

Socio-Environmental Impacts Associated with Onshore Wind Turbines in Brazil: A Systematic Literature Review (2020–2025)

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Abstract

Wind energy has gained prominence as a sustainable alternative for power generation. In Brazil, this type of renewable source gained greater visibility after the 2001 energy crisis, which accelerated the search for new energy sources. Currently, only onshore wind turbines are installed in Brazil, particularly in the Northeast, South, and Southeast regions. This study presents a systematic review that aims to understand the socio-environmental impacts associated with the deployment of onshore wind turbines in the Brazilian territory, analyzing studies published between 2020 and 2025 across the Scopus, Web of Science, and Google Scholar databases. The results indicate that current mitigation strategies could be further enhanced in view of the scale of the problems. It concludes that the sustainability of wind energy in Brazil depends on the urgent adoption of robust mechanisms for community participation, and zoning that excludes socially and ecologically sensitive areas. The study suggests that there may be a risk of reproducing in the transition toward ‘clean energy’ historical patterns of environmental and social injustice.

Keywords: wind energy; socio-environmental impacts; wind turbines; Brazil

1. Introduction

The global pursuit of replacing non-renewable energy sources with sustainable alternatives drives the search for new forms of energy production. Among these, wind energy stands out, in which wind turbines are used to convert the kinetic energy of the wind into electricity. This form of energy has come to prominence in the transition towards a system less reliant on the combustion of fossil fuels, thereby contributing to the reduction in greenhouse gas emissions [1,2].

The first wind turbine in Brazil was installed in 1992 through a partnership with a Danish institute on the island of Fernando de Noronha, in the state of Pernambuco [3]. However, it was not until the 2001 energy crisis that wind energy began to experience significant growth in Brazil. The year 2001 remains in the memory of Brazilians not only for the economic impact of energy rationing but also because of the inconvenience caused to the public by the power outages [4].



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Because of the crisis in the electricity sector, Brazil undertook a series of governmental initiatives aimed at expanding the energy matrix and reducing the predominance of hydroelectric generation within the national electricity system, particularly in a context of growing energy demand [5]. In the national context, wind energy is regarded as strategic for the diversification of the energy matrix, capable of ensuring supply security and driving regional development.

Wind farms in Brazil are predominantly concentrated in the Northeast, where wind conditions are particularly favorable. This region accounts for the vast majority of the country's installed wind power capacity [6,7]. Growth has been especially pronounced in the states of Rio Grande do Norte, Ceará, Bahia, and Piauí, which are emerging as key hubs for the sector's expansion. These areas benefit from strong and steady winds, which are essential for the efficient operation of wind turbines. In addition, the country's geographic characteristics—particularly its extensive coastline (over 8500 km) and favorable climatic conditions—support the development of onshore wind farms in coastal regions. As a result, Brazil holds a prominent position in the global wind energy sector, ranking fifth worldwide in installed onshore wind power capacity [8], behind China, the United States, Germany, and India.

However, the expansion of wind farms also poses socio-environmental challenges. Such projects require large areas for installation, which can generate conflicts with local communities and produce environmental impacts, such as disruption of local ecosystems [9]. Therefore, such problems require strategies that align the operation of the farms with social and environmental responsibility.

According to Aldabó [10], sustainable energy generation, as a social enterprise, has a responsibility to promote regional development through: (i) local energy supply; (ii) the establishment of adequate infrastructure; and (iii) the implementation of sociocultural support programs. Clean energy production must go beyond simply avoiding the emission of pollutants. It is necessary to establish a balance between the exploitation of natural resources and human needs, as well as to prioritize the mitigation of both pollutant generation and adverse effects at all stages of the production life cycle, making processes more efficient and more environmentally friendly. Therefore, it is essential to investigate the impacts generated by this technology.

In the scientific literature, both positive and negative aspects of wind energy generation projects can be identified. The main positive aspect is the reduction in CO₂ emissions and other polluting gases in the atmosphere when compared to technologies that rely on fossil fuels. However, when analyzing the life cycle of turbines (LCA), polluting gas emissions still occur during the manufacturing, installation, and maintenance phases [11,12]. In addition, wind power generation has several negative environmental impacts: (i) noise generated by the turbine rotor; (ii) visual impact, which includes the alteration of a natural landscape and the shadow flicker effect (or stroboscopic effect), when the rotating blades create intermittent, pulsating shadows that can cause visual discomfort in areas near the turbines on sunny days [13]; (iii) impacts on wildlife, particularly birds and bats; (iv) soil impacts, including soil erosion and deforestation; (v) interference with electromagnetic waves, caused mainly by the movement of metallic blades; (vi) lightning generated by towers (lightning from towers or upward lightning), a type of electrical discharge that begins from tall objects on the ground (such as wind turbines) and propagates towards clouds, potentially causing damage to blades, electrical components, or even triggering fires, thereby posing risks to people, fauna, and flora in the surrounding area [14].

In Brazil, reports of environmental impacts associated with wind turbines are more recent, and also quite significant. Therefore, this study aims to contribute to this field by presenting a systematic literature review, with the purpose of understanding the main

socio-environmental impacts generated by the deployment of onshore wind turbines in the country. The study is based on the most recent scientific literature, produced between 2020 and 2025, given that robust reviews for the preceding period have already been documented—such as in Pinto et al. [15], Albuquerque et al. [16], and Gorayeb et al. [17]. In those reviews, the authors highlighted the impact of some of the principal environmental effects of wind energy in Brazil, focusing on the initial phase of this technology's implementation in the country.

In line with the aforementioned studies, authors such as Paiva and Lima [18] and Silva et al. [19] deepened the analysis of socio-environmental conflicts and the perceptions of traditional communities in the face of these developments. At the same time, Torres Júnior et al. [20] discussed the socioeconomic impacts and the generation of green jobs. This body of academic work, consolidated prior to 2020, reflects a specific context of initial expansion and the identification of the first impacts. The 2020–2025 timeframe is justified by the need to capture the new phase of expansion of the sector.

Compared with the reviews consolidated before 2020 [15–17], the 2020–2025 literature suggests an evolving rather than merely repeating pattern of impacts. Whereas earlier work emphasized the initial land-use and habitat effects of the sector's first wave of expansion, the more recent literature increasingly documents cumulative and secondary effects of a maturing installed base—sedimentation-driven changes to interdunal lagoons and rivers and effects on aquifer recharge—as well as a markedly stronger focus on self-reported mental-health outcomes and procedural and territorial-injustice framings, which were largely absent from the pre-2020 literature. Evidence of resulting shifts in siting practice or licensing criteria remains limited, however, and is identified here as an open question for future research.

To move beyond a purely descriptive cataloguing of impacts, this review adopts energy justice as an explicit analytical lens, drawing on the tripartite framework of distributive, procedural, and recognition justice. Distributive justice concerns who bears the environmental and social costs of wind-farm deployment and who captures its economic benefits; procedural justice concerns the quality, timing, and inclusiveness of consultation and licensing processes; and recognition justice concerns whether the land rights, livelihoods, and cultural attachments of affected communities are acknowledged and respected. Concepts introduced by the studies reviewed here, such as 'green grabbing' and the 'necropolitics of the winds', are read in this review as extreme expressions of a failure of recognition justice. This framework is used in Section 3.9 to interpret cross-cutting patterns in the reported impacts and is revisited explicitly in the Conclusion (Section 4).

The remainder of this paper is organized as follows. Section 2 (Methodology) describes the systematic approach adopted, including the study selection criteria applied to publications from 2020 to 2025 across the Scopus, Web of Science, and Google Scholar databases. Section 3 (Results and Discussion) examines the reported environmental impacts based on scientific evidence, with emphasis on: (i) habitat fragmentation and loss of plant biodiversity; (ii) wildlife mortality and disturbance; (iii) soil degradation and compaction; (iv) impairment of water resources; (v) territorial conflicts and socio-environmental injustice; (vi) noise pollution and health impacts; and (vii) landscape change and environmental perception. Section 3.9 then draws on this evidence to identify cross-cutting explanatory factors behind differentiated community responses, and Section 3.10 discusses the limitations of the review. Finally, Section 4 (Conclusions) summarizes the main findings of the study.

2. Methodology

The methodological design of this systematic review was based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [21] to ensure transparency, reproducibility, and methodological rigor. The research question was structured using the Population, Exposure, and Outcome (PEO) framework, an adaptation of the PECO approach proposed for evidence synthesis in exposure-based studies [22]. The PEO framework enabled the definition of the search scope and the establishment of rigorous eligibility criteria and is particularly suitable for reviews investigating environmental and socio-environmental exposures in which an explicit comparison group is not required. Within this framework, the Population corresponded to communities and ecosystems located in the vicinity of onshore wind farms in Brazil, the Exposure to the deployment and operation of these wind farms, and the Outcome to the reported socio-environmental impacts.

The literature search was conducted across indexed databases of recognized scientific relevance using predefined keywords combined through Boolean operators. Searches were performed in Scopus, Web of Science, and Google Scholar, covering publications from 2020 to 2025. The last search conducted across these three databases, using the search terms and article counts indicated in Table 1, took place in June 2026. Records identified through the database searches were independently screened by five reviewers, organized into two pairs, with a fifth reviewer acting as arbiter in cases of disagreement. Screening was conducted in two sequential stages: (i) evaluation of titles and abstracts and (ii) full-text assessment. At each stage, the members of each pair applied the pre-established inclusion and exclusion criteria independently; cases without agreement within a pair were referred to the arbiter reviewer, whose decision was considered final. Studies meeting all inclusion criteria were retained for data extraction and synthesis. This systematic review was not prospectively registered, and no prior protocol was prepared.

Table 1. Study selection process.

Database	Keywords	Results	Selected
Scopus	“Wind energy” and “Brazil” and (“impact” or “environmental”)	94	9
	“energia eólica” and “Brasil”	4	0
	“wind energy” and “Brazilian” and (“impact” or “environmental”)	45	3
Web of Science	“Wind energy” and “Brazil” and (“impact” or “environmental”)	32	1
	“energia eólica” and “Brasil”	5	0
Google Scholar	“Wind energy onshore” and “Brazil” and (“impact” or “environmental”)	75	9
	“energia eólica onshore” and “Brasil” and (“impacto” or “ambiental”)	303	11

To ensure the relevance and consistency of the evidence base, studies were included if they met all of the following criteria: (i) publication between 2020 and 2025; (ii) focus on wind energy developments located in Brazil; (iii) investigation of onshore wind farms; (iv) assessment of socio-environmental impacts on local communities and surrounding environments; and (v) publication in English or Portuguese.

The following exclusion criteria were applied during the selection process: (i) studies exclusively addressing wind turbine technologies without discussing their socio-environmental impacts; (ii) studies focused on offshore wind energy projects; (iii) studies that did not provide specific evidence related to the Brazilian context; (iv) undergraduate monographs, master’s dissertations, doctoral theses and conference abstracts; (v) duplicate records identified across the searched databases; and (vi) studies lacking direct thematic relevance to the objectives of this review.

Following full-text screening, data were systematically extracted from the included studies and subsequently synthesized by the authors. The extracted data were subsequently synthesized using both qualitative and quantitative approaches. In the qualitative synthesis, findings were organized into thematic categories and analyzed descriptively, with emphasis on identifying recurrent patterns, convergences, divergences, and knowledge gaps in the current literature. Quantitative information, when available, was summarized to support the characterization of publication trends and the distribution of reported impacts across the selected studies. The seven thematic impact categories presented in this review were derived inductively from the data rather than defined a priori. Following a process of floating reading and open coding of the included studies, codes were grouped by semantic similarity and iteratively refined through constant comparison, resulting in the seven categories reported in Section 3.

To assess the methodological quality of the included studies, this review applied the Mixed Methods Appraisal Tool (MMAT), version 2018, which allows the appraisal of qualitative, quantitative, and mixed-methods designs within a single framework. Each of the 33 included studies in Table 2 was first classified into one of the five study-design categories covered by the tool—(1) qualitative, (2) randomized controlled, (3) non-randomized quantitative, (4) quantitative descriptive, or (5) mixed methods—and was then assessed against the five corresponding quality criteria for that category, with responses recorded as Yes, No, or Can't tell. No included study used a randomized controlled design, so category (2) was not applied; for mixed-methods studies, the corresponding qualitative and quantitative components were also appraised against their respective criteria. The complete appraisal, including the responses for every criterion and each study's final quality score, is provided in the Supplementary Materials (Table S1). Building on this appraisal, Table 3 synthesizes the strength of evidence and the main methodological weaknesses identified for each of the seven impact categories examined in this review. Because MMAT scores were uniformly high across the included studies (33/33 scored 4/5 or 5/5 on their category-specific criteria; Supplementary Table S1), the MMAT appraisal functioned primarily as a quality floor rather than as a basis for direct numerical differentiation. The strong/moderate/weak classification in Table 3 therefore reflects a broader evidence-hierarchy judgment, informed by the MMAT appraisal and further differentiated by: (i) whether the study measured the impact directly with primary, objective data or relied on secondary sources or self-reported perceptions; (ii) the geographic and sample scope of the study (e.g., national-scale or multi-site data versus a single case study); and (iii) whether the study design was specifically suited to quantifying the impact in question, as opposed to addressing it as a secondary theme.

The selected studies provided evidence regarding the socio-environmental impacts experienced by communities located in the vicinity of onshore wind farms in Brazil. The overall study selection process is summarized in the PRISMA flowchart presented in Figure 1.

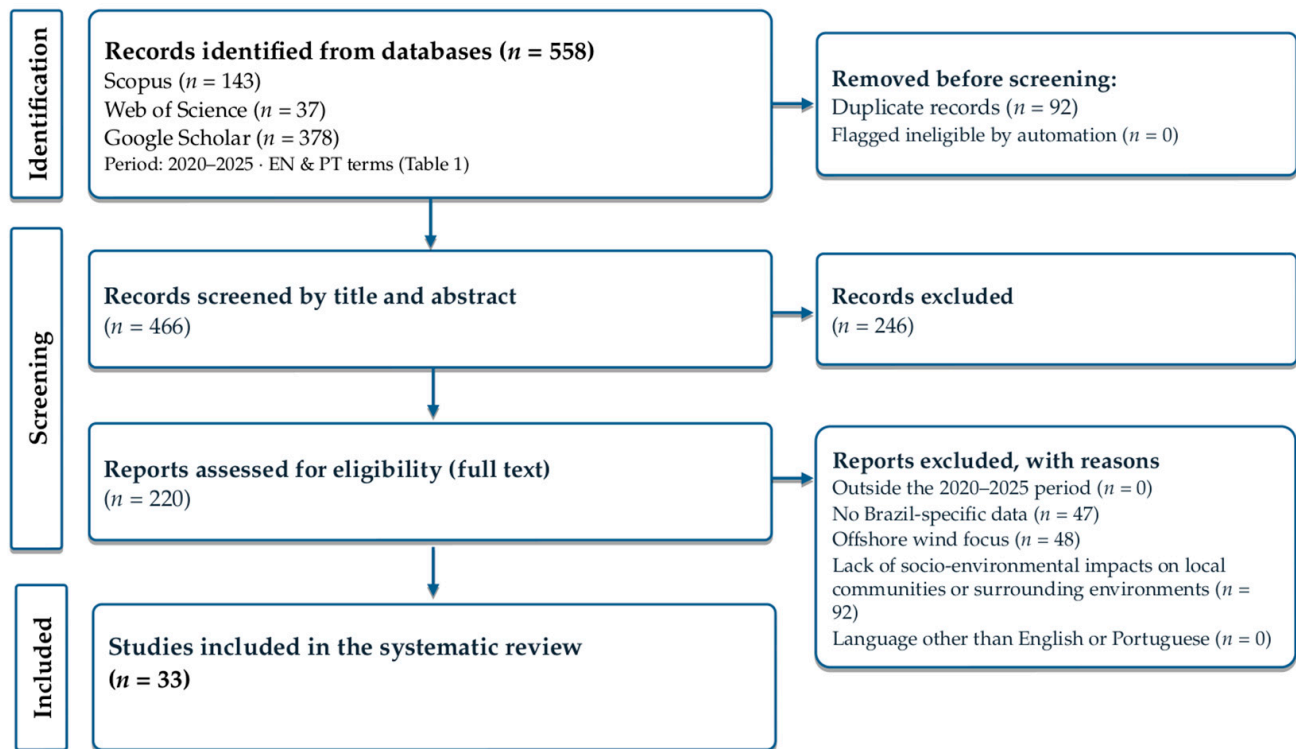


Figure 1. Flowchart of the article selection process.

3. Results and Discussion

The literature search yielded a broad set of potentially relevant studies addressing the socio-environmental impacts of onshore wind energy development in Brazil between 2020 and 2025. Table 1 presents a quantitative summary of the search terms and keywords used (in titles, abstracts, and keyword sections), as well as the number of records identified in each database before the application of the exclusion criteria and the number of studies retained after the screening process. Different sets of terms, in both English and Portuguese, were employed to broaden the search scope and ensure the identification of both national and international studies.

The analysis of the selected publications enabled the identification of seven recurring thematic categories of socio-environmental impacts associated with the construction and operation of onshore wind farms in Brazil. These categories were organized according to a progression that begins with impacts on the physical environment and biodiversity, including habitat fragmentation, wildlife mortality, soil degradation, and impairment of water resources, and then advances to impacts on human populations, such as territorial conflicts, noise pollution, and changes in landscape characteristics and environmental perception. This structure reflects both the multidimensional nature of the documented impacts and the interdependence between the ecological and social systems affected by wind energy projects, particularly in the semi-arid and coastal regions of Northeastern Brazil, where most of the reviewed studies were conducted.

The studies retained after the screening process constitute the final dataset of 33 publications analyzed in this review, all of which specifically address socio-environmental impacts observed in communities located near onshore wind farms in Brazil. The details of the studies' characteristics are shown in Table 2.

Table 2. Characteristics of the included studies ($n = 33$).

Study [Ref]	Location (State/Region)	Study Type/Method	Impact Categories	Main Focus/Key Findings
Pereira, 2023 [5]	Brazil (NE; incl. Pedra Grande–RN)	Qualitative territorial analysis	NP, LP	Role of the State in wind-project deployment; territorial displacement, landscape enclosure and noise-related out-migration
da Silva & Galvão, 2022 [6]	Northeast Brazil	Quick scoping review	HF, TC, NP, LP	Sustainability challenges of onshore wind in the Northeast; governance and community impacts
Silva & Rufino, 2024 [9]	Brazil (national)	Technical O&M analysis	TC	Operation and maintenance of onshore wind farms and how to improve sector practices
Silva et al., 2020 [19]	Xavier, Camocim–CE (coast)	Field noise measurement + perception	NP	Noise levels and community perception of impacts near a coastal wind farm
Araújo et al., 2020 [23]	Coastal Ceará (dunes)	Field sustainability assessment	HF, SD, WR, TC, NP	Deployment challenges in coastal/dune systems; vegetation, water, dust and community effects
Barrero et al., 2022 [24]	Bahia semi-arid ridges	Environmental-licensing (EIA) analysis	HF, WM, SD, NP	Licensing of wind complexes in the Caatinga; conservation-priority overlap and wildlife risk
Paula & Silva, 2024 [25]	Brazil (spatial model)	GIS multicriteria modeling	HF, TC, NP, LP	Spatial siting model to reduce environmental impacts of wind turbines
Falavigna et al., 2020 [26]	Southern Brazil (RS)	Ecological before/after field study	HF, WM, SD, LP	Shift in bird species composition after wind-farm installation
Farias et al., 2020 [27]	Brazil (national review).	Qualitative/narrative literature review.	HF, WR, TC	Negative environmental and social impacts of wind-farm installation and operation
Freitas et al., 2025 [28]	State Rio Grande do Norte (RN).	Perception-based assessment	HF, WM, SD, TC, NP, LP	Community perception used to appraise prior environmental diagnostics of wind farms
Oliveira et al., 2025 [29]	Brazil (national)	Licensing/policy analysis	HF, WM	Environmental-licensing guidelines for wind energy and implications for biodiversity
Santos et al., 2023 [30]	Southern Brazil	Environmental-performance analysis (AHP)	SD	Materiality of sustainability reports of wind farms via Analytic Hierarchy Process
Turkovska et al., 2021 [31]	Brazil (national)	Land-use/GIS modeling	HF, WM, SD, WR	Land-use footprint of Brazilian wind-power expansion
Brannstrom et al., 2022 [32]	Camocim–CE (coast)	Qualitative social study (interviews)	HF, WR, TC, LP	Determinants of community acceptance: benefits, consultation and livelihoods
Amaral et al., 2020 [33]	Rio Grande do Sul	Ecological carcass monitoring (48 mo.)	WM	266 bat carcasses (six species) across 129 turbines; temporal and environmental patterns
Barros et al., 2022 [34]	NE Brazil (wind facilities)	Methodological ecological field study	WM	Searcher efficiency and scavenger removal affecting bat-carcass mortality estimates
Pereira et al., 2022 [35]	BA, RN and PE (four complexes)	Acoustic bat monitoring	WM	Site-specific bat richness/activity; proximity of caves elevates collision risk
Revorêdo et al., 2025 [36]	Galinhos–RN (coast)	Ecological field study (collisions)	WM	Wind farm plus power line increases tern collisions; visual markers ineffective
Olofsson, 2023 [37]	Brazil	Energy-justice qualitative analysis	TC	Energy justice and territory in the present and futures of Brazilian wind energy

Table 2. *Cont.*

Study [Ref]	Location (State/Region)	Study Type/Method	Impact Categories	Main Focus/Key Findings
Sobrinho Junior et al., 2022 [38]	Serra do Mel–RN (agricultural)	Perception survey	SD, TC, NP, LP	Farmer-perceived impacts; 85% saw oversight as absent/ineffective; productive losses
Farias & Pinheiro, 2020 [39]	Galinhos–RN (dunes)	Community-psychology qualitative study	WR, TC, LP	Socio-environmental conflicts over dune/river dynamics and fishing livelihoods
Paulino et al., 2023 [40]	Xavier–CE/NE Brazil	Qualitative conflict analysis	WR, TC, NP, LP	Socio-environmental conflicts and water-body sedimentation from wind-farm siting
Cazeiro et al., 2025 [41]	Caetés–PE (100–900 m from homes)	Cross-sectional epidemiological (SRQ-20)	TC, NP	68% above distress threshold; ‘necropolitics of the winds’; mental-health burden
Teixeira et al., 2024 [42]	Rio Grande do Norte	Qualitative territorial analysis	TC, LP	Conflicts and controversies in the expansion of renewables in RN
Faustino et al., 2023 [43]	Coastal Ceará	Technical report (grey literature)	TC, LP	Socio-environmental impacts and damages of wind energy in marine–coastal Ceará
Galvão et al., 2020 [44]	Mato Grande–RN (semi-arid)	Socioeconomic analysis (MHDI)	TC	Wind energy, poverty and social sustainability; low MHDI, no royalties to settlements
Gorayeb & Brannstrom, 2020 [45]	Coastal Ceará	Case study/qualitative	TC, LP	Environmental licensing and the social gap driving opposition to wind energy
Pereira, 2024 [46]	Northeast Brazil (1998–2022)	Territorial/geographic analysis	TC	Territorial dynamics of wind-project expansion in the Brazilian Northeast
Scheifele & Popp, 2025 [47]	Brazil (national)	Econometric local-impact study	TC	Local socioeconomic effects of wind and solar parks (‘not in my backyard?’)
Miranda et al., 2025 [48]	Espírito Santo	Assessment/prospects study	NP, LP	Potential and prospects for wind energy in ES; siting and perception aspects
Silva & Silva, 2025 [49]	Northeast/Rio Grande do Norte	Energy-matrix/economic analysis	LP	Contribution of the NE and RN to diversification of the energy matrix
Luna & Palhares, 2024 [50]	Parelhas–RN (Oeste Seridó)	Legal/licensing case analysis	LP	Environmental-licensing analysis of a specific wind park in RN
Verdum et al., 2020 [51]	Tapes–RS	Landscape-perception study	LP	Perception and landscape impacts of a wind farm in Rio Grande do Sul

Impact categories: HF = habitat fragmentation and loss of plant biodiversity; WM = wildlife mortality and disturbance; SD = soil degradation and compaction; WR = impairment of water resources; TC = territorial conflicts and socio-environmental injustice; NP = noise pollution and health impacts; LP = landscape change and environmental perception.

Table 3 provides an overview of the evidence strength and the main methodological limitations associated with each socio-environmental impact category.

Table 3. Strength of evidence and methodological weaknesses identified for each socio-environmental impact category.

Impact Category and Description	Strong Evidence	Moderate Evidence	Weak Evidence	Methodological Weaknesses
Habitat fragmentation and loss of plant biodiversity The installation of wind farms requires the removal of native vegetation, road construction, and land grading activities, resulting in ecosystem fragmentation and a reduction in local plant biodiversity, with particularly severe impacts on sensitive biomes such as the Caatinga	Turkovska et al. [31]	Barrero et al. [24]; Falavigna et al. [26]; Oliveira et al. [29]; Paula & Silva [25]	Araújo et al. [23]; da Silva & Galvão [6]; Farias et al. [27]; Freitas et al. [28]; Santos et al. [30]; Brannstrom et al. [32]	Absence of fragmentation metrics (patch size, connectivity, edge effect) based on primary data. Reliance on secondary data (MapBiomas has limitations for natural vs. planted pasturelands). Grey literature (EIA/RIMA, technical reports) without independent validation. Narrative reviews without a systematic search protocol. No study included a control group.
Wildlife mortality and disturbance Wind turbines cause direct mortality of birds and bats through collisions with turbine blades, as well as disturbance to wildlife habitats. Modifications to the surrounding environment affect the availability of shelter and food resources, compromising populations of threatened species.	Barros et al. [34]; Amaral et al. [33]	Pereira et al. [35]; Revorêdo et al. [36]; Falavigna et al. [26]	Barrero et al. [24]; Freitas et al. [28]; Oliveira et al. [29]; Turkovska et al. [31]	Opportunistic data (Revorêdo et al. [36])—78–88% underestimation of collisions. Detection bias: searcher efficiency ranges from 12% (small bats in shrub vegetation during the rainy season) to 96% (large bats with no vegetation during the dry season). Absence of control groups. Few studies in the Northeast (most are from the South/Southeast). Search area reduced at some turbines due to dense vegetation (Barros et al. [34]).
Soil degradation and compaction Intensive use of heavy machinery compacts the soil, reducing its porosity and infiltration capacity. The removal of vegetation cover promotes erosion processes, while earth-moving activities alter soil microbial communities that are essential for fertility and biogeochemical cycles	—	Turkovska et al. [31]; Paula & Silva [25]	Araújo et al. [23]; Barrero et al. [24]; Falavigna et al. [26]; Freitas et al. [28]; Olofsson [37]; Santos et al. [30]; Sobrinho Junior et al. [38]	Total absence of direct measurements of compaction, erosion, organic matter, or soil microbiota. Reliance on EIA/RIMA and technical reports. Farmers' perceptions used as a proxy for erosion, without confirmation from soil data. No study used a before/after design. No experimental studies.
Impairment of water resources Soil compaction reduces infiltration and groundwater recharge, while increased erosion leads to sedimentation in rivers and reservoirs. In semi-arid regions, these effects are exacerbated by pre-existing water scarcity, threatening water availability for rural communities.	—	Araújo et al. [23]; Brannstrom et al. [32]; Freitas et al. [28]	Farias et al. [27]; Farias & Pinheiro [39]; Paulino et al. [40]; Turkovska et al. [31]	Absence of direct hydrological measurements (water-table level, streamflow, lagoon volume, water quality). Reliance on residents' perceptions, without validation against hydrological data. Land-use data used as a proxy for water-related impacts. No longitudinal water-resource monitoring study. No control group.

Table 3. *Cont.*

Impact Category and Description	Strong Evidence	Moderate Evidence	Weak Evidence	Methodological Weaknesses
Territorial conflicts and socio-environmental injustice Wind energy expansion generates conflicts when projects encroach upon the territories of traditional communities, Indigenous peoples, and small-scale farmers without adequate prior consultation or fair compensation. The loss of access to land essential for livelihoods and cultural practices constitutes a form of socio-environmental injustice and “green grabbing.”	Gorayeb & Brannstrom [45]; Scheifele & Popp [47]; Brannstrom et al. [32]; Farias & Pinheiro [39]	Cazeiro et al. [41]; Paulino et al. [40]; Pereira [46]; Galvão et al. [44]; Teixeira et al. [42]	Araújo et al. [23]; da Silva & Galvão [6]; Silva & Rufino [9]; Paula & Silva [25]; Farias et al. [27]; Faustino et al. [43]; Freitas et al. [28]; Olofsson [37]; Pereira [5]; Sobrinho Junior et al. [38]	Predominance of qualitative studies without quantification of impacts or statistical generalization. Small, convenience samples (Cazeiro et al. [41]: 50 respondents; Farias & Pinheiro [39]: 23 interviews). Selection bias: communities willing to participate may differ from those that decline. Absence of control groups. Luna & Palhares [50] acknowledge that the effectiveness of mitigation measures could not be established. Multi-themed studies with dispersed focus (Silva & Rufino [9] address O&M, not conflicts).
Noise pollution and health impacts Wind turbines generate continuous aerodynamic and mechanical noise during operation. For nearby communities, noise exposure manifests as persistent annoyance, sleep disturbance, and stress, with particularly relevant effects on mental health in rural communities of Northeastern Brazil.	Cazeiro et al. [41]	Silva et al. [19]; Araújo et al. [23]	Barrero et al. [24]; Miranda et al. [48]; da Silva & Galvão [6]; Paula & Silva [25]; Freitas et al. [28]; Paulino et al. [40]; Pereira [5]; Sobrinho Junior et al. [38]	Only one study used a validated mental-health instrument (SRQ-20 in Cazeiro et al. [41]). Absence of control groups. Perception bias: 81.2% perceive noise, but only 25% report annoyance (Silva et al. [19]). EIA/RIMA data without independent measurements. No longitudinal before/after health study. Peripheral studies (Miranda et al. [48], Silva & Rufino [9]) do not measure noise directly.
Landscape alteration and environmental perception Wind turbines visually transform natural and cultural landscapes, generating negative perceptions among local communities, including loss of territorial identity and opposition to wind energy developments. The lack of public participation in environmental licensing processes further intensifies these adverse perceptions.	—	Verdum et al. [51]; Freitas et al. [28]; Brannstrom et al. [32]	Silva & Silva [49]; da Silva & Galvão [6]; Paula & Silva [25]; Teixeira et al. [42]; Falavigna et al. [26]; Farias & Pinheiro [39]; Faustino et al. [43]; Gorayeb & Brannstrom [45]; Luna & Palhares [50]; Miranda et al. [48]; Paulino et al. [40]; Pereira [5]; Sobrinho Junior et al. [38]	Absence of objective landscape metrics (Shannon diversity, patch area, connectivity). Reliance on perception questionnaires without validation against objective data. Convenience samples (Verdum et al. [51]: 39 respondents). Acceptance bias: 92.7% favorable in Tapes (Verdum et al. [51])—possible social-desirability bias. No longitudinal before/after perception study. Peripheral studies (Silva & Silva [49], Miranda et al. [48]) do not measure landscape directly.

It is worth noting that one additional record initially retrieved met several inclusion criteria but was found, on full-text assessment, to report only general, non-Brazil-specific technical information [52]; it was therefore not counted among the studies included in the synthesis and is cited elsewhere in this review as the background literature.

The following subsections present the results of the co-occurrence network analysis of the terms identified in the bibliographic search (Section 3.1), providing an overview of the main themes and relationships emerging from the selected literature. Subsequently, Sections 3.2–3.8 discuss in detail the seven socio-environmental impact categories identified through the review: habitat fragmentation and loss of plant biodiversity; wildlife mortality and disturbance; soil degradation and compaction; impairment of water resources; territo-

rial conflicts and socio-environmental injustice; noise pollution and health impacts; and landscape alteration and environmental perception. This thematic organization provides a structured framework for understanding the principal environmental and social challenges associated with the construction and operation of onshore wind farms in Brazil, as well as the research trends highlighted in recent studies.

3.1. Bibliometric Analysis of Keyword Co-Occurrence

For the term co-occurrence analysis, the VOSviewer software, version 1.6.20, was used. The map was built based on text data, from a corpus compiled by the authors containing keywords, titles, and abstracts of the 33 included articles retrieved from the Web of Science, Google Scholar, and Scopus databases. Binary counting was adopted, with a minimum threshold of two occurrences per term, resulting in the selection of 84 terms to compose the final map. No thesaurus file was used for grouping synonyms; terms were analyzed as extracted from the corpus.

The analysis of the map (Figure 2) reveals that the analyzed bibliographic corpus is structured around four main thematic clusters, reflecting the multidimensional nature of the socio-environmental impacts associated with onshore wind energy in Brazil.

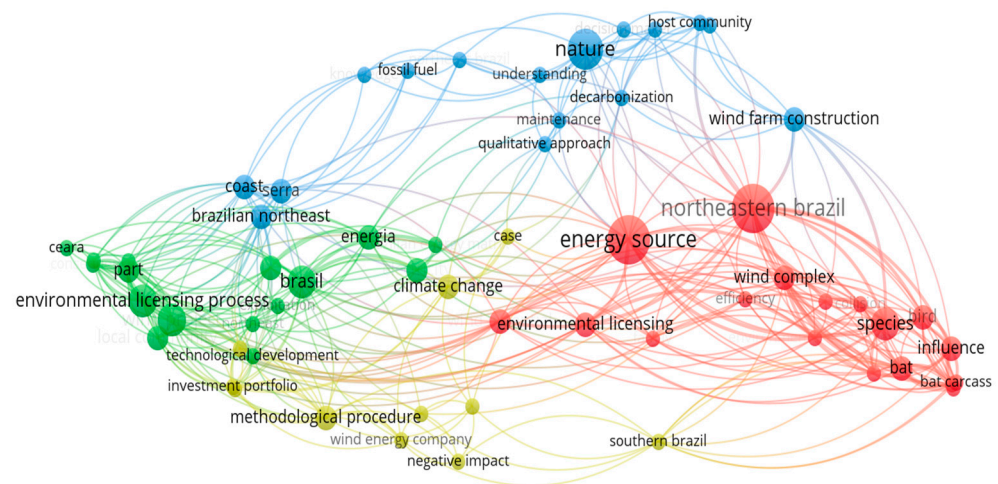


Figure 2. Keyword co-occurrence network in the literature on socio-environmental impacts of onshore wind turbines in Brazil (2020–2025).

The red cluster, the densest and most central in the network, comprises the terms ‘energy source’, ‘northeastern brazil’, and ‘wind complex’, directly connected to ‘species’, ‘bird’, ‘bat’, ‘bat carcass’, ‘collision’, ‘influence’, and ‘efficiency’. This grouping shows that a substantial share of the reviewed studies focuses on the ecological impacts of wind-complex operation, particularly on fauna (birds and bats), pointing to collision mortality as one of the most extensively investigated socio-environmental dimensions in the literature on the subject in Northeastern Brazil.

The blue cluster, formed by ‘nature’, ‘host community’, ‘decarbonization’, ‘fossil fuel’, ‘wind farm construction’, ‘maintenance’, ‘understanding’, and ‘qualitative approach’, brings together studies focused on the social and perceptual dimension of wind-energy developments, addressing the relationship between the construction/operation of wind farms and host communities, as well as the role of wind energy in decarbonization and the replacement of fossil sources, frequently under qualitative approaches.

The green cluster, with terms such as ‘environmental licensing process’, ‘brasil’, ‘ceara’, ‘technological development’, ‘part’, ‘energia’, and ‘climate change’, gathers references to the national and state context of wind-energy expansion, with particular emphasis on the state of Ceará, one of the most consolidated hubs of onshore wind energy on the northeastern

coast, in addition to associations with the sector's technological development and its relationship with the climate-change agenda. The presence of the term 'environmental licensing process' in this cluster indicates that environmental licensing is a recurring theme in the related literature.

The yellow cluster, in turn—'case', 'investment portfolio', 'methodological procedure', 'wind energy company', 'negative impact', and 'southern brazil'—brings together terms related to case studies and methodological procedures adopted in the related literature, with occasional references to the South region and the term 'negative impact', which points to the discussion of adverse effects associated with wind-energy developments.

The spatial distribution of the clusters reinforces a relevant pattern in which the Northeast region concentrates the majority of the analyzed case studies, reflecting in the academic literature the same territorial asymmetry observed in the expansion of the Brazilian wind sector itself. Although this concentration is understandable, given the region's leading position in the national wind industry, it also points to a knowledge gap regarding impacts in other regions, particularly in the South and, above all, in the North, where wind-energy expansion remains incipient or occurs in ecosystems and communities that have received comparatively limited scientific attention.

Beyond revealing the consolidated thematic cores, the co-occurrence network also allows the early identification of gaps in the literature's coverage that are revisited throughout this review. First, it is noteworthy that terms such as 'soil' or 'water resources' are absent among the 84 terms that make up the map, even though soil degradation and the impairment of water resources are among the seven impact categories identified in this review; this bibliometric under-representation is consistent with the smaller number of studies with a primary focus on these two impacts, discussed in Sections 3.4 and 3.5. Second, the prominence of the green cluster around 'ceara' and 'environmental licensing process', contrasting with the merely occasional presence of 'southern brazil' in the yellow cluster and the complete absence of any term associated with the North region, bibliometrically anticipates the geographic asymmetry revisited later in this section and discussed as a limitation in Section 3.10. Finally, the blue cluster, structured around 'host community' and 'qualitative approach', concentrates the terms that organize Sections 3.6–3.8 (territorial conflicts, noise, and landscape), indicating that the social dimension of the phenomenon, although numerically robust in the literature, remains described mostly by isolated qualitative studies, without comparative analyses between cases—a gap explored in greater depth in Section 3.6.

3.2. *Habitat Fragmentation and Loss of Plant Biodiversity*

The development of wind farms can involve, from the construction phase onward, the removal of natural habitats and structural alterations to ecosystems due to the installation of wind turbines, the opening of access roads, and the construction of transmission lines [25]. In the Brazilian context, this issue is further aggravated by the concentration of wind energy projects within the Caatinga biome, the only biome found exclusively in Brazil, recognized for its high drought resilience, carbon sequestration capacity, and provision of essential ecosystem services. The vast majority of wind turbines installed in the country are located within this biome, and part of the areas currently occupied by wind farms had previously been classified by the Ministry of the Environment as priority areas for conservation [24]. This overlap between wind energy developments and conservation-priority areas highlights a potential challenge for national energy planning, particularly regarding the need for effective ecological-economic zoning instruments for the wind energy sector.

In coastal regions, which have become a major focus of wind energy expansion, impacts on vegetation exhibit distinct characteristics. The installation of wind farms in dune systems results not only in the removal of vegetation responsible for sediment stabilization but also in alterations to sediment dynamics and the intensification of dune mobility processes, generating cascading effects on adjacent ecosystems such as interdunal lagoons and mangroves [27,31]. In communities located in the municipality of Camocim, Ceará State, residents reported the burial of interdunal lagoons and the leveling of dunes as direct consequences of wind farm installation, processes that compromise both local biodiversity and traditional livelihood strategies [32]. These findings suggest that current environmental licensing procedures may not always be sufficient to prevent substantial habitat losses in highly sensitive coastal ecosystems.

Taken together, the evidence highlights the need to strengthen wind energy zoning policies in environmentally sensitive and conservation-priority areas, as well as to consider long-term landscape impact assessments in the licensing of new projects. This pattern corresponds to the term ‘wind farm construction’ in the blue cluster of the co-occurrence network (Section 3.1) and to the geographic concentration of the green cluster around ‘ceara’, consistent with the predominantly coastal origin of the studies reviewed in this subsection.

The habitat fragmentation and habitat loss described in this section provide an ecological context in which potential impacts on wildlife may become more pronounced. The following section specifically examines the mortality and disturbance mechanisms affecting birds and bats documented in the literature, indicating that such impacts may extend beyond direct turbine collisions and highlighting the potential value of more comprehensive monitoring protocols within Brazilian environmental licensing procedures.

3.3. Wildlife Mortality and Disturbance

Among the impacts of wind farm operation on wildlife, mortality resulting from collisions with rotating turbine blades is one of the most extensively documented effects in the literature, primarily affecting birds and bats [28]. However, the extent of this impact may remain underestimated in Brazil due to the scarcity of standardized monitoring programs, the short duration of most studies, and differences in monitoring requirements within environmental licensing procedures. These limitations hinder comparisons among studies and constrain the development of evidence-based mitigation policies.

Regarding birds, the impacts extend beyond direct collisions with turbines. In Galinhos, Rio Grande do Norte State, the operation of a wind farm significantly increased collisions of Common Terns (*Sterna hirundo*) and Roseate Terns (*Sterna dougallii*) with an adjacent power distribution line. Collision rates peaked in March, during the pre-migration period, and increased substantially following the commissioning of the wind farm, suggesting a possible funnel effect or displacement of flight routes [36]. Notably, the installation of visual markers along sections of the power line did not reduce collision rates in the study area, suggesting that their effectiveness may be limited under specific conditions and supporting consideration of alternative mitigation measures, including underground cabling, where feasible [36]. At a broader scale, a study examining changes in bird communities following wind farm installation in southern Brazil identified significant shifts in species composition, with sensitive species becoming less represented relative to more common and disturbance-tolerant species, suggesting ecological effects beyond individual mortality [26]. The situation is particularly critical for threatened species. At the Canudos Wind Energy Complex, Bahia State, which overlaps with the distribution range of Lear’s Macaw (*Anodorhynchus leari*), a critically endangered species, risks associated with habitat fragmentation, noise disturbance, turbine collisions, and alterations in nesting and foraging behavior have been identified [24].

Bats are among the animal groups most vulnerable to wind farms, due to their low reproductive rates. In Brazil, a 48-month study covering 129 turbines in Rio Grande do Sul identified 266 bat carcasses belonging to six species [33]. Acoustic monitoring conducted at four wind-energy complexes in northeastern Brazil (Bahia, Rio Grande do Norte, and Pernambuco states) recorded 29 bat call types, predominantly from insect-eating species, whose activity patterns were influenced by environmental variables such as temperature, wind speed, and wind direction in some complexes, but not in others, indicating no single pattern common to all sites [35]. These findings demonstrate that each wind farm possesses unique ecological characteristics and therefore requires site-specific, long-term monitoring programs. The proximity of caves and natural roosting sites was identified as a major factor increasing both bat activity and species diversity, thereby proportionally elevating collision risk [35].

The findings of the reviewed studies indicate limitations in wildlife monitoring practices in terms of taxonomic coverage, monitoring duration, and methodological standardization within Brazilian environmental licensing procedures. The establishment of standardized national guidelines for wildlife monitoring at wind farms, including longer-term studies encompassing multiple groups of animals and plants, could improve the consistency with which biodiversity impacts are assessed and mitigated. This pattern is consistent with the red cluster identified in the co-occurrence analysis (Section 3.1), the densest in the network, confirming wildlife mortality as the bibliometrically most consolidated ecological dimension among the impacts reviewed.

While impacts on wildlife constitute the most visible manifestation of ecological disturbance associated with wind energy development, damage to the physical substrate upon which these ecosystems depend can be equally severe, although less immediately apparent. The following section examines the processes of soil degradation and compaction triggered by wind farm installation, with particular attention to the vulnerability of semi-arid and coastal soils that predominate in Brazil's principal wind energy regions.

3.4. Soil Degradation and Compaction

The installation of onshore wind farms can trigger alterations in the physical, chemical, and biological properties of soils that may extend beyond the areas directly occupied by wind turbines, potentially affecting ecological processes at the landscape scale [52]. These alterations can be organized into three major and interrelated processes: soil drying, characterized by reduced water-retention capacity; soil impoverishment, reflected in the loss of organic matter and reductions in carbon stocks; and soil warming, resulting from changes in surface thermal regimes induced by vegetation removal and modifications to local albedo [52]. Although these processes have been documented primarily in extratropical regions, their occurrence in semi-arid environments such as northeastern Brazil warrants further investigation given the characteristics and potential sensitivity of local soils and ecosystems to anthropogenic disturbance [28].

During the construction phase, the removal of native vegetation and extensive earthworks can promote surface soil compaction, alterations in soil pore structure, and increased erosion associated with tower foundation excavations and the continuous movement of heavy machinery [26,38]. In semi-arid environments, these processes may contribute to land degradation and potentially affect soil productivity and the natural regeneration capacity of native vegetation [28].

Soil-related impacts also extend to local productive activities. In Serra do Mel, Rio Grande do Norte State, farmers reported perceptible ground vibrations in areas adjacent to construction sites, as well as reductions in cashew production resulting from dust emissions generated by intense traffic on access roads serving the wind farms [38]. This effect, namely

particulate matter pollution, represents a secondary environmental impact with potential relevance to public health that may receive limited attention in environmental impact assessments. In Amontada, Ceará State, the continuous movement of trucks and heavy machinery generated persistent clouds of dust and sand, with documented implications for the respiratory health of nearby residents [23].

In coastal ecosystems, the installation of wind farms within dune fields (Figure 3) introduces an additional environmental impact through the removal of sediment-stabilizing vegetation and the alteration of dune mobility dynamics. Beyond the consequences for plant biodiversity discussed in Section 3.2, this process may alter the physical characteristics of dune substrates, with potential implications for groundwater recharge and coastal morphological stability [31]. The combined effects of soil compaction, drying, organic matter depletion, and dune destabilization therefore represent a multidimensional set of environmental changes that may benefit from integrated consideration within environmental impact assessment frameworks.



Figure 3. Wind turbines near coastal dunes in Icarai de Amontada, Ceará, Brazil. The image illustrates the occupation of sensitive coastal environments by wind energy infrastructure. Source: Noé [53], Wikimedia Commons (CC BY-SA 3.0).

The soil degradation processes documented in this section may be linked to impacts on water resources, as soil compaction, drying, and vegetation removal can alter infiltration and groundwater recharge regimes of affected ecosystems. The following section examines how these processes translate into tangible impacts on water availability and water quality for communities located in the vicinity of wind farms. This bibliometric gap, already noted in Section 3.1 through the absence of the term ‘soil’ among the terms composing the map, helps explain why this subsection relies on a comparatively smaller set of studies with a primary focus on the topic, compared with the other impact categories reviewed in this section.

3.5. Impairment of Water Resources

The impacts of wind farms on water resources occur across multiple spatial scales and environmental compartments, ranging from alterations in the surface dynamics of rivers, lakes, and lagoons to interference with groundwater systems and aquifer recharge processes. Although less visible than impacts on vegetation or wildlife, these effects may have important consequences for rural and traditional communities that depend directly on water resources for domestic supply, subsistence, and income generation [40].

The sedimentation of water bodies is among the most frequently documented impacts. In Xavier, Ceará State, interdunal lagoons were progressively filled by sediments mobilized during wind farm installation, with reported consequences for their hydrological connectivity with surrounding ecosystems and their capacity to support subsistence fishing activities [40]. In Galinhos, Rio Grande do Norte State, sedimentation of a local river caused by dune sand displacement restricted navigation routes, directly affecting the local fishing economy [39]. In both cases, the reported hydrological changes were associated with socioeconomic consequences. The progressive burial of adjacent mangrove ecosystems reduced the availability of fishery resources and compromised the livelihoods of families dependent on artisanal fishing as their primary economic activity [27]. These cases illustrate that changes in water resources associated with wind farm development may extend beyond aquatic systems, with potential social and economic consequences for surrounding communities.

Potential effects on groundwater tables and aquifers represent an important concern that may warrant greater consideration in environmental licensing processes. In communities along the coast of Ceará State, residents reported reductions in water availability from wells following excavations for turbine foundations, attributing the phenomenon to groundwater alterations caused by the large concrete structures embedded within the substrate [23,32]. This perception is complemented by hydrogeological studies conducted in the same region, which documented changes in aquifer recharge patterns in dune environments, as well as localized variations in groundwater quality in wells situated near turbine foundations, although water quality parameters remained within legal drinking-water standards [31]. The limited consideration of aquifer vulnerability assessments in the licensing of wind farms in dune systems may represent an area for regulatory improvement, given the potential sensitivity of these environments to changes in groundwater dynamics.

Alterations in tidal regimes and coastal dynamics, although less frequently documented than impacts on inland water bodies, emerge as an additional pathway of water resource impairment in wind farms installed along coastal zones. Changes in dune morphology and the removal of sediment-stabilizing vegetation modify infiltration and surface runoff patterns, affecting the ecological connectivity among coastal ecosystems, including dunes, lagoons, mangroves, and intertidal environments, which function as an integrated system [23]. Limited consideration of this interdependence in environmental impact assessments represents a methodological issue identified in the reviewed literature, with some studies indicating that hydrological compartments may be evaluated separately rather than as interconnected components of coastal ecosystems.

Taken together, the cases analyzed indicate that wind farm development in coastal and semi-arid regions would benefit from prior assessments of groundwater and sediment dynamics, consideration of protective measures around sensitive water bodies, and continued monitoring of water resources during project operation.

The water resource impacts examined in this section acquire a distinct social dimension when considering that the communities most affected by these processes are often those that depend most directly on water resources for their livelihoods and that have had limited participation in decision-making processes regarding project implementation. This perceived asymmetry between those who bear environmental costs and those who receive the benefits of wind energy expansion is an important dimension of the territorial conflicts examined in the following section. Similarly to what was observed for soil degradation (Section 3.4), the absence of the term 'water resources' among the clusters of the co-occurrence network (Section 3.1) reflects the comparatively smaller number of studies with a primary focus on this impact, indicating that impacts on water resources tend to be

documented jointly with habitat fragmentation and territorial conflicts, rather than as an isolated line of investigation in the reviewed literature.

3.6. Territorial Conflicts and Socio-Environmental Injustice

The expansion of wind farms in northeastern Brazil has been associated with a recurring set of territorial conflicts documented in the reviewed literature. These conflicts appear to stem less from opposition to renewable energy itself than from concerns regarding how projects are planned, negotiated, and implemented, including limited participation by affected communities and perceived inequalities in the distribution of costs and benefits [6,28]. These conflicts can disproportionately affect rural populations, smallholder farmers, and traditional communities, particularly where local populations perceive limited access to the economic opportunities generated by wind energy development. This situation has been interpreted as a form of environmental injustice affecting specific social groups and has been identified in the recent literature as a recurring feature of wind energy expansion in some Brazilian contexts [37,44].

The effects on community well-being are equally well documented. In the Mato Grande region of Rio Grande do Norte State, where numerous wind farms have been installed, municipalities hosting these projects exhibit low Municipal Human Development Index (MHDI) values, ranging between 0.500 and 0.599, as well as a high dependence on income-transfer programs. After more than a decade of wind farm operation, the study found no significant improvements in the indicators of rural household well-being examined. Employment opportunities generated by the sector were predominantly temporary, low-skilled, and concentrated during the construction phase, while agrarian reform settlements, whose residents do not hold individual land titles, receive no royalty payments from projects installed within their territories [44]. The prevailing perception reported in field studies is that the economic benefits of wind energy accrue primarily to private companies and government institutions rather than to local communities. In light of the available evidence, this perception should be considered as a socially grounded assessment of how the distribution of benefits from wind energy development is experienced by local communities [44].

At the community level, impacts on productive activities are both tangible and measurable. In Serra do Mel, Rio Grande do Norte State, farmers reported the loss of eight to ten hectares of productive land per property, the removal of cashew trees, reductions in nut production due to dust deposition, and substantial losses to beekeeping activities, a key component of the local economy, resulting from hive abandonment by bees disturbed by continuous noise and intense machinery traffic [38]. Significantly, 85% of respondents in this study considered environmental oversight to be either absent or ineffective, suggesting a perceived gap between mitigation obligations established during environmental licensing procedures and their implementation in the study area [38]. This gap between formal licensing requirements and perceived implementation highlights a potential weakness in environmental governance, as safeguards established during licensing may not always be experienced as effectively implemented at the local level. The persistence of these conflicts highlights the potential value of governance improvements that extend beyond technical adjustments to environmental impact assessments. These findings correspond to the blue cluster of the co-occurrence network (Section 3.1), centered on ‘host community’ and ‘qualitative approach’, and to the recurring presence of ‘environmental licensing process’ in the green cluster, both indicating that governance and the relationship with host communities constitute important thematic axes in the reviewed literature.

The following section examines reported effects of wind turbine noise on the physical and mental health of exposed populations, highlighting concerns regarding the proximity between wind turbines and residential areas.

3.7. Noise Pollution and Health Impacts

Noise generated by wind farms constitutes one of the impact categories most directly perceived by surrounding communities and may warrant greater attention within Brazilian environmental licensing procedures. Noise emitted by wind turbines results from a combination of mechanical components, originating from generators and gearboxes, and aerodynamic components generated by the interaction between turbine blades and wind. During the construction phase, these sources are compounded by noise from the intense traffic of heavy machinery and support vehicles [23]. The combined effect of these sources can contribute to changes in the local acoustic environment, while potential effects on human health have been investigated with increasing attention in both the national and international literature [6,28].

Potential mental health impacts among communities exposed to wind turbine noise have been investigated using epidemiological approaches in Caetés, Pernambuco State, where turbines are located at distances ranging from 100 to 900 m from residential areas. A cross-sectional study involving 50 residents, predominantly Black women smallholder farmers, employed the World Health Organization's Self-Reporting Questionnaire (SRQ-20) to screen for common mental disorders [41]. The results showed that 68% of participants exceeded the threshold indicative of significant psychological distress, with high prevalence rates of self-reported symptoms such as insomnia (66%), persistent nervousness and tension (70%), chronic fatigue (60%), headaches (60%), difficulty making decisions (58%), and gastrointestinal discomfort (64%) [41]. Eight participants reported suicidal ideation, two of whom attributed the onset or worsening of these thoughts to wind farm operation. Furthermore, 18 respondents reported the use of psychotropic medications, most of which had reportedly been prescribed after the installation of the wind farms [41].

It is important to note that this cross-sectional design does not allow causal attribution of these mental-health outcomes specifically to wind turbine noise. The study did not include a pre-installation baseline or a non-exposed comparison group, and plausible confounding factors—including pre-existing socioeconomic deprivation, limited access to healthcare services, and other environmental stressors common to rural communities in the region—were not controlled in [41]. The reported prevalence of psychological distress should therefore be interpreted as evidence of association rather than proof of causation, consistent with the broader epidemiological literature on wind turbine noise and health, in which findings remain heterogeneous and are similarly constrained by observational designs.

Beyond psychological effects, turbine noise has also been associated with impacts on the social and territorial dynamics of affected communities. In Caetés, noise annoyance was reported as a factor associated with territorial displacement, with families abandoning their properties due to continuous exposure to turbine noise [5]. These findings are consistent with concerns identified in the reviewed literature regarding the proximity of wind turbines to residential areas and the need to consider appropriate separation distances according to local acoustic conditions and potential noise exposure [19,48].

The development of more consistent noise-control criteria for wind farms, potentially including standardized monitoring and consideration of operational measures during nighttime periods, could contribute to the management of noise exposure and community well-being. This is consistent with the term 'negative impact' from the yellow cluster and with 'host community' from the blue cluster of the co-occurrence network (Section 3.1),

suggesting that noise figures in the literature as one of the adverse effects most directly associated with the relationship between wind-energy developments and host communities.

The noise-related impacts examined in this section form part of a broader set of transformations that wind farms impose upon the lived environments of surrounding communities. Among these transformations, landscape change occupies a distinctive position, affecting not only residents' visual comfort but also the cultural and symbolic relationships that communities maintain with their territories, as discussed in the following section.

3.8. Landscape Change and Environmental Perception

The landscape transformations associated with wind farm development represent a category of impact that extends beyond aesthetic and visual considerations, affecting the cultural, symbolic, and practical relationships that traditional communities maintain with their territories. For these populations, the landscape is not merely a physical setting but a fundamental component of identity, collective memory, and the organization of daily life. Consequently, its abrupt or poorly consulted transformation may be perceived as a form of symbolic loss that compounds the material changes documented in the preceding sections [5,28].

Landscape impacts can be particularly substantial in coastal ecosystems, where the reviewed studies associate wind farm installation in dune environments with changes in interdunal lagoons, dune morphology, and access to territories previously used collectively. In Rio Grande do Norte State, the Traditional Fishing Community of Enxú Queimado, located in the municipality of Pedra Grande, experienced the enclosure of its customary dune areas following the installation of wind turbines, disrupting access to spaces that had long been integral to everyday activities, fishing practices, and community celebrations [5]. In Ceará State, the disappearance of interdunal lagoons in communities within the municipality of Camocim was reported to affect the food security of populations that depended on these ecosystems for subsistence fishing, representing a loss that is simultaneously ecological, economic, and cultural [25,32].

Environmental perceptions among affected communities, however, are not homogeneous, and their variability reveals important social dynamics for the planning of future projects. In Serra do Mel, Rio Grande do Norte State, 75% of interviewed farmers stated that wind turbines did not constitute a visual nuisance and often associated them with progress and modernization, despite the productive losses documented in the same study [38]. A similar perception linking wind energy to modernization and development was reported among residents of the municipality of Tapes, Rio Grande do Sul State [51]. This apparent contrast suggests that acceptance or rejection of wind energy landscapes may be influenced by factors extending beyond direct visual perception, including financial compensation mechanisms, community involvement in decision-making processes, and perceptions of procedural fairness in negotiations with developers. Conversely, in coastal communities of Ceará and Rio Grande do Norte States where prior consultation was limited and impacts on natural resources were more pronounced, opposition to wind energy landscapes was reported as substantial and was associated with perceptions of loss and territorial exclusion [28,39].

A recurring concern identified in the reviewed literature is the limited information reportedly provided to some affected communities regarding project implementation. In several localities across Rio Grande do Norte and Ceará States, residents reported becoming aware of wind farm developments only after construction activities had already begun, without any consultation process or public hearing conducted in an accessible and culturally appropriate manner [28,38].

The economic dimension of landscape change deserves particular attention within territorial planning processes. The installation of large wind energy complexes in coastal regions with significant tourism potential may affect tourism development opportunities based on ecological integrity and scenic characteristics, potentially altering the distribution and duration of local economic benefits [39]. Such potential trade-offs may receive limited attention in economic impact assessments of wind energy projects, representing an area that could be further incorporated into licensing procedures.

The incorporation of visual impact assessments and environmental perception studies into environmental impact assessments, combined with meaningful participatory consultation processes, could help ensure that traditional territories and local landscape values are considered as wind energy development continues to expand across Brazil. Together with the findings of Sections 3.6 and 3.7, this subsection completes the set of themes gathered in the blue cluster of Figure 2 (Section 3.1), showing that the social dimension of wind energy is described predominantly by qualitative studies, often conducted in isolation from one another.

3.9. Cross-Cutting Analysis: Explanatory Factors Behind Differentiated Community Responses

Although the impacts documented in Sections 3.2–3.8 are organized by biophysical or social domain, the reviewed evidence also shows that communities exposed to comparable impacts respond very differently, suggesting that specific mediating factors shape acceptance or rejection. Contrasting the cases of Serra do Mel and Tapes, where turbines were frequently associated with progress and modernization despite documented productive losses [38,51], with Caetés and the coastal communities of Ceará and Rio Grande do Norte, where opposition and psychological distress were substantial [28,39,41], at least three recurring factors appear to differentiate outcomes: (i) the timing and quality of prior consultation—communities informed only after construction had begun [28,38] reported markedly more negative perceptions than those engaged earlier; (ii) the distribution of tangible economic benefits, including royalties and compensation—settlements without individual land titles received no royalties despite hosting turbines [44], whereas perceived economic inclusion elsewhere correlated with more favorable perceptions [38,51]; and (iii) the severity and reversibility of the impact itself—reversible nuisances (dust, minor visual change) were more readily tolerated than losses perceived as irreversible, such as the destruction of interdunal lagoons or customary access to communal land [5,32]. Read through the energy-justice lens introduced in Section 1, these three factors correspond respectively to procedural, distributive, and recognition dimensions of justice [54,55], and appear to be stronger predictors of community acceptance than the mere presence of turbines.

3.10. Limitations of This Review

Some limitations should be considered when interpreting the findings of this review. First, the search strategy was deliberately oriented toward studies explicitly reporting socio-environmental impacts, which may favor the identification of adverse outcomes over neutral or positive ones; the recurrence of the reported impacts should therefore be understood as characterizing the problems that accompany the prevailing deployment model, rather than as a measure of their prevalence across all wind energy developments in Brazil. Second, Google Scholar was used as one of the sources and, because its results are not fully reproducible and its ranking is not transparent. Third, although the methodological quality of the included studies was formally appraised using the MMAT [56] (Section 2; Supplementary Table S1), most of the reviewed evidence remains qualitative or descriptive in nature, several studies rely on small convenience samples (e.g., Cazeiro et al. [41]:

50 respondents; Verdum et al. [51]: 39 respondents), and no included study used a control group or a longitudinal before/after design; the quality appraisal therefore indicates the design-level rigor of each study but does not, by itself, permit a formal meta-analytic weighting of findings, so the synthesis remains predominantly narrative in nature. Finally, the review was restricted to publications in English and Portuguese, and the available evidence is strongly concentrated in Northeastern Brazil—a pattern also visible in the keyword co-occurrence network (Section 3.1; Figure 2)—which limits the extent to which the findings can be generalized to other regions. These limitations do not invalidate the synthesis, but they indicate that its findings are best interpreted as a qualitative mapping of recurrent themes and knowledge gaps rather than as a quantitative estimate of impact prevalence.

4. Conclusions

This study presented a systematic review of the literature on the socio-environmental impacts associated with the development of onshore wind farms in Brazil, revealing a complex and paradoxical scenario. Although wind energy plays a strategic role in the energy transition and decarbonization efforts, the findings indicate that its development has been associated with significant socio-environmental conflicts in some Brazilian contexts. The evidence indicates that these impacts may extend beyond localized ecological disturbances, involving multiple dimensions related to territory, water resources, livelihoods, and cultural values.

This tension mirrors a broader pattern documented in the international energy-transition literature: the same climate and energy-security imperatives that justify the rapid scale-up of wind power domestically can also compress the time available for community consultation and site-specific environmental assessment—a trade-off already noted for other renewable technologies undergoing accelerated deployment worldwide.

The analysis of the selected studies identified seven recurring thematic categories of socio-environmental impacts. Four of these are predominantly associated with the biophysical components of ecosystems—habitat fragmentation, wildlife mortality, soil degradation, and impairment of water resources—while three are primarily related to the social and territorial dimensions of wind energy expansion: territorial conflicts, noise pollution, and landscape change and environmental perception.

The synthesis of these seven thematic categories allowed the identification of three broad and interrelated dimensions. First, the findings identify limitations in governance processes, including concerns regarding the assessment of cumulative impacts, the participation of local communities in decision-making, and the implementation of mechanisms for free, prior, and informed consultation. Second, the review highlights recurring territorial conflicts in which the installation of wind energy projects in traditionally occupied territories, rural areas, and socially vulnerable regions has been associated with changes to local ways of life, habitat fragmentation, and the transformation of culturally significant landscapes. Third, the findings indicate limitations in existing mitigation and compensation measures in relation to some of the impacts identified. Strictly technical solutions, such as systems designed to reduce wildlife collisions, may be insufficient when implemented without broader approaches addressing power asymmetries and the social and territorial dimensions of energy expansion. Such approaches may prioritize the economic functions of territory while giving insufficient consideration to its long-term social, ecological, and cultural dynamics. The reviewed studies also highlight the potential value of standardized national protocols for environmental and social monitoring, particularly for assessing cumulative and long-term impacts that may not be consistently addressed within current licensing procedures.

Translating these findings into actionable policy requires distinguishing between measures that could be implemented in the short term and gaps that depend on further research. In the short term, licensing authorities could require standardized, multi-year wildlife-monitoring protocols—covering pre- and post-construction carcass-search surveys across at least two full annual cycles, using comparable methodologies across projects, with results reported publicly to the relevant environmental agency—rather than the ad hoc, single-season monitoring documented in several of the reviewed studies. Licensing files could likewise be required to disclose consultation timelines and compensation or royalty arrangements, making explicit whether and how affected communities, including those without formal land titles, are included in benefit-sharing schemes; the cross-cutting analysis in Section 3.9 indicates that this factor is among the strongest predictors of community acceptance. The zoning criteria called for in the Abstract could be operationalized through minimum setback distances from residential clusters and traditional communities, combined with the explicit exclusion of areas under customary or communal land use—such as interdunal lagoons and dune-fishing commons—unless a documented, free and prior consultation process precedes project approval.

Over the longer term, addressing the evidence gaps identified in this review will require cumulative-impact assessment frameworks capable of evaluating multiple wind complexes sharing the same airshed, watershed, or migratory corridor, rather than the project-by-project assessments that currently predominate, as well as longitudinal, before/after study designs—largely absent from the reviewed literature (Section 3.10)—and a deliberate research effort directed to other regions of Brazil, where empirical evidence remains scarce.

Therefore, the sustainability of wind energy expansion in Brazil is closely linked to improvements in the planning, governance, and management of wind energy development. The replacement of fossil fuels with renewable energy sources alone may not be sufficient to ensure a just and sustainable energy transition. A more sustainable approach could be founded upon three central pillars: (1) territorial justice, through greater recognition and protection of traditional territories and sensitive ecosystems; (2) inclusive governance, promoting meaningful participation of local communities from the early stages of project planning; and (3) comprehensive sustainability, whereby sectoral expansion is accompanied by socioeconomic benefits and effective management of socio-environmental impacts. These three pillars can be read as the practical counterparts of the tripartite energy-justice framework introduced in Section 1: territorial justice operationalizes recognition and distributive justice; inclusive governance operationalizes procedural justice; and comprehensive sustainability requires attending to all three dimensions jointly over the long term [54,55].

In this regard, the Brazilian experience with wind energy illustrates some of the contemporary challenges associated with the energy transition. Addressing the climate crisis and expanding renewable energy sources should therefore be accompanied by efforts to avoid reproducing historical inequalities or creating new forms of territorial vulnerability. The challenge ahead is to develop wind energy projects within a socio-environmental framework in which energy efficiency, technological innovation, territorial justice, and ecological protection are considered complementary dimensions. Ultimately, the sustainability of the national energy matrix will depend in part on the ability to integrate energy projects into local territories in ways that are socially legitimate, environmentally responsible, and participatory.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/wind6040059/s1>, PRISMA 2020 Checklist; Table S1: MMAT quality appraisal of the 33 included studies.

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