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Biochar's Electrochemical Properties Impact on Methanogenesis: Ruminal vs. Soil Processes

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Abstract

The chemical composition of biochar and the pyrolysis temperature, under which biochar was produced, determine its electrochemical properties. Electrical conductivity, pseudo-capacitance, and double layer capacitance are the three main electrochemical properties of biochar. Due to the electrical conductivity biochar is able to interfere with the electrons flow and play a dual role of an electron donor or an electron acceptor. The average conductivity of biochar is 229.20 S/m. Pseudocapacitance of biochar lets it serve as a hydrogen sink, taking up the hydrogen produced by protozoa and preventing it from participating in methane-producing reactions in the rumen environment. The average value of biochar's pseudocapacitance is 228 $F \cdot g^{-1}$. Positive and negative charges get stored due to the absorption of ions onto the carbon surface, which happens because of the existence of double layer capacitance as one of biochar's electrochemical properties. Biochar's double layer capacitance values can reach the point of 110.8 $F \cdot g^{-1}$. The electrochemical properties of biochar are directly co-dependent with its redox potential and pH. Electrical conductivity, pseudocapacitance, and double layer capacitance can significantly influence biochemical processes in the rumen and, thus, need to be studied practically.

Keywords

Biochar, Ruminants, Methanogenesis, Soil

1. Introduction

Ruminants play a crucial role in the global food chain, converting cellulose and non-protein nitrogen into milk and other products [1]. However, the agricultural sector is one of the main economic sectors primarily responsible for actively changing climatic conditions because it accounts for about 25.5% of total global anthropogenic emissions [2]. About 18% of these emissions are accounted for by livestock [3]. Animal husbandry produces aggravate emission of greenhouse gases (GHGs), including that of methane (CH_4). The methanogenesis process in ruminants is a prevailing mechanism of CH_4 production, and its emission from livestock [4]. CH_4 is produced as a byproduct of enteric microbial degradation and resulting fermentation, mostly by ruminants' microorganisms [4].

The mechanism of CH_4 generation in ruminants is highly complex and all inclusive. It takes place in the rumen. The rumen is a compartment of the stomach of cattle which is a primary site for microbial fermentation [5]. The process of methanogenesis in ruminants can be divided into 3 main steps: primary fermentation, secondary fermentation, and methanogenesis [2].

Primary fermentation: Different feed components (*i.e.*, starch, cell wall polymers, and protein) reach the rumen and break down to simple chemical junctures, such as simple sugars [6]. The process of breaking down is initiated by fermenting microbes in the rumen and occurs under anaerobic conditions. The major outcome of primary fermentation is to turn complex chemical compounds into simpler ones [7].

Secondary fermentation: Under the influence of rumen microflora, the products of primary fermentation turn into more simple chemicals [8]. Most commonly, they are acetate, propionate, butyrate, hydrogen ions, and carbon dioxide [9].

Methanogenesis: Some of the products of secondary fermentation are acted upon by methanogen bacteria in the rumen. Methanogens consume different substrates in the rumen, primarily hydrogen, and, as a result, methane occurs in the rumen (**Table 1**) [10].

The potential of biochar to influence the methanogenesis process is a priority issue of discussions among researchers. Biochar is a charcoal-like substance that is produced by pyrolysis of biomass under anaerobic conditions. Many different experiments have been performed to test the efficacy of biochar in methanogens activity reduction in the soil system. The potential of biochar to reduce CH_4 emissions ranges from 22% to 96% in paddy soils over two rice-growing seasons [12]. The methanogenesis processes in ruminants and soils are similar; however, the effect of biochar on CH_4 production in the rumen is debatable. Some studies point out that biochar doesn't significantly affect methanogens activity in the rumen and doesn't have a long-term effect.

Some recent studies highlight the ability of biochar to absorb nitrates and prevent nitrogen leaching from the soil system [13]. Biochar accumulates nitrogen-containing compounds and protects them from being washed out of the soil

Table 1. Substrates for methanogenesis in the rumen (Adapted from Nagaraia, 2016 [11]).

Substrate	Reactions
H_2	$4H_2 + CO_2 = CH_4 + 2H_2O$
Formate (HCOOH)	$4HCOOH = CH_4 + 3CO_2 + 2H_2O$
Acetate (CH_3COOH)	$CH_3COOH = CH_4 + CO_2$

by rainfalls. In the rumen, biochar can also be able to absorb nitrates, which can lead to an increase in nitrate contents and, consequently, to inhibition of methanogens activity. Thus, using nitrate-containing compounds as forage supplements along with biochar could serve as a potential solution to the problem caused by an intense emission of CH_4 from ruminants.

Biochar is a by-product of a by-product, which makes it highly attractive for environmentalists to discuss. Biochar usage as a forage supplement to reduce CH_4 emissions from ruminants is the focus of many current studies. The efficacy of this by-product in reducing emissions of GHGs and preventing nitrogen leaching from the soil system has been underlined in a plethora of scientific papers [14] [15]. Based on the similarities between soil microbial communities and microbial communities in the rumen, biochar is expected to cause the same effect in the rumen as it does in the soil system and affecting the methanogenesis process in the same way.

Thus, evaluating electrochemical properties of biochar can help to understand the nature of its behavior in the rumen. Therefore, a systematic assessment of the ability of biochar to inhibit methane production and explore the mechanism of the inhibition in the rumen requires in-depth studies of electrochemical properties of biochar (e.g., electrical conductivity, pseudocapacitance, and double layer capacitance).

The objectives of the study are the followings:

1) To explore the origin of biochar's electrochemical properties.

2) To assess the effect of biochar's electrochemical properties to the soil system.

3) To assume the influence of biochar's electrochemical properties on ruminal methanogenesis.

4) To study the codependency between biochar's electrochemical properties and its other characteristics.

The hypothesis of the study: electrochemical properties of biochar in the rumen manifest the same way as in the soil system, and the by-product acts as the methanogenesis process inhibitor.

2. The Origin of Biochar's Electrochemical Properties

Biochar is produced during the process of pyrolysis of biomass. Therefore, pyrolysis characteristics determine biochar's electrochemical abilities. Pyrolysis transforms polymeric components of biomass into carbon-rich biochar (solid phase), bio-oil (liquid residue), and syngas [16]. Carbon-rich biochar is heterogenous and consists of different inorganic compounds and organic aromatic chemicals. When pyrolysis temperatures are high (400˚C - 800˚C) the total contents of ash, basic functional groups (e.g., carbon, nitrogen, potassium, phosphorus, calcium, and magnesium) are enriched [17]. Carbon stability also increases, whereas the number of unstable forms of organic carbon and acidic functional groups, as well as the total content of hydrogen, oxygen, and sulfur, decreases. The overall aromaticity of the by-product also increases under the conditions of high pyrolysis temperatures. It improves the stability of biochar's structure, and, consequently, biochar's potential to sequester ions [17].

The chemical composition of biochar directly affects its electrochemical properties (**Table 2**). Moreover, it directly correlates with the intensity of the properties' manifestation and their values. There are 3 main electrochemical properties of biochar that are worth consideration.

Pseudocapacitance is the ability to store electrical energy through reduction-oxidation reactions. It is related to the presence of redox-active functional groups, metals, and free radicals on the surface of biochar. As has been already mentioned above, the total content of such metals as calcium, potassium, and magnesium increases with the pyrolysis temperature increase. This leads to the increase in pseudocapacitance value. However, pseudocapacitance is primarily determined by the content of two main organic functional groups: quinone and hydroquinone. Quinones are oxidized derivatives of aromatic compounds [21]. Hydroquinone is a type of phenols that has an aromatic structure. Both quinone and hydroquinone are strong oxidizing agents [22]. Moreover, these compounds are thermally stable even under temperatures of 400˚C and higher [23]. Their presence on the biochar surface makes it chemically active, which means that biochar can play the role of electron donor or electron acceptor, participating in redox reactions. Pseudocapacitance is pH-dependent since redox reactions involve electrons. Pseudocapacitance values are higher in the acidic environment and lower under alkaline conditions [16]. Free radicals on biochar's surface usually serve as intermediates of the quinone/hydroquinone system. The radicals can stay unbonded for a few hours or, sometimes, months [19]. Their presence in the chemical composition of biochar is related to the activity of transition metals and reactions, happening within the net of aromatic junctures [18]. However, their role in pseudocapacitance manifestation remains to be a big knowledge gap.

Electrical conductivity refers to electron migration between energy bonds with different electric potentials. If biochar was produced under the conditions of high pyrolysis temperature, the π-electrons start to accumulate in biochar,

Table 2. Biochar's chemical compounds' role in electrochemical properties formation.

Chemical compound	**Role**
Redox-active functional groups	Electrical energy storage, electrical charge formation, interference in electrons flow, ions absorption [16]
Metals	Electrical energy storage, mineral phase formation, participation in redox reactions [18]
Free radicals	Electrical energy storage [19]
Amorphous carbon	Serves as semipermeable membrane, formation of carbon-phase net [20]
Graphitic carbon	Serves as semipermeable membrane, formation of carbon-phase net [20]

creating the π-electrons system [24]. This system and accumulation of π-electrons in biochar particles allows the by-product to directly transfer electrons from an electron donor to an electron acceptor. Biochar can carry multiple π-electrons systems inside its particles. The accumulation of the conjugated π-electrons increases biochar's electrical conductivity due to the delocalization of electrons associated with π-bonds which results in their availability as charge carriers. High pyrolysis temperatures also improve the speed of electron transfer and the conductivity of the starting material [24]. Electrical conductivity promotes direct interspecies electron transfer which means that biochar with high electrical conductivity values can transfer electrons not only to other chemical compounds but also to microorganisms' cells [25]. Electron transfer does not require any chemical reactions involving functional groups on the biochar's surface [26]. The average conductivity of biochar is 229.20 S/m [27].

Double layer capacitance is the ability of a material to store energy electrostatically and form an electrical charge [16]. The activation of double layer capacitance does not require any redox reactions to happen on the biochar's surface. This electrochemical characteristic appears during the reversible absorption of ions onto the biochar surface. Double layer capacitance is highly dependent on the porosity of biochar. The porous structure of biochar determines its high values of double layer capacitance [28]. Nevertheless, double layer capacitance can be also improved by increasing the surface area of biochar. The high surface area allows biochar to absorb more ions, parallelly improving its other characteristics such as cation and anion exchange capacities. Unlike electrical conductivity, double layer capacitance is linked to the presence of functional groups on the surface of biochar [29]. However, the link between biochar's ability to absorb ions and electron flow in a specific system is not direct and doubtful because it does not provoke electrons accumulation or transfer. The role of double layer capacitance in biochemical reactions in living systems is poorly studied and remains to be an important knowledge gap that needs to be addressed.

Biochar consists of amorphous carbon, graphitic carbon, and mineral phase [20]. Mineral and carbon phases of biochar have different electrochemical potentials. All carbon phases in biochar are connected via a series of tubular pores. These pores are also connected with the mineral phase. Carbon phases can act as a semipermeable membrane, whereas mineral phases act as galvanic cells. Minerals that constitute biochar's mineral phase constantly change their oxidation state during redox reactions [20]. Consequently, the same metals in biochar can exist in different forms and affect the electrons and ions to flow separately and differently.

The origin of biochar's electrochemical properties is related to and determined by its chemical composition. Electrical conductivity, pseudocapacitance, and double layer capacitance let biochar to transfer electrons, store energy, and serve as an ions' absorbent, respectively (**Figure 1**). However, the mechanism of their manifestation and the exact pattern of biochar's interference in redox reactions, provoked by its electrochemical properties' presence, remain to be a researchable priority for further studies.

2.1. Electrical Conductivity of Biochar and Its Influence on Soil and Ruminal Methanogenesis

The impact of biochar's electrical conductivity on the rumen ecosystem is poorly studied and represents a huge knowledge gap in this area of study. However, biochar is widely studied as a soil amendment that is used to reduce CH_4 and nitrogen monoxide (NO) emissions from the soil system and to prevent nutrients from leaching. The processes of methanogenesis in soils and ruminants have a lot in common since both pedosphere and rumen have similar microbial communities (**Table 3**). Therefore, theoretical analysis, assessment, and model of biochar's behavior in the rumen can be developed based on current knowledge about biochar's impact on the pedosphere.

As has been already mentioned above, the electrical conductivity of biochar

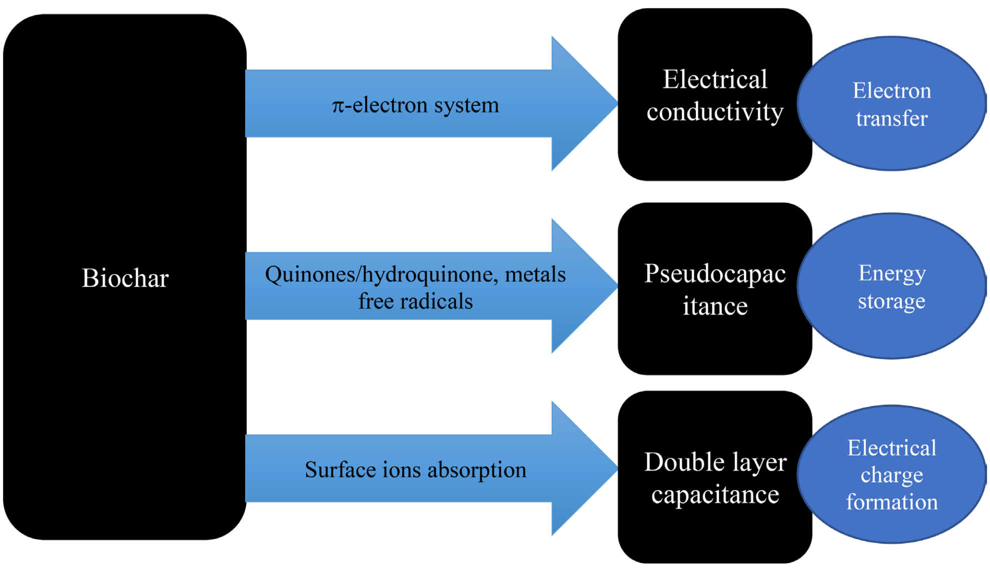

Figure 1. Electrochemical properties of biochar.

Table 3. Differences and similarities between biochar's behavior in soils and in the rumen.

Soil	Rumen
Primarily interacts with mineral phase [30]	Primarily interacts with organic matter [32]
Absorbs soil nitrogen and supplies it primarily to root systems [31]	Absorbs soil nitrogen and supplies it primarily to ruminal microbes [33]
Primarily affects nitrogen monoxide emissions [31]	Affects methane production [32]
Interacts with soil microbes, plants microbes, and soil macrofauna [30]	Interacts only with ruminal microorganisms [33]
1) Interact with methanogens and gets hydrogen produced by protozoa [33] 2) Manifests all electrochemical properties [34] 3) Can act as both electron sink and electron source [34]	

refers to its ability to provide electrons transfer in a certain system. The electron transfer can be conducted not only between chemical molecules but also between biochar particles and microorganisms in the soil system. In the pedosphere, biochar serves as a source of electrons for different microbes, and the microbes can transfer these electrons between each other, creating a net interspecies electron transfer [25]. During the interspecies electron transfer, the metabolic activities of several different microorganisms can be bonded. Some microorganisms can donate electrons directly to biochar without involving other microbial cells in the process [35]. By transferring electrons, biochar interferes in biogeochemical processes which take place in the soil system.

In the ruminal environment, we hypothesize that electrical conductivity of biochar may play a crucial role. Electrical conductivity provides the material with the ability to participate in different biochemical reactions, attracting anions and cations [24]. The presence of quinones and hydroquinone in biochar's chemical composition drives the manifestation of biochar's electrical conductivity. Quinones are electron carriers. In biochemistry, quinones are responsible for transferring protons and electron between complexes and cells, forming the electron transfer chain, which helps to produce ATP [36]. Biochar can be both electron donor and electron acceptor, depending on its oxidation state, which means that it can be involved in redox reactions in the rumen. Oxidized biochar serves as an electron acceptor, whereas reduced biochar serves as an electron donor (**Figure 2**). Biochar acts as electron donor in the reduction of nitrates to ammonium [37]. Playing the role of electron acceptor, biochar becomes an electron sink in the rumen, consuming hydrogen [37]. Hydrogen is the main substrate for methanogenesis [38]. In the rumen environment, carbohydrate polymers break down into monomers such as cellulose. During the process

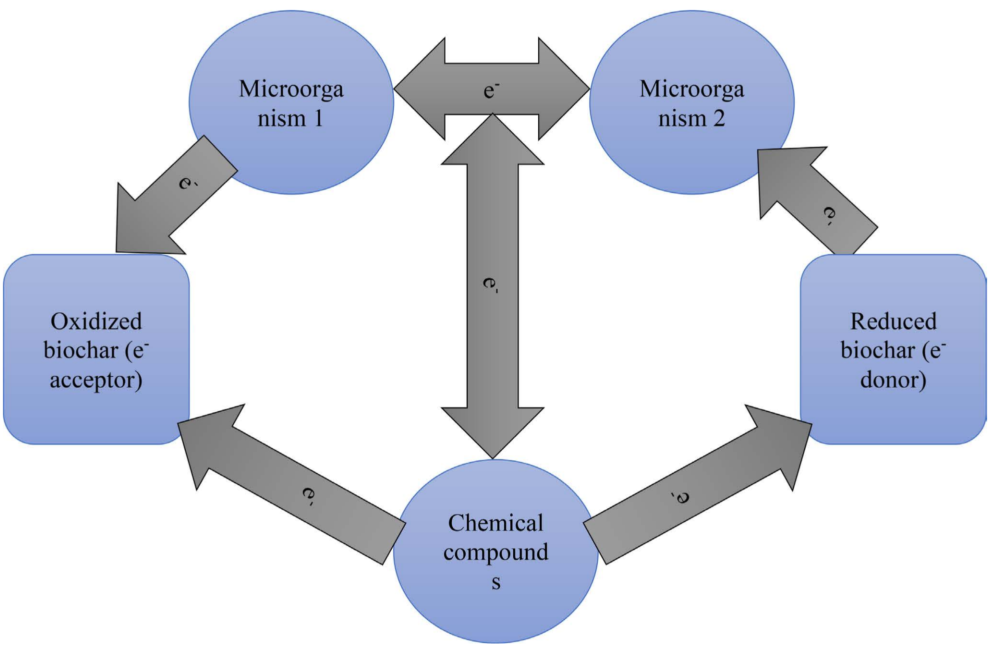

Figure 2. Electron transfer cause by biochar's electrical conductivity.

of microbial fermentation volatile fatty acids, carbon dioxide, and hydrogen get produced. In the presence of biochar, instead of participating in methane production reactions, electrons occurred during fermentation reactions become a part of the electron transfer net and may get stored in biochar particles. Acting as an electron sink, biochar may significantly inhibit methanogenesis and cause a decrease in CH_4 production in the rumen. The electrical conductivity of biochar also influences its sorption capacity, letting the material absorb different chemical compounds, including harmful ones like nitrites. Instead of getting into the animal's blood system, nitrites can get absorbed by biochar and stay in the rumen, depressing methanogens activity there.

The electrical conductivity of biochar allows it to take part in redox reactions, playing the dual role of either an electron acceptor or electron donor. Biochar's interference in the electron flow in the rumen as an electron acceptor may cause methanogenesis inhibition. However, the exact mechanism of how biochar accumulates or donates electrons is unknown as well as the factors which provoke it to act as either a sink or a source of electrons [39]. Another knowledge gap in the investigation of biochar's electrical conductivity is related to the ways of its enhancing. Biochar has natural electrical conductivity, however, theoretically, it can be changed under the influence of different factors, such as temperature [39]. Temperature increase usually leads to the increase of a material's electrical conductivity, but biochar has never been a material on which such experiments were set up. Hypothetically, a temperature increase can increase biochar's electrical conductivity and enhance the process of electrons accepting.

2.2. Pseudocapacitance of Biochar and Its Influence on Soil and Ruminal Methanogenesis

Pseudocapacitance can explain why biochar can serve as an electron sink in the rumen. In the rumen environment, some volatile fatty acids, such as propionate and butyrate, serve as important electron sinks [16]. Fermentation of one molecule of glucose to two propionates results in the net use of electrons equivalent to two H_2 [2]. This system competes with dihydrogen that is used to form methane during the methanogenesis process in the rumen. However, the presence of biochar can critically change the situation. Acting as an electron sink, biochar may attract hydrogen with its negatively charged functional groups, preventing it from participating in the process of methane production. Originally, hydrogen in the rumen is produced by protozoa. These microorganisms have an organelle called hydrogenosome, which is responsible for hydrogen production [11]. Thus, protozoa actively participate in the process of methane formation in the rumen, serving as a hydrogen source for further biochemical reactions. Once biochar reaches the rumen, it can start to act as a hydrogen sink, taking hydrogen produced by protozoa from the rumen environment and preventing the ions from taking part in methanogenesis. When it comes to extracellular electron cycling, quinones become the focus of interest. Different types of quinones are associated with different types of rumen bacteria. For instance, 4-Amino-1,2-naphthoquinone is associated with a group of bacteria called Sphingomonas xenophaga. 4-Amino-1,2-naphthoquinone allows biochar to transfer electrons to Sphingomonas xenophaga and vice versa [40]. Extracellular polymeric substances act as transient media for microbial extracellular electron transfer [41]. Biochar itself is negatively charged due to the presence of functional groups containing OH^-, which can serve as one of the reasons why biochar's environment might be attractive to hydrogen. However, because of the extracellular electron exchange between biochar and ruminal microbes, which is happening because of the presence of functional groups, like quinones, on its surface, biochar can also receive electrons dumped into it by microorganisms [3]. It is important to remember that not only protozoa produce hydrogen in the rumen. Hydrogen can get produced during microbial fermentation of hydrogenase. The rumen bacterium Ruminococcus albus, for example, can produce H_2 from NADH in confurcation with the oxidation of Fd_{red}^{2-} [42]. Therefore, biochar interacts with hydrogen-producing bacteria and can possibly accept electrons from them as well as from protozoa.

Due to the presence of chemical functional groups on biochar's surface, the by-product of biomass pyrolysis has its own electrochemical gradient. Electrochemical gradient of biochar determines the direction in which biochar transfers its electrons and its manifestation is higher when the concentration of ions across biochar's surface is unequal [43]. Assuming that biochar absorbs hydrogen produced by protozoa in the rumen, its negatively charged functional groups will be moving across its surface until the concentration of hydrogen and the charges are balanced across the biochar's particles. It may mean that biochar has a limit of hydrogen absorption, but because of its original negative charge, biochar is supposed to absorb a huge amount of hydrogen to balance the charges. In overall, pseudocapacitance of biochar may change the electron flow in the rumen, inhibiting the formation of methane (**Figure 3**).

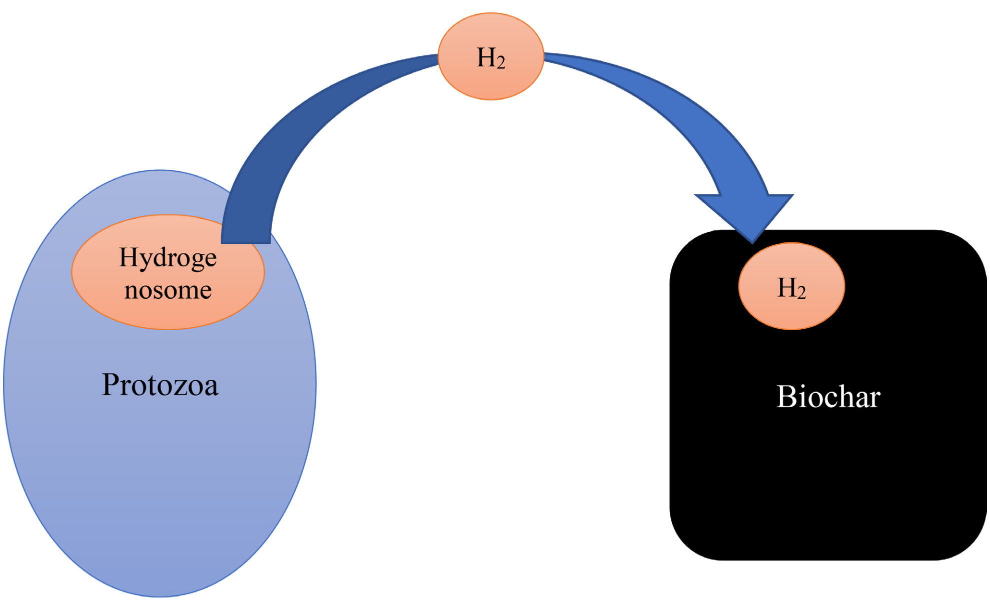

Figure 3. Hydrogen transfer from protozoa to biochar in the rumen.

Due to biochar's ability to store electrons, extracellular electron cycling might limit production of H_2 that is needed by hydrogenotrophic methanogens. If so, then if protozoa consume small biochar particles, the process could be intracellular and therefore facilitate alternate respiratory pathways. In contrast with the larger entodiniomorphids that consume large particles, the isotrichid protozoa that are known to be more O_2 tolerant and respond to electrical current [44] [45]. This ability of biochar can significantly decrease methane production in the rumen. However, the mechanism of hydrogen absorption by biochar is not studied well and remains to be an unaddressed research question.

2.3. Double Layer Capacitance of Biochar and Its Influence on Soil and Ruminal Methanogenesis

The double layer capacitance of biochar may enhance surface absorption of different ions. However, researchers point out that this electrochemical property does not contribute a lot to any biogeochemical processes in the soil system [16]. Nevertheless, electrostatic absorption of ions is used to remove contaminants such as heavy metals from soils or to desalinize soils [46]. In the soil system, double layer capacitance, as well as the electrical conductivity of biochar, prevents nitrogen leaching by storing it in biochar particles.

Double layer capacitance effect on CH_4 production in the rumen is unknown. However, there is a probability that this electrochemical characteristic of biochar may influence ruminal methanogenesis indirectly. Biochar's surface can absorb nitrates (NO_3^-), and some time NO_3^- break down into nitrites (NO_2^-) (**Figure 4**). Nitrite inhibits methanogens activity in the rumen; however, if nitrite is absorbed into the ruminants' blood system, methemoglobin is formed [18] [47]. Perhaps, biochar helps to prevent nitrite absorption into the blood system by storing nitrite inside its particles. Being stored in biochar, nitrite can stay in rumen fluid, potentially interacting with methanogens and depressing their activity. Methanogens' activity inhibition slows down the process of methane production in the rumen. Therefore, double layer capacitance is also responsible for the appearance of biochar's ability to negatively affect methanogenesis in the rumen environment.

Double layer capacitance manifestation may indirectly inhibit methanogenesis in the rumen in the presence of nitrate–containing compounds. Even though previously performed studies claim that electrostatic absorption of ions does not

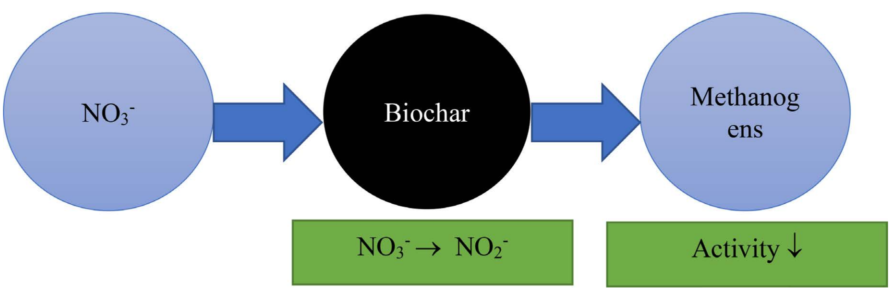

Figure 4. The mechanism of methanogens' activity inhibition by nitrites.

significantly affect methane production, the situation can change under the conditions of the rumen environment [16]. Therefore, this electrochemical property of biochar and its contribution to enteric fermentation should be studied.

3. The Codependency between Electrochemical Properties and Other Characteristics of Biochar

The three main electrochemical properties of biochar are co-dependent with some of its other characteristics. Biochar's original pH levels also should be taken into account. The pH of biochar varies from 3.1 to 12.0 [48]. Alkaline biochars are usually preferable as a soil amendment since its chemical composition contains more functional groups which improve its redox potential. Alkaline biochar is also produced under high pyrolysis temperatures [49].

As it has been mentioned before, it is also important to pay attention to the pyrolysis temperature under which biochar was produced since it affects biochar's electrochemical properties. Pyrolysis temperatures determine the structure and oxidation state of the organic phase of biochar [50]. When temperatures reach 400˚C and higher, the crystalline structure of cellulose becomes amorphous and thermal depolymerization takes place. Free monomeric phenols, as well as alcohols, get produced due to the cellulose and hemicellulose destruction, causing the appearance of redox-active functional groups. The presence of the groups increases the electron exchange capacity of biochar, making it more chemically reactive. Biochar produced under high temperatures has a bigger sorption capacity compared to the ones which were produced under temperatures lower than 400˚C [51].

Biochar's electrochemical properties are highly related to its redox potential and pH. High levels of pH and redox potential values improve its electrochemical characteristics. It is important to pay attention to biochar's pH and redox values and adjust them if needed.

4. Major Known Unknowns

Many studies related to the investigation of biochar's electrochemical properties have been done over the past few decades. However, there are still some knowledge gaps that should be filled by further research. Major gaps are presented in the table below (**Table 4**).

5. Conclusions

Biochar's electrochemical properties determine its behavior in relation to the ruminal ecosystem. They provide biochar with the ability to have its own electrical charge, absorb ions, store energy, and participate in electrons flow and redox reactions, serving as an electron donor or an electron acceptor. Studying of electrochemical properties of the material and their improvement could become a clue for solving the problem of intense methane production in the rumen.

In the scope of the review the following conclusions were made:

Table 4. The main knowledge gaps related to biochar's electrochemical properties.

Knowledge gaps
The exact mechanism of how biochar accumulates or donates electrons remains unknown as well as the factors which provoke it to act as either a sink or a source of electrons.
Ways to improve biochar's electrical conductivity are unstudied.
The mechanism of hydrogen absorption by biochar remains to be an unaddressed research question.
Relationships between double layer capacitance manifestation and the methanogenesis process in the rumen remain undetermined.
Biochar's electrochemical properties and their overall influence on the rumen environment are still of focus of further studies.

1) Biochar's electrochemical properties origin is connected to its chemical composition. Redox-active functional groups, metals, free radicals, and carbon presence on the biochar's surface are responsible for electrical conductivity, pseudocapacitance, and double layer capacitance occurrence.

2) Biochar's presence in the soil system helps to prevent greenhouse emissions from soils into the atmosphere and nutrients' leaching from the pedosphere.

3) It is assumed that biochar in the rumen environment will serve as nitrogen absorbent and help to depress methane production in the rumen by consuming hydrogen produced by protozoa.

4) Biochar's electrochemical properties are interconnected with its redox potential and pH level. The higher are the pH levels and redox potential, the higher are the valued of the properties.

The hypothesis of the review is analytically proven. However, theoretical assumptions on biochar's behavior in the rumen based on how it acts in the soil system may be refuted by the results of further *in-vitro* and *in-vivo* experiments. In order to properly assess the impact of biochar' electrochemical properties and biochar as a treatment, the knowledge gaps should be addressed and fulfilled. To achieve the goal, analytical studies should be done and supported by an *in-vitro* and *in vivo* series of experiments. Understanding biochar's electrochemical characteristics can help to develop a model of its behavior in the rumen and its potential contribution to methane emissions production.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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