Enhancing anaerobic digestion through the integration of microbial electrolysis cells: A comprehensive review

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Abstract
Anaerobic digestion is a great approach in recovering sustainable bioenergy from complex organic matters. However, many constrains have limited the application of the digester, like systems instability and inhibition of methane producing microbes due to the accumulation of Volatile Fatty Acids (VFAs) causing system’s pH to drop drastically. Systems instability could be tackled by adding additives to improve the digester’s performance and integrating microbial electrolysis cell with the digester to provide system’s stability while maintaining high biogas production. Microbial community are the driving force in the conventional and hybrid system, altering the microbial community could improve the substrate degradation and selectivity of the biogas produced. This review discusses the microbial community in the anaerobic digester and hybrid system, in terms of the effect of inoculum source, biofilm and microbial suspension community, altering the microbial community for biogas production selectivity, effect of applied voltage and electrodes choice on the hybrid system. Ultimately, these findings hold the potential to benefit society by offering innovative solutions to enhance bioenergy production efficiency and addressing environmental challenges associated with organic waste management.

Keywords: Anaerobic digester; Carbon electrodes; MEC-AD hybrid system; Methanogenesis; Microbial community; Microbial electrolysis cell

Introduction
The biological treatment of organic feedstock has been rising in the past few years. While low strength waste is treated using aerobic digestion, anaerobic digestion has grabbed the attention to recover sustainable bioenergy from complex organic matters (plants, agriculture and animal residues, sludge biomass, etc.) [1]. In the anaerobic digestion (AD) process, the mesophilic and thermophilic methanogenic
microorganisms anaerobically break down complex organic matters with the production of a mixture of gases containing methane as the main constituent. While anaerobic digestion is a great approach for treating organic waste, many constraints limiting this application like the accumulation of volatile fatty acids (VFAs) causing system’s pH to drop drastically, leading to digester’s instability and inhibition of methane producing microbes. Many approaches have been employed to improve the performance of the microbes in the digester, like integrating the system with microbial electrolysis cell [2]. Integrating microbial electrolysis cell with the digester is reported to increase the VFA’s degradation, thus providing stability to the digester while maintaining high biogas production rate. It also has been investigated to improve biomethane recovery from high-strength waste/wastewater generated from various industries and municipal services (e.g., wastewater treatment, landfill operation, etc.) [3]. The digester could be integrated to the microbial electrolysis cell (MEC) system in two ways, either hydraulically connected to the MEC system externally, or by the direct insertion of electrodes into the digester [4]. Direct insertion of electrodes to the digester has been mostly and widely studied. The microbial community in the hybrid system is quite similar to those in the conventional digester in terms of fermentative bacteria and biomethane producing bacteria. However, the hybrid system offers a higher surface area for microbes to grow, in addition to electroactive microbes [5]. Electroactive microbes grow and create a biofilm on both anode and cathode offering a new pathway for biomethane production. A voltage potential is applied to the electrodes to initiate a reaction and to activate the electroactive microbes [6]. The microbial community in the hybrid system is quite similar to those in the conventional digester in terms of fermentative bacteria and biomethane producing bacteria. However, the hybrid system offers a higher surface area for microbes to grow, in addition to electroactive microbes, which not only offers a new biomethane production pathway, but also co-exists with fermentative bacteria and enhances the VFA’s degradation, hence reduce the accumulation and pH drop [7]. The microbial community is the driving force in the biogas production. Inoculum source highly affects the system’s performance, since it provides the initial microbial community for the substrate degradation, hence biogas production. Many methods of altering the microbial community have been successfully proven to increase the biogas selectivity and volume through the enrichment of certain microbial consortia [8]. Carbonic material has been proven to enhance microbial prefoliation and density [9]. In addition to increasing electrode’s biocompatibility. Although microbes are the main operator of the biomethane production system, up to our knowledge, minimal number of reviews have been focusing and reporting on the effect of additives and operational factors on the microbial consortia, while none has comprehensively explained the changes, shifts, and effects on the microbial community, hence the biogas production. This review discusses the microbial community in the anaerobic digester and hybrid system, in terms of the effect of inoculum source, biofilm and microbial suspension community, altering the microbial community for biogas production selectivity, effect of applied voltage and electrode’s choice on the hybrid system.

**Anaerobic digestion**

The biological conversion process is achieved by four steps: (1) hydrolysis of complex organic matter, (2) acidogenesis, (3) acetogenesis, and (4) methanogenesis [10]. During hydrolysis, complex organic matters are broken into their monomer constituents, next, during acidogenesis, facultative anaerobes such as Ruminococcus and Paenibacillus breaks soluble monomers into VFAs, alcohols and some gasses. During acetogenesis, Aminobacterium, Acidaminococcus, Desulfo-vibrio produces
acetic acids from monomers [11], followed by acetalactone and hydrogenotrophic methanogenesis utilizing the products to produce methane. (Fig. 1) shows the simplified scheme of pathways in anaerobic digestion.

**Microbial electrolysis cell and anaerobic digestion**

Recent studies demonstrated that integrating microbial electrolysis cell with anaerobic digester offers a great number of advantages in the system’s performance, stability, and methane production compared to conventional anaerobic digester [2, 12]. A few studies found that microbial electrolysis cell anaerobic digestion (MEC-AD) combined system provides better resistance to AD inhibitors, namely phenol and ammonia, high organic loading, and low operating temperatures [13, 14]. In addition, MEC-AD, can enhance process kinetics by stimulating another pathway for methane production through electro-methanogenesis along with the conventional pathways. Electro-methanogenesis is the most favourable pathway of methanogenesis, utilizing electrons from the cathode directly for carbon dioxide reduction to methane. Hence, improving the biogas production quality (Fig. 2) [2].

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**Figure 1: simplified scheme of pathways in anaerobic digestion**

**Figure 1: typical MEC-AD single system with the microbial community**
As mentioned previously, hydrolytic bacteria break down complex matters to their monomers, followed by fermentation producing volatile fatty acids by fermentative bacteria. The electroactive bacteria attached to the electrode oxidize organic matters to CO₂, electrons and protons as shown in equation 1 [15].

\[
\text{CH}_3\text{COOH} + 2\text{H}_2\text{O} \rightarrow 2\text{CO}_2 + 8\text{H}^+ + 8e^- (1)
\]

Electrons then travel to the cathode where they’re consumed by methanogenesis. In the hybrid system, there are three pathways to produce methane with two mechanisms: directly and indirectly. Directly through the novel pathway by electro-trophic methanogenesis as mentioned previously, in which they utilize electrons to reduce carbon dioxide (CO₂) to methane, as shown in equation 2 [16].

\[
\text{CO}_2 + 8\text{H}^+ + 8e^- \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} (2)
\]

Indirectly, hydrogen reduction occurs abiotically as shown in equation 3 [6]. Then, hydrogenotrophic methanogenesis utilize H₂ along with CO₂, producing methane and water, as shown in equation 4, or by acetalactic methanogenesis, as shown in equation 5 [16]:

\[
\text{2H}^+ + 2e^- \rightarrow \text{H}_2 (3)
\]
\[
\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} (4)
\]
\[
\text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2 (5)
\]

**The effect of microbial culture source**

Inoculum plays a crucial role in providing the initial microbial community, which in return highly affects the biomethane production rate. MECs inoculated with a wide diversity of inoculant from both natural freshwater environments and engineered reactors (e.g., wastewater treatment plants), typically converge to communities containing predominantly *Geobacter sulfurreducens* [5, 17].

*Geobacter* are exo-electrogenic anaerobic microbes, mainly utilize VFA's and hydrocarbons; they coexist and cooperates with other fermentative or syntrophic VFA degrading bacteria such as *Smithella, Bifidobacterium, and Clostridium* [7].

To test the effect if inoculum community structure on the biomethane production from acetate; two inoculum sources were used: (AD) sludge dominated by *acetalactic Methanoseta*, and an anaerobic bog sediment where hydrogenotrophic methanogens were detected. The study tested the effect of inoculum mass on the system’s performance. Interestingly, chambers inoculated with anaerobic bog sediment showed better performance in COD removal (>80%) and biomethane production compared to anaerobic sludge. In addition, increasing the inoculum mass has increased the biomethane production up to 0.27 mL mL⁻¹ cm⁻² for systems inoculated with AD bog, but with no effect for systems fed with AD sludge [18].

Similarly, [19] tested the effect of using three different inoculums, namely fresh cow manure, activated sludge, and excess sludge, on the biomethane production by AD of primary sludge with fruit and vegetable waste. The results showed that reactors inoculated with activated sludge had the highest CH₄ content, with a value of 200 ml/g VS. The inoculum of activated sludge clearly showed higher methanogenic activity. On the contrary, reactors inoculated with cow dung showed the lowest methane production with a value of 50 ml/g VS.

Agricultural residues are used as substrates in the production of biomethane using AD. However, due to the high content of lignocellulose, it is hard for microorganisms to uptake. On the contrary, recent studies reported that the type of microorganisms involved, highly affects the degradation and biogas production rate. To test the hypothesis, [20] studied the effect of using three different inoculum sources (wastewater treatment plant, stillage from ethanol production process, agricultural biogas plant) on the biogas production from agricultural substrates. Generally, inoculums that had high concentration of ammonia showed lower performance and microbial diversity; ammonia has strong inhibitory effects on...
methanogenesis, with minimal effects on hydrolytic and acidogenic microbes [21]. Reactors inoculated with waste-water treatment plant sludge had the highest methane production and microbial diversity. The high diversity of microbial community simulated the diversity of multiple degradation pathways, hence reducing the retention time and increasing the biomethane yield. Similar to the previous study [21], reported that reactors inoculated with digested manure has outperformed reactors inoculated with acclimatized sludge and septic tank sludge in the production of biogas from sunflower straw.

While the inoculum source is very important to the system, the inoculum to organic loading ratio is as important. Providing the optimum amount of inoculum to substrate is crucial in providing a balanced population of microbial community for the treatment and biomethane production process. In addition, the biodegradation rate and lag time relies greatly on the concentration of microorganisms and consortia provided by the inoculum [22]. Higher organic loading rates (OLRs) can induce a process instability due to the accumulation of volatile fatty acids (VFAs) followed by irreversible acidification of digesters.

**Biofilm and microbial suspension**

The microbial community in the suspension is very similar to the ones on the anode, mainly, electroactive geo-bacter. The specie is specialized in making electrical contacts with extracellular electron acceptors and other organisms like electro- trophic methanogenesis. This gives Geobacter an important role in the diversity of anaerobic environments. Geobacter species appear to be the primary agents for coupling the oxidation of organic compounds to the reduction of insoluble Fe (III) and Mn (IV) oxides in many soils and sediments [7, 23]. Among the archaeal community, hydrogenotrophic methanogenesis are reported to dominantly present in the suspension, similar to cathodic biofilm. Hydrogenotrophic methanogenesis utilizes hydrogen and oxidise carbon dioxide to biomethane [18, 24, 25].

Bioresource Technology inoculated an MEC-AD system with an anaerobic leachate sludge. The anode was mainly dominated by Desulfuromondales, which are a type of species capable of growing by transferring electrons from the oxidation of H₂ or organic compounds (i.e., long chain fatty acid) to insoluble Fe (III) oxides [26]. Pseudomonas was another genus of bacteria that was enriched on the anode surface, which are known for degrading aromatic compounds. The cathodic chamber was mainly dominated by Methanobactin species, an acetolactic methanogenesis which are capable of direct interspecies electron transfer (DIET) with exo-electrogenic bacteria such as Geobacter species using hydrogen, formats, insoluble electron shuttles, or conductive materials [27]. Similarly, inoculated system with waste activated sludge were primary dominated by Geobacter, and with Methanocorpusculum from the archaeal genera, both microorganisms were responsible for the enhancement and production of methane in the system [28].

**Altering the microbial community in the system**

The addition of activated carbon increases the surface area for microbial attachment and growth [8, 29], performed a study using powdered activated carbon (PAC) and granulated activated carbon (GAC). PAC is used to enrich the growth of methanogens and syntrophic VFAs-oxidizing bacteria [9]. Studies have shown that iron-based materials like zero valent iron, iron-biochar, or magnetite can adsorb some of the salts which makes the reactor a more hospitable environment for microorganisms involved in wastewater treatment [30, 31]. Magnetite is an ideal adsorbent of harmful salt, in addition to high insoluble surface area, which acts as a host for microbial enrichment. [32] reported that the
proportion of bacterial genera of *Pseudomonas* has doubled in digesters amended with magnetite. *Pseudomonas* is known for the ability of transferring electrons to insoluble electron acceptors and electrodes, and to accept electrons from a variety of extracellular electron donors. This ability to transfer electrons extracellularly would be needed for electron transfer to an electron accepting methanogen or to a magnetite particle via DIET [33, 34]. In addition to *Pseudomonas*, two other genera were substantially enriched by magnetite’s addition: *Soehngenia*, *Thermanaerothrix*.

In addition to conductive additives and substrates, applied voltage plays a significant role in determining microbial domination. Applying a voltage as low as 0.1V has enriched the archaeal community, namely *Methanothrix* in waste-water anaerobic digester [35]. *Methanothrix* is a type of methanogenesis that utilizes acetic acid and is able to perform DIET [36], which explains why VFA’s degradation has increased. In addition to *Methanothrix*, *Methanolinea*’s population has also increased with the applied voltage. *Methanolinea* utilizes H₂ and formic acid to produce methane [37]. Similarly, [38] compared the microbial community of two MEC-AD systems fed with waste activated sludge, one with applied voltage of 0.8V, vs 0V for control. Interestingly, the applied voltage had more effect on the biofilm than the microbial suspension, namely hydrolytic and fermentative microbes. Hence, reducing cumulative proteins and polysaccharides, which increased the methane production in the following stages. Similarly, [39] studied different voltage on the treatment of waste activated sludge. The hydrolysis and acidification process has improved significantly at 0.6V, hence, enhancing the methane production by 76.2%.

**Enriching methane producing microbes**

Methanogenesis are an extraordinary microbe responsible for the anaerobic digestion of organic compounds like reduction or dismutation of carbon dioxide, methyl compounds, or acetate to methane, or methane and carbon dioxide in several ecosystems and consortia [40]. In addition, Methanogenesis has a very low reducing potential compared to other aerobic and anaerobic microbes. Diverse environments are home for Methanogenesis like the deep ocean, rice paddies, wetlands, landfills, and the gastrointestinal tracts of termites, ruminants, and humans. There are three types of Methanogenesis: acetolactic, methyl-trophic, and hydrogenotrophic Methanogenesis. Of the three classes of Methanogenesis; class one and most of class two belong to hydrogenotrophic Methanogenesis, namely *Methanobacterium*, *Methanobrevibacter*, *Methanosprillum*, *Methanococcus*, *Methanogenium*, and *Methanoculleus* [41].

Carbon material improves the direct interspecies electron transfer between bacteria and methanogens, thus improving biomethane production. Several studies were performed using different types and forms of carbon to enhance biomethane production. [42] studied the effect of carbon nanotube (CNT) on a pure culture of methanogens, in addition to typical fatty acid degrading in syntrophic methanogenic coculture. Interestingly, the activity of hydrogenotrophic methanogens was higher compared to acetolactic methanogens. In general, the biomethane production in pure cultures was improved substantially compared to syntrophic cultures-system. Likewise, granular activated carbon (GAC) is reported to enhance biomethane production by multiple folds. [43] exploited GAC in an AD, the biomethane production has noticeably improved and doubled for supported reactors. Similarly, [44] enhanced the performance of a food-waste AD by adding GAC to the system; Lag phase was shortened from 7 to 3 days and the biomethane production has increased up to 80% compared to control reactor. Correspondingly, the addition of GAC to AD treating food dog has substantially increased the chemical oxygen demand.
(COD) removal from 30% to 80%, VFA’s removal from 54-64% to 78-81%, thus increasing the biomethane production to 772–1428mmol vs 80mml for control reactor [45]. [46] studied the effect of graphene on enhancing biomethane production; the study showed that using an optimal amount of 0.5g/L can significantly improve production. However, increasing the amount of graphene added can substantially decrease the biomethane yield. The bacterial population in AD has increased by 40% when integrated with MEC, compared to control; hence, increasing the removal of organic matters and the conversion of volatile fatty acids (VFAs) [47]. Packed activated carbon (PAC) is also reported to enhance biogas production by multiple folds in anaerobic digesters (AD) and integrated systems of AD-MEC [9, 48, 49]. [50] suggested that carbon fibers have a high capacity of adsorbing microbial cells due to less negative zeta potential and the large Hamaker constant for interaction between carbon. Hence, [51] tested the effect of incorporating carbon fiber into AD to enhance methanogenic co-digestion and biomethane production. Interestingly, biomethane production has increased by 2.4 folds compared to control reactors. Increasing the surface area available for microorganisms and the addition of conductive systems to improve (DIET) between electroactive microbes and methanogenesis can improve the performance of the system [21, 52, 53]. [52] added a conductive high surface carbon brush to multiple anaerobic digester systems. Interestingly, the methane generation rate was 57-82% higher for all modified digesters than control. Moreover, the VFA’s consumption rate has substantially increased owing to the high microbial density growing on the added brush, therefore improved the system’s performance [54]. [21] reported that magnetite accelerates biomethane production; the lag phase was reduced from 12 to 8 days. Similarly, [32] used magnetite to enhance AD's performance in high salinity organic wastewater; biomethane production has increased by 1.54 folds. Examining the effect of combining magnetite and external voltage on dairy anaerobic digester by [55], showed that both strategies were effective in enhancing the process performance and stability. However, adding magnetite improved stimulatory effect, while External voltage contributed little to the methane yield, and digester incorporated with magnetite alone had stable performance, comparable to that of the digester where both strategies were combined. Conductive granular graphite (GG) as fillers was developed to enhance direct interspecies electron transfer (DIET) between syntrophic electroactive bacteria and methanogens to stimulate methanogenesis process [7, 56]. A few studies reported that adding phosphate buffer solution (PBS) to the system could potentially enhance biomethane production by facilitating the release of organics into mixed liquor [57]. [58] reported that the addition of (PBS) has improved the methane production by 1.8 folds. In addition, reactors enhanced with PBS had a more diverse microbial community in comparison with control. Moreover, the PBS addition could enhance the growth of acetolactic methanogens (Methanosaeta) and inhibit a portion of hydrogenotrophic methanogens (Methanobacterium) which was also reported by [59]. [60] reported employing electrodeposited cobalt phosphate to MEC-AD coupled reactors to improve the performance of the stainless steel and carbon cloth electrodes. Interestingly the system’s performance has enhanced by 48% and CH₄ production has improved by 80% compared to control reactor utilization of endogenous hydrogen. Electrodeposited cobalt phosphate is deemed to be a valid alternative to noble metals as an electrocatalyst [61]. **Inhibiting methane producing microbes for hydrogen production**
Methanogenesis is perceived to be a significant challenge to the production of hydrogen in the MEC system. Methanogenesis consumes H₂ to produce CH₄, thus reducing hydrogen production. Hydrogenotrophic Methanogenesis is mainly responsible for the utilization of H₂ to biomethane. Many methods have been implied to inhibit methanogenesis without affecting the biohydrogen production, one of the mostly used methods is antibiotics. Methanogenesis prefers neutral pH environment, reducing or increasing the pH to slightly acidic/alkaline could inhibit methanogenesis [62]. The effect of pH ranging from 8.5-11.2 was tested to inhibit the activity of methanogenesis. The activity and abundance of methanogenesis, mainly Methanobacteriaceae reached the absolute lowest at pH 11.2, while the hydrogen production substantially increased up to 90% [63]. Similarly, [64] studied the effect of different applied potentials under alkaline conditions to inhibit methane producing microbes. Interestingly, the H₂ production varied greatly with different applied potential. The maximum hydrogen production was 97% at an applied potential of 1.6V with alkaline pH of 11.2 which was greatly comparable to systems operating under neutral pH, which is preferable by methanogenesis.

Acetylene has inhibitory effects on methanogenesis, [65] reported that the addition of 1-5% of acetylene has dropped the methane production from 70% to less than 5%, while increasing the hydrogen production up to 70% in 10 days. Acetylene binds to nickel presenting in the cofactor of methyl-coenzyme M reductase, a critical enzyme methanogenesis. Also, acetylene was reported to decrease the ability of methanogens to maintain or generate the transmembrane proton gradient for ATP synthesis and methanogenesis [66].

The effect of applied voltage on the hybrid system
Combining anaerobic digestors with bio-electrochemical system has proven to enhance not only the biomethane production rate, but also biomethane percentage [67, 68]. Applying low voltage as low as 0.5 can substantially improve methane production by affecting both bioelectrode and bulk solution microbial communities. However, the effect of voltage on the AD microbial suspension consortia enhancement was not thoroughly tested [69]. A recent study reported that applying voltage potential enriched and enhanced DIET-associated organisms and methanogens performance, however the applied potential had a negative effect with higher organic loading rates [70]. Thus, it is crucial to study the effect of voltage on the system fed with different substrates. Two studies showed that increasing the voltage up to 2V substantially enhanced the system’s performance, despite the increased potential for failure due to electrolysis [71, 72]. [73] studied the effect of increasing the voltage over 2V. The results showed a deterioration in the system’s performance with a voltage over 2.25V. However, the addition of granular activated carbon (GAC) to the reactor at a high applied voltage of 2.75 has substantially increased methane production compared to control reactor by up to 25 folds. Oppositely, [35] reported that the COD, VFA removal and biomethane production was the highest when the voltage applied was as low as 0.1V. Not only improving methane production, but also the secretion of extracellular polymeric substances (EPS) which improves the electron transfer and interaction between microorganisms. On the other hand, [25] reported no major effect of voltage on the microbial community, namely hydrogenotrophic methanogens, while there was an improvement in the methane production.

Effect of electrode’s choice on the hybrid system
Electrode’s material plays a significant role in the bio-electrochemical system; Biofilm formation and density depends greatly on the biocompatibility and morphology of the
electrodes. The anodic reaction of electroactive bacteria plays a significant role in boosting methanogenesis performance. Thus, it is crucial to choose the right electrode material for microbial interactions and growth. The chosen electrode should have high conductivity, excellent chemical stability, high mechanical strength, biocompatibility, high surface area, low cost and low over potential [74]. Carbon based electrode namely, carbon brush, fibre, and felt have been widely employed in the system, owing to their high surface area, biocompatibility and low cost [24, 29, 52, 75-77]. In addition, newly developed 3D-prous carbon electrodes are reported to be a great host for biofilm development and bacterial growth [24, 40, 54, 70, 75, 78, 79]. However, carbon-based electrodes provide slow catalysis for cathodic HER, which seems to be critical for enriching hydrogenotrophic methanogens [59]. Previous studied reported improving carbon-based electrode’s cathodic HER with precious metal catalyst (ex. Nickel, platinum, titanium). However, these catalysts are expensive [80-82]. Multiple modifications to carbon-electrodes are made to improve bacterial adhesion and conductivity specifically, and overall performance generally. Like modification of carbon fibre with self-supported N-doped C/Fe3O4-nanotube composite arrays [83], carbon black with humic-acid [84], carbon felt with carbon derived from mango wood biomass [85], preparing porous carbon cloth using Nickel doped) [14] and much more other studies reported electrode’s surface modification, in terms of surface charge, functional group, and roughness [86]. Among the tightly studied 3D-carbon material is reticulated vitreous carbon, the 3D electrode has a highly porous structure, but with lower biocompatibility [76]. Modifying the electrodes surface with carbon nanotubes (CNT) has substantially improved the biofilm formation on the porous electrode, along with an increase in the biogas production by multiple folds [24]. Many other types of materials have been employed in the hybrid system like metal electrodes, commonly stainless steel. The (Table 1) below summarizes different electrode types from different studies:

**Table 1: Different electrode's types from different studies**

<table>
<thead>
<tr>
<th>Anode</th>
<th>Cathode</th>
<th>modification</th>
<th>Biogas enhancement</th>
<th>Substrate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon felt</td>
<td>Carbon felt</td>
<td>Chitosan poly-neutral red</td>
<td>75% 62.5%</td>
<td>Synthetic waste water</td>
<td>[75]</td>
</tr>
<tr>
<td>Platinum foil</td>
<td>Stainless steel mesh</td>
<td>Heating</td>
<td>75%</td>
<td>Waste water</td>
<td>[20]</td>
</tr>
<tr>
<td>Carbon cloth</td>
<td>Stainless steel mesh</td>
<td>Plasma-treatment</td>
<td>80%</td>
<td>nm</td>
<td>[81]</td>
</tr>
<tr>
<td>Carbon-modified copper foam</td>
<td>Carbon-modified copper foam</td>
<td>Multi-wall carbon nanotube</td>
<td>86%</td>
<td>Food waste</td>
<td>[87]</td>
</tr>
<tr>
<td>Graphite carbon mesh coated with Ni</td>
<td>Graphite carbon mesh coated with Ni</td>
<td>-</td>
<td>3%</td>
<td>Food waste</td>
<td>[12]</td>
</tr>
<tr>
<td>Carbon fiber brush</td>
<td>Carbon cloth</td>
<td>Magnetite/zeolite nanocomposite</td>
<td>15%</td>
<td>n.m</td>
<td>[88]</td>
</tr>
<tr>
<td>Graphite fiber fabric</td>
<td>Graphite fiber fabric</td>
<td>Ni, MWNT</td>
<td>53%</td>
<td>Distillery wastewater</td>
<td>[69]</td>
</tr>
<tr>
<td>Carbon felt</td>
<td>Carbon felt</td>
<td>Neutral red</td>
<td>500%</td>
<td>Sodium bicarbonate</td>
<td>[89]</td>
</tr>
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</table>
Conclusion
This review provides an overview on enhancing anaerobic digesters by integrating it with microbial electrolysis cell. Integrating MEC with an AD in one system can potentially increase the digester’s performance by increasing the VFA’s degradation, thus providing stability to the digester while maintaining high biogas production rate by multiple folds compared to conventional digester. It was also proven that the inoculum source highly affects the performance of the digester, hence, altering the microbial community through the addition of additives can potentially increase the population of VFA degrading and methane producing microbes while inhibiting methanogenesis is reported to improve the hydrogen production up to 97%. Moreover, applied voltage activates electroactive microbes to produce Extracellular polymer substance, which is important for DIET, hence increasing the activity and interaction between VFA degrading microbes, third pathway of biomethane production.
In addition, Electrode’s type plays a crucial role in the performance of the hybrid system. Carbonic materials which are highly biocompatible, chemically stable, and conductive are preferred in as electrode’s choice for their low cost and proven efficiency.

Authors’ contributions
Conceived and collected relevant materials: SK Devrajani, GA Jamali, SK Mahro & HU Rehman, Wrote up this review article: SK Devrajani, Z Memon & GA Jamali, Contributed reagents/ materials/ analysis tools: MA Kapri & C Kumar, Proofread & editing: SK Devrajani & SAK Hashmani.

References

<table>
<thead>
<tr>
<th>Sludge-modified titanium</th>
<th>Platinum-coated titanium mesh tube</th>
<th>Electrodes were not modified</th>
<th>150%</th>
<th>Food waste</th>
<th>[90]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel plate</td>
<td>SS316</td>
<td>Cathode: Ni-Co-P deposit</td>
<td>215.7%</td>
<td>Sodium acetate</td>
<td>[91]</td>
</tr>
<tr>
<td>n.m</td>
<td>Stainless steel mesh</td>
<td>Anodization using TiO₂ nanotubes</td>
<td>150%</td>
<td>Macroalgae</td>
<td>[92]</td>
</tr>
</tbody>
</table>

150


