharge in underdeveloped and developing regions.

Keywords

carbon nanosheet; groundnut shell; KOH; sewage wastewater treatment

Introduction

Globalization has increased efficiency and comfort in many areas of life but has also contributed to pollution, particularly from industrial wastewater discharge. In underdeveloped and developing nations, most wastewater is released untreated or only mechanically treated, leading to a high organic load with complex environmental chemicals (1, 2). Emerging organic pollutants from institutional and hostel wastewater have raised concerns about their environmental impact. Although various conventional treatment methods like microbial degradation, coagulation, oxidation,

membrane separation, and reverse osmosis have been explored, they are insufficient because they fail to entirely remove a wide range of emerging and persistent pollutants. Adsorption, especially using activated carbon, has gained attention as an effective method for wastewater treatment, endorsed by the US Environmental Protection Agency (USEPA) (3, 4).

Nano carbon materials, known for their excellent properties, are gaining importance, and agro-waste, like groundnut shells, offers a sustainable source of carbon materials. Groundnut shells, often discarded or burned, contribute to environmental pollution. In 2018, India cultivated 41.35 lakh hectares of groundnuts, yielding 52.75 lakh tons, with shells accounting for 25% of the mass. Such waste can be transformed into alternative value-added products (5-7). Chemical activation and carbonization, using KOH, can transform groundnut shells into carbon nanosheets, offering a low-cost, eco-friendly solution to utilize the groundnut shell agro-waste and reduce pollution. This article focuses on producing GSCNS through a simple, cost-effective method. It explores its efficiency as the cheapest activated carbon material for sewage (grey) water treatment.

Materials and Methods

Groundnut shell carbon nanosheet synthesis and standardization of the chemical activation process

The preparation and precarboniztion of groundnut shells began by washing and drying them at 80°C for 24 hours, followed by treatment with 0.5M hydrochloric acid (HCl) for 24 hours. After this, the groundnut shells were washed with Milli-Q water and dried under the same condition. The precarbonization process is done through carbonization or pyrolysis of the carbonaceous materials at elevated temperatures (450°C for 2 hr) under an argon atmosphere. An argon atmosphere is crucial because it prevents oxidation during pyrolysis, ensuring carbonization occurs without reacting with oxygen. This is important to maintain the integrity of the carbon structure and prevent unwanted reactions that could affect the material's properties. The chemical activation procedure utilizing KOH (solute and solid) was conducted as outlined below.

For the solid KOH treatment, precarbonized groundnut shells (0.5 g) were mixed with solid KOH at a 1:1 mass ratio and blended using a mortar for 1 hour. The mixed groundnut shells were heat treated at 800°C for 60 minutes in a stainless-steel tube furnace under an argon atmosphere. After this process, carbon was extracted from KOH mixture using ethyl acetate (8). The layered carbon structure was separated through exfoliation by treating the activated shells with 10% sulfuric acid (H_2SO_4), stirring for approximately 1 hour, then washing with distilled water and drying at 80°C for 24 hours (9). A schematic illustration of this carbon nanosheet preparation process from groundnut shells is shown in Fig. 1. The surface texture and morphological characteristics of the samples were analyzed using a field emission scanning electron microscope (FESEM) (HITACHI S-4800, ZEISS EVO-MA10).

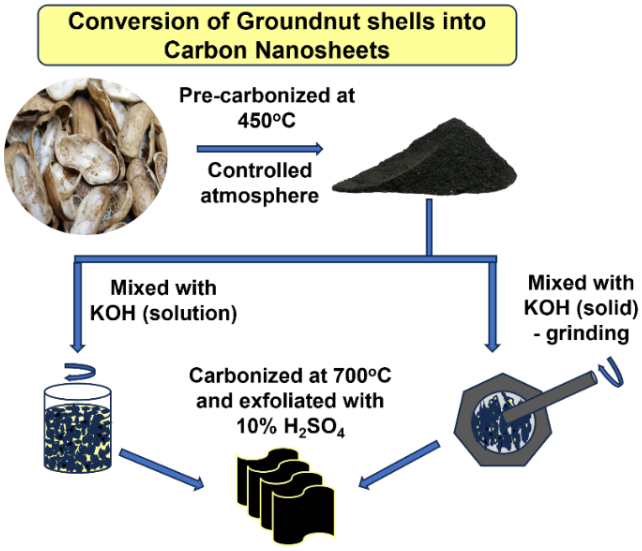

Fig. 1. Schematic illustration of the preparation of carbon nanosheets from groundnut shells.

The samples were ground to a size of 2 mm and placed on a double-sided conductive carbon tape affixed to the stub. After achieving a high vacuum, the filament was activated. Various parameters such as electron beam intensity, spot size, voltage, and emission current were adjusted, and FE-SEM images of the samples were captured, following a standardized protocol (10). Besides the microstructure and morphology, chemical composition was analyzed through energy-dispersive X-ray spectrometry, and the crystal structure and phase purity of the samples were derived using X-ray diffraction.

Collection and characterization of sewage water

For the sewage water characterization, greywater was collected from the student's Tamil Nadu Agricultural University (TNAU) hostels, which accommodate about 2000 students and have separate greywater and black water systems. The water samples were collected using composite sampling, with greywater taken at two-hour intervals from 7 a.m. to 7 p.m. to assess quality variations throughout the day (11). The composition of the greywater was estimated by analyzing pH, electrical conductivity (EC), total suspended solids (TSS), total dissolved solids (TDS), total hardness, chlorides (Cl), calcium (Ca), magnesium (Mg), BOD, COD and total coliforms by adopting standard American Public Health Association (APHA) procedures (11).

Column study for treating sewage waste water

Polyvinyl chloride columns of 45 x 7 cm size (L x D) were used for the study. Pebbles (10 cm height), sand (10 cm height), and carbon were added to all the columns. Activated carbon (T_1-10 cm) and groundnut shell carbon nanosheet (T_2) were added at 5 cm height beneath the sand layer in respective columns. Glass wool of 2 cm height was kept at the bottom of the activated carbon layer. The overall treatment structure is: T_1: Pebbles (10 cm) + sand (10 cm) + commercial activated carbon (10 cm) T_2: Pebbles (10 cm) + sand (10 cm) + groundnut shell nanosheet (5 cm). Each treatment is replicated twice with the completely randomised design. Collected physicochemical parameters of before and after treated

GSNS (groundnut shell nano sheet) mentioned in Tables 1 and 2 data were analyzed through one-way analysis of variance (ANOVA) in R software to investigate significant differences among treatment statistics and graphics that supported it, and all were done in Prism10 (GraphPad Software, Inc., La Jolla, California, USA).

Results and Discussion

Characterization of groundnut shell nanosheet

Carbonization of 10 kg of groundnut shell at an elevated temperature of about 450°C yielded 3 kg of precarbonized charcoal, and characterization and proximate analysis were also conducted. The raw groundnut shell had a high volatile content of 65%, which decreased significantly to 8.2% in the biochar produced at 450°C, as shown in Table 3. This reduction is primarily attributed to the loss of organic matter during pyrolysis at elevated temperatures. The loss of highly volatile components led to a well-developed porosity and enhanced stability of the carbon structure in biochar, which is ideal for preparing nanosheets at 800°C. The perfect temperature of 800°C for nanosheet preparation because it provides optimal conditions for the decomposition of organic precursors, enhances crystallization without causing aggregation, and activates the material's surface, improving porosity, conductivity, and catalytic activity while maintaining the nanosheets' structural integrity for various applications such as catalysis, energy storage, and environmental remediation. Groundnut shell carbon nanosheets activated with solid KOH exhibit a multilayered structure composed of ultra-fine nanosheets and dispersed carbon fragments that overlap, with thicknesses ranging from 30 to 45 nm. The carbon nanostructure is predominantly made up of carbon (12). In contrast, FESEM images of groundnut shell carbon activated with aqueous KOH (Fig. 2) show a smooth surface with well-formed carbon nanosheets of 42-44 nm thickness. Overlapping nanosheets and ultra-thin structures were also observed (Fig. 3), verified through elemental composition and energy-dispersive X-ray spectroscopy (EDS).

While the carbon particles in KOH (solute) resemble those in solid KOH in terms of packing, they are more easily separable. The KOH solution distributes evenly, penetrates the sample effectively, and influences the microstructure more significantly than solid KOH. Consequently, the shell's microstructure changed after treatment with KOH and H_2SO_4, combined with thermal processing. The EDS spectrum (Fig. 4) confirmed that carbon is the primary element, as detailed in Table 4. The XRD pattern in Fig. 5 shows that GSBC (groundnut shell biochar) has a broad peak around 23° and significant single sharp peaks, indicating crystallinity. In contrast, GSCNS has distinct peaks at 2θ values of about 23° and 44°, corresponding to the (002) and (100) planes of graphitic crystallites, with broad peaks suggesting an amorphous nature. The amorphous nature of GSCNS enhances the material's surface area and pore structure, which are critical for improving its adsorption capacity, reactivity, and overall application performance (13).

Characterization of sewage (greywater) from TNAU students' hostel

Greywater was sampled at bihourly intervals from 7 a.m. to 7 p.m. to understand the changes in quality over different time intervals. The composition of the greywater

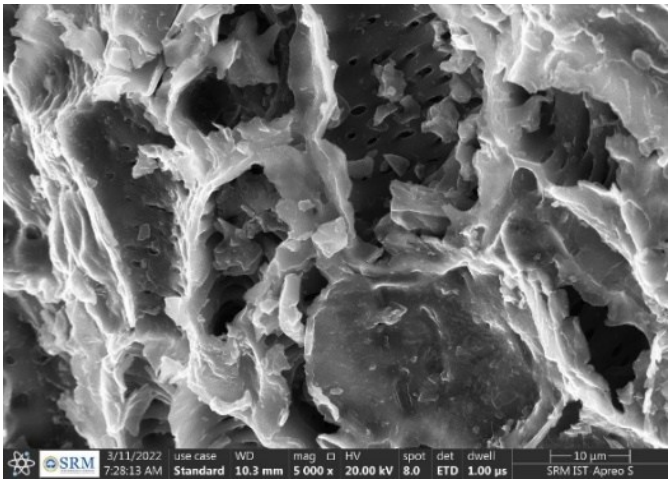

Fig. 2. FESEM (10 µm) micrographs of groundnut shell carbon mixed with KOH.

Table 1. Characterisation of TNAU students' hostel sewage wastewater/greywater

S. No.	Sampling time	pH	EC (dS m^{-1})	TDS (mg L^{-1})	TSS (mg L^{-1})	Chlorides (mg L^{-1})	Total hardness ($CaCO_3$) (mg L^{-1})	BOD (mg L^{-1})	COD (mg L^{-1})	Fat, oil, and grease (mg L^{-1})	Coliforms (MPN per 100 mL)
1	7:00 a.m.	7.24	2.31	1407	383	69.80	125.20	314.90	506.20	1322	17.00
2	9:00 a.m.	7.33	2.47	1620	674	79.84	210.40	458.80	510.32	1780	11.00
3	11:00 p.m.	7.36	2.66	1846	524	78.55	180.80	374.60	545.26	1187	14.00
4	1:00 p.m.	7.45	2.49	1710	618	63.10	120.40	280.20	508.12	1249	16.00
5	3:00 p.m.	7.34	2.16	1394	650	64.25	150.80	320.40	506.75	1467	7.80
6	5:00 p.m.	7.76	2.51	1650	662	74.27	200.40	490.15	515.84	1696	17.00
7	7:00 p.m.	7.65	2.49	1615	446	76.82	210.30	512.10	568.11	1842	9.20
AVERAGE		7.44	2.40	1606	565.28	72.37	171.18	393.02	522.94	1506.14	13.14
SE		1.24	0.44	291.50	97.10	13.14	31.54	18.32	10.21	267.18	2.29
C.D. (p=0.05)		2.45	0.82	555.75	175.19	25.10	61.07	35.73	20.22	497.67	4.19

Table 2. Characteristics of treated water with groundnut shell nanosheet

Initial characteristics		Characteristics of water after treatment with activated carbon														
		Days														
RGW	GWA	Treatments	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
pH																	
7.44	7.38	T1	6.28	6.31	6.4	6.52	6.65	6.73	6.84	6.95	7.0	7.15	7.20	7.34	7.38	7.40	7.41
		T2	6.13	6.25	6.31	6.47	6.53	6.68	6.72	6.81	6.90	6.98	7.07	7.11	7.18	7.21	7.23
EC (dS m^{-1})																	
2.40	2.32	T1	0.88	0.95	0.98	1.01	1.18	1.25	1.42	1.75	1.82	1.95	2.10	2.24	2.28	2.31	2.32
		T2	0.51	0.71	0.80	0.95	1.02	1.15	1.31	1.60	1.71	1.88	2.01	2.08	2.12	2.17	2.21
TDS (mg L^{-1}) *																	
1606	1532	T1	-	428	-	451	-	562	-	638	-	952	-	1239	-	1525	-
		T2	-	316	-	452	-	517	-	607	-	794	-	1048	-	1322	-
Total hardness (mg L^{-1}) *																	
171.18	165.11	T1	-	81.1	-	98.4	-	112.1	-	128.6	-	135.9	-	152.1	-	163.4	-
		T2	-	45.1	-	61.2	-	75.9	-	98.1	-	115.4	-	135.1	-	161.2	-
Chlorides (mg L^{-1}) *																	
72.37	65.18	T1	-	45.17	-	48.31	-	51.25	-	58.75	-	63.87	-	65.62	-	71.14	-
		T2	-	42.22	-	44.12	-	47.59	-	53.13	-	59.15	-	63.14	-	69.16	-
BOD (mg L^{-1}) *																	
393.02	355.17	T1	-	285.14	-	187.31	-	135.21	-	121.14	-	132.14	-	138.91	-	145.14	-
		T2	-	245.12	-	165.98	-	128.36	-	112.23	-	121.68	-	128.27	-	134.25	-
COD (mg L^{-1}) *																	
512.70	456.90	T1	-	180.41	-	161.4	-	172.22	-	180.51	-	170.23	-	160.35	-	160.12	-
		T2	-	150.37	-	171.8	-	140.64	-	125.83	-	145.96	-	150.21	-	175.81	-
Coliform population (MPN per 100 mL) *																	
13.14	13.14	T1	-	12.13	-	11.84	-	11.57	-	11.43	-	11.61	-	11.85	-	11.97	-
		T2	-	11.95	-	11.72	-	11.41	-	11.23	-	11.54	-	11.71	-	11.83	-

* Sample collected in alternate days; RGW – Raw greywater; GWA – Greywater after air floatation; T1-Commercial activated carbon; T2- Groundnut shell carbon nanosheet

was estimated by analyzing pH, EC, TDS, TSS, total hardness, Cl, Ca, Mg, BOD, COD, and total coliforms by adopting standard procedures, and the results are given in Table 1.

The results of different sampling times showed wide variations in greywater quality with time. The pH was observed to be in the slightly alkaline range (7.24 to 7.76). This is expected since hostel waters contain residues of cleaning solutions and alkaline detergents. Regional differences, like climate and household practices, can significantly affect greywater composition. For instance, in drier regions like Rajasthan, the greywater may have higher concentrations of salts and detergents due to reduced water availability and increased use of cleaning agents.

Table 3. Precarbonized groundnut shell (450°C) – Characteristics

Parameter	Adsorbent carbon
Electrochemical properties	
pH	8.81
EC (dS m^{-1})	0.38
Bulk density (g cm^{-3})	0.44
Total organic carbon (%)	8.12
Cation exchange capacity (cmol (p^+) kg^{-1})	13.2
Proximate analysis (wt. %)	
Moisture content	6.64
Volatile matter	8.2
Ash content	26.2
Fixed carbon	53.40
Mineral constituents (g kg^{-1})	
Potassium (K)	1.52
Phosphorus (P)	0.17
Calcium (Ca)	1.12
Magnesium (Mg)	0.28
Zinc (Zn)	0.01
Iron (Fe)	0.31
Copper (Cu)	0.09

In contrast, in more humid or tropical regions, greywater might contain higher organic matter levels from washing fruits, vegetables, and other organic residues. Additionally, cultural practices, such as water conservation methods or the use of certain soaps and detergents, can further alter greywater characteristics across different areas. A comparable outcome was noted in Jaipur, Rajasthan (14), and in Egypt (15), where the pH range of greywater fluctuated between 6.70 and 8.34. Alkaline cleansers like sodium hydroxide (NaOH) or KOH, calcium hypochlorite ($CaOCl_2$), and ammonia (NH_3) are added in washing agents to dissolve fats and grease oil stains. Also, bar soaps make the water very basic, but liquid soaps do not change the pH. The EC of the greywater varied between 2.16 and 2. 66 dSm^{-1}.

Electrical conductivity in greywater is caused by dissolved salts that break down into positively and negatively charged ions, which conduct electricity. The conductivity is proportional to their concentration. The dissolved solids in greywater primarily consist of salts like sodium, Ca, Mg, Cl, and bicarbonates (16). In a study from Nagpur, a conductivity value of 4.36 dSm^{-1} in grey water was generated from the outlet of a residential building consisting of eight flats. The highest TDS was recorded at 11.00 a.m. (1846 mg L^{-1}) and the lowest at 3:00 p.m. (1394 mg L^{-1}) (17). A wide variation in TDS was also reported in greywater from Chennai (18).

The hardness of the greywater was recorded as highest at 9:00 a.m. (210.40 mg L^{-1}) and the lowest at 1:00 p.m. (120.40 mg L^{-1}). In Maharashtra, remarkably elevated levels of 440.36 mg L^{-1} were recorded (19), similar to findings from another study that reported an average of 485.6 mg L^{-1} for untreated greywater, which dropped to 318.4 mg L^{-1} following filtering (17). The highest BOD value recorded

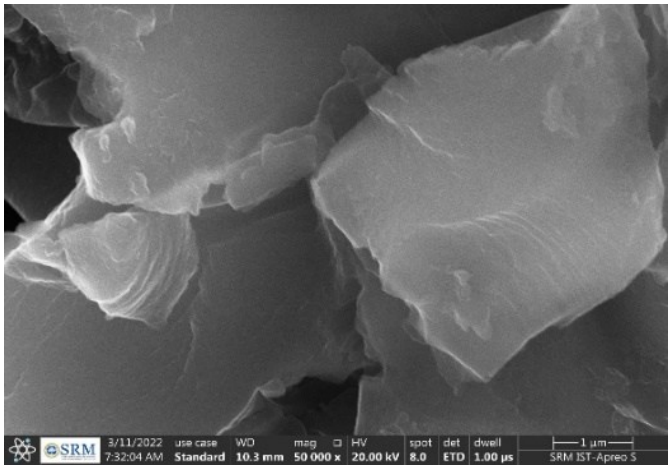

Fig. 3. FESEM (1 µm) micrographs of groundnut shell nanosheet.

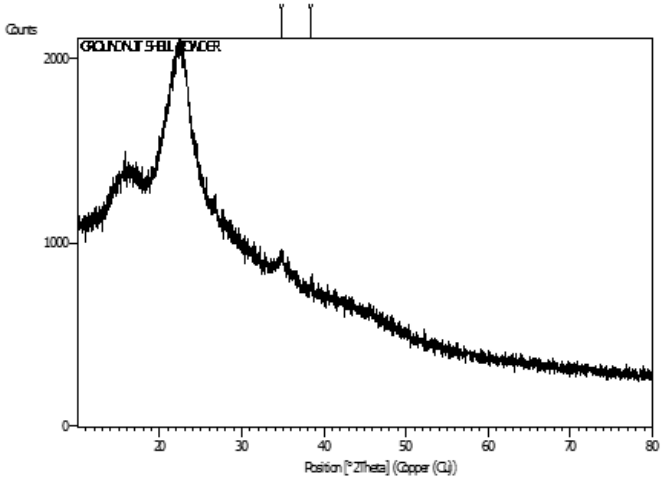

Fig. 4. XRD pattern of groundnut shell nanosheet.

Table 4. Energy dispersive X-ray spectroscopy spectral composition of groundnut shell nanosheet

Element	Line type	k factor	Wt%	Wt% sigma	Atomic %
C	K series	2.769	95.13	0.19	96.30
O	K series	2.020	4.87	0.19	3.70
Total			100.00		100.00

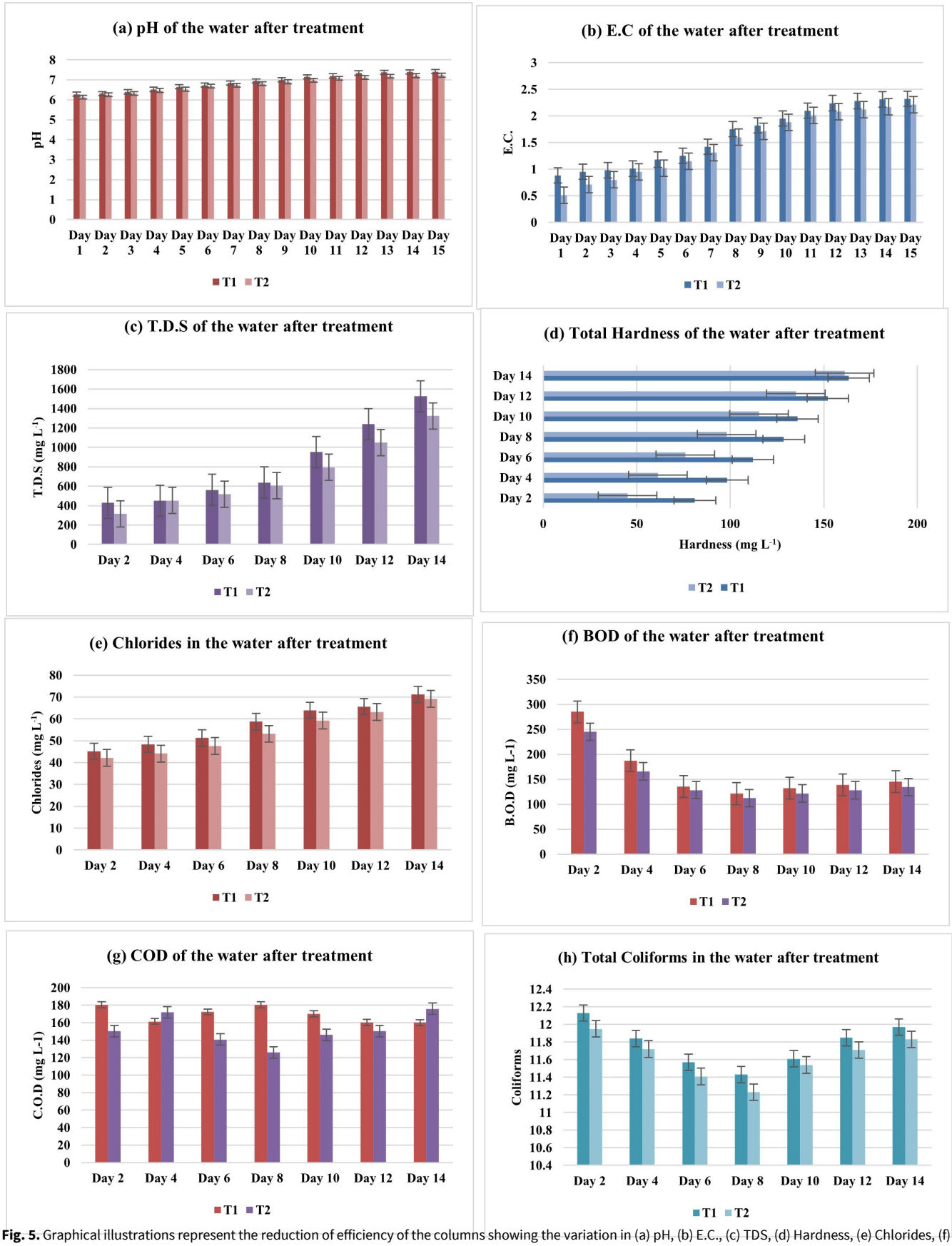

Fig. 5. Graphical illustrations represent the reduction of efficiency of the columns showing the variation in (a) pH, (b) E.C., (c) TDS, (d) Hardness, (e) Chlorides, (f) BOD, (g) COD and (h) Coliforms.

was 512.10 mg L^{-1} at 7.00 p.m., and the lowest BOD in the day was at 1.00 p.m. (280.20 mg L^{-1}). In Chennai, similar results of BOD values from 120 mg L^{-1} to 350 mg L^{-1} were also reported (18). In Malaysia, an identical result was recorded with a BOD range of 155 mg L^{-1} to 213 mg L^{-1} in raw greywater subjected to treatment in granular activated carbon (GAC) biofilm reactors (20).

The COD of TNAU greywater varied from 506.20 mg L^{-1} (7:00 p.m.) and 568.11 mg L^{-1} (7:00 p.m.). These variations were comparable to the findings of a previous study, which reported COD values between 383.57 mg L^{-1} and 434 mg L^{-1}in Nagpur (20). Another study in Nagpur revealed an average COD value of 183.25 mg L^{-1} in untreated greywater (21). Similarly, Chennai reported a range of COD values from 254 mg L^{-1} to 618 mg L^{-1} in greywater (18). However, in Brazil, higher values ranging from 622 mg L^{-1} to 4796 mg L^{-1} were reported (22). The oil and grease values were highest (1842 mg L^{-1}) at 7.00 p.m. and lowest (1187 mg L^{-1}) at 11.00 a.m. The coliform population was maximum (17 MPN per 100 mL) at 7.00 a.m. and minimum (7.8 MPN per 100 mL) at 3.00 p.m. Total coliforms are one of the bio-indicator organisms for fecal contamination in greywater. Coliform counts of 8.5 x 10^5 to 8.9 x 10^5 MPN per 100 mL were reported and recorded as 5 x 10^4 to 6 x 10^4 MPN per 100 mL in greywater (23, 24). The sources of coliforms in greywater are fecal spills, improper sanitation in bathrooms, wetted dresses of children, and splash waters from lavatories.

Treatment of greywater using groundnut shell nanosheet

The suspended solids in the greywater were removed by passing it through commercially procured nylon wires with a mesh size of 2 mm. This way, larger particles such as food particles, hair, plastics, papers, and other organics suspended in the greywater were removed, and the water was subjected to the next stage of treatment. The air floatation method was adopted to remove fat, oil, and grease impurities. The characteristics of raw and treated greywater (after air floatation) were analyzed. Test verification of the suitability of different raw materials as filters was done using sand, pebbles, and commercially activated carbon to compare the efficiency of groundnut shell nanosheet filters. Sand and pebbles were standard filter materials because they provide an effective, low-cost medium for removing suspended particles, debris, and some impurities through physical filtration. Their porous structure allows water to pass through while trapping larger contaminants. However, compared to nanosheets, sand and pebbles are less effective in removing finer particles, organic compounds, and pollutants at the molecular level. Nanosheets, with their high surface area and enhanced adsorption capabilities, can capture smaller pollutants and provide more efficient filtration of contaminants like heavy metals or organic molecules. In this study, the height of commercial activated carbon was standardized at 10 cm.

In comparison, the groundnut shell nanosheet was fixed at 5 cm, demonstrating the greater efficiency of nanosheets in achieving similar or better filtration performance with less material. The sewage wastewater's physicochemical parameters (colour, pH, EC, TDS, TSS, BOD, COD, cations, and anions) were significantly reduced during the treatment. The color was reduced within a few days of treatment and became colorless. The greenish color of the untreated greywater was mainly due to the pigmentation of the organic pollutants and dirt arising from cleaning operations in the home (25).

After treatment with a GSCNS, greywater became transparent. This may be attributed to the adsorption and absorption of particles responsible for the apparent color by activated carbon filters with micropores (26). In a separate study, it was demonstrated that activated carbon -produced crop residues effectively reduced both methyl blue (acidic) and methyl orange (basic) dyes from wastewater (27). The BOD of greywater was reduced from 393 mg L^{-1} to 112.23 mg L^{-1}, indicating a 71.5% reduction, during an experiment utilizing GSCNS. Additionally, sewage water treatment with optimized activated carbon lowered the pH from alkaline to near-neutral (28).

The BOD, TDS, and TSS were also significantly reduced under optimal conditions due to the larger pore structure, enhancing the material's capacity to absorb molecules. Optimized activated carbon is preferred over minimum activated carbon because of its higher operating conditions, which result in complete activation due to increased activation time, temperature, and larger pore formation. This study demonstrated a reduction in COD from 512.70 mg L^{-1} to 125 mg L^{-1}, indicating a 75.6% decrease. Chemical oxygen demand was selected as a key parameter for adsorption, as its adsorption behavior is frequently evaluated to assess the overall performance in wastewater treatment (29). A higher COD value indicates a higher concentration of organic pollutants, while a reduction in COD after filtration reflects the filter's effectiveness in capturing and removing these contaminants. Since organic pollutants are typically a major target in wastewater treatment, COD is a comprehensive metric for monitoring the performance of filtration systems, including the removal capacity of filters like nanosheets, activated carbon, or sand. Efficient adsorption of organic compounds reduces COD, making it a reliable parameter for comparing different filtration materials and optimizing treatment processes. These results align with a study on municipal wastewater treatment in Mashhad, Iran, where GAC was used (30). The GAC dosages of 0.15, 0.2, and 0.25, with a surface area of 644.5 m^2/g and a particle size of 14.89 nm, demonstrated high effectiveness, achieving 91% and 93% removal of COD and BOD, respectively.

In the treatment of raw textile water, the cations and anions were reduced by 40-60% using GSCNS, as shown in Table 2. The amalgamation of sludge and poultry manure-derived carbons may also be efficacious in eliminating modest concentrations of cations and anions typically found in municipal and industrial wastewater (31). The experiment's removal efficiency is illustrated in Fig. 5, highlighting differences in performance between commercial carbon and groundnut shell nano carbon,

likely due to variations in surface texture, porosity, surface chemistry, and the inorganic content and composition of the chars.

In summary, carbon nanosheets were successfully synthesized from groundnut shells through treatment with KOH (solid and solute) and carbonization at 800°C for 1 hour. Nanosheets produced under KOH (solute) conditions displayed flatter surfaces and better dispersion than KOH (solid) activation. This process's smallest GSCNS had a thickness of less than 50 nm. The water became colorless within a few days in a column study using these carbon nanosheets for sewage wastewater treatment. Biological oxygen demand was reduced from 393 mg L^{-1} to 112.23 mg L^{-1} (71.5%), COD from 512.70 mg L^{-1} to 125 mg L^{-1} (75.6%), and cations and anions from grey wastewater were reduced by 40-60%.

Conclusion

This study successfully demonstrated the potential of using GSCN as an effective, low-cost material for treating sewage (grey) wastewater, contributing to the principles of a circular economy. By utilizing agricultural waste, specifically groundnut shells, and employing a simple chemical activation process using KOH, the research achieved significant results in the infiltration of pollutants and reducing landfill use, lowering the carbon footprint, and supporting the circular economy by providing an eco-friendly, cost-effective, and sustainable alternative to conventional materials. The comparison between solid and solute KOH activation showed that solute KOH produced more efficient carbon nanosheets with improved surface structure and dispersion. The GSCN proved highly effective in reducing key pollutants such as BOD and COD by 71.5% and 75.6%, respectively. Furthermore, cations and anions were reduced by 40-60%, indicating the GSCN's capacity for adsorbing a wide range of contaminants. The findings highlight the significance of transforming agricultural waste into useful carbon materials for environmental restoration, providing a sustainable and eco-friendly solution to the escalating problem of untreated wastewater in emerging areas. Future research could explore scaling up the process and investigating the long-term durability of GSCN in various wastewater treatment applications.

Acknowledgments

The authors thank the Department of Physics and Nanotechnology, SRM Institute of Science and Technology, for providing the analyzed data on microstructure, morphology, chemical composition, crystal structure, and phase purity for the collected samples.

Authors' contributions

PPC conceived the study and contributed to the overall design and progress. KR contributed to the sample collection and participated in the characterization of the sewage samples. RSS participated in the standardization of the chemical activation process and contributed to the column study of the collected samples. RK participated in the FESEM image generation, X-ray diffraction, and spectrometry analysis of the samples. RPT contributed to the sewage sample analysis and carbon nanosheet synthesis. PC participated in the derivation of statistical analysis and contributed to the writing of the manuscript. MT participated in the characterization of the sewage samples and contributed to the writing and editing of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. Okoya AA, Akinyele AB, Farinde OO. Adsorptive properties of sawdust activated carbon for the 2,2-dichlorovinyl-dimethyl-phosphate removal from agrochemical industrial wastewater. Res J Environ Sci. 2023;17:1-11. https://doi.org/10.3923/rjes.2023.1.11
2. Sarkar UK, Roy K, Naskar M, Karnatak G, Puthiyottil M, Baksi S, et al. Assessing vulnerability of freshwater minnows in the Gangetic floodplains of India for conservation and management: Anthropogenic or climatic change risk? Clim Risk Manag. 2021;33:100325. https://doi.org/10.1016/j.crm.2021.100325
3. Ahmedna MO, Marshall WE, Rao RM. Production of granular activated carbons from select agricultural by-products and evaluation of their physical, chemical and adsorption properties. Bioresour Technol. 2000;71(2):113-23. https://doi.org/10.1016/S0960-8524(99)00070-X
4. Najm IN, Snoeyink VL, Lykins Jr BW, Adams JQ. Using powdered activated carbon: A critical review. Journal-American Water Works Association. 1991;83(1):65-76. https://doi.org/10.1002/j.1551-8833.1991.tb07087.x
5. Liu Y, Chang X, Guo Y, Meng S. Biosorption and preconcentration of lead and cadmium on waste Chinese herb Pang Da Hai. J Hazard Mater. 2006;135(1-3):389-94. https://doi.org/10.1016/j.jhazmat.2005.11.078
6. Tang W, Zhang Y, Zhong Y, Shen T, Wang X, Xia X, Tu J. Natural biomass-derived carbons for electrochemical energy storage. Mater Res Bull. 2017;88:234-41. https://doi.org/10.1016/j.materresbull.2016.12.025
7. Zhang J, Li Y, Zhang C, Jing Y. Adsorption of malachite green from aqueous solution onto carbon prepared from Arundo donax root. J Hazard Mater. 2008;150(3):774-82. https://doi.org/10.1016/j.jhazmat.2007.05.036
8. Hameed BH, Rahman AA. Removal of phenol from aqueous solutions by adsorption onto activated carbon prepared from biomass material. J Hazard Mater. 2008;160(2-3):576-81. https://doi.org/10.1016/j.jhazmat.2008.03.028
9. Nuilek K, Simon A, Baumli P. Influence of KOH on the carbon nanostructure of peanut shell. Resolution and Discovery. 2018;3(2):29-32. https://doi.org/10.1556/2051.2018.00060
10. Chester AW, Derouane EG. Zeolite characterization and catalysis: A tutorial. Springer; 2009.

11. APHA. Standard methods for the examination of water and wastewater. 21st ed. Washington, DC: American Public Health Association, American Water Works Association, Water Environment Federation; 2005.
12. Yallappa S, Deepthi DR, Yashaswini S, Hamsanandini R, Chandraprasad M, Kumar SA, et al. Natural biowaste of groundnut shell derived nano carbons: Synthesis, characterization and its *in vitro* antibacterial activity. Nano-Struct Nano-Objects. 2017;12:84-90. https://doi.org/10.1016/j.nanoso.2017.09.009
13. Mohanavel V, Rajan K, Kumar SS, Vijayan G, Vijayanand MS. Study on mechanical properties of graphite particulates reinforced aluminium matrix composite fabricated by stir casting technique. Mater Today: Proc. 2018;5(1):2945-50. https://doi.org/10.1016/j.matpr.2018.01.090
14. Sharma H, Chhipa RC. An opportunity for water conservation: A grey water (cloth washings) and its application. Int J Res Aspects Eng Manag. 2014;1(2):2348-6627.
15. Smith E, Bani-Melhem K. Grey water characterization and treatment for reuse in an arid environment. Water Sci Technol. 2012;66(1):72-8. https://doi.org/10.2166/wst.2012.167
16. Asano T, Smith RG, Tchobanoglous G. Municipal wastewater: Treatment and reclaimed water characteristics. In: Pettygrove GS, editor. Irrigation with reclaimed municipal wastewater: A guidance manual. CRC Press; 1985.
17. Kundu S, Khedikar IP, Sudame AM. Laboratory scale study for reuse of greywater. IOSR J Mech Civil Eng. 2015;12(3):40-47.
18. Abinaya MP, Loganath R. Reuse of grey water using modified root zone system. Int J Eng Resour Technol. 2015;4(02):454-58.
19. Tilve MM. Seasonal variation in greywater quality for a real-life system. Inter J Res Engg Tech. 2014;3(3):768-70. https://doi.org/10.15623/ijret.2014.0315145
20. Al-Mughalles MH, Rahman RA, Suja FB, Mahmud M, Abdullah SM. Greywater treatment using GAC biofilm reactor and sand filter system. Aust J Basic Appl Sci. 2012;6(3):283-92.
21. Shegokar VV, Ramteke DS, Meshram PU. Design and treatability studies of low-cost grey water treatment with respect to recycle and reuse in rural areas. Int J Curr Microbiol Appl Sci. 2015;4(8):113-24.
22. Braga J, Varesche M. Commercial laundry water characterisation. Am J Anal Chem. 2014;5:8-16. https://doi.org/10.4236/ajac.2014.51002
23. Stevik TK, Ausland G, Hanssen JF, Jenssen PD. The influence of physical and chemical factors on the transport of *E. coli* through biological filters for wastewater purification. Water Res. 1999;33(18):3701-06. https://doi.org/10.1016/S0043-1354(99)00077-9
24. Surendran S, Wheatley AD. Greywater reclamation for non-potable re-use. Water Environ J. 1998;12(6):406-13. https://doi.org/10.1111/j.1747-6593.1998.tb00209.x
25. Farid HU, Ameen A. Greywater characteristics and treatment processes: A review. JBEM. 2023;2(2):22-44.
26. Ridder DJ. Adsorption of organic micropollutants onto activated carbon zeolite. Water Management. Academic Press; 2012.
27. Singh KP, Mohan D, Sinha S, Tondon GS, Gosh D. Color removal from wastewater using low-cost activated carbon derived from agricultural waste material. Ind Eng Chem Res. 2003;42(9):1965-76. https://doi.org/10.1021/ie020800d
28. Oladimeji TE, Odunoye BO, Elehinafe FB, Oyinlola RO, Olayemi AO. Production of activated carbon from sawdust and its efficiency in the treatment of sewage water. Heliyon. 2021;7(1):e05960. https://doi.org/10.1016/j.heliyon.2021.e05960
29. Mohan D, Singh KP, Singh VK. Wastewater treatment using low-cost activated carbons derived from agricultural byproducts—A case study. J Hazard Mater. 2008;152(3):1045-53. https://doi.org/10.1016/j.jhazmat.2007.07.079
30. Zahmatkesh S, Gholian-Jouybari F, Klemeš JJ, Bokhari A, Hajiaghaei-Keshteli M. Sustainable and optimized values for municipal wastewater: The removal of biological oxygen demand and chemical oxygen demand by various levels of granular activated carbon-and genetic algorithm-based simulation. J Clean Prod. 2023;417:137932. https://doi.org/10.1016/j.jclepro.2023.137932
31. Fitzmorris KB, Lima IM, Marshall WE, Reimers RS. Anion and cation removal from solution using activated carbons from municipal sludge and poultry manure. J Residuals Sci Technol. 2006;3(3):161-67.