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Review

Bioenergy with Carbon Capture and Storage (BECCS) in Brazil: A Review

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Abstract: BECCS (bioenergy with carbon capture and storage) is an important technology to achieve international and Brazilian climatic goals, notably because it provides negative emissions. In addition, Brazil presents favorable conditions for the development of BECCS, given the country's mature biofuel industry. Therefore, this research aims to provide a systematic literature review of the effective potential of and barriers to implementing bioenergy with carbon capture and storage in Brazil. The platforms chosen for this study are Science Direct and Integrated Search Portal, which is a search portal administered by the University of São Paulo. The search initially identified 667 articles, of which 24 were analyzed after selection and screening. The results show that technical factors are not a current barrier to the implementation of BECCS in Brazil, especially in ethanol production. However, the economic results vary among articles, but no BECCS plant has been shown to be economically feasible without enhanced oil recovery. In addition, the concentrations of most ethanol distilleries in the southeast region of Brazil point to them as long-hanging fruit for the country. Nevertheless, due to limitations in CO_2 transportation, the costs of implementing BECCS increase significantly as CO_2 capture is expanded away from the southeast region.

Keywords: BECCS; Brazil; negative emissions; decarbonization; developing countries; climate change

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1. Introduction

The Paris Agreement's final report reinforced the International Panel on Climate Change (IPCC)'s goal to maintain the increase in global average temperature between 1.5 and 2 °C above pre-industrial levels [1]. In this context, in 2015 Brazil presented its first National Determined Contribution (NDC), in which it has committed to reducing the country's emissions by 37% until 2025 and by 43% until 2030, both in comparison to 2005 levels [2]. In 2020, Brazil presented its new NDC to the Paris Agreement, in which it reaffirmed the commitments presented in the previous NDC and added the objective of achieving climate neutrality by 2060 [2].

In this framework, BECCS (bioenergy with carbon capture and storage) becomes an important technology, notably because it provides negative emissions [1,3,4]. BECCS represents a series of processes through which the carbon dioxide generated during bioenergy production is captured, transported, and stored in deep geological formations [3,5]. Since the growth of biomass captures CO_2 through photosynthesis—which normally returns to the atmosphere during bioenergy production, the implementation of a carbon capture and storage system to a bioenergy plant provides the possibility to generate negative emissions [5]. This can help reduce emissions and adopt less drastic changes in the productive system, and in everyday life, to achieve the Paris Agreement's goals [1,6,7]. In addition, Consoli [6] describes BECCS as indispensable to achieving the established climate goals and the best option out of the available negative emissions technologies.

However, the literature review developed by Babin et al. [8] and Stavrakas et al. [9] pointed out environmental, social, and economic limitations that can work as significant barriers to the large-scale implementation of BECCS. The environmental limitations are represented by the risk of BECCS not delivering negative emissions since it depends on the resources employed during biomass harvesting (e.g., pesticides), the transportation stages, the result in land use change, and others [1,10,11]. On the other hand, the land competition between bioenergy and food production can be a result of the large-scale implementation of BECCS, which can represent a significant social barrier [9]. Lastly, the economic limitations are represented by the high costs of implementing BECCS and the dependence on generating economies of scale to lower these costs [4].

In this case, the generation of economies of scale depends on the regional concentration of bioenergy plants, transportation technologies, and others [8]. Specifically related to the transportation stage, according to Daioglou et al. [12], BECCS face greater transportations limitations than fossil-based CCS, because the volume of CO_2 captured from bioenergy plants is not enough to pay for the transportation network [12].

In Brazil, Köberle et al. [13] use a scenario-building method to build a scenario in which both the Brazilian energy demand and emission targets are reached. The authors conclude that land-based mitigation strategies are not enough to help Brazil with the energy and environmental challenges. Instead, disruptive technologies, especially BECCS, play a fundamental role. Similarly, Köberle et al. [14] perform a literature review to present the variation in results across integrated assessment models (IAMs), to understand if there is a defined land-use strategy in Brazil. These authors conclude that, although there is no consensus on what should be the land-use strategy for the country, BECCS is fundamental in most.

On the other hand, by using the JULES land surface model coupled with an inverted form of the IMOGEN climate simulator, Hayman et al. [15] highlight the importance of Brazil and Russia for BECCS large-scale implementation, because of these countries' biomass and bioenergy production. Additionally, the results of Hayman et al. [15] show that in the scenarios in which BECCS is implemented, the targets are reached with more agricultural production.

In addition, Ketzer et al. [3] present an atlas of BECCS in Brazil and show the conditions that make the implementation of BECCS favorable in the country, such as the country's mature biofuel industry, the concentration of most biofuel refineries in the southeast region, and the high potential of CO_2 storage in the Paraná, Campos, Santos, Potiguar, and Reconcavo basins. In the same direction, Moreira et al. [16] assess the potential of capturing CO_2 from sugarcane bioenergy plants—such as ethanol refineries and biomass-based power plants – and storing it in the Guarani Aquifer, in the state of São Paulo. The results demonstrate that the project has a mean estimated cost of US\$27.20/tCO_2, which is in line with the costs faced by BECCS projects from electricity generation plants in Europe [16] (p. 59).

Additionally, Rochedo et al. [17] examined the costs of capturing CO_2 in the main emitting sectors in Brazil: offshore oil and gas extraction, oil refineries, ethanol distilleries, and industries. The study showed a high variance of capture costs between ethanol distilleries. This variance is a consequence of the geographic dispersion of these companies in Brazil, which results in a high divergence in transportation costs. For example, the costs range from US\$28/tCO_2 to US\$50/tCO_2, and it increases as the distance from the ethanol distilleries to the storage site increases [17] (p. 289).

Poblete et al. [18] evaluated the economic and thermodynamic aspects of a CCS plant applied to a biogas-combined-cycle power plant. The BECCS power plant was estimated using a dynamic model and expanded to implement time-varying aspects, such as external temperature and feedstock conditions. The authors conclude that implementing CCS in a biogas power plant can provide electricity to remote areas, such as the Brazilian Amazon Forest, and provide net-negative emissions. In addition, when combined with EOR, it can be economically feasible [18].

Focusing on the transportation stage, Nogueira et al. [19] simulated an infrastructure for CO_2 transportation through the Brazilian coast, comparing offshore pipelines and ships. According to the authors, shipping has shown to be an interesting option for CO_2

transportation provided from bioenergy plants, since it is less impacted when there are uncertainties and small volumes. Because of this, shipping can also be a great option during the beginning of the CO_2 market in Brazil.

Regarding regulation, Arlota and Costa [20] apply the legal comparative methodology to analyzing the regulations towards CCS in Brazil, Canada, the European Union, and the United States. The authors conclude that there is a potential of implementing BECCS in Brazil because of this country's recent effort, and even state that these efforts are "more effective than those made by the United States" but highlight the need for further studies [20] (p. 241).

Thus, although it is possible to initially observe the potential of adding BECCS to simulated ethanol plants in Brazil, the barriers that are described in the literature as common to the implementation of BECCS—such as food and energy land competition [8], potential to deliver negative emissions [1,9,21], and transportation costs [17,21]—require further investigation in Brazil. Also, Stavrakas et al. [9] defend the need for more studies focused on examining the potential of CO_2 capture from different biomass alternatives, assessing the BECCS potential on a regional scale, and investigating key determinants for BECCS implementation.

Thus, this article performs a systematic literature review aiming at a comprehensive assessment of the barriers and effective potential of implementing BECCS in Brazil. To do so, it is important to understand the regional and sector distribution of this potential, as well as in what contexts the research is being conducted and the methodologies used.

2. Materials and Methods

To reach the proposed objective, the methodology consists of a systematic literature review, which is a scientific method that requests the adoption of systematic criteria to search, filter, screen, and analyze the literature [22,23]. By following this methodology, the review can be checked, improved, and updated [24–26].

In the energy field, this methodology has been applied to provide a more comprehensive analysis of renewable energy policies [23,27]. In addition, Sorrel [25] argues that building a systematic literature review is fundamental in order to provide information for evidence-based policies and practices in the energy field.

Given the relevance of this methodology, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was created with the goal to help systematic reviewers transparently report why the review was done, what the authors did, and what they found [28]. Thus, the PRISMA statement consists of a checklist of items that should be present in the introduction, methodology, results, and discussion sections, and of a flow diagram to describe the inclusion and exclusion criteria adopted [28,29]. Therefore, to ensure the reliability and reproducibility of the systematic review, this article is based on the PRISMA guidelines.

2.1. Definition of the Research Question

The research question (RQ) under a systematic literature review must be a clear question to be answered and/or a hypothesis to be tested [25]. In this context, Shamseer et al. [29] recommend the use of the PICO anagram, according to which the RQ should present a population or problem (P), intervention (I), comparison (C)—Galvão and Pereira [22] and Galvão and Ricarte [26] see the last as optional—and an outcome (O). Therefore, the RQs developed to guide this article's systematic review were based on the PICO anagram, and on the important aspects surrounding BECCS, such as its mitigation potential, the sources of biogenic CO_2, social impacts, the transportation stage, and regulatory barriers, as pointed out by Babin et al. [8] and Stavrakas et al. [9].

The CO_2 storage stage was not used to form a research question because the literature mentions it as a matter of research for CCS independently of the CO_2 source [3,5]; therefore, it is not an issue that this BECCS-specific review will focus on. One could argue the same about the transportation stage, but because of the difference of the volume of CO_2 captured in BECCS and fossil-CCS facilities and the impact of this difference on the ability of paying for CO_2 transportation networks [8,9], this article decided to analyze this issue for Brazil. Consequently, Table 1 presents the RQs developed for this systematic literature review.

Table 1. Research questions for this article's systematic literature review.

Research Question (RQ)	Population	Intervention	Comparison	Outcome	Study Type
What is the CO_2 mitigation potential of implementing BECCS in Brazil?	Brazil	Implementation of BECCS	No comparison	Mitigation of CO_2 emissions	Research and review articles
What is the best bioenergy industry to provide CO_2 for BECCS in Brazil?	BECCS in Brazil	Bioenergy industries	No comparison	Provide biogenic CO_2	Research and review articles
What impact can the implementation of BECCS in Brazil have on food and land competition in the country?	Brazil	Implementation of BECCS	No comparison	Impact the competition for food and land in Brazil	Research and review articles
Is the CO_2 transportation stage a limitation for the implementation of BECCS in Brazil?	Brazil	CO_2 transportation	No comparison	Limit the implementation of BECCS in Brazil	Research and review articles
Are there regulatory barriers for the implementation of BECCS in Brazil?	Brazil	Regulatory barriers	No comparison	Difficult the implementation of BECCS in Brazil	Research and review articles

Source: author's elaboration.

2.2. Application of Boolean Connectors

To maximize the results found, to guarantee that the articles searched by the platform are more in line with what we look for, it is best to list the keywords, and then apply the Boolean operators to them [26]. With the application of the Boolean connectors, we have the final search terms for each research question. Thus, on each platform (PBi, Science Direct and Scopus), five different searches were performed, corresponding to the five different research questions. Table 2 presents these final search terms.

Table 2. Definition of search terms using Boolean connectors.

Research Question	Keywords	Boolean Connectors/Final Search Terms
What is the CO_2 mitigation potential of implementing BECCS in Brazil?	BECCS; Bio-CCS; mitigation; "negative emissions"; net-zero; Brazil	(BECCS OR Bio-CCS) AND (mitigation OR "negative emissions" OR "net zero" OR reduction OR diminution OR abatement) AND Brazil
What is the best bioenergy industry to provide CO_2 for BECCS in Brazil?	BECCS; Bio-CCS; "carbon capture"; "biogenic CO_2"; bioenergy; biofuel; Brazil	(BECCS OR Bio-CCS) AND ("carbon capture" OR "biogenic CO_2" OR bioenergy OR biofuel OR bioindustry) AND Brazil
What impact can the implementation of BECCS in Brazil have on food and land competition in the country?	BECCS; Bio-CCS; competition; distribution; food; land; security; Brazil	(BECCS OR Bio-CCS) AND (food AND land) AND (competition OR distribution OR security) AND Brazil
Is the CO_2 transportation stage a limitation for the implementation of BECCS in Brazil?	BECCS; Bio-CCS; transportation; road; pipeline; ship; Brazil	(BECCS OR Bio-CCS) AND (transport OR transfer OR distribute OR road OR pipeline OR ship) AND Brazil
Are there regulatory barriers for the implementation of BECCS in Brazil?	BECCS; Bio-CCS; regulation; law; legislation; Brazil	(BECCS OR Bio-CCS) AND (regulation OR law OR legislation OR rule OR directive OR guide) AND Brazil

Source: author's elaboration.

2.3. Definition of the Database and Search Criteria

To perform the search, the database chosen was the Brazilian platform Integrated Search Portal (PBi, in Portuguese: Portal Busca Integrada)—which is owned by the University of São Paulo, so its inclusion allows this article to expand its search to Brazilian journals—and the international platform Sciende Direct. As default, all the documents' fields were considered during the search, meaning that the selected documents presented the search terms in any of their fields. This was chosen with the objective of maximizing the number of documents found. However, only research and review articles were filtered. Table 3 summarizes the search criteria adopted for this systematic review.

Table 3. Summary of the criteria defined for searching the literature.

Search Criteria	
Databases	Integrated Search Portal, and Science Direct
Search fields	All fields
Document type	Research and review articles
Date of publication	2018–2022

Source: author's elaboration.

2.4. Definition of the Database and Search Criteria

After the five searches in each platform, the documents were gathered, and the duplicates were removed. From this moment forward, the researchers had no knowledge of which search terms generated the analyzed document. After this, the first screen applied was based on the article's keywords, following these criteria: all articles that had countries, continents, or economic groups in their keywords that were not Brazil, America, South America, or others that represent Brazil, were excluded; all articles that had medical-related terms in their keywords were excluded. This last criterion was adopted because in the medical field CCS can stand for Clinical Classification System, Chronic Coronary Syndromes, Canadian Cardiovascular Society, Chinese Cardiac Study, and others. The next step was to read the remaining article's abstract and to exclude those not focusing on BECCS and/or on Brazil.

It is important to highlight that BECCS stands for bioenergy with carbon capture and storage, so studies that researched biogenic carbon capture for products development, such as for the chemistry industry, were excluded. The CO_2 geological storage is an important stage of BECCS because it allows for the occurrence of negative emissions [3,5,8,9], whereas carbon usage can only postpone the return of the captured CO_2 to the atmosphere, introducing this CO_2 to a circular economy and expanding its lifecycle, but the CO_2 will eventually return to the atmosphere [30].

In addition, articles that evaluated the capture of carbon dioxide through biomass growth only were also excluded, because this process is part of an approach named nature-based solutions, which is also important to achieve the goals set in the Paris Agreement, but it is not BECCS [1].

3. Results

3.1. Introduction to Findings

The review initially identified 667 documents in the two databases used, which were combined for duplicates removal and screening. First, the documents were screened based on their title and keywords. Second, the remaining studies were filtered through abstract reading. In the final screening phase, the studies were screened based on their full-text content. Figure 1 summarizes the results of each step of the screening process. The inclusion and exclusion criteria were based on the research questions set for this research, therefore, only studies that explicitly analyzed BECCS in Brazil were included; these results are also shown in Figure 1.

3.2. General Aspects of Included Articles

Of the 24 studies included for review, 4 were published in 2018, 6 in 2019, 3 in 2020, 9 in 2021, and 2 in 2022. Figure 2 presents the distribution of the included articles according to the year of publication. In addition, Figure 3 shows the distribution of the included articles according to the scientific journal in which they were published, and it is possible to see that the International Journal of Greenhouse Gas Control was the most frequent, with 6 articles selected.

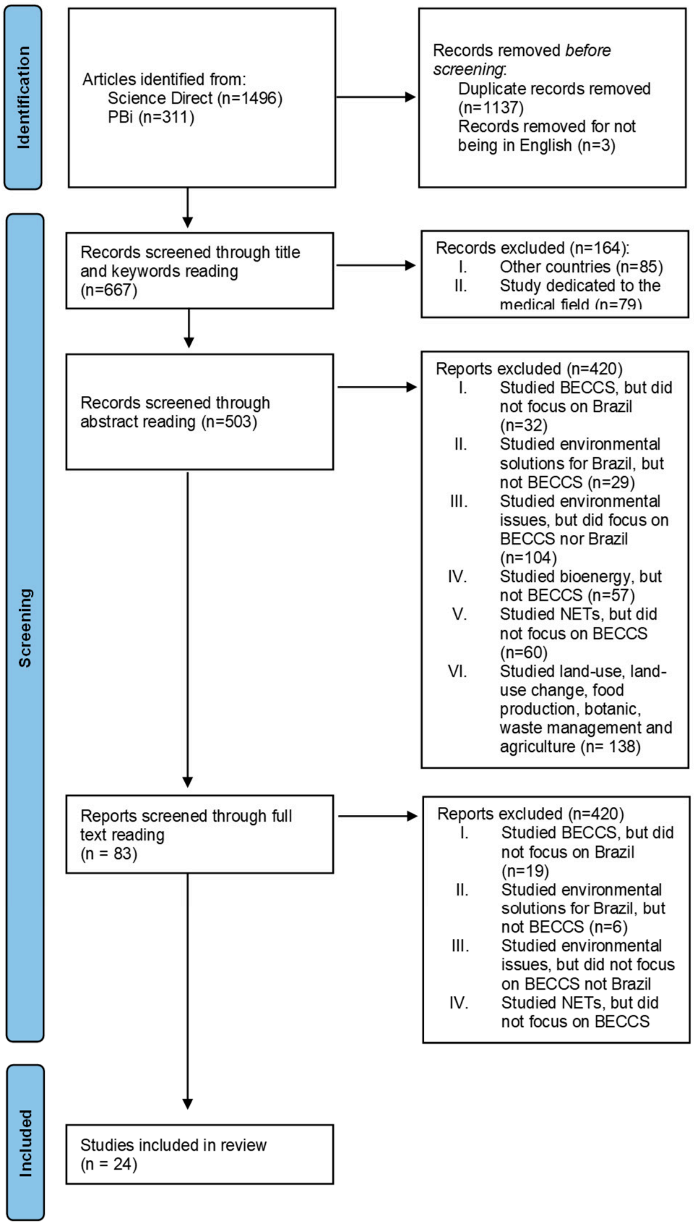

Figure 1. PRISMA flowchart for description of screening criteria and results. Source: author's elaboration.

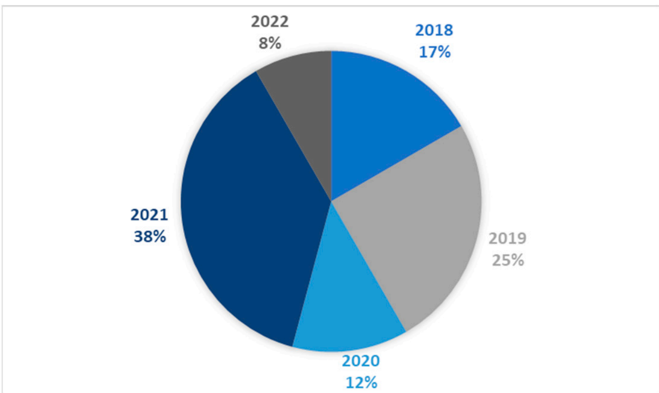

Figure 2. Distribution of included articles according to year of publication. Source: author's elaboration.

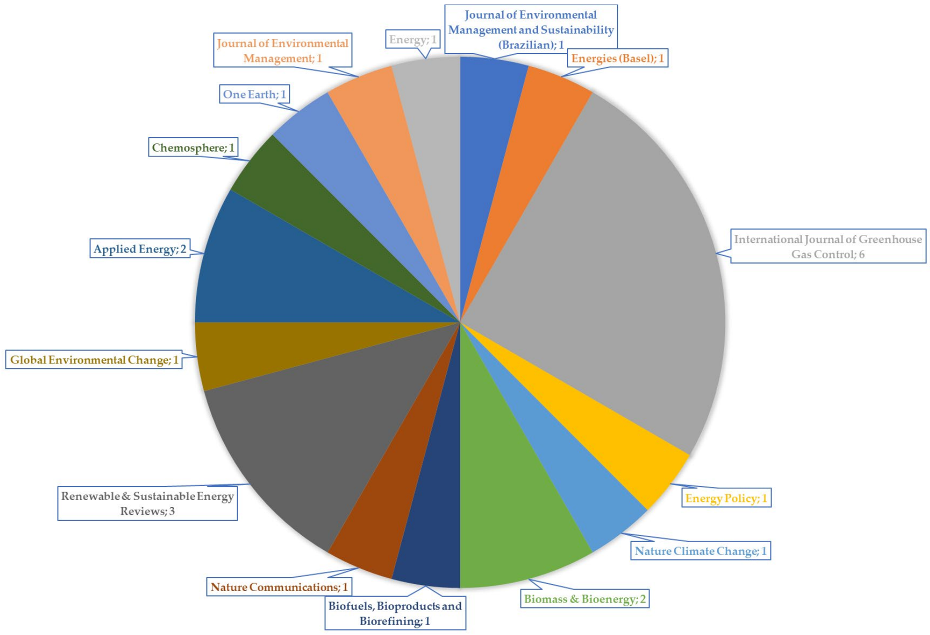

Figure 3. Number of included articles based on the journal in which they were published. Source: author's elaboration.

To understand the potential of deploying BECCS in Brazil, the following sections present the included articles, their methodologies, and results.

3.3. Technical, Economic, and Emissions Assessments of Developing BECCS in Brazil

3.3.1. Simulation of BECCS Connected to Ethanol Plants, and CHP Units in Ethanol Distilleries

Neto et al. [31] argue that the bagasse-fired combined heat and power (CHP) system is the biggest source of CO_2 emissions in ethanol distilleries in Brazil, and yet it is not commonly evaluated as a possibility for BECCS retrofitting. Thus, the authors simulate the application of a promising carbon capture process, named calcium looping (CaL), to a mid-south Brazilian cogeneration plant fueled with sugarcane bagasse. This simulation is named as Bio-Cal case, and it is compared to a base case that does not use CCS, and to an amine-based carbon capture unit (which is more largely used than the CaL process). Also, in both Bio-Cal and amine-based BECCS plants, the captured CO_2 is directed to enhanced oil recovery (EOR).

Based on this, the technical results show that the Bio-Cal case shows the largest gross and net electricity production, and a lower plant-specific CO_2 emission rate when compared to the amine-based case. In addition, the Bio-Cal plant captures 188 tCO_2/h, while the amine-based plant captures only 97 tCO_2/h. On the other hand, the plant capital costs for the Bio-Cal and amine-based cases are, respectively, $1434 million, and $429.2 million. Additionally, the total capital requirement (which represents the cost for each net kW produced) is almost 4 times higher for the Bio-Cal than for the amine-base. Thus, Neto et al. [31] conclude that although the Bio-Cal technology is more efficient and environmentally friendly, it is not yet economically feasible.

Still focusing on bioenergy CHP, Bressanin et al. [32] simulate a combined-cycle system for a biomass-based electricity cogeneration plant integrated to a sugarcane ethanol distillery in Brazil, and the addition of a carbon capture and storage complex. The results show that both electricity generation and carbon capture are not economic feasible in the current context but do become profitable when there is an increase in electricity prices and the implementation of a payment for avoided carbon emissions, respectively. In this context, the authors highlight the importance of the Renovabio Programme in Brazil and suggest the expansion of this Programme's benefits to the electricity generation industry [32].

Also, Wiesberg et al. [33] estimate the fixed capital investment (FCI), the labor, manufacturing, and utility costs (COM), and the carbon capture costs related to the addition of a CCS system to a CHP plant in a sugarcane-biorefinery in the Brazilian southeast region. To estimate these parameters, the authors simulate a plant with the CCS complex and one without, where the revenues in the BECCS case are achieved by selling CO_2 for EOR in the Petrobras' Campos Basin and selling CO_2 credits in a cap-and-trade system. The results show a 63.5% efficiency of the BECCS plant. The CHP plant without CCS showed an FCI of 68.7 MMUSD, whereas the CHP-BECCS has an FCI of 256 MMUS, in which 50–75% accounts for pipeline costs. In addition, manufacturing costs increased more than 40% in the BECCS case when compared to the CHP without CCS plant. In summary, the high costs—mostly due to the need to invest in pipeline infrastructure—and the low revenues—given the current carbon price—make the project economically unfeasible. Moreover, the authors emphasize that even though the carbon capture cost is within the literature range, it is still too expensive considering the current carbon price [33].

On the other hand, considering both CHP and distillation processes in ethanol plants in Brazil, Carminati et al. [34] simulate the retrofitting of a conventional large-scale sugarcane-biorefinery as a large-scale plantation-biorefinery connected to a combined-heat-and-power (CHP) system and to a carbon-capture-pipeline-EOR (Enhanced Oil Recovery) complex, where the carbon dioxide was captured during the fermentation for ethanol production and during the bagasse combustion for electricity generation. According to the authors, capturing the CO_2 during these two stages would allow for a high BECCS efficiency. In this case, retrofitting is simulated for a typical biorefinery plant located in the southwest region of Brazil, the CO_2 captured is transported through CO_2 pipelines and stored in deep-water offshore Pre-Salt Basin. Additionally, the project operates for 23 years, and four cases are evaluated (cold, warm, hot, and boiling) considering changes in external conditions, such as oil prices, energy demand, and cap-and-trade [34].

The base case simulates the biorefinery with CHP plant, but without carbon capture and storage. In addition to the base-case, four BECCS scenarios were implemented, being Cold, Warm, Hot and Boiling, with the efficiency parameters growing across these scenarios, as well as the oil price and cap-and-trade prices (these parameters affect only the economic analysis). Thus, comparing the simulated plants, the authors show that the BECCS-case recovers "more than 93% of its CO_2eq. production", which resulted in 781.0 kgCO_2eq negative emission per ton of sugarcane, and a total of 5.22 MtCO_2Eq/year drained from the atmosphere [34] (p. 12). However, considering the economic results, only the hot and boiling scenarios show positive NPV and payback periods for BECCS, but when comparing to the base case, they both show higher NPV and similar PB. This economic result is related to the technical aspects resulting from the simulation. As shown by the authors, BECCS-case has a greater power consumption than the base case, and 74% of the power consumed in the BECCS-case is allocated to CCS. In addition, [34] performed a sensitivity analysis for net present value (NPV) and payback (PB). The results show that, considering only NPV, the BECCS-case is always more attractive than the base case when oil prices are greater than 80 US$/bbl [34] (p. 12). Similarly, BECCS continues to be a better option if the cap-and-trade system provides carbon prices greater than 70US$/t$CO_2$.

Similarly, Milão et al. [35] and Restrepo-Valencia and Walter [36] use economic and thermodynamic evaluation to analyze a BECCS plant. These articles analyze the implementation of CCS to a large-scale sugarcane-based ethanol refinery, and a typical Brazilian sugarcane mill, respectively. The results in both articles show greater thermodynamic efficiency when comparing the projects to non-CCS plants. In the study by Restrepo-Valencia and Walter [36], carbon capture is feasible considering the fermentation and biomass combustion stages. However, these authors demonstrate that the CO_2 capture during fermentation is more efficient and should pre prioritized in case of limited economic resources.

Considering the economic evaluation, the results in Milão et al. [35] show that the revenues generated from selling the CO_2 abated to EOR are greater than the costs of implementing the CCS structure, which means a profit potential otherwise ignored. On the other hand, the revenues in Restrepo-Valencia and Walter [36] are not based on CO_2-to-EOR, but instead, on purchasing CO_2 credits. In this context, the BECCS project estimated by the authors is economically viable when using carbon credits indicated in the literature. Nevertheless, Restrepo-Valencia and Walter [36] argue that there is a lot of room for achieving economies of scale in the process, and consequently lowering the costs and improving the project's profitability.

Milão et al. [37] simulate three innovative distillation schemes for large-scale sugarcane-ethanol biorefineries, and analyze each scheme's ethanol production, power production through CHP, heat and steam demand, water usage, carbon emissions, and the possibility of adding a CCS complex. The distillation schemes vary among themselves in the attributes of the triple-column multi-effect distillation (MED) preconcentrator. Also, this research is formulated based on the Brazilian context, and the simulation is based on a typical large-scale Brazilian autonomous biorefinery. The results show that the complex plantation-biorefinery emits a total of 700 tCO_2/h, of which 39.7 tCO_2/h results from ethanol fermentation, 659.6 tCO_2/h from the CHP cogeneration, and the rest from the degassing scrubber and the sugarcane supply-chain. When applying the CCS complex to the plant, the simulation showed that 633.34 tCO_2/h could be captured, resulting in a negative emissions capacity of 5.1×10^6 $tCO_2/year$ [37]. In addition, authors assume that the captured CO_2 should be destined to EOR but do not perform a financial analysis of this possibility.

3.3.2. Simulation of BECCS Connected to Biodiesel Plants

Tagomori et al. [38] apply a georeferenced and process analysis to estimate the potential of producing diesel biofuel based on forestry residues in Brazil. To evaluate the mitigation potential of this technology, the authors estimate the process with and without the implementation of CCS. The results identified 21 production hotspots, allowing the deployment of 27 facilities across the country, mostly concentrated in the South, Midwest, and Southeast region of Brazil. In this context, because the Fischer-Tropsch synthesis require proper CO_2 and H_2S removal, CO_2 capture is intrinsic to the process simulated in the article, meaning that the 21 hotspots identified for biodiesel production are also hotspots for the implementation of BECCS. Therefore, the simulations found a potential of capturing 184.9 tCO_2/h when using eucalyptus as feedstock, and 191.6 tCO_2/h when using pine, and a total mitigation potential of nearly 25 $MtCO_2/year$ [38] (p. 141).

However, the economic evaluation performed in Tagomori et al. [38] showed that the production of biodiesel based on forestry residues is not yet cost-competitive when compared to conventional fossil-diesel [38]. In this context, the implementation of CCS could improve the revenues for the biodiesel plant by selling CO_2, but the authors argue that the break-even point would be reached only if the carbon price reaches a range of 84–94 US$/$tCO_2$ [38] (p. 146). From this study, it is possible to argue the technical potential of implementing BECCS, but the economic potential is not yet clear.

3.3.3. Simulation of BECCS Connected to Electricity Generation Plants, except CHP Units in Ethanol Distilleries

Poblete et al. [39] simulated a biogas plant sourced by sewage-water and sewage-sludge as a profitable bioenergy producer, which exports reusable water and electricity, and promotes carbon capture directed to EOR. The simulation parameters were based on Brazilin data, such as the country's biogas production, electricity price and others. According to the results, the biogas-BECCS plant removes 5.98 $kgCO_2$ for each ton of reusable water produced and removes 0.76 tons of CO_2 per MWh exported to the electricity grid, which is more environmentally friendly than oil- and gas-fired thermoelectric plants, whose carbon emissions are, respectively, of 0.76 and 0.53 tons of CO_2 per MWh exported to the grid [39].

3.3.4. Simulation of BECCS Connected to Industrial Processes

Tanzer et al. [40] simulated the implementation of BECCS in multiple steelmaking routes, analyzing the life cycle emission of 45 cases, in which some only adopted CCS to the currently fossil-fuel steel-making process, others only changed the fuel source to bioenergy (but without CCS), and other cases used bioenergy and CCS to the steelmaking process (BECCS scenarios). As to the biogenic source of energy, the authors used charcoal, which is frequently used in Brazilian steelmaking industries, and wood chips. The results showed that the cases that added CCS alone presented a higher decrease in net CO_2 emissions than the bioenergy-only cases. However, the BECCS cases resulted in greater net CO_2 reductions than the sum of CO_2 reductions of the other two possibilities. Also, of the five steelmaking technologies analyzed (they vary in efficiency, and other technical aspects), the BECCS case were able to generate high net CO_2 removal for two, and small net CO_2 removal for three, but all showed net CO_2 removal. However, it is worth highlighting that, in order to achieve these results, it was necessary to include CO_2 capture and storage on all flue gases during the steelmaking process, as well as during bioenergy production [40].

3.4. Biomass Availability as the Greatest Endowment of Brazil for BECCS Implementation

Van Soest et al. [41] perform a literature review to present the variation in results across integrated assessment models (IAMs). In this context, the authors argue that the implementation of BECCS in Brazil is important not only for this country's mitigation target, but also to the achievement of the Paris Agreement in general. The authors' arguments are based on the current and projected source availability (biomass) in Brazil. However, they do not consider storage capacity, or economic feasibility.

Mantulet et al. [42] use the scenario-building model named POLES, which has already been used in IPCC's studies, to analyze the production and consumption of bioenergy in the world, to respect the carbon budget of 900 $GtCO_2eq$ emissions until the end of the century, which is compatible with the 2 °C warming limit goal in the Paris Agreement. The authors build 2 scenarios: (i) a baseline scenario where the current climate policies are maintained with no further efforts, and (ii) a 2 °C scenario where a carbon tax is implemented. In addition, the authors assess regional potential to apply the methanization and gasification (in this last CCS can be implemented) technologies to help achieve the goal. Based on this, the results show that Brazil is an important biomass supplier in the future because in 2050 the country will use only between 40% and 55% of its massive proportion to produce bioenergy, and the growth is very high until 2100 (between 70% and 80%). Most part of this bioenergy is exported in the form of biofuel. Additionally, because of the potential of expending its bioenergy production and exportation in the future, Brazil is part of the few countries that will act as biomass traders, along with Australia, Russia, and Canada. On the other hand, accounting for both exportation and self-consumption, the top producers are China, USA, and Brazil. Regarding the technology employed, the results show a 50% more gasification than methanization in Brazil, which shows a potential of implementing BECCS [42].

Asibor et al. [43] discuss the deployment of carbon dioxide removal technologies (CDR) in different countries, based on responsibility, capability, and requirement. According to the authors, Brazil shows a potential of cumulative removal of 2.20 $GtCO_2$ through forestation, 2.65 $GtCO_2$ through enhanced weathering, 2.50 GtC02 through direct air carbon capture and storage (DACCS), 3.60 $GtCO_2$ through BECCS, and 3.00 $GtCO_2$ through biochar. The availability of biomass was the most important criteria to place Brazil as an important country for the future development of BECCS [43].

3.5. Importance of Implementing BECCS in Brazil for World-Wide Mitigation Targets

Morris et al. [44] develop a method for modeling the competition between different electricity technologies, based on the relation of each technology's costs and the revenue for their sold electricity (named markup by the authors), so that if the markup is greater than one, it is not economically feasible by itself. The calculation of the costs includes capital costs, fixed and variable operating and maintenance costs, fuel costs, transmissions and distribution costs, and backup equipment for renewable technologies. In this context, Canada showed the greatest markup of the studied countries, with a value of 5.68, Mexico the smallest (2.12), and Brazil had a markup of 2.68 (the same as Russia).

Fajardy and Mac Dowell [45] assess the future deployment of BECCS in different regions, based on their CO_2 removal targets, energy sectors, biomass supply, CO_2 storage capacity, and local costs to remove CO_2 from a bioelectricity plant (only BECCS plant considered in the study). Based on this, the authors calculated the levelized cost of electricity and the breakeven negative emission credit (NEC), which represent the value that the negative emission credit should have so that its value, added to the revenue from selling electricity, equals the costs of the total BECCS system. Based on this, the results show that because of Brazil's low cost to implement BECCS and high energy price, the country was the only one to show a negative NEC in the second half of the century, which could become an important revenue for Brazil. However, Brazil becomes a BECCS player only in the scenarios with high emissions reduction targets and cooperation among countries, because the authors assume limited CO_2 storage capacity in Brazil, so the biomass would have to fuel a BECCS plant elsewhere. This context results in high costs for the large-scale deployment of BECCS in Brazil (mainly due to CO_2 transportation), and thus it is only feasible in more environmentally aggressive scenarios. This shows the importance of improving the mapping of probable CO_2 storage sites in Brazil.

The same complaint was presented by Lap et al. [46], since the authors build different technology scenarios for Brazil, aiming at achieving the 2 °C target set under the Paris Agreement and the estimated energy demand, but conclude that given the status of BECCS in the country (research and development stage), and the lack of information regarding transportation costs, seasonality, and reservoir capacity, it is not possible to draw a conclusion about the role that the bioenergy with carbon capture and storage technology will have on the Brazilian mitigation pathway. In this context, the only article that provided information about the potential capacity of storing CO_2 in Brazil was Wei et al. [47], in which the authors point out that Brazil could provide nearly 7% of the global CO_2 storage capacity.

In addition, Audoly et al. [48] analyze 342 emission-reduction pathways, extracted from the Intergovernmental Panel on Climate Change (IPCC), to study the carbon content of electricity technologies and provide policy-relevant insights about them for policymakers. Thus, focusing on Brazil, the authors argue that the country does not show need for BECCS to reduce the emissions in the electricity sector, because the Brazilian electricity matrix already present high share of renewable and low-carbon energies.

3.6. Potential Impacts on Food and Land Competition and Availability

Babin et al. [8] perform a literature to assess the challenges and potential to implement BECCS in the world and argue that the Brazilian land distribution can help ease the food and energy land competition. In this context, the authors mention studies that highlight the possibility to use moderately devastated land in Brazil to foster energy crops, instead of healthy land, and articles that have proven the economic and technical feasibility to fuel BECCS power plants in the country with forestry residues.

In addition, Doelman et al. [49] apply the Shared Socio-economic Pathways (SSPs) to the IMAGE 3.0 integrated assessment model (IAM) aiming to understand the impacts on land-use change and potential land-based climate change mitigation approaches. Although the article does not focus on the direct implementation of BECCS in Brazil, it discusses the areas where biomass production in the future can have the smaller effect on land and food competition, even in the scenarios with BECCS deployment. In this context, the scenarios show that great part of today's productive areas will be abandoned (especially north-west and central of Brazil), showing a high potential for bioenergy production. On the other hand, the authors argue that in the scenarios with higher energy demand, most biomass for bioenergy generation will come from deforestation in Brazil and the Gran Chaco region in Bolivia, Argentina, and Paraguay [49].

3.7. Aspects of CO_2 Transportation for BECCS Implementation

Focusing on the transportation stage of the BECCS lifecycle, Silva et al. [50] analyzed the economic and technical viability of capturing CO_2 from 236 Brazilian ethanol distilleries and selling it to EOR operation in the Campos Basin. The authors designed three different transportation strategies: (1) CO_2 pipeline transportation from the distilleries to a single hub located in the São Paulo state, followed by a single pipeline to the Campos Basin; (2) CO_2 road transportation from distilleries to a single hub located in the São Paulo state, followed by a single pipeline to the Campos Basin; (3) CO_2 pipeline transportation from the distillery to the nearest hub—considering the construction of 8 hubs throughout the country—followed by CO_2 pipeline transportation from each hub to the Campos Basin.

The results have shown that the most economically viable strategy is the third—composed of 8 hubs—because of economies of scale, with a network abatement cost of US$ 42/ton of CO_2 [50]. The inter-modal and the single-hub scenarios presented a network abatement cost of US$67.7/ton of CO_2 and US$63.63/ton of CO_2, respectively. These results provide interesting insights about the implementation of BECCS in Brazil, because the possibility of using the road modal decrease the transportation costs for small scale distilleries located far from the hub. For these companies, the use of the road modal made the integration to the hub economically feasible. According to the authors, for the 236 distilleries studied, 70 showed better results in the inter-modal scenarios, which could be explained by not needing to allocate capital to pipeline construction and specialized personnel to deal with the bureaucracy involved, and by the preponderance of road transportation in Brazil. On the other hand, the use of road transportation can decrease the negative emissions potential of implementing BECCS, since many trucks are fueled by diesel.

Similarly, Tagomori et al. [51] simulate a CO_2 transportation network to transport the CO_2 captured from ethanol distilleries in the center-east region of Brazil. Because the seasonality and idleness of this CO_2 source is a challenge (because of the seasonality of biomass harvest), the authors evaluate what other CO_2 sources could be combined with the bio-CO_2 from ethanol distilleries to help create economies of scale and ease the transportation costs faced by these BECCS plants. In this context, four scenarios are analyzed: (i) baseline, with CO_2 from distilleries' ethanol fermentation only; (ii) case A, with CO_2 from distilleries' ethanol fermentation and biomass cogeneration; (iii) case B, which adds CO_2 from oil refineries to the case A scenario; and (iv) case C, in which CO_2 is captured from distilleries' ethanol fermentation, and from oil refineries.

Thus, the case that showed the lowest levelized costs was case C, because of the regularity shown by the CO_2 supply from oil refineries, but also because the cost to capture CO_2 from biomass cogeneration (in cases A and B) increased the overall costs more than it helped with CO_2 flows. In contrast, case A showed the highest costs, because even though the increase of CO_2 flow from biomass cogeneration helped easing the costs for transportation, the increase in costs from CO_2 capture in biomass cogeneration was greater. A similar result was observed in case B, where the increase in costs to capture the CO_2 from biomass cogeneration was greater than the benefits provided from oil refineries. In conclusion, authors argue that increasing CO_2 flow to create economies scale should not be the only goal when planning a transportation case (given the results in cases A and B). Additionally, other transportation modals should be evaluated, as well as different hubs geographic distribution [51].

3.8. Brazilian Regulatory Efforts towards CCS, CCUS and BECCS

Netto et al. [52] apply a legal comparative methodology to defend the implementation of BECCS in Brazil. By examining the policies implemented in other countries with the focus of achieving the goals set at the Paris Agreement, the authors also highlight the importance of the Renovabio Programme for the development of CCS and BECCS in Brazil [52].

Machado et al. [53] perform an interview with experts from different areas—from industry to academia—about the implementation of CCS in Brazil, including BECCS, and more specifically about the uncertainties in the future of CCS in Brazil. Brazil was chosen as the case study because of the country's knowledge on using CCS for Enhanced Oil Recovery (EOR). A total of 12 experts are interviewed, and the uncertainty parameters about the implementation of CCS in Brazil involve the volume of CO_2 captured and stored, CCS policy, CCS investment, and the government share in the investments. The results show that most experts mentioned the Biofuel Decarbonisation Credit (CBio) as an important financial instrument to attract investments for biofuel production and for BECCS, since this instrument provides bonus for biofuel producers that prove negative emissions. However, they argue that current CBio price is too low to draw investments to BECCS plants. In contrast to the CBIO cap-and-trade strategy, experts argue that the carbon market is the most probable incentive instrument to take place in the country, followed by tax exemptions, such as the Brazil's tax exemptions adopted for the infrastructure and energy sectors. Another approach mentioned is the taxation of CO_2 emissions. On the other hand, experts did not provide an expect timeline for the implementation of these policies, since the first law for CCS operation started its approval process in 2022 [53].

4. Discussion

4.1. CO_2 Mitigation Potential of BECCS in Brazil

Some of the analyze articles simulated the effective implementation of BECCS plants in Brazil and were able to provide reliable expectation about the mitigation potential that this technology may have in Brazil. Table 4 presents a summary of these article's findings. However, no article discussed how these mitigation values can be checked or supervised by the government. In other words, no article raised or evaluated methodologies to help with the right emissions accounting in the context of BECCS implementation, which is an important aspect raised by Stavrakas et al. [9], and Silveira et al. [4].

Table 4. Summary of articles that evaluated the CO_2 mitigation potential of implementing BECCS in Brazil.

Article	Summary of the Article's Content	Mitigation Results Found
Neto et al. [31]	Simulation of a calcium looping (CaL) carbon capture process, and an amine-based carbon capture process, to a mid-south Brazilian cogeneration plant fueled with sugarcane bagasse.	CaL carbon capture process: captures 188 tCO_2/h. Amine-based carbon capture process: captures 97 tCO_2/h.
Carminati et al. [34]	Simulate the carbon capture during the fermentation and the bagasse combustion stages, in a conventional large-scale sugarcane-biorefinery	781.0 $kgCO_2eq$ negative emission per ton of sugarcane, and a total of 5.22 $MtCO_2Eq/year$ drained from the atmosphere.
Milão et al. [37]	Simulate the carbon capture during the fermentation stage in a large-scale sugarcane-ethanol-biorefinery in Brazil.	633.34 tCO_2/h could be captured, resulting in a negative emissions capacity of 5.1×10^6 $tCO_2/year$.
Tagomori et al. [38]	Apply georeferenced and process analysis to estimate the potential of producing diesel biofuel based on forestry residues in Brazil.	When using eucalyptus as feedstock: potential of capturing 184.9tCO_2/h. When using pine as feedstock: potential of capturing 191.6 tCO_2/h. Total mitigation potential of nearly 25 $MtCO_2/year$.
Poblete et al. [39]	Simulate a carbon capture and storage complex in a biogas platn sourced by sewage-water and sewage-sludge.	Removal of 5.98 $kgCO_2$ for each ton of reusable water produced. Removal of 0.76 tons of CO_2 per MWh exported to the electricity grid.
Asibor et al. [43]	Discuss the deployment of carbon dioxide removal technologies (CDR) in different countries, based on responsibility, capability, and requirement.	Brazil shows a potential of cumulative removal of 3.60 $GtCO_2$ through BECCS.

Source: author's elaboration.

On the other hand, Silva et al. [50], Babin et al. [8], and Doelman et al. [49] do provide insights on how to lower the emissions throughout the BECCS life cycle, but they are restricted to the transportation [50] and land use [8,49] stages.

4.2. Highlighted Industries in the Review

From the Results section, it was possible to see that the biofuel industry in Brazil, especially focusing on the production of ethanol, shows the greatest potential for the implementation of BECCS. To produce ethanol, the technical factors involving the retrofitting for BECCS plants are very advanced, with simulation regarding the distillation stage, CHP, and both. Figure 4 shows the distribution of the analyzed studies according to the bioenergy use. However, it is possible to argue that there are areas of application still understudied, such as waste-to-energy and electricity generation.

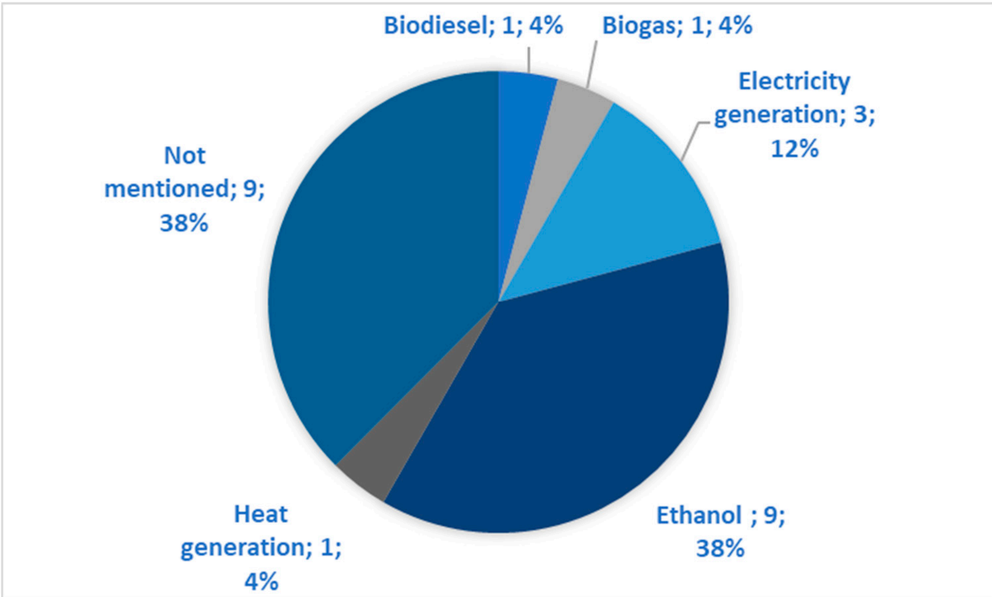

Figure 4. Number and share of studied articles according to the bioenergy use. Source: author's elaboration.

4.3. Economic Viability

Of the 24 articles examines, 10 performed economic analysis [31–39,50], in which the authors evaluated the economic factors of BECCS plants in Brazil by selling the captured CO_2 to EOR activities [31,35,37,39,50], by acquiring carbon credits (when the CO_2 is destined to permanent geological storage) [32,36,38], or a combination of both [33,34]. Of the ones that destined the CO_2 to EOR, only Milão et al. [35] and Silva et al. [50] have found profitable results, while the others have mentioned this activity but limited the research to the potential revenues without comparing the costs. On the other hand, of the studies that based their revenue in carbon credit acquisition, or carbon credit and EOR, none have found profitable results, arguing that the current carbon price is still too low to justify an investment in BECCS in Brazil [32–34,36,38]. In summary, the sum of the investment and operating costs of capturing, transporting, and storing CO_2 from bioenergy sources is still not offset by the income provided by current carbon credits. However, the revenues from oil production (final product of the EOR activity) were capable of offseting these costs in [35] and [50], thus making the BECCS plants profitable.

In this sense, the regulation approach is also related to the need of implementing more audacious carbon-pricing policies to make the investment in BECCS feasible, even when not connected to an EOR initiative [52,53]. The evaluation of possible pathways for the Brazilian regulation and policies regarding the promotion of BECCS is performed by Araújo et al. [54], Costa and Musarra [55], and Silveira et al. [56].

On the other hand, parallel to the importance of increasing the carbon price, other economic strategies are related to creating economics of scale and lowering the costs of implementing BECCS in Brazil. In this framework, due to the existing infrastructure and the dispersion of biomass sources in the Brazilian territory, the implementation of BECCS in the southeast region represents a low-hanging-fruit for the country. However, the costs increase significantly as it becomes necessary to expand the CO_2 capture away from the southeast region, mainly due to transportation restrictions [50,51].

4.4. Gaps Identified in the Literature

The literature pointed the lack of information regarding transportation costs, the seasonality that BECCS may face in Brazil, and the reservoir capacity in the country [8,46]. This is also shown in the absence of studies focusing on the storage stage of the BECCS life-cycle [45–47]. In addition, Hayman et al. [15] indicate the need for more studies regarding the risk of water constraint, and land competition between bioenergy and food production if BECCS is to be deployed in large-scale in Brazil.

4.5. This Article's Limitations

It is worth highlighting that this article has not provided a comprehensive distribution of the costs throughout BECCS stages, i.e., capture, transportation, and storage. Thus, future research will focus on this limitation, aiming to provide a diagram of the levelized costs of energy, net present value, and other indicators, based on the work performed by [57] and [58]. Additionally, this article could not contribute to the discussion of carbon emission reduction accounting. Therefore, future study should improve the research question to filter articles that address this important issue. This work has provided a broad review on the demand side for the implementation of BECCS in Brazil, however, an assessment of the prerequisites for joining the supply side are still required in order to draw a complete picture of the effective potential of BECCS in the country.

5. Conclusions

This article aimed at this providing a comprehensive assessment of the effective potential of implementing BECCS in Brazil. To achieve this goal, a systematic literature was performed, with the following research questions: (i) "what is the CO_2 mitigation potential of implementing BECCS in Brazil?", (ii) "what is the best bioenergy industry to provide CO_2 for BECCS in Brazil?", (iii) "what impact can the implementation of BECCS in Brazil have on food and land competition in the country"; (iv) "is the CO_2 transportation stage a limitation for the implementation of BECCS in Brazil?", and (v) "are there regulatory barriers for the implementation of BECCS in Brazil?"

The searching process identified 667 studies, of which, after selection and screening, 24 were analyzed. In these, the most common topic of research was the simulation of BECCS plants in ethanol distilleries, considering both the distillation and combined heat and power stages. On the other hand, the food and energy competition for land, and the regulatory barriers still need to be further studies.

Moreover, it was possible to organize the main topics raised by the literature in three: regulation approaches, economic strategies, and need of further studies. The first is related to the need of better regulations to improve the revenues of BECCS projects in Brazil when they are no directed to EOR. On the other hand, the economic strategies concern the need for economies and scale to lower the costs of this technology in the country, especially in the transportation stage. Lastly, more studies are needed in the following areas: transportation costs, seasonality, reservoir capacity, risk of water constraint, and land competition between energy and food production industries.

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