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Agro-Waste based Antibacterial Cellulosic Nanogel for Heavy Metal Adsorption from Contaminated Water

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KEYWORDS

Cellulose, Nanogels, Arsenic, Chromium, Contaminated water, Antibacterial activity.

ABSTRACT:
India being an agricultural land, generates a lot of agricultural wastes. In the present study, cellulose was extracted using different methods using waste sugarcane bagasse one of the agricultural wastes generated in India including rice husk and rice straw, which was utilized to prepare a nanogel (waste valorisation). According to the pollution control board, India emits one of the highest levels of heavy metals, including chromium (VI) and arsenic (As III), a major source of water pollution. The heavy metals in high quantities in effluents interfere with natural water bodies and supplies, have severe toxicological consequences for the environment, and influence human health significantly. Discharge of heavy metals such as arsenic and chromium spreads toxicity as well as decreases the water quality. As a result, effluents must be thoroughly treated before discharging which emphasizes the need of water reusability options. The idea for the current work is to design an efficient, sustainable and cost-effective nanogel to remove heavy metals from contaminated water. The cellulose nanogels have exceptional stability, dispersion of functional groups, and even a large surface area. The nanogels had strong antibacterial activity against E. coli, S. aureus, P. aeruginosa, and E. gergoviae, which are generally present in contaminated water. The nanogels also have an excellent adsorption ability for arsenic ions (As III) as well as chromium ions (Cr VI), commonly found in contaminated water. This study demonstrates the adaptability of cellulosic nanogels as potential wastewater treatment materials, with dual functionality in heavy metal adsorption and antibacterial activity. It emphasizes the value of sustainable material design and the use of cellulose (renewable resource) in various environmental applications. Chemical and Structural characterization were performed using Fourier Transform Infrared spectroscopy, X-Ray Diffraction, and Scanning Electron Microscopy. Arsenic adsorption was investigated using both a qualitative (strip assay) and quantitative (ICPMS) recorded 94% arsenic removal and chromium adsorption was recorded by using UV-Visible Spectroscopy (Qualitative) at 540 nm and ICPMS (Quantitative) recorded 60% removal.

INTRODUCTION

India, being an agrarian economy, generates a significant amount of agricultural waste, with an estimation of 500 million tons per year (Cardoen et al., 2015, Kapoor et al., 2020, Koul et al., 2022). Agricultural waste, a consequence of agricultural activity, has emerged as a key worldwide issue, posing environmental issues but also possess the potential to be a beneficial resource for sustainable development. Crop leftovers, rice husks, rice stalks, rice straws, sugarcane bagasse are all examples of agricultural waste that are frequently dumped or burnt, causes pollution in the environment. Agriculture produces roughly 998 million tons of agricultural waste yearly. Global sugarcane production is calculated to be over 1.8 billion tons per year, with bagasse accounting 30% roughly of total output, 500 million tons per year or more (Hanan et al., 2023).

Globally, comparable practices in Brazil and China showed the common issues connected with agricultural waste management (de Campos et al., 2020, Zhao et al., 2021). India, the world's second-largest sugarcane grower after Brazil, which contributes to this total. The country produces over 370 million tons of sugarcane each year, approximately yields 120 million tons of bagasse (Shukla et al., 2017, Dwivedi 2021, Konde et al., 2021). Agricultural waste pollutes the air, land, and water due to its improper disposal. For example, in India (northern part), burning crop residues such as rice straw worsens air pollution, leads to serious health and environmental risks (Singh et al., 2022). Efforts to adequately manage agricultural waste are critical to reduce its impact on environment, increasing its economic worth. Researchers are developing new, scalable solutions and policy interventions for sustainable management of waste. Sustainable practices are critical for mitigating obstacles and realizes the potential of agricultural waste on a worldwide scale.

Plant biomass generally consists of lignocellulosic components, such as cellulose, hemicellulose, and lignin. Byproducts from plant biomass are a sustainable, renewable, and cost-effective source and also act as a raw material for production of various industrial biopolymers (Shaghaleh et al., 2018, Jha and Kumar, 2019). Bagasse is rapidly being used in India to make paper, bioplastics, and other value-added products, indicates a shift toward circular economy practices (Hossam and Fahim, 2023, Solomon and Misra, 2024). As bagasse is generated in large amount however, open burning of bagasse or incorrect disposal can lead to various environmental problems such air pollution and emission of greenhouse gas (Kumar et al., 2020, Powar et al., 2022). Sugarcane bagasse contains 40-50 % is glucose polymer which is a part of cellulose content, an example of agricultural biomass (Shaikh et al., 2009). The cellulose present in SCB is mostly crystalline in nature, hemicelluloses are amorphous and 25-35% present in SCB and the last is the lignin content with wax, mineral and other compounds (Wyman, 1999, Jacobsen and Wyman, 2002). Cellulosic fibres isolated from sugarcane bagasse and their derivatives have been used for various applications such as paper, packaging, water, textiles, purification, biomedical devices, sensors, and drug delivery due to their rare properties includes high surface area, low density, and mechanical strength (Michel et al., 2013, Gond and Gupta, 2020, Mahmud and Anannya, 2021, Chandel et al., 2023).

Cellulose includes hydroxyl groups because of its special structure as it can be modified chemically to improve its ability for adsorption of heavy metals (Yu et al., 2013, Ahmad et al., 2015, Kaur et al., 2022) such as Lead Pb (II) (Gómez et al., 2021). Cellulose-based biomaterials such as membranes, hydrogels, aerogels and nanocellulose composites display exceptional adsorption capabilities because of their porosity, high surface area, and functionalized surface chemistry due to the presence of functional groups like amine, carboxyl, and thiol groups can be grafted to cellulose, increasing the material's affinity for heavy metal ions (Patel et al., 2023). Additionally, cellulose composites exhibits synergistic activity when incorporated with nanoparticles like silver or graphene oxide improving adsorption efficiency and reusability (Liu et al., 2022). Agricultural residues generated globally or in India, such as sugarcane bagasse, rice straws, rice husks, and wheat straw, are significant sources of cellulose for heavy metal adsorption applications. By utilizing these residues, its provides a sustainable feedstock for biomaterial synthesis and also plays a role in waste management challenges in the field of agriculture (Kumar et al., 2023).

Water is a vital resource for sustaining life on Earth, faces major challenges due to overgrowing population and dwindling of surface water resources. Groundwater, comprising a mere of 10.63 million-km^3 of freshwater and 30.1% of 1386 million-km^3 of total water

(Mukherjee, 2018). By the growing heavy metal poisoning of water supplies there are serious issues in public health and environment due to the presence of contaminants such as arsenic, chromium, lead, cadmium, and mercury are generally bioaccumulative in nature, hazardous, and non-biodegradable, removing them from water systems is a crucial task (Ali et al., 2022). In the Earth's crust, Arsenic (As) is ranked the 53rd most abundant element in the earth's crust with the level of 1.5 mg/L (National Research Council 1977; Sarkar et al., 2011). confronts mounting pressure exacerbated by high arsenic concentrations—a pervasive global issue threatening the health of an estimated 200 million people exposed to arsenic levels exceeding WHO limits in drinking water (George et al., 2014).

In Asia arsenic contamination is found in India and Bangladesh (Sracek et al., 2004; Mukherjee et al., 2008; Mukherjee et al., 2011) leads to various diseases like skin cancer, lung cancer, reproductive, neurological, and immnunological (Ferreccio et al., 2000, Centeno et al., 2006, Ameer et al., 2015, Ahmad and Bhattacharya, 2019). The major route of Arsenic entry in humans is majorly *via* the intake of drinking water rich in Arsenic (Shahid et al., 2017b; Tabassum et al., 2018). Chromium is also reported as heavy metal contamination in India and globally (Akhtar et al., 2020). In Vellore, Tamil Nadu due the the presence of Tannery industries results in contamination of chromium in the local environment, human health is affected by many groundwater areas (Saha et al., 2011). Sukinda valley is one of the major mining sites in Odisha, India as a source of chromite is recognized as one of the most polluted places globally due to its highly toxic nature. The hexavalent chromium contamination results in almost 95% of India's chromium production (Das et al., 2021). Among all 300 sites were identified as chromium exposure globally which results in various defects in human health and in worldwide 16 million peoples are at risk of chromium exposure. As per the reported studies and survey carried out, natural water bodies can contain high levels of chromium up to 4000 nmol/L (Rahman et al., 2023).

To overcome all the harmful effects there are various treatment methods reports among which, Arsenic treatment methods reported till date are chemical precipitation and Ion exchange by the addition of aluminium or iron salts to arsenic contaminated water resulting in precipitation of arsenic and can be easily removed by sedimentation or filtration (Fu and Wang, 2011), Bioremediation process where microorganisms convert arsenic to less toxic forms, immobilizing it in soils or sediments which is easily manageable (Rahman et al., 2023), nanofiltration or reverse osmosis selectively removes arsenic ions based on their charge and size resulting in producing high quality water (Pezeshki et al., 2023), The most used treatment for removal of heavy metals is Adsorption process where , graphene oxide, silica nanoparticles and activated carbon are used to bind and remove arsenic ions from water. This method is generally used due to its high surface area and affinity of these materials for arsenic (Das et al., 2021). Chromium treatment methods reported till date are reduction-precipitation method where chromium (VI) can be reduced to chromium (III) which is less toxic form by using reducing agents like ferrous sulphate. The chromium (III) can be precipitated and easily removed and chemical precipitation method by using sodium hydroxide or lime which converts chromium (VI) to chromium hydroxides which are insoluble in nature and can be easily removed (Fu and Wang, 2011), The process of bioremediation converts chromium (VI) to less toxic chromium (III) and can be easily removed from the environment (Rahman et al., 2023), and adsorption process can be done with Silica nanoparticles and carbon nanomaterials like activated carbon (Das et al., 2021).

Similarly, studies have also been reported on Biomaterials derived from natural sources like cellulose, alginate and chitosan are biodegradable and eco-friendly. Biomaterials can aslo be modified to adsorb selective heavy metal ions from contaminated or polluted water (Yu et al., 2021). Cellulose and cellulose based products used as an adsorbent for various pollutants (Mubarak et al., 2024). Cellulose films and hydrogels have superior moisture retention and antimicrobial qualities in the field of wound healing, which speeds up the recovery process (Li et al., 2023, Deng et al., 2023, Meng et al., 2023). In addition, bagasse cellulose is reported for sustainable packaging materials (Patel et al., 2023, Yin et al., 2024). Cellulose aerogels for heavy metals removal from water (Zhou et al., 2004, Wang et al., 2019, Chen et al., 2019, Syeda et al., 2022). The rice straw extracted cellulose is used for hydrogel preparation and its application in Cu (II) absorption, cellulose based biomass materials are used for wastewater treatment where oil-water separation, dye adsorption and heavy metals adsorption are studied. Plant based agricultural waste adsorbents are used for dye removal as well as heavy metal removal (Kadry et al., 2019, Jiang et al., 2021, Boakye et al., 2022). The present study is based on waste valorisation in which cellulose is extracted from sugarcane bagasse (agricultural waste) and further used in the nanogel preparation which has dual functionality of antibacterial activity and heavy metal adsorption capacity.

1. EXPERIMENTAL PROCEDURE

Materials

Sugarcane bagasse was obtained from a sugarcane juice vendor in Raipur, Chhattisgarh. Sodium hydroxide flakes or pellets (Loba Cheime Pvt. Ltd.) 97% extra pure, Sodium hypochlorite, Sodium arsenite, and Potassium dichromate (Loba Cheime Pvt. Ltd.)

Extraction of cellulose from sugarcane bagasse (SCB)

Sequential treatment of sugarcane bagasse with alkali and acidified bleaching agent

Sugarcane bagasse was grounded to powdered from and was added in a beaker containing 100 ml of distilled water boiled in water bath at 60°C for 4-5 hr, cool and filtered. The residue was treated with 4.5% sodium hydroxide for 4-5 hr at room temperature and the mixture was filtered. The filtered residue was further treated with 4.5% sodium hypochlorite was acidified with the help of acetic acid to pH4 and 2.5% sodium hydroxide for 4 hr at 100°C before washing with distilled water to pH neutral and the reaction mixture was filter. The final product was dried at 50-60°C in hot air oven for 12-14 hr with small optimization in the protocol by Mzimela and his coworkers as shown in Figure 1 (Mzimela et al., 2018).

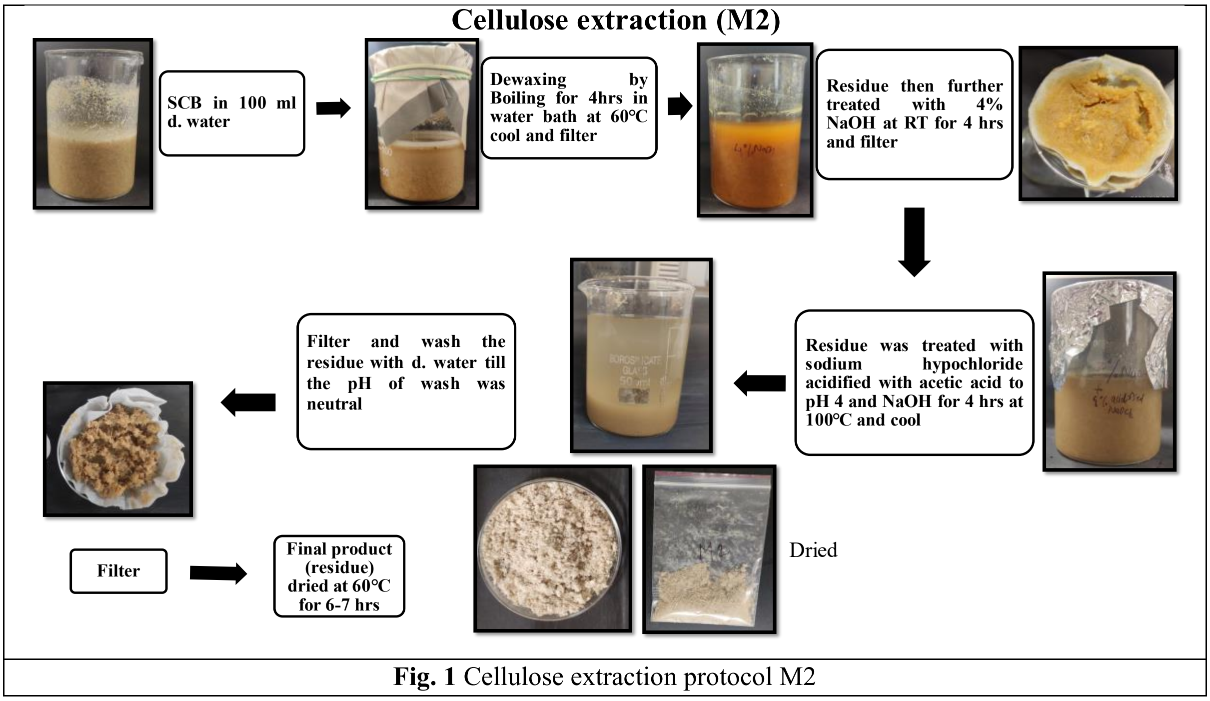


Fig. 1 Cellulose extraction protocol M2

Characterization Techniques of extracted cellulose

Fourier Transform infrared (FTIR) spectroscopy

The extracted cellulose was observed for the presence of functional groups and Infra-red spectra of the samples were recorded on a Benchtop Lt4100 Labtronics spectrophotometer equipped with a standard ATR crystal cell detector. The spectra were recorded within a range of wavenumber of 400-4000 cm^{-1} wavelength (Mzimela 2018, Sun 2004, Feng 2018).

X-Ray Diffraction (XRD) analysis

To study the crystalline nature of extracted cellulose the samples were characterized by XRD analysis, and diffraction patterns of the cellulosic materials were investigated at room temperature using an Advanced Bruker AX D8 diffractometer in the range $2\theta = 10 - 90^{\circ}$, equipped with nickel-filtered Cu Kα radiation ($\lambda = 1.542$ Å) at 40 kV and 40 mA. The scan speed was 0.5 sec/step (Mzimela 2018, Sun 2004, Feng 2018).

Scanning Electron Microscopy (SEM)

The extracted cellulose studied by Scanning electron microscopy Model number EM 30 Analytical Technologies SEM-3000 with different resolution ranges to study the surface morphology of the samples (Mzimela 2018, Sun 2004, Feng 2018).

Preparation of extracted cellulosic nanogel

Keratin solution (7%) was prepared by dissolving 7 gm commercial keratin powder mixed with 1 M urea (6 gm), 1.44 gm of (Sodium dodecyl sulphate) SDS (0.05 M) and 2% β-mercaptoethanol in 100 ml distilled water was on magnetic stirrer till homogenized form is obtained (Nayak 2015).

Extracted cellulose powder was mixed with keratin solution in the ratio of 7:3 and mxed by using magnetic stirrer for 2-3 hr, pH was set to alkaline by using 1M sodium hydroxide (NaOH) and further 4-5% of cross-linker glutaraldehyde (25%) was added in the mixture and stirred for 2-3 hours till homogenous form is obtained and the nanogel was cast in plates and further dried in hot air oven at 50-60°C for 24-48 hrs till dry as shown in Figure 2.

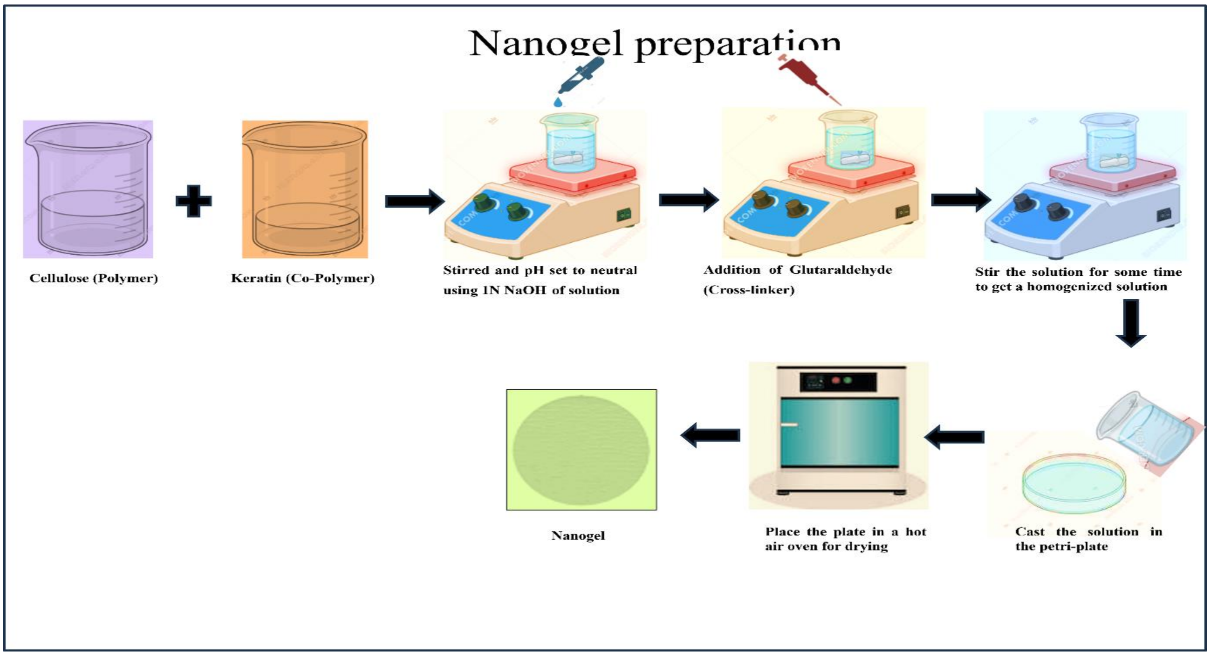


Fig. 2 Nanogel preparation protocol

Characterization of prepared cellulosic nanogel

Fourier Transform Infrared Spectrum Analysis (FTIR)

To study the presence of functional groups the prepared cellulose nanogels were characterized, IR spectra of the prepared cellulose nanogels were to identify the possible chemical constituents involved in the preparation procedure of cellulosic nanogels. The prepared nanogels were homogenized with potassium bromide (KBr) analytical-grade and proceeded for FTIR analysis. The samples were pressed into disks under vacuum using KBr-press. The FTIR spectra were recorded using Benchtop Lt4100 Labtronics, the spectra within the range of 400-4000 cm^{-1} was read at a resolution of 4 cm^{-1}. The FTIR analysis was performed at Agilent

Technologies Mumbai, Maharashtra, India (Navya and Sujatha, 2023).

X-Ray Diffraction Analysis (XRD)

The diffraction patterns of the cellulosic materials were investigated using an Advanced Bruker AX D8 diffractometer in the range 2θ = 10 - 90º, equipped with nickel-filtered Cu Kα radiation (λ = 1.542 Å) at 40 kV and 40 mA with scan speed was 0.5 sec/step at room temperature (Navya and Sujatha, 2023).

Scanning Electron Microscopic Analysis (SEM)

Scanning Electron Microscopy was used to characterize the morphology and particle size of prepared cellulosic nanogel using scanning electron microscopy Model number EM 30 Analytical Technologies SEM-3000 with different resolution ranges. The samples were analyzed at Mumbai, Maharashtra, India (Navya and Sujatha, 2023).

Swelling rate capacity of prepared cellulosic nanogel

To study the water retention capacity of the prepared cellulosic nanogel, the dry nanogel (dry weight) was incubated in distilled water for the period of 6-7 hrs, the swollen weight is measured, and the swelling rate was calculated by applying the Archimedes principle and its calculation was done using dry and soaked weights of the nanogels as shown in the following Eq 1:

$$Wr = \frac{W2-W1}{W1} x100$$
(1)

Where, W1=dry weight of the nanogel, W2=soaked weight of the nanogel

(Nayak 2015, Zhang 2020, Kabiri 2004).

Antibacterial activity of prepared cellulose nanogel

The inhibition of bacterial growth of cellulosic nanogel was carried out using the disk diffusion method. Bacterial species such as *Escherichia coli*, *Pseudomonas aeruginosa, Staphylococcus aureus*, and *Enterobacter gergoviae* were used for the present study.

Fresh culture was prepared for the study, 5 ml of nutrient broth was allowed to get inoculated by the pure culture which was incubated at 37°C for 24 hours. Once the growth was observed in the nutrient broth was set for a particular optical density by considering McFarland turbidity standard. In this study, O.D. at 0.5 was considered and set for inoculation, was achieved by adding sterile nutrient water or sterile nutrient broth in the culture broth till the desired O.D. was achieved. Further, 10µl bacterial broth was inoculated on the solidified Mueller-Hinton agar plates and spread throughout the plate by a spreader. The culture was allowed to diffuse completely in the agar medium for 5 minutes and the cellulosic nanogels disc and the (positive control) antibiotic disc Tetracycline 30 mcg was placed with the help of forceps and pressed gently to position them perfectly on the agar surface.

Once the plates were diffused completely, they were incubated at 37°C for 24 hours. After incubation time the zone was observed, the zone of inhibition in millimetres (mm) was recorded by using Himedia inhibition scale (Tendencia et al., 2004, Cauwelier et al., 2004, Patel et al., 2011, Jorgensen et al., 2015).

Heavy metal adsorption using cellulosic nanogels

The prepared cellulosic nanogels were tested for various heavy metals present in industrial wastewater or contaminated water.

Arsenic Adsorption

Qualitative analysis of Arsenic Adsorption (strip test)

To perform a qualitative analysis of Arsenic adsorption using cellulosic nanogels, they were incubated with Arsenic contaminated solution for 6-7 hrs and was removed using forceps and supernatant and nanogel were used for further study.

In the present study, the qualitative analysis of arsenic adsorption was carried out using a Merquant test kit, provides a visual indicator of arsenic presence in the solution. In this technique the first step is by inserting a test strip partly into the slot of the reaction vessel's top, then carefully transfer 5 ml of the solution to be tested into the vessel using a syringe. In step 2 teaspoon of Reagent 1 was added to the vessel, and it was shake it well. Step 3 includes addition of 8-10 drops of Reagent 2 (HCL 32%), and the jar was quickly shut using cap. The reaction was left to react for 30 minutes, with periodic gentle spinning. After the reaction period, the test strip was withdrawn from the jar and quickly washed with water, shaking removes any surplus liquid. The color change in the response zone on the strip was then compared to the supplied color scale. This qualitative evaluation of the color shift was used to identify the presence of arsenic in the solution, with the intensity of the color change indicates the amount of arsenic (Narkhede et al., 2024).

Quantitative analysis of Arsenic Adsorption (ICPMS analysis)

The prepared cellulosic nanogels were incubated in contaminated water containing different concentrations of arsenic (1, 2, and 3 ppm) for 6-7 hours and the nanogels were dried. Further were characterized for heavy metal adsorption using ICP-MS. The ICP-MS studies were performed at NEERI, Nagpur, Maharashtra, India (Narkhede et al., 2024).

Chromium Adsorption

Qualitative and Quantitative analysis of Chromium Adsorption

The cellulosic nanogels were incubated with chromium-contaminated solution for 6-7 hrs and was removed using forceps further the nanogels and the supernatant were used for the chromium adsorption via UV-visible spectrophotometer at 540 nm and ICPMS analysis was done by using Agilent 8900 ICP-MS Triple Quad instrument (Shakya 2022).

2. RESULTS AND DISCUSSION

Extraction of cellulose from sugarcane bagasse (SCB)

As mentioned before, the extracted cellulose from sugarcane bagasse is cream colour as shown in Figure 3.

Fig. 3 Cellulose extracted from SCB by different methods

Characterization of extracted cellulose

The extracted cellulose was characterized for the presence of functional groups, and surface morphology by using FTIR and SEM. The phases and crystallinity of extracted cellulose were characterized by XRD studied for the crystalline structure.

Fourier Transform infrared (FTIR) spectroscopy

The functional groups present on the extracted cellulose the peak observed bending C-H bond observed between 1366.1 cm^{-1}, 1315-1335 cm^{-1} shows the presence of C-H rocking (alkyl group), C-O, C-O-C and β-glycosidic linkages shows stretching and glycosidic bond in the range of 1235-1265 cm^{-1}, 1155-1170 cm^{-1} and 895-900 cm^{-1} and peaks between 980-990 cm^{-1} shows the presence of -OH group (Hydroxyl group), skeletal vibrations are due to polysachride backbone between 500-800 cm^{-1} and peaks observed between 445-460 cm^{-1} bending of C-H and O-H associated with cellulose, respectively as shown in Figure 4 when compared with the analysis of FTIR peaks reported O-H stretching broad band at 3500-3200 cm^{-}1; C-H stretching 2923-2906, 3420, 2894 and 2910 cm^{-1}; 1428 cm^{-1} shows the presence of CH_2 bending; C-O-C pyranose ring skeletal vibration occurs in the range of 1076-1023, 1054 and 1044 cm^{-1}; C-O antisymmetric bridge stretching and β-glycosidic linkages at 1248-1255, 1169, 1044, 902 and 903 cm^{-1} (Sun et al., 2004, Ren et al., 2007, Mandal et al., 2011,

Owi et al., 2016, Mzimela et al., 2018, George et al., 2020).

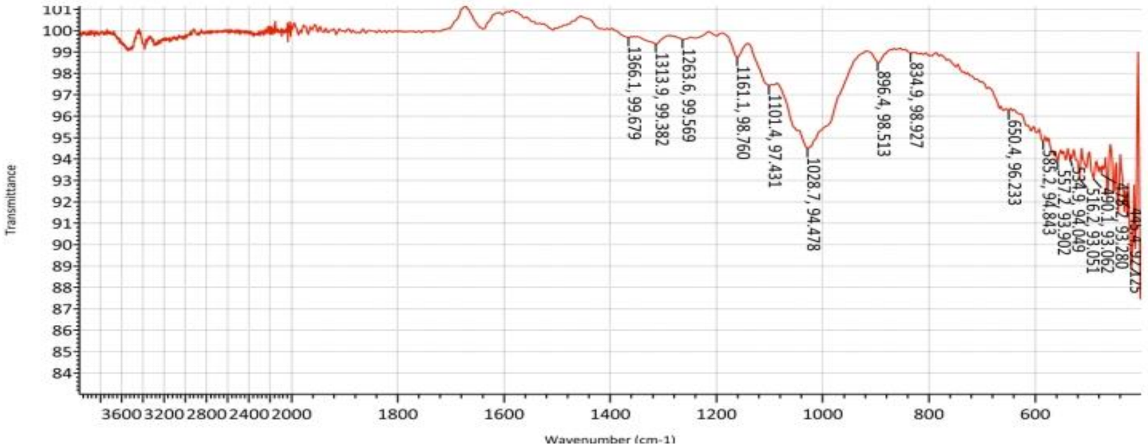
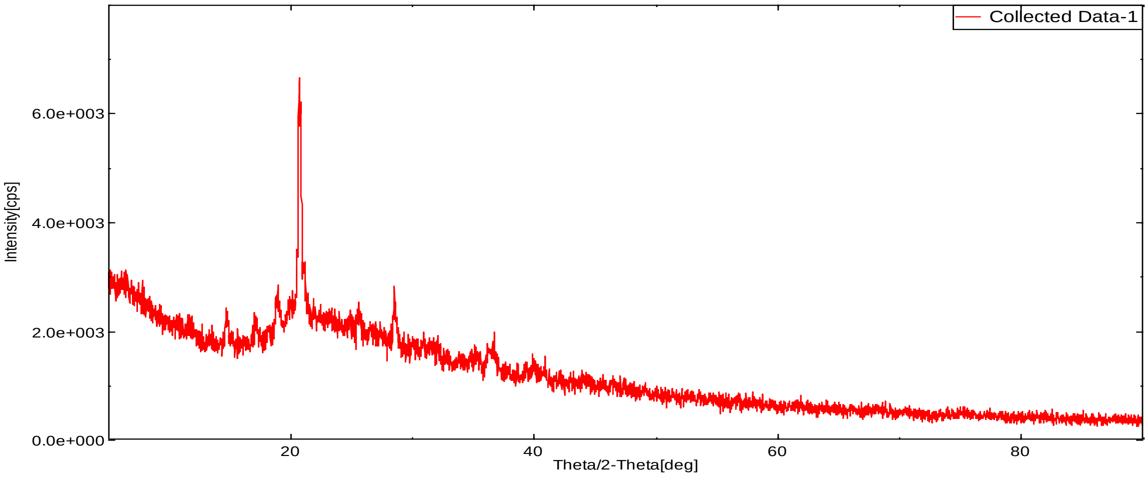


Fig. 4 FTIR analysis of M2 cellulose

X-Ray Diffraction (XRD) analysis

The extracted cellulose was studied for its crystalline structure where 2θ peaks were observed 14.8°-16.5° with plane/index of (110) and (1̅10) and other peak at 22.5°-23.5° with 2θ and (200) plane/index as reported in Figure 5 when compared with the control cellulose and other reported values shows well defined peaks at 2θ=12.5° (for 110 planes) and 22.5° (for 200 planes); similar peaks reported where the diffraction peaks observed around 2θ=15.3 and 22.7° these are the characteristics peaks of cellulose I designated by (100) and (002) planes the strong diffraction peak of cellulose crystalline regions (Sun et al., 2004, Liu et al., 2006, Mandal et al., 2011, Owi et al., 2016, Mzimela et al., 2018, Melesse et al., 2022).



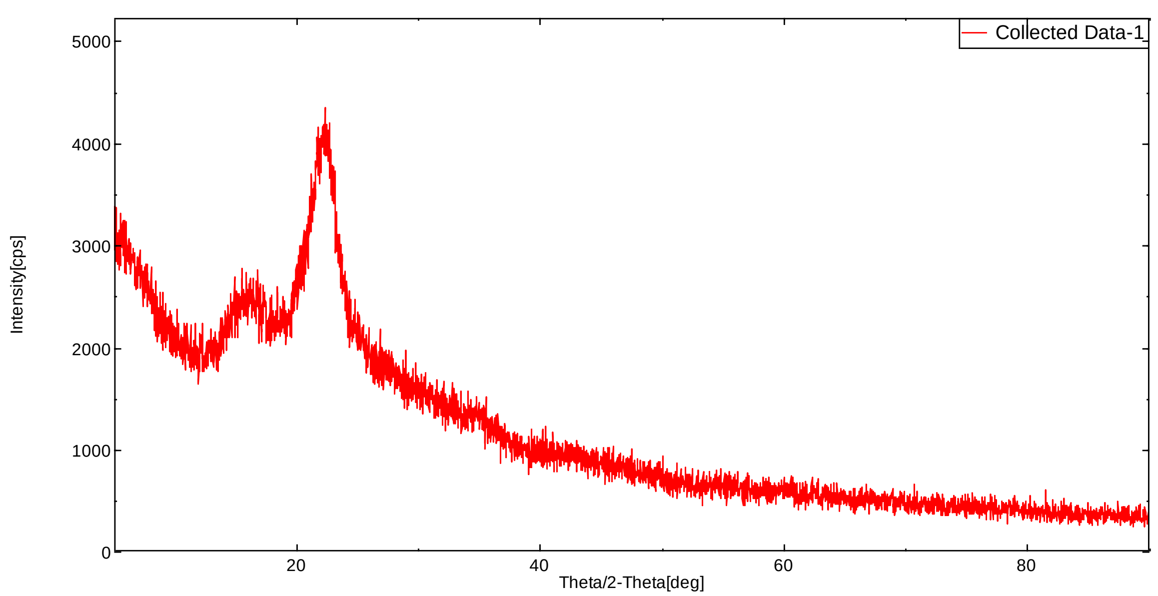


Fig. 5 XRD peaks control and extracted M2 cellulose

Scanning Electron Microscopy (SEM)

The extracted cellulose shows thin elongated fibres with smooth-rough structure as observed in Figure 6 when compared with the control cellulose shows aggregations observed at 10µm resolution (Mandal et al., 2011, Owi et al., 2016, Mzimela et al., 2018, George et al., 2020, Melesse et al., 2022).

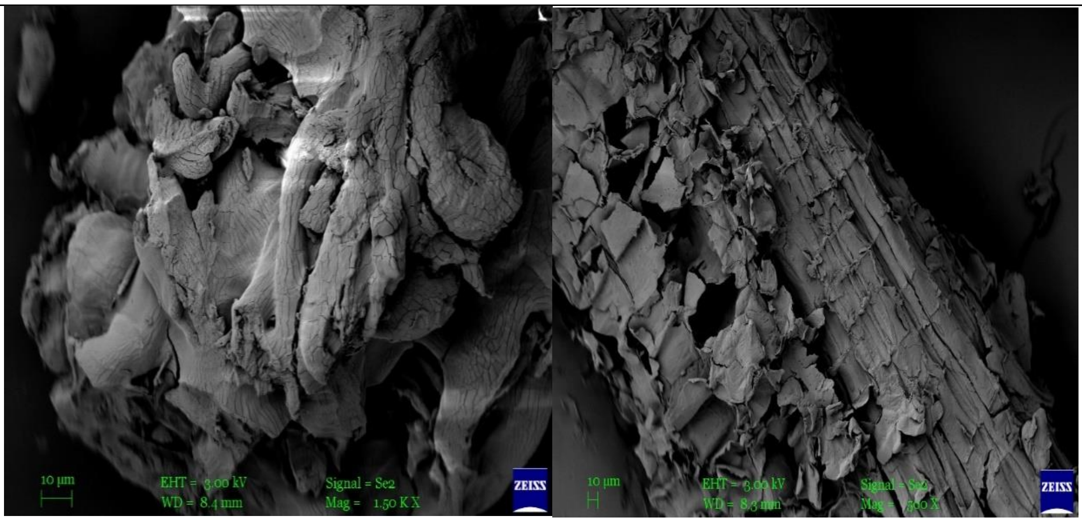


Fig. 6 SEM analysis of control and extracted M2 cellulose

Characterization of prepared cellulosic nanogel

The extracted cellulose is mixed with keratin to form a homogenized form (nanogel) which is yellowish brown in colour as shown in Figure 7. The prepared cellulose nanogels were characterized for surface morphology, presence of functional groups was carried out by Scanning Electron Microscopy and Fourier Transform InfraRed spectroscopy, and the phases and crystallinity of cellulose nanogels were characterized by X-Ray Diffraction.

M2

Fig. 7 Cellulosic nanogels prepared from extracted cellulose

Fourier Transform infrared (FTIR) spectroscopy

The cellulose nanogel was studied for presence of functional groups the ftir peaks observed between 3200-3400 cm^{-1} determines O-H stretching of cellulose, 2953 cm^{-1} N-H stretching of keratin, 1638.2 cm^{-1} amide I, C=O stretching of keratin, 1589.7 cm^{-1} amide II (N-H bending) of keratin, 1215.1 cm^{-1} CH2 /CH3 bending and Amide III (C-N stretching), 1130 cm^{-1} (C-O stretching of cellulose), 1012.0, 821.9 cm^{-1} and 575 cm^{-1} shows the presence of β-glycosidic linkages of cellulose and skeletal vibrations of cellulose/keratin when compared with the reported results as Figure 8 (Navya and Sujatha, 2023).

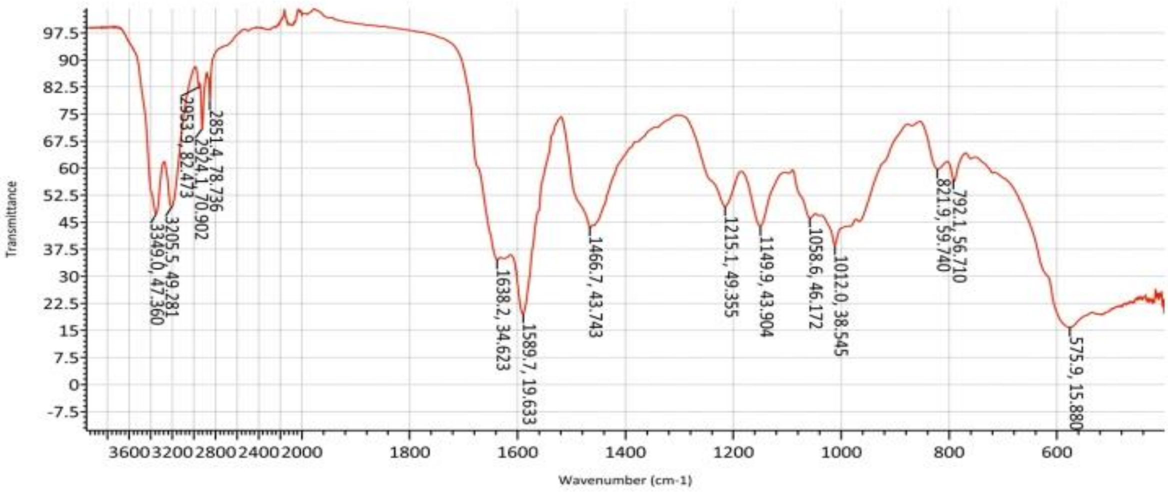


Fig. 8 FTIR analysis of control and M2 nanogel

X-Ray Diffraction (XRD) analysis

The XRD peaks of cellulose nanogels shows the peak at 18-20°, 22-33°, 25-30° and 35-40° with 2θ values, the intense peak attributed to the β-sheet or α-helix structures in keratin, the (002) plane confirming the crystalline nature of cellulose, due to interaction between cellulose and keratin in nanogel matrix and also due to structural modifications or crosslinking during nanogel synthesis as showcased in Figure 9 when compared with the reported data where the hydrogel synthesized showcased amorphous nature. (Navya and Sujatha, 2023).

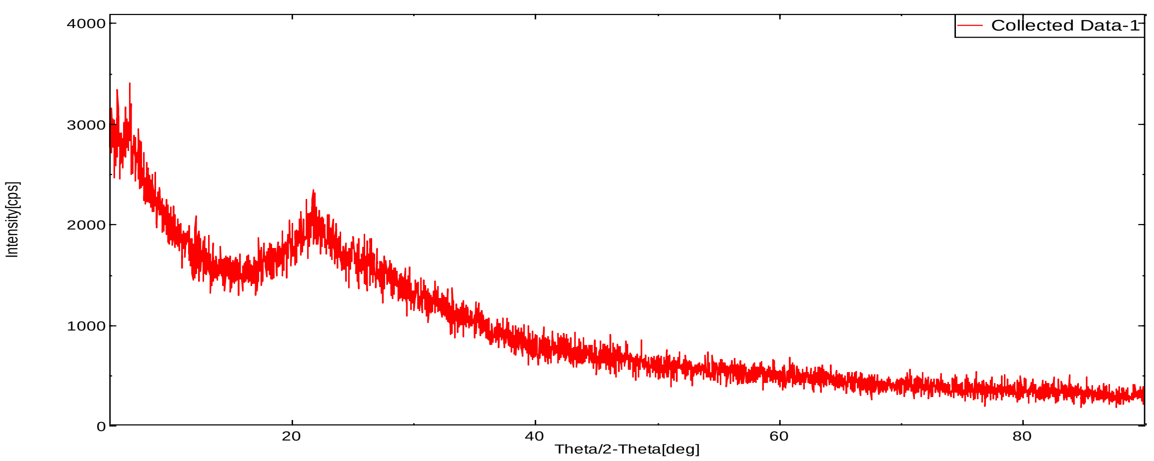


Fig. 9 XRD peaks of M2 nanogel

Scanning Electron Microscopy (SEM)

The surface morphology of extracted cellulose nanogel shows homogenous formation as well as successful blending of cellulose and keratin with smooth and uniform surfaces and some rough texture indicates the presence of keratin as observed in Figure 10 (Navya and Sujatha, 2023).

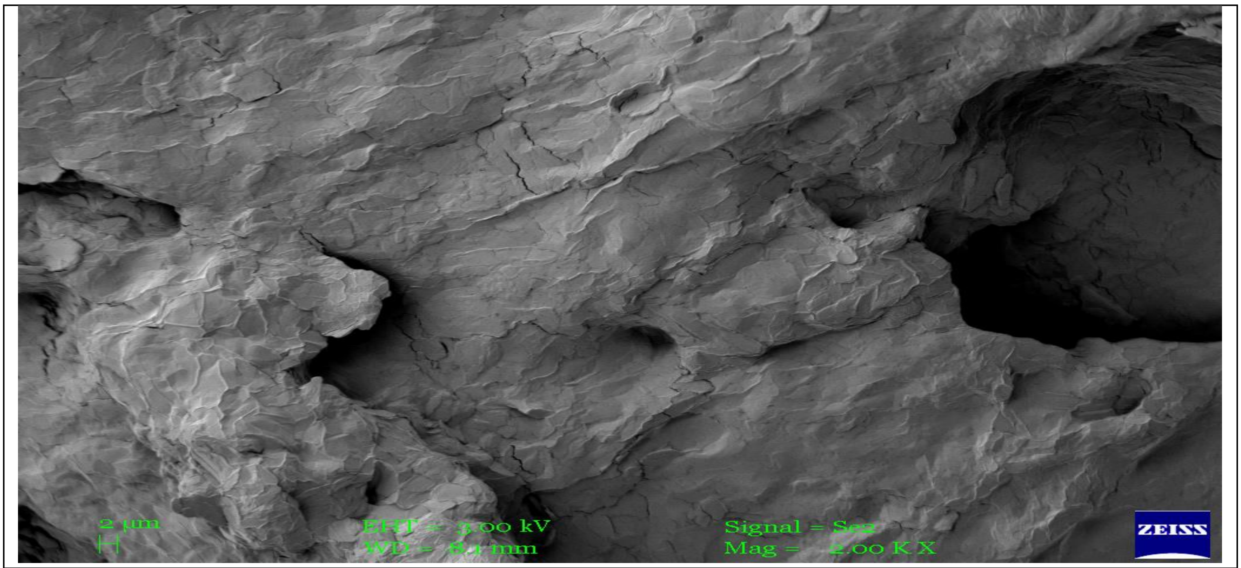


Fig. 10 SEM analysis of M2 nanogel

Swelling rate capacity of prepared cellulosic nanogel

The swelling rate of extracted cellulose nanogels showcased 167.425% compared with the control nanogel (497.153%) as observed in Figure 11, when compared with the cellulose hydrogel reported by Navya 2023 shows 200% swelling capacity at pH 10 (Navya and Sujatha, 2023).

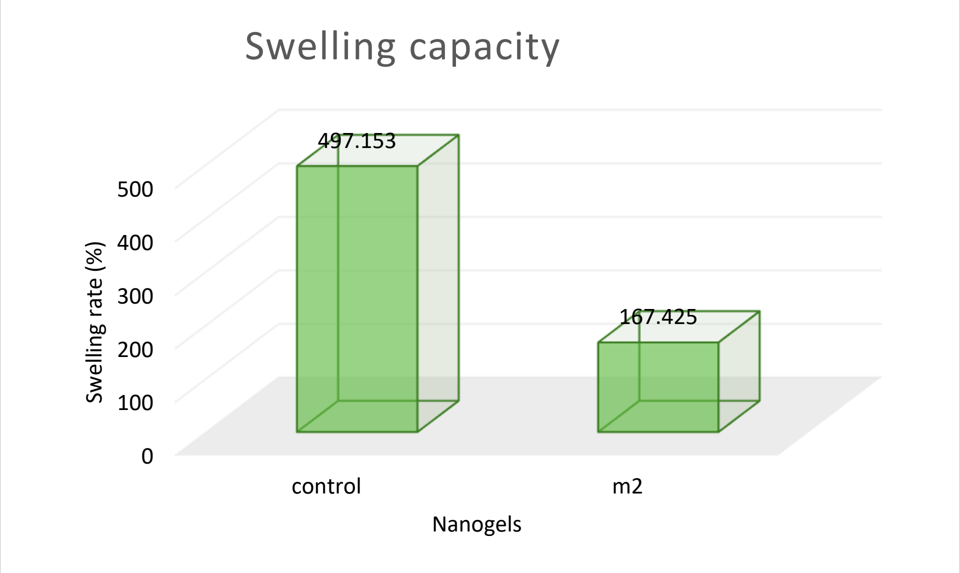


Fig. 11 Swelling rate of extracted cellulose nanogels

Antibacterial activity of prepared cellulose nanogel

The antimicrobial activity of prepared cellulosic nanogels against bacterial species such as *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa* and *Enterobacter gergoviae* when compared with control Tetracycline 30 mcg M2 nanogel showcased Zone of inhibition such as 18±1; 17±1, 18.33±1.53; 17.33±1.15mm when compared with the control 37.66±2.08; 26.33±0.57; 28.66±0.57; 21±1 mm as shown in Table 1 and Figure 12, 13. As per the reported data by cellulose biomaterials showcased antibacterial activity against *E. coli, S. aurues* and *C. albicans* (Hou et al., 2009, Patel et al., 2021, Nemes et al., 2022).

Table 1 Antibacterial activity of cellulose nanogels

	TET 30mcg	**M2**
E. coli	37.66±2.08	18±1
S. aureus	26.33±0.57	17±1
P. aeruginosa	28.66±0.57	18.33±1.53
E. gergoviae	21±1	17.33±1.15

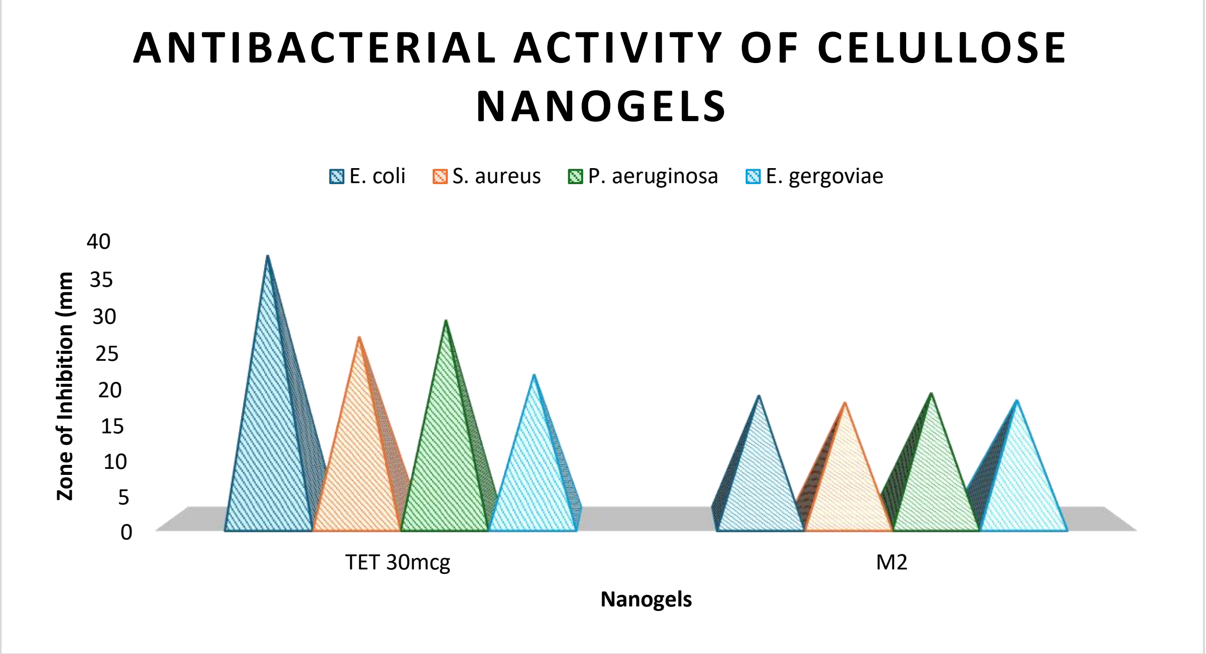
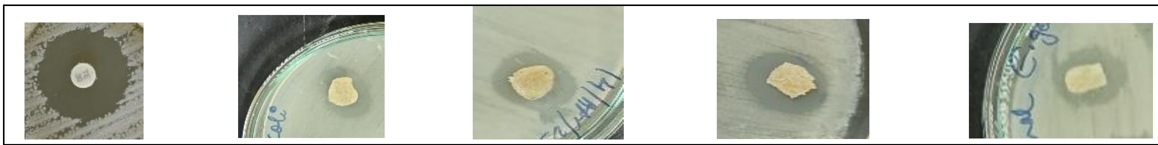


Fig. 12 Antibacterial activity of extracted cellulosic nanogels



Control *E. coli* *S. aureus* *P. aeruginosa* *E. gergoviae*

Fig. 13 Antibacterial activity of cellulosic nanogels

3. CONCLUSION

The extracted cellulose and the cellulose nanogels were characterized using various techniques such as XRD to determine the crystalline nature, FTIR for the presence of functional groups, and SEM analysis morphology of the extracted cellulose appears to be rod shaped fibres and nanogels were homogenous sheets. The cellulose nanogels showcased antibacterial activity against gram-positive and gram-negative bacterial species such as *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa* and *Enterobacter gergoviae*. The prepared cellulose nanogels also show synergistic activity with 94% arsenic and 60% chromium removal from contaminated water.

FUTURE PROSPECTS

The cellulose nanogel prepared from extracted cellulose from sugarcane bagasse has bright future potential for adsorbing heavy metals from contaminated water such as arsenic and chromium, providing an effective and environmentally friendly method for water purification. Using agricultural waste, the waste valorisation approach lessens the need for hazardous chemicals and improves the nanogel biocompatibility. Because of their large surface area and active adsorption sites, the cellulose nanogels are useful for removing heavy metals. Future studies might concentrate on incorporating these nanomaterials into scalable filtering systems, investigating regeneration strategies and reusable for economical reuse, and improving synthesis conditions to increase adsorption capacity. Furthermore, research into their effectiveness in various water matrices and long-term environmental effects will be essential for real-world use.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare in this study.

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REFERENCES

1. Ahmad, A. and Bhattacharya, P., 2019. Arsenic in drinking water: is 10 μg/L a safe limit?. *Current Pollution Reports*, *5*, pp.1-3. https://doi.org/10.1007/s40726-019-0102-7
2. Ahmad, M., Ahmed, S., Swami, B.L. and Ikram, S., 2015. Adsorption of heavy metal ions: role of chitosan and cellulose for water treatment. *Langmuir*, *79*, pp.109-155. http://dx.doi.org/10.13040/IJPSR.0975-8232.IJP.2(6).280-89
3. Akhtar, F.Z., Archana, K.M., Krishnaswamy, V.G. and Rajagopal, R., 2020. Remediation of heavy metals (Cr, Zn) using physical, chemical and biological methods: a novel approach. *SN Applied Sciences*, *2*, pp.1-14. https://doi.org/10.1007/s42452-019-1918-x
4. Ali, M.M., Rahman, S., Islam, M.S., Rakib, M.R.J., Hossen, S., Rahman, M.Z., Kormoker, T., Idris, A.M. and Phoungthong, K., 2022. Distribution of heavy metals in water and sediment of an urban river in a developing country: a probabilistic risk assessment. *International journal of sediment research*, *37*(2), pp.173-187. https://doi.org/10.1016/j.ijsrc.2021.09.002
5. Ameer, S.S., Engström, K., Harari, F., Concha, G., Vahter, M. and Broberg, K., 2015. The effects of arsenic exposure on blood pressure and early risk markers of cardiovascular disease: evidence for population differences. *Environmental research*, *140*, pp.32-36. https://doi.org/10.1016/j.envres.2015.03.010
6. Assembly of Life Sciences (US). Committee on Medical and Biologic Effects of Environmental Pollutants, 1977. *Arsenic*. National Academies Press.
7. Boakye, P., Ohemeng-Boahen, G., Darkwah, L., Sokama-Neuyam, Y.A., Appiah-Effah, E., Oduro-Kwarteng, S., Osei, B.A., Asilevi, P.J. and Woo, S.H., 2022. Waste biomass and biomaterials adsorbents for wastewater treatment. *Green Energy and Environmental Technology*. https://doi.org/10.5772/geet.05
8. Cardoen, D., Joshi, P., Diels, L., Sarma, P.M. and Pant, D., 2015. Agriculture biomass in India: Part 2. Post-harvest losses, cost and environmental impacts. *Resources, Conservation and Recycling*, *101*, pp.143-153. http://dx.doi.org/10.1016/j.resconrec.2015.06.002
9. Cauwelier B, Gordts B, Descheemaecker P, Van Landuyt H. Evaluation of a disk diffusion method with cefoxitin (30 μg) for detection of methicillin-resistant Staphylococcus aureus. European Journal of Clinical Microbiology and Infectious Diseases. 2004 May;23:389-92. https://doi.org/10.1007/s10096-004-1130-8
10. Centeno, J.A., Tchounwou, P.B., Patlolla, A.K., Mullick, F.G., Murakata, L., Meza, E., TodorTodorov, D.L. and Yedjou, C.G., 2006. Environmental pathology and health effects of arsenic poisoning. *Managing arsenic in the environment: from soil to human health*, pp.311-327.
11. Chandel, N., Jain, K., Jain, A., Raj, T., Patel, A.K., Yang, Y.H. and Bhatia, S.K., 2023. The versatile world of cellulose-based materials in healthcare: from production to applications. *Industrial Crops and Products*, *201*, p.116929. https://doi.org/10.1016/j.indcrop.2023.116929
12. Chen, Q., Zheng, J., Wen, L., Yang, C. and Zhang, L., 2019. A multi-functional-group

modified cellulose for enhanced heavy metal cadmium adsorption: Performance and quantum chemical mechanism. *Chemosphere*, *224*, pp.509-518. https://doi.org/10.1016/j.chemosphere.2019.02.138

13. Das, P.K., Das, B.P. and Dash, P., 2021. Chromite mining pollution, environmental impact, toxicity and phytoremediation: a review. *Environmental Chemistry Letters*, *19*(2), pp.1369-1381. https://doi.org/10.1007/s10311-020-01102-w

14. de Campos, V.A.F., Silva, V.B., Cardoso, J.S., Brito, P.S., Tuna, C.E. and Silveira, J.L., 2021. A review of waste management in Brazil and Portugal: Waste-to-energy as pathway for sustainable development. *Renewable Energy*, *178*, pp.802-820. https://doi.org/10.1016/j.renene.2021.06.107

15. Deng, L., Huang, Y., Chen, S., Han, Z., Han, Z., Jin, M., Qu, X., Wang, B., Wang, H. and Gu, S., 2023. Bacterial cellulose-based hydrogel with antibacterial activity and vascularization for wound healing. *Carbohydrate polymers*, *308*, p.120647. https://doi.org/10.1016/j.carbpol.2023.120647

16. Dwivedi, N., 2021. Dynamics Of Sugarcane Production In Major Producing States Of India.

17. Feng, Y.H., Cheng, T.Y., Yang, W.G., Ma, P.T., He, H.Z., Yin, X.C. and Yu, X.X., 2018. Characteristics and environmentally friendly extraction of cellulose nanofibrils from sugarcane bagasse. *Industrial Crops and Products*, *111*, pp.285-291. https://doi.org/10.1016/j.indcrop.2017.10.041

18. Ferreccio, C., González, C., Milosavjlevic, V., Marshall, G., Sancha, A.M. and Smith, A.H., 2000. Lung cancer and arsenic concentrations in drinking water in Chile. *Epidemiology*, *11*(6), pp.673-679. https://doi.org/10.1097/00001648-200011000-00010

19. Fu, F. and Wang, Q., 2011. Removal of heavy metal ions from wastewaters: a review. *Journal of environmental management*, *92*(3), pp.407-418. https://doi.org/10.1016/j.jenvman.2010.11.011

20. George, C.M., Sima, L., Arias, M., Mihalic, J., Cabrera, L.Z., Danz, D., Checkley, W. and Gilman, R.H., 2014. Arsenic exposure in drinking water: an unrecognized health threat in Peru. *Bulletin of the World Health Organization*, *92*, pp.565-572. http://dx.doi.org/10.2471/BLT.13.128496

21. George, D., Begum, K.M.S. and Maheswari, P.U., 2020. Sugarcane bagasse (SCB) based pristine cellulose hydrogel for delivery of grape pomace polyphenol drug. *Waste and Biomass Valorization*, *11*, pp.851-860. https://doi.org/10.1007/s12649-018-0487-3

22. Gómez-Aguilar, D.L., Rodríguez-Miranda, J.P., Baracaldo-Guzmán, D., Salcedo-Parra, O.J. and Esteban-Muñoz, J.A., 2021. Biosorption of Pb (II) using coffee pulp as a sustainable alternative for wastewater treatment. *Applied Sciences*, *11*(13), p.6066. https://doi.org/10.3390/app11136066

23. Gond, R.K. and Gupta, M.K., 2020. A novel approach for isolation of nanofibers from sugarcane bagasse and its characterization for packaging applications. *Polymer Composites*, *41*(12), pp.5216-5226. https://doi.org/10.1002/pc.25788

24. Hanan, E., Ahmad, F.J., Sharma, V., Bashir, O., Malik, M. and Jan, Y., 2023. Characterization of Food and Agricultural Wastes: Global Scenario of Waste Generation. In Integrated Waste Management Approaches for Food and Agricultural Byproducts (pp. 1-24). Apple Academic Press. https://doi.org/10.1201/9781003282327-1

25. Hossam, Y. and Fahim, I.S., 2023. Towards a circular economy: fabrication and characterization of biodegradable plates from sugarcane waste. *Frontiers in Sustainable Food Systems*, *7*, p.1220324. https://doi.org/10.3389/fsufs.2023.1220324

26. Hou, A., Zhou, M. and Wang, X., 2009. Preparation and characterization of durable antibacterial cellulose biomaterials modified with triazine derivatives. *Carbohydrate Polymers*, *75*(2), pp.328-332. https://doi.org/10.1016/j.carbpol.2008.07.032

27. Jacobsen, S.E. and Wyman, C.E., 2002. Xylose monomer and oligomer yields for uncatalyzed hydrolysis of sugarcane bagasse hemicellulose at varying solids concentration. *Industrial & engineering chemistry research*, *41*(6), pp.1454-1461. https://doi.org/10.1021/ie001025+

28. Jha, A. and Kumar, A., 2019. Biobased technologies for the efficient extraction of biopolymers from waste biomass. *Bioprocess and biosystems engineering*, *42*, pp.1893-1901. https://doi.org/10.1007/s00449-019-02199-2

29. Jiang, Z., Ho, S.H., Wang, X., Li, Y. and Wang, C., 2021. Application of biodegradable cellulose-based biomass materials in wastewater treatment. *Environmental Pollution*, *290*, p.118087. https://doi.org/10.1016/j.envpol.2021.118087

30. Jorgensen, J.H. and Turnidge, J.D., 2015. Susceptibility test methods: dilution and disk diffusion methods. *Manual of clinical microbiology*, pp.1253-1273. https://doi.org/10.1128/9781555817381.ch71

31. Kabiri, K. and Zohuriaan-Mehr, M.J., 2004. Porous superabsorbent hydrogel composites: synthesis, morphology and swelling rate. *Macromolecular Materials and Engineering*, *289*(7), pp.653-661. https://doi.org/10.1002/mame.200400010

32. Kadry, G., Aboelmagd, E.I. and Ibrahim, M.M., 2019. Cellulosic-based hydrogel from biomass material for removal of metals from waste water. *Journal of Macromolecular Science, Part A*, *56*(10), pp.968-981. https://doi.org/10.1080/10601325.2019.1640063

33. Kapoor, R., Ghosh, P., Kumar, M., Sengupta, S., Gupta, A., Kumar, S.S., Vijay, V., Kumar, V., Vijay, V.K. and Pant, D., 2020. Valorization of agricultural waste for biogas based circular economy in India: A research outlook. *Bioresource Technology*, *304*, p.123036. https://doi.org/10.1016/j.biortech.2020.123036

34. Kaur, J., Sengupta, P. and Mukhopadhyay, S., 2022. Critical review of bioadsorption on modified cellulose and removal of divalent heavy metals (Cd, Pb, and Cu). *Industrial & Engineering Chemistry Research*, *61*(5), pp.1921-1954. https://doi.org/10.1021/acs.iecr.1c04583

35. Konde, K.S., Nagarajan, S., Kumar, V., Patil, S.V. and Ranade, V.V., 2021. Sugarcane bagasse based biorefineries in India: potential and challenges. *Sustainable Energy & Fuels*, *5*(1), pp.52-78. https://doi.org/10.1039/D0SE01332C

36. Koul, B., Yakoob, M. and Shah, M.P., 2022. Agricultural waste management strategies for environmental sustainability. *Environmental Research*, *206*, p.112285. https://doi.org/10.1016/j.envres.2021.112285

37. Kumar Sarangi, P., Subudhi, S., Bhatia, L., Saha, K., Mudgil, D., Prasad Shadangi, K., Srivastava, R.K., Pattnaik, B. and Arya, R.K., 2023. Utilization of agricultural waste biomass and recycling toward circular bioeconomy. *Environmental Science and Pollution Research*, *30*(4), pp.8526-8539. https://doi.org/10.21203/rs.3.rs-1178197/v1

38. Kumar, I., Bandaru, V., Yampracha, S., Sun, L. and Fungtammasan, B., 2020. Limiting rice and sugarcane residue burning in Thailand: Current status, challenges and strategies. *Journal of Environmental Management*, *276*, p.111228. https://doi.org/10.1016/j.jenvman.2020.111228

39. Li, L., Wang, L., Luan, X., Pang, Y., Zhang, K., Cheng, Y., Ji, Z. and Pang, J., 2023. Adhesive injectable cellulose-based hydrogels with rapid

self-healing and sustained drug release capability for promoting wound healing. *Carbohydrate polymers*, *320*, p.121235. https://doi.org/10.1016/j.carbpol.2023.121235

40. Liu, C.F., Ren, J.L., Xu, F., Liu, J.J., Sun, J.X. and Sun, R.C., 2006. Isolation and characterization of cellulose obtained from ultrasonic irradiated sugarcane bagasse. *Journal of agricultural and food chemistry*, *54*(16), pp.5742-5748. https://doi.org/10.1021/jf060929o
41. Liu, Z., Wang, Q., Huang, X. and Qian, X., 2022. Surface functionalization of graphene oxide with hyperbranched polyamide-amine and microcrystalline cellulose for efficient adsorption of heavy metal ions. *ACS omega*, *7*(13), pp.10944-10954. https://doi.org/10.1021/acsomega.1c06647
42. Mahmud, M.A. and Anannya, F.R., 2021. Sugarcane bagasse-A source of cellulosic fiber for diverse applications. *Heliyon*, *7*(8). https://doi.org/10.1016/j.heliyon.2021.e07771
43. Mandal, A. and Chakrabarty, D., 2011. Isolation of nanocellulose from waste sugarcane bagasse (SCB) and its characterization. *Carbohydrate polymers*, *86*(3), pp.1291-1299. https://doi.org/10.1016/j.carbpol.2011.06.030
44. Melesse, G.T., Hone, F.G. and Mekonnen, M.A., 2022. Extraction of cellulose from sugarcane bagasse optimization and characterization. *Advances in Materials Science and Engineering*, *2022*(1), p.1712207. https://doi.org/10.1155/2022/1712207
45. Meng, S., Wu, H., Xiao, D., Lan, S. and Dong, A., 2023. Recent advances in bacterial cellulose-based antibacterial composites for infected wound therapy. *Carbohydrate Polymers*, *316*, p.121082. https://doi.org/10.1016/j.carbpol.2023.121082
46. Michel, D., Bachelier, B., Drean, J.Y. and Harzallah, O., 2013. Preparation of cellulosic fibers from sugarcane for textile use. In *Conference Papers in Science* (Vol. 2013, No. 1, p. 651787). Hindawi Publishing Corporation. https://doi.org/10.1155/2013/651787
47. Mubarak, A.A., Ilyas, R.A., Nordin, A.H., Ngadi, N. and Alkbir, M.F.M., 2024. Recent developments in sugarcane bagasse fibre-based adsorbent and their potential industrial applications: a review. *International Journal of Biological Macromolecules*, p.134165. https://doi.org/10.1016/j.ijbiomac.2024.134165
48. Mukherjee, A., 2018. *Overview of the groundwater of South Asia* (pp. 3-20). Springer Singapore. https://doi.org/10.1007/978-981-10-3889-1_32
49. Mukherjee, A., Bhattacharya, P. and Fryar, A.E., 2011. Arsenic and other toxic elements in surface and groundwater systems. *Applied Geochemistry*, *26*(4), pp.415-420. https://doi.org/10.1016/j.apgeochem.2011.01.001
50. Mukherjee, A., Bhattacharya, P., Savage, K., Foster, A. and Bundschuh, J., 2008. Distribution of geogenic arsenic in hydrologic systems: controls and challenges. *Journal of Contaminant Hydrology*, *99*(1-4), pp.1-7. https://doi.org/10.1016/j.jconhyd.2008.04.002
51. Mzimela, Z.N.T., Linganiso, L.Z., Revaprasadu, N. and Motaung, T.E., 2018. Comparison of cellulose extraction from sugarcane bagasse through alkali. *Materials Research*, *21*, p.e20170750. https://doi.org/10.1590/1980-5373-MR-2017-0750
52. Narkhede, S., Parkhey, P., Dadsena, A., Singhai, A., Phillips, E., Kolla, V.P., and Sahu, R., 2024. Green synthesis of silver nanoparticles for Arsenic (III) removal from contaminated water. *Journal of Chemical Health Risks, 14*(6), pp.1851-1868. https://doi.org/10.52783/jchr.v14.i6.7100
53. Navya, K.N. and Sujatha, C.H., 2023. A Green Chemistry Approach on Synthesis,

Characterization and Properties of Cellulose Based Eco-friendly Hydrogel. *Chemistry Africa*, *6*(2), pp.1037-1050. https://doi.org/10.1007/s42250-022-00539-6

54. Nayak, K.K. and Gupta, P., 2015. In vitro biocompatibility study of keratin/agar scaffold for tissue engineering. *International journal of biological macromolecules*, *81*, pp.1-10. https://doi.org/10.1016/j.ijbiomac.2015.07.025

55. Nemeş, N.S., Ardean, C., Davidescu, C.M., Negrea, A., Ciopec, M., Duţeanu, N., Negrea, P., Paul, C., Duda-Seiman, D. and Muntean, D., 2022. Antimicrobial activity of cellulose based materials. *Polymers*, *14*(4), p.735. https://doi.org/10.3390/polym14040735

56. Owi, W.T., Lin, O.H., Sam, S.T., Chia, C.H., Zakaria, S., Mohaiyiddin, M.S., Villagracia, A.R., Santos, G.N. and Md Akil, H., 2016. Comparative study of microcelluloses isolated from two different biomasses with commercial cellulose. BioResources, 11(2), pp.3453-3465. https://doi.org/10.5555/20163175532

57. Patel, D.K., Dutta, S.D., Ganguly, K. and Lim, K.T., 2021. Multifunctional bioactive chitosan/cellulose nanocrystal scaffolds eradicate bacterial growth and sustain drug delivery. *International Journal of Biological Macromolecules*, *170*, pp.178-188. https://doi.org/10.1016/j.ijbiomac.2020.12.145

58. Patel, J.B., Tenover, F.C., Turnidge, J.D. and Jorgensen, J.H., 2011. Susceptibility test methods: dilution and disk diffusion methods. *Manual of clinical microbiology*, pp.1122-1143. https://doi.org/10.1128/9781555816728.ch68

59. Patel, P.K., Pandey, L.M. and Uppaluri, R.V., 2023. Cyclic desorption based efficacy of polyvinyl alcohol-chitosan variant resins for multi heavy-metal removal. *International Journal of Biological Macromolecules*, *242*, p.124812. https://doi.org/10.1016/j.ijbiomac.2023.124812

60. Patel, R., Dhar, P., Babaei-Ghazvini, A., Dafchahi, M.N. and Acharya, B., 2023. Transforming lignin into renewable fuels, chemicals, and materials: A review. *Bioresource Technology Reports*, *22*, p.101463. https://doi.org/10.1016/j.biteb.2023.101463

61. Pezeshki, H., Hashemi, M. and Rajabi, S., 2023. Removal of arsenic as a potentially toxic element from drinking water by filtration: a mini review of nanofiltration and reverse osmosis techniques. *Heliyon*, *9*(3). https://doi.org/10.1016/j.heliyon.2023.e14246

62. Powar, R.V., Mehetre, S.A., Powar, T.R. and Patil, S.B., 2022. End-use applications of sugarcane trash: A comprehensive review. *Sugar Tech*, *24*(3), pp.699-714. https://doi.org/10.1007/s12355-022-01107-5

63. Rahman, Z., Thomas, L., Chetri, S.P., Bodhankar, S., Kumar, V. and Naidu, R., 2023. A comprehensive review on chromium (Cr) contamination and Cr (VI)-resistant extremophiles in diverse extreme environments. *Environmental Science and Pollution Research*, *30*(21), pp.59163-59193. https://doi.org/10.1007/s11356-023-26624-y

64. Ren, J.L., Sun, R.C., Liu, C.F., Lin, L. and He, B.H., 2007. Synthesis and characterization of novel cationic SCB hemicelluloses with a low degree of substitution. *Carbohydrate Polymers*, *67*(3), pp.347-357. https://doi.org/10.1016/j.carbpol.2006.06.002

65. Saha, R., Nandi, R. and Saha, B., 2011. Sources and toxicity of hexavalent chromium. *Journal of Coordination Chemistry*, *64*(10), pp.1782-1806. https://doi.org/10.1080/00958972.2011.583646

66. Sarkar, D., Datta, R. and Hannigan, R. eds., 2011. *Concepts and applications in environmental geochemistry*. Elsevier. https://doi.org/10.1016/S1474-8177(07)05007-3

67. Shaghaleh, H., Xu, X. and Wang, S., 2018. Current progress in production of biopolymeric

materials based on cellulose, cellulose nanofibers, and cellulose derivatives. *RSC advances*, *8*(2), pp.825-842. https://doi.org/10.1039/c7ra11157f

68. Shahid, M., Khalid, M., Dumat, C., Khalid, S., Niazi, N.K., Imran, M., Bibi, I., Ahmad, I., Hammad, H.M. and Tabassum, R.A., 2018. Arsenic level and risk assessment of groundwater in Vehari, Punjab Province, Pakistan. *Exposure and Health*, *10*, pp.229-239. https://doi.org/10.1007/s12403-017-0257-7

69. Shaikh, H.M., Pandare, K.V., Nair, G. and Varma, A.J., 2009. Utilization of sugarcane bagasse cellulose for producing cellulose acetates: Novel use of residual hemicellulose as plasticizer. *Carbohydrate Polymers*, *76*(1), pp.23-29. https://doi.org/10.1016/j.carbpol.2008.09.014

70. Shakya, A., Vithanage, M. and Agarwal, T., 2022. Influence of pyrolysis temperature on biochar properties and Cr (VI) adsorption from water with groundnut shell biochars: Mechanistic approach. *Environmental Research*, *215*, p.114243. https://doi.org/10.1016/j.envres.2022.114243

71. Shukla, S.K., Sharma, L., Awasthi, S.K. and Pathak, A.D., 2017. Sugarcane in India. *Package of practices for different agro–climatic zones, All Indian Coordinated Research Project on Sugarcane, IISR Lucknow, Uttar Pradesh*, pp.1-64.

72. Singh, S., Singh, P., Sharma, A. and Choudhury, M. eds., 2022. *Agriculture Waste Management and Bioresource: The Circular Economy Perspective*. John Wiley & Sons.

73. Solomon, S. and Misra, V., 2024. Sugarcane By-Product-Based Industries in Asian Countries. In *Value Addition and Product Diversification in Sugarcane* (pp. 1-31). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-7228-5_1

74. Sracek, O., Bhattacharya, P., Jacks, G., Gustafsson, J.P. and Von Brömssen, M., 2004. Behavior of arsenic and geochemical modeling of arsenic enrichment in aqueous environments. *Applied Geochemistry*, *19*(2), pp.169-180. https://doi.org/10.1016/j.apgeochem.2003.09.005

75. Sun, J.X., Sun, X.F., Zhao, H. and Sun, R.C., 2004. Isolation and characterization of cellulose from sugarcane bagasse. *Polymer degradation and stability*, *84*(2), pp.331-339. https://doi.org/10.1016/j.polymdegradstab.2004.02.008

76. Syeda, H.I. and Yap, P.S., 2022. A review on three-dimensional cellulose-based aerogels for the removal of heavy metals from water. *Science of the Total Environment*, *807*, p.150606. https://doi.org/10.1016/j.scitotenv.2021.150606

77. Tabassum, R.A., Shahid, M., Dumat, C., Niazi, N.K., Khalid, S., Shah, N.S., Imran, M. and Khalid, S., 2019. Health risk assessment of drinking arsenic-containing groundwater in Hasilpur, Pakistan: effect of sampling area, depth, and source. *Environmental Science and Pollution Research*, *26*, pp.20018-20029. https://doi.org/10.1007/s11356-018-1276-z

78. Tendencia E. Disk diffusion method. InLaboratory manual of standardized methods for antimicrobial sensitivity tests for bacteria isolated from aquatic animals and environment 2004 (pp. 13-29). Aquaculture Department, Southeast Asian Fisheries Development Center.

79. Wang, J., Liu, M., Duan, C., Sun, J. and Xu, Y., 2019. Preparation and characterization of cellulose-based adsorbent and its application in heavy metal ions removal. *Carbohydrate polymers*, *206*, pp.837-843. https://doi.org/10.1016/j.carbpol.2018.11.059

80. Wyman, C.E., 1999. Biomass ethanol: technical progress, opportunities, and commercial challenges. *Annual review of energy and the*

environment, *24*(1), pp.189-226. https://doi.org/10.1146/annurev.energy.24.1.189

81. Yin, Y. and Woo, M.W., 2024. Transitioning of petroleum-based plastic food packaging to sustainable bio-based alternatives. *Sustainable Food Technology*, *2*(3), pp.548-566. https://doi.org/10.1039/D4FB00028E
82. Yu, G., Wang, X., Liu, J., Jiang, P., You, S., Ding, N., Guo, Q. and Lin, F., 2021. Applications of nanomaterials for heavy metal removal from water and soil: A review. *Sustainability*, *13*(2), p.713. https://doi.org/10.3390/su13020713
83. Yu, X., Tong, S., Ge, M., Wu, L., Zuo, J., Cao, C. and Song, W., 2013. Adsorption of heavy metal ions from aqueous solution by carboxylated cellulose nanocrystals. *Journal of Environmental Sciences*, *25*(5), pp.933-943. https://doi.org/10.1016/S1001-0742(12)60145-4
84. Zhang, K., Feng, W. and Jin, C., 2020. Protocol efficiently measuring the swelling rate of hydrogels. *MethodsX*, *7*, p.100779. https://doi.org/10.1016/j.mex.2019.100779
85. Zhao, H., Chang, J., Havlík, P., van Dijk, M., Valin, H., Janssens, C., Ma, L., Bai, Z., Herrero, M., Smith, P. and Obersteiner, M., 2021. China’s future food demand and its implications for trade and environment. *Nature Sustainability*, *4*(12), pp.1042-1051. https://doi.org/10.1038/s41893-021-00784-6
86. Zhou, D., Zhang, L., Zhou, J. and Guo, S., 2004. Cellulose/chitin beads for adsorption of heavy metals in aqueous solution. *Water research*, *38*(11), pp.2643-2650. https://doi.org/10.1016/j.watres.2004.03.026