

**Supplementary Information for**

**The overlooked role of lignin: Comparable enhancement on  
colloid transport with humic acid in porous media**

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**Text S1.** The details for the quartz sand preparation and the packing of the columns.

Ultrapure quartz sand (Minghai Quartz Sand Factory, Zhengzhou, China), ranging from 425 to 700  $\mu\text{m}$  in size, was used as porous media for the nano-colloids, micro-colloids and HA, lignin transport experiments. The quartz sand was cleaned by soaking in concentrated HCl for at least 24 h and 1 M NaOH solution for a further 24 h. The quartz sand was then repeatedly washed with DI water until a neutral pH was obtained. The sand was then dried at 105°C overnight and baked at 850°C for at least 8 h.

Prior to packing, the cleaned quartz sand was rehydrated by boiling in DI water for at least 0.5 h. After cooling the rehydrated quartz sand, the columns were packed with wet quartz sand that was added in small increments ( $\sim 1$  cm) under mild vibration, minimizing layering or air entrapment. An 80-mesh fabric screen was placed at each end of the column.

**Table S1.** The breakthrough mass recovery of colloids and HA and lignin under different solution conditions.

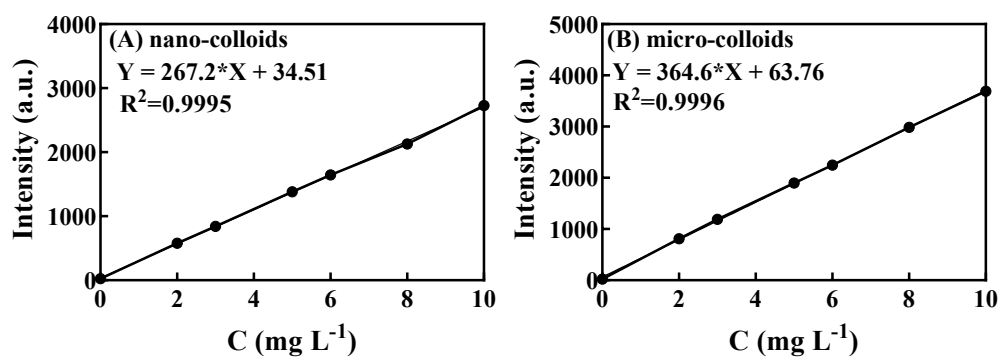
<b>Particles</b>	<b>Solution chemistry</b>	<b>Condition</b>	<b>Mass recovery (%)</b>
<b>nano-colloids</b>	10 mM NaCl	single	32.07±1.36
		w/ 1 mg L <sup>-1</sup> HA	78.99±2.19
		w/ 1 mg L <sup>-1</sup> lignin	67.20±1.26
		w/ 10 mg L <sup>-1</sup> HA	96.23±1.03
		w/ 10 mg L <sup>-1</sup> lignin	96.04±1.28
		pre-treated w/ 10 mg L <sup>-1</sup> HA	77.37±1.26
		pre-treated w/ 10 mg L <sup>-1</sup> lignin	80.73±0.01
	1 mM CaCl <sub>2</sub>	single	35.20±0.23
		w/ 1 mg L <sup>-1</sup> HA	87.72±2.06
		w/ 1 mg L <sup>-1</sup> lignin	93.48±0.05
w/ 10 mg L <sup>-1</sup> HA		99.87±0.27	
<b>micro-colloids</b>	10 mM NaCl	w/ 10 mg L <sup>-1</sup> lignin	83.94±1.14
		single	57.38±0.96
		w/ 1 mg L <sup>-1</sup> HA	78.98±0.85
		w/ 1 mg L <sup>-1</sup> lignin	77.50±2.94
		w/ 10 mg L <sup>-1</sup> HA	88.17±0.32
		w/ 10 mg L <sup>-1</sup> lignin	94.82±1.42
		pre-treated w/ 10 mg L <sup>-1</sup> HA	85.75±1.35
		pre-treated w/ 10 mg L <sup>-1</sup> lignin	77.58±0.22
	1 mM CaCl <sub>2</sub>	single	72.23±2.17
		w/ 1 mg L <sup>-1</sup> HA	88.65±5.32
w/ 1 mg L <sup>-1</sup> lignin		96.01±0.01	
w/ 10 mg L <sup>-1</sup> HA		99.28±0.20	
<b>HA</b>	10 mM NaCl	w/ 10 mg L <sup>-1</sup> lignin	94.89±0.22
		1 mg L <sup>-1</sup>	80.39±1.06
	1 mM CaCl <sub>2</sub>	10 mg L <sup>-1</sup>	97.41±1.45
		1 mg L <sup>-1</sup>	54.45±1.59
<b>lignin</b>	10 mM NaCl	10 mg L <sup>-1</sup>	78.34±0.73
		1 mg L <sup>-1</sup>	36.69±5.49
	1 mM CaCl <sub>2</sub>	10 mg L <sup>-1</sup>	68.90±3.90
		1 mg L <sup>-1</sup>	37.15±0.26
		10 mg L <sup>-1</sup>	79.49±1.08

**Table S2.** The hydrodynamic size of HA and lignin, nano-colloids and micro-colloids, zeta potential of HA, lignin, and quartz sand, and zeta potential of colloids in the absence and presence of HA or lignin.

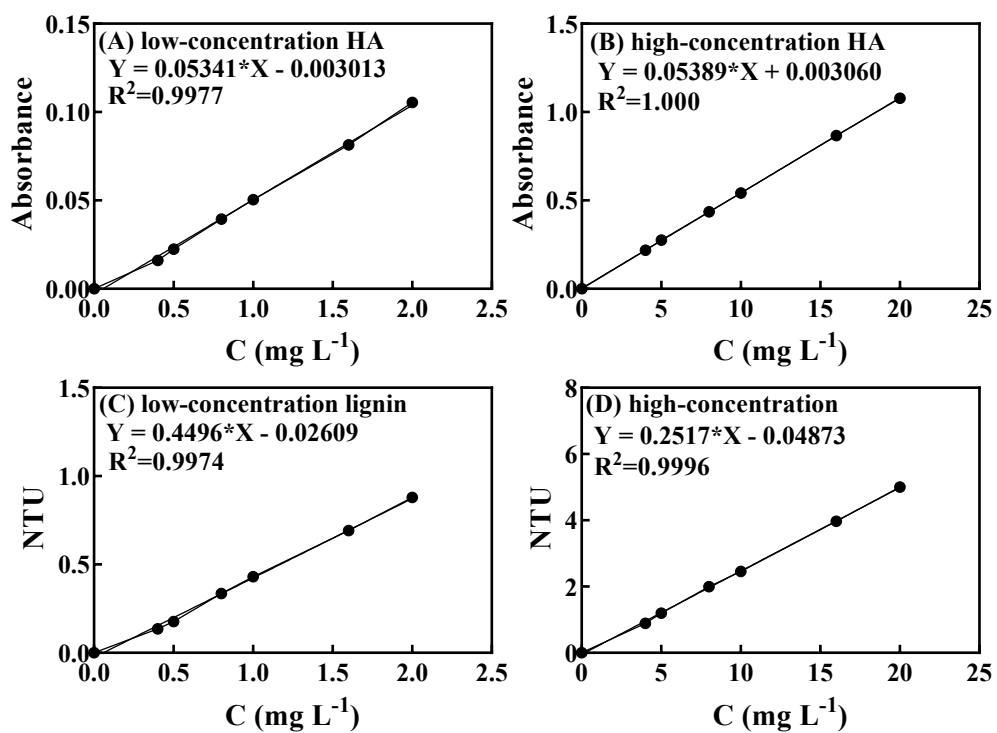
<b>Particles</b>	<b>Solution chemistry</b>	<b>Condition</b>	<b>Zeta potential (mV)</b>	<b>Hydrodynamic size (nm)</b>
sand	10 mM NaCl	single	-45.98±0.64	NA
	1 mM CaCl <sub>2</sub>	single	-32.92±0.95	NA
HA	10 mM NaCl	single	-13.45±2.5	51.62±11.89
	1 mM CaCl <sub>2</sub>	single	-18.47±4.52	23.28±0.21
lignin	10 mM NaCl	single	-23.16±0.00	506.4±23.70
	1 mM CaCl <sub>2</sub>	single	-31.74±3.87	490.5±22.68
nano-colloids		single	-63.63±1.94	519.94±9.79
		w/ 1 mg L <sup>-1</sup> HA	-59.79±2.69	NA
	10 mM NaCl	w/ 1 mg L <sup>-1</sup> lignin	-56.30±2.77	NA
		w/ 10 mg L <sup>-1</sup> HA	-54.42±1.49	NA
		w/ 10 mg L <sup>-1</sup> lignin	-39.65±2.23	NA
		single	-33.65±1.20	558.31±6.84
		w/ 1 mg L <sup>-1</sup> HA	-29.56±0.62	NA
	1 mM CaCl <sub>2</sub>	w/ 1 mg L <sup>-1</sup> lignin	-24.96±2.40	NA
		w/ 10 mg L <sup>-1</sup> HA	-29.83±1.56	NA
		w/ 10 mg L <sup>-1</sup> lignin	-25.85±1.86	NA
micro-colloids		single	-63.48±1.84	992.87±32.29
	10 mM NaCl	w/ 1 mg L <sup>-1</sup> HA	-57.03±1.11	NA
		w/ 1 mg L <sup>-1</sup> lignin	-45.62±2.85	NA
		w/ 10 mg L <sup>-1</sup> HA	-56.11±1.70	NA

	w/ 10 mg L <sup>-1</sup> lignin	-45.36±2.07	NA
	single	-39.26±1.97	1064.38±11.7
	w/ 1 mg L <sup>-1</sup> HA	-37.01±0.99	NA
1 mM CaCl <sub>2</sub>	w/ 1 mg L <sup>-1</sup> lignin	-36.21±1.44	NA
	w/ 10 mg L <sup>-1</sup> HA	-36.94±0.57	NA
	w/ 10 mg L <sup>-1</sup> lignin	-35.12±3.77	NA

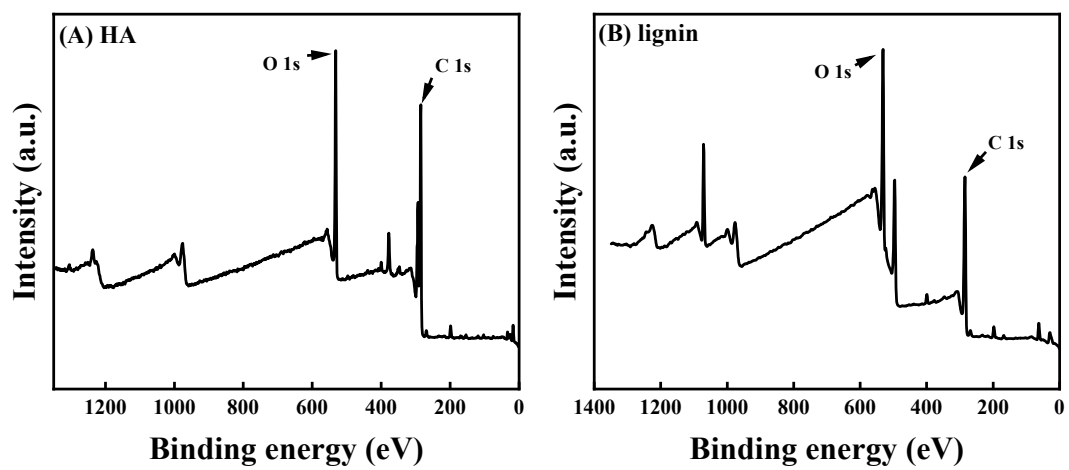
NA: Not analyzed.



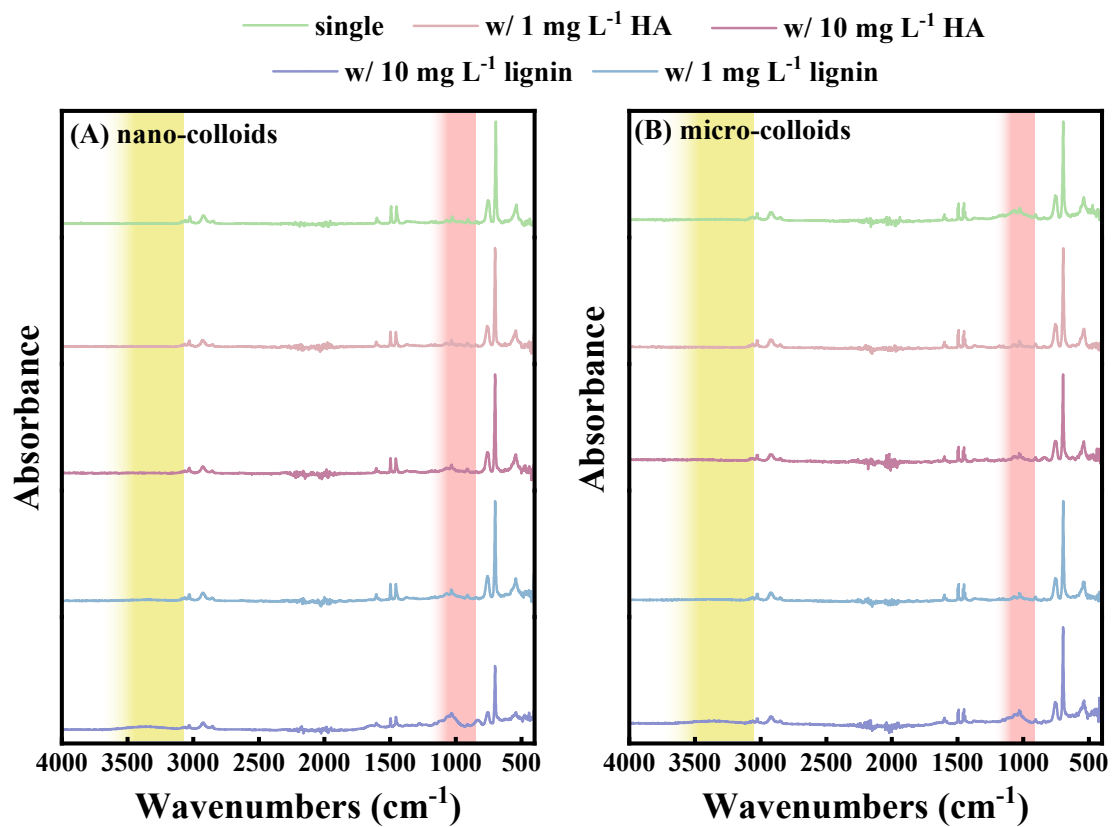
**Fig. S1.** The calibration curves of nano-colloids (A) and micro-colloids (B) using fluorescence spectrophotometer.



**Fig. S2.** The calibration curves for both HA (A and B) and lignin (C and D) using UV-Vis spectrophotometer and turbidity meter, respectively.



**Fig. S3.** XPS survey spectra of HA (A) and lignin (B).



**Fig. S4.** FTIR spectra of nano-colloids and micro-colloids in the absence and presence of HA or lignin.