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BIOSTIMULANTS FOR ENHANCING METHANOGENIC ACTIVITY IN ANAEROBIC DIGESTION: A REVIEW

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Abstract

Anaerobic digestion is limited by the low activity of methanogenic archaea, which depend on metal cofactors, rapid syntrophic electron transfer and the absence of inhibitors. This narrative review compares six classes of additives (biostimulants): trace elements, conductive materials, nanomaterials, organic compounds, hydrolytic enzymes and mineral carriers. They are compared by the limitation each targets, mechanism, reported effect and main caution. Trace elements are best supported for deficient substrates, whereas conductive materials act mainly through direct interspecies electron transfer, with widely varying effects. The main gaps are speciation-based dosing, dissolved-ion controls, pilot-scale tests and comparable reporting.

Keywords: anaerobic digestion; methanogenic archaea; biostimulants; trace elements; biogas

Annotatsiya

Anaerob hazm qilish metanogen arxeylarning past faolligi bilan cheklanadi: ular metall kofaktorlarga, tez sintrof elektron almashinuviga va ingibitorlarning yo‘qligiga bog‘liq. Ushbu sharhda metanogenez faolligini oshiruvchi oltita qo‘shimcha sinfi (biostimulyatorlar) taqqoslanadi: mikroelementlar, o‘tkazuvchan materiallar, nanomateriallar, organik birikmalar, gidrolitik fermentlar va mineral tashuvchilar. Taqqoslash ular bartaraf etadigan cheklov, ta’sir mexanizmi, ma’lum samaradorlik va asosiy ehtiyot choralari bo‘yicha o‘tkazildi. Mikroelementlar tanqis substratlar uchun eng yaxshi asoslangan; o‘tkazuvchan materiallar asosan to‘g‘ridan-to‘g‘ri turlararo elektron uzatish orqali ta’sir qiladi, natijalari esa keng farq qiladi. Asosiy bo‘shliqlar: shakllanish shakliga asoslangan dozalash, erigan ion nazoratlari, pilot miqyosdagi sinovlar va solishtirish mumkin bo‘lgan hisobot.

Kalit so‘zlar: anaerob hazm qilish; metanogen arxeylar; biostimulyatorlar; mikroelementlar; biogaz

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Аннотация

Анаэробное сбраживание ограничивается низкой активностью метаногенных архей, которые зависят от металлических кофакторов, быстрого синтрофного переноса электронов и отсутствия ингибиторов. В обзоре сравниваются шесть классов добавок (биостимуляторов): микроэлементы, проводящие материалы, наноматериалы, органические соединения, гидролитические ферменты и минеральные носители. Сравнение проведено по ограничению, на которое направлено действие, механизму, описанному эффекту и основным предостережениям. Микроэлементы наиболее обоснованы для дефицитных субстратов, тогда как проводящие материалы действуют главным образом через прямой межвидовой перенос электронов, причём эффекты сильно различаются. Основные пробелы: дозирование с учётом форм металлов, контроли с растворёнными ионами, пилотные испытания и сопоставимая отчётность.

Ключевые слова: анаэробное сбраживание; метаногенные археи; биостимуляторы; микроэлементы; биогаз

1. Introduction

Anaerobic digestion (AD) converts organic wastes into biogas and a nutrient-rich digestate, but low methane yield and process instability still limit its wider application, and inhibitory substances are a primary cause of digester upset or failure [1]. Methane is formed in the last step of the process by methanogenic archaea, whose energy metabolism is restricted to a narrow set of substrates such as CO_2 with H_2, formate and methyl compounds [2]. Methanogens are therefore the rate-limiting and most fragile link in many digesters.

Their activity depends on metalloenzymes. Methanogenic archaea require large amounts of Fe, Ni and Co, and some Mo/W and Zn, and low bioavailability of Fe, Ni and Co limits methanogenesis in pure cultures, mixed cultures and environmental studies [3]. Supplementing these elements is one of the best-studied ways to restore methanogenic activity [4]. Over the past decade, other additives have been proposed to act on different limitations: conductive materials that connect syntrophic partners, nanomaterials, organic compounds, hydrolytic enzymes and mineral carriers [5–8].

In the anaerobic digestion literature these substances are usually called *additives*. In this review the term *biostimulant* is used operationally for any non-substrate material added to raise the activity of the methanogenic consortium, either directly (for example by supplying cofactor metals) or indirectly (for example by relieving syntrophic,

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inhibitory or nutritional limitations). This working definition is broader than the agricultural one, and it also covers cases where an additive does not stimulate at all: humic substances, for instance, have been reported to both promote and inhibit different stages of digestion [9].

Existing reviews tend to treat one additive class at a time, such as trace elements [4], conductive materials [6,7] or nanomaterials [8]. That makes it difficult to see which class addresses which limitation, and where evidence conflicts. This review therefore:

1. summarises the biochemical and process limitations that biostimulants are meant to relieve;
2. compares six classes of biostimulants by mechanism, reported effect and limitations;
3. identifies contradictions, dosing and bioavailability problems, and research gaps that currently block scale-up.

2. Review Methodology

This is a narrative review. Its search was not systematic and a PRISMA-guided database search was not performed; targeted web-based searches were run for each additive class in November 2026, peer-reviewed review articles were preferred, primary studies were used when a specific result was needed, and 25 sources were included.

Because dose units, substrates and inocula differ widely between studies, effect sizes were compared qualitatively and no pooled estimate was calculated. Several numerical results are taken from compilations in other reviews rather than from the original studies, and the text says so where this applies.

Generative AI (Claude, Anthropic) was used to support literature searching, to draft and edit the text, and to prepare Figure 1. The author checked all sources and statements against the original publications and takes full responsibility for the content.

3. Methanogenesis and the Limitations That Biostimulants Target

Three kinds of limitation recur in the literature: energetic and syntrophic constraints, shortage of metal cofactors, and inhibition. Each class of biostimulant discussed in Section 4 is aimed at one or more of them.

3.1. Energy Conservation and Syntrophy

Most methanogens can reduce CO_2 with H_2 to methane, but they do not all conserve energy in the same way. Methanogens with cytochromes couple the first and last steps

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of CO_2 reduction chemiosmotically, whereas those without cytochromes couple them through a cytoplasmic complex that performs flavin-based electron bifurcation. These differences affect growth yield, ATP gain and the H_2 threshold, and explain why methanogens without cytochromes generally out-compete those with cytochromes at low H_2 concentrations [2]. In a digester, low H_2 concentration is maintained by syntrophic partners. When electron exchange between fatty-acid-oxidising bacteria and methanogens is slow, volatile fatty acids (VFAs) accumulate and methane formation falls. This is the target of the conductive materials discussed in Section 4.2.

3.2. Metal Cofactor Requirements

Fe, Ni and Co are required in large amounts by methanogens, with Mo/W and Zn needed in smaller amounts, because the enzymes of all three methanogenic pathways contain these metals [3]. Their availability, not their total concentration, controls activity. In sulfidic digesters, metals can be scavenged by sulfide, and optimal metal concentrations in pure cultures are far above those found in most natural waters [3]. This is the rationale for trace-element supplementation (Section 4.1).

3.3. Inhibition

Inhibitors commonly present in digesters include ammonia, sulfide, light metal ions, heavy metals and organic compounds, and the reported inhibitory levels vary widely because inocula, wastes and experimental conditions differ [1]. Ammonia is the most discussed case for nitrogen-rich wastes such as poultry manure and food waste [10,11]. The share of free ammonia in total ammonia nitrogen rises with pH and temperature, so thermophilic digesters are especially exposed [12]. Co-digestion, adaptation and removal of the toxicant are established countermeasures [1], and several additives (biochar, zeolite, trace elements) are used to extend them (Sections 4.2 and 4.5).

4. Classes of Biostimulants

Figure 1 shows which stage each class of biostimulant acts on; Sections 4.1 to 4.6 discuss them in turn.

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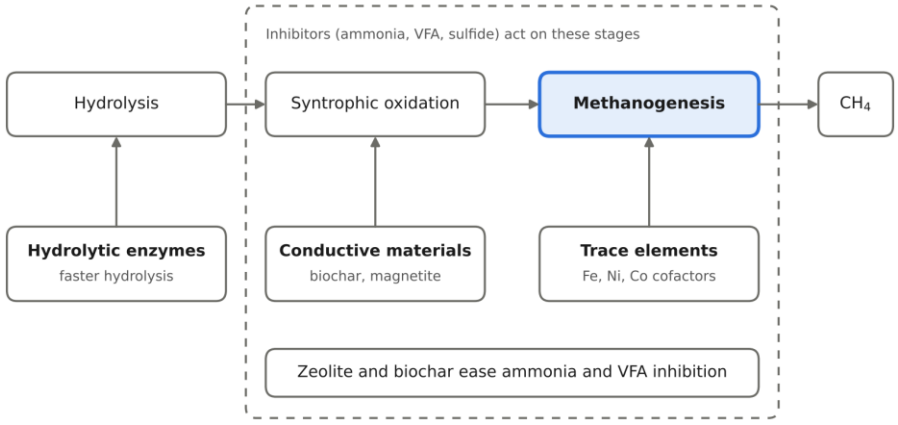

Figure 1. *Where the classes of biostimulants act. Enzymes act on hydrolysis, conductive materials on syntrophic electron transfer and trace elements on methanogenesis. Zeolite and biochar ease inhibition of the two later stages. Nanomaterials act through redox effects and released metals and so span the last two stages. VFA: volatile fatty acid.*

4.1. Trace Elements (Fe, Ni, Co, Mo, W, Se)

Trace-element supplementation is the most direct response to the cofactor requirement described in Section 3.2. A critical review of the field concluded that dosing at (sub)optimum levels mainly improves digester stability over the longer term, with greater organic-matter degradation, lower VFA concentrations and higher biogas production [4]. Fe, Ni and Co are the most studied and most desirable elements, a well-chosen multi-element mix can work better than a single element, and supplementation is especially recommended for mono-digestion of micronutrient-deficient substrates [4]. Studies on maize-silage-based substrates, which test Ni, Co and Mo and mixed trace-element supplements, are typical of this literature [14,15].

The main weakness is that the effects and requirements are explained case by case [4]. Added elements do not stay in one form: depending on pH, sulfur compounds and organic macromolecules they may be free ions, complexes or precipitates, and most studies report only total concentrations, which says little about bioavailability or toxicity [13]. Overdosing heavy metals can harm the microbial community and, through the digestate, the environment [13]. Dose, chemical form and dosing frequency are therefore the parameters that determine whether a trace-element addition counts as a biostimulant or as a pollutant.

4.2. Conductive Materials and Direct Interspecies Electron Transfer (DIET)

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Conductive materials act on the syntrophic limitation described in Section 3.1. Electrically conductive magnetite particles have been shown to carry electrons between two bacterial species that otherwise could not cooperate, although that experiment used *Geobacter* and *Thiobacillus* rather than a methanogenic consortium [16]. Interspecies electron transfer as an electric current through pili, or through conductive minerals and carbon particles, is now described as a general feature of syntrophic communities [17].

DIET is thermodynamically more favourable than transfer through H_2 or formate because it needs no redox mediators [6]. It can also work under high H_2 partial pressure, where H_2-based transfer is thermodynamically limited, and a model cited by Chen et al. gave a DIET electron-transfer rate 8.57 times that of interspecies H_2 transfer [18]. Bacteria that lack conductive pili can take part in DIET once a conductive material such as granular activated carbon, biochar, carbon cloth, carbon nanotubes, graphene or magnetite is added [18]. Besides DIET, conductive materials may act by immobilising microbes, buffering pH and adsorbing inhibitors [18].

Two families are used: carbon-based materials (activated carbon, biochar, carbon cloth and fibre, graphite, graphene, carbon nanotubes) and iron-based materials (magnetite and other iron oxides, zero-valent iron) [7]. The reported effects are consistent in direction but very different in size. Studies compiled by Kong and Zhang include a 23.5–47.1% higher maximum methane production rate with 10 g/L biochar in a glucose batch test, a 2.3-fold higher maximum rate and almost delay-free start-up with 2.5 g/L nano-magnetite on wastewater, and only a 6% methane increase with 1.5 g/L magnetite on glycerol [7]. Reviews on biochar report improved methane production and buffering, relief of ammonia and VFA inhibition, delayed VFA accumulation at high organic loading, and support for cell immobilisation [19,20]. Mild ammonia inhibition (up to 2.1 g total ammonia nitrogen per kg) was prevented by biochar in one study, whereas strong inhibition was not [5]. A critical review of conductive materials stresses that pilot-scale evidence is still missing and that material choice, dose, cost and effects on downstream processing must be evaluated [21].

4.3. Nanomaterials

The number of studies on nanomaterials in AD has grown exponentially in recent years. Reported benefits include higher biogas production, methane enrichment of the biogas, elimination of foaming, and more stable operation without inhibition problems [8]. Metallic and especially iron-based nanoparticles are the most frequently tested. The most accepted explanation is an effect on redox potential, but supplementation with trace metals released from the particles and changes in the microbial community have

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also been proposed [8]. Because dissolution supplies Fe, Ni or Co ions, a nanoparticle effect can only be attributed to nanoscale properties if a control with the same dose of dissolved ions is included. Batch biochemical methane potential (BMP) tests are a reasonable first approach, but continuous operation is needed to show that effects persist [8].

4.4. Organic Compounds

The evidence for organic biostimulants is much weaker and more conflicting than for the classes above. Humic substances are the clearest example. Depending on conditions they can positively or negatively affect hydrolysis, acidification and methanogenesis, for example by acting as surfactants or as electron acceptors [9]. Quinone-modified humic compounds at concentrations above 1 g/L lowered the energetic status of cells and the efficiency of methanogenesis, and they were studied as a way of *suppressing* methane from landfill-gas-producing consortia [22]. Humic substances therefore cannot be assumed to stimulate methanogens, and dose, redox state and origin must be reported. Vitamins (such as B12), algal extracts and amino acids were not supported by consolidated evidence in the sources reviewed here and are treated as research gaps (Section 6).

4.5. Hydrolytic Enzymes and Mineral Carriers

Two further groups are covered in additive reviews: enzymes added to speed up hydrolysis, and zeolite used for its cation-exchange properties and as a support for biomass immobilisation [5]. Enzymes act on the hydrolysis step and reach methanogens only indirectly, by supplying substrate faster. Zeolite has been tested on ammonium-rich wastes such as piggery waste [23] and sludge [24], and activated zeolite has been examined as a microbial carrier [25].

4.6. Comparison

Table 1 compares the six classes by the limitation each targets and by the main caution from the reviewed literature.

Table 1. *Biostimulant classes, the limitation each targets, and the main caution from the reviewed literature.*

Class	Examples	Limitation targeted	Main caution

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Trace elements	Fe, Ni, Co, Mo, W, Se salts	Cofactor shortage	Speciation, bioavailability and overdosing [4,13]
Carbon-based conductive materials	Biochar, activated carbon, carbon cloth, graphene	Syntrophic electron transfer; inhibition	Large variation in effect size; pilot data scarce [7,21]
Iron-based conductive materials	Magnetite, zero-valent iron	Syntrophic electron transfer; Fe supply	Effect ranged from 6% to 2.3-fold in compiled studies [7]
Nanomaterials	Fe, Ni, Co and oxide nanoparticles	Redox balance; cofactor supply	Mechanism unclear; ionic controls needed [8]
Organic compounds	Humic substances	Redox mediation	Can inhibit methanogenesis [9,22]
Enzymes	Cellulase, protease, amylase	Hydrolysis	Indirect effect on methanogens [5]
Mineral carriers	Zeolite	Ammonium inhibition; immobilisation	Evidence mainly from ammonium-rich wastes [5,23,24]

5. Process Factors and Scale-Up

The size of a biostimulant effect depends less on the additive than on the system it is added to, and this is the main reason results cannot yet be transferred between studies.

Substrate and inoculum. Reported inhibitory levels and responses differ with the waste, the inoculum and the experimental method [1]. Trace-element dosing mainly pays off on micronutrient-deficient substrates [4], whereas biochar and zeolite are most often justified for nitrogen-rich, inhibition-prone wastes [5,19]. An additive tested on one substrate should not be assumed to work on another.

Temperature. Free ammonia increases with temperature and pH, so thermophilic digesters are more exposed to ammonia inhibition [12]. Additives that relieve ammonia stress (Sections 4.2 and 4.5) may therefore matter more at 55 °C than at 35 °C, but most evidence in the reviewed sources comes from batch tests.

Batch versus continuous tests. Batch BMP tests are useful for first screening and kinetic data, but continuous operation is required to show persistence of an effect,

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accumulation of the additive and washout [8]. A review of conductive materials calls for pilot-scale trials that compare material choice, dose and cost [21].

Cost, digestate and downstream effects. Economic assessments are increasingly included in biochar reviews [20]. Added metals can end up in the digestate and create environmental risk [13], and conductive materials may affect downstream processing and the wider environment [18,21].

Reporting. Comparison across studies is hindered by inconsistent reporting. A minimum set of data would make future work comparable:

- substrate characteristics (total and volatile solids, C/N ratio, total ammonia nitrogen) and inoculum origin;
- inoculum-to-substrate ratio and temperature;
- dose in both g/L and mg/g volatile solids, and the chemical form of the additive;
- an unamended control and, for metals and nanomaterials, a dissolved-ion control;
- methane yield, maximum rate, lag phase, VFA and pH, with replicates and statistical tests;
- microbial data (for example 16S rRNA sequencing and *mcrA* gene abundance) linked to the performance data.

6. Discussion

6.1. Matching the Biostimulant to the Limitation

The classes in Table 1 are not interchangeable. Trace elements address a cofactor shortage [3,4], conductive materials a syntrophic bottleneck [6,18], zeolite and biochar an inhibition problem [5,19], and enzymes the hydrolysis step [5]. A digester that is limited by Ni or Co will gain little from magnetite, and one inhibited by ammonia may gain little from a trace-element mix. Choosing an additive without first diagnosing the limitation turns the test into trial and error. A diagnostic-first design, in which VFA profile, total ammonia nitrogen, trace-metal speciation and substrate composition are measured before the additive is selected, would make results easier to interpret.

6.2. Contradictions and Gaps

- **Variable effect size.** Magnetite produced a 6% methane increase in one compiled study and a 2.3-fold rate increase in another [7]. Substrate, dose and inoculum are confounded in these comparisons.

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- **Confounded mechanisms.** Conductive materials may act through DIET, buffering, adsorption or immobilisation [18], and nanomaterials through redox effects, released metals or community shifts [8]. Separating these effects requires dedicated controls, and the best-known demonstration of mineral-mediated electron transfer used a non-methanogenic pair [16].
- **Direction of effect.** Humic substances can promote or inhibit methanogenesis [9,22]. Dose and redox state decide the outcome, so they cannot be treated as a simple stimulant.
- **Bioavailability.** Total metal concentration is the usual dosing basis, although speciation controls availability and toxicity [13].
- **Scale and persistence.** Evidence from continuous and pilot-scale operation, with cost and digestate effects, is limited [8,21].
- **Untested classes.** Vitamins, algal extracts and amino acids lack consolidated evidence, and combinations of classes (for example a trace-element mix with a conductive material) should be compared with each class alone, since multi-element mixes can outperform single elements [4].

Future work should use factorial designs with dissolved-ion and unamended controls, report doses in comparable units, combine performance data with microbial data (16S rRNA and *mcrA*), and include continuous trials of at least several hydraulic retention times. Studies on regionally important substrates, such as cattle and poultry manure and agricultural residues in Central Asia, would test whether the conclusions above hold under new conditions.

6.3. Limitations of This Review

This is a narrative review of English-language sources found through targeted web-based searches, so coverage is not exhaustive and a systematic database search could change the balance of evidence. Effect sizes are compared qualitatively, because dose units, substrates and inocula differ too much for a pooled estimate. Some numerical results are quoted from compilations in other reviews rather than from the original studies, and are marked as such in the text.

7. Conclusions

Biostimulants raise methanogenic activity only when they match the limitation of the digester. Trace elements (Fe, Ni, Co) are the best-supported option for cofactor-deficient substrates, but their benefit depends on bioavailability and dose, not on total concentration. Conductive materials, especially biochar and magnetite, can accelerate

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syntrophic methanogenesis, yet reported effects range from a few per cent to more than a two-fold rate increase and the underlying mechanisms are often confounded. Nanomaterials, enzymes and zeolite address specific problems, and humic substances can inhibit methanogenesis rather than stimulate it.

Three steps would move the field forward: diagnosing the limiting factor before choosing an additive, reporting doses, chemical forms and controls in comparable units, and testing the most promising combinations in continuous and pilot-scale digesters with cost and digestate effects included.

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References

1. Chen, Y.; Cheng, J.J.; Creamer, K.S. Inhibition of anaerobic digestion process: A review. *Bioresour. Technol.* **2008**, *99*, 4044–4064. https://doi.org/10.1016/j.biortech.2007.01.057
2. Thauer, R.K.; Kaster, A.-K.; Seedorf, H.; Buckel, W.; Hedderich, R. Methanogenic archaea: Ecologically relevant differences in energy conservation. *Nat. Rev. Microbiol.* **2008**, *6*, 579–591. https://doi.org/10.1038/nrmicro1931
3. Glass, J.B.; Orphan, V.J. Trace metal requirements for microbial enzymes involved in the production and consumption of methane and nitrous oxide. *Front. Microbiol.* **2012**, *3*, 61. https://doi.org/10.3389/fmicb.2012.00061
4. Choong, Y.Y.; Norli, I.; Abdullah, A.Z.; Yhaya, M.F. Impacts of trace element supplementation on the performance of anaerobic digestion process: A critical review. *Bioresour. Technol.* **2016**, *209*, 369–379.
5. Paritosh, K.; Yadav, M.; Chawade, A.; Sahoo, D.; Kesharwani, N.; Pareek, N.; Vivekanand, V. Additives as a support structure for specific biochemical activity

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boosts in anaerobic digestion: A review. *Front. Energy Res.* **2020**, *8*, 88. https://doi.org/10.3389/fenrg.2020.00088

6. Baek, G.; Kim, J.; Kim, J.; Lee, C. Role and potential of direct interspecies electron transfer in anaerobic digestion. *Energies* **2018**, *11*, 107.
7. Kong, T.; Zhang, W. Enhanced anaerobic digestion using conductive materials through mediation of direct microbial interspecies electron transfer: A review. *Fermentation* **2023**, *9*, 884. https://doi.org/10.3390/fermentation9100884
8. Barrena, R.; Moral-Vico, J.; Font, X.; Sánchez, A. Enhancement of anaerobic digestion with nanomaterials: A mini review. *Energies* **2022**, *15*, 5087. https://doi.org/10.3390/en15145087
9. Long, S.; Yang, J.; Hao, Z.; Shi, Z.; Liu, X.; Xu, Q.; Wang, Y.; Wang, D.; Ni, B.-J. Multiple roles of humic substances in anaerobic digestion systems: A review. *J. Clean. Prod.* **2023**, *418*, 138066. https://doi.org/10.1016/j.jclepro.2023.138066
10. Rajagopal, R.; Massé, D.I.; Singh, G. A critical review on inhibition of anaerobic digestion process by excess ammonia. *Bioresour. Technol.* **2013**, *143*, 632–641.
11. Yenigün, O.; Demirel, B. Ammonia inhibition in anaerobic digestion: A review. *Process Biochem.* **2013**, *48*, 901–911.
12. James, A.; Shi, Y.; Hussain, S.S.; Guo, W.; Liu, Q.; et al. Mitigation of ammonia inhibition during anaerobic digestion: A comprehensive update. *Agric. Ecol. Environ.* **2025**, *1*, e012. https://doi.org/10.48130/aee-0025-0011
13. van Hullebusch, E.D.; Guibaud, G.; Simon, S.; et al. Methodological approaches for fractionation and speciation to estimate trace element bioavailability in engineered anaerobic digestion ecosystems: An overview. *Crit. Rev. Environ. Sci. Technol.* **2016**, *46*, 1324–1366.
14. Evranos, B.; Demirel, B. The impact of Ni, Co and Mo supplementation on methane yield from anaerobic mono-digestion of maize silage. *Environ. Technol.* **2015**, *36*, 1556–1562.
15. Pobeheim, H.; et al. Influence of trace elements on methane formation from a synthetic model substrate for maize silage. *Bioresour. Technol.* **2010**, *101*, 836–839.
16. Kato, S.; Hashimoto, K.; Watanabe, K. Microbial interspecies electron transfer via electric currents through conductive minerals. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 10042–10046. https://doi.org/10.1073/pnas.1117592109
17. Kouzuma, A.; Kato, S.; Watanabe, K. Microbial interspecies interactions: Recent findings in syntrophic consortia. *Front. Microbiol.* **2015**, *6*, 477. https://doi.org/10.3389/fmicb.2015.00477

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18. Chen, L.; Fang, W.; Chang, J.; Liang, J.; Zhang, P.; Zhang, G. Improvement of direct interspecies electron transfer via adding conductive materials in anaerobic digestion: Mechanisms, performances, and challenges. *Front. Microbiol.* **2022**, *13*, 860749. https://doi.org/10.3389/fmicb.2022.860749
19. Qiu, L.; Deng, Y.F.; Wang, F.; Davaritouchaee, M.; Yao, Y.Q. A review on biochar-mediated anaerobic digestion with enhanced methane recovery. *Renew. Sustain. Energy Rev.* **2019**, *115*, 109373. https://doi.org/10.1016/j.rser.2019.109373
20. Zhao, W.; Yang, H.; He, S.; Zhao, Q.; Wei, L. A review of biochar in anaerobic digestion to improve biogas production: Performances, mechanisms and economic assessments. *Bioresour. Technol.* **2021**, *341*.
21. Nguyen, L.N.; et al. Promotion of direct interspecies electron transfer and potential impact of conductive materials in anaerobic digestion and its downstream processing—A critical review. *Bioresour. Technol.* **2021**, *341*, 125847.
22. Efremenko, E.; Senko, O.; Stepanov, N.; Mareev, N.; Volikov, A.; Perminova, I. Suppression of methane generation during methanogenesis by chemically modified humic compounds. *Antioxidants* **2020**, *9*, 1140. https://doi.org/10.3390/antiox9111140
23. Milán, Z.; Sánchez, E.; Weiland, P.; Borja, R.; Martín, A.; Ilangovan, K. Influence of different natural zeolite concentrations on the anaerobic digestion of piggery waste. *Bioresour. Technol.* **2001**, *80*, 37–43.
24. Tada, C.; Yang, Y.; Hanaoka, T.; Sonoda, A.; Ooi, K.; Sawayama, S. Effect of natural zeolite on methane production for anaerobic digestion of ammonium rich organic sludge. *Bioresour. Technol.* **2005**, *96*, 459–464.
25. Weiß, S.; Lebuhn, M.; Andrade, D.; Zankel, A.; Cardinale, M.; Birner-Grünberger, R.; Somitsch, W.; Guebitz, G.M. Activated zeolite—suitable carriers for microorganisms in anaerobic digestion processes? *Appl. Microbiol. Biotechnol.* **2013**, *97*, 3225–3238.