Cellulose nanofibrils from Miscanthus floridulus straw as green particle emulsifier for O/W Pickering emulsion

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ABSTRACT

For high value utilization of energy crops, in this work, a high stable O/W Pickering emulsion had been prepared successfully by using cellulose nanofibrils (CNFs) obtained from Miscanthus floridulus straw (MFS). The effect of high pressure homogenization time on the physicochemical properties of the resulted CNFs had been investigated. The obtained CNFs had high surface activity and could spontaneously diffuse to the interface of the O/W phase. The particle adsorption kinetics of CNFs was characteristic of soft particles or Pickering emulsifiers, and the adsorption was irreversible. Therefore, stable oil-in-water Pickering emulsion was obtained by using the CNFs as particle emulsifiers, and the emulsion stabilized by CNFs with only 0.15 wt% exhibited outstanding stability. Moreover, the environmental factors, such as pH values, ionic strength, and temperature had little influence on the stability of the emulsion. All the results indicated that CNFs exhibited promising interfacial activity and powerful emulsifying ability. Owing to the flexible shape of the CNFs, it was concluded that MFS as a kind of energy crop was a promising source to obtain the CNFs for the fabrication of novel food-grade Pickering emulsions.

1. Introduction

Miscanthus, a fast-growing perennial C_{4} rhizomatous grass, has a high yield of biomass per unit planted area (Peng, Li, Liu, Yi, & Han, 2017). Historically, it was widely used as forage, roofing materials, and clothing. Until the end of 20th century, it was gradually considered as a high-potential energy crop owing to its high tolerance for various climate conditions and even for an infertile and poor land (Si et al., 2015; Brosse, Dufour, Meng, Sun, & Ragauskas, 2012). Among all the species, M. floridulus has received extensive attention in the biofuel applications like enzymatic saccharification and bioethanol (Lee & Kuan, 2015). However, the multi-step biochemical conversion processes were normally consisted of various pretreatments. Enzymatic hydrolysis and yeast fermentation were often combined with high cost and eco-unfriendly biomass conversion (Wang, Xu, & Peng, 2014). The usage of the M. floridulus was still limited (Cheng et al., 2018). M. floridulus is mainly composed of cellulose, hemicelluloses and lignin. As the pretreatment is the initial step for biomass process, it becomes essential to find out the optimal pretreatments that enhance biomass conversion. Using conventional pretreatments method to obtain cellulosic particles, additional energy or chemicals were needed, which further increased capital cost or environmental implication (Dahunsi, Oranusi, & Efekobokhan, 2017; Janke et al., 2017; Kalyani, Zamanadeh, Mueller, & Horn, 2017; Peng et al., 2019; Xu, Mao, Peng, Luo, & Chang, 2018). As a result, it is constructive and meaningful to widen the application of M. floridulus.

Emulsion is one of the major systems in the field of food technology, to meet with the basic requirements of food emulsion technology, natural and sustainable emulsifiers are needed (Dickinson, 2017; McClements, Bai, & Chung, 2017; Xia et al., 2018; Zhang, Cheng, Ye, & Chang, 2017). Previous works about food-grade Pickering emulsion stabilizers were focused on the proteins, lipids, and starch based particles (Tavernier, Wijaya, Van der Meeren, Dewettinck, & Patel, 2016; Xiao, Li, & Huang, 2016a; Yang et al., 2017). In order to improve the...
stability and the resistance to digest of these emulsions, lots of works have been performed based on cellulosic biomass, which was prepared from conventional plants or through fermentation (bacterial cellulose) (Bai, Huan, Xiang, & Rojas, 2018; Fujisawa, Togawa, & Kuroda, 2017; Grishkewich, Mohammed, Tang, & Tam, 2017; Khan, Wen, Huq, & Ni, 2018; Tang, Sisler, Grishkewich, & Tam, 2017). However, due to the resurgent interest of cellulosic biomass, the growing demands for cellulosic-based materials have been attracted an increasing interest (Isogai, 2013; Klemm et al., 2018). Considering the components of MFS, based on our research works, it can be used an ideal candidate for the preparation of cellulose, which can be used in the food system as water-insoluble dietary fiber. However, little research work had been conducted on the utilization of cellulose particle from energy crop, like MFS.

Inspired by our previous works on the physical modification of bacterial cellulose (Li et al., 2019), in this work, we prepared CNFs from MFS via high pressure homogenization (HPH) process, and developed an effective strategy to fabricate a stable Pickering emulsion. The effect of the homogenization time on the physicochemical and emulsifying properties of CNFs has been clarified, and the stability and morphology of the resultant emulsions have been investigated. With the economically feasible and eco-friendly pretreatment method, MFS is a potential source of CNFs, which could be used as Pickering emulsion stabilizers in food applications.

2. Material and methods

2.1. Materials

Dodecane and sodium hydrochloride (AR grade) were purchased from Aladdin Reagent Database Co. (Shanghai, China). All other chemicals with analytical grade were purchased from Sinopharm Chemical Reagent Co., Ltd (SCRC).

2.2. Preparation of cellulose nanofibrils (CNFs)

In order to remove other components, like lignin or hemicellulose, a combination of hot alkaline treatment followed by a treatment with high pressure homogenization was applied to MFS (Seibert-Ludwig, Hahn, Hirth, & Zibek, 2019). The MFS was firstly ground into powders, and then treated with NaOH (5 wt%) and NaClO (0.5 wt%) alternately at 60 °C for 5 h and 3 times. The solid components were filtered and washed with distilled water to neutral, and then it was treated with a high pressure homogenization (HPH, AH-1500, ATS, Canada.) for different cycle times. The obtained CNFs treated with HPH for 20, 30, 50, and 80 times were coded as HPH-20t, HPH-30t, HPH-50t, and HPH-80t CNFs, respectively.

2.3. Preparation of pickering emulsions

In order to investigate the influence of the particle size of the CNFs on the stability of Pickering emulsions, CNFs obtained from different homogenization times were used. Firstly, coarse oil-in-water emulsions were prepared by mixing dodecane (10 v%) with water (90 v%) containing with 0.2 wt% of HPH-20t, HPH-30t, HPH-50t, and HPH-80t CNFs, respectively. Then the coarse emulsions were treated by using a high shear blender at a speed of 11,000 rpm for 4 min to produce Pickering emulsions. In order to investigate the effect of CNFs content on the emulsion stability, different amounts of HPH-30t CNFs (0.05, 0.1, 0.15, and 0.2 wt%) were used to fabricate Pickering emulsions.

2.4. Characterization

Atomic Force Microscopy (MultiMode8, Bruker, USA) was used to observe the topography of CNFs. Fourier transform infrared (FT-IR) tests were carried out with a FT-IR analyzer (470-Nexus, Nicolet, USA) in wavenumbers ranged from 400 to 4000 cm⁻¹. Wide-angle X-ray diffraction (WAXRD) measurements were performed with an XRD diffractometer (D8-Advance, Bruker, USA), and the patterns were recorded in the region of 2θ from 5 to 40° with Cu Kα radiation at 40 kV and 30 mA. The crystallinity index (CrI %) of CNFs was calculated by using Eq. (1) (French, 2014):

\[
CrI(\%) = \frac{I_{002} - I_{am}}{I_{002}} \times 100\%
\]

where CrI was calculated as the ratio of height of intensity of the crystalline peak close to 2θ = 22.2° (I_{002}) and the intensity of the non-crystalline material diffraction peak close to 2θ = 18° (I_{am}). The surface charge of the CNFs was determined by using a dynamic light scattering/electrophoresis instrument (Zetasizer Nano ZS, Malvern Instruments, Worcestershire, UK). The tests were performed in triplicate and the results were presented as an average value. Water holding capacity (WHC) of CNFs with different physical size was measured, and it was calculated by using the following formula (Shezad, Khan, Khan, & Park, 2010):

\[
WHC(\%) = \frac{M_{net} - M_{dry}}{M_{dry}} \times 100\%
\]

where the M_{net} was the wet weight of the CNFs, the M_{dry} was the dry weight of CNFs.

The stability of Pickering emulsions was characterized through evaluating creaming index (CI %) and droplet size. CI was calculated by using the following formula (Ines et al., 2016):

\[
CI(\%) = \frac{H_w}{H_s} \times 100\%
\]

where H_w was the height of the serum layer and H_s was the total height of the emulsion. The droplet polydispersity was measured by using MasterSizer2000 (Malvern Instruments, Worcestershire, UK). The Masterpolydispersity was expressed as the surface-weighted mean diameter:

\[
d_{3,2} = \sum \frac{n_i d_i^3}{\sum n_i d_i^2}
\]

where n_i was the number of droplets of diameter d_i. All the tests were performed in triplicate and the results were exhibited as the average value.

The interfacial tension of CNFs (0.01 w%) treated with different homogenized times was tested by using a drop shape analyzer rheometer (Tracker Teclis/TF Concept, France) at 25 °C. Briefly, the aqueous phase was placed in an optical glass cuvette, and a syringe filled with dodecane as the oil phase was then submerged into the optical glass cuvette. During the whole experiment, the initial volume of the oil drop was all ~10μL. Distilled water was used as the control. The rheological properties of the emulsions were characterized by using a Discovery HR-2 Hybrid Rheometer (TA Instruments, New Castle, DE, USA) equipped with concentric cylinder geometry. The temperature was set to 25.0 ± 0.1 °C. A dynamic frequency sweep was carried out by applying a constant strain of 2% (selected by measuring the linear domain), and the storage modulus (G’), and loss modulus (G″) as a function of frequency were obtained. All the experiments were performed in triplicate and the results were exhibited as the average value.

2.5. Statistical analyses

All measurements were carried out in triplicate unless otherwise stated. Results were expressed as the mean value ± standard deviation. Statistical analysis was performed using origin 9.0.

3. Results and discussion

Fig. 1 showed the AFM images of CNFs obtained from different
homogenization cycle times. The cellulose nanofibrils were entangled with each other, showing a relatively loose network structure. The average width of the CNFs was decreased from 49 to 33 nm with the increasing the homogenization times from 20 to 30 times, but the average height of the CNFs was changed slightly with the increasing the homogenized times, as it was shown in Table 1. Comparing with our previous works on bacterial cellulose nanofibrils under the same treatment conditions, the CNFs that obtained from MFS exhibited smaller in average height (Li et al., 2019). The average height of CNFs would further influence the physical stability of the suspension. It was worth noting that the aqueous CNFs dispersions had a good stability with solid content up to 0.6 wt%, and they could be stored at ambient conditions for about 2 months without precipitation, suggesting that the HPH process had a significant influence on the physical size of CNFs, it could be confirmed that the physical size of CNFs could be successfully reduced by HPH process for 30 cycle times.

FT-IR spectra of CNFs treated with different homogenized times were shown in Fig. 2a. The broad absorption band located at 3349 cm\(^{-1}\) was ascribed to the stretching of \(-\text{OH}\) groups and an absorption peak at 2904 cm\(^{-1}\) was related to C–H stretching vibration. The peak centered at 1427 cm\(^{-1}\) was resulted from the intermolecular hydrogen bonding at the C\(_6\) group, and the absorption peak at around 1370 cm\(^{-1}\) was ascribed to the bending vibration of the C–H and C–O bonds of aromatic ring in polysaccharides (Hafiz, Hassan, Zakaria, & Inuwa, 2014). In addition, the absorption peak at 1100 - 1108 cm\(^{-1}\) was attributed to the C–O–C glycosidic ether bond. Meanwhile, the peak around 1039 cm\(^{-1}\) was associated with the stretching vibration of C–O–C pyranose ring (Mandal & Chakrabarty, 2011). These absorption peaks at around 3349, 2904, 1427, 1370, 898 cm\(^{-1}\) were associated with the characteristics of native cellulose (Rosa, Rehman, de Miranda, Nachtigall, & Bica, 2012). It indicated that the native crystalline structure of cellulose obtained from MFS was not affected by the HPH process. The crystallinity of the CNFs obtained from MFS was characterized by using XRD. As shown in Fig. 2b, the main diffraction peaks at 2\(\theta\) values of 16.3°, 22.4°, 34.6° were ascribed to the typical diffraction peaks of cellulose I. The crystallinity of CNFs was varied from 55.88–64.13%. With the removal of the main components of lignin and hemicellulose or amorphous cellulose from the MFS by treatment with alkali and bleaching agents, the purified cellulose with increased crystallinity was obtained, and the crystallinity of CNFs was increased slightly with increasing the homogenization cycles.

The zeta potential of CNFs homogenized for different times was shown in Fig. 3a. With the increase of homogenization times from 20 to

Table 1
The average width and height of CNFs obtained by AFM.

<table>
<thead>
<tr>
<th></th>
<th>average width (nm)</th>
<th>average height (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPH-20t CNFs</td>
<td>49.79 ± 17.62</td>
<td>7.55 ± 2.76</td>
</tr>
<tr>
<td>HPH-30t CNFs</td>
<td>33.27 ± 7.30</td>
<td>3.68 ± 1.17</td>
</tr>
<tr>
<td>HPH-50t CNFs</td>
<td>40.52 ± 11.03</td>
<td>5.12 ± 1.22</td>
</tr>
<tr>
<td>HPH-80t CNFs</td>
<td>38.64 ± 10.17</td>
<td>3.77 ± 0.71</td>
</tr>
</tbody>
</table>

Fig. 1. AFM tapping-mode height images of CNFs homogenized with different time, (a) was for HPH-20t, (b) was for HPH-30t, (c) was for HPH-50t, and (d) was for HPH-80t, respectively.

Fig. 2. (a) FT-IR spectra of CNFs treated for different homogenized times, and (b) XRD spectra of CNFs treated for different homogenized times.
and gradually leveled-off CNFs with different physical morphology and were lower than that of blank. It suggested that the relaxation time (adsorption and rearrangement) was decreased when the CNFs were used, which were the key factors affecting the emulsion formation. When the CNFs were used for the stabilization of the emulsions, both adsorption and rearrangement of the CNFs at the interface had appreciable contributions to the dynamic interfacial tension. The effective diffusion coefficients at long time \( t \to \infty \) was further used to evaluate the adsorption process, which could be obtained by following equation (Fainerman, Makievska, & Miller, 1994):

\[
D_m = \frac{\gamma}{R} \left( \frac{\partial \ln c}{\partial t} \right) \left( RT_c \left( \frac{\partial}{\partial t} \right) \right)^2 \left( \frac{1}{t_{eq}} \right)
\]

(5)

where \( \gamma \) was the interfacial tension, \( R \) was the universal gas constant, \( T \) was the temperature, \( c \) was the particle concentration in the bulk phase, and \( t \) was the adsorption time. In Fig. 4b, it could be seen that the \( \gamma t^{-1/2} \) was linear dependencies, which indicating the equation was applicable. There was no appreciable difference between the different CNF samples. Moreover, the CNFs had low rearrangement and equilibrium time, which was typical for Pickering solid particle stabilizers (Miller et al., 2010). The relative soft fibrils with larger and heterogeneous wetting radius, which was caused by the deformable nature of the fibrils, displayed stronger attractive capillary than other rigid particles (Chen et al., 2017). This result indicated that the CNFs at the interface showed strong interactions during rearrangement.

Fig. 5 showed the images of the emulsions stabilized with CNFs. Obviously, all the emulsions had a typical unimodal distribution of droplet size. Consistent with the distribution of droplet size, emulsions containing the HPH-30t CNFs or HPH-50t CNFs were more stable over time against coalescence or phase separation (as shown in Fig. 6). This phenomenon could be associated with the change of the wettability of the cellulose particles. From Fig. 3b, with the increase of homogenized times, the WHC of the CNFs was gradually increased. If the particles were too hydrophilic, they would tend to disperse into the water phase. Therefore, the HPH-30t and HPH-50t CNFs with adequate hydrophilicity had increased emulsifying capacity than that of the others. From the perspective of energy conservation and environmental protection, the HPH-30t CNFs were selected for the following research. As all the emulsions displayed different degrees of sedimentation due to the density difference between oil and water phase, HPH-30t CNFs with different solid contents was used. The effect of solid contents of HPH-30t CNFs on the stability of the emulsions was subsequently investigated. As shown in Figs. 7 and 8, the emulsion prepared with 0.2% HPH-30t CNFs didn’t show any phase separation, which indicated excellent physical stability against coalescence. However, with the increase of the content of CNF, the excess CNF in the aqueous phase could lead to aggregation of droplets, causing a slight increase on the emulsion droplet size. As a result, it could be seen that the droplet size of emulsions stabilized with 0.2 wt% CNFs was larger than others (Table 2). The long-term stability of emulsions stabilized with different contents of HPH-30t CNFs were also investigated. When the content of CNF was low, a large excess of oil-water interface compared with the amount that could be covered by the presence of solid particles were produced during agitation. When the agitation process was stopped, the partially protected droplets were aggregated, thus reducing the total amount of oil-water interface until the interface was sufficiently covered. This phenomenon was shown in Table 2. It indicated that the droplet size of emulsion was slightly increased with the increase of the storage time. The droplet size of the emulsions was measured by using a laser particle size analyzer and the majority of the droplet had small size around 10 μm. Moreover, the emulsions stabilized with higher contents of CNFs appeared to be more stable with smaller droplet sizes after 14 days. However, the emulsion stabilized with 0.2% HPH-30t CNFs showed a bimodal distribution of droplet size (Fig. 8a). This phenomenon could be explained as the smaller peak was attributed to the minor fraction of larger CNFs particles, which had sizes around 100 μm (Tenorio, Gielteling, Nikiforidis, Boom, & Van Der Goot, 2017). Moreover, the creaming index was reduced with the increase of the solid content of CNFs. It indicated that the increased number of CNFs particles might contribute to the network formation in the continuous phase (Zhai, Lin, Liu, & Yang, 2018; Zhu et al., 2016).

The total droplet surface area \( (S_d) \) was calculated according to the oil volume and the average droplet size (Capron & Cathala, 2013):
The theoretical maximum surface, $S_p$, was defined by:

$$S_p = N_p L I = \frac{M_p}{\rho}$$  \hspace{1cm} (7)$$

where $N_p$ was the amount of CNFs, $L$ and $I$ were represented for the length and width, $M_p$ was the mass of CNFs included in the emulsion (g), $h$ was the thickness which was defined by AFM, and $\rho$ was the CNFs density (1.6 g/cm$^3$).

The theoretical surface coverage ratio ($C$) was calculated by the following equation:

$$C(\%) = \frac{S_p}{S_d} = \frac{M_p R}{3h\rho V_{oil}} \times 100\%$$  \hspace{1cm} (8)$$

Based on our previous work, the adsorption behavior of cellulose at the oil/water interface was irreversible (Li et al., 2019). Using different contents of HPH-30t CNFs as the emulsion stabilizer, the surface coverage (128%) gradually increased with the increase of the solid content of CNFs, and reached to 578% with the 0.20 wt% CNFs, which meant that lots of free CNFs were dispersed in aqueous phase. Consistent with Fig. 8a, the emulsion stabilized with 0.2% HPH-30t CNFs showed a bimodal distribution of droplet size. This could be due to the further aggregation of extra CNFs particles, which had sizes around 100 μm. This could further cause the coalescence, yielding larger droplets with higher polydispersity, as it was listed in Table 3. It could be concluded that the smaller size of emulsion droplets would further contributed to a relatively limited coalescence, exhibiting the formation of a highly stable emulsion. In fact, the decrease of the emulsion droplet size was also associated with larger amounts of cellulose nanofibrils adsorbed into oil-water interface. As a result, the solid content of CNFs played a crucial role in the formation of the high stable emulsion system via
Fig. 5. Optical Microscopy images of the Pickering emulsions stabilized with 0.1 wt% CNFs homogenized for different times, (a) HPH-20t, (b) HPH-30t, (c) HPH-50t, and (d) HPH-80t, and the volume ratio of oil to water was 1:9.

Fig. 6. (a) Particle size distribution and (b) creaming index of the emulsions stabilized with 0.2 wt% CNFs homogenized for different times, the particle size distribution of emulsions was measured after 1 d, and the volume ratio of oil to water was 1:9.

Fig. 7. Micrographs of emulsions stabilized with different content of HPH-30t CNFs: (a) 0.05 wt%, (b) 0.10 wt%, (c) 0.15 wt%, and (d) 0.20 wt%, and the volume ratio of oil to water was 1:9.

Fig. 8. (a) Particle size distribution and (b) creaming index of emulsions stabilized with different contents of HPH-30t CNFs, the particle size distribution of emulsions was measured after 1 d and the volume ratio of oil to water was 1:9.
Table 2
The droplet size of Pickering emulsions stabilized with different contents (0.05–0.20 wt%) of HPH-30t CNFs.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( D_{3,2} ) (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1d</td>
</tr>
<tr>
<td>0.05%</td>
<td>10.88 ± 0.02</td>
</tr>
<tr>
<td>0.10%</td>
<td>10.62 ± 0.06</td>
</tr>
<tr>
<td>0.15%</td>
<td>10.72 ± 0.01</td>
</tr>
<tr>
<td>0.20%</td>
<td>12.33 ± 0.04</td>
</tr>
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</table>

Table 3
The surface coverage of Pickering emulsions stabilized with different contents (0.05–0.20 wt%) of HPH-30t CNFs after different storage times.

<table>
<thead>
<tr>
<th>CNF contents</th>
<th>Surface coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1d</td>
</tr>
<tr>
<td>0.05%</td>
<td>1.28</td>
</tr>
<tr>
<td>0.10%</td>
<td>2.49</td>
</tr>
<tr>
<td>0.15%</td>
<td>3.77</td>
</tr>
<tr>
<td>0.20%</td>
<td>5.78</td>
</tr>
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</table>

Fig. 9. Rheological properties of freshly prepared emulsion stabilized with different contents of HPH-30t CNFs: (a) apparent viscoelastic as a function of shear rate and (b) \( G' \) (closed symbols), and \( G'' \) (open symbols) as a function of angular frequency measured at 2% strain, and the volume ratio of oil to water was 1:9.

Fig. 10. Effect of pH on the morphology of emulsion stabilized with 0.2 wt% HPH-30t CNFs, (a) pH 3, (b) pH 4.5, (c) pH 7, and (d) pH 11, and the volume ratio of oil to water was 1:9.

Fig. 11. (a) Droplet size of emulsions stabilized with HPH-30t CNFs (0.2 wt%) after different storage times at 25 °C, and (b) particle size distribution of emulsions stabilized HPH-30t CNFs (0.2 wt%) under different pH values, the particle size distribution of emulsions was measured after 1 d and the volume ratio of oil to water was 1:9.
The emulsions were prepared under different pH values (3–11), which were controlled by using 0.1 M citrate/phosphate buffer solution. The effect of pH on the droplet size of the emulsions was shown in Fig. 10a. Based on our previous study, the zeta potential of BCNFs was influenced by pH, and the stability of the BCNFs suspensions was improved when the pH value was slightly increased (Li et al., 2019). Consistent with this result, it could be found in Fig. 11a that smaller emulsion droplet size was formed under pH = 4.5–7.0. All of the emulsions revealed excellent storage stability, regardless of pH values. However, the zeta-potential of CNFs suspensions was decreased with the increasing pH, indicating a relative poor stability. For the emulsion system, when the pH increasing, the stability of the emulsions would decrease which further leading to an aggregation. As a result, the emulsion droplet size would increase at pH 9.5 and 11. Different from pH = 4.5–7.0, the emulsions prepared under pH 9.5 and 11 exhibited bimodal distribution of droplet size, which showed a small peak at around 100 μm (Fig. 10b). The results were also consistent with the microstructure of the emulsions (Fig. 11). In order to clarify the observed trend, zeta potential of HPH-30t CNFs under different pH values was further measured (as shown in Fig. 12). Obviously, when the pH value of the suspensions was 4.5 or 7, zeta potential of the suspensions was closed to −35 mV, indicating a more stable system (Mikulcova, Bordes, Minarik, & Kasparkova, 2018). However, the emulsions tended to aggregate when the pH was 4.5 (Fig. 10). As a result, the droplet size and distribution of showed distinct difference under pH 7. The influence of temperature on the droplet size and stability of the emulsions was shown in Fig. 13. The emulsions stabilized with 0.2 wt% HPH-30t CNFs exhibited almost the same droplet size (10 μm) after different temperature treatments. Moreover, the increase in the temperature showed insignificant decrease on the stability of the emulsion, and the droplet size distribution was unimodal (Fig. 13d). Further, no phase separation was visible for the Pickering emulsions after long-term storage, making them suitable for food-grade emulsion formulations. Remarkably, oil-in-water Pickering emulsions containing concentrated edible oil that was stable against oil coalescence during storage was interesting. To our knowledge, the results in this study would open an opportunity for the application of CNFs from energy crops in food science and technology.

4. Conclusions

Cellulose nanofibrils obtained from MFS through HPH process could be used to stabilize O/W Pickering emulsions at a relatively low solid content of CNFs. The water holding capacity of CNFs was significantly enhanced with the increase of the homogenized times. As a result, the emulsion stabilized by CNFs exhibited the small droplet size and the high stability. Moreover, higher content of the CNFs could also remarkably improve the stability of the emulsions. The rheology results revealed that the obtained emulsions stabilized by CNFs exhibited a typical shear thinning behavior. For all the emulsions, the value of storage modulus was higher than loss modulus, indicating a typical elastic behavior of particle-stabilized emulsions. Based on the above results, it could be concluded that the content of CNFs significantly influence on the O/W interface associating with the strengthened intermolecular cross-linking and increased steric hindrance. As the whole physical modification process conducted without using any organic solvents, it provided a facile, “green” method to fabricate a potential CNFs-based eco-friendly food-grade stabilizer for Pickering emulsion processing.

Notes

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