Biochar Promotes Methane Production During Anaerobic Digestion of Organic Waste

Leilei Xiao
Yantai Institute of Coastal Zone Research for Sustainable Development: Yantai Institute of Coastal Zone Research
Eric Lichtfouse (eric.lichtfouse@inra.fr)
Aix-Marseille University https://orcid.org/0000-0002-8535-8073
Senthil Kumar
Sri Sivasubramaniya Nadar College of Engineering
Quan Wang
Yantai Institute of Coastal Zone Research for Sustainable Development: Yantai Institute of Coastal Zone Research
Fanghua Liu
Yantai Institute of Coastal Zone Research for Sustainable Development: Yantai Institute of Coastal Zone Research

---

Research Article

Keywords: anaerobic digestion, biochar, biomethane, meta-analysis

Posted Date: March 18th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-298852/v1

Version of Record: A version of this preprint was published on May 8th, 2021. See the published version at https://doi.org/10.1007/s10311-021-01251-6.

Abstract

Climate change and energy demand are calling more sustainable fuels such as biomethane produced by anaerobic digestion of organic waste. Biochar addition to waste is presumed to enhance the efficiency of methane production, yet individual reports disclose contradictory results. Therefore, we performed a meta-analysis of 27 selected publications containing 156 paired measurements of control and biochar-amended treatments to assess the impact of biochar on methanogenic performance. Results show that biochar promotes biomethane production substantially with a high Hedge's *d* value of 5.7 ± 1.04, yet sporadic publications report a methane decline. Methanogenic performance is statistically controlled by feedstock type, pyrolysis temperature and biochar concentration, but not controlled by pH, size, surface area and methanogen species. Our findings should help to tune the parameters of anaerobic digestion with biochar to optimize biomethane productions.

1. Introduction

Global warming and the rising energy demand is calling for an increase of circular processes where waste is recycled into materials and energy. Biomethane is a carbon-neutral, sustainable fuel produced by anaerobic fermentation of organic matter in natural and anthropic environments, yet the efficiency of actual processes is limited (Chen et al., 2018; Gao et al., 2020; Garcia-Mancha et al., 2017). Strategies have been recently developed to improve anaerobic fermentation by microbial immobilization, pH buffering and enzymatic induction (Gao et al., 2020; Xiao et al., 2020a). Anaerobic degradation and biomethane production are also promoted by electromethanogenesis using electroactive microorganisms and conductive materials such as biochar (Fig. 1, Li et al., 2018; Xiao et al., 2020b; Yuan et al., 2018). Recent research has also focused on the use of nanomaterials to favor methanogenesis (Ma et al., 2020; Xiao et al., 2018; Xiao et al., 2019c).

Biochar is carbon negative and comprises a wide variety of complex materials produced by pyrolysis of biomass (Glaser et al., 2009, Wang and Wang, 2019, Gunarathne et al., 2019, Karthick et al., 2020). Biochar has been applied to reduce nutrient leaching from soils, to recover resources from water, to accelerate waste disposal and for biomethane production (Lorenz and Lal, 2014, Fagbohungbe et al., 2017; Masebinu et al., 2019; Qiu et al., 2019, Yang et al., 2020). Biochar properties and molecular composition vary widely with the nature of the feedstock and pyrolysis conditions (Keiluweit et al., 2010, Gao et al., 2020). Several biochar properties have been proposed to favor biomethane production, e.g. microbial immobilization and pH buffering capacity, by providing control metal ion availability and enzymatic processes (Yuan et al., 2018, Xiao et al., 2019b, Gao et al., 2020; He et al., 2020). Overall, mechanisms fostering methanation by biochar are better understood but individual studies report sometimes contradictory results, e.g. rising or declining biomethane production (Cheng et al., 2018; Luo et al., 2015; Shen et al., 2016). Therefore we report here a meta-analysis in order to clarify the impact of biochar properties on methanogenesis during anaerobic digestion of environmental waste.

2. Experimental

2.1 Biochar data

We found 105 publications in the Web of Science and Microsoft's Bing search engine for documents on biochar application to methane production during anaerobic digestion (AD) for treating environmental waste and pollution, excluding soil related research, from 1 January 2010 to 15 June 2020, using the keywords “biochar” AND “methane” OR “CH_4”. We extracted the following variables: feedstock, pyrolysis temperature, pH, size, surface area, conductivity and methanogen species on methanogenic performance. Variable means, standard deviations and sample replicates number were extracted from publication tables and text. When data were only reported in image format in graphs, data points were extracted using Plot Digitizer 2.6.8 and Web Plot Digitizer. When relevant data was not present in publications, corresponding authors were contacted to get the data. We first considered the highest rate of methane production, but, if not available, we used the highest yield of methane. When accurate maximum rate of methane production or yield could not be obtained due to too much fluctuation of methane concentrations, publications were excluded from this study.

From this initial pool, we selected only documents reporting three or more replicates for each run, and we found 19 publications containing 105 data pairs of treatment data versus control data (Table S1). Control is defined as runs without biochar. We used the Hedges method, rather than the response ratio, because this method is adapted to data samples of relatively small size (Jeffery et al., 2016; Larry and Ingram, 1985). Therefore, a minimum of two replicates can meet the analysis standard. Consequently, data on biomethane production were collected from 27 articles containing 156 paired measurements of control and biochar-amended treatments for disposal of environmental waste and pollution (Table S1).

Biochar variables were grouped to facilitate cross-comparisons, e.g. the nature of biochar feedstock was grouped as either wood and sawdust, herbaceous and lignocellulosic waste, manure, or sludges (Table S1). Similarly, pyrolysis temperatures were grouped as below 500°C, or 500–700°C, or above 700°C. Conductivities were grouped as either below 450 µS/cm or above 450 µS/cm. Biochar pH were grouped into acidic below 7, weakly alkaline from 7 to 9, and alkaline above 9. Sizes were grouped below or above 1 mm. Brunauer, Emmett and Teller (BET) surface areas were grouped below or above 100 $m^2\ g^{-1}$. Biochar concentrations were grouped in below, equal to and above 10 $g\cdot dm^{-3}$. Two types of methanogenic archaea were considered: acetoclastic methanogen and hydrogenotrophic methanogen.

2.2 Meta-analysis

We used the standardized mean difference metric Hedge's *d* in Eq. 1, which induces less biases that the Hedge's *g* factor in Eq. 2 (Larry and Ingram, 1985):

$$d = \left(1 - \frac{3}{4(n-2)-1}\right) g \qquad \text{Equation 1}$$

$$g = \frac{\bar{x}_1 - \bar{x}_2}{S_p} \qquad \text{Equation 2}$$

$$S_p = \sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{(n_1-1)+(n_2-1)}} \qquad \text{Equation 3}$$

where *n* denotes the total sample size, $\bar{x}_1$ and $\bar{x}_2$ depict the means of experimental and control treatments. Experimental data refers to the treatment with biochar, whereas control data refers to the treatment without biochar. A categorical random effect model was applied to *d*, with means weighted by the inverse of the variance. Here S_p is the pooled standard deviation in Eq. 3, where n_1 and n_2 are the number of repetitions in the control and experimental groups, and s_1 and s_2 depict the standard deviations of control and experimental groups.

Contrary to the response ratio commonly used in ecological research the standardized mean effect sizes are probabilistic (Hedges et al., 1999; Larry and Ingram, 1985). That is, the mean effect sizes describe the probability that a sample would fall between the experimental mean and the control mean, assuming a normal distribution (Hedges et al., 1999). Consequently, confidence intervals of 95% were generated based on a normal distribution. When the 95% confidence interval of the parameter does not overlap with Hedge's *d* of 0, this implies that the variable promotes biomethane production, which suggests the promotion of anaerobic digestion for environmental waste and pollution. When the 95% confidence interval of a biochar parameter does not overlap with that of another variable, there is a statistically significant difference.

By convention, for variables that do not overlap with the Hedge's *g* of 0, a *d* value higher than 0.8 indicates a large effect, *d* of 0.2–0.8 shows a moderate effect, and *d* of 0.0-0.2 displays a small effect (Hedges et al., 1999; Jeffery et al., 2016). A key point is that, using the Hedge's *d* metric, an effect size of a variable analysis does not equate to an effect size of others in independent analyses presented in this study. As a consequence, only categories within individual analyses, e. g. feedstocks, as differentiated by the horizontal dotted bars, can be compared relatively. The effect sizes do not mean that the extent of the actual biomethane production increase or decrease. Small effect sizes may indicate significant value in biomethane production in absolute terms. For instance,in small effect sizes, the actual biomethane parameter may be several times larger than that of the large effect sizes.

3. Results And Discussion

3.1 Overall effect of biochar addition

We assessed the global effect of biochar addition on anaerobic methanogenesis by calculating the grand mean of the Hedge's *d* for 156 published data pairs of treatment versus control (Fig. 2). Results show a *d* value of 5.70 ± 1.04, which evidences a large effect size and implies that the presence of biochar statistically induces an increase in biomethane in most investigations. Yet sporadic studies have also shown the inhibitory effect of biochar or no effect (Cheng et al., 2018; Shen et al., 2016). This discrepancy is probably due to the high heterogeneous nature of biochar (Diao et al., 2020; Gao and Goldfarb, 2019), suggesting that biomethane production may be enhanced by specific biochar properties, as discussed below.

3.2 Effect of biochar feedstock

We calculated *d* values of feedstock including sludges, manure, herbaceous and lignocellulosic waste, and wood and sawdust (Fig. 2). All feedstock types show high *d* values from 4.71 ± 1.72 to 7.99 ± 1.51, implying that biochar addition improves biomethane generation whatever the type of feedstock. Furthermore, there is no statistical difference within feedstock types, sludges displaying the highest *d* of 7.99. Manure, plant waste and woody materials appear equally competitive with Hedge's *d* values around 5.0. Results on sludges are supported by the fact that sludge biochar provides more nutrients for fermentative bacteria and methanogens (Wang et al., 2020). Biochar from sludge has also induced significant effects on pollutant removal and heavy metal adsorption (Diao et al., 2020; Regkouzas and Diamadopoulos, 2019; Singh et al., 2020), which may be explained by a more favorable living environment for microorganisms. Overall, the slight advantage of sludge biochar in terms of methanogenesis is likely due to its ability to adsorb and store nutrients for activating methanogens. We conclude that biochar improves methanogenesis for all biochar feedstocks, but there is no statistical advantage of the feedstock type.

3.3 Effect of pyrolysis temperature

We calculated *d* values of biochar produced by pyrolysis below 500°C, of 6.72 ± 1.86, between 500 and 700°C, of 6.40 ± 1.11, and above 700°C, of 0.840 ± 1.50 (Fig. 2). Results imply that biochar favors biomethane generation below 700°C. There is no significant difference between 500–700°C-produced biochar and biochar produced below 500°C. On the other hand, pyrolysis above 700°C induces a drastic decline of biomethane promotion. These findings may be explained by changes of molecular structure with temperature (Hao et al., 2018). Indeed, Keiluweit et al. (2010) observed a gradual change in the molecular structure of plant biomass-derived biochar with temperature. High-temperature biochar is characterized by fewer labile compounds at the surface of biochar particles, and therefore less microbial substrates for fermentative bacteria and methanogenic archaea (Bruun et al., 2011). This explanation is strengthened by the declining CH_4 and N_2O emissions from soils amended with high-temperature biochar, which are thus better suited for mitigation of greenhouse gas emissions (Cayuela et al., 2015). By contract, slow pyrolysis at low temperature yields more biochar with diverse chemical groups (Chen et al., 2019; Sohi et al., 2010), which are likely to promote biomethane production in anaerobic digester or emission from soils (Jeffery et al., 2016). Overall, our findings show that biochar produced below 700°C improves methanogenesis. Pyrolysis at lower temperature will also save energy.

3.4 Effect of biochar conductivity

Biochars having low conductivity, below 450 µS/cm, show a much higher *d* value, of 7.58 ± 1.79, than high-conductivity biochar, displaying a d value of 2.06 ± 1.29 (Fig. 2). Low conductivity biochar is therefore statistically more effective at accelerating biomethane production. This finding is unexpected because recent research suggests that biochar acts as an electron shuttle, which should favor microbial activity (Viggi et al., 2017; Xiao et al., 2019b; Yuan et al., 2018). Nonetheless, a recent report shows that electrical conductivity of biochar is controlling only the rate of anaerobic degradation, not the yield of biogas (Rasapoor et al., 2020). Conductivity does not appear as a precise factor to choose which biochar is beneficial for the degradation of environmental waste, and some studies suggest that attributing rising biomethane production to high material conductivity requires caution (Martins et al., 2018; Van Steendam et al., 2019). Overall, our findings show that low conductivity biochar favors methanogensis, yet underlying mechanisms are unclear.

3.5 Effect of biochar pH

Figure 2 displays the effect of biochar of different pH on biomethane production. Results show that varying the biochar pH induces no statistical difference in biomethane production, despite the fact that pH is known to modify fermentation rates (Begum et al., 2018; Feng et al., 2020; Mao et al., 2017). Yet, most investigations included in this meta-analysis did not report the pH of the system before and after biochar application, though pH is expected to vary widely because some biochar contain oxygen-containing organic anions and carbonates that increase alkalinity (Fidel et al., 2017; Yuan et al., 2011). Overall, varying the pH of biochar does not statistically improve methanogenesis.

3.6 Effect of surface area and biochar size

Values of *d* for biochar with BET surface area above 100 m^2/g, of 5.06 ± 1.83, are not statistically different from those of biochar with surface area below 100 m^2/g, of 4.45 ± 1.06 (Fig. 2). Similarly, the size to biochar particles does not appear to modify biomethane generation, yet a trend for higher *d* value is observed for particle size below 1 mm. This implies that smaller particles of biochar may be beneficial to the degradation of environmental waste. For instance, the addition of powdered biochar to a pig manure/wheat straw aerobic compost increased biomethane emissions by 57%, whereas granular biochar decreased biomethane emissions by 22% (He et al., 2018). On the contrary, other investigations have shown that large biochar particles promote methanogenesis (Cheng et al., 2018; Viggi et al., 2017). Overall, there is not a clear global effect of surface area and size on anaerobic degradation of waste and pollutant and biomethane production.

3.7 Effect of biochar concentration

Biochar concentration caused a strong and statistically significant difference in the strength of biomethane production, with a maximal impact for concentrations exceeding 10 g/L and a *d* value of 7.87 ± 0.35 (Fig. 2). Increasing biochar concentration is therefore a means to improve methanogenesis, which may further result in a promotion of waste degradation. This finding is supported by biochar properties that are likely to stabilize anaerobic digestion and rise biomethane yield (Gao et al., 2020; Lim et al., 2020). For instance, providing immobilization sites for microorganisms could explain the higher anaerobic degradation and methanogenic performance (Zhang et al., 2018; Zhang and Wang, 2020). Moreover, even though biochar itself is not a substantial source of labile carbon, biochar is a sponge-like material able to adsorb and store organo-mineral nutrients for further microbial feeding (Cross and Sohi, 2011; Demisie et al., 2014). In this line, elevated biochar concentrations have been shown to increase the availability of organic carbon for fermentation bacteria and methanogenic archaea (Zhang et al., 2020). Based on this, environmental waste and pollution can be degraded more easily. Overall, high biochar concentrations foster methanogenesis, yet underlying mechanisms remain undeciphered.

3.8 Methanogenic species

Values of *d* for acetoclastic methanogens, of 5.19 ± 2.06, and hydrogenetrophic methanogens, of 3.08 ± 1.4, are not statistically different, implying a similar contribution to biomethane production (Fig. 3). Both acetoclastic and hydrogenetrophic methanogens produce more biomethane following biochar addition. This finding is strenghtened by an investigation revealing that *Methanosarcina*, *Methanosaeta* and *Methanobacterium* methanogens predominate in paddy soil-amended biochar during the anaerobic decomposition of rice straw (Huang et al., 2020). Trophic methanogens, hydrogenetrophic and acetoclastic methanogens may actively participate in the methane production process. Indeed, reports have shown that methanogens that use acetate and hydrogen as substrates coexist in the anaerobic fermentation system (Madigou et al., 2019; Zhang et al., 2019). Compared to hydrogenetrophic methanogens, acetoclastic methanogens should contribute more to methane production with sufficient organic substrates (Garcia-Mancha et al., 2017; Lim et al., 2020; Xiao et al., 2019a). Overall, biochar addition improves biomethane production by methanogens, yet acetoclastic and hydrogenetrophic methanogens display similar performances.

4. Concusion

Our findings show that, on the average, biochar addition is favoring biomethane generation, whereas this was not clear in previous individual reports. Our identification of biochar properties that favor or do not favor methanogenesis will be helpful for basic research to decipher underlying mechanisms, and for applied research to improve biomethane production as a sustainable fuel and benefit perfection of environmental waste and pollution control measures. Last, the fact that biochar globally promotes biomethane generation in anaerobic media is casting some doubt on the use of biochar to sequester carbon in soils. Indeed, our findings suggests that soils amended with biochar may accelerate methane emissions in the atmosphere, notably in anaerobic soils where fermentation of organic matter and pollution takes place, thus counteracting the sequestrating effect of biochar.

Declarations

Acknowledgements

This research was financially supported by the National Natural Science Foundation of China (no. 42077025).

Author contributions

LX and EL designed the research. LX and ZL collected the data. LX, EL, SK, ZL, FL analyzed the data. LX and EL wrote the article.

Notes

Authors declare no competing financial interest

References

1. Begum S, Anupoju G, Sridhar S, Bhargava S, Jegatheesan V, Eshtiaghi N (2018) Evaluation of single and two stage anaerobic digestion of landfill leachate: Effect of pH and initial organic loading rate on volatile fatty acid (VFA) and biogas production. Bioresour. Technol 251:364-373.
2. Bruun E, Hauggaard-Nielsen H, Ibrahim N, Egsgaard H, Ambus P, Jensen P, Dam-Johansen K (2011) Influence of fast pyrolysis temperature on biochar labile fraction and short-term carbon loss in a loamy soil. Biomass Bioenergy 35:1182-1189.
3. Cayuela M, Jeffery S, van Zwieten L (2015) The molar H:Corg ratio of biochar is a key factor in mitigating N_2O emissions from soil. Agr Ecosyst Environ 202:135-138.
4. Chen R, Jiang H, Li Y (2018) Caffeine degradation by methanogenesis: Efficiency in anaerobic membrane bioreactor and analysis of kinetic behavior. Chem. Eng. J 334:444-452.
5. Chen W, Wei R, Yang L, Yang Y, Li G, Ni J (2019) Characteristics of wood-derived biochars produced at different temperatures before and after deashing: Their different potential advantages in environmental applications. Sci. Total Environ 651:2762-2771.
6. Cheng Q, de los Reyes F, Call D (2018) Amending anaerobic bioreactors with pyrogenic carbonaceous materials: the influence of material properties on methane generation. Environ Sci-Wat Res 4:1794-1806.
7. Cross A, Sohi S (2011) The priming potential of biochar products in relation to labile carbon contents and soil organic matter status. Soil Biol Biochem 43:2127-2134.
8. Demisie W, Liu Z, Zhang M (2014) Effect of biochar on carbon fractions and enzyme activity of red soil. Catena 121:214-221.
9. Diao Z, Dong F, Yan L, Chen Z, Qian W, Kong L, Zhang Z, Zhang T, Tao X, Du J, Jiang D, Chu W (2020) Synergistic oxidation of bisphenol A in a heterogeneous ultrasound-enhanced sludge biochar catalyst/persulfate process: Reactivity and mechanism. J. Hazard. Mater 384, 121385.
10. Fagbohungbe M, Herbert B, Hurst L, Ibeto C, Li H, Usmani S, Semple K (2017) The challenges of anaerobic digestion and the role of biochar in optimizing anaerobic digestion. Waste Manage 61:236-249.

11. Feng K, Wang Q, Li H, Zhang Y, Deng Z, Liu J, Du X (2020) Effect of fermentation type regulation using alkaline addition on two-phase anaerobic digestion of food waste at different organic load rates. Renew Energ 154:385-393.
12. Fidel R, Laird D, Thompson M, Lawrinenko M (2017) Characterization and quantification of biochar alkalinity. Chemosphere 167:367-373.
13. Gao L, Goldfarb J (2019) Heterogeneous biochars from agriculture residues and coal fly ash for the removal of heavy metals from coking wastewater. RSC Adv 9:16018-16027.
14. Gao M, Zhang L, Liu Y (2020) High -loading food waste and blackwater anaerobic co -digestion: Maximizing bioenergy recovery. Chem. Eng. J 394, 124911.
15. Garcia-Mancha N, Monsalvo V, Puyol D, Rodriguez J, Mohedano A (2017) Enhanced anaerobic degradability of highly polluted pesticides-bearing wastewater under thermophilic conditions. J. Hazard. Mater 339:320-329.
16. Glaser B, Parr M, Braun C, Kopolo G (2009) Biochar is carbon negative. *Nature Geosci* **2:** 2.
17. Gunarathne V, Ashiq A, Ramanayaka S, Wijekoon P, Vithanage M (2019) Biochar from municipal solid waste for resource recovery and pollution remediation. Environ Chem Lett 17, 1225–1235.
18. Hao S, Zhu X, Liu, Y, Qian F, Fang Z, Shi Q, Zhang S, Chen J, Ren Z (2018) Production Temperature Effects on the Structure of Hydrochar-Derived Dissolved Organic Matter and Associated Toxicity. Environ. Sci. Technol 52:7486-7495.
19. He P, Zhang H, Duan H, Shao L, Lu F (2020) Continuity of biochar-associated biofilm in anaerobic digestion. Chem. Eng. J 390, 124605.
20. He X, Yin H, Sun X, Han L, Huang G (2018) Effect of different particle-size biochar on methane emissions during pig manure/wheat straw aerobic composting: Insights into pore characterization and microbial mechanisms. Bioresour. Technol 268:633-637.
21. Hedges L, Gurevitch J, Curtis P (1999) The meta-analysis of response ratios in experimental ecology. Ecology 80:1150-1156.
22. Huang J, Ma K, Xia X, Gao K, Lu Y (2020) Biochar and magnetite promote methanogenesis during anaerobic decomposition of rice straw. Soil Biol. Biochem 143, 107740.
23. Jeffery S, Verheijen F, Kammann C, Abalos D (2016) Biochar effects on methane emissions from soils: A meta-analysis. Soil Biol. Biochem 101:251-258.
24. Karthik V, Kumar PS, Vo DVN, Sindhu J, Sneka D, Subhashini B, Saravanan K, Jeyanthi J (2020). Hydrothermal production of algal biochar for environmental and fertilizer applications: a review. Environ Chem Lett (2020).
25. Keiluweit M, Nico P, Johnson M, Kleber M (2010) Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar). Environ. Sci. Technol 44:1247-1253.
26. Larry H, Ingram O. Statistical Methods for Meta-analysis (1985) In Academic Press: New York 20: 369.

27. Li J, Xiao L, Zheng S, Zhang Y, Luo M, Tong C, Xu H, Tan Y, Liu J, Wang O, Liu F (2018) A new insight into the strategy for methane production affected by conductive carbon cloth in wetland soil: Beneficial to acetoclastic methanogenesis instead of CO_2 reduction. Sci. Total Environ 643:1024-1030.
28. Lim E, Tian H, Chen Y, Ni K, Zhang J, Tong Y (2020) Methanogenic pathway and microbial succession during start-up and stabilization of thermophilic food waste anaerobic digestion with biochar. Bioresour. Technol 314, 123751.
29. Lorentz K, Lal R (2014) Biochar application to soil for climate change mitigation by soil organic carbon sequestration. J Plant Nutr Soil Sci 177: 651-670.
30. Luo C, Lu F, Shao L, He P (2015) Application of eco-compatible biochar in anaerobic digestion to relieve acid stress and promote the selective colonization of functional microbes (vol 68, pg 710, 2014). Water Res 70:496-496.
31. Ma W, Li H, Zhang W, Shen C, Wang L, Li Y, Li Q, Wang Y (2020) TiO_2 nanoparticles accelerate methanogenesis in mangrove wetlands sediment. Sci. Total Environ 713, 136602.
32. Madigou C, Le Cao K, Bureau C, Mazeas L, Dejean S, Chapleur O (2019) Ecological consequences of abrupt temperature changes in anaerobic digesters. Chem. Eng. J 361:266-277.
33. Mao C, Zhang T, Wang X, Feng Y, Ren G, Yang G (2017) Process performance and methane production optimizing of anaerobic co-digestion of swine manure and corn straw. Sci Rep-Uk 7: 9379.
34. Martins G, Salvador A, Pereira L, Alves M (2018) Methane Production and Conductive Materials: A Critical Review. Environ. Sci. Technol 2:10241-10253.
35. Masebinu S, Akinlabi E, Muzenda E, Aboyade A (2019) A review of biochar properties and their roles in mitigating challenges with anaerobic digestion. Renew Sust Energ Rev 103:291-307.
36. Qiu L, Deng Y, Wang F, Davaritouchaee M, Yao Y (2019) A review on biochar-mediated anaerobic digestion with enhanced methane recovery. Renew Sust Energ Rev 115, 109373.
37. Rasapoor M, Young B, Asadov A, Brar R, Sarmah A, Zhuang W, Baroutian S (2020) Effects of biochar and activated carbon on biogas generation: A thermogravimetric and chemical analysis approach. Energ Convers Manage 203, 112221.
38. Regkouzas P, Diamadopoulos E (2019) Adsorption of selected organic micro-pollutants on sewage sludge biochar. Chemosphere224:840-851.
39. Shen Y, Linville J, Ignacio-de Leon P, Schoene R, 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.
40. Singh S, Kumar V, Dhanjal D, Datta S, Bhatia D, Dhiman J, Samuel J, Prasad R, Singh J (2020) A sustainable paradigm of sewage sludge biochar: Valorization, opportunities, challenges and future prospects. J Clean Prod 269, 122259.

41. Sohi S, Krull E, Lopez-Capel E, Bol R (2010) A Review of Biochar and Its Use and Function in Soil. Adv Agron 105:47-82.
42. Tang S, Wang Z, Liu Z, Zhang Y, Si B (2020) The Role of Biochar to Enhance Anaerobic Digestion: A Review. J Renew Mater 8:1033-1052.
43. Van Steendam C, Smets I, Skerlos S, Raskin L (2019) Improving anaerobic digestion via direct interspecies electron transfer requires development of suitable characterization methods. Curr. Opin. Biotechnol 57:183-190.
44. Viggi C, Simonetti S, Palma E, Pagliaccia P, Braguglia C, Fazi S, Baronti S, Navarra M, Pettiti I, Koch C, Harnisch F, Aulenta F (2017) Enhancing methane production from food waste fermentate using biochar: the added value of electrochemical testing in pre-selecting the most effective type of biochar. Biotechnol. Biofuels 10:303.
45. Wang J, Wang S (2019) Preparation, modification and environmental application of biochar: A review. J Cleaner Prod 227, 1002-1022. https://doi.org/10.1016/j.jclepro.2019.04.282
46. Wang H, Xiao K, Yang J, Yu Z, Yu W, Xu Q, Wu Q, Liang S, Hu J, Hou H, Liu B (2020) Phosphorus recovery from the liquid phase of anaerobic digestate using biochar derived from iron-rich sludge: A potential phosphorus fertilizer. Water Res 174, 115629.
47. Xiao L, Zheng S, Lichtfouse E, Luo M, Tan Y, Liu F (2020a) Carbon nanotubes accelerate acetoclastic methanogenesis: From pure cultures to anaerobic soils. Soil Biol. Biochem 150, 107938.
48. Xiao L, Liu F, Lichtfouse E, Zhang P, Feng D, Li F (2020b) Methane production by acetate dismutation stimulated by Shewanella oneidensis and carbon materials: An alternative to classical CO_2 reduction. Chem. Eng. J 389, 124469.
49. Xiao L, Liu F, Liu J, Li J, Zhang Y, Yu J, Wang O (2018) Nano-Fe_3O_4 particles accelerating electromethanogenesis on an hour-long timescale in wetland soil. Environ Sci-Nano 5:436-445.
50. Xiao L, Liu F, Xu H, Feng D, Liu J, Han G (2019a) Biochar promotes methane production at high acetate concentrations in anaerobic soils. Environ. Chem. Lett 17:1347-1352.
51. Xiao L, Sun R, Zhang P, Zheng S, Tan Y, Li J, Zhang Y, Liu, F (2019b) Simultaneous intensification of direct acetate cleavage and CO_2 reduction to generate methane by bioaugmentation and increased electron transfer. Chem. Eng. J 378, 122229.
52. Xiao L, Wei W, Luo M, Xu H, Feng D, Yu J, Huang J, Liu F (2019c) A potential contribution of a Fe(III)-rich red clay horizon to methane release: Biogenetic magnetite-mediated methanogenesis. Catena 181, 104081.
53. Yang H, Ye S, Zeng Z, Zeng G, Tan X, Xiao R, Wang J, Song B, Du L, Qin M, Yang Y, Xu F (2020) Utilization of biochar for resource recovery from water: A review. Chem. Eng. J 397, 125502.
54. Yuan H, Ding L, Zama E, Liu P, Hozzein W, Zhu Y (2018) Biochar Modulates Methanogenesis through Electron Syntrophy of Microorganisms with Ethanol as a Substrate. Environ. Sci. Technol 52:12198-12207.

55. Yuan J, Xu R, Zhang H (2011) The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresour. Technol 102:3488-3497.
56. Zhang J, Zhao W, Zhang H, Wang Z, Fan, C, Zang L (2018) Recent achievements in enhancing anaerobic digestion with carbon-based functional materials. Bioresour. Technol. 266:555-567.
57. Zhang L, Lim E, Loh K, Ok Y, Lee J, Shen Y, Wang C, Dai Y, Tong Y (2020) Biochar enhanced thermophilic anaerobic digestion of food waste: Focusing on biochar particle size, microbial community analysis and pilot-scale application. Energ. Convers. Manag. 209, 112654.
58. Zhang L, Loh K, Zhang J (2019) Jointly reducing antibiotic resistance genes and improving methane yield in anaerobic digestion of chicken manure by feedstock microwave pretreatment and activated carbon supplementation. Chem. Eng. J 372:815-824.
59. Zhang M, Wang Y (2020) Effects of Fe-Mn-modified biochar addition on anaerobic digestion of sewage sludge: Biomethane production, heavy metal speciation and performance stability. Bioresour. Technol. 313, 123695.

Figures

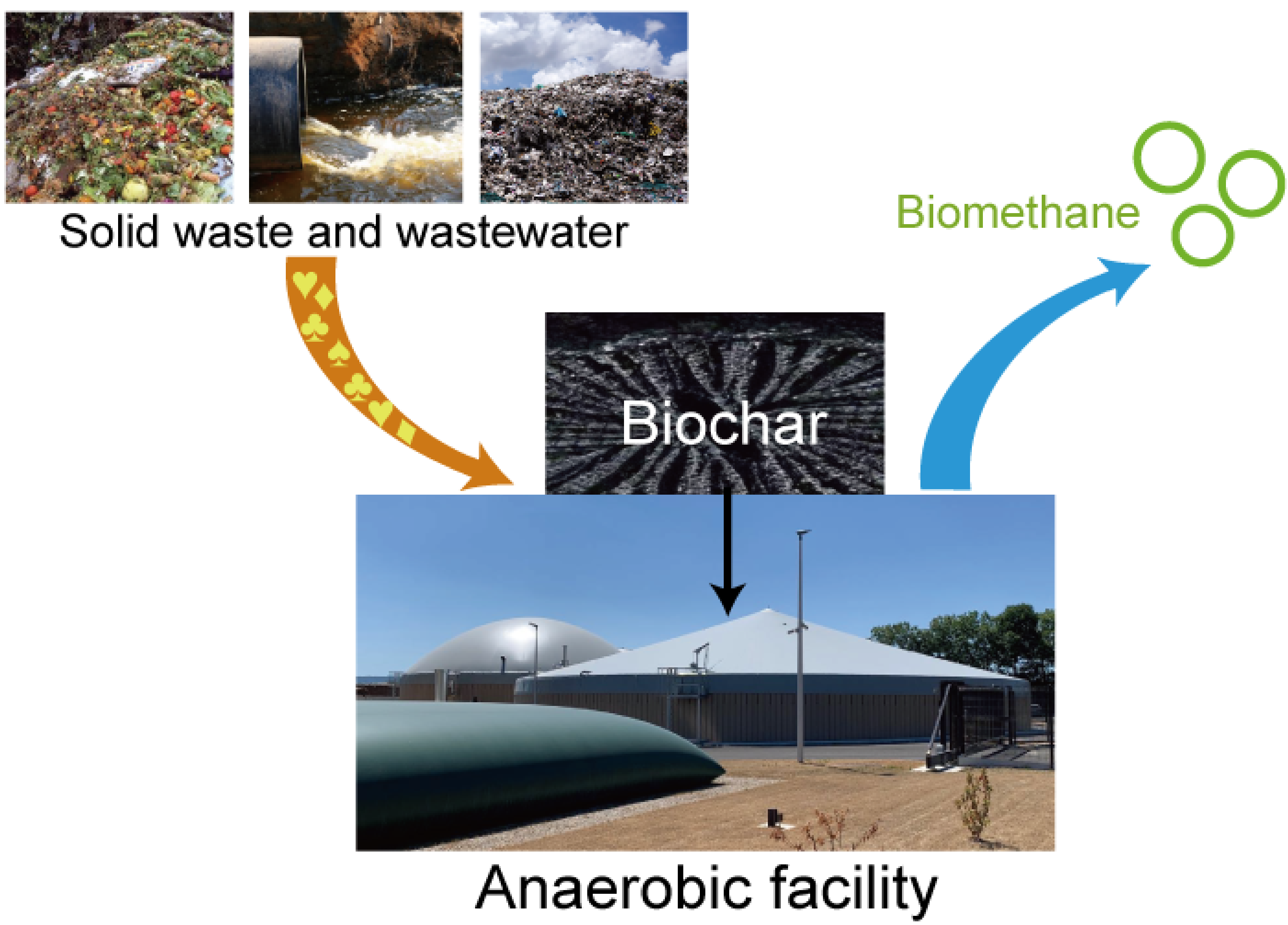

Figure 1

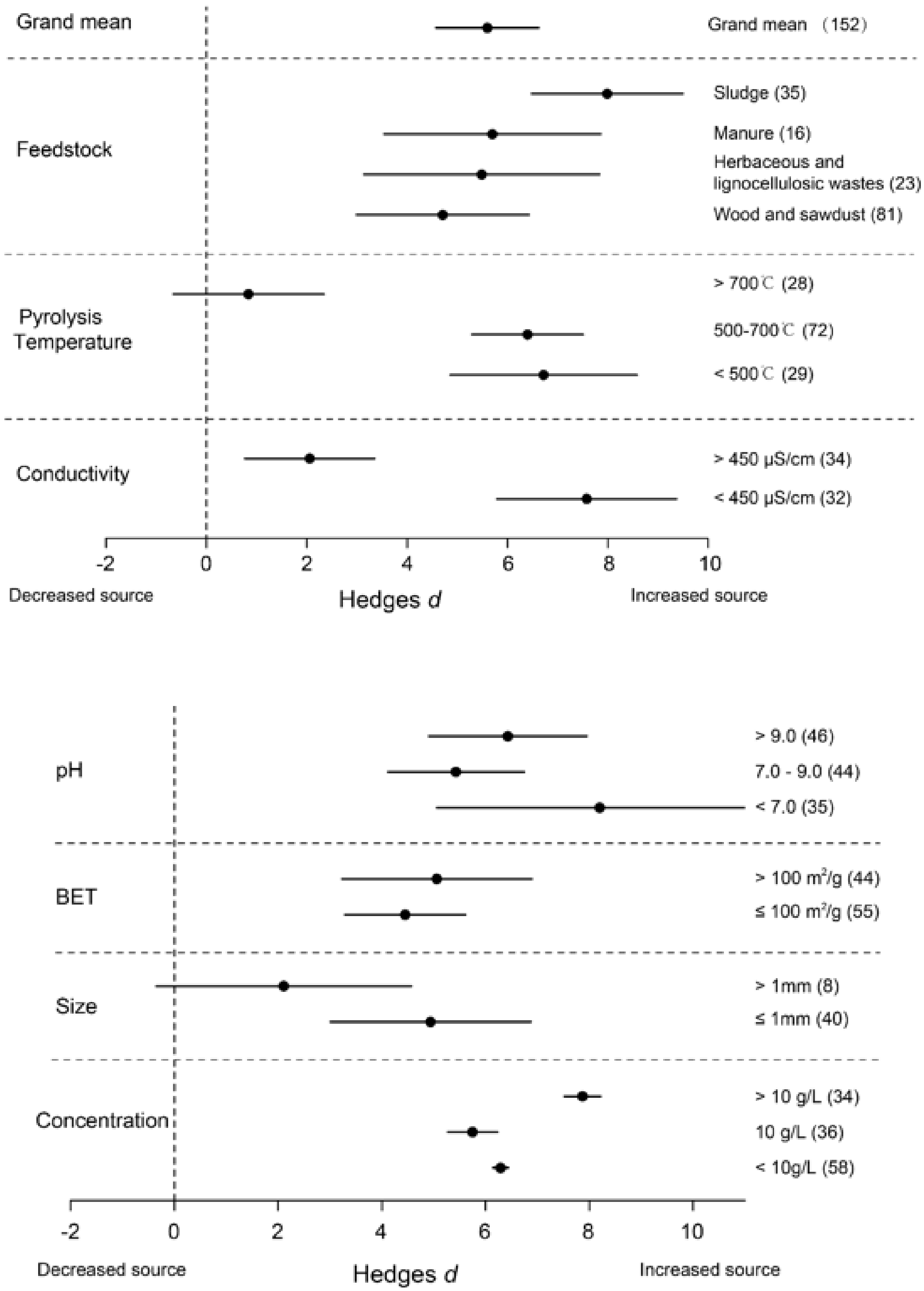

Figure 2

Forest plot of Hedge's d calculated from published literature (Table S1). Top: grouping by feedstock, pyrolysis temperature and conductivity of biochar. Bottom: grouping by biochar concentration, size, BET surface area and pH. Points show means, bars show 95% confidence intervals. The numbers in parentheses indicate the number of pairwise comparisons of treatment with biochar versus control without biochar. BET: Brunauer, Emmett and Teller.

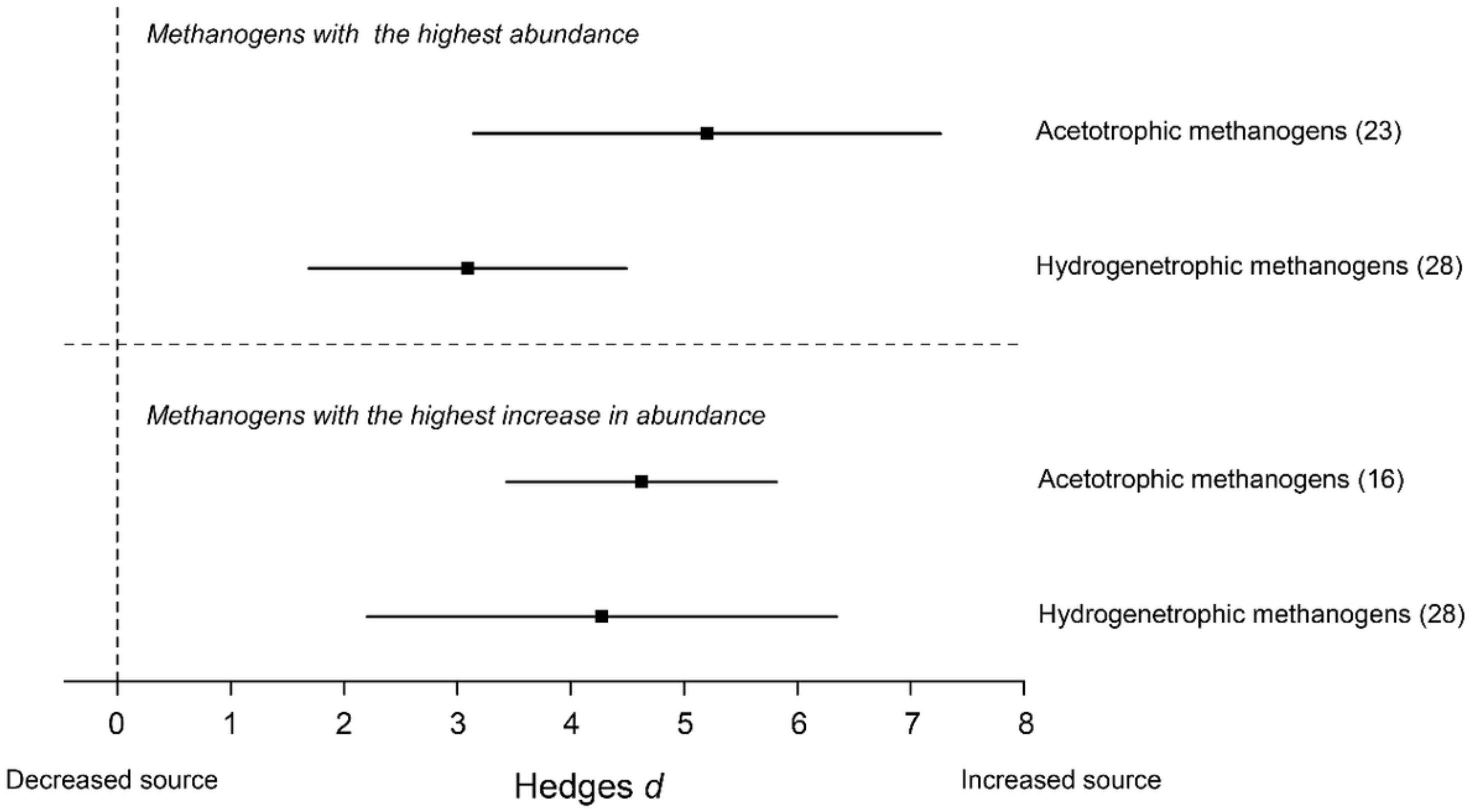

Figure 3

Forest plot of Hedge's d calculated from published literature grouped by Methanogens with the highest abundance and Methanogens with the highest increase in abundance. Points show means, bars show 95% confidence intervals. The numbers in parentheses indicate the number of pairwise comparisons on which the statistic is based. 'Methanogens with the highest abundance' means that the highest abundance of methanogens in samples. That is to say, which kind of methanogens have the highest abundance. "Methanogens with the highest increase in abundance' means which methanogens have the most changes in abundance, or the greatest increase.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SM.docx