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Immobilizing laccase on kaolinite and its application in treatment of malachite green effluent with the coexistence of Cd (II)

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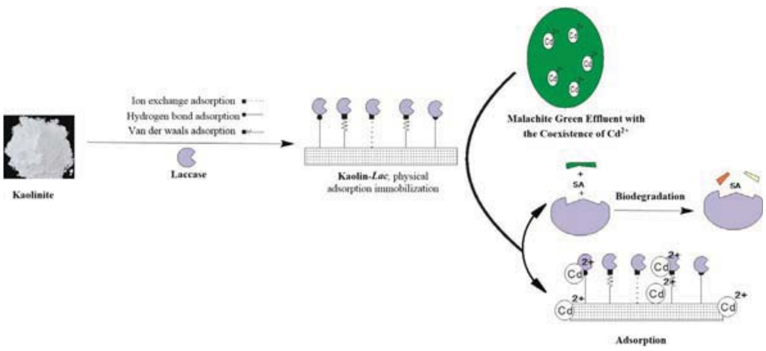
HIGHLIGHTS

- Laccase was immobilized on kaolinite and achieved the kaolinite-laccase (Kaolin-*Lac*).
- Kaolin-*Lac* could obtain a loading efficiency and capacity of 88.22%, 12.25 mg/g, and the highest activity of 839.01 U/g.
- MG effluent with the coexistence of Cd (II) was nearly decolorized totally after 300 min incubation in the presence of SA.
- Low concentration of Cd (II) could enhance the degradation of MG by Kaolin-*Lac*.

GRAPHICAL ABSTRACT



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ABSTRACT

Malachite green effluent with the Coexistence of Cd (II) was efficiently decolorized by kaolinite-*laccase* (Kaolin-*Lac*). Laccase from *Trametes versicolor* was immobilized onto the kaolinite through physical adsorption contact. The optimal conditions were 180 min of immobilization time and 0.8 mg/mL of enzyme solution. Kaolin-*Lac* could obtain a loading efficiency of 88.22%, a loading capacity of 12.25 mg/g, and the highest activity of 839.01 U/g. Moreover, the process of immobilization increased its pH stability and operational stability. Kaolin-*Lac* retained above 50% of the original activity and nearly 80% decolorization for MG after 5 cycles. In the presence of 3, 5-Dimethoxy-4-hydroxybenzaldehyde (SA), Kaolin-*Lac* could degrade over 98% of malachite green. The coexistence of Cd (II) was beneficial to the decolorization of malachite green by Kaolin-*Lac*. The structural and morphological features of kaolinite, Kaolin-*Lac* and Kaolin-*Lac* after degradation were determined by scanning electron microscopy-energy spectrum analysis (SEM-EDS) and Fourier transform infrared spectroscopy (FTIR). Cadmium appeared on the Kaolin-*Lac* after degradation. After immobilization and degradation, the surface groups on

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kaolinite were changed. Kaolin-*Lac* showed its more potential continuous employment than free laccase in practical malachite green dyes effluent mixed with Cd (Π).

1. Introduction

Immobilization could improve laccase properties and it is an effective way to overcome the application limitations of laccase, such as low stability and high production costs (Mohamad et al., 2015; Prasad and Palanivelu, 2015). The exploration of immobilization methods of laccase has been predominantly focused (Barbosa et al., 2013; Guzik et al., 2014). The immobilization methods can increase the stability of laccases, thus significantly reducing the cost burden (Datta et al., 2013; Sheldon and van Pelt, 2013).

In the laccase immobilization process, various carriers have been reported to immobilize laccase successfully (An et al., 2015; Tan et al., 2015). Among various carriers, kaolinite as an aluminosilicate mineral is cost-efficient, facility of reusability, low mass transfer resistance and microbial corrosion resistance (Abdul Rahman et al., 2005; Hu et al., 2007). Kaolinite has negative sites on the basal surface owing to isomorphic substitution and amphoteric sites on the edge surface (Liang et al., 2017; Shu et al., 2016). The amphoteric sites are conditionally charged and pH dependent because a net positive or net negative charge can be produced due to proton adsorption (An et al., 2015; Zhang et al., 2015). Kaolinite has a low permanent charge and a significant variable charge (Sinegani et al., 2005; Xu et al., 2012a,b). Attributing to these distinctive characters, kaolinite has rather high adsorption ability. Kaolinite is widely used in adsorption studies.

Malachite green (MG) was produced from the textile staining, aquaculture, food and medical domains (Chen et al., 2015; Sinha and Osborne, 2016). The MG belongs to persistent contaminant, and it can be readily adsorbed on solid or absorbed by organism thus leading to the accumulations in organisms (Gong et al., 2009). The accumulation of MG hinders organisms' growth, reproduction and development, and they can generate mutagenic and carcinogenic influence. Furthermore, the MG effluent is always released to environment combining with heavy metals like Cd (Π) in realistic situations (Deng et al., 2013; Jasinska et al., 2012). The Cd (Π) has been listed as one of the top toxic heavy metals since it can cause cancer, bone lesions, lung insufficiency, anemia, hypertension and weight loss (Long et al., 2011; Wan et al., 2018). Elevated level of Cd (Π) could lead to the acute and chronic disorders in nervous, kidney, liver and cardiovascular system, therefore, efficient removal of Cd (Π) makes sense (Tang et al., 2014; Wu et al., 2017). The mixing of Cd (Π) makes the MG effluent more difficult to treat (Ren et al., 2018; Xu et al., 2012a,b).

The redox-mediated bio-oxidation of MG, catalyzed by immobilized laccase, is a current technology for MG degradation (Kuhar et al., 2015; Zhang et al., 2016). Utilizing laccase immobilized on numerous carriers to catalyze MG degradation is an effective and straight forward method (Zhou et al., 2018). There are varieties of carriers, including chitosan beads, PAN/O-MMT composite nanofibers, a sponge-like hydrogel, and amino-functionalized magnetic nanoparticles were applied to immobilize laccase to degrade the MG effluent (Kumar et al., 2014; Li et al., 2016; Sun et al., 2015; Zheng et al., 2016). However, immobilizing laccase from *Trametes versicolor* on kaolinite to degrade MG effluent with the coexistence of Cd (II) was not fully explored. The existence of Cd (II) does have effect on the activity of free laccase and the degradation of MG by laccase (Cheng et al., 2016a,b). Furthermore, during the laccase immobilization process, immobilization carrier also has important effect on laccase activity and stability (Zheng et al., 2016). Hence, whether if utilizing kaolinite to immobilize laccase from *Trametes versicolor* could degrade MG effectively, if the coexistence of Cd (II) could affect the degradation of MG and what is the remove efficiency of Cd (II) by immobilized laccase on kaolinite should be fully explored.

In the current study, kaolinite that has rather high adsorption ability was used for laccase physical adsorption immobilization. The efficiency of loaded laccase on kaolinite was characterized by relative activity (%) and stability studies. Kaolinite-*laccase* (Kaolin-*Lac*) was applied in continuous treatment of MG effluent mixed with Cd (Π) in the presence of redox mediators SA to explore the removal efficiency of MG and Cd (II) by Kaolin- *Lac*, the effect of Cd (II) on the degradation efficiency of MG by Kaolin- *Lac*. The detailed characterizations changes of kaolinite, Kaolin-*Lac*, Kaolin-*Lac* after treatment were carried out by FT-IR, SEM-EDS.

2. Materials and methods

2.1. Materials

Laccase from *Trametes versicolor*, 3, 5-Dimethoxy-4-hydroxybenzaldehyde(SA) and 2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) were obtained from Sigma-Aldrich. Malachite Green (MG) and Kaolinite were provided by Sinopharm Chemical Reagent Shanghai (China). All other chemicals were of analytical grade and were used as received without further purification.

2.2. Enzyme activity assay

Laccase activity was tested by analyzing the product formation rate of ABTS at the absorbance of 420 nm. One unit of laccase activity was defined as the amount of free laccase required to oxidize 1 μM of substrate per minute. The activity of laccase in this study was expressed as the relative activity (%). During the immobilization and stability assessing process, the maximal value of laccase activity under each certain condition (such as a certain laccase concentration, immobilizing time or pH) was set as 100% (Liu et al., 2012; Zheng et al., 2016).

2.3. Immobilization of laccase

The immobilization process was carried out by the physical adsorption contact (such as ion exchange adsorption, hydrogen bond adsorption, and Van der waals adsorption) of kaolinite and laccase. Kaolinite was added in 5 mL of citrate phosphate buffer (0.1 M, pH 5) containing laccase (0.01, 0.05, 0.5, 0.8, 1 mg/mL). The mixtures were incubated in a rotary shaker at 30 °C and shake at 200 rpm for 15, 30, 60, 120, 180, 300 min. Then, the sample was centrifuged and the bottom solid was collected to wash a few times with buffer. The final solid was kaolin-*Lac* after freeze drying at −100 °C for 12 h. The Fig. 1 demonstrated the process of immobilization.

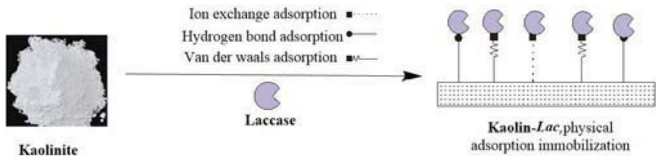

Fig. 1. The process of laccase immobilized on kaolinite.

2.4. Stability assessment

2.4.1. pH stability of immobilized laccase

The pH value has great influence on the laccase activity. For pH stability, the samples were added to tubes that contained buffers (pH range of 3–6) and incubated at 30 °C and kept at 200 rpm. The residual enzyme activity of samples was determined.

2.4.2. Thermal stability of immobilized laccase

The thermal stability of immobilized laccase and free laccase were assessed. Free and immobilized laccase were kept from 30 °C to 80 °C. Then the free and immobilized laccase were separately reacted with ABTS and centrifuged and the absorbance of supernatant was measured at 420 nm.

2.4.3. Storage stability of immobilized laccase

To test the storage stability, the immobilized laccase and free laccase samples were stored at 4 °C for 30 days of incubation cycles and residual activities were measured at every 5 day.

2.4.4. Operational stability of immobilized laccase

Kaolin-*Lac* was dispersed incitrate-phosphate buffer (pH 5) containing 1 mM ABTS and cultured for 5 min. The sample was centrifuged and the content of transformed ABTS in the supernatant was determined. The Kaolin-*Lac* was washed with citrate-phosphate buffer, decanted and the procedure was repeated for 5 cycles.

2.5. Immobilized laccase system for treatment of MG effluent mixed with Cd (Π)

The decolorization efficiency of MG by Kaolin-*Lac* was analyzed by the decrease in absorbance at the absorption wavelength of 623 nm. The removal capacity of Cd (Π) was analyzed by atomic absorption spectrophotometer (AAS). Effect of parameters such as the concentration of SA and Cd (Π), reaction time were studied. The reaction mixture, containing kaolin-*Lac* and 10 mg/L of MG and Cd (Π) solution, was incubated at 30 °C. After centrifuged, the residual contaminants concentration in the supernatant was analyzed. All the experiments were examined in triplicate.

2.6. Characterization analytical methods

The SEM imaging was applied to characterize kaolinite, kaolin-*Lac* before and after degradation. The sample was gold-coated using a sputter coater before imaging. Micrographs were captured at 20 kV accelerating voltage on a scanning electron micro scope (FEI, QUANTA F250). Elemental analysis was determined with electronic differential system (EDAX, GENESIS). FT-IR spectra were recorded in the range of 500–4000 cm^{-1} by a Nicole 5700 FT-IR Spectrometer.

3. Results and discussion

3.1. Characterization analysis

3.1.1. SEM and elements analysis

The SEM aimed to observe possible morphological changes of kaolinite, Kaolin-*Lac*, and Kaolin-*Lac* after degradation. Kaolinite, it is a 1:1 type swelling clay (Huang et al., 2017a; Shu et al., 2016). The kaolinite lattice layers are made up of tetrahedral Si—O and octahedral Al—O. They are connected with the van der waals' forces. The structure lamella is filled with commutative cations and water molecules (Huang et al., 2018a; Shu et al., 2014). They can be replaced by ion exchange and inter layer exchange (Shu et al., 2016). The morphology of kaolinite and Kaolin-*Lac* samples has been displayed on the SEM images (Fig. 2). There was no obvious distinction of different surface morphologies can be observed directly. The relevant EDS confirmed no obvious elements changed after immobilization in Fig. 2a and b. However, the relevant EDS in Fig. 2c revealed elemental difference of Kaolin-*Lac* after treatment of MG effluent with Cd (Π). The appearance of cadmium (Cd) in Fig. 2c relevant EDS visually indicated the Cd (Π) was adhered to Kaolin-*Lac* external and internal pore through adsorption. For the sake of preferably comprehending the formation element of materials, the percentages of seven mainly changed elements which are carbon, oxygen, sodium, magnesium, aluminum and calcium

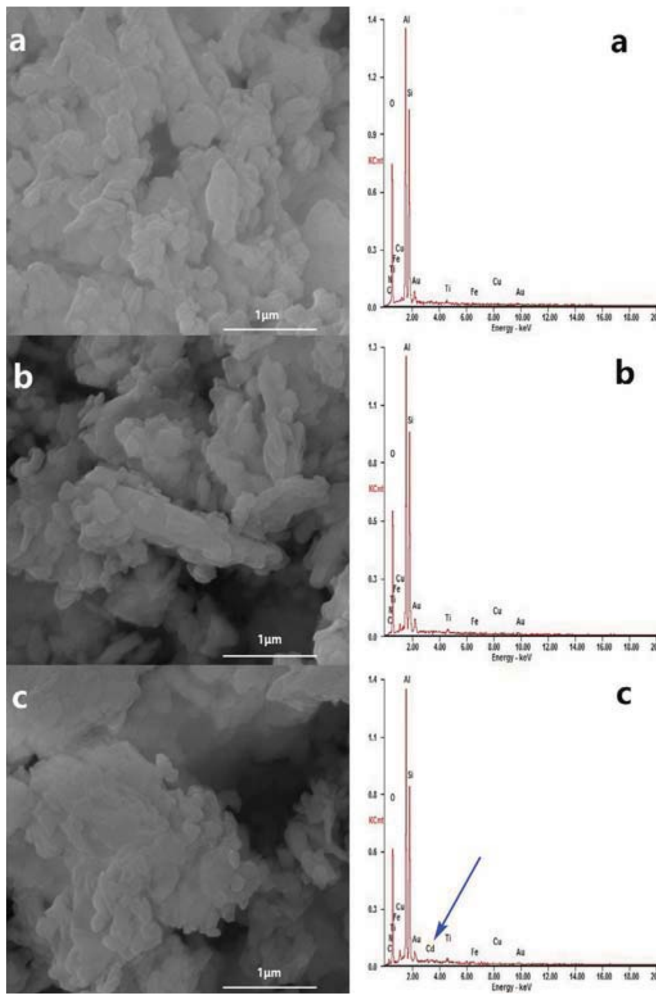

Fig. 2. SEM images and relevant EDS of the a) kaolinite, b) Kaolin-*Lac*, c) Kaolin-*Lac* after treatment.

are listed in Table 1.

3.1.2. FTIR analysis

The FTIR spectra of kaolinite, Kaolin-*Lac* and Kaolin-*Lac* after treatment were shown in Fig. 3. Infrared spectrum determines the quantity of radiation absorbed by atoms at different frequencies (Chen et al., 2017a,b; Huang et al., 2017b). Whilst the infrared radiation irradiated the compound, the dissimilarity of charge between carbon atoms evokes the formation of an electric dipole that can form detectable signals (Cheng et al., 2016a,b; Huang et al., 2016). FT-IR spectras of the powder samples (Fig. 3) were surveyed with KBr pellets in the scope of 500–4000 cm^{-1}.

Some clear adsorption bands among all samples confirmed that Si—OH and Al—OH were existed in these samples. Among the sample of Kaolinite and Kaolin-Lac, a clear band peak in 3779 cm^{-1} can be ascribed to the vibration of Si—OH (Shu et al., 2016; Ztrk et al., 2008). Another adsorption band at 1627 cm^{-1} belongs to the stretching vibration of H—OH, which was crystal water molecules in the lattice (Wen et al., 2018; Chen et al., 2017a,b; Xue et al., 2018). Absorption bands around 1170 cm^{-1}, 827 cm^{-1}, 570 cm^{-1} of spectrum a, b, c are assigned to the bending vibration of Si—O, respectively (Huang et al., 2018b; Shu et al., 2016). The adsorption bands among the range of 400–500 cm^{-1} were belonging to the group of Si—O and Al—O (Shu et al., 2016). After immobilization and treatment, a red shift occurred on the group of Si—O, Si—OH and H—OH. This phenomenon indicated that the surface groups became unstable after immobilization and treatment (Andjelkovi et al., 2015). Due to the "broken-bond" surface, kaolinite has certain of cation exchange capacity. There are a large number of negative charges on $Si—O^-$ and $Al—O^-$ groups (Tan et al., 2018). The loading of laccase on kaolinite, the adsorption of Cd (II) on kaolinite and the adsorption or degradation of MG on kaolinite could occupy the binding sites of the exchangeable cations and thus lead to the change on surface charge density of Kaolinite (Huang et al., 2018c). At the same time, the π interactions between the oxygen plane of the aluminosilicate layer of the clay mineral and MG, decrease of inner surface hydroxyl group due to the prototropy also could lead to the instability of different surface groups (Johnston et al., 1984). As a whole, it means that immobilization of laccase on kaolinite and degradation of MG effluent coexisting with Cd (II) on the surface of kaolinite had a certain influence on surface functional groups of kaolinite.

3.2. Optimum conditions of laccase immobilization

Laccase immobilization process is affected by many factors (Liu et al., 2012). The initial laccase concentration had great influence on the immobilization process. To study the influence of the initial laccase concentration on the activity of immobilized laccase, the initial laccase concentration was varied from 0.01 mg/mL to 1 mg/mL. As shown in Fig. 4a, the adsorbed laccase increased with the increase of initial laccase concentration. However, the activity of immobilized laccase increased until 0.8 mg/mL, whilst the laccase concentration was larger than 0.8 mg/mL, a decrease in the relative activity of the Kaolin-*Lac* was observed. Similar phenomenon was also observed for some previous supporting materials (Kadam et al., 2017; Liu et al., 2012). This could ascribe to the agglomeration or crowding of enzyme molecules onto the surface of kaolinite when the laccase was overloaded on the kaolinite (Gong et al., 2017; Liu et al., 2012). The agglomeration or crowding of laccase molecules on surface of kaolinite could constraint the dispersion and transmission of laccase, even change the conformation of laccse and thus lead to the change of laccse activity. Thus, the appropriate laccase concentration was set as 0.8 mg/mL for next studies.

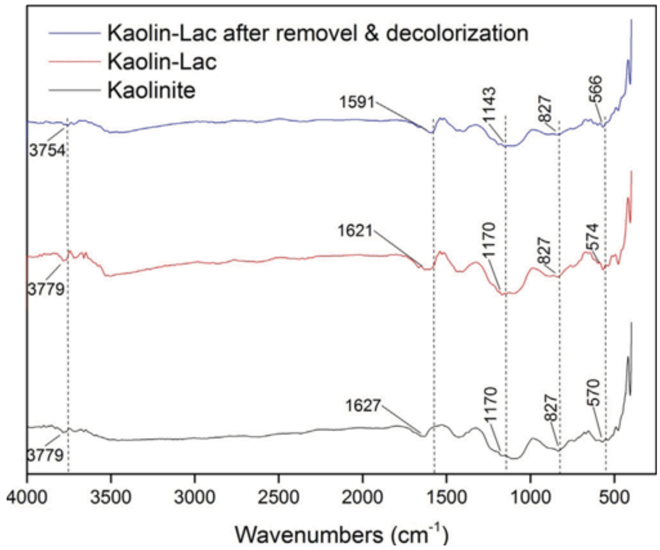

Fig. 3. FT-IR spectrum of kaolinite, Kaolin-*Lac*, Kaolin-*Lac* after treatment.

The immobilization time also remarkably influences the immobilization laccase activity (Huang et al., 2017c; Zheng et al., 2016). As demonstrated in Fig. 4b, the relative activity of Kaolin-*Lac* changed with the immobilization time increased from 15 min to 300 min. The relative activity of Kaolin-*Lac* increased strikingly until 180min, and then the relative activity decreased (Huang et al., 2018d). Activity of immobilized enzymes seemed to rely on the nature of the protein. With time increasing, the possible inactivation amounts of laccase increased during immobilization. In the meantime, the laccase flexibility also reduced. As physical adsorption immobilization time increased, the adsorption site on kaolinite was eliminated (Huang et al., 2017d). The relevant steric hindrance and diffusion limitations might also lead to loss of laccase activity (Prasad and Palanivelu, 2015). The optimum immobilization time was 180 min. Under above optimal condition, the acquired immobilized laccase (Kaolin-*Lac*) could achieve a loading efficiency of 88.22%, a loading capacity of 12.55 mg/g, and the highest enzyme activity of 839.01 U/g.

Table 1
The element analysis of kaolinite, Kaolin-Lac, Kaolin-*Lac* after treatment.

Samples	Element							
	C %	O %	Al %	Si %	Fe %	Cu %	Ti %	Cd %
Kaolinite	1.89	40.76	27.28	27.77	0.71	0.62	0.97	0
Kaolin-*Lac*	2.84	37.72	27.87	29.08	0.63	0.66	1.18	0
Kaolin-*Lac* after treatment	3.18	40.13	26.64	27.45	0.73	0.66	0.97	0.21

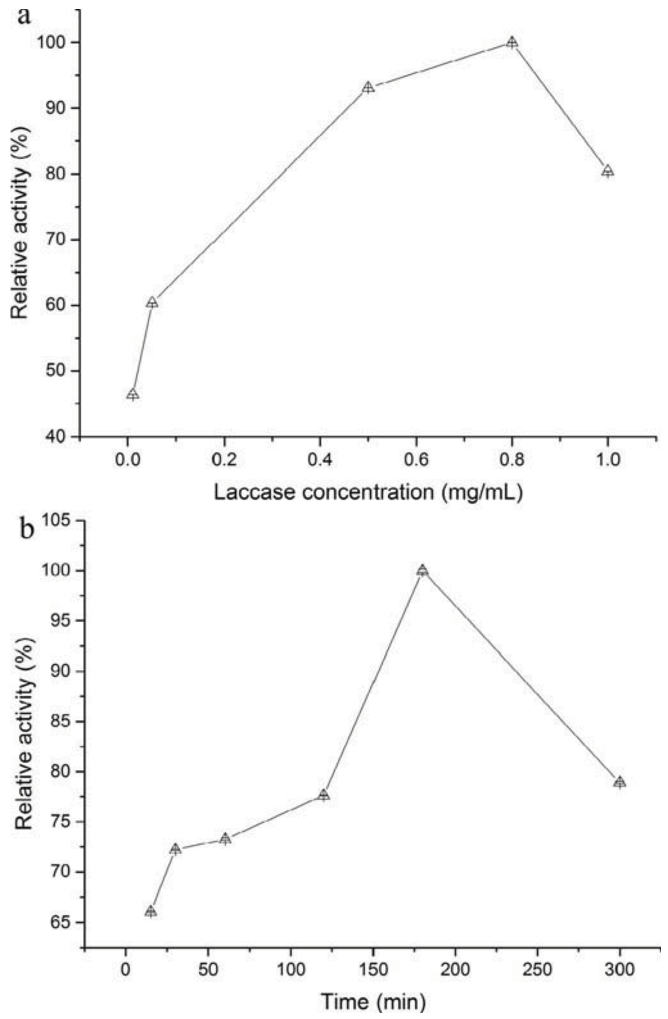

Fig. 4. a) Effect of laccase concentration on the activity of the immobilized laccase; b) Effect of time on the activity of the immobilized laccase.

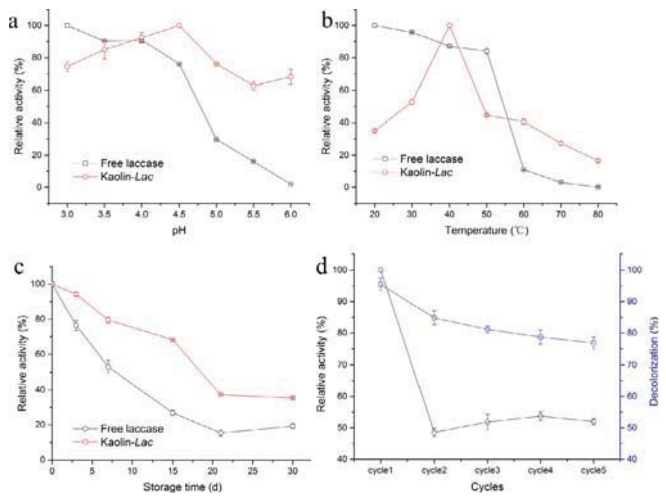

Fig. 5. a) pH stability of free laccase and Kaolin-*Lac*; b) Thermal stability studies of free laccase and Kaolin-*Lac* at 20–80 °C up to 120 min; c) Storage stability of free laccase and Kaolin-*Lac*; d) Operational stability of Kaolin-*Lac* and reusability of Kaolin-*Lac* for MG with the coexistence of Cd (II) decolorization.

3.3. Properties of immobilized laccase

3.3.1. pH stability

The pH stability of immobilized laccase is a key factor for practical use (Mahmoodi et al., 2014). The results presented in Fig. 5a showed that the Kaolin-*Lac* exhibited more stable relative activity over a broad pH range from 3.0 to 6.0. The minimum relative activity of Kaolin-*Lac* could maintain more than 60%. And the relative activity of free laccase was strikingly decreased from pH 3.0. When pH value was 6, the relative activity of free laccase almost decreased to 2%. The phenomenon suggested that immobilization of laccase improved its pH stability and enhanced its adaptive capacity to the environment. The change of pH stability could be ascribed to the proton production on the surface of support. Relative stable proton production could retain the activity of laccase. The laminated structure of kaolinite maintained a balance proton quantity in the microenvironment around the laccase. This causation could explain the higher pH stability of Kaolin-*Lac* (Skoronski et al., 2017).

3.3.2. Thermal stability

The thermal stability of immobilized laccase is important for its practical application as biocatalyst (Li et al., 2016). As showed in Fig. 5b, when the temperature was lower than 40 °C, the activity of Kaolin-*Lac* was increasing with the increase of temperature. Kaolin-*Lac* showed its highest stability at 40 °C. Then the activity of Kaolin-*Lac* began to decrease. From 20 °C to 80 °C, the relative activity of free laccase was decreased all the way. Especially, the activity of free laccase strikingly decreased when temperature was higher than 50 °C. And free laccase nearly lost its activity when the temperature was higher than 70 °C. However, when temperature was higher than 50 °C, the Kaolin-*Lac* decreased more tardily and Kaolin-*Lac* could still maintain 18% of its original activity when temperature was 80 °C. Obviously, immobilization process improved the tolerance of laccase for high temperature. The phenomenon was attributed to the augment of enzyme rigidity and decrease of conformational enzyme flexibility which was caused by the high stability towards denaturation on enzyme by high temperatures. Similarly, the results can be ascribed to the stronger physical bond between the supports and enzyme or the lower restriction of substrate diffusion when the temperature was high (Andjelkovi et al., 2015). The improved thermal stability of immobilized laccase is beneficial to its practical application because the industrial waste water was usually high temperatures (Chang et al., 2016).

3.3.3. Storage stability

Storage stability is of key influence on the practical utilize of immobilized enzyme (Wang et al., 2013). Generally, the free enzyme is not stable and it could lose its activity by degrees during storage period (Chang et al., 2016). The free and immobilized laccase were kept at 4 for 30 days and their activities were measured per five days to analyze their storage stability. The results were depicted in Fig. 5c and confirmed that the Kaolin-*Lac* had higher storage stability than the free laccase. During the whole 30 days, nearly 40% activity was retained for Kaolin-Lac whilst almost only 20% activity of free laccase was retained. Similar increases of storage stability have been reported by Asgher et al. and Ghiaci et al. after immobilizing laccase on chitosan microspheres and bentonite (Asgher et al., 2017; Ghiaci et al., 2009). The improvement in storage stability of immobilized laccase can be ascribed to the structural rigidness of laccase, the stabilization of support and the protection of laccase from unfolding and denaturation by supports (Andjelkovi et al., 2015).

3.3.4. Operational stability and reusability

The operational stability and reusability of immobilized laccase are of important significances for practical use. The operational stability and reusability of Kaolin-*Lac* was explored through a series of cyclic experiments using ABTS as standard substrate and degraded MG effluent with the coexistence of Cd (II). The results shown in Fig. 5d, the Kaolin-*Lac* lost nearly 50% of its activity after 2 cycles and then the Kaolin-*Lac* could maintain nearly 50% of its initial activity. The Kaolin-*Lac* could retain nearly 80% decolorization for MG after five cycles. The physical adsorption immobilization had weak bonds between enzyme and support, hence, the loss of enzyme activity can be ascribed to the enzyme leaching during washing process (Liu et al., 2012). However, the laccase sited in the slit of kaolinite was difficult to leak, which resulted in a relatively stable operational stability (Zheng et al., 2016). The stable operational stability could afford stable degradation ability for MG. Immobilization could provide protection for laccase through the carrier kaolinite and retained laccase activity and the degradation ability for MG.

3.4. Treatment of MG effluent mixing with Cd (Π)

3.4.1. Effect of concentration of SA

The existence of mediator SA could markedly improve the react velocity. The mediator could decrease the energy required for the reaction need, thus accelerating reaction (Murugesan et al., 2009). The Fig. 6a and b demonstrated the effect of different concentrations of mediator SA on the decolorization of MG mixed with Cd (Π). As shown in the Fig. 6a, the decolorization of MG had been strikingly improved while the concentration of SA changed from 0 to 0.5 mg/L. However, the decolorization of MG by Kaolin-*Lac* began to decrease when the concentration of SA exceeded 0.5 mg/L. This phenomenon demonstrated that the concentration of SA was important for decolorization of MG by Kaolin-*Lac*. And the optimum concentration of SA could provide moderate amount for the oxidation reduction cycle of laccase which was immobilized on the kaolinite (Chhabra et al., 2009). Superfluous mediator, SA, which couldn't be oxidized by laccase might possess toxicity to laccase. In the Fig. 6b, the concentration of SA had little influence on the removal of Cd (Π). This result can be ascribed to which the removal of Cd (Π) was the adsorption function of kaolinite and laccase. The adsorption ability had nothing with the activity of laccase, hence, the concentration of SA had little effect on the removal of Cd (II).

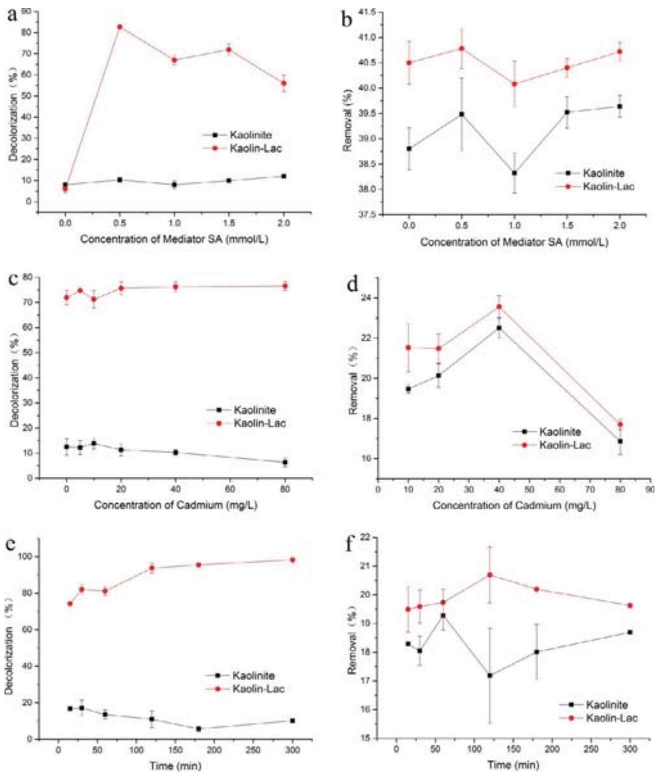

Fig. 6. a)&b) Effect of concentration of mediator SA on treatment of MG effluent mixing with Cd (Π) by Kaolin-*Lac*; c)&d)Effect of concentration of cadmium on treatment of MG effluent mixing with Cd (Π) by Kaolin-*Lac*; e)&f)Effect of time on removal rates of MG effluent mixing with Cd (Π) by Kaolin-*Lac*.

3.4.2. Effect of concentration of Cd (Π)

Generally, metal ions could bind with the enzyme and change the activity of enzyme (Jadhav et al., 2010). Different types and concentrations of metal ions have different influence on the laccase activity. Most of them had negative effect on laccase. But several studies confirmed that free laccase had tolerance to different concentration of Ca (Π), Mg (Π), Cu (Π) and Mn (Π) (Casas et al., 2009; Wang et al., 2017). As a common deleterious metal, Cd (Π) is often mixed in the textile industries. Some studies have reported that free laccase has tolerance to Cd (Π) (Casas et al., 2009; Jadhav et al., 2010). However, there were few reports about the influence of Cd (Π) on the degradation of MG effluent by immobilized laccase. The property of laccase may change after immobilization. The effects of Cd (II) on activity of laccase maybe also change. As depicted in the Fig. 6c, when the concentration of Cd (Π) was lower than 5 mg/L, the decolorization of Kaolin-Lac for MG increased as concentration of Cd (Π) increased. When the concentration of Cd (Π) ranged from 5 mg/L to 20 mg/L, the decolorization of Kaolin-Lac for MG was unstable. When the concentration of Cd (Π) was higher than 20 mg/L, the decolorization of Kaolin-Lac for MG maintained with nearly 75%. This phenomenon demonstrated that low contration of Cd (II) could improve the decolorization of Kaolin-*Lac* for MG, and high concentration of Cd (II) didn't strikingly decrease the decolorization of Kaolin-Lac for MG. It indicated that Kaolin-*Lac* also had certain tolerance to Cd (Π) and the immobilization process had little effect on the tolerance of laccase for Cd (Π). From the Fig. 6d, it could be seen that Kaolin-*Lac* had certain removal ability for Cd (Π). Comparing with kaolinite, the Kaolin-*Lac* had higher removal ability for Cd (Π). When the concentration of Cd (Π) was 40 mg/L, Kaolin-*Lac* had the highest removal efficiency of Cd (Π), which was close to 23%. The higher removal ability for Cd (Π) of Kaolin-*Lac* could be attributed to the synergetic effect of kaolinite and laccase (Yang et al., 2017). Immobilization of laccase on kaolinite might change the surface charge density, surface functional groups of kaolinite that confirmed by FTIR results, leading to the change of adsorption ability of kaolinite. Also, laccase could interact with Cd (II) through the Van der waals adsorption or hydrogen bond adsorption.

3.4.3. Effect of time

The Fig. 6e and f districted the decolorization of MG mixing with Cd (Π) in a 5 h successive experiment. By contrast, the decolorization of MG and the removal of Cd (Π) by kaolinite were compared. As shown in Fig. 6e, the decolorization of MG by Kaolin-*Lac* could achieve 74% after 15 min incubation. As the decolorization time increased, the decolorization velocity became slow. After 300 min incubation, MG was nearly decolorized totally. However, the kaolinite only achieved 10% decolorization after 5 h reaction. This phenomenon could confirm the more important contribution of the laccase catalytic process for decolorization of MG. And with time increasing, the lower decolorization velocity might attribute to the effect of the accumulation of degradation products on laccase activity. As depicted in Fig. 6f, the removal of Cd (Π) by Kaolin-*Lac* and kaolinite demonstrated 21% and 19%, separately. The higher removal ability of Kaolin-*Lac* might be ascribed to the adsorption of ions by laccase and the change of adsorption ability of kaolinite (Chen et al., 2017a,b; Zeng et al., 2017). As shown in Fig. 6, the removal of MG and Cd (Π) could be attributed to the united effects of degradation by the laccase and the adsorption by the kaolinite support (Yang et al., 2017).

4. Conclusion

This study demonstrated the gradual progress of immobilizing laccase on kaolinite. Successful preparation of Kaolin-*Lac* was confirmed by structural characterizations using FT-IR, SEM-EDS. The stabilities of Kaolin-*Lac* were enhanced compared to free laccase. The Kaolin-*Lac* retained 50% of the original activity and nearly 80% decolorization for MG after 5 cycles. In the presence of mediator SA, the Kaolin-*Lac* used to degrade MG exhibited nearly 100% in 300 min, and almost 25% removal for Cd (Π). This study confirms that kaolinite can serve as microreactor for biomacromolecule immobilization. The low concentration coexistence of Cd (II) could improve the degradation of MG by Kaolin-*Lac*. Kaolin-*Lac* had certain tolerance to high concentration of Cd (Π). As obtained Kaolin-*Lac* is an economically, ecofriendly biocatalyst, it has extensive applicability for the treatment of MG effluent mixing with Cd (Π).

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