

## **Supplemental Information**

### **Sparking Anaerobic Digestion: Promoting Direct Interspecies Electron Transfer to Enhance Methane Production**

**Zhiqiang Zhao, Yang Li, Yaobin Zhang, and Derek R. Lovley**

**Title:**

Sparking Anaerobic Digestion: Promoting Direct Interspecies Electron Transfer to Enhance Methane Production

**Authors:**

Zhiqiang Zhao<sup>a,d</sup>, Yang Li<sup>b,d</sup>, Yaobin Zhang<sup>a,\*</sup> and Derek R. Lovley<sup>c,d</sup>

**Affiliations:**

<sup>a</sup>Key Laboratory of Industrial Ecology and Environmental Engineering (Ministry of Education), School of Environmental Science and Technology, Dalian University of Technology, Dalian 116024, China.

<sup>b</sup>School of Ocean Science and Technology, Dalian University of Technology, Panjin 124221, China

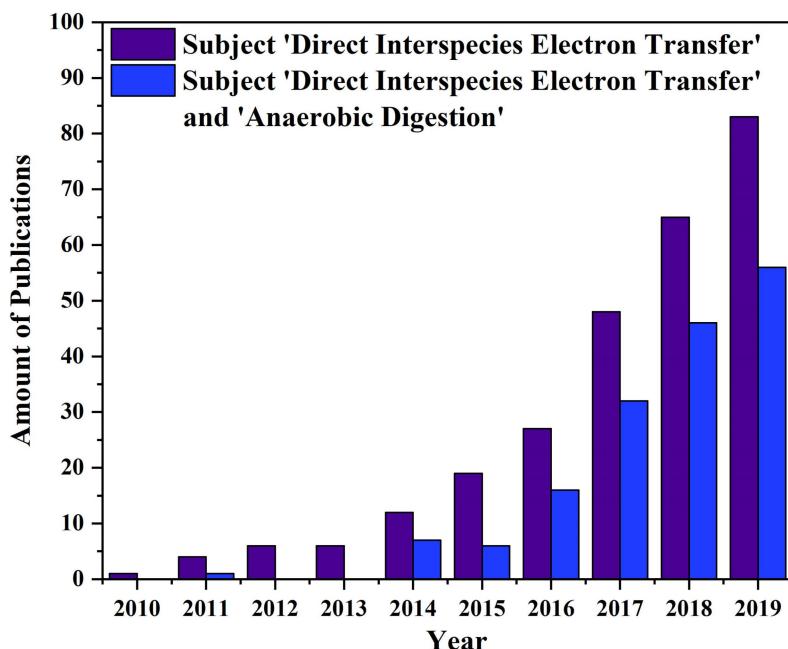
<sup>c</sup>Electrobiomaterials Institute, Key Laboratory for Anisotropy and Texture of Materials (Ministry of Education), Northeastern University, Shenyang 110819, China

<sup>d</sup>Department of Microbiology, University of Massachusetts, Amherst, MA 01003-9298, USA

**\* Correspondence:**

Tel: +86 411 8470 6460; Fax: +86 411 8470 6263;

E-mail address: zhangyb@dlut.edu.cn.



**Figure S1.** Publications on the subject of ‘Direct Interspecies Electron Transfer’ and ‘Anaerobic Digestion’ within ‘Direct Interspecies Electron Transfer’ (Data was derived from **Web of Science**).

**Table S1.** Summary of studies on stimulating anaerobic digestion with different types of conductive materials.

**Table S2.** Summary of DIET-based syntrophs and methanogens in methanogenic environments with conductive materials.

#### Supplemental References:

- Baek, G., Kim, J., Cho, K., Bae, H., and Lee, C. (2015). The biostimulation of anaerobic digestion with (semi)conductive ferric oxides: their potential for enhanced biomethanation. *Appl. Microbiol. Biotechnol.* 99, 10355-10366.
- Baek, G., Kim, J., and Lee, C. (2016). A long-term study on the effect of magnetite supplementation in continuous anaerobic digestion of dairy effluent – Enhancement in process performance and stability. *Bioresour. Technol.* 222,

344-354.

- Barua, S., Zakaria, B.S., and Dhar, B.R. (2018). Enhanced methanogenic co-degradation of propionate and butyrate by anaerobic microbiome enriched on conductive carbon fibers. *Bioresour. Technol.* *266*, 259-266.
- Barua, S., and Dhar, B.R. (2017). Advances towards understanding and engineering direct interspecies electron transfer in anaerobic digestion. *Bioresour. Technol.* *244*, 698-707.
- Burboa Charis, V.A., and Alvarez, L.H. (2020). Methane production from antibiotic bearing swine wastewater using carbon-based materials as electrons' conduits during anaerobic digestion. *Int. J Energ. Res.*
- Capson-Tojo, G., Moscoviz, R., Ruiz, D., Santa-Catalina, G., Trably, E., Rouez, M., Crest, M., Steyer, J., Bernet, N., and Delgenès, J., *et al.* (2018). Addition of granular activated carbon and trace elements to favor volatile fatty acid consumption during anaerobic digestion of food waste. *Bioresour. Technol.* *260*, 157-168.
- Chen, Q., Liu, C., Liu, X., Sun, D., Li, P., Qiu, B., Dang, Y., Karpinski, N.A., Smith, J.A., and Holmes, D.E. (2020). Magnetite enhances anaerobic digestion of high salinity organic wastewater. *Environ. Res.* *189*, 109884.
- Cheng, Q., Xu, C., Huang, W., Jiang, M., Yan, J., Fan, G., Zhang, J., Chen, K., Xiao, B., and Song, G. (2020). Improving anaerobic digestion of piggery wastewater by alleviating stress of ammonia using biochar derived from rice straw. *Environ. Technol. Inno.* *19*, 100948.
- Chowdhury, B., Lin, L., Dhar, B.R., Islam, M.N., McCartney, D., and Kumar, A. (2019). Enhanced biomethane recovery from fat, oil, and grease through co-digestion with food waste and addition of conductive materials. *Chemosphere* *236*, 124362.
- Cruz, V.C., Rossetti, S., Fazi, S., Paiano, P., Majone, M., and Aulenta, F. (2014). Magnetite particles triggering a faster and more robust syntrophic pathway of methanogenic propionate degradation. *Environ. Sci. Technol.* *48*, 7536-7543.

- Dang, Y., Holmes, D.E., Zhao, Z., Woodard, T.L., Zhang, Y., Sun, D., Wang, L., Nevin, K.P., and Lovley, D.R. (2016). Enhancing anaerobic digestion of complex organic waste with carbon-based conductive materials. *Bioresour. Technol.* *220*, 516-522.
- Dang, Y., Sun, D., Woodard, T.L., Wang, L., Nevin, K.P., and Holmes, D.E. (2017). Stimulation of the anaerobic digestion of the dry organic fraction of municipal solid waste (OFMSW) with carbon-based conductive materials. *Bioresour. Technol.* *238*, 30-38.
- Fagbohungbe, M.O., Herbert, B.M.J., Hurst, L., Li, H., Usmani, S.Q., and Semple, K.T. (2016). Impact of biochar on the anaerobic digestion of citrus peel waste. *Bioresour. Technol.* *216*, 142-149.
- Fu, L., Song, T., Zhang, W., Zhang, J., and Lu, Y. (2018). Stimulatory Effect of Magnetite Nanoparticles on a Highly Enriched Butyrate-Oxidizing Consortium. *Front. Microbiol.* *9*, 1480.
- Guo, B., Zhang, Y., Yu, N., and Liu, Y. (2020a). Impacts of conductive materials on microbial community during syntrophic propionate oxidization for biomethane recovery. *Water Environ. Res.*
- Guo, B., Zhang, Y., Zhang, L., Zhou, Y., and Liu, Y. (2020b). RNA-based spatial community analysis revealed intra-reactor variation and expanded collection of direct interspecies electron transfer microorganisms in anaerobic digestion. *Bioresour. Technol.* *298*, 122534.
- Guo, Z., Gao, L., Wang, L., Liu, W., and Wang, A. (2018). Enhanced methane recovery and exoelectrogen-methanogen evolution from low-strength wastewater in an up-flow biofilm reactor with conductive granular graphite fillers. *Front. Environ. Sci. Eng.* *12*, 1-10.
- Hu, Q., Sun, D., Ma, Y., Qiu, B., and Guo, Z. (2017). Conductive polyaniline nanorods enhanced methane production from anaerobic wastewater treatment. *Polymer* *120*, 236-243.
- Im, S., Yun, Y., Song, Y., and Kim, D. (2019). Enhanced anaerobic digestion of

- glycerol by promoting DIET reaction. *Biochem. Eng. J.* 142, 18-26.
- Jing, Y., Wan, J., Angelidaki, I., Zhang, S., and Luo, G. (2017). iTRAQ quantitative proteomic analysis reveals the pathways for methanation of propionate facilitated by magnetite. *Water Res.* 108, 212-221.
- Kato, S., Hashimoto, K., and Watanabe, K. (2012). Methanogenesis facilitated by electric syntrophy via (semi)conductive iron-oxide minerals. *Environ. Microbiol.* 14, 1646-1654.
- Lee, J., Lee, S., and Park, H. (2016). Enrichment of specific electro-active microorganisms and enhancement of methane production by adding granular activated carbon in anaerobic reactors. *Bioresour. Technol.* 205, 205-212.
- Lei, Y., Sun, D., Dang, Y., Chen, H., Zhao, Z., Zhang, Y., and Holmes, D.E. (2016). Stimulation of methanogenesis in anaerobic digesters treating leachate from a municipal solid waste incineration plant with carbon cloth. *Bioresour. Technol.* 222, 270-276.
- Lei, Y., Sun, D., Dang, Y., Feng, X., Huo, D., Liu, C., Zheng, K., and Holmes, D.E. (2019). Metagenomic analysis reveals that activated carbon aids anaerobic digestion of raw incineration leachate by promoting direct interspecies electron transfer. *Water Res.* 161, 570-580.
- Lei, Y., Wei, L., Liu, T., Xiao, Y., Dang, Y., Sun, D., and Holmes, D.E. (2018). Magnetite enhances anaerobic digestion and methanogenesis of fresh leachate from a municipal solid waste incineration plant. *Chem. Eng. J.* 348, 992-999.
- Li, H., Chang, J., Liu, P., Fu, L., Ding, D., and Lu, Y. (2015a). Direct interspecies electron transfer accelerates syntrophic oxidation of butyrate in paddy soil enrichments. *Environ. Microbiol.* 17, 1533-1547.
- Li, L., Tong, Z., Fang, C., Chu, J., and Yu, H. (2015b). Response of anaerobic granular sludge to single-wall carbon nanotube exposure. *Water Res.* 70, 1-8.
- Li, Q., Xu, M., Wang, G., Chen, R., Qiao, W., and Wang, X. (2018). Biochar assisted thermophilic co-digestion of food waste and waste activated sludge under high feedstock to seed sludge ratio in batch experiment. *Bioresour. Technol.* 249,

1009-1016.

- Lim, E.Y., Tian, H., Chen, Y., Ni, K., Zhang, J., and Tong, Y.W. (2020). Methanogenic pathway and microbial succession during start-up and stabilization of thermophilic food waste anaerobic digestion with biochar. *Bioresour. Technol.* *314*, 123751.
- Lin, L., Chowdhury, B., Zakaria, B.S., and Dhar, B.R. (2020). Temperature-dependent (20–55 °C) electrocatalytic characteristics during ethanol/propionate degradation by methanogenic communities grown on conductive carbon fibers. *Chem. Eng. J* *391*, 123566.
- Lin, R., Cheng, J., Ding, L., and Murphy, J.D. (2018). Improved efficiency of anaerobic digestion through direct interspecies electron transfer at mesophilic and thermophilic temperature ranges. *Chem. Eng. J* *350*, 681-691.
- Lin, R., Cheng, J., Zhang, J., Zhou, J., Cen, K., and Murphy, J.D. (2017). Boosting biomethane yield and production rate with graphene: The potential of direct interspecies electron transfer in anaerobic digestion. *Bioresour. Technol.* *239*, 345-352.
- Liu, J., Liu, T., Chen, S., Yu, H., Zhang, Y., and Quan, X. (2020). Enhancing anaerobic digestion in anaerobic integrated floating fixed-film activated sludge (An-IFFAS) system using novel electron mediator suspended biofilm carriers. *Water Res.* *175*, 115697.
- Luo, C., Lu, F., Shao, L., and He, P. (2015). Application of eco-compatible biochar in anaerobic digestion to relieve acid stress and promote the selective colonization of functional microbes. *Water Res.* *68*, 710-718.
- Ma, J., Wei, H., Su, Y., Gu, W., Wang, B., and Xie, B. (2020a). Powdered activated carbon facilitates methane productivity of anaerobic co-digestion via acidification alleviating: Microbial and metabolic insights. *Bioresour. Technol.* *313*, 123706.
- Ma, W., Li, H., Zhang, W., Shen, C., Wang, L., Li, Y., Li, Q., and Wang, Y. (2020b). TiO<sub>2</sub> nanoparticles accelerate methanogenesis in mangrove wetlands sediment.

Sci. Total Environ. 713, 136602.

- Mei, R., Nobu, M.K., Narihiro, T., Yu, J., Sathyagal, A., Willman, E., and Liu, W. (2018). Novel Geobacter species and diverse methanogens contribute to enhanced methane production in media-added methanogenic reactors. Water Res. 147, 403-412.
- Mostafa, A., Im, S., Song, Y.C., Kang, S., and Kim, D.H. (2020). Enhanced Anaerobic Digestion of Long Chain Fatty Acid by Adding Magnetite and Carbon Nanotubes. Microorganisms 8.
- Mumme J, Srocke F, Heeg K, Werner M. (2014) Use of biochars in anaerobic digestion. Bioresour. Technol. 164, 189-197.
- Park, J., Park, J., Je Seong, H., Sul, W.J., Jin, K., and Park, H. (2018). Metagenomic insight into methanogenic reactors promoting direct interspecies electron transfer via granular activated carbon. Bioresour. Technol. 259, 414-422.
- Ren, S., Usman, M., Tsang, D., O-Thong, S., Angelidaki, I., Zhu, X., Zhang, S., and Luo, G. (2020). Hydrochar-Facilitated Anaerobic Digestion: Evidence for Direct Interspecies Electron Transfer Mediated through Surface Oxygen-Containing Functional Groups. Environ. Sci. Technol. 54, 5755-5766.
- Rotaru, A.E., Calabrese, F., Stryhanyuk, H., Musat, F., Shrestha, P.M., Weber, H.S., Snoeyenbos-West, O., Hall, P., Richnow, H.H., and Musat, N., *et al.* (2018). Conductive Particles Enable Syntrophic Acetate Oxidation between Geobacter and Methanosarcina from Coastal Sediments. mBIO 9.
- Shen, N., Liang, Z., Chen, Y., Song, H., and Wan, J. (2020). Enhancement of syntrophic acetate oxidation pathway via single walled carbon nanotubes addition under high acetate concentration and thermophilic condition. Bioresour. Technol. 306, 123182.
- Shen, Y., Linville, J.L., Ignacio-de Leon, P.A.A., Schoene, R.P., and Urgun-Demirtas, M. (2016). Towards a sustainable paradigm of waste-to-energy process: Enhanced anaerobic digestion of sludge with woody biochar. J Clean. Prod. 135, 1054-1064.

- Sun, W., Fu, S., Zhu, R., Wang, Z., Zou, H., and Zheng, Y. (2020). Improved anaerobic digestion efficiency of high-solid sewage sludge by enhanced direct interspecies electron transfer with activated carbon mediator. *Bioresour. Technol.* *313*, 123648.
- Tan, J., Wang, J., Xue, J., Liu, S., Peng, S., Ma, D., Chen, T., and Yue, Z. (2015). Methane production and microbial community analysis in the goethite facilitated anaerobic reactors using algal biomass. *Fuel* *145*, 196-201.
- Tian, T., Qiao, S., Li, X., Zhang, M., and Zhou, J. (2017). Nano-graphene induced positive effects on methanogenesis in anaerobic digestion. *Bioresour. Technol.* *224*, 41-47.
- Usman, M., Hao, S., Chen, H., Ren, S., Tsang, D.C.W., O-Thong, S., Luo, G., and Zhang, S. (2019). Molecular and microbial insights towards understanding the anaerobic digestion of the wastewater from hydrothermal liquefaction of sewage sludge facilitated by granular activated carbon (GAC). *Environ. Int.* *133*, 105257.
- Wang, C., Liu, Y., Gao, X., Chen, H., Xu, X., and Zhu, L. (2018a). Role of biochar in the granulation of anaerobic sludge and improvement of electron transfer characteristics. *Bioresour. Technol.* *268*, 28-35.
- Wang, C., Qiao, W., Chen, H., Xu, X., and Zhu, L. (2019a). A short-term stimulation of ethanol enhances the effect of magnetite on anaerobic digestion. *Appl. Microbiol. Biotechnol.* *103*, 1511-1522.
- Wang, C., Wang, C., Jin, L., Lu, D., Chen, H., Zhu, W., Xu, X., and Zhu, L. (2019b). Response of syntrophic aggregates to the magnetite loss in continuous anaerobic bioreactor. *Water Res.* *164*, 114925.
- Wang, C., Wang, C., Liu, J., Han, Z., Xu, Q., Xu, X., and Zhu, L. (2020a). Role of magnetite in methanogenic degradation of different substances. *Bioresour. Technol.* *314*, 123720.
- Wang, C., Wang, C., Liu, J., Xu, Q., Han, Z., Xu, X., and Zhu, L. (2020b). Tolerance of Aceticlastic Methanogenesis Enhanced by Magnetite under the Condition of

- Ammonia Stress. ACS Sustain. Chem. Eng. 8, 1417-1426.
- Wang, D., Ai, J., Shen, F., Yang, G., Zhang, Y., Deng, S., Zhang, J., Zeng, Y., and Song, C. (2017). Improving anaerobic digestion of easy-acidification substrates by promoting buffering capacity using biochar derived from vermicompost. Bioresour. Technol. 227, 286-296.
- Wang, D., Han, Y., Han, H., Li, K., Xu, C., and Zhuang, H. (2018b). New insights into enhanced anaerobic degradation of Fischer-Tropsch wastewater with the assistance of magnetite. Bioresour. Technol. 257, 147-156.
- Wang, G., Gao, X., Li, Q., Zhao, H., Liu, Y., Wang, X.C., and Chen, R. (2020c). Redox-based electron exchange capacity of biowaste-derived biochar accelerates syntrophic phenol oxidation for methanogenesis via direct interspecies electron transfer. J Hazard. Mater. 390, 121726.
- Wang, G., Li, Q., Gao, X., and Wang, X.C. (2018c). Synergetic promotion of syntrophic methane production from anaerobic digestion of complex organic wastes by biochar: Performance and associated mechanisms. Bioresour. Technol. 250, 812-820.
- Wang, P., Peng, H., Adhikari, S., Higgins, B., Roy, P., Dai, W., and Shi, X. (2020d). Enhancement of biogas production from wastewater sludge via anaerobic digestion assisted with biochar amendment. Bioresour. Technol. 309, 123368.
- Xia, X., Zhang, J., Song, T., and Lu, Y. (2019). Stimulation of *Smithella*-dominating propionate oxidation in a sediment enrichment by magnetite and carbon nanotubes. Environ. Microbiol. Rep. 11, 236-248.
- Xing, L., Wang, Z., Gu, M., Yin, Q., and Wu, G. (2020). Coupled effects of ferroferric oxide supplement and ethanol co-metabolism on the methanogenic oxidation of propionate. Sci. Total Environ. 723, 137992.
- Xu, H., Wang, C., Yan, K., Wu, J., Zuo, J., and Wang, K. (2016). Anaerobic granule-based biofilms formation reduces propionate accumulation under high H<sub>2</sub> partial pressure using conductive carbon felt particles. Bioresour. Technol. 216, 677-683.

- Xu, S., Han, R., Zhang, Y., He, C., and Liu, H. (2018). Differentiated stimulating effects of activated carbon on methanogenic degradation of acetate, propionate and butyrate. *Waste Manage.* *76*, 394-403.
- Xu, S., He, C., Luo, L., Lü, F., He, P., and Cui, L. (2015). Comparing activated carbon of different particle sizes on enhancing methane generation in upflow anaerobic digester. *Bioresour. Technol.* *196*, 606-612.
- Yamada, C., Kato, S., Ueno, Y., Ishii, M., and Igarashi, Y. (2015). Conductive iron oxides accelerate thermophilic methanogenesis from acetate and propionate. *J Biosci. Bioeng.* *119*, 678-682.
- Yan, W., Mukherjee, M., and Zhou, Y. (2020). Direct interspecies electron transfer (DIET) can be suppressed under ammonia-stressed condition – Reevaluate the role of conductive materials. *Water Res.* *183*, 116094.
- Yan, W., Shen, N., Xiao, Y., Chen, Y., Sun, F., Kumar Tyagi, V., and Zhou, Y. (2017). The role of conductive materials in the start-up period of thermophilic anaerobic system. *Bioresour. Technol.* *239*, 336-344.
- Yan, W., Sun, F., Liu, J., and Zhou, Y. (2018). Enhanced anaerobic phenol degradation by conductive materials via EPS and microbial community alteration. *Chem. Eng. J* *352*, 1-9.
- Yang, L., Si, B., Zhang, Y., Watson, J., Stablein, M., Chen, J., Zhang, Y., Zhou, X., and Chu, H. (2020). Continuous treatment of hydrothermal liquefaction wastewater in an anaerobic biofilm reactor: Potential role of granular activated carbon. *J Clean. Prod.* *276*, 122836.
- Yang, Y., Zhang, Y., Li, Z., Zhao, Z., Quan, X., and Zhao, Z. (2017). Adding granular activated carbon into anaerobic sludge digestion to promote methane production and sludge decomposition. *J Clean. Prod.* *149*, 1101-1108.
- Yang, Z., Guo, R., Shi, X., Wang, C., Wang, L., and Dai, M. (2016). Magnetite nanoparticles enable a rapid conversion of volatile fatty acids to methane. *RSC Adv.* *6*, 25662-25668.
- Yang, Z., Xu, X., Guo, R., Fan, X., and Zhao, X. (2015). Accelerated methanogenesis

- from effluents of hydrogen-producing stage in anaerobic digestion by mixed cultures enriched with acetate and nano-sized magnetite particles. *Bioresour. Technol.* *190*, 132-139.
- Yin, Q., He, K., Liu, A., and Wu, G. (2017a). Enhanced system performance by dosing ferroferric oxide during the anaerobic treatment of tryptone-based high-strength wastewater. *Appl. Microbiol. Biotechnol.* *101*, 3929-3939.
- Yin, Q., Miao, J., Li, B., and Wu, G. (2017b). Enhancing electron transfer by ferroferric oxide during the anaerobic treatment of synthetic wastewater with mixed organic carbon. *Int. Biodeter. Biodegr.* *119*, 104-110.
- Yin, Q., Yang, S., Wang, Z., Xing, L., and Wu, G. (2018). Clarifying electron transfer and metagenomic analysis of microbial community in the methane production process with the addition of ferroferric oxide. *Chem. Eng. J* *333*, 216-225.
- Zhang, F., Qian, D.K., Wang, X.B., Dai, K., Wang, T., Zhang, W., and Zeng, R.J. (2020a). Stimulation of methane production from benzoate with addition of carbon materials. *Sci. Total Environ.* *723*, 138080.
- Zhang, J., Mao, L., Zhang, L., Loh, K.C., Dai, Y., and Tong, Y.W. (2017a). Metagenomic insight into the microbial networks and metabolic mechanism in anaerobic digesters for food waste by incorporating activated carbon. *Sci. Rep.* *7*, 11293.
- Zhang, J., and Lu, Y. (2016). Conductive Fe<sub>3</sub>O<sub>4</sub> Nanoparticles Accelerate Syntrophic Methane Production from Butyrate Oxidation in Two Different Lake Sediments. *Front. Microbiol.* *7*, 1316.
- Zhang, L., Zhang, J., and Loh, K. (2018a). Activated carbon enhanced anaerobic digestion of food waste – Laboratory-scale and Pilot-scale operation. *Waste Manage.* *75*, 270-279.
- Zhang, S., Chang, J., Lin, C., Pan, Y., Cui, K., Zhang, X., Liang, P., and Huang, X. (2017b). Enhancement of methanogenesis via direct interspecies electron transfer between Geobacteraceae and Methanosaetaceae conducted by granular activated carbon. *Bioresour. Technol.* *245*, 132-137.

- Zhang, W., Zhang, J., and Lu, Y. (2018b). Stimulation of carbon nanomaterials on syntrophic oxidation of butyrate in sediment enrichments and a defined coculture. *Sci. Rep.* *8*, 12185.
- Zhang, Y., Guo, B., Zhang, L., and Liu, Y. (2020b). Key syntrophic partnerships identified in a granular activated carbon amended UASB treating municipal sewage under low temperature conditions. *Bioresour. Technol.* *312*, 123556.
- Zhang, Y., Zhang, L., Guo, B., Zhou, Y., Gao, M., Sharaf, A., and Liu, Y. (2020c). Granular activated carbon stimulated microbial physiological changes for enhanced anaerobic digestion of municipal sewage. *Chem. Eng. J* *400*, 125838.
- Zhao, Z., Li, Y., Quan, X., and Zhang, Y. (2017a). New Application of Ethanol-Type Fermentation: Stimulating Methanogenic Communities with Ethanol to Perform Direct Interspecies Electron Transfer. *ACS Sustain. Chem. Eng.* *5*, 9441-9453.
- Zhao, Z., Zhang, Y., Holmes, D.E., Dang, Y., Woodard, T.L., Nevin, K.P., and Lovley, D.R. (2016a). Potential enhancement of direct interspecies electron transfer for syntrophic metabolism of propionate and butyrate with biochar in up-flow anaerobic sludge blanket reactors. *Bioresour. Technol.* *209*, 148-156.
- Zhao, Z., Zhang, Y., Li, Y., Dang, Y., Zhu, T., and Quan, X. (2017b). Potentially shifting from interspecies hydrogen transfer to direct interspecies electron transfer for syntrophic metabolism to resist acidic impact with conductive carbon cloth. *Chem. Eng. J* *313*, 10-18.
- Zhao, Z., Zhang, Y., Woodard, T.L., Nevin, K.P., and Lovley, D.R. (2015). Enhancing syntrophic metabolism in up-flow anaerobic sludge blanket reactors with conductive carbon materials. *Bioresour. Technol.* *191*, 140-145.
- Zhao, Z., Zhang, Y., Yu, Q., Dang, Y., Li, Y., and Quan, X. (2016b). Communities stimulated with ethanol to perform direct interspecies electron transfer for syntrophic metabolism of propionate and butyrate. *Water Res.* *102*, 475-484.
- Zhao, Z., and Zhang, Y. (2019). Application of ethanol-type fermentation in establishment of direct interspecies electron transfer: A practical engineering case study. *Renew. Energ.* *136*, 846-855.

- Zhu, M., Peng, S., Tao, W., Wang, J., Tang, T., Chen, T., and Yue, Z. (2017). Response of methane production and microbial community to the enrichment of soluble microbial products in goethite-dosed anaerobic reactors. *Fuel* *191*, 495-499.
- Zhu, Y., Zhao, Z., and Zhang, Y. (2019). Using straw as a bio-ethanol source to promote anaerobic digestion of waste activated sludge. *Bioresour. Technol.* *286*, 121388.
- Zhuang, L., Ma, J., Yu, Z., Wang, Y., and Tang, J. (2018). Magnetite accelerates syntrophic acetate oxidation in methanogenic systems with high ammonia concentrations. *Microp. Biotechnol.* *11*, 710-720.
- Zhuang, L., Tang, J., Wang, Y., Hu, M., and Zhou, S. (2015a). Conductive iron oxide minerals accelerate syntrophic cooperation in methanogenic benzoate degradation. *J Hazard. Mater.* *293*, 37-45.
- Zhuang, L., Xu, J., Tang, J., and Zhou, S. (2015b). Effect of ferrihydrite biomineralization on methanogenesis in an anaerobic incubation from paddy soil. *J Geophys. Res.* *120*, 876-886.