Inhibition effect of polyvinyl chloride on ferrihydrite reduction and electrochemical activities of *Geobacter metallireducens*

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**Abstract**
*Geobacter metallireducens* GS15, a model of dissimilatory iron-reducing bacteria, is the key regulator in biogeochemical iron cycling. How the emerging contaminant microplastics involved in the iron cycling are driven by microbes on the microscale remains unknown. Hence, the influences of two typical microplastics, polybutylene terephthalate-hexane acid (PBAT) and polyvinyl chloride (PVC), were explored on the activity of *G. metallireducens* GS15 with ferrihydrite or ferric citrate as the respective electron acceptors. The results showed that the iron (II) contents in PBAT- and PVC-treatment groups were 16.79 and 6.81 mM, respectively, at the end of the experiment. Compared with the PBAT-treatment group, scanning electron microscopy and energy dispersive spectrometry revealed that merely a small amount of iron-containing products covered the surface of PVC. Moreover, PBAT and PVC could both retard the electroactivity of *G. metallireducens* GS15 at the beginning of microbial fuel cell operation. On the basis of the results above, microplastic PVC might exhibit potential inhibition of the iron cycling process driven by *G. metallireducens* GS15 with ferrihydrite as the terminal electron acceptor. This study extended our understanding of the influence of the microplastics PBAT and PVC on microbially mediated biogeochemical iron cycling. The findings might have an important implication on the biogeochemical elements cycling in the ecosystem with the involvement of emerging contaminant microplastics.

**KEYWORDS**
biogeochemical iron cycling, electroactivity, *Geobacter metallireducens* GS15, iron (III) reduction ability, microplastics

**1 INTRODUCTION**

Plastics, a series of versatile materials, have enabled extensive societal and economic benefits due to their low production cost, lightweight, and adaptable properties [1].
The most commonly employed plastics include polyvinyl chloride (PVC), polybutylene terephthalate-hexane acid (PBAT), polyethylene, and polypropylene [2]. Owing to their durability and resistance to biodegradation, plastics exist for hundreds to thousands of years and break down into smaller debris due to long-term physicochemical effects, such as ultraviolet radiation, wave motion, and chemical erosion [3,4]. It has been suggested that plastic particles in the <5 mm range are defined as microplastics [5].

As an emerging pollutant, microplastics are ubiquitous in estuaries, coastal zones, and offshore seas, including lakes, subtidal sediments, straits, and bays [6,7]. They pose a threat to a wide range of marine biota, including birds, fishes, turtles, mammals, and invertebrates. For instance, microplastics could be ingested by marine organisms in benthic and pelagic ecosystems, which would damage or block their intestines, thereby affecting nutrition with often lethal effects [8,9]. In addition, microplastics could serve as mediators for pollutant transport, along with ocean currents, such as heavy metals and persistent organic pollutants [10,11]. The pollutant uptake through ingestion generates toxic effects and may ultimately affect human health through the food chains [12,13]. Recently, microplastics have been reportedly entering into terrestrial ecosystems, including soil, earthworm, chicken stomach, and manure [14,15]. For example, soil microbial diversity and enzyme activities decreased significantly with the addition of microplastics.

Environmentally abundant iron is one of the essential elements for living organisms. Iron usually plays a significant role in controlling both redox balance and biogeochemical biogenic element cycling [16]. The electrostatic interaction force between some microplastics and negatively charged Fe₂O₃ results in the electrostatic interaction force between some microplastics and biogeochemical biogenic element cycling [16]. The microbial dissimilatory iron reduction may be one of the earliest microbial respiration processes of global significance. Iron (III)-containing minerals possess different functions, including redox, catalysis and adsorption/desorption, which affect soil and water bodies [20]. Microorganisms that participate in the extracellular reduction of iron (III) oxides coupled with energy harvest are defined as dissimilatory iron-reduction bacteria (DIRB) [21]. Under different conditions, the DIRB respiration process is often accompanied by the precipitation of an assortment of iron (II)-containing minerals, such as magnetite (Fe₃O₄), siderite (FeCO₃), vivianite (Fe₅(PO₄)₂·8H₂O), and so on. The secondary products may facilitate the iron (III) reduction process through removing or attenuating the thermodynamic activities of byproducts (e.g., ferrous ions) or by impeding bioreduction by coating or passivating the residual iron (III) oxides on DIRB surfaces [22,23]. In addition, the iron (III) reduction process is usually coupled with heavy metal, carbon, nitrogen, or sulfur cycles, and occurs in almost all environments [24].

DIRB are ubiquitous in the environment, and their activities have major implications for natural biogeochemical cycling processes, such as iron, carbon, oxygen, and sulfur cycles. DIRB could utilize various iron (III)-containing minerals as terminal electron acceptors. Among them, poorly crystalline ferrihydrite is especially significant to DIRB in aquifers, sediments, and soils due to its benign bioavailability. Moreover, DIRB are promising microorganisms that could participate in environmental bioremediation, heavy metal reduction [25], and energy harvesting processes [26]. Geobacteraceae, a group of typical electroactive microorganisms, are one of the most important iron (III)-reducing bacteria and mainly exist in sediments, landfills, sandy aquifers, and in petroleum and uranium pollution deposits [27,28]. By default, extracellular electron transfer is involved in the dissimilatory iron-reduction process. In general, multihaem c-type cytochromes as critical components participate directly in mediating electron transfer from the inner membrane to the surface of insoluble iron (III) oxides. Current studies suggest that c-type cytochromes OmcS and OmcE play an important role in electron shuttle between Geobacter spp. and iron (III) oxides [29]. Nevertheless, the abovementioned proteins do not have any impacts on soluble ferric citrate (FC) reduction mediated by Geobacter spp. Hence, the mechanisms of electron transfer may be significantly different for soluble/insoluble iron (III) reduction [30].

Factors including the identity of substrates and electron acceptors, as well as the existence of electron shuttles and chelating agents, have been shown to influence electroactivity and the ability of extracellular electron transfer of Geobacteraceae [31–33]. Moreover, current evidence suggests that conductive materials such as magnetite, granular activated carbon or biochar, could effectively stimulate electron
transfer [34–37]. It has been reported that the Geobacter sulfurreducens strain PCA could obtain energy through extracellular electron transfer coupling with reduction of iron (III) oxides or hydroxides and then donate the received electrons to other microorganisms [38]. Therefore, the electrical interplay between microorganisms and minerals links the redox transformation of iron-containing minerals to the oxidation of organic carbon compounds.

Investigation of the interactions between microplastics and microbial activity contributes to the understanding of the potential effects of these particles on the microbial-participating biogeochemical iron cycling process. In this study, the Geobacter metallireducens strain GS15 was used as a model of iron-reducing bacteria with soluble FC or insoluble poorly crystalline ferrihydrite as terminal electron acceptors. Two types of microplastics (PBAT and PVC) were employed to study their impacts on the electroactivity and iron (III) reduction ability of G. metallireducens GS15. This may provide insights into how microplastics participate in the microbially driven biogeochemical iron cycling process.

2 | MATERIALS AND METHODS

2.1 | Bacterial strain and growth condition

G. metallireducens strain GS15 (ATCC 53774) was stored in our laboratory and was incubated in FC medium, as previously described [34] or in a defined freshwater (FW) medium with 20 mM ethanol as the sole electron donor and 60 mM FC or poorly crystalline ferrihydrite as terminal electron acceptors, respectively. The cultivation was conducted in 100-ml serum bottles with 40 ml of FC or FW medium. The bottles were sealed with thick butyl rubber and aluminum caps.

In the experiment, the diameters of two employed microplastics, PBAT and PVC, were both approximately 4 mm. PBAT and PVC were immersed in 75% ethanol for 24 h and rinsed with sterile water on a clean bench before use. Then, 5% (vol/vol) G. metallireducens strain GS15 in the exponential growth phase and microplastics were transferred into FC or FW medium. In addition, a modified medium without microplastics or G. metallireducens GS15 served as the positive and negative control, respectively. All incubations and samplings were carried out in triplicate to ensure reproducibility.

2.2 | The synthesis of ferrihydrite

Poorly crystalline ferrihydrite was synthesized according to the protocols described by the Lovley Laboratory [39]. Briefly, 108 g of FeCl3 was dissolved into 400 ml of deionized water, with the pH adjusted to 7.0. The precipitate was washed with deionized water, resuspended and centrifuged again until the supernatant was no longer clear, but instead yellow or red. Then, the final precipitate was purged with N2 for 30 min, autoclaved, and stored in the dark at 4°C before use.

2.3 | Measurement of the iron (II) concentration

Iron (II) was measured using the ferrozine method [40], described as follows: the samples were withdrawn at regular intervals with sterile, N2-flushed syringes, and acidified with 0.5 M HCl for 24 h in the dark at room temperature, followed by centrifugation at 7,100g. The supernatant was determined by ultraviolet-visible (UV/vis) spectrophotometer at 562 nm after complexation with ferrozine.

2.4 | Electroactivity assay

The electrochemical activity of G. metallireducens GS15 during cultivation with microplastics was investigated in a two-chambered H-type microbial fuel cell (MFC). The effective volume for each chamber was 100 ml, and they were separated by a cation exchange membrane (Ultrex CMI-7000). The graphite plates (20 mm × 20 mm × 2 mm) served as electrodes and were twisted by titanium wire (0.8 mm in diameter). Five percent G. metallireducens GS15 and microplastics were transferred into the anode chamber with FW medium as the anolyte and operated for 6 days. The cathode was filled with the same volume of 50 mM potassium ferricyanide as the catholyte. All media and solutions were prepared under strictly anaerobic conditions. The potential was determined by a data acquisition system (Keithley 2700, Tektronix Co.).

2.5 | Surface morphologies of microplastics

The surface morphologies of the microplastics PBAT and PVC were characterized by a scanning electron microscope and an energy dispersive spectrometer (SEM/EDS; Hitachi S-4800, Japan), along with X-ray diffraction (XRD; XRD-6100, Japan). The samples were prepared by fixation with 2.5% glutaraldehyde for 12 h, rinsed three times with 100X phosphate-buffered salines, dehydrated...
by gradient ethanol elution, and stored at 4°C before characterization.

2.6 | Data processing

All statistical analyses were performed with Excel 2003 and Origin 8.0 (Origin Lab Corporation) software. The means and standard deviations were calculated based on at least three replicates.

3 | RESULTS

3.1 | The influence of microplastics on the reduction ability of *G. metallireducens* GS15

*Geobacter* spp. is the primary organism capable of using iron minerals as terminal electron acceptors. Here, we used *G. metallireducens* GS15 as model bacteria with poorly crystalline ferrihydrite and FC as the electron acceptor to study the effects of the microplastics PBAT and PVC on the *G. metallireducens* GS15 iron-reduction ability.

The influences of PBAT and PVC on the *G. metallireducens* GS15 capability of iron reduction with soluble FC as the electron acceptor are shown in Figure 1a. During the cultivation (12 days), the concentration of iron (II) remained stable in the negative control treatment (containing PBAT/PVC alone without *G. metallireducens* GS15), indicating that microplastics PBAT and PVC made no contribution to the reduction of the microplastics GS15 iron-reduction ability. Compared with the positive control (containing *G. metallireducens* GS15 alone), no obvious variation was observed with the addition of microplastics PBAT and PVC. This may imply that PBAT and PVC exert no obvious toxic effects on the activity of *G. metallireducens* GS15 due to their stable nature.

The effects of PBAT and PVC on iron reduction with insoluble ferrihydrite as the electron acceptor are shown in Figure 1b. During cultivation for 39 days, no obvious iron (II) was generated in the negative control, indicating that the microplastics PBAT and PVC could not reduce the insoluble iron (III). The iron (II) contents in the positive control and treatment groups in the presence of PBAT both increased gradually and reached the maximum value on the Day 12 (15.88 and 16.79 mM, respectively). This demonstrates that PBAT had no significant adverse effect on the insoluble iron (III) reduction process by *G. metallireducens* GS15. However, compared with the positive control, the iron (II) content increased slowly and was 6.81 ± 0.64 mM at Day 38, and merely 2.4 mM iron (III) was reduced, which showed that PVC could significantly inhibit the utilization of insoluble ferrihydrite by *G. metallireducens* GS15.

3.2 | The influence of microplastics on the electrochemical activity of *G. metallireducens* GS15

The transformation of poorly crystalline ferrihydrite was clearly restrained in the presence of microplastic PVC. Therefore, the impacts of PBAT and PVC on the electrochemical activity of *G. metallireducens* GS15 were further explored by constructing a dual-chamber MFC in the presence of ferrihydrite in the anode. Figure 2
demonstrates the change in current density over time in the MFC. It shows that the current density increased rapidly and reached a plateau at 80 h with/without the addition of microplastics PBAT and PVC. Compared with the control group, there was an obvious lag time of the current density in the presence of PBAT and PVC, and the discrepancy reached the maximum at 69 h (172.34, 84.57, and 61.11 A/m², respectively). It is indicated that PBAT and PVC could extend the electroactivity of *Geobacter metallireducens* GS15 at the beginning of experimentation. However, the current densities gradually became closer after 69 h, and no apparent differences were observed in the end of the experiment. Taking the adsorption properties of microplastics into consideration, it is supposed that PBAT and PVC might immobilize a part of *G. metallireducens* GS15 and further retard the starting time due to the low biomass in the early stage of the experiment. The delay of current density was weakened with the growth of *G. metallireducens* GS15. Hence, both microplastics PBAT and PVC had a significantly negative effect on the electroactivity of *G. metallireducens* GS15 at the beginning of MFC operation through the discrepancy of the treatment groups and control group decreased gradually.

### 3.3 Surface characterization of microplastics

Several environmental factors could affect mineral transformation to more crystalline iron (III) oxides [41], such as the solution composition, pH, and temperature. Therefore, we intentionally devoted significant efforts to the morphological characterization of mineral phase transitions during iron (III) reduction by *G. metallireducens* GS15 in the presence of microplastics via SEM and EDS. It can be seen from Figure 3a,b that PBAT and PVC possess high specific surface areas owing to the existence of wrinkles, which is beneficial to the attachment of microorganisms and their metabolites. At the end of the experiment, the surface morphologies of the PBAT and

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**Figure 2** Influence of microplastics (PVC and PBAT) on the electroactivity of *Geobacter metallireducens* GS15 in the presence of poorly crystalline ferrihydrite ion (FeOOH). PBAT, polybutylene terephthalate-hexane acid; PVC, polyvinyl chloride

**Figure 3** Scanning electron microscope (SEM) micrographs of microplastics with ferric citrate as the electron acceptor: morphologies of (a) PBAT, (b) PVC, and (c) SEM after cultivation of (c)PBAT and (d) PVC (right and inset figures are high-resolution graphs of the images on the left). The average diameters of PBAT and PVC are both 4 mm. The density of PBAT and PVC is 1.3 and 1.3 g/cm², respectively. PBAT, polybutylene terephthalate-hexane acid; PVC, polyvinyl chloride
PVC were characterized, as shown in Figure 3c,d. They revealed that the surfaces of PBAT and PVC were covered with a dense mineral film when accompanied by FC as the electron acceptor. High-resolution images showed that the mineral morphologies on the surfaces of PBAT and PVC were similar: a rhombic-shaped structure with a length of approximately 2–5 μm (the right side and inset of Figure 3c,d). The EDS analysis suggested that the mineral is ferrous phosphate, the main component of vivianite (Figure 4).

The poorly crystalline ferrihydrite is often transformed into secondary ferrous-containing minerals [42], including siderite, vivianite, magnetite, and others. By the end of the experiment, the reddish-brown ferrihydrite transformed into black ferromagnetic iron oxides over time. Figure 4a,b represents the characterization of the surfaces of PBAT and PVC, respectively. As shown in Figure 5, the metabolites of G. metallireducens GS15 formed a dense film on the surface of PBAT, while adhesion on PVC was sparse. The physical characterizations appear obviously different, as abundant spherical and peanut-like substances existed on the surface of PBAT (Figure 5). EDS analysis indicated that these were iron (II)-containing minerals, and XRD patterns implied that magnetite (Fe₃O₄) and siderite (Fe₂CO₃) were the predominant phases present at the end of the experiment (Figure 6). Microbially mediated iron (III) mineral reduction process generally invokes strategies for extracellular electron transfer between microorganisms and iron (III) minerals. The dense mineral film on the surface of PBAT might compensate for the impact of PBAT for the magnetite is conducive to microbial extracellular electron transfer [35]. However, no similar structures were found on the surface of PVC. Adhesions on PVC were smaller-sized and aggregated together. The mineral composition on the surface of PVC was primarily vivianite (Fe₃(PO₄)₂·8H₂O; Figure 6). EDS analysis suggested an organic composition (only 0.57% iron content), rather than biominerals. It is supposed that the constituents of adhesion are mainly the extracellular polymer and metabolites secreted by G. metallireducens GS15, which are not conducive to the utilization of insoluble iron (III) by G. metallireducens GS15.

4 | DISCUSSION

In this study, two types of typical microplastics, PBAT and PVC, were employed for the study of their impacts on the electroactivity and iron (III) reduction ability of G. metallireducens GS15 with soluble FC or insoluble poorly crystalline ferrihydrite as respective terminal electron acceptors. This study may provide insights into how microplastics participate in the microbial-driven biogeochemical iron cycling process.

In the microbial system, extracellular electron transfer plays an important role in energy transfer and conversion, especially in solid-phase substrates, including iron/manganese oxides, electrodes, or soluble humic acid used as an electron acceptors. Poorly crystalline iron (III) oxides are common iron (III)-containing minerals existing in soils, aquatic sediments, and geologic materials. Among these minerals, ferrihydrite is particularly important due to its high surface area and good bioavailability to DIRB.

The study found that no obvious negative impact on the FC reduction was observed with addition of PBAT and PVC because (a) microbes capable of iron (III) reduction are prone to utilizing soluble iron (III) as an electron acceptor; (b) the microplastics PBAT and PVC possess high stability and a hydrophobic nature. The SEM results are consistent with the FC reduction process (Figure 1a). It further indicated that microplastics PBAT and PVC had no obvious negative influence on iron (III) reduction with soluble FC as the terminal electron acceptor.
Extracellular electron transfer plays an important role in biogeochemical cycles when iron (III) oxides or electrodes are used as an electron acceptor. Geobacter spp. genome studies identified multiheme c-type cytochromes that are necessary for iron (III) oxide reduction in the inner membrane (MacA), the periplasm (PpcA), and the outer membrane (OmcB, OmcS, and OmcE) [43,44]. Herein, PpcA and OmcB are required for the reduction of soluble, chelated Fe (III) or poorly soluble Fe (III) oxidation, whereas outer membrane multiheme c-type cytochromes OmcS and OmcE are only essential for insoluble iron (III) oxide reduction [45,46]. Hence, compared with FC, Geobacter spp. might have alternate electron transport pathways with ferrihydrite as the terminal electron acceptor. It has been reported that the transformation of insoluble iron (III) oxides by G. metallireducens GS15 is commonly successfully conducted and accompanied by secretion of electronic shuttles or direct contact with mineral surfaces [24]. Given that PVC is resistant to bioavailability, it is difficult for G. metallireducens GS15 to form dense biofilm on the surface of PVC. Therefore, due to its excellent insulation effect, PVC could impede direct contact and further inhibit the electron transfer from G. metallireducens GS15 to poorly crystalline ferrihydrite. Hence, an apparent inhibition effect existed on the utilization of insoluble iron (III) oxides in the presence of PVC. The SEM findings confirmed the result that PVC could significantly impede insoluble iron (III) reduction with ferrihydrite as an electron acceptor (Figure 1b). Conversely, compared with PVC, G. metallireducens GS15 more preferentially adheres...
to the surface of PBAT owing to its effective biodegradation. The microbially mediated biomineralization products are extremely important since they influence the overall thermodynamics of the bioreduction process. Compared with the PVC treatment group, SEM-EDS and XRD analyses revealed that there were abundant secondary minerals on the surface of PBAT, and two possible reasons are provided. One reason is that the minerals were aggregated by the adhesive effect of *G. metallireducens* GS15 or its secretion. The other is that PBAT has a remarkable adsorption capacity for magnetite and siderite. It has been reported that magnetite could function as c-type cytochrome OmcS and facilitate microbial extracellular electron transfer process [35]. The existence of abundant minerals on the surface of PBAT would eliminate the negative impact of microplastics on ferrihydrite reduction. Perhaps it is a consequence of both the bacteria and the nature of PBAT. More research is necessary to elucidate the mechanism. Dissimilatory iron-reduction microbes have evolved specialized mechanisms for the exchange of electrons. These observations implied that the interaction between microbially mediated biogeochemical iron (III) reduction and emerging contaminant microplastics is complicated and might depend on the specific conditions. More research is needed to elucidate the mechanism.

In the meantime, the study found that the microplastics PBAT and PVC could retard the starting time in the MFC. It is supposed that PBAT and PVC might immobilize part of *G. metallireducens* GS15 and further retard the starting time due to the low biomass in the early stage of the experiment. Moreover, the influence of this debris might also gradually weaken as the increasing of biomass, which reviewed more suspended microorganisms could donate electrons to the electrode. However, the treatment groups exhibited good stability compared with control ones. It is probably because biofilm evolved on the surface of PBAT and PVC could act as a barrier that enhances resistance to external disturbance [47]. The microorganism was embedded by secondary minerals or detached as the reduction of ferrihydrite. Therefore, no bacterial cells were observed on the surface of the microplastic. While, more studies are still required to clarify the interaction between microplastics and electroactive microorganisms.

*Geobacter* species, a type of metal-reducing bacteria, possesses extraordinary electron transfer capability and play important roles in the global cycling of metals and carbon. Current studies suggest that this organism could extensively be involved in bioremediation of organic waste and bioenergy production with iron (III) oxides or electrode as a terminal electron acceptor [48–50]. Hence, the inhibition effect of PVC on ferrihydrite reduction and electrochemical activities of *G. metallireducens* GS15 might affect the application of this organism involved in the environmental remediation and energy harvest.

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**CONFLICT OF INTERESTS**

The authors declare that there are no conflict of interests.

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**REFERENCES**

[1] Andrady AL, Neal MA. Applications and societal benefits of plastics. Philos Trans R Soc Lond B Biol Sci. 2009;364:1977-84.
[2] Andrady AL. Microplastics in the marine environment. Mar Pollut Bull. 2011;62:1596-605.
[3] Wu XJ, Pan J, Li M, Li Y, Bartlam M, Wang YY. Selective enrichment of bacterial pathogens by microplastic biofilm. Water Res. 2019;165:114979.
[4] Rochman CM. Microplastics research—from sink to source. Science. 2018;360:28-9.
[5] Cole M, Lindeque P, Halbrendt C, Galloway TS. Microplastics as contaminants in the marine environment: a review. Mar Pollut Bull. 2011;62:2588-97.
[6] Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, et al. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ Sci Technol. 2011;45:9175-9.
[7] Eriksen M, Mason S, Wilson S, Box C, Zellers A, Edwards W, et al. Microplastic pollution in the surface waters of the Laurentian Great Lakes. Mar Pollut Bull. 2013;77:177-82.
[8] Wright SL, Darren R, Thompson RC, Galloway TS. Microplastic ingestion decreases energy reserves in marine worms. Curr Biol. 2013;23:R1031-3.
[9] Browne MA, Niven SJ, Galloway TS, Rowland SJ, Thompson RC. Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. Curr Biol. 2013;23:2388-92.
[10] Derraik JGB. The pollution of the marine environment by plastic debris: a review. Mar Pollut Bull. 2002;44:842-52.
[11] Rochman CM. The complex mixture, fate and toxicity of chemicals associated with plastic debris in the marine...
environment. Marine Anthropogenic Litter. Cham, Switzerland: Springer; 2015. p. 117-40.

[12] Oliveira M, Ribeiro A, Hylland K, Guilhermino L. Single and combined effects of microplastics and pyrene on juveniles (0+ group) of the common goby Pomatoschistus microps (Teleostei, Gobiidae). Ecol Indic. 2013;34:641-7.

[13] Reddy MS, Basha S, Adimurthy S, Ramachandraiah G. Description of the small plastics fragments in marine sediments along the Alang-Sosiya ship-breaking yard, India. Estuar Coast Shelf Sci. 2006;68:656-60.

[14] Ramos L, Berenstein G, Hughes EA, Zalts A, Montserrat JM. Polyethylene film incorporation into the horticultural soil of small periurban production units in Argentina. Sci Total Environ. 2015;523:74-81.

[15] Rillig MC. Microplastic in terrestrial ecosystems and the soil? Environ Sci Technol. 2012;46:6453-4.

[16] Hauck S, Benz M, Brune A, Schink B. Ferrous iron oxidation by denitrifying bacteria in profundal sediments of a deep lake (Lake Constance). FEMS Microbiol Ecol. 2001;37:127-34.

[17] Besseling E, Quik JTK, Sun M, Koelmans AA. Fate of nano- and microplastic in freshwater systems: a modeling study. Environ Pollut. 2017;220:540-8.

[18] Li Y, Wang XJ, Fu WY, Xia XH, Liu CQ, Min JC, et al. Interactions between nano/micro plastics and suspended sediment in water: Implications on aggregation and settling. Water Res. 2019;161:486-95.

[19] Koelmans AA, Besseling E, Wegener A, Foekema EM. Correction to plastic as a carrier of POPs to aquatic organisms: a model analysis. Environ Sci Technol. 2013;47:7812-20.

[20] Wu WF, Li B, Hu J, Li JH, Wang FP, Pan YX. Iron reduction and magnetite biominalerization mediated by a deep-sea iron-reducing bacterium Shewanella piezotolerans WP3. J Geophys Res-Biogeo. 2011;116:G04034.

[21] Amos BK, Sung Y, Fletcher KE, Gentry TJ, Wu WM, Criddle CS, et al. Detection and quantification of Geobacter lovleyi strain SZ: Implications for bioremediation at tetrachloroethene- and uranium-impacted sites. Appl Environ Microbiol. 2007;73:6898-904.

[22] Zachara JM, Kukkasapu RK, Fredrickson JK, Gorby YA, Smith SC. Biominalerization of poorly crystalline Fe (III) oxides by dissimilatory metal reducing bacteria (DMRB). Geomicrobiol J. 2002;19:179-207.

[23] Liu CX, Sota Z, Zachara JM, Fredrickson JK, Brinkman CK. Kinetic analysis of the bacterial reduction of goethite. Environ Sci Technol. 2001;35:2482-90.

[24] Melton ED, Swanner ED, Behrens S, Schmidt C, Kappler A. The interplay of microbially mediated and abiotic reactions in the biogeochemical Fe cycle. Nat Rev Microbiol. 2014;12:797-908.

[25] Wilkins MJ, Verberkmoes NC, Williams KH, Callister SJ, Mouser PJ, Elfantz H, et al. Proteogenomic monitoring of Geobacter physiology during stimulated uranium bioremediation. Appl Environ Microbiol. 2009;75:6591-9.

[26] Srikanth S, Marsili E, Flickinger MC, Bond DR. Electrochemical characterization of Geobacter sulfurreducens cells immobilized on graphite paper electrodes. Biotechnol Bioeng. 2010;99:1065-73.

[27] Stein LY, La Duc MT, Grundl TJ, Nealson KH. Bacterial and archaeal populations associated with freshwater ferromanganese micronodules and sediments. Environ Microbiol. 2001;3:10-8.

[28] Holmes DE, O’Neil RA, Vonisaa HA, N’guessan LA, Ortiz-Bernad I, Larrahondo MJ, et al. Subsurface clade of Geobacteraceae that predominates in a diversity of Fe (III) reducing subsurface environments. ISME J. 2007;1:663-77.

[29] Holmes DE, Shrestha PM, Walker DJF, Dang Y, Nevin KP, Woodard TL, et al. Metatranscriptomic evidence for direct interspecies electron transfer between Geobacter and Methanothrix species in methanogenic rice paddy soils. Appl Environ Microbiol. 2017;83:e00223-17.

[30] Mehta T, Coppi MV, Childers SE, Lovley DR. Outer membrane c-type cytochromes required for Fe (III) and Mn (IV) oxide reduction in Geobacter sulfurreducens. Appl Environ Microbiol. 2005;71:8634-41.

[31] Speers AM, Reguera G. Electron donors supporting growth and electroactivity of Geobacter sulfurreducens anode biofilms. Appl Environ Microbiol. 2012;78:437-44.

[32] Lovley DR, Woodward JC. Mechanisms for chelator stimulation of microbial Fe (III)-oxide reduction. Chem Geol. 1996;132:19-24.

[33] Doong RA, Schink B. Cysteine-mediated reductive dissolution of poorly crystalline iron (III) oxides by Geobacter sulfurreducens. Environ Sci Technol. 2002;36:2939-45.

[34] Liu FH, Rotaru AE, Shrestha PM, Malvankar NS, Nevin KP, Lovley DR. Promoting direct interspecies electron transfer with activated carbon. Environ Sci Technol. 2012;5:8982-9.

[35] Liu FH, Amelia ER, Shrestha PM, Malvankar NS, Nevin KP, Lovley DR. Magnetite compensates for the lack of a pilin-associated c-type cytochrome in extracellular electron exchange. Environ Microbiol. 2015;17:648-55.

[36] Chen SS, Rotaru AE, Liu FH, Philips J, Woodard TL, Nevin KP, et al. Carbon cloth stimulates direct interspecies electron transfer in syntrophic co-cultures. Bioresearch Technol. 2014;173:82-6.

[37] Zheng SL, Liu FH, Li M, Xiao LL, Wang O. Comparative transcriptomic insights into the mechanisms of electron transfer in Geobacter co-cultures with activated carbon and magnetite. Sci China Life Sci. 2018;61:787-98.

[38] Lovley DR. Live wires: direct extracellular electron exchange for bioenergy and the bioremediation of energy-related contamination. Energ Environ Sci. 2011;4:4896-906.

[39] Lovley DR, Phillips EJP. Organic matter mineralization with reduction of ferric iron in anaerobic sediments. Appl Environ Microbiol. 1986;51:683-9.

[40] Viollier E, Inglett PW, Hunter K, Roychoudhury AN. The ferrozine method revisited: Fe (II)/Fe (III) determination in natural waters. Appl Geochem. 2000;15:785-90.

[41] Xiong HX, Liao YH, Zhou LX. Influence of chloride and type cytochrome in extracellular electron ex- change. Geochim Cosmochim Acta. 2003;67:2977-90.

[42] Zachara JM, Kukkadapu RK, Fredrickson JK, Gorby YA, Kukkadabu RK, Fendorf S. Secondary mineralization pathways induced by microbial iron reduction of ferrihydrite under advective flow. Geochim Cosmochim Acta. 2003;67:2869-77.

[43] Zachara JM, Kukkadapu RK, Fredrickson JK, Gorby YA. Biochemical and genetic characterization of PpcA, a periplasmic c-type cytochrome in Geobacter sulfurreducens. Biochem J. 2003;369:153-61.

[44] Leang C, Coppi MV, Lovley DR. OmEB, a c-type polyheme cytochrome, involved in Fe (III) reduction in Geobacter sulfurreducens. J Bacteriol. 2003;185:2096-103.
[45] Shi L, Squier TC, Zachara JM, Fredrickson JK. Respiration of metal (hydr)oxides by Shewanella and Geobacter: a key role for multihaem c-type cytochromes. Mol Microbiol. 2010;65:12-20.
[46] Methé BA, Nelson KE, Eisen JA, Paulsen IT, Nelson W, Heidelberg JF, et al. Genome of Geobacter sulfurreducens: metal reduction in subsurface environments. Science. 2003;302:1967-9.
[47] Clarelli F, Russo CD, Natalini R, Ribot M. A fluid dynamics multidimensional model of biofilm growth: stability, influence of environment and sensitivity. Math Med Biol. 2016;33:371-95.
[48] Zhang T, Tremblay PL, Chaurasia AK, Smith JA, Bain TS, Lovley TR. Anaerobic benzene oxidation via phenol in Geobacter metallireducens. Appl Environ Microbiol. 2013;79:7800-6.
[49] Lovley DR, Ueki T, Zhang T, Malvanker NS, Shrestha PM, Flanagan KA, et al. Geobacter: the microbe electric's physiology, ecology, and practical applications. Adv Microb Physiol. 2011;59:1-100.
[50] Botton S, Harmelen MV, Braster M, Parsons JR, Röhling WF. Dominance of Geobacteraceae in BTX-degrading enrichments from an iron-reducing aquifer. FEMS Microbiol Ecol. 2010;62:118-30.

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