Adsorption performance of human-like collagen by alkali-modified Kapok fiber: a kinetic, equilibrium, and mechanistic investigation

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Abstract Collagen-based dressings achieve excellent repair of the skin during medical cosmetology, which has received a lot of attention recently. Although great progress has been made on using biomass fiber as dressing carrier, more research is required on developing novel biomass fibers because of the limitations of (i.e., high cost and complex processing) of existing materials. In this study, the adsorption behaviors of two human-like collagen were studied by examining the Kapok fiber that was modified using alkali consisting of various amounts of the mass fraction. Results show that the alkali-modified Kapok fiber surface becomes rough with vertically arranged grooves, and the cross-section depicts the hollow cavity structure. The composition analysis of alkali-modified Kapok shows that alkali dissolves part of the hemicellulose and lignin. Additionally, the surface energy rises sharply and the water contact angle changed from hydrophobic to hydrophilic. The adsorption amount of raw Kapok fiber is around 0.6 g/g, which accounts for only one twenty-first of the adsorption amount of alkali-treated Kapok (around 12.6 g/g), while the equilibrium adsorption amount was not sensitive to alkali concentration. The kinetics of human-like collagen followed both Quasi first and Quasi second order kinetic model, implying that the adsorption process where characterized by both physisorption and chemisorption. Finally, characterization of the AKF-2 coupled with the studies based on the inter-particle diffusion model showed a three-step of human-like collagen diffusion consisting of surface diffusion, inter-fiber diffusion and fiber’ hollow cavity diffusion. Our results demonstrate a perfect high absorption performance of Kapok fiber providing a potential for application of collagen-base dressings.

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Keywords Alkali-modified Kapok · Human-like collagen · Adsorption kinetics · Diffusion

Introduction

Since the 1970s, medical cosmetology has become one of the fastest-growing and closest-commercialize industries. Medical cosmetology primarily focuses on repairing and reshaping various parts of the human body through drugs, surgery, medical equipment and other traumatic or irreversible medical technology methods. However, the application of medical cosmetology can inevitably damage the barrier function of the skin and cause postoperative complications, including skin pigmentation, contact dermatitis, superficial ulcers and other skin diseases. Among several methods to deal with skin damage, postoperative repair dressing is one of the most widely and commonly used methods. Recently, collagen is the main dressings used in postoperative repair dressings to deal with skin damage. The research of collagen-based dressings are mainly focused on three areas: (1) preparation (Ge et al. 2018); (2) healing mechanism (Ge et al. 2018; Lozeau et al. 2018; Pallaske et al. 2018); and (3) application (Ye et al. 2014). When collagen is used, a biomass fiber based dressing-carrier is widely used including seaweed (Andryukov et al. 2020), chitin (Hao et al. 2020) and protein (Guo et al. 2020) fibers. Although great progress has been made on using biomass fiber as dressing carried, more research is required on developing novel biomass fibers because of the limitations of existing materials (high cost and complexity of process). Additionally, novel biomass fiber can help to maintain product diversity and provide avenues of opportunities to examine the effects of different biomass fiber dressings on skin problem.

Kapok is a biomass fiber known for its lightweight (Yang et al. 2018) and thinness (20–45 μm) among all the natural fibers. Single Kapok fiber has a big cylindrical hollow cavity structure (Macedo et al. 2020) and is characterized nearly transparent and very thin cell wall (Abdullah et al. 2010). Moreover, it has a hollow rate of > 86%, which is the highest hollow rate in nature fiber (Xiang et al. 2013). It has excellent moisture absorption and breathability characteristics due to the physicochemical property mentioned above (Yang et al. 2018). Furthermore, Kapok fiber has superior biocompatibility, biodegradability and natural antibacterial properties, with an antibacterial rate of > 91.9% (Liu et al. 2016). These unique properties have promoted Kapok fiber as dressing carrier materials for the collagen-based postoperative repair dressing. Because of the hydrophobic characteristics of Kapok fiber, earlier studies were mainly focused on oil removal (Dong et al. 2015b, c; Zhang et al. 2021), wastewater treatment (Sun et al. 2018; Wang and Wang 2018; Wang and Zheng 2017) as well as dye adsorption (Li et al. 2015; Zhang et al. 2015). Nevertheless, there have been no more studies to evaluate the performance of Kapok as a potential fiber for collagen-based dressings.

In collagen-based dressings, adsorption characteristics play an important role in the overall performance of the postoperative repair. In the study, the adsorption
performance of alkali modified Kapok fiber for various human-like collagen was quantified by evaluating the equilibrium time and amount of adsorption. Meanwhile, the effect of different alkali concentrations on the adsorption performance were also examined during this study. Additionally, the adsorption kinetic model of human-like collagen on the Kapok fiber, including two Quasi (first- and second-order kinetic models) and a Weber–Morris model were discussed. Finally, the adsorption process and mechanism were investigated. The alkali-modified Kapok fiber has potential to be used as an alternative material in collagen-based dressings application.

Material and methods

Alkali-modified Kapok fiber

The Kapok fiber used in this experiment came from Pate County, Java Tengah, Indonesia. The samples (6 g) were put into a beaker with different NaOH solution mass fractions (2%, 4%, 6%, 8%), which was then placed in a thermostat water bath (HH-4, ZENROE, China) to maintain a constant temperature around 70 °C for alkali-modification. After 6 h of reaction/treatment, the Kapok fibers were washed with deionized water and dried naturally at room temperature (26 °C, 68%) to obtain alkali-modified samples. The obtained samples were marked as AKF-2, AKF-4, AKF-6 and AKF-8, which refers to 2%, 4%, 6% and 8% alkali concentration, respectively.

Characterization of fibers

Their surface and cross-sectional morphologies were examined using field emission scanning electron microscopy (SU8010, Hitachi, Japan) by exerting an accelerating voltage of 20 kV on a simple sputter-coated with gold. Fourier transformed infrared (FTIR) spectrometer (Nicolet6700, Thermo Fisher, USA) was used to record diversification between raw and alkali-modified fibers. X-ray diffraction (XRD) experiments were executed on a diffractometer (D/MAX-2500 PC, Rigaku, Japan) by applying Cu Ka radiation (λ=0.154 nm, 40 kV, 200 mA) to separate the crystal phase of the raw and alkali-modified fibers. Shredded fibers were scanned at a step size of 0.05° with 20 between 5° and 60°. Cellulose samples are routinely analyzed by X-ray diffraction to determine the crystallinity (French 2014; French and Santiago Cintrón 2013). The Peak deconvolution was performed by curve fitting to the observed pattern (French 2020). In particular, subtracting instrumental background before peak deconvolution ensures a stable baseline fitting and reduces fitting error (Yao et al. 2020). The crystallinity (x) was calculated using the following equation:

\[
x = \frac{\sum I_c}{\sum I_c + \sum I_a} \times 100\%
\]

where \(\sum I_c\) represents the peak diffraction integral intensity crystalline region of the samples, and \(\sum I_a\) represents the intensity scattered by the amorphous fraction of the material.

The surface energies of samples, including surface tension, and polar and dispersion-component were calculated based on Owens–Wendt–Rabel–Kaelble method (OWRK). The slope and intercept of fitting line with three different liquids (water, ethylene glycol, ethanol) were obtained using the OWRK method (Table 1). The OWRK method expresses the surface energy between liquid and solid using the following equations:

\[
\delta_l(1 + \cos \theta) = 2 \left( \sqrt{\delta_s^d \delta_l^d} + \sqrt{\delta_s^p \delta_l^p} \right) \\
(1 + \cos \theta) \cdot \frac{\delta_l}{\delta_l^d} = \sqrt{\delta_s^d} \cdot \frac{\delta_l^p}{\delta_l^d} + \sqrt{\delta_s^d}
\]

where \(\delta_l\) is surface energy of liquid, \(\delta_s\) is surface energy of solid, \(\cos \theta\) is the contact angle, while superscript p and d represent polar and dispersion components, respectively (Kaelble 1970; Owens and

| Liquid type    | Surface tension (mN/m) | Polar componenta (mN/m) | Dispersion componenta (mN/m) |
|---------------|------------------------|-------------------------|------------------------------|
| Water         | 72.1                   | 52.2                    | 19.9                         |
| Ethylene glycol | 48.0                   | 29.0                    | 19.0                         |
| Ethanol       | 22.1                   | 4.6                     | 17.5                         |

aUsing figure from liquids database of tensiometer (DCAT11, Dataphysics, Germany)
Wendt 1969; Rabel 1971). Equation (3) can be further expressed into slope and intercept as follows:

\[ y = \sqrt{\delta_l^p} x + \sqrt{\delta_l^d} \]  

(4)

\[ x = \sqrt{\frac{\delta_l^p}{\delta_l^d}} \]  

(5)

Chemical composition

Composition analysis of samples were performed according to standardized methods of fibrous materials. The proportions of the chemical composition were based on GB/T standard methods. Holocellulose (sum of the cellulose and hemicelluloses), acid-soluble lignin and Klason-lignin were determined according to GB/T 2677.10-1995, GB/T 2677.8-94 and GB/T 10.337-2008, respectively. The cellulose of samples was quantified using TAPPI standard methods, followed by averaging of the results and comparison among experiments.

Characterization of human-like collagen

Two types of human-like collagen, Trauer (Guangzhou Trauer Biotechnology Co., Ltd.) and MeiQ (Yangzhou Merry Bio-Technology Co., Ltd.), was employed in this experiment, with the pure water as blank simple. The densities and surface tensions of three liquids were measured by a tension meter (DCAT11, Dataphysics, Germany), while viscosities were determined using a viscosimeter (DV2TLV, Brookfield, USA) at a temperature of 25 °C, with a spindle speed of 200 rpm and a rotor (SC4-18(18)). The pH of liquids was determined by pH-220B from China. The detailed properties of experimental liquids are shown in Table 2.

| Solution type | Density (g/cm³) | Viscosity (mPa s) | Surface tension (mN/m) | pH |
|---------------|----------------|------------------|------------------------|----|
| Trauer        | 1.00           | 1.65             | 48.14                  | 5.42 |
| MeiQ          | 1.01           | 20.98            | 37.90                  | 5.33 |
| Water         | 1.01           | 1.07             | 68.38                  | 7.18 |

Evaluation of liquid sorption rate

As shown in Fig. 1, the adsorption experiment was carried out using the tensiometer DCAT11. First, the sample was evenly distributed into a cylindrical container (2) that consisted of a length of 40 mm and an inner diameter of 12 mm. The sample filling mass, length and density were 0.2 g, 20 mm and 0.084 g/cm³, respectively. Then, the sample container (2) was hung under the microbalance using a unique sample rack. The beaker containing the test liquid was placed in the constant temperature liquid reservoir (3) on the elevator (5). The temperature of the test liquid was set to 25 °C through a thermostatic bath. Finally, recording was done by opening computer (6) and testing the software performance. The change in absorbed mass was recorded using the microbalance (1) at the same intervals and plotted in the form of a curve using the computer (6).
**Fig. 1** Diagram of device for adsorption

**Fig. 2** SEM image of surface morphologies in Kapok fiber (a), AKF-2 (c, d, f), AKF-4 (h), AKF-6 (i) and AKF-8 (j) and the cross-section in Kapok fiber (b, e) and AKF-2 (d)
Results and discussions

Characterization of fiber

Morphology and structure

The morphologies of Kapok fibers (raw and different alkali modification) are illustrated in Fig. 2. Because of the plant wax coverage, the raw Kapok fiber shows a cylindrical shape with a smooth surface (Fig. 2a). Following alkali modification (Fig. 2f–j), the fiber surface becomes rough due to the shedding of surface plant wax. The vertically arranged grooves have shown in fiber surface on AKF-4 (Fig. 2h), AKF-6 (Fig. 2i) and AKF-8 (Fig. 2j). And severe damage on the surface structure was observed on AKF-8, consisting of apparent traces of alkali corrosion.

Figure 2b, d shows the cross-sections of raw Kapok fiber and AKF-2. The raw Kapok fiber has a hollow cavity structure consisting of numerous multilevel buckling micropores in the cell wall Fig. 2e. Several studies have found excellent oil absorption capacity in the Kapok fiber largely because oil can easily enter the hollow cavity through the open ends of the fiber wall and through the multi-level buckling micropores on cells (Dong et al. 2015a) (Dong et al. 2014). As shown in Fig. 2d, the AKF-2 still depicts the hollow cavity structure with a thinner cell wall, indicating that the fibril structure is still intact. When adsorption occurs, the liquid can still enter the hollow cavity through the open ends of the fiber wall. Previous studies (Wang et al. 2012) have also shown that the appropriate NaOH modification is beneficial for improving absorbency depending on the modification concentration, temperature and time.

Composition analysis

The absorption peaks at 3400–3200 cm⁻¹ and 2918–2901 cm⁻¹ are attributed to OH and C-H’s stretching vibration, respectively. These peaks are characteristics of the presence of cellulose (George et al. 2015). Figure 3a shows that the raw Kapok fiber has two absorption peaks at 3335.36 cm⁻¹ and 2919.35 cm⁻¹. However, no significant changes were observed as the alkali concentration increased, indicating no damage to the cellulose of the Kapok fiber. The absorption peaks at 1736.14 cm⁻¹, 1593.44 cm⁻¹ and 1239.33 cm⁻¹ are attributed to the carbonyl group, the aromatic ring skeleton group, and the phenolic hydroxyl group; respectively, which are characteristics of absorption peak for lignin. It can be seen from Fig. 3a that the absorption peaks start to disappear at 1736.14 cm⁻¹ and 1239.33 cm⁻¹, and the absorption peak became weaker at 1593.44 cm⁻¹, indicating the partial removal of lignin. The absorption peaks about alkanes (1371.00 cm⁻¹ and 2919.35 cm⁻¹) become weaker after alkali modification.

Figure S1 shows that the diffraction peaks of raw fiber and alkali-modified Kapok fiber have no significant fluctuations. And Fig. S2 shows the peak deconvolutions of raw fiber and alkali-modified Kapok fiber, five crystalline peaks are discovered and they are the most characterized crystalline peaks for cellulose I (Yao et al. 2020). Their shape and amplitude are tuned by Profile Fitting in Jade 6 and fit with the pseudo-Voigt peaks. It indicates that the crystal structure of cellulose has not changed by alkali-modified, and the profile has been considered as the pure amorphous cellulose XRD profile (Yao et al. 2020). The crystallinity using the ratio of the crystalline peak areas and the total XRD profile area was calculated by the peak deconvolution method after subtracting the background intensity. Figure 3b shows that the raw fiber’s crystallinity is 35.71%, which is likely due to the presence of amorphous components including lignin, hemicellulose, and wax. The crystallinity increased from 35.71 to 48.22% following the increase in alkali concentration from 2 to 6%. Further increases in alkali concentration from 6 to 8% resulted in dropping fiber’s crystallinity from 48.22 to 43.94%. The increase in crystallinity after alkali treatment can be associated with the dissolution of free molecular chains in the amorphous region. The dissolution of free molecular chains increased the proportion of crystalline regions, thereby increasing the crystallinity.

The results obtained by examining the yield and chemical components of alkali-modified Kapok fiber are summarized in Fig. 3c, d. As shown in Fig. 3c, the yield decreases from 71.2 to 59.5% as the alkali concentration increases from 2 to 8%. Likewise, the raw Kapok fiber mainly consists of cellulose (39.95%), hemicellulose (37.01%), acid-soluble lignin (11.09%) and Klason lignin (4.46%) (Fig. 3d). Results also show that the chemical composition of different alkali-modified Kapok fibers has a substantial effect
on the hemicellulose and lignin content. For example, 38.17% of hemicellulose and 39.46% of acid-soluble lignin were removed in AKF-2, while 69.46% of hemicellulose and 73.54% of acid-soluble lignin were removed in AKF-8. However, our results show that the proportion of cellulose and Klason lignin experience an upward trend. The results indicate that the alkali dissolves part of the hemicellulose and lignin; however, the cellulose and Klason lignin are insensitive to the alkali concentration.

**Surficial wettability**

To characterize the surface property of fibers, the contact angle of liquid was measured. As shown in Fig. 4a, the raw Kapok fiber showed the water contact angle was 129.2°, which is considered as a hydrophobic surface. However, the water contact angle decreased below 50° with decreasing concentration of alkali (2 wt%: 48.3°, 4 wt%: 44.6°, 6 wt%: 45.2°, 8 wt%: 44°), the AKF-2, AKF-4, AKF-6, and AKF-8, which is considered as hydrophilic. The contact angle of human-like collagen showed a similar trend (Fig. 4b, c). The lower contact angle achieved
in alkali-modified fiber was supposed to be related with the surface energy. As depicted in Table S1, the surface energy of fiber rose rapidly from 7.80 to 125.05–140.06 mN/m with polar component playing a central role in stimulating the surface energy. On the other hand, Fig. 4d shows that the surface energies increase with an increase in NaOH concentration from 2 to 4%, with the highest surface energy of 140.06 mN/m at 4% NaOH concentration. However, there was a downward trend in surface energies with an increase in NaOH concentration from 4 to 8%. Generally, the higher surface energy of the substance indicates the better wettability of water on the surface and the smaller contact angle of water. Ko et al. (1981) also suggested that the surface energy increases with the rise in hydrophilic compared to the hydrophobic groups. In this study, the NaOH-modification removed the surface wax and exposed hydrophilic hydroxyl groups, which played an important role in hydrophilicity and fiber-matrix adhesion.

**Characterization of adsorption capacity**

Figure 5a–b shows the equilibrium adsorption amount \( (q_e) \) and equilibrium time \( (t_e) \) of fibers. The absorption curves of water and human-like collagen to alkali-modified Kapok fibers are shown in Fig. 5c–e. Results showed that the adsorption amount of raw Kapok fiber is around 0.6 g/g, which accounts for only one twenty-first of the adsorption amount of alkali-treated Kapok. Given that the adsorption amount was almost negligible, we did not proceed with further analysis of the adsorption curve. The equilibrium time of AKF-2 to MeiQ was 1399.80 s, while that of Water and Trauer were only 274.80 s and 300.00 s, indicating that Water and
Trauer had an adsorption time that was shorter than MeiQ by approximately 4–5 times. The equilibrium adsorption amounts of water, MeiQ and Trauer were 12.61 g/g, 11.96 g/g and 12.10 g/g, respectively, without significant variation. Similar trends were found in the AKF-4, AKF-6 and AKF-8.

It is likely that the difference in equilibrium time is related to changes in liquid viscosity. As illustrated in Table 1, water and Trauer have similar liquid viscosity resulting in similar adsorption times. However, the viscosity of MeiQ’s (20.98/mPa) was 20 times higher than water and Trauer. The fiber has small particle size and weak adhesion to low-viscosity liquids, but large particle size and strong adhesion to high-viscosity liquids (Dong et al. 2015a). MeiQ with high viscosity is more likely to be around the Kapok assembly’s pores, which can prevent the liquid from entering the interior.

However, it is noteworthy that the equilibrium adsorption time had inverse relationship with the alkali concentration. The equilibrium time of AKF-4 for MeiQ was 169.80 s, which was shorter than that of AKF-2 by 49.97%. The adsorption time in AKF-6 showed similar trend as AKF-4, with AKF-6 shorter than AKF-2 by 42.99%. For AKF-8, there were more significant gaps in equilibrium adsorption time, but the gaps were shortened at 24.98% for the MeiQ. The adsorption time showed similar tendency for water and Trauer, which was likely due to an increase in the alkali concentration that exposed more hydrophilic groups due to the removal of fiber surface wax. Compare to the equilibrium time, the equilibrium adsorption amount of AKF-2 on three different liquids was similar under the same filler density (0.0884 g/cm³), with only an 0.65 g/g discrepancy between the smallest in MeiQ and the largest in water. A similar result appears in AKF-2, AKF-4, AKF-6 and AKF-8 to the adsorption of liquids. Besides, as illustrated in Table S2, different alkali-modification seems to exert negligible influence on the equilibrium adsorption.
amount for three liquids, with only 0.1 g/g difference for AKF-2 and AKF-8. Several studies have reported that the oil absorbency of the Kapok assembly’s depend on effective inter-fiber pore volumes and hollow cavity structure (Dong et al. 2015a; Abudlallah et al. 2010; Rengasamy et al. 2011). Therefore, it is likely that the four fibers mentioned above have a minimal difference in equilibrium adsorption amount largely due to same filler density (0.0884 g/cm\(^3\)) and pore volume.

Absorption kinetics

To further study the human-like collagen adsorption mechanism of AKF, the Kapok fibers’ cumulative adsorption data treated under different alkali concentrations were fitted using the mathematical model of adsorption kinetics. The adsorption kinetic process of solid to liquid phase is generally described using the Quasi-first-order and Quasi-second-order kinetic model (ZengxiaoCai et al. 2019; Tanzifi et al. 2018), and Weber–Morris internal diffusion model (Hubbe et al. 2019; Haque et al. 2020; Bortoluz et al. 2020).

(1) Quasi-first-order kinetic model

The Quasi-first-order kinetic model is a first-order rate equation based on solid adsorption, which is applied to liquid phase adsorption. It is one of the most common models which can be expressed using the following equation:

\[
\log(q_e - q_t) = \log q_e - \frac{k_f}{2.303} t
\]

where \(q_e (g/g)\) is the equilibrium adsorption amount, \(q_t (g/g)\) is the adsorption amount at time \(t\) and \(k_f\) is the first-order adsorption rate constant.

(2) Quasi-second-order kinetic model

It is based on the assumption that the chemical adsorption mechanism controls the adsorption rate. The chemical adsorption mainly refers to the electron sharing and electron transfer between the adsorbent and adsorbate. The following equation is used to express the Quasi-second order kinetic model:

\[
\frac{t}{q_t} = \frac{1}{k_s q_e^2} + \frac{1}{q_e}
\]

where \(k_s\) represents the second-order adsorption rate constant.

(3) Weber–Morris model

The Weber–Morris internal diffusion model is often used to describe the process of adsorbate diffusion in the adsorbent pores. The model first analyzes the control steps in the reaction, followed by

| Adsorbate | Adsorbent | \(q_{e,exp} \,(g \, g^{-1})\) | Pseudo-first-order | Pseudo-second-order |
|-----------|-----------|----------------------------|---------------------|---------------------|
|           |           | \(q_{e,cal} \,(g \, g^{-1})\) | \(k_f \,(s^{-1}) \times 10^3\) | \(R^2\) \(k_s \,(10^{-3}) \,(g \, g^{-1} \, s^{-1})\) | \(R^2\) |
| AKF-2     | Water     | 12.615                     | 12.364              | 21.991              | 0.845                   | 6.854                     | 10.962                     | 0.572                     |
|           | Trauer    | 11.965                     | 15.528              | 18.400              | 0.995                   | 15.318                     | 0.817                     | 0.941                     |
|           | MeiQ      | 12.105                     | 13.564              | 3.039               | 0.998                   | 15.413                     | 0.174                     | 0.957                     |
| AKF-4     | Water     | 12.630                     | 12.406              | 36.251              | 0.992                   | 35.842                     | 0.774                     | 0.223                     |
|           | Trauer    | 11.440                     | 9.153               | 25.056              | 0.983                   | 13.349                     | 2.523                     | 0.992                     |
|           | MeiQ      | 12.063                     | 12.316              | 7.254               | 0.992                   | 13.762                     | 0.556                     | 0.989                     |
| AKF-6     | Water     | 12.583                     | 12.365              | 51.112              | 0.992                   | 21.353                     | 2.178                     | 0.872                     |
|           | Trauer    | 11.309                     | 8.574               | 55.018              | 0.982                   | 12.766                     | 6.673                     | 0.992                     |
|           | MeiQ      | 11.869                     | 12.533              | 8.198               | 0.975                   | 12.755                     | 1.316                     | 0.998                     |
| AKF-8     | Water     | 13.055                     | 12.299              | 114.632             | 0.984                   | 18.382                     | 2.949                     | 0.887                     |
|           | Trauer    | 12.014                     | 8.592               | 36.341              | 0.984                   | 13.430                     | 4.603                     | 0.992                     |
|           | MeiQ      | 12.018                     | 12.552              | 8.544               | 0.982                   | 13.518                     | 0.957                     | 0.992                     |
calculation of the diffusion rate constant in the adsorbent particles. The following equation is used to calculate the diffusion:

\[ q_t = k_{ip} t^{1/2} + C \]  

(8)

where \( C \) is a constant related to the thickness and boundary layer, \( k_{ip} \) is internal diffusion adsorption rate constant.

The Quasi-first-order and Quasi-second-order kinetic models’ Parameters are exhibited in Table 3, where \( q_{e,exp} \) and \( q_{e,cal} \) represents the equilibrium adsorption amount estimated from the experiment and model; respectively, while \( R \) represent the fitting coefficient. Results show that the Quasi-first-order kinetic model had a better fitting effect than the Quasi-second-order kinetic model for water, primarily due to closer equilibrium adsorption amount \( (q_{e,exp} \) and \( q_{e,cal} \)) and higher \( R^2 \) values. However, the fitting effect for human-like collagens indicated that the adsorptions were aligned with both Quasi first- and second-order kinetic models (Fig. 6). Herein, it is more likely that the fiber’s adsorption to water is the physisorption mechanism rather than the chemisorption, resulting from Van Der Waals, while the adsorption of human-like collagen is due to the coexistence of physisorption and chemisorption. In the Quasi-first-order kinetic model, the rate constant \( (k_f) \) of three liquids decreases with increase in liquid viscosity. Water has the largest rate constant because of its lowest viscosity (1.07 mPa s). Compare to lower viscosity liquids, the higher viscosity liquids are more difficult to diffuse under small sized pores of the fiber assembly. The \( k_s \) in the Quasi-second-order kinetic model of human-like collagens show a similar trend as \( k_f \). Overall, results showed that the higher viscosity liquid has a stronger interaction force on fiber compared to the lower viscosity liquid.

The Weber–Morris model was further used to evaluate the contribution of surface and intraparticle...
diffusion in the adsorption process. Suppose that the relationship between $q_t$ and $t^{1/2}$ is not only linear but also passes through the origin. In that case, the Weber–Morris pore diffusion model believes that intraparticle diffusion is assumed to be controlled by a sole rate. As shown in Fig. 7, $q_t$ and $t^{1/2}$ have a linear relationship, but does not pass through the origin, indicating that the intraparticle diffusion played a positive role in the adsorption steps. However, intraparticle diffusion is not the only step to control the adsorption process because there is other simultaneous adsorption mechanism that control adsorption. The curves of $q_t$ and $t^{1/2}$ are divided into three linear stages (Fig. 7), which implies that there are three consecutive adsorption steps. In the three consecutive adsorption stages of AKF-2, the adsorption capacity of the liquid accounted for 7.42–19.23%, 64.38–84.61% and 5.55–16.39%; respectively, of the total adsorption. Among the three adsorption stages, the second is the main adsorption stage, which resulted in the adsorption of about 57.21–81.08%, 43.78–70.57% and 55.32–75.92% by AKF-4, AKF-6 and AKF-8, respectively. The $K_{ip}$ value decreases with an increase in human-like collagen’s viscosity (Table 4), indicating that lower viscosity can promote diffusion in the fibers. Herein, the adsorption kinetics of AKF to human-like collagen is attributed to both surface and intra-particle diffusion, with the latter

$$
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Adsorbate} & \text{Adsorbent} & \text{Weber–Morris} & \text{Second stage} & \text{Third stage} \\
\hline
& & \text{First stage} & \text{Second stage} & \text{Third stage} \\
& & C_1 & k_{ip1} & R_1^2 & C_2 & k_{ip2} & R_2^2 & C_3 & k_{ip3} & R_3^2 \\
\hline
\text{AKF-2} & \text{Water} & 0.468 & 0.199 & 0.850 & 16.079 & 2.030 & 0.994 & 8.113 & 0.284 & 0.933 \\
& \text{Trauer} & 0.023 & 0.267 & 0.948 & 3.014 & 1.210 & 0.985 & 8.848 & 0.182 & 0.886 \\
& \text{MeiQ} & 0.178 & 0.161 & 0.963 & 2.473 & 0.512 & 0.987 & 7.101 & 0.133 & 0.925 \\
\text{AKF-4} & \text{Water} & 0.165 & 0.183 & 0.963 & 7.980 & 2.328 & 0.977 & 9.891 & 0.214 & 0.902 \\
& \text{Trauer} & 0.133 & 0.698 & 0.985 & 0.989 & 1.361 & 0.978 & 9.973 & 0.099 & 0.942 \\
& \text{MeiQ} & 0.072 & 0.382 & 0.988 & 0.247 & 0.584 & 0.952 & 7.391 & 0.165 & 0.923 \\
\text{AKF-6} & \text{Water} & 1.039 & 1.135 & 0.924 & 4.775 & 2.237 & 0.990 & 9.512 & 0.290 & 0.828 \\
& \text{Trauer} & 0.143 & 0.965 & 0.995 & 1.103 & 2.092 & 0.970 & 10.308 & 0.093 & 0.820 \\
& \text{MeiQ} & 0.219 & 0.720 & 0.972 & 2.846 & 0.464 & 0.962 & 10.034 & 0.064 & 0.777 \\
\text{AKF-8} & \text{Water} & 0.728 & 1.384 & 0.959 & 5.815 & 3.886 & 0.968 & 11.835 & 0.168 & 0.845 \\
& \text{Trauer} & 0.079 & 0.668 & 0.978 & 1.294 & 1.880 & 0.947 & 11.024 & 0.076 & 0.920 \\
& \text{MeiQ} & 0.038 & 0.553 & 0.9983 & 0.4136 & 0.660 & 0.957 & 8.444 & 0.146 & 0.931 \\
\hline
\end{array}
$$

Fig. 7 Weber–Morris model plots of AKF-2, AKF-4, AKF-6 and AKF-8 on Water (a), MeiQ (b) and Trauer (c), respectively.
Fig. 8 Adsorption morphology of human-like collagen on the fiber surface, raw Kapok (a) and AKF-2 (b). Micrograph of AKF-2 in nature state (a), water (b) penetrating fiber' hollow cavity.

Fig. 9 The three processes of the adsorption of liquid, (a) surface diffusion, (b) inter-fiber diffusion and (c) fiber' hollow cavity diffusion.
playing a more dominant role as the main form of diffusion.

**Adsorption mechanism**

As shown in Fig. 9, the adsorption could be broadly divided into three stages which includes surface-, inter-fiber-, and hollow cavity-diffusion. In the first step (i.e., surface diffusion) alkali modification can stimulate the removal of surface wax and expose the hydrophilic hydroxyl groups, which is advantageous in fiber-matrix adhesion and wettability. Compared to raw Kapok fiber, the human-like collagen diffuses on the AKF-2’s surface and slowly forms larger liquid droplets (Fig. 8a, b). In the second step (i.e., inter-fiber diffusion) a wicking phenomenon occurred under the capillary action of the inter fiber gap to liquid, resulting in the diffusion of adsorbed molecules diffuse to the depths. In the third step (i.e., fiber hollow cavity diffusion), Fig. 8c, d) shows that the liquid molecules enter the fiber’s hollow cavity because of the presence of numerous multi-level buckling micropores on the cell wall and the open ends of the fiber wall, through which the liquid enter the fiber’s hollow cavity. These micropores connect the liquid between the hollow cavity and fiber’s surface, forming a microporous channel for liquid flow. It is important to note that the second and third step of the adsorption process is intra-particle diffusion caused by the capillary action of effective pore volume and hollow cavity on the liquid. The Kapok fiber’s absorption shows a dual-scale liquid adsorption behavior that occurs through both inter-fiber pores and fiber’s hollow cavity. The dual adsorption behavior is the primary reason for the better adsorption capacity of the Kapok fiber. The force of adsorption is mainly manifested as an orientation force because of the polar macromolecule characteristics of Kapok fiber, and the presence of great dipole moment in the human-like collagen. When two polar molecules approach each other, the molecules will rotate and arrange in a specific direction due to the repulsion of the same polarity, followed by electrostatic attraction. Therefore, the orientation force plays an important role in generating the electrostatic attraction between the permanent dipole of polar molecules (Fig. 9).

The FTIR spectra of AKF-2 and human-like collagen were investigated before and after adsorption to further explore the existence of adsorption mechanisms. The collagen is a polypeptide chain composed of α-amino acids formed through peptide bonds. The α-carboxylic and α-amino at both ends of the polypeptide chain can receive or release protons (Han et al. 2019; Pawelec et al. 2016). In the process of adsorption, these groups can form ionic and covalent bonds with hydroxyl and carboxyl groups on the fiber. And the collagen contains a large number of carboxyl, amino and hydroxyl groups, cellulose contains hydroxyl and a small amount of carboxyl groups. The carboxyl, amino and hydroxyl in collagen and the non-ionic area’s hydroxyl groups on the plant fiber’s surface can form numerous intermolecular hydrogen bonds.
bonds (Lohrasbi et al. 2020). As shown in Fig. 10a, three absorption peaks at 923.57 cm\(^{-1}\), 859.80 cm\(^{-1}\), and 993.63 cm\(^{-1}\), corresponding to the C-H out-of-plane bending vibration of MeiQ, and 2880.88 cm\(^{-1}\), corresponding to C-H stretching vibration, diminish and disappear after adsorption. The absorption peak at 3304.51 cm\(^{-1}\), corresponding to the O–H stretching vibration of AKF-2, slightly shifted, intensified and expanded after adsorption. In comparison (Fig. 10b), The absorption peak at 3304.51 cm\(^{-1}\), corresponding to the O–H stretching vibration of Traure, slightly shifted and intensified after adsorption. Two absorption peaks at 1554.20 cm\(^{-1}\), corresponding to the C=C stretching of Traure, and 1039.80 cm\(^{-1}\), corresponding to the C–C stretching of Traure, amplify after adsorption, while the absorption peak at 1657.96 cm\(^{-1}\), corresponding to the C=C stretching of AKF-2, diminish after adsorption. Herein, results show that the physisorption process was primarily accompanied by chemisorption.

Conclusion

This paper investigates the kinetics, equilibrium, and mechanistic investigation of the adsorption performance of human-like collagen for alkali-modified Kapok fiber using a wicking method. According to the SEM, the surface morphology of AKF becomes rough with vertically oriented grooves, whereas AKF-2 retains the hollow cavity structure. The crystallinity increases and subsequently falls with increasing alkali content, reaching a maximum of 48.22% at AKF-6. According to the chemical composition analysis, the alkali dissolves a portion of the hemicellulose and lignin, while the cellulose and Klason lignin are insensitive to the alkali concentration. Compare with Kapok fiber, the surface energy of AKF rises rapidly, and the contact angle shifts from hydrophobic to hydrophilic. Kapok fiber has an adsorption capacity of roughly 0.6 g/g, which accounts for only one twenty-first of the adsorption capacity of alkali-treated Kapok. The adsorption time of human-like collagen decreased as the NaOH concentration increased. High viscosity, on the other hand, increased the adsorption time. The reason for this is that diffusion was hampered by high adhesion and large adhesion particle sizes. Due to the same filler density (0.0884 g/cm\(^3\)) and pore volume in the Kapok assembly, the adsorption quantity is not sensitive to alkali concentration. The Quasi-first-order, Quasi-second-order, as well as the Weber–Morris kinetic model, accurately described the absorption of human-like collagen, indicating the presence of both physisorption and chemisorption, and that intra-particle diffusion played a positive role in the adsorption steps. The adsorption process may be broken down into three stages: surface, inter-fiber, and hollow cavity diffusion.

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Declarations

Conflict of interest  The authors declare that they have no conflict of interest.

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