

ELECTROLYZERS APPLIED TO GREEN FERTILIZER PRODUCTION: OPPORTUNITIES AND CHALLENGES FOR BRAZILIAN AGRIBUSINESS

ELETROLISADORES APLICADOS À PRODUÇÃO DE FERTILIZANTES VERDES: OPORTUNIDADES E DESAFIOS PARA O AGRONEGÓCIO BRASILEIRO

ELECTROLIZADORES APLICADOS A LA PRODUCCIÓN DE FERTILIZANTES VERDES: OPORTUNIDADES Y DESAFÍOS PARA EL AGRONEGOCIO BRASILEÑO



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ABSTRACT

The increase in fertilizer prices, the significant national dependence on imports of these inputs, the intense debate on the energy transition in Brazil, and the development of new water electrolysis technologies have led to the possibility of using renewable energy in the production of green fertilizers. This article addresses the role of electrolyzers in the production of green fertilizers and their implications for Brazilian agribusiness, considering the opportunities and challenges associated with the adoption of this technology, with the general objective of analyzing the potential application of electrolyzers in the production of green fertilizers, identifying opportunities, technical limitations, and regulatory challenges for their sustainable integration into Brazilian agribusiness. At the end of the study, it is recommended that the academic community develop new technologies aimed at reducing the cost of electrolyzer use, considering studies developed worldwide on the subject and applying them to the Brazilian context, and that policymakers make efforts to consolidate regulatory frameworks in the sector and advance regulatory issues.

Keywords: Green Fertilizers. Electrolyzers. Energy Transition. Agribusiness.

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RESUMO

O aumento do preço dos fertilizantes, a considerável dependência nacional de importações desses, o intenso debate acerca da transição energética no Brasil e o desenvolvimento de novas tecnologias para eletrólise de água culminam na possibilidade de se usar energias renováveis na produção de fertilizantes verdes. Neste artigo, foi abordado o papel dos eletrolisadores na produção de fertilizantes verdes e suas implicações para o agronegócio brasileiro, considerando oportunidades e desafios associados à adoção dessa tecnologia, com objetivo geral de analisar o potencial de aplicação de eletrolisadores na produção de fertilizantes verdes, identificando oportunidades, limitações técnicas e desafios regulatórios para sua inserção sustentável no agronegócio brasileiro. Ao final da pesquisa, recomenda-se ao meio acadêmico o desenvolvimento de novas tecnologias com o intuito de baratear o uso de eletrolisadores, observando os artigos desenvolvidos sobre o tema a nível mundial e aplicando-os a realidade brasileira, e aos agentes políticos esforços para consolidar os marcos regulatórios no setor e amadurecer as questões regulatórias.

Palavras-chave: Fertilizantes Verdes. Eletrolisadores. Transição Energética. Agronegócio.

RESUMEN

El aumento del precio de los fertilizantes, la considerable dependencia nacional de las importaciones de estos insumos, el intenso debate sobre la transición energética en Brasil y el desarrollo de nuevas tecnologías para la electrólisis del agua culminan en la posibilidad de utilizar energías renovables en la producción de fertilizantes verdes. En este artículo se abordó el papel de los electrolizadores en la producción de fertilizantes verdes y sus implicaciones para el agronegocio brasileño, considerando las oportunidades y desafíos asociados a la adopción de esta tecnología, con el objetivo general de analizar el potencial de aplicación de los electrolizadores en la producción de fertilizantes verdes, identificando oportunidades, limitaciones técnicas y desafíos regulatorios para su inserción sostenible en el agronegocio brasileño. Al final de la investigación, se recomienda al ámbito académico el desarrollo de nuevas tecnologías con el objetivo de reducir el costo del uso de electrolizadores, considerando los estudios desarrollados a nivel mundial sobre el tema y aplicándolos a la realidad brasileña, y a los agentes políticos realizar esfuerzos para consolidar los marcos regulatorios en el sector y avanzar en las cuestiones regulatorias.

Palabras clave: Fertilizantes Verdes. Electrolizadores. Transición Energética. Agronegocio.

1 INTRODUCTION

The production of nitrogen fertilizers is of paramount importance to modern agriculture, but it has traditionally relied on carbon-intensive industrial processes. In this context, electrolyzers emerge as a sustainable alternative, as they allow the production of hydrogen through the electrolysis of water using renewable electricity. This technology enables the production of so-called "green" fertilizers, reducing carbon emissions and opening up new opportunities for Brazilian agribusiness.

The research followed a qualitative approach and used the literature review procedure. The general objective of this article is to analyze the potential application of electrolyzers in the production of green fertilizers, identifying opportunities, technical limitations and regulatory challenges for their sustainable insertion in Brazilian agribusiness.

The planned specific objectives are to examine the technological underpinnings of electrolyzers and their integration into green fertilizer production processes, with an emphasis on the synthesis of low-emission hydrogen and ammonia; to evaluate the economic and environmental opportunities associated with the use of electrolyzers in Brazilian agribusiness, considering the national energy matrix and the demand for sustainable agricultural inputs, and to identify the main technical, regulatory and infrastructural challenges for the large-scale adoption of electrolyzers in the fertilizer chain in Brazil.

This article was structured in four sections. The first is the introduction in which the objectives of this research were explained. The second is the methodology where the methodological procedures used for the development of this study were explained. The third was the theoretical foundation, which constituted a discussion between authors who deal with the same theme addressed here. In the fourth section, the final considerations were elaborated.

2 METHODOLOGY

The approach adopted for the development of this study is characterized as qualitative (Creswell, 2014). This article was developed based on a narrative and exploratory literature review, with the objective of gathering and analyzing relevant information on the use of low-carbon hydrogen in fertilizer production, focusing on technical, environmental, economic aspects and future perspectives (Batista; Kumada, 2021).

The bibliographic research was carried out between October 2025 and March 2026. Data collection was carried out from publicly available sources. The main sources are scientific articles and academic productions, technical reports, case studies and news.

The choice of this procedure is justified by the fact that the investigated theme, electrolyzers aimed at the production of green fertilizers, involves a relatively recent field, whose understanding depends on the systematization of academic studies and reports produced by national and international organizations.

The main authors who contributed the most to this research were: Costa (2025) , Lin et al. (2025) , Irena (2020), Menegat, Ledo and Tirado (2022) and Martins (2023).

3 THEORETICAL FOUNDATION

This article was divided into three subtopics. In the first, electrolyzers and the technological basis of green fertilizers were discussed. In the second topic, the economic and environmental opportunities that can arise with the production of green fertilizers were addressed. In the third and last topic, the main challenges for consolidating this technology were discussed.

3.1 ELECTROLYZERS AND THE TECHNOLOGICAL BASIS OF GREEN FERTILIZERS: OPERATING PRINCIPLES, PRODUCTION ROUTES AND ENERGY REQUIREMENTS

Green fertilizers have a technological basis that is directly related to the use of electrolyzers to generate low-emission hydrogen, which is essential in the production of ammonia for nitrogen fertilizers. As discussed by Costa et al. (2025), the interface between process engineering and sustainable energy solutions transforms the usual production trajectories by exchanging fossil inputs for hydrogen produced by water electrolysis, provided that specific conditions of energy efficiency and reliability in the supply of electricity are met. The interaction between the operation of electrolyzers and the availability of renewable sources shapes both the performance of the process and the technical feasibility of the production of green fertilizers, which highlights the need for an alignment between technology, energy consumption and industrial structure in the context of Brazilian agribusiness.

Electrolysis is a technique that uses direct electric current (DC) to promote a chemical reaction that would not otherwise occur spontaneously, with the electrolyzer being a system that performs electrolysis. Electrolysis is commercially important as a step in separating elements from natural sources, such as ores, by means of an electrolytic cell.

In the context of green hydrogen production, electricity is used to separate water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2). The production of zero-carbon hydrogen is possible when the electrolyzer is powered by renewable energy sources, such as solar and wind. For this reason, electrolyzers are expected to play a relevant role in the

decarbonization of the energy, refining, transportation, chemical production, and steelmaking sectors.

The first experimental records of water electrolysis date back to 1789, when Adriaan Paets van Troostwijk and Johan Rudolph Deiman conducted trials using an electrostatic generator and gold electrodes (Abudureyimu et al., 2025). By subjecting the water to the action of electricity, they observed the release of gaseous bubbles, indicating the occurrence of chemical reactions. These studies demonstrated that water could be broken down into hydrogen and oxygen exclusively through the application of electrical energy. Since then, with technological advances, we have several types of electrolyzers aimed at the electrolysis of water, the most notable being Alkaline Electrolyzers, PEM (*Proton Exchange Membrane*) and SOEC. The chemical reaction of hydrogen production through the electrolysis of water is as follows: $2\text{H}_2\text{O}(l) \rightarrow 2\text{H}_2(g) + \text{O}_2(g)$

In the case of alkaline electrolyzers, the process is based on the transport of hydroxide ions (OH^-) through the electrolyte, from the cathode to the anode, with hydrogen production concentrated in the cathode compartment. For this purpose, a strongly alkaline liquid solution of potassium hydroxide or sodium hydroxide is used as an electrolyte. Alkaline electrolyzer technology presents specific demands related to water use and operating conditions that distinguish it from other electrolysis routes. In general, these systems operate in a temperature range between 30 °C and 90 °C, using aqueous solutions of KOH or NaOH with typical concentrations between 20% and 30%.

As for the use of water resources, alkaline electrolyzers have a consumption intensity of approximately 22.3 L of water per kilogram of hydrogen produced, while the intensity of water withdrawal can reach 32.2 L/kg of H_2 . The operation of these systems requires makeup water with a high degree of purity, which is then mixed with the alkaline electrolyte to achieve the proper concentration.

The highly alkaline character of the medium imposes particular challenges to the maintenance of water quality, prioritizing the removal of solid particles to the detriment of the control of ionic contaminants, due to the effect of saline precipitation in concentrated solutions. In this context, AWE systems usually incorporate specific filters for alkaline solutions, integrated into the deionized water and electrolyte circuit, whose function is to remove particles and impurities from the solution. These devices are key to preventing fouling and clogging in the electrolyzer, ensuring stable and efficient operational performance over time (Lin et al., 2025).

In PEM electrolyzers, in which the electrolyte is made up of a solid polymeric membrane, water is oxidized at the anode, generating oxygen and protons. As electrons

travel through an external circuit, hydrogen ions selectively pass through the membrane to the cathode, where they recombine with electrons, forming hydrogen gas. This technology is recognized for its high efficiency in water use, with an average consumption of about 17.5 L per kilogram of hydrogen produced, a value considerably lower than that observed in alkaline electrolyzers and in routes based on hydrocarbon reforming with carbon capture. Although the theoretical minimum water consumption in electrolysis is approximately 9 L/kg H₂, in practice the systems require larger volumes, usually between 20 and 30 L/kg H₂, due to the additional purification steps and cooling requirements.

As with alkaline electrolyzers, the operation of PEM systems requires the supply of ultrapure water, but with more restrictive quality limits, in order to preserve the integrity of the proton exchange membrane. In energy terms, PEM electrolysis has a typical consumption of between 45 and 55 kWh per kilogram of hydrogen, which is equivalent to approximately 0.16 to 0.2 L of ultrapure water per kWh consumed. Although alkaline electrolyzers are more tolerant of high levels of water conductivity, when compared to PEM systems, water quality assurance remains a critical factor for the reliability and operational efficiency of both technologies over time.

The consumption of water for cooling varies widely depending on the scale and configuration of the system. In smaller or more efficient installations, the demand for cooling water can be relatively low. On the other hand, in large industrial plants, especially those that use cooling towers, consumption can vary from approximately 26.5 L/kg of H₂ in systems powered by solar or wind sources, to values of the order of 89 L/kg of H₂ in installations associated with nuclear generation. This difference is associated with factors such as the local climate, the efficiency of the electrolyzer, and the cooling technology employed. Although electrolysis presents, in general terms, greater water efficiency than routes such as SMR or ATR with CCS, the variability of water use, especially for cooling, reinforces the importance of adequate water management strategies (Lin et al., 2025). The various routes for hydrogen production are commonly identified by a color. Figure 1 denotes the most common production routes:

Figure 1*Hydrogen production routes*

Cor	Classificação	Descrição
■	Hidrogênio Preto	Produzido por gaseificação do carvão mineral (antracito), sem CCUS
■	Hidrogênio Marrom	Produzido por gaseificação do carvão mineral (hulha), sem CCUS
■	Hidrogênio Cinza	Produzido por reforma a vapor do gás natural, sem CCUS
■	Hidrogênio Azul	Produzido por reforma a vapor do gás natural (eventualmente, também de outros combustíveis fósseis), com CCUS
■	Hidrogênio Verde	Produzido via eletrólise da água com energia de fontes renováveis (particularmente, energias eólica e solar).
■	Hidrogênio Branco	Produzido por extração de hidrogênio natural ou geológico
■	Hidrogênio Turquesa	Produzido por pirólise do metano, sem gerar CO ₂
■	Hidrogênio Musgo	Produzido por reformas catalíticas, gaseificação de plásticos residuais ou biodigestão anaeróbica de biomassa ou biocombustíveis, com ou sem CCUS
■	Hidrogênio Rosa	Produzido com fonte de energia nuclear

Source: Taken from Vellardo (2023).

Even with the use of renewable energies, there are challenges due to the high cost of electrolysis and the intermittency of renewable sources (Irena, 2020).

3.2 ECONOMIC AND ENVIRONMENTAL OPPORTUNITIES OF GREEN FERTILIZER PRODUCTION IN THE CONTEXT OF BRAZILIAN AGRIBUSINESS

The production of green fertilizers in Brazilian agribusiness opens up economic and environmental opportunities that are directly linked to the introduction of low-emission hydrogen as an industrial input, especially when integrated into the country's energy matrix. As Andrade et al. (2025) assess, using electrolyzers to produce hydrogen for the purpose of synthesizing nitrogen fertilizers is a way to reduce dependence on fossil inputs that need to be imported, in addition to reducing emissions from traditional methods and favoring the use of renewable sources that are already available in the country. Thus, the economic viability of green fertilizer production depends on the intertwining of energy costs, production scale, and location of the industry, while the environmental benefits come from the progressive replacement of carbon-intensive processes with others that meet the requirements for sustainable inputs in the Brazilian agricultural sector.

Brazil is an important ally in the race against food shortages, as it is among the largest exporters of agricultural *commodities* in the world (Ferreira; Kreter; Souza Jr, 2023). On the other hand, Brazilian soil has acidic characteristics, with low availability of nutrients and organic matter, which characterizes soil with low natural productivity (Degaspari, 2020).

As a result, Brazil becomes an importer of fertilizers, being dependent on countries such as Russia (Vegro; Angelo, 2023). In addition, Brazilian soils have faced problems

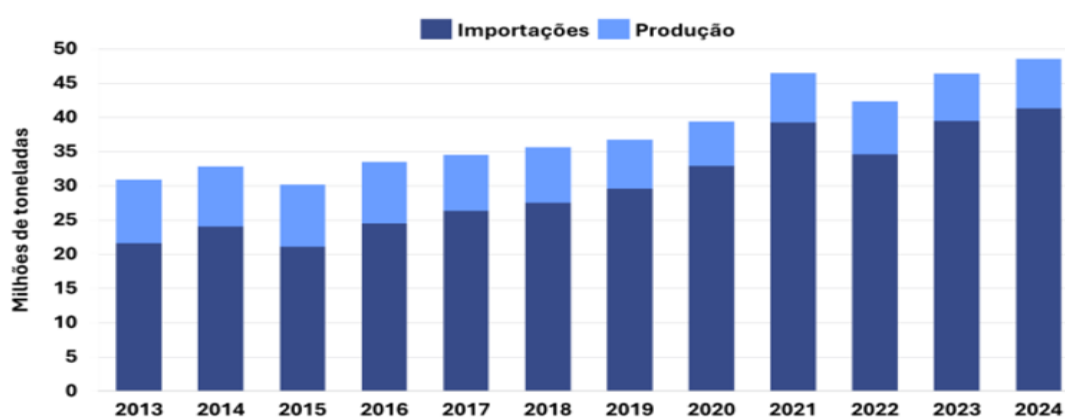
related to degradation, such as erosion, reduction of organic carbon, and nutrient imbalance (Prevedel, 2024).

Thus, in the search for production that meets future needs and also conserves the environment, studies related to techniques for generating ammonia in a sustainable way, such as water electrolysis and anaerobic digestion, have become fundamental techniques to reduce the country's dependence on fertilizer imports, in order to cooperate with global goals regarding the environment.

Currently, Brazil is responsible for about 8% of global fertilizer consumption, being the fourth country in the world, behind only China, India and the United States, and is also the largest importer of fertilizers in the world. The speed of growth of Brazilian demand has exceeded the growth of national supply and its fulfillment has occurred through an increase in imports. The country went from being a fertilizer exporter to being a major importer between 1992 and 2020. More than 80% (eighty percent) of the fertilizers consumed in Brazil are of foreign origin, despite the existence of large reserves of raw materials necessary for the production of fertilizers in its territory (Brasil, 2020), and in 2021, fertilizers made up 30% of agricultural costs (Carregosa; Barbosa, 2022). The outbreak of the war between Ukraine and Russia revisited Brazil's fragility in relation to the need for fertilizers from other countries (Nery, 2024).

Figure 2

Evolution of Brazilian fertilizer consumption derived from imports and domestic production, between 2013 and 2024, in millions of tons



Source: Cardoso et al., 2025.

From an economic **point of view**, the production of green fertilizers can contribute to reducing Brazil's external dependence. Currently, the country imports a large part of the fertilizers it uses, especially nitrogen and potassium, which makes agribusiness vulnerable to price fluctuations and international geopolitical crises.

From an **environmental** perspective, green fertilizers have the potential to significantly reduce greenhouse gas emissions. Traditional ammonia production, the basis of most nitrogen fertilizers, uses hydrogen obtained from natural gas through the steam reforming process, which generates large carbon dioxide emissions.

By replacing this fossil hydrogen with green hydrogen, produced with renewable energy, it is possible to drastically reduce these emissions. Considering that global fertilizer production accounts for up to 2.1% of greenhouse gas emissions (Menegat; Ledo; Tirado, 2022), this technological change represents an important advance in the transition to a low-carbon economy.

3.3 ELECTROLYZERS AND THE TECHNOLOGICAL BASIS OF GREEN FERTILIZERS: OPERATING PRINCIPLES, PRODUCTION ROUTES AND ENERGY REQUIREMENTS

In Brazil, the dissemination of electrolyzers within the green fertilizer chain faces obstacles that go beyond technology, touching on regulatory and institutional issues. According to Rocha and Pompeu (2024), despite the initiatives in favor of a green neo-industrialization linked to low-carbon hydrogen, there are still limitations due to the lack of defined regulatory frameworks, institutional fragmentation, and insufficient infrastructure for these technologies to be integrated on an industrial scale. It is also necessary to have an articulation between industrial, energy and agricultural policies, in order to reduce uncertainties for investors and economic agents. Therefore, the challenges pointed out are not only related to the efficiency of electrolyzers, but to the creation of a normative and institutional environment that enables their adoption in an integrated and constant manner in the fertilizer sector in Brazil, as discussed by Rocha and Pompeu (2024).

Two of the main obstacles to the diffusion of electrolyzers are the high cost and **restricted technological maturity of large-scale electrolysis systems**. The production of green hydrogen depends on the electrolysis of water powered by renewable electricity, a process that still has significantly higher costs than traditional methods based on fossil fuels. Currently, renewable hydrogen can cost **six to eight times more than hydrogen produced from natural gas**, which reduces the competitiveness of green ammonia compared to conventional ammonia (Cantarella, 2025). Other important technological obstacles are the high cost of capital (CAPEX) of electrolyzers, absence of support infrastructure and external technological dependence.

As for regulatory issues, there is the difficulty in labeling fertilizers with green ammonia; (Cantarella, 2025) suggests that fertilizer producers will use a blend of hydrogen

from natural gas (current industry standard) and renewable hydrogen until cost and availability issues are resolved (Pereira, 2024).

The diffusion of electrolyzers for the production of green fertilizers in Brazil faces challenges related mainly to the **incipient regulatory framework for the low-carbon hydrogen market**. As it is an emerging technology, many of the regulatory instruments necessary to ensure legal certainty and predictability of investments are still in the formulation or consolidation phase (Martins 2023).

At the institutional level, the diffusion of electrolyzers depends on **coordination between different public and private agents**, including the federal government, states, research centers, the chemical industry and the electricity sector. The absence of integrated industrial policies can hinder the formation of a technological ecosystem capable of sustaining the development of the sector (Pereira, 2024).

4 FINAL CONSIDERATIONS

The research highlighted the need and opportunities regarding the use of electrolyzers for the production of green fertilizers. Present technical and regulatory limitations must be overcome in the face of national needs to reduce carbon emissions and reduce spending on fertilizers, which make up a significant portion of food prices.

As seen, Brazil has promising rates in the production of renewable energy, mainly solar and wind, and can make use of these conditions to, through the use of electrolyzers, produce green fertilizers and reduce dependence on imports, which are strongly subject to the international geopolitical scenario.

To deepen knowledge in this area, future research may focus on reducing the prices of green ammonia and the implementation of electrolyzer technology on a large scale, also focusing on the technological maturation of these. In addition, it is suggested that society demand from political agents for the consolidation of legal frameworks and maturation of regulatory issues.

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