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ORIGINAL RESEARCH

Transformation and immobilization of hexavalent chromium in the co-presence of biochar and organic acids: effects of biochar dose and reaction time

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Abstract

A batch experiment was conducted to examine the effects of biochar dose and reaction duration on the transformation and immobilization of Cr(VI) in the combined biochar and low-molecular-weight organic acid systems. The results showed that increase in the dosage level of biochar caused increase in the solution pH, particularly for the Biochar300 treatments but did not enhance the reduction of Cr(VI) after 1-day reaction. Over 35% of the converted Cr(III) was immobilized by sorption to the biochar due to increased negatively charged sites on the biochar surfaces driven by pH rise. The elevated pH due to biochar dose increase tended to slow down the reduction of Cr(VI) to Cr(III), resulting in more Cr(VI) being adsorbed at a higher biochar dose. For the higher-temperature biochars, the increase in biochar dose did not markedly change the transformation and immobilization of the added Cr. Increase in the reaction duration markedly increased the pH for Biochar300. This resulted in the disappearance of all Cr(VI) in the solution after the 7-day reaction, possibly through sorption of cationic Cr(III) to the biochar surfaces. Increase in reaction time for the higher-temperature biochars resulted in re-oxidation of Cr(III) to Cr(VI) due to the increased exposure of solution Cr(III) to atmospheric oxygen. The research findings obtained from this study have implications for optimizing treatment procedure for wastewater that contains elevated level of toxic Cr(VI). Simulation experiments are required to determine appropriate biochar dose and reaction time to achieve cost-effective treatment goals.

Keywords Chromium · Detoxification · Biochar · Low-molecular-weight organic acids · Reaction kinetics

1 Introduction

Chromium is an element of significant environmental concern (Fruchter 2002; Oze et al. 2007; Kazakis et al. 2018). The toxicity of chromium to biota depends on its oxidation state of presence with free hexavalent chromium (Cr(VI)) as the most toxic form among the chromium pools (Abreu et al. 2014; Antoniadis et al. 2018; Patra et al. 2018). Immobilization of aqueous Cr(VI) or transformation of Cr(VI) to other less toxic species, mainly trivalent chromium (Cr(III)), is among the major strategies for reducing the environmental impacts from chromium. Cr(VI) usually occurs in oxy-anionic forms as chromate (CrO_4^{2-}) or dichromate ($Cr_2O_7^{2-}$). Conversion of Cr(VI) into Cr(III) via reduction results in the change of chromium from an oxy-anionic form to a cationic form (Owlad et al. 2009). Unlike chromate or dichromate, cationic Cr^{3+} is subject to immobilization through hydrolysis or adsorption by negatively charged colloids under non-acidic environmental conditions (Tytłak et al. 2015).

Organic acids act as reductants to reduce Cr(VI) in environmental media (Deng and Stone 1996). It was shown that Cr(VI) could be transformed to Cr(III) by Fe^{2+} in the presence of fulvic acids (Agrawal et al. 2009). Cr(VI) can also be photochemically reduced to Cr(III) by low-molecular-weight organic acids in the presence of either dissolved Fe^{3+} or

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adsorbed Fe^{3+} (Sun et al. 2009). Biochar has the capacity to immobilize trace elements (Heaney et al. 2018; Qin et al. 2020a, b). Chen et al. (2015) compared the immobilization of Cr(III) and Cr(VI) by biochar and found that the biochar material removed more Cr(III) than Cr(VI). This was attributed to cation exchange and precipitation of Cr^{3+} on the biochar surface due to biochar-driven increase in pH, which, on the other hand, disfavoured adsorption of Cr(VI) that was present in oxy-anionic forms (Saha and Orvig 2010).

In the co-presence of biochar and LMWOAs, the surfaces of biochar could be protonated by LMWOAs (Heaney et al. 2020), which complicates the processes regulating immobilization of trace elements by the biochar (Alozie et al. 2018; Achor et al. 2020). Qin et al. (2020a, b) investigated the effects of pyrolysis temperature and types of LMWOAs on biochar-driven reduction of Cr(VI) and found that oxalic acid and malic acid tended to have better effects on enhancing biochar-driven Cr(VI) reduction compared to citric acid, and biochar produced at 300 °C was more favourable for Cr(VI) reduction compared to the higher-temperature biochars. However, the above work was limited to a fixed dose of biochar and a relatively short period of reaction time. Increase in biochar application rate and reaction time is likely to markedly affect the behaviour of chromium in the combined biochar and LMWOA reaction systems but such effects are still unclear. This knowledge gap needs to be filled to optimize the reaction conditions for developing cost-effective procedures for treating Cr(VI)-containing wastewater. The objective of this work was therefore to examine the effects of biochar dose and reaction time on the fate of chromium in the biochar–LMWOA–Cr(VI) systems.

2 Materials and methods

2.1 The biochar materials used in the experiment

Three biochar materials made from the stalks of *Pennisetum hydridum* at a pyrolysis temperature of 300, 500 and 700 °C (labelled as Biochar300, Biochar500 and Biochar700, respectively) were used in the experiment. The details of the procedure for producing these biochar materials have been reported previously (Qin et al. 2020a, b). The physiochemical characteristics of the three biochar materials are shown in Table 1. Biochar300 had a porous structure with thick pore walls. In contrast, Biochar500 and Biochar700 showed much thinner pore walls and greater uniformity. The amount of flakes inside the pores of biochar increased with increasing pyrolysis temperature.

The biochar materials were ground with a pestle and mortar to pass a 2 mm sieve prior to use in the experiment. The major characteristics of the biochar materials are provided in the Supplementary document.

2.2 Batch experiment design

Consistent with the previously reported work (Qin et al. 2020a, b), the concentration of citric acid, oxalic acid and malic acid was set at 0.01 M; the reacting solution was fixed at 100 mL and the concentration of Cr(VI) in the solution was set at 100 mg/L. However, the dose of biochar materials was doubled to 20 g/L for the current experiment. The experimental set-up is detailed in Table 2.

Plastic bottles with a capacity of 150 mL were used as batch reactors. For the controls, 100 mL of Cr(VI) solution at a concentration of 100 mg/L was used. For the LMWOA treatments, 50 mL of Cr(VI) solution at a concentration of 200 mg/L was mixed with 50 mL of a respective organic acid at 0.02 mM. For the added biochar treatments, 2 g of biochar was added into each batch reactor. After adding all the ingredients, the batch reactors were shaken in a rotary shaker for 2 h and then allowed to stand in dark during the period of the experiment. The pH and electrical conductivity (EC) of the solutions were determined after 1 and 7 days of the experiment. An aliquot of solution in each batch reactor was also taken after pH and EC measurements for determination of total Cr and Cr(VI). The spent biochar materials for the control and various treatments were washed with deionized water three times for preparation of samples for XPS and SEM–EDS analyses.

2.3 Analytical methods

The pH and EC in the solution samples were measured with a PHSJ-5 pH meter and PXSJ-216F EC meter, respectively. After filtration with a 0.45 µm membrane filter, Cr(VI) in the solutions was determined by the diphenylcarbazide colorimetric method (Deng and Stone 1996). The total Cr in

Table 1 The pH, EC, BET and elemental composition of the biochar materials produced under different pyrolysis temperatures

Biochar type	pH	EC (dS/m)	BET surface area (m^2/g)	Zeta potential (mV)	C (%)	H (%)	N (%)	S (%)
300 °C	6.35 ± 0.05	7.07 ± 0.01	2.24	− 42.0	56.74	4.77	0.34	0
500 °C	10.11 ± 0.03	33.1 ± 0.18	10.89	− 48.1	59.81	2.53	0.65	0.57
700 °C	10.35 ± 0.03	38.6 ± 0.26	14.48	− 57.9	56.73	1.74	0.68	0.23

Table 2 Experimental setup details

Biochar dose	Treatments	Cr(VI)	Biochar300 or Biochar500 or Biochar700 (g)	Solution (mL)
No added biochar	Control	100 mg/L	0	100
	0.01 M citric acid	100 mg/L	0	100
	0.01 M oxalic acid	100 mg/L	0	100
	0.01 M malic acid	100 mg/L	0	100
Added biochar at 20 g/L	Control	100 mg/L	2	100
	0.01 M citric acid	100 mg/L	2	100
	0.01 M oxalic acid	100 mg/L	2	100
	0.01 M malic acid	100 mg/L	2	100

the solutions was measured by inductively coupled plasma mass spectrometry (Agilent 7700 ICP-MS) and the operating conditions for the ICP–MS are provided in Supplementary Table S1. The surface morphology and structure of the spent biochar samples were observed using a scanning electron microscope (SEM, Merlin, Zeiss, Germany). The chemical composition of the spent biochar surfaces was determined by energy-dispersive X-ray spectroscopy (Quantax200 with X-Flash 6/100, Brüker, USA). XPS analysis of the spent biochar surfaces was performed using a Kratos X-ray photoelectron spectrometer (Axis Ultra DLD).

2.4 QA/QC and statistical analysis methods

The experiment was performed in triplicate. All chemical reagents used in the experiments were of analytical reagent grade. Ultrapure water (18.2 MΩ/cm) was used throughout the entire course of all the experiments. The statistically significant difference between the treatment means was determined by Duncan's multiple range test using SPSS (IBM SPSS software Version 23.0).

3 Results

3.1 No-added biochar reaction system

The control had a pH of 2.20 after 1 day of the experiment, which was significantly higher ($p < 0.05$) than that in the citric acid treatment and the oxalic acid treatment, but not significantly ($p > 0.05$) different from that in the malic acid treatment. The oxalic acid treatment had the lowest pH ($p < 0.05$) among the control and treatments. The solution pH tended to increase after 7 days for both the control and the treatments except for the citric acid treatment (Fig. 1a).

The value of EC after 1 day of experiment showed the following decreasing order (significant at $p < 0.05$): oxalic acid treatment > citric acid treatment > malic acid treatment > control. The pattern was not changed after 7 days of the experiment (Fig. 1b).

The total Cr concentration in all the solutions was around 100 mg/L after both 1 and 7 days of the experiment, comparable to the theoretical concentration of the added Cr(VI). However, Cr(VI) concentration was significantly lower in all the treatments than that in the control. There was no significant difference in Cr(VI) concentration between the oxalic acid treatment and the malic acid treatment, and the concentration of Cr(VI) in both was significantly lower ($P < 0.05$) than that in the citric acid treatment. After 7 days of the experiment, the Cr(VI) concentration was markedly reduced for the oxalic acid and malic acid treatments, while the concentration of Cr(VI) in the control and the citric acid treatment remained at around 100 mg/L (Fig. 1c, d).

3.2 Added biochar reaction system

3.2.1 1-day reaction time

For Biochar300, the EC value in the control was 4.9 dS/m. The addition of a LMWOA raised the EC to nearly 6.0 dS/m. The solution EC increased to nearly or above 11.0 dS/m in the Biochar500 treatments and nearly or 13.0 dS/m in the Biochar700 treatments. The pH in the control was 5.60 for Biochar300, but significantly dropped to 4.27, 4.13 and 4.50 in the citric acid treatment, oxalic acid treatment and malic acid treatment, respectively. For the control and any LMWOA treatments, the pH significantly increased from the Biochar300 treatment to the Biochar500 treatment to the Biochar700 treatment, with the pH being always significantly higher in the control than in any of the LMWOA treatments (Table 3).

For Biochar300, no Cr(VI) was detected for any of the LMWOA treatments but there was still 41.5 mg/L of Cr(VI) in the solution for the control. The concentration of total Cr in the control and all the LMWOA treatments was lower than the theoretical concentration of added Cr(VI). For Biochar500, the concentration of Cr(VI) in both the control and

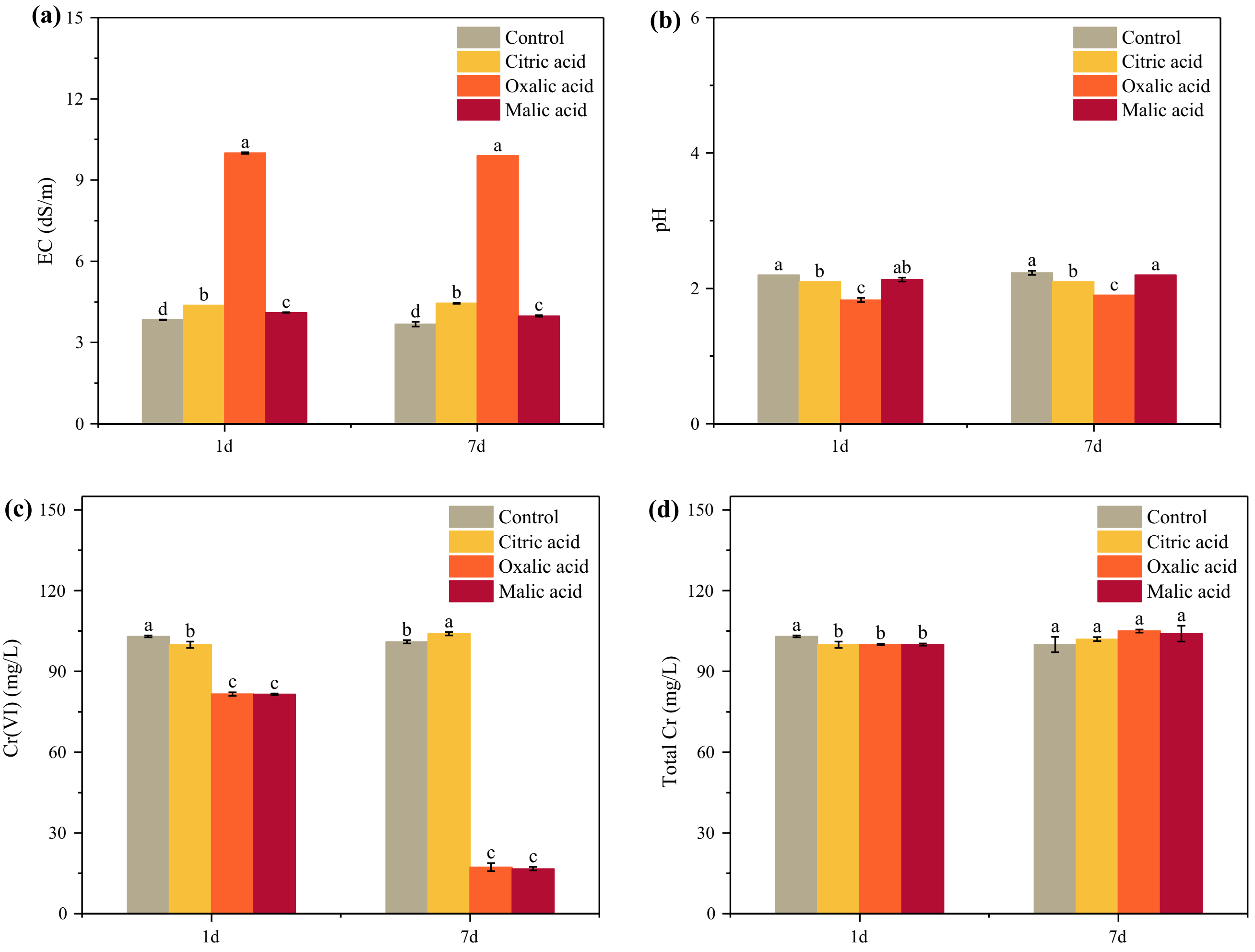


Fig. 1 EC (**a**), pH (**b**) and concentration of Cr(VI) (**c**) and total Cr (**d**) in the control and various LMWOA treatments in the absence of biochar. All values are presented as mean ± standard error ($n = 3$). Means with different letters in the same column for each parameter are significantly different at $p < 0.05$

all the treatments was lower than the theoretical concentration of the added Cr(VI) with the following decreasing order: oxalic acid > (insignificant) malic acid > (significant) citric acid > (insignificant) control. The concentration of Cr(VI) in the control for Biochar700 was lower than the theoretical concentration of the added Cr(VI) and the same decreasing order as that of Biochar500 was observed. Overall, there was a general trend in that Cr(VI) and the total Cr increased with the pyrolysis temperature for the control or a respective organic acid treatment (Table 3).

For Biochar300, no Cr(VI) was detected for any of the LMWOA treatments, but there was still 41.5 mg/L of Cr(VI) in the solution for the control. The concentration of total Cr in the control and all the LMWOA treatments was lower than the theoretical concentration of added Cr(VI). For Biochar500, the concentration of Cr(VI) in both the control and all the treatments was lower than the theoretical concentration of the added Cr(VI) with the following decreasing order: oxalic acid > (insignificant) malic acid > (significant) citric acid > (insignificant) control. The concentration of Cr(VI) in the control for Biochar700 was lower than the theoretical concentration of the added Cr(VI) and the same decreasing order as that of Biochar500 was observed. Overall, there was a general trend in that Cr(VI) and the total Cr increased with the pyrolysis temperature for the control or a respective organic acid treatment (Table 3).

3.2.2 7-day reaction time

After 7 days of reaction, there was only little change in pH and EC in all reaction systems except for the pH of the Biochar300 system, which showed an increase, as compared to the 1-day system. Cr(VI) in the control disappeared. For Biochar 500, Cr(VI) in the control and the citric acid treatment increased compared to the 1-day treatment. For Biochar700, increase in the control and all the LMWOA treatments was

Table 3 Solution EC, pH, Cr(VI) and total Cr after the 1-day reaction in the control and the treatments with different LMWOAs in the presence of different biochar types

Parameter	Biochar300	Biochar500	Biochar700
EC (dS/m)			
Control	4.90 ± 0.05Cc	11.3 ± 0.07Ba	12.8 ± 0.06Aab
Citric acid	5.83 ± 0.03Cb	10.7 ± 0.07Bb	12.8 ± 0.03Ab
Oxalic acid	5.97 ± 0.03Ca	11.3 ± 0.07Ba	13.0 ± 0.05Aa
Malic acid	5.77 ± 0.03Cb	10.8 ± 0.12Bb	13.0 ± 0.10Aab
pH			
Control	5.60 ± 0.00Ca	10.5 ± 0.00Ba	10.6 ± 0.01Aa
Citric acid	4.27 ± 0.03Cc	9.10 ± 0.02Bc	9.47 ± 0.00Ad
Oxalic acid	4.13 ± 0.03Cd	9.71 ± 0.01Bb	9.82 ± 0.02Ac
Malic acid	4.50 ± 0.00Cb	9.75 ± 0.01Bb	9.87 ± 0.01Ab
Cr(VI) (mg/L)			
Control	41.5 ± 1.18Ca	66.1 ± 2.54Bb	74.8 ± 0.39Ac
Citric acid	0.00 ± 0.00Bb	68.7 ± 2.41Ab	72.8 ± 2.46Ac
Oxalic acid	0.00 ± 0.00Cb	83.2 ± 0.48Ba	87.0 ± 1.17Aa
Malic acid	0.00 ± 0.00Bb	80.9 ± 0.42Aa	80.3 ± 1.82Ab
Total Cr(mg/L)			
Control	65.8 ± 0.24Cb	107 ± 0.92Aa	101 ± 0.26Bab
Citric acid	87.0 ± 1.16Ba	100 ± 2.26Ab	104 ± 1.79Aa
Oxalic acid	64.7 ± 2.37Bb	102 ± 1.14Ab	99.3 ± 1.71Aab
Malic acid	51.8 ± 2.81Bc	101 ± 0.77Ab	96.8 ± 2.28Ab

All values are presented as mean ± standard error ($n = 3$). Means with different lowercase letters in the same column for each parameter are significantly different at $p < 0.05$. Means with different capital letters in the same row are significantly different at $p < 0.05$

observed especially for the control, which had a concentration of Cr(VI) close to the theoretical concentration of the added Cr(VI). The concentration of the total Cr in all the Biochar300 treatments decreased compared to the 1-day treatment, while the Biochar500 and Biochar700 treatments all had a total concentration of Cr close to the theoretical concentration of the added Cr(VI) (Table 4).

3.3 XPS and SEM–EDS analyses of the spent Biochar300

Since no significant Cr adsorption was observed for Biochar500 and Biochar700, XPS and SEM–EDS results presented here are only limited to the spent Biochar300. No Cr(III) oxide peak at ~ 576 and Cr(VI) oxide peak at ~ 580 eV were identifiable from the XPS spectra for the control and any of the three LMWOA treatments (Fig. 2). EDS analysis showed the presence of C, O, Si and K on the surfaces of all the spent biochar materials. However, Cr was not detectable on the spent biochar surfaces. Cu was detected in the control and the citric acid treatment, while Ca was detected in the malic acid treatment (Fig. 3).

Table 4 Solution EC, pH, Cr(VI) and total Cr after the 7-day reaction in the control and the treatments with different LMWOAs in the presence of different biochar types

Parameter	Biochar300	Biochar500	Biochar700
EC (dS/m)			
Control	4.82 ± 0.14Cb	11.6 ± 0.08Ba	12.9 ± 0.06Aab
Citric acid	5.10 ± 0.00Cb	10.7 ± 0.12Bc	12.7 ± 0.04Ab
Oxalic acid	5.57 ± 0.15Ca	11.2 ± 0.04Bb	13.2 ± 0.04Aa
Malic acid	5.10 ± 0.10Cb	11.0 ± 0.12Bbc	13.0 ± 0.11Aa
pH			
Control	6.20 ± 0.21Ba	10.3 ± 0.02Aa	10.5 ± 0.01Aa
Citric acid	5.37 ± 0.12Cbc	9.26 ± 0.01Bc	9.56 ± 0.00Ad
Oxalic acid	4.97 ± 0.29Bc	9.65 ± 0.00Ab	9.83 ± 0.00Ac
Malic acid	5.70 ± 0.20Bab	9.68 ± 0.00Ab	9.88 ± 0.00Ab
Cr(VI) (mg/L)			
Control	0.00 ± 0.00Ca	93.3 ± 1.64Ba	100 ± 0.40Aa
Citric acid	0.00 ± 0.00Ba	85.8 ± 0.74Ab	84.5 ± 0.20Ac
Oxalic acid	0.00 ± 0.00Ba	88.5 ± 0.60Ab	91.3 ± 2.86Ab
Malic acid	0.00 ± 0.00Ba	86.7 ± 1.09Ab	89.2 ± 1.14Abc
Total Cr(mg/L)			
Control	30.0 ± 0.98Bc	99.5 ± 1.37Aa	100 ± 0.40Aa
Citric acid	58.6 ± 2.88Ba	100 ± 1.16Aa	98.6 ± 2.48Aa
Oxalic acid	50.3 ± 3.65Bb	97.8 ± 0.89Aa	101 ± 1.45Aa
Malic acid	49.6 ± 1.30Bb	98.6 ± 1.59Aa	98.0 ± 1.12Aa

All values are presented as mean ± standard error ($n = 3$). Means with different lowercase letters in the same column for each parameter are significantly different at $p < 0.05$. Means with different capital letters in the same row are significantly different at $p < 0.05$

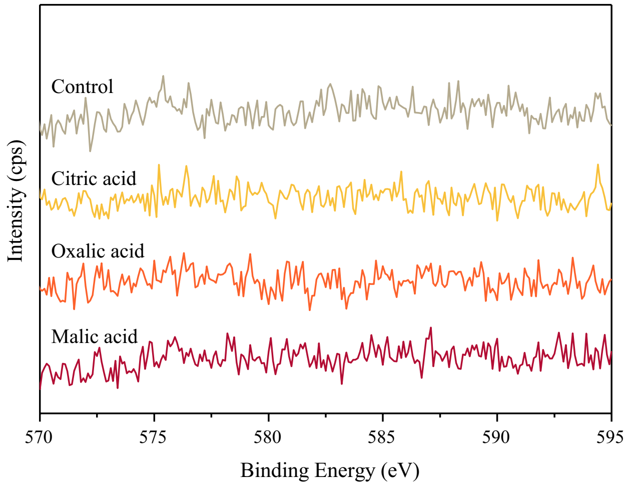
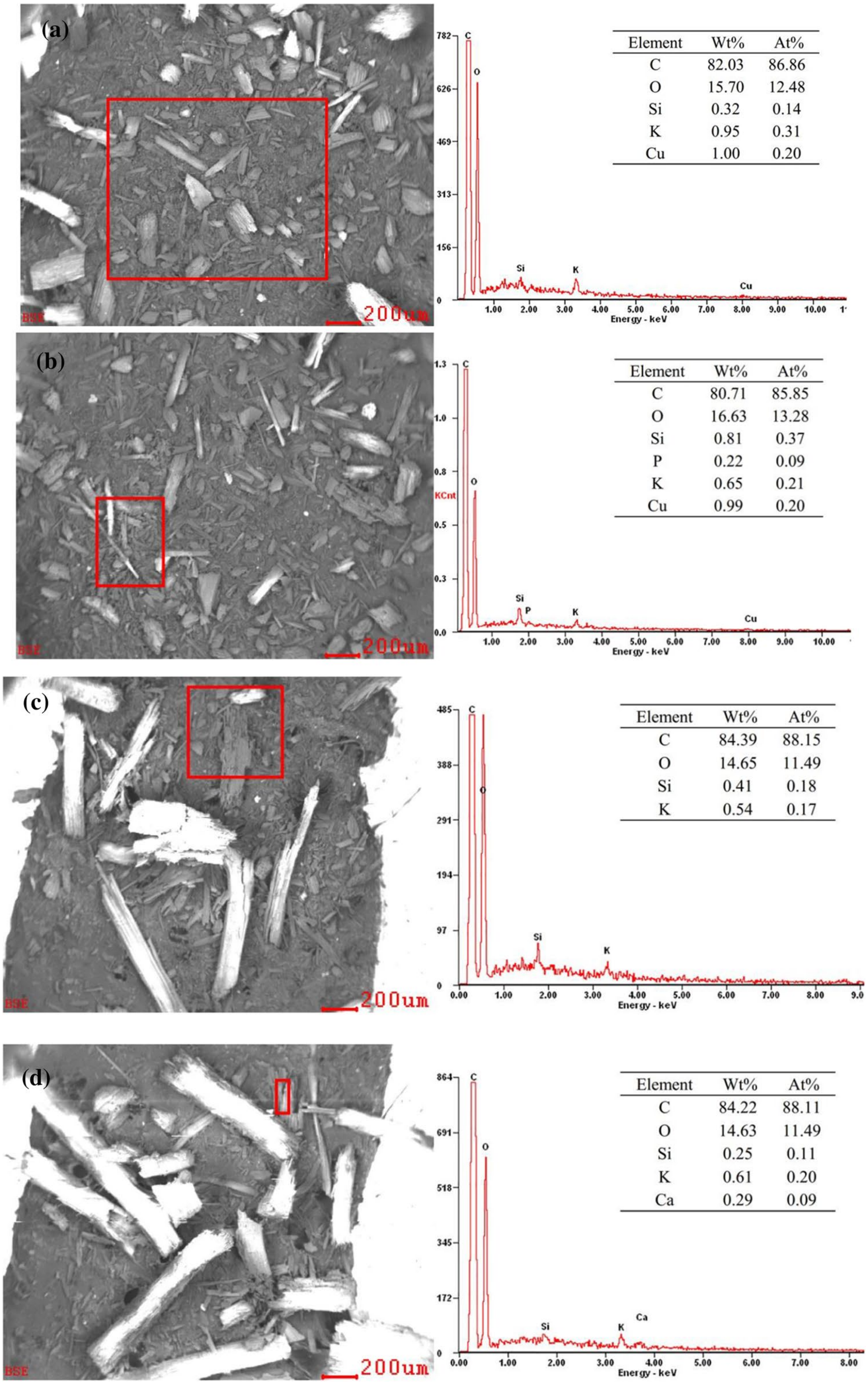


Fig. 2 XPS spectra in the area from 570 to 595 eV for the spent Biochar300 in the control and the three LMWOA treatments

Fig. 3 SEM images and EDS results for the spent Biochar300 in **a** the control, **b** citric acid treatment, **c** oxalic acid treatment and **d** malic acid treatment



(a)

Element	Wt%	At%
C	82.03	86.86
O	15.70	12.48
Si	0.32	0.14
K	0.95	0.31
Cu	1.00	0.20

(b)

Element	Wt%	At%
C	80.71	85.85
O	16.63	13.28
Si	0.81	0.37
P	0.22	0.09
K	0.65	0.21
Cu	0.99	0.20

(c)

Element	Wt%	At%
C	84.39	88.15
O	14.65	11.49
Si	0.41	0.18
K	0.54	0.17

(d)

Element	Wt%	At%
C	84.22	88.11
O	14.63	11.49
Si	0.25	0.11
K	0.61	0.20
Ca	0.29	0.09

4 Discussion

The results from the experiment without added biochar (Fig. 1) suggested that citric acid had no effect on reducing Cr(VI), while reduction of Cr(VI) took place in the presence of oxalic acid and malic acid at a concentration of 0.01 M with nearly 20% and over 80% of the added Cr(VI) being transformed into possibly Cr(III) after 1 day and 7 days, respectively. The capacity of oxalic acid and malic acid to reduce Cr(VI) at the concentration set for the experiment was very similar and the oxalic acid- or malic acid-driven reduction of Cr(VI) was under kinetic control. These results differ from those of some published studies (Kim and Choi 2011; Mu et al. 2018), where at 24 h and 90 min, respectively, Cr(VI) reduction to Cr(III) was only slightly influenced by the presence of organic acids. However, the current findings are consistent with the findings of Chen et al. (2013), who demonstrated negligible citric acid-driven reduction of Cr(VI), but observed that 19% and 68% of Cr(VI) were reduced by malic acid and tartaric acid, respectively, after 10 h contact time. The greater percentage of transformed Cr(VI) in the current study may be due to the longer contact time between Cr(VI) and the organic acids. In addition, the reduction of Cr(VI) to Cr(III) was likely to be via the formation of Cr(III)–malic and oxalic acid complexes, which may be kinetically stable (Uluçinar and Nur Onar 2005). By comparison with the previous results (Qin et al. 2020a, b) with the biochar dose being set at 10 g/L, the increase in the biochar dose to 20 g/L raised the solution pH due to more OH^- being added into the reaction system. The pH rise in the control was evident for the Biochar300 treatment that had relatively lower pH status, as compared to the higher-temperature biochar treatments. The mean pH of all the LMWOA-treated solutions was increased with increasing dosage level for the three biochar treatments (Fig. 4a). The pH rise due to increased biochar dosage level favoured the removal of water-borne Cr by Biochar300 in the control and LMWOA treatments (Fig. 4b). This is attributable to the enhanced de-protonation of the biochar surfaces, which allows adsorption of cationic Cr(III) by the increased negatively charged biochar surface sites. Lower-temperature biochar tends to have a stronger reducing capacity (Klüpfel et al. 2014). This explains the dominant presence of Cr(III) in the Biochar300 systems in contrast to the Biochar500 and Biochar700 systems.

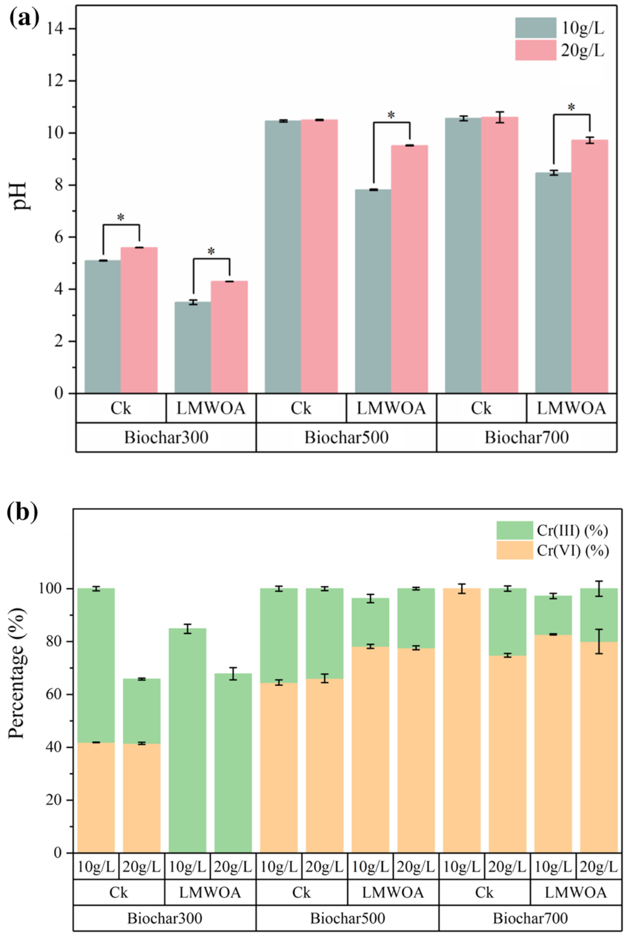


Fig. 4 Comparison of **a** pH and **b** Cr in the solutions between different biochar doses for various treatments [data concerning the treatments with a biochar dose at 10 g/L were derived from Qin et al. (2020a, b)]

Increase in the length of reaction time markedly raised the pH for Biochar300. But for the higher-temperature biochars, only slight increase or decrease in pH was observed (Fig. 5a). For the control in Biochar300 system, this resulted in the disappearance of all Cr(VI) in the solution after the 7-day reaction time (Fig. 5b). It was likely that increased dosage level of biochar enhanced the reduction of Cr(VI). It is not clear whether the adsorbed Cr on the biochar was in a form of Cr(VI) or Cr(III), because XPS analysis failed to detect the Cr species on the surface of the spent Biochar300. The adsorption rates of Cr in the control and the LMWOA treatment for Biochar300 were approximately 3.5 and 2.5 mg of Cr per gram of biochar. The low density of Cr on the spent biochar surfaces made the Cr 2p peaks unidentifiable in the presence of background noise (Fig. 2). This also explains the absence of any Cr peaks in the EDS spectra (Fig. 3). However, the increase in pH favoured the deprotonation of the biochar surfaces, which could promote the sorption of cationic Cr(III). This also applies to the LMWOA treatments for Biochar300 where the solution pH increased after the 7-day reaction. It is interesting to note that increase in reaction time for the higher-temperature biochars did not bring about further reduction of Cr(VI) to Cr(III). On the contrary, it caused re-oxidation of Cr(III) to Cr(VI) since the proportion of Cr(III) in the total Cr decreased over time (Fig. 5b). This was particularly evident for the controls where the reducing strength was relatively weaker, as compared to the LMWOA counterparts. The re-oxidation of Cr(III) was related to the increased exposure of the Cr(III) to atmospheric oxygen, but the exact mechanism responsible for this process requires further investigation.

The research findings obtained from this study have implications for optimizing treatment procedure for wastewater that contains elevated level of toxic Cr(VI). Simulation experiments are required to determine appropriate biochar dose and reaction time to achieve cost-effective treatment goals.

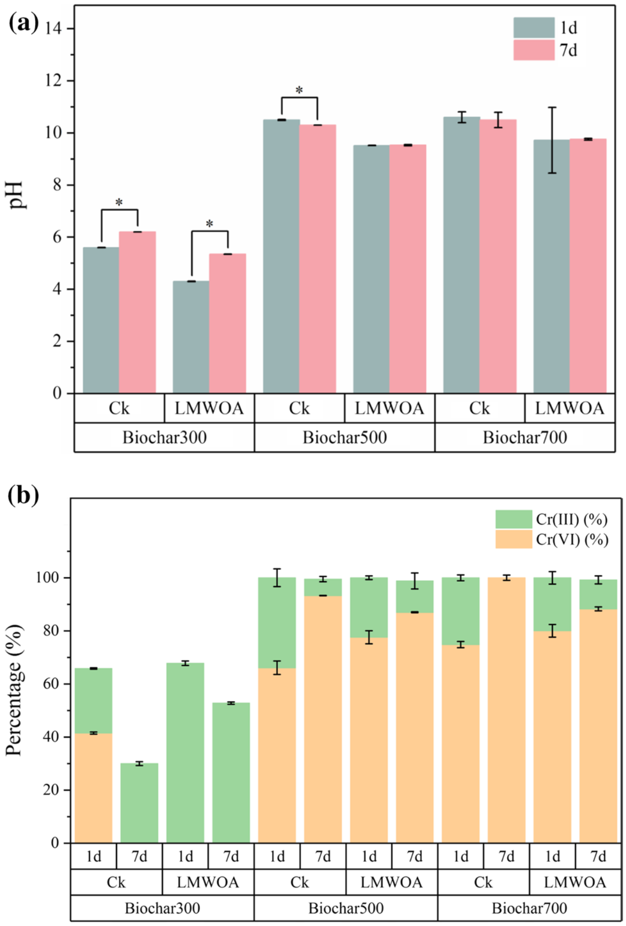


Fig. 5 Comparison of **a** pH and **b** Cr in the solutions at different reaction durations for various treatments

5 Conclusions

Increased biochar dose raised solution pH particularly for the Biochar300 treatments, but did not enhance the reduction of Cr(VI) after the 1-day reaction. Part of the Cr(III) converted from Cr(VI) was adsorbed by the biochar due to increase in the negatively charged sites on the biochar surfaces. The elevated pH due to biochar dose increase tended to slow down the reduction of Cr(VI) to Cr(III), resulting in more Cr(VI) being adsorbed at a higher biochar dose. For the higher-temperature biochars, the increase in biochar dose did not markedly change the transformation and immobilization of the added Cr except for the control for the Biochar700 treatment where the increase in biochar dose enhanced the reduction of Cr(VI) to Cr(III). Increase in the length of reaction time markedly raised the pH for Biochar300. However, only slightly increase or decrease in pH was observed for the higher-temperature biochars. For the Biochar300 treatments, this resulted in the disappearance of all Cr(VI) in the solution after the 7-day reaction, most likely due to sorption of cationic Cr(III) to the biochar surfaces. Increase in reaction time for the higher-temperature biochars caused re-oxidation of Cr(III) to Cr(VI), particularly for the controls. The re-oxidation of Cr(III) was likely related to the increased exposure of atmospheric oxygen.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42773-021-00117-y.

Author contributions Conceptualization: JQ, YJL and WX; methodology: JQ, YJL and WX; investigation: XW, YJL and WX; resources: JQ and YJL; data curation: JQ; writing—original draft preparation: JQ and CL; writing—review and editing: JQ and CL; visualization: JQ; supervision: JQ; project administration: JQ and YJL; funding acquisition: YJL and JQ.

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Data availability The data are available upon demand by request to the corresponding author.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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