SUPERABSORBENT HYDROGEL FROM EXTRACTED OIL PALM FROND WASTE CELLULOSE USING MICROWAVE IRRADIATION FOR CADMIUM ION REMOVAL FROM AQUEOUS SOLUTION

Nesha Selvakumaran[1], Azwan Lazim[1, ✉]

Abstract. This research report facile approach on dispersion of cellulose fiber extracted from oil palm frond waste in a "green-solution" prepared by using urea and sodium hydroxide while the polymerization is carried out using microwave to form hydrogels. Effects of adding cellulose was determined by comparing the swelling degree between 0% and 2% cellulose hydrogel. Results showed that swelling ratio enhanced by the presence of cellulose. SEM images exposed that hydrogel with cellulose has rough surface compared to the hydrogels without cellulose. The XRD demonstrated that cellulose hydrogel lost its crystallinity upon polymerization. The DSC analysis showed that upon polymerization the hydrogel has better heat stability compared to the raw oil palm frond cellulose fiber. The FTIR shows successful polymerization has occurred between polyacrylamide and cellulose with a reference to band at 1657.99 cm^{-1}, which indicated the N–H bond. The capacity of cellulose hydrogel at different ratios to adsorb cadmium as a function of pH has also been carried out. Results showed that hydrogel made of 2% cellulose at pH 4 adsorbed the most cadmium. Therefore, this sorbent can potentially be used as Cd ion remover in aqueous solution.

Keywords: oil palm frond, cellulose, hydrogel, microwave, cadmium.

1. Introduction

Cadmium has polluted the environment for at least the past 50 years, moving into and throughout aquatic and soil ecosystems. This naturally occurring metal is found in both water and soil or in sediments at low concentrations due to natural processes, namely volcanic eruptions, natural crust erosion and also anthropogenic activities such as mining and smelting [1]. These non-essential life forms are commonly toxic even at relatively low concentrations and may cause adverse effects due to their high bioaccumulation tendency [2]. The International Agency for Research on Cancer (1993) classified cadmium as carcinogenic and teratogenic substance with probable mutagenic properties. Direct exposure to cadmium has been recognised as an urgent public health issue especially in many developing countries as it can cause detrimental effects on the kidneys and bones [3]. Amongst the worst case recorded was *itai-itai* disease (epidemic bone disease) reported in the late 1960's, that occurred in Japan due to the Cd contamination [4]. Another worrying consequence of cadmium exposure is the risk of developing acute cardiovascular disease [5].

There are various common and conventional analytical instruments or techniques used for CD detection of cadmium in water or food samples such as voltammetry, inductively couple plasma optic emission spectrometry (ICP-OES), inductively couple plasma mass spectrometry (ICP-MS), and atomic absorption spectrometry (ICP-MS) [6]. Other typical methods used to remove heavy metals from effluents include chemical precipitation, electrolysis, membrane separation, ion exchange, and absorption by activated carbon [7]. Most of these methods suffer from a combination of high capital, high operational cost and disposal of resulting sludge or any of those drawbacks [8]. Hence, researches have focused on investigating low-cost materials such as agricultural by-products, industrial wastes and biological materials as adsorbents to remove heavy metals from industrial wastewater. Usually, these wastes are further functioning by introducing new functional groups to improve their performance as adsorbent. As example, apple waste, sawdust and rice husk were modified to perform as bio-sorbent [9, 10].

Oil palm biomasses are produced in large quantity in Malaysia as the palm oil industry is among the major contributors of the agro-industry. The leftover mainly consists of cellulose and hemicellulose with the former constituting one of the most abundant natural polymers on earth [11]. Oil palm frond (OPF) is one of the hugely

---

[1] School of Chemical and Food Science, Faculty of Science and Technology,
University Kebangsaan Malaysia, 436000 UKM Bangi, Selangor, Malaysia
✉ *azwanlazim@ukm.edu.my*

produced biomasses at oil palm plantations. It was reported that approximately 50 million tons of OPF were produced per annum in Malaysia, which are available throughout the year as the fronds are frequently cut during the harvesting of fresh fruit bunches. The fibers of cellulose are soft thus making it easy to be processed. The structure is built by a number of glucose units that are linked by β (1-4) glycosidic linkage in a long chain and have a very strong affinity. The hydrogen bonding through van der Waals forces makes this structure very stable and insoluble not only in water but also in the majority of organic and inorganic solvents. Per previous reports, fibers/cellulose extracted from different parts of oil palm tree was successfully performed in removing heavy metal from waste water [12].

Hydrogels are 3-D cross-linked polymer networks that have gained marked attention for their wide applications in drug delivery, tissue engineering, removal of metal ions and dyes [13]. Having a three-dimensional network structure, hydrogels are able to absorb and retain water without losing their network structure [14]. Moreover, this material is easy to tailor accordingly to the purpose and its end use. Apart from that, it is also an intelligent material that elegantly maintains its unique physical characteristics such as tissue-like elasticity and mechanical strength even after swelling in aqueous medium [15]. However, forming hydrogels by incorporating natural polysaccharides have improved its properties significantly. For example, grafting of vinyl monomers onto natural polysaccharides results in fine-tuned products for industrial applications [16]. Since the hydrogel continuously gains demand from the industry, microwave irradiation is emerging as an efficient source of thermal energy and constitutes a very original procedure of heating materials which are different from the classical approach that was commonly used to prepare hydrogel. The application of microwave irradiation as the source of thermal energy lies in its effectivity due to the small amount of time that is needed for it [17].

The objective of this study is to prepare hydrogel from oil palm frond cellulose incorporated with polyacrylamide. The cadmium adsorption capacity of this bio-composite was evaluated as a function of pH. The hydrogel was prepared by using simple one-pot step using microwave heating. The morphology, chemical, thermal and swelling properties of the hydrogels was investigated and subjected to a systematic cadmium absorption study.

2. Experimental

2.1. Materials

Oil palm frond (OPF) cellulose was obtained from University Putra Malaysia. Urea (Systerm), sodium hydroxide (NaOH) (Systerm), polyacrylamide (Sigma Aldrich), *N,N'*-methylenebisacrylamide (MBA) (Merck 8), potassium persulfate (KPS) (Merck 8), nitric acid (HNO$_3$) (Systerm) and cadmium sulpahate (3CdSO$_4$·8H$_2$O) (AnalaR) were used. The stock solution containing 1000 mg/l of Cd(II) was prepared by dissolving a known quantity of cadmium sulphate in 1000 ml of distilled water. This stock solution was diluted as required to obtain a series of working solutions. The solution pH was adjusted by adding 0.1 mol/l of HNO$_3$ or NaOH solution. All chemicals used were of analytical reagent grade, and all solutions were prepared with distilled water unless stated otherwise.

2.2. Dissolution of Cellulose

OPF cellulose was dispersed in urea/NaOH solution. The ratio of urea to NaOH to distilled water prepared is 7:12:81. The solution was pre-cooled at 268 K prior to dissolving the cellulose [18]. A calculated amount that corresponded to 2 % (w/v) of cellulose fiber was added to the solution and shaken vigorously by hand, since according to the literature this dissolution is regarded as the most optimum one, since with the increases of cellulose concentration in the hydrogel more –COOH groups become available for the absorption of cadmium ions. Amount of optimum cellulose fiber was fixed at 2 % according to the preliminary studies conducted using different concentration of cellulose fiber.

2.3. Preparation of Hydrogel

Cellulose hydrogel was prepared by mixing 4 g of polyacrylamide, 0.2 g of *N,N'*-methylenebisacrylamide (MBA) as a cross-linker and 15 ml of the dispersed 2 % cellulose solution. 0.2 g of potassium persulfate was used as the initiator and graft copolymerization was carried out [19]. The solution was casted on Petri dish and polymerization was initiated by using a microwave at 100 W for 2 min. The hydrogel was then washed with plenty of distilled water and dried in oven at 313 K overnight. Zero hydrogel was prepared by using the same method but without adding dispersed cellulose solution. Once dried, the hydrogels were peeled off the petri dish and cut into small pieces weighing 50 mg each [20].

2.4. Swelling Index Hydrogel

About 50 mg of hydrogel was weighed and left in 25 ml of distilled water overnight. It was then filtered using filter funnel and filter paper was used to remove any excessive water. Moreover, the swelling behavior of the hydrogel was assessed by using the swelling ratio, which is expressed by the ratio of swollen sample weight over the weight of the dry sample and the weight of the

hydrogel was measured after swelling [21]. Each test was carried out in triplicate. The formula used to calculate the swelling index of the hydrogel is:

$$S_{eq} = \frac{M - M_0}{M_0} \cdot 100 \qquad (1)$$

where M and M_0 (g) is the mass of swollen and dried hydrogels, respectively, g [22].

2.5. Adsorption Experiments

Adsorption experiments were performed in a series of 50 ml conical flasks containing 50 mg of hydrogel and 25 мд of 2 ppm Cd(II) solution. The adsorbents were then separated by direct filtration after a given time. The concentration of Cd(II) in the solution was measured by using atomic absorption spectrometry (AAS). To study the effects of pH on the adsorption capacity, the adsorption experiments were performed at five pH values: 2, 3, 4, 5, and 6 with an initial concentration of 2 mg/l and the contact time of 120 min [23]. The term contact time is defined as to describe the time of adhesion between an adhesive and a surface, before performing further measurements. The adsorption capacity of the hydrogel was calculated using Eq. (2):

$$q_e = \frac{(C_0 - C_e) \cdot V}{m} \qquad (2)$$

where q_e is the adsorption capacity, mg/g; C_0 and C_e are the initial and equilibrium concentrations, mg/l; m is the mass of the adsorbent used, mg; V is the volume of the solution used, ml [24].
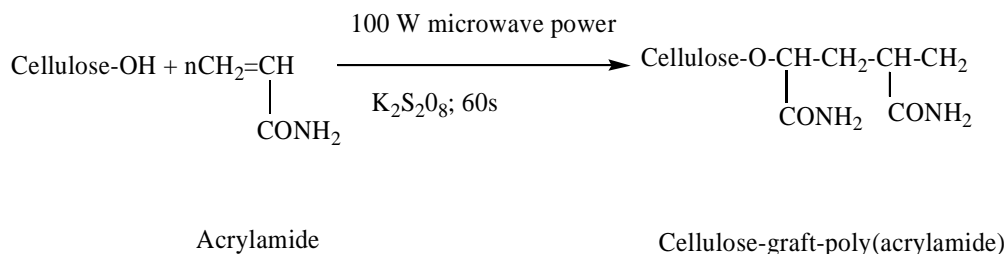
2.6. Characterization

FTIR-ATR was used to detect the chemical bonds and functional groups of the hydrogel. Spectrums were collected for each of the samples within the wavenumber range of 650–400 cm^{-1}. The surface morphology of the hydrogels was examined by SEM. The samples were coated with a thin gold layer (two times, 40 Ma, 60 s^{-1}, approx. 30 nm) by a sputter coater unit (BALZER SCD 050 Sputter Coater, BAL-TEC) and surface topography was analyzed using JEOL JSM 6300F SEM operated at an acceleration voltage of 5 kV. The X-ray diffraction pat-terns (XRD) of the hydrogels were recorded with oriented mounts using Philips X'Pert Pro X-ray diffractometer. The radiation used was 45 kV and 40 mA for two ranges of 0–60°. In order to investigate the thermal properties of starch, polyacrylamide, and synthesized hydrogels, differential scanning calorimetry (DSC) analysis of the samples were carried out with Perkin-Elmer Diamond TG/DSC Analyzer. The analyses were made using aluminum pans under a dynamic nitrogen atmosphere in the temperature range of 253–73 K and the heating rate of 10 K/min.

3. Results and Discussion

3.1. Synthesis of Grafted Cellulose-Polyacrylamide Hydrogel (C-g-pAam)

Scheme 1 shows the homogeneous modification of cellulose with acrylamide in NaOH/urea aqueous solution. The mechanism proposed that only low concentration of potassium persulfate is needed to promote acrylamide grafted efficiently onto OPF cellulose under microwave irradiation. The reaction is highly associated with the hydroxyl group of cellulose in combination with NaOH/urea. The heat produced consequently became reactive and accessible to interact with media such as acrylamide. The significant increase in reaction rates for both organic and inorganic reactions undergone a microwave irradiation is observed [25]. In comparison with conventional procedures, oxygen becomes a very potent inhibitor for most common vinyl monomers because it combines with active free radicals to give relatively inactive ones which are capable of propagating the chain reaction. To overcome this, the reaction media are usually thoroughly purged with inert gas to eliminate the existence of O_2 or otherwise the reaction may not occur. Unlikely, under microwave conditions, the presence of O_2 does not affect the normal graft co-polymerization reaction. It is assumed that under the influence of microwaves the oxygen reversibly combines with the primary free radicals and thus the oxygen is unable to inhibit the chain propagation and polymerization.

100 W microwave power

Cellulose-OH + nCH$_2$=CH $\xrightarrow{\quad\text{K}_2\text{S}_2\text{O}_8;\ 60s\quad}$ Cellulose-O-CH-CH$_2$-CH-CH$_2$
                | | |
                CONH$_2$ CONH$_2$ CONH$_2$

Acrylamide   Cellulose-graft-poly(acrylamide)

Scheme 1. Proposed mechanism for the synthesis of OPF cellulose grafted polyacrylamide using microwave
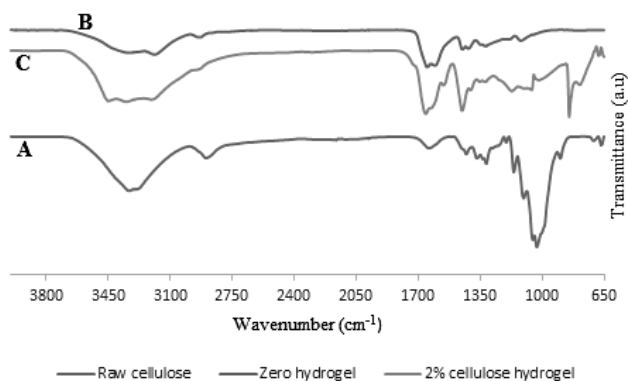
Fig. 1. The FTIR spectra of raw cellulose (A),
zero hydrogel (B) and 2 % cellulose hydrogel (C)

3.2. Fourier Transformed Infrared (FTIR)

The FTIR spectra of raw cellulose, zero hydrogel and cellulose hydrogel is shown in Fig. 1.

The absorption peak observed at 3334 cm^{-1} is related to the O–H stretching vibration of hydroxyl group. The peak observed at 2900 cm^{-1} corresponds to CH$_2$ groups. Absence of peaks located in the range of 1509–1609 cm^{-1} corresponds to C=C aromatic skeletal vibrations, which indicates the complete removal of lignin. The absorption band that corresponds to either acetyl or uronic ester groups of hemicellulose and normally appears in the region of 1700–1740 cm^{-1} was absent. This indicates the removal of hemicellulose during acid hydrolysis. The two bands around 1060 and 895 cm^{-1} are associated with C–O stretching and C–H rocking vibrations of the carbohydrates, respectively [26].

The zero hydrogel band observed at 3350 and 3189 cm^{-1} is the primary N–H stretch of polyacrylamide. The band at 1648 cm^{-1} corresponds to N–H bending while the band at 1120 cm^{-1} to the C–N stretch of the polyacrylamide. As for the cellulose hydrogel, the broad band at 3342 cm^{-1} is characteristic of O–H vibration that is unique to cellulose. The band at 1658 cm^{-1} indicates the N–H bond in acrylamide. This band confirms the polymerization between cellulose and acrylamide. Meanwhile, the band at 1452 cm^{-1} confirms the stretching vibration of C–OH while the band observed at 847 cm^{-1} is the C–O vibration of epoxy group. In addition, the absorption at ~1645 cm^{-1} in all samples is indicative of the water molecule absorption due to strong interaction between cellulose and water. The broad peaks within 3382–3353 cm^{-1} constitute a further confirmation of the existence of carboxylic O–H groups (2500–3500 cm^{-1}). Therefore, based on the porous structure and the irregular surface along with high amounts of introduced free carboxyl groups, it can be concluded that the hydrogel presents an adequate physical and chemical characteristic to adsorb metals.

3.3. Scanning Electron Emission (SEM)

The SEM results for raw cellulose fiber, zero hydrogel and 2 % cellulose hydrogel are shown in Fig. 2. Raw cellulose fibers are made of rigid, highly ordered fibrils (Fig. 2a). There were no particles and the surface morphology was flat with a very clear and smooth outer for zero hydrogel sample (Fig. 2b). On the contrary, the 2 % cellulose hydrogel (Fig. 2c) has spherical rod particles of cellulose homogenously dispersed on the surface [27]. This image verifies that the cellulose hydrogel has porous structure, which is important from the viewpoint of its application in different fields. In general, water permeation, as well as the interaction of external stimuli with polymers hydrophilic groups occur in these pores. The porous architecture could be also loaded with inorganic compounds or any material. Therefore, the porous structure is the predominant reason for the cellulose hydrogel high swelling capacity rate [28].

3.4. Thermal Analysis of Cellulose and Hydrogel

DSC is an excellent technique to assess the miscibility of the components within a hydrogel network and to prove the existence of intermolecular interactions between the components. The thermograms of raw cellulose fibers, zero hydrogels and 2 % cellulose hydrogels are presented in Fig. 3. From the DSC analysis, it can be observed that the heat of decomposition and the crystallinity index have same trend which is attributed to the occurrence of heterolytic thermolysis of glycosidic bonds along the ordered chains. It was also observed that the temperature onset (T_i), melting temperature (T_m) and the enthalpy of heating (ΔH) for hydrogel was higher than those values for OPF cellulose. Higher onset temperatures are often associated with higher thermal stability. In Fig. 3a, raw cellulose exhibits sharp endothermic peak at 336.01 K. Meanwhile, zero hydrogel (Fig. 3b) exhibits a sharp peak at 367.01 K. The cross-linking between polyacrylamide and cellulose increases the endothermic peak of 2% cellulose hydrogel (Fig. 3c) to 374.95 K and the maximum temperature shifted to higher temperature. Cellulose hydrogel also denatures at temperature above 433.00 K, which means that it is thermally stable in the aforementioned temperatures used [29].

3.5. X-Ray Diffraction (XRD)

The X-ray diffractograms of raw cellulose fiber and hydrogels are shown in Fig. 4. It is widely known that cellulose contains both crystalline and amorphous region. Diffraction peak measured at 22.5° is sharp, indicating high crystallinity of the raw cellulose fiber (Fig. 4a). It is

believed that improving the cellulose crystallinity increases their rigidity, which leads to the increase in mechanical properties of cellulose. Both intra- and inter-molecular hydrogen bonding occur in cellulose *via* hydroxyl groups, which results in various crystalline arrangements in an orderly fashion. The X-ray diffractograms show that the majority of the peak intensity is located at 2θ value of around 22.6°, which is related to the crystalline structure of cellulose for all samples, whilst the amorphous background is characterized by the low diffracted intensity at a 2θ value of around 16°. Meanwhile, the absence of a sharp crystalline peak in the XRD plots of hydrogels (Fig. 4b) suggests that they are mainly amorphous in nature. Grafting is further confirmed by comparison of the XRD of cellulose-graft-poly(acrylamide) (Fig. 4c) with those of raw OPF cellulose fiber, while cellulose-graft-poly(acrylamide) shows halos typical for amorphous polymers. It has been also observed that the crystallinity is lost upon grafting [30].

3.6. Swelling Properties of Hydrogel

In previous sections, the surface morphology and hydrogel porosity has been discussed. A noticeable property of the hydrogel is its ability to swell in aqueous media without dissolving in it. Swelling occurs due to the elastic stretching of the polymer chain fragments between cross-linking points. Stretching of chain fragments increases the elastic retractive force of the entropic origin, which in turn counteracts the network expansion. The balance of these two opposing contributions is governed by the equilibrium volume of the polymer network. The hydrogel swelling is a consequence of the balance between cohesive and dispersive forces on the hydrated polymer chains. Through the swelling test, it has been found that zero hydrogel has a swelling index of 15 %, while the 2% cellulose hydrogel has a swelling index of 1814 %. The swelling index corresponds to the fractional increase of a hydrogel weight, due to the absorption of water [31]. The swelling of hydrogel increased tremendously with the addition of cellulose fiber. It is noted that high swelling ratio is related to the formation of vastly porous structure that consequently increases the transparency of hydrogels. According to Flory-Huggins-Tanaka theory, the swelling ability of hydrogels is controlled by the amount of carboxyl group. High equilibrium swelling ratio indicates that the samples are superabsorbent hydrogels. It is important for biodegradable materials to have high swelling ratio for wide application in the industry. Examples of such applications include biomedicine (contact lenses, tissue engineering scaffolds, wound dressings), hygienic products, and agriculture [32]. Without the addition of cellulose fiber, the hydrogel is very stiff and thus not flexible as zero hydrogel does not absorb much water when immersed in it. But with the addition of cellulose fiber, the hydrogel becomes soft and flexible. This improvement in the swelling capacity of the hydrogel is attributed to the presence of cellulose with different morphology and surface charges. Besides, cellulose in the hydrogel can expand the hydrogel network and increase the pores and free spaces within this network to enable water absorption. In the present work, the prepared hydrogel contained hydrophilic functional groups such as –COOH, that are ionisable in aqueous media and can therefore be used for absorption of pollutants such as heavy metals from contaminated water.
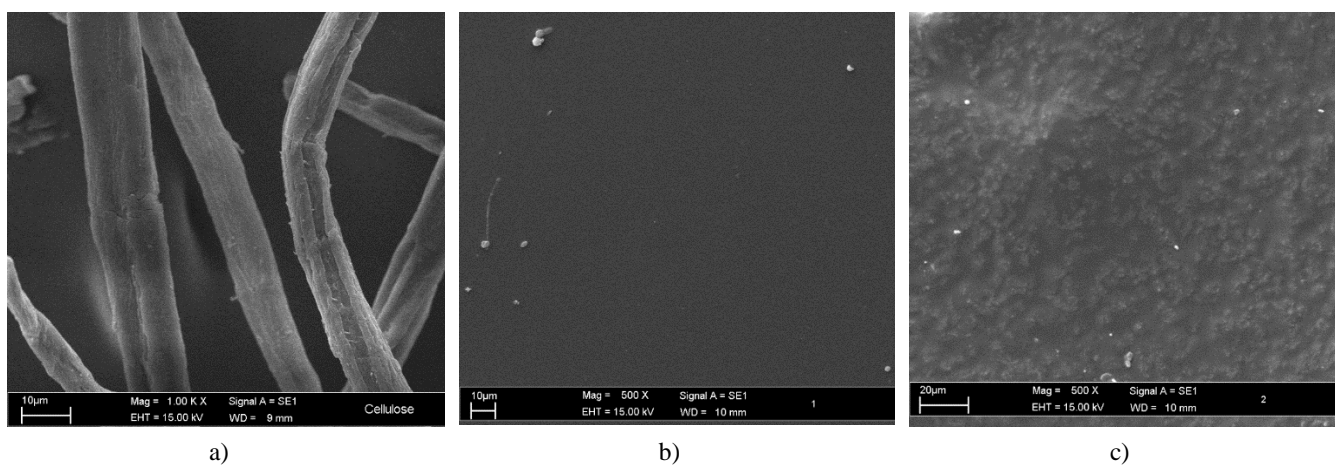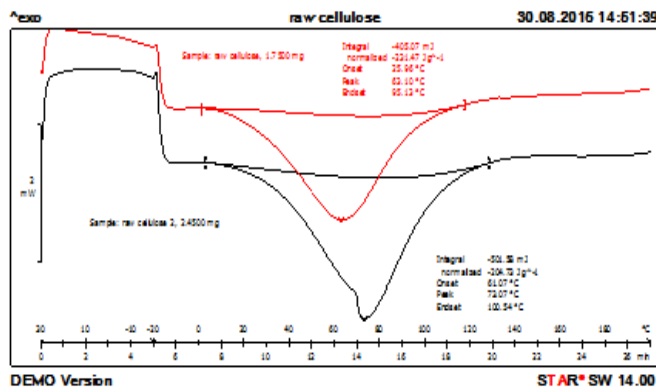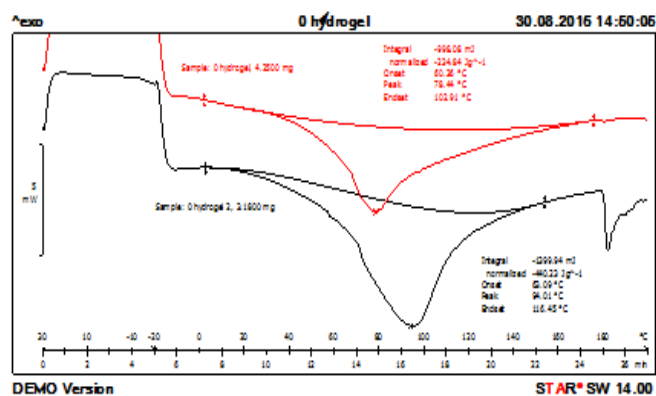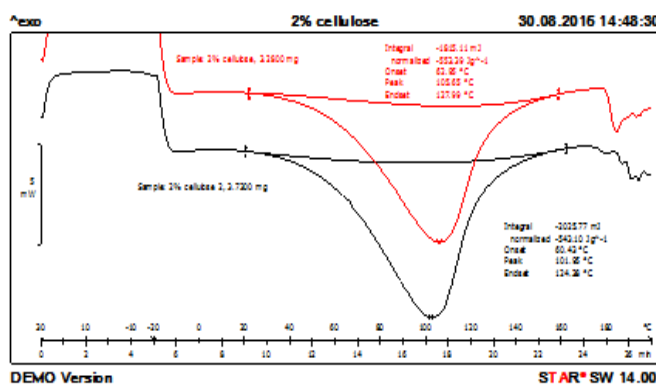

a)   b)   c)

Fig. 2. SEM micrographs of raw cellulose fiber (a), zero hydrogel (b) and 2 % cellulose hydrogel (c)

Fig. 3. DSC thermograms of raw cellulose fiber (a), zero hydrogel (b) and 2 % cellulose hydrogel (c)
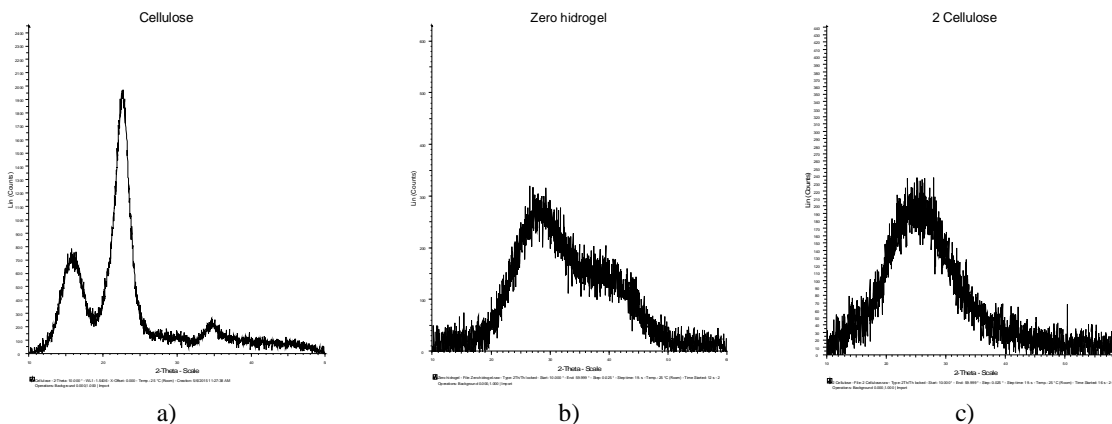

Fig. 4. X-ray diffractograms of raw cellulose fiber (a), zero hydrogel (b) and 2 % cellulose hydrogel (c)

3.7. Application

Absorption studies were performed in 100 ml conical flask at ambient temperature. Cadmium concentration was determined at the end of each experiment with AAS by diluting the solution accordingly.

3.7.1. Effect of cellulose concentration on cadmium absorption

Fig. 5 shows the effects of cellulose concentration in hydrogel on cadmium adsorption. The results show that as the concentration of cellulose increases in the hydrogel, the adsorption of cadmium increases as well. The optimum concentration of cellulose for cadmium adsorption is 2 % of dissolved cellulose. As the concentration of cellulose increases in the hydrogel, more –COOH groups become available for the absorption of cadmium ions. It also increases the flexibility of the hydrogel to absorb more water and increase the swelling [33]. However, when the concentration of cellulose is higher than 2 %, the hydrogel becomes too rigid and tough, which causes the loss of hydrogel ability to absorb more water and decreases its swelling ability. Hence, it can be concluded that the cadmium absorption of the hydrogel decreases when the concentration of cellulose is more than 2 %.
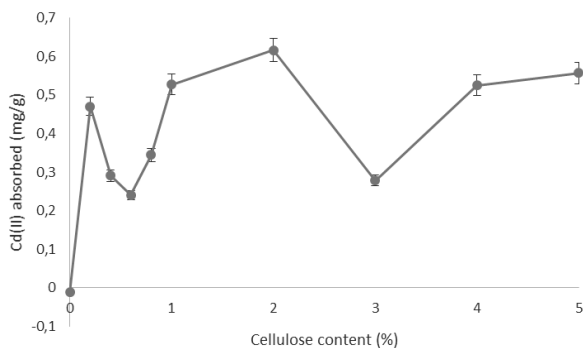

Fig. 5. Effect of cellulose content in hydrogel on Cd(II) absorption

3.7.2. Effect of pH on swelling behavior

Generally, the pH value is one of the most important parameters affecting the adsorption process. Hydrogels containing one or more electron donor atoms (Lewis base) such as N, S, O, and P form coordinate bonds with most of the toxic metal ions (Lewis acid) [34]. In this study, the binding properties of cellulose hydrogel for Cd^{2+} metal ions were tested under non-competitive conditions by immersing a sample in a solution containing metal ions. In order to investigate the influence of different pH values on cadmium adsorption, zero hydrogel and 2 % cellulose hydrogel were studied at various pHs

ranged from pH 2 to pH 6. The pH dependence of q_e for the Cd^{2+} is shown in Fig. 6. The increase in adsorption corresponds with the increase in the pH_0 of the solution in the range of 2.0–6.0. At $pH_0 > 4$, the q_e values decrease [35]. $pH_0 = 4$ was found to be an optimum for Cd^{2+} adsorption on 2 % cellulose hydrogel. The value of pH plays a vital role in adsorption of Cd(II) ion because hydrogen ions in the solution compete with the positive charge interacted with the negative charge on active sites of the adsorbent. The study has showed that the system is strongly pH dependent. To our best knowledge, this behavior can be explained in these three steps. Firstly, at a low pH value, the positively charged ions occur in a higher density due to the increase of adsorbed protons on the surface resulting in lower efficiency. Secondly, with an increasing pH value, the electrostatic repulsion decreases because of the reduction of positive charge density on adsorption sites, which in turn results in an increase in the adsorption of metal ions. Finally, at the higher pH value (pH ≥ 5) that has been optimized, the OH⁻ ions completely react with metal ions at the active sites on the adsorbent surfaces, which results in a decrease in the adsorption capacity. In this study, Cd^{2+} adsorption onto the surface of these hydrogels is assumed to occur through ion-exchange and chelation between positively charged Cd^{2+} and non-ionized or ionized carboxylic groups within the polymer hydrogels.
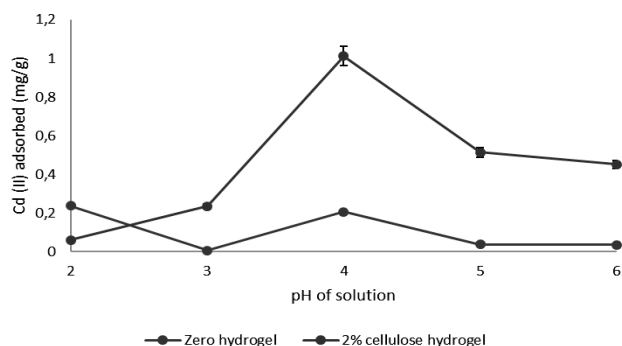

Fig. 6. Cd(II) absorption by different hydrogel samples (with 2 % cellulose and without cellulose) as a function of pH

4. Conclusions

Cellulose grafted polyacrylamide (C-g-pAam) hydrogels were synthesized using *N,N'*-methylenebisacrylamide as a cross-linking agent and their effiency to absorb cadmium in water sample was investigated. From the experiments performed we can conclude that adding OPF cellulose fiber will increase the swelling index of the hydrogel and its flexibility, which are very important characteristics of hydrogels. It was also found that cadmium absorption of 2 % cellulose hydrogel is

56.84 % at pH 4, demonstrating that the system we used is pH dependent.

Acknowledgements

References

[1] Caló E., Khutoryanskiy V.: Eur. Polym. J., 2015, **65**, 252. https://doi.org/10.1016/j.eurpolymj.2014.11.024
[2] Liu X., Zhong L., Meng J. *et al.*: Environ. Pollut., 2018, **239**, 308. https://doi.org/10.1016/j.envpol.2018.04.033
[3] Fan R., Hu P., Wang Y. *et al.*: Toxic. Lett., 2018, **299**, 56. https://doi.org/10.1016/j.toxlet.2018.09.003
[4] Nogawa K., Suwazono Y., Nishijo M. *et al.*: Environ. Res., 2018, **164**, 379. https://doi.org/10.1016/j.envres.2018.03.019
[5] Tinkov A., Filippini T., Ajsuvakavo O. *et* al.: Sci. Total Environ., 2017, **601-602**, 741. https://doi.org/10.1016/j.scitotenv.2017.05.224
[6] Cervantes A., Rodriguez R., Ferrer L. *et al.*: Microchem. J., 2017, **132**, 107. https://doi.org/10.1016/j.microc.2017.01.016
[7] Kurchatov I., Laguntsov N., Neschimento Y., Feklistov D.: Phys. Procedia, 2015, **72**, 89. https://doi.org/10.1016/j.phpro.2015.09.025
[8] Gitis V., Hankins N.: J. Water Proc. Eng., 2018, 25, 34. https://doi.org/10.1016/j.jwpe.2018.06.003
[9] Nguyen T., Ngo H., Guo W. *et al.*: Biores. Technol., 2013, **148**, 574. https://doi.org/10.1016/j.biortech.2013.08.124
[10] Tovar-Carrillo K., Nakasone K., Sugita S. *et al.*: Mater. Sci. Eng. C, 2014, **42**, 808. https://doi.org/10.1016/j.msec.2014.06.023
[11] Loh S.: Energ. Convers. Manage., 2017, **141**, 285. https://doi.org/10.1016/j.enconman.2016.08.081
[12] Rahmi, Lelifajri, Julinawati, Shabrina: Carbohydr. Polym., 2017, **170**, 226. https://doi.org/10.1016/j.carbpol.2017.04.084
[13] Rui-Hong X., Peng-Gang R., Jian H. *et al.*: Carbohyd. Polym., 2016, **138**, 222. https://doi.org/10.1016/j.carbpol.2015.11.042
[14] Soares P., De Seixas J., Albuquerque P. *et al.*: Carbohyd. Polym., 2015, **134**, 673. https://doi.org/10.1016/j.carbpol.2015.08.042
[15] Perez R., Won J., Knowles J., Kim H.: Adv. Drug Deliv. Rev., 2013, **65**, 471. https://doi.org/10.1016/j.addr.2012.03.009
[16] Sharma R., Kumar R., Singh A.: Separ. Purif. Technol., 2019, **209**, 684. https://doi.org/10.1016/j.seppur.2018.09.011
[17] Bardajee G., Azimi S., Sharifi M.: Microchem. J., 2017, **133**, 358. https://doi.org/10.1016/j.microc.2017.03.037
[18] Kojima Y., Takayasu M., Toma M., Koda S.: Ultrasonic. Sonochem., 2019, **51**, 419. https://doi.org/10.1016/j.ultsonch.2018.07.030
[19] Maitra J., Shukla V.: Am. J. Polym. Sci., 2014, **4**, 25. https://doi.org/10.5923/j.ajps.20140402.01
[20] Ahmed E.: J. Adv. Res., 2015, **6**: 105. https://doi.org/10.1016/j.jare.2013.07.006
[21] Sun X., Zhao X., Zhao L. *et al.*: J. Mater. Chem. B, 2015, **3**, 6368. https://doi.org/10.1039/C5TB00645G
[22] Selvakumaran N., Lazim M.: AIP Conf. Proc., 2016, **1784**, 030018. https://doi.org/10.1063/1.4966756
[23] Robles J., Peresin M., Tamminen T. *et al.*: Int. J. Biol. Macromol., 2018, **115**, 1249. https://doi.org/10.1016/j.ijbiomac.2018.04.044
[24] Li X., Wang S., Liu Y. *et al.*: J. Chem. Eng. Data, 2017, **62**, 407. https://doi.org/10.1021/acs.jced.6b00746
[25] Hu X., Wang Y., Xu M. *et al.*: Polym. Test., 2018, **71**, 344. https://doi.org/10.1016/j.polymertesting.2018.09.027
[26] Ilyas R., Sapuan S., Ishak M.: Carbohyd. Polym., 2018, **181**, 1038. https://doi.org/10.1016/j.carbpol.2017.11.045
[27] Isobe N., Komamiya T., Kimura S. *et al.*: Int. J. Biol. Macromol., 2018, **117**, 625. https://doi.org/10.1016/j.ijbiomac.2018.05.071
[28] Hu W., Zhang P., Liu X. *et al.*: Chem. Eng. J., 2018, **353**, 708. https://doi.org/10.1016/j.cej.2018.07.147
[29] Haafiz M., Eichhorn S., Hassan A., Jawaid M.: Carbohyd. Polym., 2013, **93**, 628. https://doi.org/10.1016/j.carbpol.2013.01.035
[30] Liang X., Qu B., Li J. *et al.*: React. Funct. Polym., 2015, **86**, 1. https://doi.org/10.1016/j.reactfunctpolym.2014.11.002
[31] Teow Y., Kam L., Mohammad A.: J. Environ. Chem. Eng., 2018, **6**, 4588. https://doi.org/10.1016/j.jece.2018.07.010
[32] Abdel-Halim E., Al-Deyab S.: React. Funct. Polym., 2014, **75**, 1. https://doi.org/10.1016/j.reactfunctpolym.2013.12.003
[33] Kim Y., Kim Y.-K., Kim S. *et al.*: Chem. Eng. J., 2017, **313**, 1042. https://doi.org/10.1016/j.cej.2016.10.136
[34] Omondi B., Okabe H., Hidaka Y., Hara K.: React. Funct. Polym., 2018, **130**, 90. https://doi.org/10.1016/j.reactfunctpolym.2018.06.006
[35] Pal P., Pal A.: Int. J. Biol. Macromol., 2017, **104**, 1548. https://doi.org/10.1016/j.ijbiomac.2017.02.042

СУПЕРАБСОРБУЮЧИЙ ГІДРОГЕЛЬ З ЕКСТРАГОВАНОЮ З ВІДХОДІВ ЛИСТЯ ОЛІЙНОЇ ПАЛЬМИ ЦЕЛЮЛОЗОЮ З ВИКОРИСТАННЯМ МІКРОХВИЛЬОВОГО ВИПРОМІНЮВАННЯ ДЛЯ ВИЛУЧЕННЯ КАДМІЙ-ЙОНІВ З ВОДНОГО РОЗЧИНУ

Анотація. Проведено диспергування целюлозного волокна, екстрагованого з відходів листя олійної пальми в «зеленому розчині», одержаному з сечовини та гідроксиду натрію. Для синтезу гідрогелів застосовано реакцію полімеризації з використанням мікрохвилього випромінення. Вплив додавання целюлози визначено внаслідок порівняння ступеня набухання гідрогелю з 0% і 2 % целюлози. Показано, що коефіцієнт набухання збільшується за наявності целюлози. За допомогою скануючої електронної мікроскопії доведено, що гідрогель з целюлозою має нерівну поверхню в порівнянні з гідрогелями без неї. Методами рентгено-структурного аналізу та сканувальна калориметрії встановлено, що гідрогелі з целюлозою втрача-ють кристалічність при полімеризації, а полімеризований гідрогель має кращу термостабільність, порівняно з необроб-леним целюлозним волокном. Результати Фур'є-спектроскопії свідчать про полімеризацію між поліакриламідом та целю-лозою, з посиланням на смугу при 1657,99 см$^{-1}$, характерної для N–H. Досліджено здатність гідрогелю з різним вмістом целюлози до адсорбції кадмію як функції рН. Встановлено, що максимальну кількість кадмію адсорбує гідрогель з 2 % це-люлози за рН 4. Показано, що такий сорбент може бути використаний для видалення йонів Cd з водного розчину.

Ключові слова: листя олійної пальми, целюлоза, гідрогель, мікрохвилі, кадмій.