

Superabsorbent Hydrogel derived from Lemon Juice/Ethylenediamine with Maleic Acid as a Cross-Linker

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Abstract Hydrogels are 3-dimensional polymer network materials with the ability to absorb a large amount of water. The current advancement in technology has increased their demand in the fields of industrial and environmental applications. This study reports the synthesis and characterization of superabsorbent hydrogels derived from lemon juice. The preparation involved linking lemon juice (LJ) with Ethylenediamine (EDA) via an amide linkage to obtain HLE-1 hydrogel. The polymer hydrogel was then cross-linked with maleic acid via an ester linkage to form HLE-2 hydrogel. Characterization was done using FT-IR, SEM, and XRD. The optimization of the swelling conditions was studied by varying contact time and the dosage of both lemon juice and the cross-linker. XRD analysis showed the conversion of amorphous hydrogel HLE-1 to crystalline hydrogel HLE-2 upon cross-linking. The FT-IR spectra showed a new strong symmetric stretching -COO- peak at 1079.83 cm⁻¹ in HLE-2 indicating successful ester linkage. SEM analysis showed pores of different sizes and shapes in HAE-2 compared to a rigid, concrete, and smooth surface in HLE-1. Upon the optimization of the synthesis conditions of the cross-linked hydrogel, a swelling capacity of 925% was obtained. Crosslinking the hydrogel improved its water absorption ability. The high swelling capacity of the hydrogel provides a baseline for potential application in agriculture, especially in semi and arid regions.

Keywords Characterization, Lemon juice, Cross-linking, Ethylenediamine, Superabsorbent hydrogel

1. Introduction

Polymer superabsorbent hydrogels are three-dimensional hydrophilic structures that are prepared through the linking of materials either chemically or physically to form copolymers with super absorbing characteristics. The hydrophilic groups in hydrogels polymer backbone (-CONH₂, -OH, -COOH, -SO₃H) have the ability to absorb water many times the original weight while maintaining their structures [1]. The recent rapid increase in population growth has led to the development of new technologies of synthesizing hydrogels towards major applications in wastewater treatment, agriculture, and food industry, biotechnological and medical fields. Researchers have drawn interest in this field due to the increasing demand for hydrogels [2]. Permanent and reversible hydrogels depend on the nature of cross-linkers in the network of polymer [3]. Reversible hydrogel has a non-homogeneous network as a result of non-covalent bonds and temporary chain

entanglements [4]. Currently, most hydrogels in literature have been developed in the laboratory with their large-scale production being costly, toxic, complex in synthesis, and non-biodegradable, with minimal reports in Africa on their use [1], [5]. The availability of lemon juice coupled with its rich carboxylic groups makes it a potential monomer in hydrogel synthesis [6]. On the other hand, lemon juice incorporated with ethylenediamine organic surfactant forms polymer gel which when cross-linked with maleic acid can form crystalline phases with small particle size and large surface area for water absorption. This study aimed at synthesizing and characterizing a green superabsorbent hydrogel from bio-derived materials to try and address the technical limitations of the existing hydrogels.

2. Materials and Methods

2.1. Reagents and Chemicals

The lemons were obtained from the local market in Machakos County - Kenya then transported to Kenyatta University laboratory. Ethylenediamine was obtained from Merck Chemical Co (Darmstadt, Germany), and maleic acid was purchased from Kenya science chemical limited Kenya.

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Received: Sep. 29, 2021; Accepted: Oct. 15, 2021; Published: Oct. 30, 2021

Published online at <http://journal.sapub.org/cmaterials>

2.2. Extraction of Lemon Juice from Lemon Fruits

During the extraction of lemon juice, the peels of lemon fruits were removed to obtain the inner part. The fresh soft parts of the fruit were cut into smaller sizes, put into an electric blender machine for blending. After blending the mixture was then filtered using a standard sieve of 14-16 micropores to obtain lemon juice [7].

2.3. Preparation of Hydrogel from Lemon Juice and Ethylenediamine (HLE-1)

145.0mL of lemon juice and 90.0mL of ethylenediamine (14.8M) were measured and put in an aluminum container. 100 mL of distilled water was added to the mixture to aid in the solvation process. The mixture was then heated at a temperature of 373 K to 405 K in an oven to form a viscous gel. The gel was allowed to cool to form solid hydrogel HLE-1.

2.4. Preparation of Cross-Linked Hydrogels (HLE-2)

The cross-linked HLE-2 superabsorbent hydrogel was prepared by adding 75.0mL of 3.5M maleic acid to HLE-1 hydrogel. The mixture was stirred and heated continuously at a temperature of 373K to 405K to form a viscous gel. It was then cooled to form HLE-2 hydrogel. Figure 1 shows the preparation scheme of HLE-2 hydrogel.

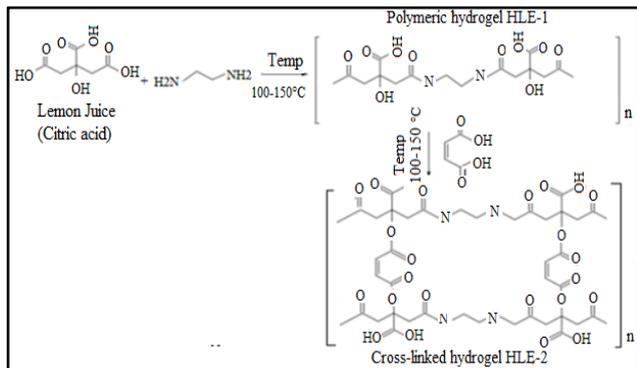


Figure 1. Scheme of preparation of HLE-2 hydrogel

2.5. Characterization of the Hydrogel

2.5.1. Fourier Transform Infrared (FT-IR) Analysis of the Superabsorbent Hydrogels

The functional group analysis of the uncross-linked HLE-1 and cross-linked HLE-2 was done using FT-IR spectroscopy [8]. The obtained crystal samples were dried at a temperature of 305K in an oven for 6 hours until a constant weight was attained. The dry sample of each hydrogel HLE-1 and HLE-2 were mixed with pre-dried KBr in a ratio of 25: 1 mg respectively. The fine homogenous mixture was compressed to form a transparent pellet then analyzed using the transmission method at 4000-200 cm^{-1} wavelength range (Shimadzu IR Tracer-100) [9].

2.5.2. Phase Composition Analysis of the Superabsorbent Hydrogels

The XRD analysis procedure for phase composition of the HLE-1 and HLE-2 hydrogels was adopted from Aikawa *et al.* [10]. The samples of superabsorbent hydrogels were cut into smaller sizes of 1 cm^2 followed by drying the samples at a temperature of 305K for 6 hours. The dry samples were placed on a silicon wafer, the measurement of phase and morphology of samples taken continuously from scattering angle (2θ) ranging 10 to 90° at 40 kV and a current of 15 mA with Cu ka radiation (1.54059-1.54441) using XRD (model Hossein Beygin German).

2.5.3. Microstructural Analysis of the Superabsorbent Hydrogels

The superabsorbent hydrogel microstructures of HLE-1 and HLE-2 were determined using a (ZEISS SUPRA 60 German) bright microscope at an accelerating voltage of 250 kV. The prepared samples were dried in the oven at 45°C for 6 hours until a constant weight was attained followed by coating with gold then placing them in an enclosed glass slide to obtain micrographs [11].

2.6. Effect of Lemon Juice (LJ) Dosage on Swelling Capacity of Cross-Linked Hydrogel

The hydrogels were prepared by varying dosage of lemon juice (LJ) from (0.9, 1.8, 3.6, 5.4, 7.2, and 9.0mL) while maintaining the volume of ethylenediamine and maleic acid as 4.5mL and 5.0mL respectively. 2.0g of each prepared sample gel was put in a uniform polyester bag and immersed in water for 24 hours to determine the swelling capacity.

2.7. Effect of Maleic Acid Dosage on the Swelling Capacity of the Hydrogel

The effect of the maleic acid (cross-linker) concentration was studied by varying dosages (1.25, 2.5, 3.75, 5.0, 6.25, and 7.5mL) while maintaining the volume of lemon juice at 7.2mL, and that of ethylenediamine as 4.5mL. 2.0 g of each gel sample weighed accurately was then immersed in water for 24 hours to determine the swelling capacity.

2.8. Equilibrium Water Content (EWC)

The swelling percentage capacity of HLE-2 samples was determined gravimetrically in deionized water at 25°C using a polyester bag method [12], [13], [14]. The prepared samples were allowed to dry to a constant weight in an oven at 45°C. 2.0 g of the dried sample was put in a polyester bag made of 200 mesh nylon and then immersed in the water to swell. The sample was then removed from the water and excess water was removed using Whatman filter paper. The equilibrium swelling capacity of the hydrogel was determined using equation 1 [13], [15].

$$EWC (\%) = \frac{Q_t - Q_x}{Q_x} \times 100 \quad (1)$$

Where Q_x is the initial weight of hydrogel before

swelling and Q_t is the final mass of the swollen hydrogel.

2.9. The Effect of Contact Time on the Swelling Capacity of the Hydrogel

The procedure of studying the effect of contact time on the swelling capacity of HLE-2 was adopted from Takigami *et al.* [16]. Varying contact times in the range (0.5, 1, 2, 4, 6, 12, and 24 hours) were used to study the effect of contact time on swelling capacity. 2.0 g of HLE-2 hydrogel was immersed in 500 mL of distilled water for a specified contact time. The samples were then removed periodically after the expiry of the specified time and new mass determined. The swelling capacity was then determined using equation 1 provided in section 2.8.

3. Results and Discussion

3.1. FT-IR Spectrum of Superabsorbent Hydrogels

FT-IR was used to determine the functional groups present in the green superabsorbent hydrogel before and after cross-linking with maleic acid. Figure 2 shows the IR spectrum of the hydrogel before crosslinking. The hydrogel was coded as HLE-1.

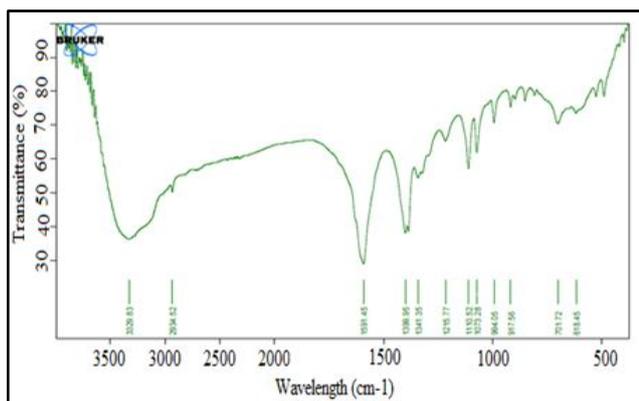


Figure 2. FT-IR spectrum of HLE-1 hydrogel

The broadband at 3329.83 cm^{-1} is a characteristic of the aliphatic secondary amine NH stretching vibration while the band at 2934.52 cm^{-1} represents the C–H stretching asymmetric vibration in the methyl group in lemon juice [17]. The absorptions bands at 1591.45 cm^{-1} , 1399.95 cm^{-1} , and 1341.35 cm^{-1} are assigned to aromatic ring stretching, tertiary alcohol -OH bending, and primary -OH in-plane bending respectively [18]. In addition, the absorption band at a wavelength of 1215.77 cm^{-1} , 1073.28 cm^{-1} , 1110.52 cm^{-1} , 701.72 cm^{-1} and 618.45 cm^{-1} , represents aromatic secondary amine CN stretching, cyanate –OCN, C-OCN stretch, and primary amine CN stretch respectively while 994.05 cm^{-1} , and 917.56 cm^{-1} represents C-O bend associated with lemon juice, and Vinylidene C-H out of plane bend [18].

Figure 3 shows the spectrum of the cross-linked hydrogel HLE-2. The new sharp peaks at a wavelength of 3948.89 cm^{-1} and 3909.17 cm^{-1} observed in HLE-2 are associated

with stretching frequency of the –OH group as well as intramolecular and intermolecular hydrogen bonds. The band at 3787.88 cm^{-1} is assigned to NH-NH₂ dimeric stretching vibration [19]. In addition, the new small absorption band at 3371.58 cm^{-1} is attributed to the presence of strong H-OH interaction. The spectra bands around 1989.08 cm^{-1} and 1947.47 cm^{-1} are attributed to –CN bending and (–CONH₂) amide functional groups as well as decreased bending vibration of –OH from 701.72 cm^{-1} to 671 cm^{-1} , shows amide linkage between lemon juice and ethylenediamine in HLE-2 hydrogel [20]. The new broad bands around 2371.58 cm^{-1} , 1577.76 cm^{-1} , 1383.61 cm^{-1} , 1205.20 cm^{-1} , and 885 cm^{-1} are due to C=O stretching in ester aldehyde, primary amine -NH bending, -OH bending in ester, phenol C-O stretching and C-O-C stretching respectively. The presence of those functional groups illustrates that there was an ester cross-link between the hydrogel HLE-1 and maleic acid [21]. In addition, IR spectra in figure 3 showed a new strong symmetric stretching -COO⁻ peak at 1079.83 cm^{-1} indicating successful ester linkage formation [22].

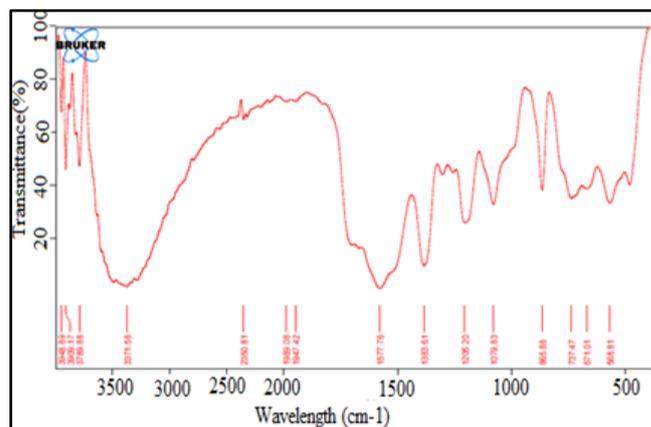


Figure 3. FT-IR spectrum of HLE-2 hydrogel

3.2. Phase Composition of HLE-1 and HLE-2 Hydrogels

The phase composition of the samples was determined using the XRD technique. The figure 4 and 5 represents the diffraction patterns of HLE-1 and HLE-2 hydrogels respectively.

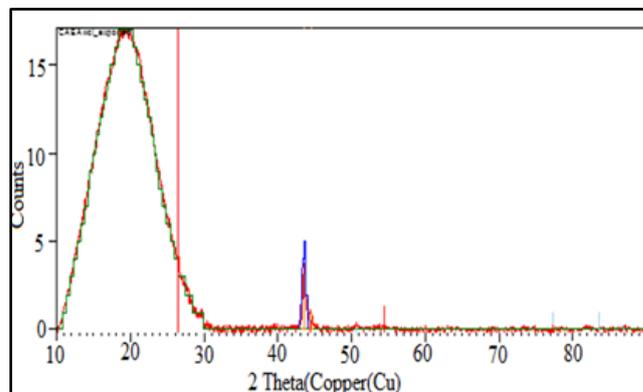


Figure 4. Powdered diffraction pattern of HLE-1 hydrogel

The diffraction pattern of HLE-1 (Figure 4) shows a broad hump between $11\text{--}32^\circ$ (2θ) which is associated with the amorphous nature of the hydrogel. The sharp peaks at (2θ) 43.49 and 44.51° were attributed to the presence of graphite crystalline phases in the polymer network in the hydrogel [23]. The diffraction pattern shows that the hydrogel HLE-1 was mainly amorphous.

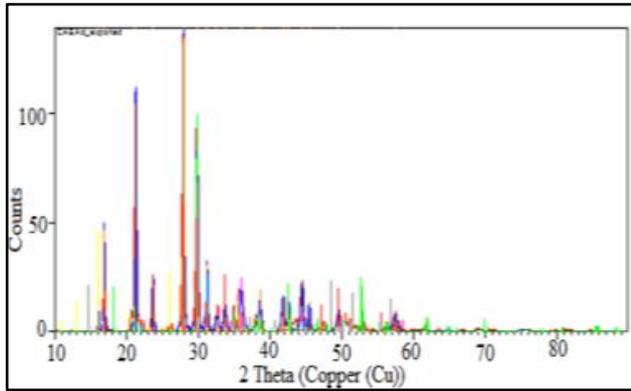


Figure 5. Powdered diffraction pattern of HLE-2

The diffraction pattern of HLE-2 shows the appearance of new sharp peaks with relatively high intensity at 15.96 , 16.81 , 21.21 , 23.59 , 27.88 , 29.77 (2θ). These peaks were as a result of the presence of crystalline phase of $\text{Ca}(\text{NH}_2\text{-OH})$, $(\text{C}_8\text{H}_6\text{O}_2)_4\text{H}_2\text{O}$, SF_6 , $\text{BiLaO}_{.833}$, $\text{K}_4\text{Ti}_4\text{F}_{10}\text{O}_6 \cdot 3\text{H}_2\text{O}$, and $\text{MgCH}_3 \cdot 4\text{NH}_3$ respectively [24]. In addition peaks between 31.20 to 38.24 , and 41.78 to 49.49 (2θ) are assigned to $\text{C}_5\text{H}_3\text{N}_4\text{NaO}_2 \cdot \text{H}_2\text{O}$ and $\text{Pb}(\text{OH})_4 \cdot 3\text{H}_2\text{O}$ crystalline phases respectively [25]. The crosslinking of the hydrogel with maleic acid yielded a polymerization reaction forming a high crystalline three-dimensional structure in HLE-2 super hydrogel [26]. XRD analysis shows a phase shift of the hydrogels from amorphous to crystalline upon cross-linking.

3.3. Microstructural Analysis of HLE-1 and HLE-2 Hydrogels

The microstructural analysis of the hydrogels was carried out using a scanning electron microscope. Figure 6 (A and B) shows the micrographs of both the uncross-linked and cross-linked hydrogels HLE-1 and HLE-2 respectively.

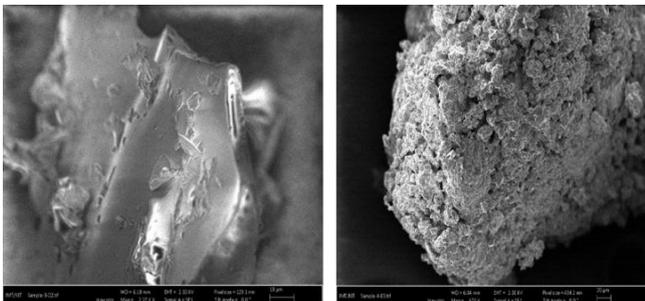


Figure 6. SEM micrographs of the (A) HLE-1 and (B) HLE-2 hydrogel

A rigid, concrete and smooth surface was observed in HLE-1 (Figure 6(A)). Upon cross-linking, the microstructure of the hydrogel changed to an uneven surface indicating

dispersal of the polar phase. The spherical and spindle-shaped structures on the surface of HLE-1 indicate a copolymerization reaction between lemon juice with ethylenediamine [27]. The SEM micrograph of HLE-2 contains pores of different sizes and shapes with an external surface full of cavities which may have occurred due to the presence of maleic acid as a cross-linker between different monomers during polymerization reaction [28].

3.4. The Effect of Lemon Juice Dosage on the Swelling Capacity of HLE-2 Hydrogel

Figure 7 shows the percentage swelling obtained when 2.0 g of the hydrogel was immersed in distilled water.

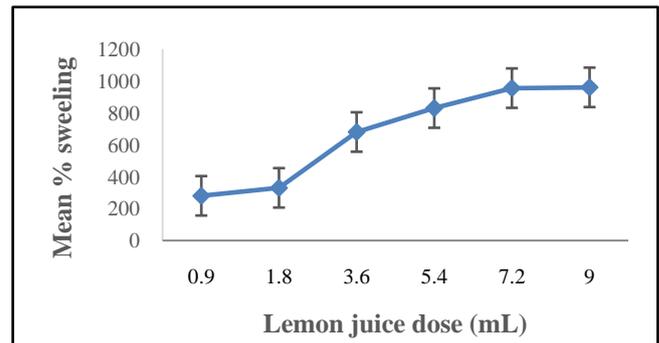


Figure 7. The effect of lemon juice dosage on the percentage swelling of 2.0 g of HLE-2

The percentage swelling of HLE-2 (Figure 7) increased from 280% to 955% when lemon juice dosage was increased from 0.9 to 7.2 mL then remained fairly constant. The increased swelling percentage may be associated with increased hydrophilic nature and ionic pressure effect due to the increased dosage of lemon juice [29]. On the other hand, a decrease in the swelling capacity after the optimal dosage of lemon juice may be as a result of the inadequate entropy and internal energy caused by the shielding effect of increased hydroxyl groups from the citric acid in lemon juice, leading to a low rate of diffusion of water molecules into the hydrogel [30], [31]. 7.2 mL produced HLE-2 hydrogel with the optimal water absorption capacity.

3.5. The Effect of Maleic Acid Dosage on the Swelling Capacity of HLE-2 Hydrogel

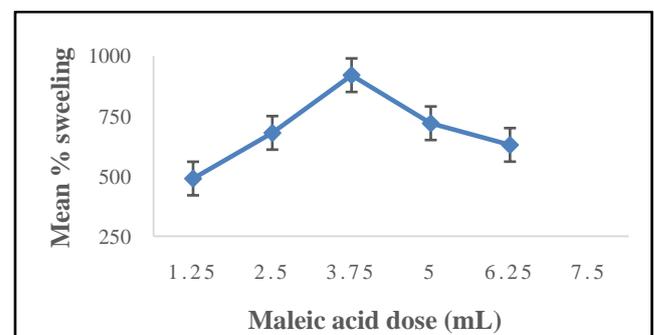


Figure 8. The effect of maleic acid dosage on the percentage swelling of 2.0 g of HLE-2 hydrogel immersed in 500 mL of distilled water and swelling period of 24 hours

Figure 8 shows the effect of varying dosages of maleic acid cross-linker on the swelling capacity of super absorber hydrogel HLE-2.

Figure 8 indicated that an increase in cross-linker dosage from 1.25 to 3.75mL gradually increased the percentage swelling capacity of HLE-2 super hydrogel from 490 to 920%. The increased swelling capacity suggested that an increased dosage of maleic acid increased the number of hydrophilic groups in the hydrogel. Swelling occurs through electrostatic repulsion between anions inside the hydrogel network and its elasticity [32]. The decreased swelling capacity of HLE-2 hydrogel after a cross-linker dosage of 3.75mL was observed. The decrease in swelling capacity after the optimal cross-linker dosage of 3.75mL could be a result of the decrease in an expansion of the hydrogel structure caused by increased crosslinking points. The decreased expansion of the hydrogel leads to shielding of the water molecules from being absorbed into the three-dimensional structure of hydrogel [32]. The addition of a chemical cross-linker is important to improve both the integrity of the gel and the predictability of mechanical properties [33].

3.6. Effect of Contact Time on the Swelling Capacity of the Hydrogel

Figure 9 shows the effect of contact time on the swelling capacity of green superabsorbent hydrogels HLE-2 at different contact times.

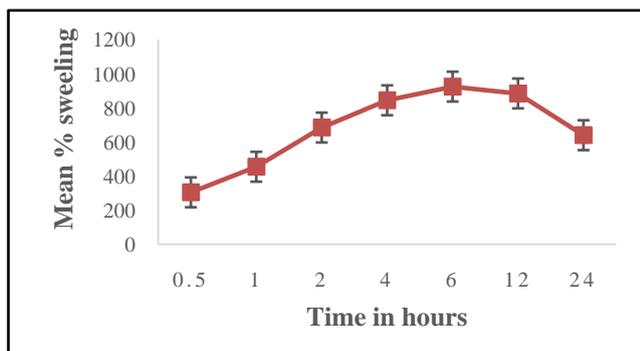


Figure 9. The effect of contact time on the percentage swelling of 2.0 g of HLE-2 hydrogel prepared using LJ, EDA, and maleic acid at a volume ratio of 144:90:75 respectively immersed in 500 mL of distilled water

Figure 9 show that the percentage swelling of hydrogel increased from 305% to 925% for HLE-2 when the contact time was increased from 0.5 to 6 hours followed by a decrease to 640% after 6 hours. The increase in swelling capacity may be as a result of water penetration in the hydrogel through capillary and diffusion in the glassy state and then absorbed by hydrophilic groups such as carboxylate through the formation of hydrogen bonds [34]. The swelling of the hydrogel is driven by the repulsion of hydrophilic groups inside the network and the osmotic pressure difference between the hydrogel. The decreased rate of water absorption after the optimal contact time may be attributed to saturation of the porous network hence the unavailability of vacant sites for water molecules [35].

4. Conclusions

The study showed that the cross-linked hydrogel prepared using LJ, EDA, and maleic acid in the volume ratio of 144:90:75 respectively produced maximum water absorption as well as the swelling capacity of 925%. The appearance of FT-IR symmetric stretching -COO^- peak at 1079.83 cm^{-1} is an indication of successful ester linkage in the formation of HLE-2 cross-linked hydrogel. XRD analysis of the hydrogels showed that cross-linking transformed the hydrogel from amorphous to crystalline nature. SEM analysis suggested a rigid, concrete, and smooth surface in HLE-1 as compared to the uneven surface with the dispersal of a polar phase in HLE-2. HLE-2 showed a maximum swelling capacity of 925% when subjected to 6 hours in 500 mL deionized water. The hydrogel synthesized being a good water absorber has a high potential of being used in agriculture to improve on the yields especially in arid and semi-arid regions.

ACKNOWLEDGEMENTS

The authors gratefully appreciate the insight assistance offered by the department of chemistry of Kenyatta University and the department of science technology and engineering of Kibabii University during the research period.

Declaration of Interest

The authors declare no conflict of interest in the work described in this study.

REFERENCES

- [1] Koetting, M., Peters, J., Steichen, S., and Peppas, N. (2015). Stimulus-responsive hydrogels: Theory, modern advances, and applications, *Material Science Engineering Research*, 93: 1-49.
- [2] Cruz, H., Law, Y., Guest, J., Rabaey, K., Batstone, D., Laycock, B., Verstraete, W., and Pikaar, I. (2019). Mainstream Ammonium Recovery to Advance Sustainable Urban Wastewater Management, *Environmental Science Technology*, 53: 11066-11079.
- [3] Cheng, W. M., Hu, X. M., Wang, D. M., and Liu, G. H. (2015). Preparation and characteristics of corn straw-co-amps-co-aa superabsorbent hydrogel, *Polymers*, 7: 2431-2445.
- [4] Shukla, N., Rattan, S., and Madras, G. (2012). Swelling and Dye-Adsorption Characteristics of an Amphoteric Superabsorbent Polymer [Article], *Industrial & Engineering Chemistry Research*, 51: 14941-14948.
- [5] Guilherme, M., Aouada, F., Fajardo, A., Martins, A., Paulino, A., Davi, M., Rubira, A., and Muniz, E. (2015). Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioner and nutrient carrier: A review. *European Polymer Journal*, 72: 365-385.

- [6] Meng, Y., and Ye, L. (2017). Synthesis and swelling property of superabsorbent starch grafted with acrylic acid/2-acrylamido-2-methyl-1-propanesulfonic acid. *Journal Science Food Agricultural*, 97(11): 3831-3840.
- [7] Coolman, R., Kanamori, T., and Kim, T. (2008). Biodegradable Polymers: Investigating the Reaction between Tartaric Acid and Glycerol Oregon State University.
- [8] Krauklis, A., Gagani, A., and Echtermeyer, A. (2018). Near infrared spectroscopic method for monitoring water content in epoxy resins and fiber reinforced composite, *Journal of Environmental Chemical Engineering*, 11: 586–599.
- [9] Hammond, P., Ali, D., and Cumming, R. (2005). A system on chip digital pH meter for use in a wireless diagnostic capsule, *Biomedical Engineering*, 4: 687-694.
- [10] Aikawa, K., Matsumoto, K., Uda, H., Tanaka, S., Shimamura, H., Aramaki, Y., and Tsuchiya, S. (1998). Hydrogel formation of the pH response polymer polyvinylacetal diethylaminoacetate (AEA), *International Journal of Pharmaceutics*, 167: 97-104.
- [11] Zhu, S., Wang, J., Yan, H., Wang, Y., Zhao, Y., Feng, B., Duan, K., and Weng, J. (2017). An injectable supramolecular self-healing bio-hydrogel with high stretchability, extensibility and ductility, and a high swelling ratio, *Journal of Material Chemistry*, 5: 7021.
- [12] Al, E., Güçlü, G., İyim, T., Emik, S., and Özgümüş, S. (2008). Synthesis and properties of starch-graft-acrylic acid/na-montmorillonite superabsorbent nanocomposite hydrogels, *Journal of Applied Polymer Science*, 109: 16-22.
- [13] Dalaran, M., Emik, S., Güçlü, G., İyim, T. B., and Özgümüş, S. (2009). Removal of acidic dye from aqueous solutions using poly (DMAEMA-AMPSHEMA) terpolymer/MMT nanocomposite hydrogels, *Polymer Bulletin*, 63: 159-171.
- [14] Yazdani-Pedram, M., Retuert, J., and Quijada, R. (2000). Hydrogels based on modified chitosan, I Synthesis and swelling behavior of poly(acrylic acid) grafted chitosan, *Macromol Applied Surface Science*, 201(9): 923-930.
- [15] Çöle, G., Gök, M. K., and Güçlü, G. (2013). Removal of basic dye from aqueous solutions using a novel nanocomposite hydrogel: N-vinyl 2-pyrrolidone/itaconic acid/organo clay. *European Polymer Journal*, 224(1760): 1-16.
- [16] Takigami, M., Nagasawa, N., Hiroki, A., Tagichi M., and Takigami, S. (2012). Preparation of stable CMC-Acid Gel. *Gums Stabilisers Food Ind*, 16: 175–182.
- [17] Mishra, R. K., Datt, M., Pal, K., and Banthia, A. K. (2008). Preparation and characterization of amidated pectin based. Hydrogels for drug delivery system, *Journal Material Science: Mater Med* 19: 2275–2280.
- [18] Bakravi A., Ahamadian Y., Hashemi H., and Namazi, H. (2018). Synthesis of gelatin-based biodegradable hydrogel nanocomposite and their application as drug delivery agent. *Advanced Polymer Technology*, 37(7): 2625-2635.
- [19] Viera, R. G., Filho G. R., Assuncao R. M. N., Meireles C. S., Vieira J. G., and Oliveira G. S. (2007). Synthesis and characterization methylcellulose from sugar cane bagasse cellulose, *Carbohydrate Polymers*, 67: 182-189.
- [20] Yeasmin, M. S., and Mondal, M. I. H. (2015). Synthesis of highly substituted carboxymethyl cellulose depending on cellulose particle size, *International Journal of Biological Macromolecules*, 80: 725-731.
- [21] Khan, A., El-Toni, A. M., Alrokayan, S., Alsalhi, M., Alhoshan, M., and Aldwayyan, A. (2011). Microwave assisted synthesis of silver nanoparticles using poly-N-isopropylacrylamide/acrylic acid microgel particles, *Colloidal Surface Physicochemical Engineering Aspects*, 377: 356-360.
- [22] Thombare, N., Mishra, S., Siddiqui, M., Jha, U., Singh, D., and Mahajan, G. (2018). Design and development of guar gum based novel, superabsorbent and moisture retaining hydrogels for agricultural applications [Article], *Carbohydr Polym*, 185: 169-178.
- [23] Li, Z., and Liu, S. (2007). Influence of slag as additive on compressive strength of fly ash-based geopolymer, *Journal of Materials in Civil Engineering*, 19: 470–474.
- [24] Wang, J., and Ye, L. (2015). Structure and properties of polyvinylalcohol/polyurethane blends, *Composite Part B-Engineering*, 69: 389-396.
- [25] Hassan, C., and Peppas, N. (2000). Structure and Morphology of Freeze/Thawed PVA Hydrogels, *Macromolecules*, 33: 2472-2479.
- [26] Guo, X., Shi, H., and Dick, W. (2010). Compressive strength and microstructural characteristics of class C fly ash geopolymer, *Cement and Concrete Composites*, 32: 142–147.
- [27] Pandey, A., and Negi, S. (2015). Removal of chromium (VI) from aqueous medium using chemically modified banana peels as efficient low adsorbent, *Journal of Bioresource Technology*, 192:115.
- [28] Mohanty, K., Das, D., and Biswas, M. N. (2005). Adsorption of phenol from aqueous solutions using activated carbons prepared from *Tectona grandis* sawdust by ZnCl₂ activation, *Chemical Engineering Journal*, (115): 121–131.
- [29] Parvathy, P., Jyothi, A., John, K., and Sreekumar, J. (2014). Cassava Starch Based Superabsorbent Polymer as Soil Conditioner: Impact on Soil Physico-Chemical and Biological Properties and Plant Growth, *Clean-Soil Air Water*, 42(11): 1610-1617.
- [30] Harsh, D., and Gebrke, S. (1991). Controlling the swelling characteristics of temperature sensitive cellulose ether hydrogels, *Journal of controlled release*, 17: 175-186.
- [31] Witono, J., Noordergraaf, I., Heeres, H., and Janssen, L. (2014). Water absorption, retention and the swelling characteristics of cassava starch grafted with polyacrylic acid, *Carbohydrate Polymers*, 103: 325-332.
- [32] Mahdavinia, G. R., Massoumi, B., Jalili, K., and Kiani, G. (2012). Effect of sodium montmorillonite nanoclay on the water absorbency and cationic dye removal of carrageenan-based nanocomposite superabsorbents, *Journal of Polymer Research*, 19(9): 1–13.
- [33] Durrani, A., and Donald, M. (1995). Physical Characterization of Amylopectin Gels, *Polymer Gels and Networks*, 3: 1-27.
- [34] Ji, H., Song, X., Shi, Z., Tang, C., Xiong, L., Zhao, W., and Zhao, C. (2018). Reinforced-Concrete Structured Hydrogel Microspheres with Ultrahigh Mechanical Strength, Restricted Water Uptake, and Superior Adsorption Capacity,

Sustainable Chemical Engineering, 6: 5950–5958.

[35] Gharekhani, H., Olad, A., Mirmohseni, A., and Bybordi, A. (2017). Superabsorbent hydrogel made of NaAlg-g-poly

(AAco- AAm) and rice husk ash: Synthesis, characterization, and swelling kinetic studies, *Carbohydrate Polymer*, 168: 1–13.

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