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Assessment of life cycle environmental impacts of onshore wind turbines in the Global South

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Abstract
The rapid expansion of onshore wind energy has intensified concerns regarding its life-cycle environmental impacts. This study integrates a multi-level impact classification and an expert-driven Fuzzy DEMATEL approach to identify, quantify, and map causal relationships that shape the environmental footprint of onshore WTs. Five broad categories and 12 subcategories of impact were evaluated using inputs from seven experts. Results reveal that end-of-life and recycling exert the highest systemic influence, followed by material production and fabrication, and pre-construction site preparation. These stages drive cascading effects on downstream ecological disturbance, resource depletion, and cumulative emissions. Conversely, operational impacts exert limited causal influence. The analysis highlights critical gaps in the Global South context, including weak environmental assessments, limited circularity frameworks, and a lack of recycling infrastructure for composite materials and rare-earth materials. Policy recommendations emphasize the implementation of embedded carbon standards, the establishment of regional recycling hubs, and the strengthening of ecological survey protocols.

Keywords Onshore wind energy, Environmental impact, Life-cycle, Sustainability, Wind energy

1 Introduction

Mitigation of climate change requires a massive effort to transition from fossil fuels to low-carbon energy generation. Renewable energy provides the solution for decarbonizing the economy. Among the renewable energy technologies, wind energy and solar energy receive the most attention. Solar Photovoltaic (PV) is expected to drive nearly 80% of global renewable energy capacity growth, with annual solar additions anticipated to average 540 GW through 2035. By the end of 2024, global solar PV cumulative capacity is expected to surpass 2.2 TW, reflecting more than 600 GW of new additions. Onshore wind energy capacity is expected to grow by 45% globally, reaching 732 GW by 2030.

By 2030, the wind and solar energy generation in the Global South is anticipated to increase by more than four times, exceeding 2000 TWh per year. Wind energy installations in the Global South experienced a surge in 2025, driven by significant growth in

China, India, and Brazil. China alone accounted for about 72% of global additions in the first half of 2025, while India added around 3.5 GW and is now the third-largest wind energy manufacturing hub globally [18]. Therefore, it is crucial to comprehend the overall sustainability of the wind energy sector in the Global South.

Wind energy is a critical component in building sustainability in the energy mix, providing clean, renewable power while minimizing environmental harm, conserving resources, and supporting long-term economic and social growth. WT(s) (Wind Turbines) generate electricity without emitting greenhouse gases, do not require water for cooling, and leave a relatively small land footprint. Wind energy reduces dependency on fossil fuels, enhancing energy security and price stability, and provides protection from global fluctuations in the fuel market. This sector creates jobs and engages in community participation, meeting energy transition with energy justice.

Though the benefits of wind energy outweigh the negative impacts [50]. It is essential to examine the negative impacts of WTs to further enhance the overall sustainability of the sector. In the literature on wind energy and environmental impacts, a study examined the material demand for WTs in the USA and the rest of the world, and compared these values with expected production until 2050. Findings reveal that the demand in 2032-36 could be twice as much as the current amount, while the demand for rare-earth elements is expected to increase by 254–815% in 2033 compared to 2018 [15]. The materials account for the largest portion of emissions during the turbines' life cycle. Over 90% of the carbon footprint comes from the manufacturing stage, particularly the production of steel, concrete, composites, and rare-earth for generator magnets and blades. The typical life-cycle carbon dioxide emission from onshore WTs ranges from 7 to 11 g of CO_2 equivalent per kilowatt-hour [52]. The supply of key minerals is geographically concentrated. To address material security concerns and mitigate emissions, recycling has emerged as a viable option. Prototypes are being explored for recovering carbon and glass fibers [41]. Other studies provided evidence that the construction phase of WTs contributed to the largest share of environmental damage [5].

The impact of WTs on wildlife is evident. One study indicates that a standard deviation increase in WTs results in a 9.75% reduction in bird abundance and a 12.2% decrease in bird species richness [33]. Another study identifies four broad categories and fourteen individual impacts of wind projects on the environment, as well as social, economic, technical, and legal systems. The authors argue that some recurring issues, such as bird collisions, noise, health impacts, and weather changes, are not substantial when compared to other more challenging issues, including lengthy approval processes, dependence on critical minerals, and the recycling of blades [31]. Most of the studies on wind energy sustainability rely on conventional Life-Cycle Analysis (LCA), hotspot analysis, or narrative environmental reviews [5, 52]. However, these approaches identify magnitudes of impacts but do not capture interdependencies across project phases. Only a limited number of studies have applied multi-criteria decision making (MCDM) to wind energy, and these have focused primarily on siting or economic trade-offs rather than life cycle environmental impacts [31].

Overall, onshore wind energy can lead to habitat loss, fragmentation, and disturbances to wildlife, particularly birds and bats. Some of these impacts can be solved by careful siting and monitoring. Wind farms moderately alter local climate conditions, such as increasing turbulence, and impact vegetation growth in the vicinity of the turbines. The manufacturing and decommissioning of turbine blades present challenges, including ecotoxicity from blade polymers and the management of end-of-life waste.

For the most part, the studies are not comprehensive enough to systematically identify and prioritize the key environmental impacts caused by WTs. Moreover, most studies focus on the overall sustainability of wind energy in the Global North, while the Global South, where a large-scale deployment of renewable energy sources is expected due to the climate crisis and energy insecurity, has received limited attention. The above gaps, namely, the lack of MCDM-based causal mapping of the wind turbine life cycle impact, the almost complete emphasis on Global North, and the absence of policy gap analysis are the direct impulse behind the three research questions in this study. Gap (i) in particular, motivates RQ1 and RQ2, whereas gap (ii) and (iii) motivate RQ3.

This study intends to answer the following questions

RQ1: What are the most crucial categories and sub-categories in the environmental impact of onshore WTs?.

RQ2: How do these categories interact within the wind energy system?.

RQ3: What are the key policies and technological gaps that hinder sustainable WT development, especially in the Global South? How can they be strengthened to align with best practices?

The objective of this study is, firstly, to systematically identify, classify, and evaluate the environmental impacts of onshore WTs across their entire life cycle, using an extensive literature review. Secondly, to apply the fuzzy DEMTEL method to quantify causal relationships among environmental impact categories and determine the most influential impacts. Thirdly, to compare the results with the best practices and identify technological and policy gaps.

To the best of the authors' knowledge, no prior published study has simultaneously: (i) constructed a multi-level environmental impact taxonomy for onshore WTs covering all five lifecycle phases, (ii) applied Fuzzy DEMATEL to quantify directional causal relationships among those phases, and (iii) integrated the results with a structured comparative policy gap analysis specifically targeting the Global South. This combination addresses a clear methodological and geographical gap in the existing literature.

The results rank end-of-life & recycling, materials & fabrication, and preconstruction & site preparation as the top three ranks. Among the sub-categories, rare earths and metals, as well as recycling, took the first and third ranks, both of which are from the end-of-life & recycling category. With the help of these results, the study guides policymakers, investors, developers, and the supporting industry in focusing their attention on specific environmental impacts caused by the onshore wind energy sector in the Global South.

The remaining sections are structured as follows: Sect. 2 provides a review of the literature, Sect. 3 examines relevant policies, Sect. 4 outlines the methodology, Sect. 5 presents the results and discussion, Sect. 6 provides policy recommendations, and Sect. 7 concludes the study.

2 Literature review

This study is grounded in two complementary theoretical frameworks. First, the Life Cycle Thinking (LCT) paradigm, which extends analysis beyond a single production phase to encompass all upstream and downstream environmental burdens (ISO

14040/14044) [38]. Second, the Circular Economy (CE) framework, which emphasizes resource looping, waste elimination, and regenerative design [25]. CE is directly relevant to the end-of-life challenges identified in this study. These frameworks guide the classification of environmental impact categories and the interpretation of fuzzy DEMATEL results.

Production Stage

The construction stage involves the daily transit of workers, cranes, and equipment to the site, as well as 3D printing of concrete and assembly. A considerable increase in CO_2 can be observed during this phase. Previous studies estimate that up to 92% of the CO_2 emissions occur during its life. Steel, concrete, and aluminum are significant contributors to environmental damage, accounting for over 80% of CO_2, NO_X, $PM_{2.5}$, and SO_2 emissions [57]. Steel towers have a lower impact on total emissions than concrete towers. Steel requires less print time and fewer tower sections to assemble. The overall environmental impact intensity for the real case was 0.012 kg CO_2/kWh. The lowest CO_2 emissions per kWh were found on 3 MW WTs [55]. Regional disparities also exist; a study conducted on WT in China shows that Henan has the highest emissions, at 34.50 g CO_2 eq/kWh, and Yunnan has the lowest, at 13.59 g CO_2 eq/kWh [53]. The carbon emissions from onshore wind in France in 2015 were at 14 g CO_2 eq/kWh; this is much lower than coal-fired power plants of 986 g CO_2 eq/kWh and solar PV of 44 g CO_2 eq/kWh [12].

Certain operations, including excavation and establishment, may have an impact on the local biosystem during the construction of a wind farm. Removing surface plants would expose the soil to heavy rainfall and wind, leading to soil erosion. Oil and wastewater from the building site have the potential to seep into the ground, causing major environmental issues [8]. Also, wind projects in forested regions, particularly in Northern Europe, often lead to deforestation due to favorable policies and reduced restrictions. A case study in Sweden found that there was only a 3.8% increase in annual energy output when expanding clear-felling from 1 ha to 23.04 ha. The study further evaluated CO_2 loss, finding that a 1 ha deforestation could be offset in approximately seven months, while 23.04 ha would take over 13 years, indicating limited CO_2 savings with increased deforestation [13].

The construction phase has a Global Warming Potential (GWP) of 77.39%, compared to the operational phase at 11.61% and transportation to the site at 10.77%. The pollutant emissions vary depending on material composition, technological advancement, and processing procurement. The blade, hub, gearbox, nacelle cover, tower, and generator consume the most.

materials. The tower consumes 95,191 kg of steel, while the generator consumes 12,000 kg. Blade requires 7,200 kg of glass fiber, and the gearbox consumes 8,160 kg of cast iron [11].

The steel towers outperform concrete in terms of ozone depletion, fossil fuel depletion, and.

eutrophication, primarily due to the materials used in production. Steel causes 6.7 times more fossil fuel depletion than concrete. Fossil fuel depletion for concrete is higher than for steel due to the weight of concrete. Steel emits 15.7 times more GWP than 35-MPa 3D printed concrete per unit weight, indicating that concrete towers are preferred as long as their mass does not exceed this factor [24].

Operations Stage

WTs are alleged to emit large amounts of microplastics and bisphenol A (BPA) into the environment. However, previous studies have found only traces of residual BPA, rejecting the claims of large emissions to the environment [34]. Another claim by environmentalists is that of erosion of microplastics and BPA from WTs. In contrast, WT blades have non-toxic coatings, and the blades are designed to withstand high resistance to extreme weather conditions [39]. WTs are not immune to accidents; they occasionally catch fire, leak lubricant fluid, and collapse in extreme weather conditions. These are rare occurrences. Some technical issues can be resolved through regular maintenance and the replacement of worn-out equipment [56].

The social acceptance of the new WTs is low in most Western European countries. The effects of WTs on people's proximity are linked to health impacts, including nausea and sleep disturbances. However, some studies disproved these theories [45]. The public outcry against wind farms in the name of NIMBY (Not in My Backyard) caused many of the wind farm developers to shut down their operations before the end of their life [26]. The story of NIMBY stems from social inclusion and classism, but some of the activists have taken the environmental aspects and claim protection of local flora and fauna [35].

The complexities of noise impacts were explored, and methods were used to mitigate them [26]. WT noise is caused by aerodynamic and mechanical sources and propagates through various terrains and atmospheric conditions. Research has been focusing on developing low-noise WTs. Innovations in low-noise airfoils and trailing-edge serration have reduced noise [2]. However, further strategies must be aligned to increase energy yield and enable higher rip speeds [27]. WT is characterized by variable audible sound levels over time, known as Amplitude Modulated (AM) sound, linked to the blade passing frequency, which ranges between 0.5 Hz and 1 Hz, producing a pulse of 1–2 s. Swishing sound - between 400 Hz and 1 kHz - caused by the trailing edge of the blades, adds to the AM sound along with mechanical noise [6].

Bird collisions are considered a significant threat to wind energy developers. For example, the Altamont Pass Wind Farm has been criticized for causing bird fatalities, particularly among hawks, raptors, and golden eagles. Environmental groups, such as the Center for Biological Diversity and the Golden Gate Audubon Society, have filed complaints and lawsuits demanding either the shutdown of wind farms or the replacement of older WTs, which are poorly sited and disrupt migratory patterns. Våler and Frøya Wind Farms in Norway, Tarifa in Spain, the Black Forest in Germany, and the Shetland Islands in Scotland all faced similar environmental challenges, resulting in losses for the wind developers. Previous studies have explored the challenges of balancing climate change, energy security, and biodiversity protection through wind energy [48]. One such study focused on the Court of Justice of the European Union case law and Danish experiences in wind energy development. The article suggests that instead of softening the environmental protection requirements for protected regions such as Natura 2000 sites (Europe-wide network of protected areas developed under the European Commission's Habitats Directive (92/43/EEC) and Birds Directive (79/409/EEC), the focus should be on revisiting the Birds and Habitat Directives [4]. It advocates for a shift in focus from safeguarding individual birds to evaluating the impact on populations in cases of unintentional disturbances, aiming to balance biodiversity protection with the expansion of wind energy development. The wind farm layout is vital in reducing the collision risk of the birds; a greater distance between adjacent WT reduces the likelihood that birds perceive them as an impenetrable barrier [58].

Recycling Stage

Recycling WTs after decommissioning can reduce GHG emissions by nearly half.

Previous studies about recycling of WT have predominantly investigated the economic feasibility, technical methods, and construction of recycling facilities [46]. Few studies explored waste management and how the components of the WT can be recycled effectively [3, 29]. However, most of this research is from a macro perspective. The current recycling technologies are still in the laboratory, awaiting economic viability. Chemical recovery has proven technically viable, but it remains commercially unviable [46]. Thermal recovery is often used to recover the WT blades since polymer materials are challenging to recycle. Previous studies predict a significant number of WT retirements by 2036, primarily from Europe and China. Europe has promoted recycling in many sectors, but the renewable energy sector remains underdeveloped [9]. The solar PV sector sees many panels being sent to landfills, which spreads toxic metals such as lead, cadmium, and zinc into the environment. Though China and the US are increasing their share of renewables in their energy mix, recycling has largely been undiscussed. These giants in RE development have yet to establish a market mechanism for RE recycling; in other words, they are potential exporters of RE waste for recycling (Chen et al., 2024). WT waste is projected to reach 43 million tons by 2050; China is expected to account for 40%, followed by Europe and the US, with 25% and 16%, respectively [30].

WTs require rare earth materials, including dysprosium, terbium, neodymium, and praseodymium. These materials contribute to the strength of the magnets and improve resistance to demagnetization, especially at high temperatures. Recycling metals presents a challenge similar to extracting them from ore and separating them from one another [17]. Traditional rare earth is an energy-intensive process, and recycling methods require hazardous chemicals such as hydrochloric acid. Recycling rare earth metals is 88% less energy-intensive than mining and has a human toxicity score 98% lower [47].

For concrete components, the recycling rate is 70%, while the remaining 30% is sent to landfills [24]. The steel tower is made from basic oxygen furnace steel, which is composed of 30% recycled materials. The flanges and bolts are made using electric arc furnaces and steel produced by 90% recycled materials. Some studies have shown that recycled materials exhibit no significant change in mechanical strength, with a 10–15% loss in strength [29]. Extending the lifetime of the concrete towers can reduce the overall emissions and environmental impacts; a 50-year tower can reduce 3.7 million kg CO_2 eq, compared to a 25-year lifetime tower [24].

The review of literature is initially in three stages: production, operations, and recycling. Based on the review, we were able to further categorize the factors into five categories and 12 subcategories (Table 1).

3 Policy review

This session reviews the current policies related to the five broad categories identified through the literature review.

Material Production and Fabrication Policies

The decarbonization of the steel and concrete sectors has garnered significant attention over the past five years. Countries are moving towards finding alternatives to coal,

Table 1 Classification of environmental impacts caused by wind turbines (WTs)

Broad category (5)	Sub-category (12)	Variables
1. Pre-Construction & Site Prep	Presurvey	Land use assessment; Site biodiversity survey; Soil & hydrology assessment; Cultural & social acceptance studies (EIA, SIA baseline)
	Deforestation	Land clearing for wind farms; Soil erosion & hydrological disruption; Carbon stock loss from vegetation; Habitat fragmentation; Long-term offset vs. permanent biodiversity loss
	Rehabilitation	Soil stabilization & erosion prevention; Revegetation & reforestation; Wildlife habitat restoration; Waste & oil spill cleanup; Community/environmental compensation
2. Material Production & Fabrication	Greenhouse Gases (GHG)	Emissions from material extraction (steel, concrete, aluminum); Transportation-related emissions; Construction & installation emissions; Operation vs. maintenance; End-of-life & recycling emissions
	Transportation	Sea freight (manufacturing to site); Road freight & local logistics; Worker commute & mobility; Fuel use (cranes/heavy equipment); Regional disparities
	Fabrication	Steel, aluminum, iron production; Concrete (traditional vs. 3D-printed); Blade manufacturing (fiberglass, resin, coatings); Gearbox, nacelle, and generator assembly
3. Construction & Installation	Installation	Site operations (cranes, excavation, cement mixing); On-site tower/blade assembly; Energy use during installation; Wastewater & lubricant leaks; Worker & equipment safety
	Construction & Maintenance Pollution	Particulate matter release; greenhouse gas emissions (maintenance); Oil & lubricant runoffs; Noise & dust pollution; Waste management (damaged blades, parts replacement)
4. Operation & Environmental Impacts	Operation Stage	Air contaminants ($NO_x,\ PM_{2.5}$); Microplastics & BPA claims; Visual pollution; Noise pollution (aero + mechanical); Accidents (fire, collapse, oil leaks); Bird & bat collisions; Cable/grid pollution
5. End-of-Life & Recycling	Recycling	Steel, aluminum, concrete recovery; Rare earth recovery (toxicity & processes); Blade recycling (thermal/chemical/landfill); Lifetime extension vs. repowering; Recycling economics & policy gaps
	Rare Earth & Metals	Mining vs. recycling trade-offs; Toxicity & hazardous chemicals; Energy intensity of separation; Human toxicity risks; Circular economy opportunities
	Landfill Pollution	Non-recyclables (blades, composites); Leaching of hazardous chemicals (resins, epoxy); Landfill overcapacity risks

and green hydrogen; some countries have made significant strides towards reducing their dependence on coal [1]. India plans to decarbonize hard-to-abate sectors using green hydrogen, as outlined in the National Green Hydrogen Mission (2023). Schemes like Perform, Achieve, and Trade (PAT) provide energy efficiency incentives for the cement and metal industries [20]. The United States introduced the Inflation Reduction Act and the DOE's Industrial Demonstration Program to support low-carbon materials and green hydrogen. The European Union initiated 'Green Steel' under the European Clean Hydrogen Alliance to promote hydrogen-based Direct Reduced Iron (DRI) methods. The EU's Carbon Border Adjustment Mechanism (CBAM) penalizes carbon-intensive imports, thereby incentivizing the production of low-carbon steel and cement [22]. Although the policies address major issues in the material production area, they lack depth in terms of traceability of embodied carbon in the WT supply chain and exhibit weak enforcement of environmental standards during component fabrication in developing countries [44].

Presurvey and Site Preparation

Most policies regarding pre-survey points emphasize the need for Strategic Environmental Assessments (SEA), Environmental Impact Assessments (EIA), habitat mapping, and biodiversity offsetting. The European Union spearheaded the SEA directives in 2001, requiring ecosystem-level assessment before project permitting. EU biodiversity strategy 2030 links renewable energy expansion with the 'no net loss' principle. For the approval of wind energy projects in the United States, the EIA is mandatory under the National Environmental Policy Act (NEPA). India notified EIA in 2006, with an amendment in 2020 for wind energy projects; however, compliance is weak [23]. China introduced the Ecological Red Line Policy and the Environmental Impact Assessment Law (amended in 2018), which requires consideration of early-stage habitats [19]. The Five-Year Plans featured ecological restoration quotas for renewable energy projects. In large part, the EIAs are found to have poor enforceability in the Global South. While inadequate capacity for ecological monitoring and rehabilitation follow-up remains.

Construction and Installation Policies

The most effective way to achieve sustainability in this phase is to transition to sustainable construction practices, minimize emissions during installation, and adopt environmentally friendly logistics. The EU has emphasized low-emissions construction equipment and biofuels through the Renewable Energy Directives II [14]. Green Public Procurement (GPP) criteria include the life cycle carbon of minerals and construction fuel use. The United States adopted Clean Construction USA, promoting diesel retrofit programs and the use of alternative fuels for heavy equipment. The EPA's SmartWay program encourages low-emission freight in the transportation sector. China promoted prefabrication and modular design to minimize on-site waste. Chinese policies were aligned towards running pilot programs for electric and hydrogen-powered cranes and trucks. India's policies are centred around the Energy Conservation Building Code (ECBC), which indirectly affects the civil structures of WTs [43]. In developing economies, policies specific to green construction logistics for wind energy are largely lacking. There is a lack of fuel efficiency standards for heavy construction machinery, and a weak integration between renewable energy project approval and local pollution control regulations.

Operation and Maintenance Policies

The EU, US, and China have given clear attention to other stakeholders during the operation of the wind energy farms. Wind energy farms typically operate for 20–30 years, although they can be extended with maintenance and repowering with powerful turbines. During the operation, it can negatively affect wildlife with habitat loss and fragmentation. The impact of WTs on the local population is also observed with its severe visual and noise impacts. To mitigate some of the impacts, the EU enforced the Birds and Habitats Directive for wildlife-friendly operations (Wilson, Darío Fernández-Bellon, Sandra Irwin, John, 2015). Furthermore, the operation should be conducted after the biodiversity monitoring plans have been implemented. China initiated low-impact siting and encouraged the use of AI-enabled smart monitoring systems, mandating the reporting of environmental performance during wind farm operations. The US, under NEPA and the Migratory Bird Treaty Act, requires operators to conduct post-construction monitoring and adaptive management [42]. The adoption of technology such as radar-based curtailment and seasonal shutdown was encouraged in sensitive areas. India currently lacks a unified framework for assessing bird mortality or conducting post-commissioning audits. However, the Wildlife Protection Act (1972) governs the siting in protective areas. The policies are silent on adaptive management protocols, continuous environmental performance evaluation, and integration of biodiversity data into operations.

End of Life and Recycling Policies

Countries consider the circular economy when drafting end-of-life policies, including landfill bans, recycling infrastructure, and extended producer responsibility. The EU is moving towards a ban on landfilling blades by 2025–2030. They encourage circular designs and extended producer responsibility under the EU Waste Framework Directives and the Circular Economy Action Plan. EU's WindEurope's Zero Wind Blade initiative promotes reuse, repurposing, and co-processing of composites [46]. The United States plans for complete circularity by 2035. DOE's 'Wind Energy Technology Office' funds research and development for thermoplastic resin blades and recyclable composite technologies. China has issued a national standard for WT recycling, promoting reuse and prohibiting the uncontrolled burning or disposal of these turbines. In the 14th FYP, circular materials management in renewable energy technologies was included [19]. India lags behind in the wide turbine policy framework. Apart from the Solid Waste Management Rules of 2016 and the Extended Producer Responsibility of 2022, there is hardly any mention of the recycling and end-of-life regulations.

To provide a structured comparison across major wind energy markets, Table 2 summarizes key policy instruments, their enforcement strength, and the corresponding gaps relevant to the Global South.

The comparison reveals that while developed and centrally coordinated economies demonstrate stronger enforcement and lifecycle integration, Global South countries face persistent gaps in implementation, monitoring, and circularity frameworks. These gaps reinforce the need for context-specific policy adaptation rather than direct policy transfer.

4 Materials and methods

The review of the literature is followed by a multi-level classification of the environmental factors caused by onshore WTs. With a special focus on the Global South, seven experts were selected through purposive sampling. Experts were selected using

Table 2 Comparative Policy Landscape Across Lifecycle Stages in Major Wind Energy Markets

Country / Region	Lifecycle stage	Key policy / Instrument	Enforcement strength	Gap for Global South
European Union	End-of-Life & Recycling	Circular Economy Action Plan; Waste Framework Directive; WindEurope blade ban initiatives	Strong	High compliance capacity not easily replicable; capital-intensive recycling infrastructure
United States	Material Production & Recycling	Inflation Reduction Act; DOE Wind Energy Programs; Wind Energy Technology Recycling R&D Program	Strong	Policy fragmentation across states; limited transferability to centralized governance systems
China	Manufacturing & Lifecycle Control	14th Five-Year Plan; Ecological Red Line Policy; Emerging National recycling standards for WTs	Strong	State-led enforcement model difficult to replicate; high dependence on centralized planning
India	Pre-construction & Environmental Assessment	EIA Notification (2006, 2020 amendment); PAT Scheme; National Green Hydrogen Mission	Weak–Moderate	Weak enforcement of EIA; lack of recycling-specific regulations; limited lifecycle monitoring
Brazil	Construction & Environmental Licensing	Environmental licensing framework (IBAMA); renewable expansion policies	Moderate	Inconsistent enforcement; limited integration of lifecycle-based environmental metrics

purposive sampling based on three criteria: (i) a minimum of ten years of professional experience in renewable energy systems, LCA, environmental planning, or wind turbine technology; (ii) geographic diversity, ensuring representation from both the Global South (India, Brazil, South Africa) and the Global North; and (iii) professional diversity across academic, policy, and industry roles. No expert held a direct financial interest in any wind energy project included in the analysis. A questionnaire is rolled out to the experts, and their inputs are quantified using the Fuzzy Decision-Making Trial and Evaluation Laboratory (Fuzzy DEMATEL) approach to identify, quantify, and visualize the causal relationships among the major barriers and sub-barriers that influence WTs on their environment. Experts evaluated the influence of each impact category on others using a 5-level linguistic scale (no influence to very high influence). The scale was validated through a pilot test with two external reviewers. Each linguistic term was mapped to Triangular Fuzzy Numbers (TFNs) as shown in Table 3.

The Fuzzy DEMATEL method was employed to quantify both direct and indirect causal relationships among environmental impact categories. The procedures consist of the following steps.

Step 1: Construction of the Fuzzy Direct-Relationship Matrix.

Each expert *k* provides a fuzzy evaluation of the influence between *i* and *j*, denoted as.

$$\tilde{x}_{ij}^{(k)} = \left(l_{ij}^{(k)}, m_{ij}^{(k)}, u_{ij}^{(k)}\right) \tag{1}$$

The individual expert matrices are aggregated to obtain the average fuzzy direct-relation matrix.

$$\tilde{x}_{ij} = \frac{1}{K}\sum_{k=1}^{K}\tilde{x}_{ij}^{(k)} = (\frac{1}{K}\sum_{K=1}^{K}l_{ij}^{(k)},\ \frac{1}{K}\sum_{K=1}^{K}m_{ij}^{(k)}, \frac{1}{K}\sum_{k=1}^{K}u_{ij}^{(k)}) \tag{2}$$

Step 2: Defuzzification.

The aggregate fuzzy values are converted into crisp scores using the centroid method.

$$x_{ij} = \frac{l_{ij} + m_{ij} + u_{ij}}{3} \tag{3}$$

This results in a defuzzied direct-relation matrix $A = [\, x_{ij}]$.

Step 3 is normalization of direct-relation matrix.

$$X = \frac{A}{\max_i \left(\sum_{j=1}^{n} x_{ij}\right)} \tag{4}$$

Table 3 Linguistic Scale and Corresponding TFNs

Linguistic term	Description of influence	Triangular fuzzy number (TFN) (l, m, u)
No Influence (NI)	No causal impact between categories	(0.00, 0.00, 0.25)
Low Influence (LI)	Very weak influence, barely noticeable	(0.00, 0.25, 0.50)
Medium Influence (MI)	Moderate or average influence	(0.25, 0.50, 0.75)
High Influence (HI)	Strong and clearly noticeable influence	(0.50, 0.75, 1.00)
Very High Influence (VHI)	Extremely strong and dominant causal influence	(0.75, 1.00, 1.00)

This scales all influence values to the [0,1] interval.

Step 4 The Total Relation Matrix (*T*) was computed using the standard DEMATEL function.

$$T = X\left(I - X\right)^{-1} \tag{5}$$

Where *X* is a normalized direct-relation matrix and *I* is the identity matrix. This matrix shows both direct and indirect effects among the barriers.

Step 5: The prominence and relation analysis.

For each factor *i*, the following indices are calculated.

$$D_i = \sum jt_{ij} \ \text{(sum of row values : influence exerted)} \tag{6}$$

$$R_i = \sum jt_{ij} \ \text{(sum of column values : influence received)} \tag{7}$$

$\text{Prominence } = D_i + R_i$

$$\text{Relation} = D_i - D_i$$

Prominence $(D_i + R_i)$ reflects the overall importance of a factor within the system, while relations ($D_i - R_i$) distinguishes between cause (positive) and effect (negative) factors.

The categories are ranked according to the prominence value (D + R) with the higher the value, the more overall importance in the system. The DEMATEL approach, unlike traditional approaches to ranking based on factors, only by magnitude, provides direct and indirect impact between factors. Consequently, a category that scores high on prominence not only exerts huge individual influence but also it interacts with other lifecycle stages in a strong manner. Also, the relation value (D-R) differentiates between causal drivers and dependent factors. Categories having positive (D -R) values are considered as net causes whereas those with negative values as net receivers. This two-fold interpretation allows a more in-depth consideration of both significance and directional impact in the system.

Fuzzy DEMATEL was selected because it allows the study to capture both uncertainty in expert judgment and complex causal relationships among environmental impacts, which conventional LCA and narrative reviews cannot quantify. This methodology enables us to move beyond identifying impact magnitudes and instead reveal directional influential pathways, offering deeper insights into where policy and technological interventions in the Global South can create the greatest systemic improvements.

5 Discussion

The analysis based on the DEMATEL shows that end-of-life and recycling are the most significant barriers, with a prominence (D + R) of 62.36, followed by material production and fabrication (61.07) and pre-construction and site preparation (60.59) (Fig. 1). Construction, Installation, and Operations score lower in the prominence, with 40.78 and 19.46, respectively. The elevation of the end-of-life and recycling area of the WTs is the highlight of this study. There is an increasing interest in both academic and grey literature that blade waste and limited scalable recycling technologies pose an imminent materials and policy challenge as the fleet ages and retires [30]. While most materials,

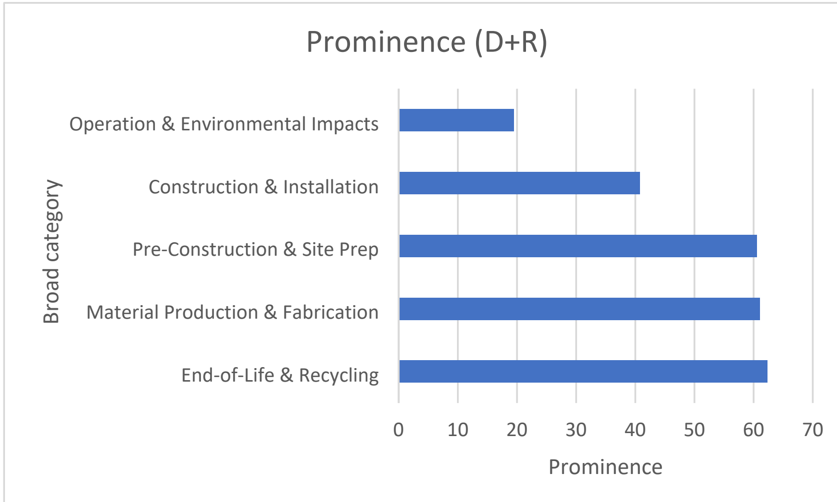

Fig. 1 Prominence (D + R) values for the five broad environmental impact categories of onshore wind turbines, derived from the Fuzzy DEMATEL analysis. Higher values indicate greater systemic importance. End-of-Life & Recycling ranks highest (62.36), followed by Material Production & Fabrication (61.07) and Pre-Construction & Site Preparation (60.59)

such as steel and copper, are readily recyclable, blades made of fiberglass and carbon fiber-reinforced polymer composites often end up in landfills, posing a significant waste challenge [34]. Landfilling is increasingly restricted, and EU and industry leaders are moving towards landfill bans for blades, driven by a focus on near circularity. The United States, under DOE/NREL, reports and recommends scaling recycling. The existing US infrastructure can process 90% of the turbine mass and targets complete circularity [7]. China proposed standards that prioritize recycling and reuse, and restrict the landfilling and burning of blades. Denmark plans to develop a value chain for WT blades through an industry cluster approach (IEA, [21]). Recent advancements in technology have led to a rapid shift from conventional glass fiber composites to advanced carbon fiber composites, graphene-enhanced materials, and hybrid systems, offering superior mechanical strength, weight reduction, and enhanced fatigue resistance [39]. These advancements would reduce the environmental burdens in the future; however, the WTs, which are nearing the end of their life, currently have limited options.

The dominance of end-of-life recycling in the Global South is intensified by inadequate recycling systems, dependence on imported components, and the absence of regulations governing blade waste, thereby amplifying downstream environmental burdens (Table 3). Fuzzy DEMTEL highlights this category as a strong causal driver, showing that waste accumulation feeds back into material demand, extraction pressure, and local ecological risks. This behavior reinforces the novelty of the study by revealing directional cause-and-effect relationships rather than static impact magnitudes. The analysis shows that Global South countries should embed circularity standards at the production stage rather than at the decommissioning stage. The best practices adopted by the Global North should be integrated into planning at the outset to address challenges at the end of the life stage. Policy mechanisms, such as Extended Producer Responsibility (EPR), regional recycling hubs, and landfill restrictions, can directly mitigate the causal influence of high-impact categories. To further contextualize the findings, illustrative lifecycle evidence from selected Global South wind projects is presented in Table 4.

Table 4 Illustrative LCA Data from Global South Wind Projects

Country	Project / study context	Key lifecycle findings	Relevance to this study
India (Karnataka) [51]	Vestas V82 wind turbines (10 units)	Recycling of turbine materials reduces total environmental impact by 71–75%; wind power emissions significantly lower than coal (≈ 85× lower)	Strongly supports the high prominence of End-of-Life & Recycling as a dominant lifecycle stage
Brazil [37]	Onshore wind deployment studies in emerging markets	High lifecycle emissions concentrated in material production and construction phases, driven by steel, concrete, and logistics intensity	Reinforces ranking of Material Production & Fabrication as a key upstream driver
India / Global South (Ecological studies) [49]	Wind farms in ecologically sensitive regions (e.g., Western Ghats)	Significant biodiversity disruption due to deforestation, habitat fragmentation, and weak pre-survey assessments	Validates causal importance of Pre-Construction & Site Preparation in DEMATEL results

The case-based evidence reported in Table 4 also strengthens the soundness of the DEMATEL results as it compares the empirical lifecycle data with the rankings obtained with the aid of models. An example is that End-of-Life and Recycling ($D+R$ = 62.36) is highly visible, which is in line with the reductions of 71–75% in environmental impact with recycling in Indian wind projects. Equally, the upstream causal effect found in this research is supported by Brazilian evidence that material production and construction phases are the most important sources of lifecycle emissions. These empirical results indicate that the ranking of the DEMATEL is structurally rooted on expert inputs, as well as in line with the real-life lifecycle performances in the Global South settings.

The findings from this study align with previous observations on the environmental impact of materials production for wind energy [32]. Steel, concrete, and mined resources are significant sources of greenhouse gas emissions throughout their life cycle. The tower accounts for 70–75% of the total mass, mostly steel; steel itself accounts for 40–60% of the total GHG emissions, composites for 15–20%, and copper for 10%. The minerals require high energy for smelting, forging, and curing composites, accounting for 75–98% of the cumulative environmental impacts associated with wind energy [5]. Manufacturing WTs contributes to marine eutrophication, metal depletion, and local air or water emissions associated with the mining, fabrication, and transportation stages.

The large CO_2 emissions from the construction phase, resulting from steel production, can be mitigated by utilizing renewable sources. Green Hydrogen can not only reduce CO_2 emissions from fossil fuel use but also mitigate the intermittency caused by renewables, which could otherwise hinder the energy required for blast furnaces. China's 14 Five-Year Plan shifted its focus from quantity to quality for WT. Emission reduction became central to its efforts. Larger turbines and advanced designs, curtailment reduction, and optimization gained attention [19]. An advanced design could reduce the emission intensity by 21.6% well within the target for global climate targets. China has invested heavily in energy storage, which helps reduce curtailment. Improvements in transmission networks also support this purpose. These investments lowered curtailment from 21% in 2016 to 4% in 2019. The optimization of materials and innovations in technology has led to a decline in environmental impacts, from manufacturing to the recycling phase [54].

The fuzzy DEMATEL results indicate that in the Global South, upstream material emissions are influential drivers due to coal-based steel manufacturing, the lack of embodied carbon tracking, and long-distance logistics from turbine manufacturing hubs in Europe, the US, and China. The results indicate that without policy intervention that promotes green hydrogen for hard-to-abate sectors, transparent carbon intensity benchmarks, and domestic fabrication clusters powered by renewable energy, the Global South will continue to bear disproportionate environmental burdens from imported turbine infrastructure.

Deforestation and rehabilitation ranked seventh and eighth, respectively. Site preparation for construction involves clearing for turbine pads, roads, a substation, and transmission lines. These activities significantly alter the ecosystem. A study on wind farms and their impact on the Western Ghats ecosystem in India highlights the irreversible damage to biodiversity and the ecosystem. Soil erosion has increased due to the loss of groundwater, predator-prey dynamics have changed, and revegetation efforts have been minimal [49].

The operations stage of WTs is ranked ninth in our study (Table 5). However, other studies emphasize the importance of this stage for overall sustainability [10]. The impacts on birds and their habitats are a concern, along with technical, economic, and institutional challenges. Potential effects include disturbance through direct or indirect habitat loss, as well as fatality due to collision. Birds may exhibit behavior change, for example, common eiders avoid flying close to wind farms, which can decrease habitat availability. Capercaillie showed reduced habitat selection near turbines, indicating habitat deterioration up to 650 m from the turbines. Bird species richness, functional richness, and phylogenetic diversity increase with distance from WTs, particularly beyond 500 m [33]. Proper placement of wind farms and Environmental Impact Assessments can mitigate adverse effects. Sensitivity maps and buffer zones can help in planning to minimize impacts on the bird population. The EIA should not only focus on the impact on the bird species and their habitat, but also on bird movement patterns in onshore wind farms. The impact of WT turbulence on specific bird species, such as ducks, is currently absent from the existing literature [58]. Some of the recommendations derived from the existing literature on bird and bat conservation include the implementation

Table 5 The prominence and rank of sub-categories

Sub-category	D (sum rows)	*R* (sum cols)	Prominence (D + *R*)	Relation (D-*R*)	Broad category	Rank
Rare Earth & Metals	11.08921	10.61024	21.69944	0.47897	End-of-Life & Recycling	1
Installation	10.86622	10.78465	21.65087	0.081577	Construction & Installation	2
Recycling	10.44143	10.88808	21.32951	-0.44666	End-of-Life & Recycling	3
Presurvey	10.75918	10.40989	21.16907	0.349283	Pre-Construction & Site Prep	4
Transportation	10.74778	10.39497	21.14275	0.352819	Material Production & Fabrication	5
Fabrication	10.76213	9.991933	20.75406	0.770193	Material Production & Fabrication	6
Deforestation	10.01353	9.761272	19.7748	0.25226	Pre-Construction & Site Prep	7
Rehabilitation	10.37454	9.270426	19.64497	1.104117	Pre-Construction & Site Prep	8
Operation Stage	8.826086	10.6332	19.45928	-1.80711	Operation & Environmental Impacts	9
Landfill Pollution	8.804735	10.53023	19.33496	-1.72549	End-of-Life & Recycling	10
Greenhouse Gases (GHG)	10.08929	9.085254	19.17454	1.004035	Material Production & Fabrication	11
Construction & Maintenance Pollution	9.358965	9.772957	19.13192	-0.41399	Construction & Installation	12

of radar technology, turbine curtailment, and habitat restoration [36, 40]. A case study from France on the impacts of WTs on bats reveals that more than 90% of the locations identified have high significance to bats [16]. Environmental monitoring and management should be considered at the construction and operational stages, including timely restoration and compensation for environmental pollution caused by wind power operations.

The installation stage is the second most environmentally impactful stage in the life cycle of WTs. The installation phase involves significant use of resources, particularly diesel fuel, which contributes to emissions and other environmental impacts. Diesel fuel accounted for the largest part in the installation stage, and the transportation and maintenance stage included less than 1%. The installation stage has a direct impact on the ecosystem, as it can displace or cause habitat loss. Waste management is another concern during the installation phase; the toxic waste polluting the water streams poses a crucial risk that must be mitigated to achieve overall sustainability.

Interestingly, presurvey has appeared third among the broad categories. The role of pre-surveys is positively viewed in the existing literature. This stage reduces exposure to sensitive habitats, thereby minimizing the project's impact on wildlife and the ecosystem. The initial survey would provide insights into wind speed throughout the year, aiding in the optimal design of a wind farm. However, the long-term impacts of the pre-survey, its absence, or improper conduct are a concern for developing economies trying to transition to low-carbon energy sources. One such argument was made by Roy et al., [42], who claimed that pre-survey and regional planning in the Thar Desert have not captured the full scale of avifaunal use of the landscape, nor have they adjusted siting/spacing to avoid high-risk locations. Similar findings were observed by Lintott et al., [28], who noted that surveys often used short time windows, limited detectors/monitoring methods, or inappropriate seasonal coverage, thereby missing peaks in bat activity and leading to false negatives or underestimates of risk, which in turn resulted in insufficient mitigation in siting/permit decisions. Countries that follow strict EIA protocols have found that mitigating the long-term impacts; in contrast, in the Global South, EIA appears on paper but performs poorly. This is due to limited institutional capacity for regulators and consultants. Political/economic pressure favors rapid development over thorough assessment. The results of this study indicate that the operational phase has a minimal causal influence on other life-cycle stages, meaning it does not trigger downstream or upstream environmental burdens compared to the most impactful phases, such as material production or end-of-life recycling.

In the Global South, weak EIAs, short survey windows, insufficient biodiversity baselines, and politically accelerated permitting cause this category to have a cascading impact on the wildlife. The results suggest that an early-stage ecological decision has a stronger impact on multiple downstream consequences in the Global South than in the Global North. This also highlights that stronger pre-survey protocols, mandated multi-season ecological assessments, and an established independent EIA authority are not just procedural improvements, but also a system-level intervention that disrupts harmful causal chains.

Table 5 ranks the sub-categories according to the prominence values (D + R), which indicates the overall systemic significance of the sub-categories. By doing that, the ranking will allow capturing the impact of influence exerted and received, as opposed to the

Table 6 Sensitivity Analysis of Prominence Value with ± 10% variation

Broad Category	Baseline (D + *R*)	−10% Scenario	+ 10% Scenario	Rank Stability
End-of-Life & Recycling	62.36	56.12	68.6	1 → 1 → 1
Material Production & Fabrication	61.07	54.96	67.18	2 → 2 → 2
Pre-Construction & Site Preparation	60.59	54.53	66.65	3 → 3 → 3
Construction & Installation	40.78	36.7	44.86	4 → 4 → 4
Operation & Environmental Impacts	19.46	17.51	21.41	5 → 5 → 5

measures of influence being isolated. Consequently, the ranking is an environmental impact hierarchy that is obtained through structural derivation in the lifecycle of wind turbines. The ordering of sub-categories is based on their prominence score (D + R); the higher the D + R, the greater the overall significance in the system. Net causal drivers are sub-categories that have a positive D -R value (relation > 0) - they have a greater impact on others than they are impacted by. Sub-categories with negative D-R are net receivers, implying they are influenced by upstream stages. Strong drivers are Rare Earth & Metals (D – R = + 0.479) and Fabrication (D – R = + 0.770), whereas the most obvious receiver is Operation Stage (D – *R* = – 1.807). This interpretation is in line with the wider DEMATEL literature on causal mapping.

6 Sensitivity analysis

The sensitivity analysis to assess the robustness of the results was conducted by introducing a 10% perturbation to the scores of individual experts and refining the prominence (D + R) values for each broad category. The perturbations are used to simulate positive (+ 10%) and negative (-10%) changes in expert judgment without altering the structural relationships of the DEMATEL framework.

Table 6 gives the recalculated prominence values under various scenarios. The findings suggest that the absolute prominence values differ proportionally, but the rank ordering is the same in all situations, with End-of-Life and Recycling, Material Production and Fabrication, and Pre-Construction and Site Preparation always taking the first 3 positions. This is a confirmation of the stability and strength of the causal structure determined in the baseline model.

The relative change in the prominence values proves that the DEMATEL structure is not sensitive to moderate differences in the expert input. The rank-order invariance indicates that the causal hierarchy it determines is not driven by marginal differences in expert ratings, but rather by the hierarchy's structural nature. This supports the main conclusion of the study, which is that upstream and end-of-life stages have a greater impact on the environmental system of onshore wind turbines in the Global South.

7 Policy recommendation

Based on the fuzzy DEMATEL analysis, the most influential categories are end-of-life recycling, materials, production and fabrication, and pre-construction and site preparation. These categories require targeted interventions. End-of-life recycling ranked first in our analysis. In the Global South, there are limited recycling policies, no mention of blade mandates, inadequate infrastructure, and limited attention at the national level to enforcing circularity. Lessons learned from Europe and the US can be applied in the Global South, including Extended Producer Responsibility and the creation of a circular economy compliance index for developers, linked to approvals and fiscal incentives.

Following the EU model of phased landfill bans is a step toward overall sustainability. The highest prominence ($D + R = 62.36$) and the strongest causal relationship in the DEMATEL analysis (End-of-Life) was associated with Recycling, hence the policy interventions addressing this step are of the greatest systemic leverage and should be prioritized.

The second rank went to material production and fabrication. The high emissions from steel/concrete production, the lack of embodied carbon traceability, and the reliance on imported components with large transport footprints are some of the major issues facing wind energy sustainability. The policies should focus on developing alternative energy sources for steel component manufacturing, such as green hydrogen; developing domestic manufacturing clusters; and implementing carbon-intensity benchmarking for turbine components, similar to CBAM and EU product standards. As Material Production & Fabrication has a high prominence value ($D + R = 61.07$) and ranks as a major upstream driver, policies aimed at decarbonizing material feeds, enhancing embodied carbon tracking, and encouraging the uptake of green hydrogen are important for reducing lifecycle environmental impacts on a large scale.

The pre-construction and site preparation received 3rd rank; it is a result of weak EIA, short survey windows, poor enforcement, and insufficient biodiversity data collection. Policies shall focus on mandating a multi-season, multi-species ecological survey, adopting sensitivity and exclusion maps similar to those used in the US's mandatory NEPA-based assessments, as well as species-specific guidelines and bird and bat sensitivity maps. Creating an independent EIA authority to reduce political interference and weak enforcement is another recommendation.

Since Pre-Construction and Site Preparation demonstrate a high level of prominence ($D + R = 60.59$) and affect subsequent ecological results, reinforcing Environmental Impact Assessments (EIA), biodiversity mapping, and site selection procedures can help effectively address the cascading environmental risks.

The construction and installation phase shall be given lower priority. Some of the issues related to this phase include high diesel consumption, soil disturbances, lubrication leaks, the absence of fuel standards for machinery, and a lack of pollution control norms. These issues are controllable and, hence, are expected to have a lower impact on the environment of the developing economies. However, to further fine-tune and improve the efficiency of total sustainability, the policies should adopt fuel-efficiency and emission norms, promote electric construction vehicles, implement strict guidelines for soil stabilization, and mandate green logistics plans. Despite the relative low prominence of Construction & Installation ($D + R = 40.78$), incremental performance gains in the area of fuel consumption, building logistics, and pollution prevention can still be achieved.

The operational phase has shown a limited impact on the environment; however, its presence can be further reduced by adopting the latest technologies, which could decrease the footprint due to operations and maintenance activities. The policies should support radar-based or camera-based smart curtailment to protect birds and bats. Its category, Operation and Environmental Impact ($D + R = 19.46$), is the least prominent, indicating it cannot have a systemic effect; nevertheless, localized impact reduction is still possible through specific technological measures, including smart curtailment and ecological surveillance.

8 Conclusion

This study provides a comprehensive understanding of the environmental impacts associated with onshore wind energy by integrating an extensive literature review with an expert-driven Fuzzy DEMATEL analysis. The results demonstrate that while wind energy remains one of the cleanest and most climate-friendly technologies, its life cycle is categorized by complex and interconnected environmental impacts that extend from material extraction to end-of-life management. Among the five broad categories, end-of-life and recycling emerged as the most influential and prominent barriers, underscoring the urgent need for scalable, economically viable, and technologically mature recycling pathways. Materials production & fabrication, as well as pre-construction & site preparation, are ranked higher, highlighting the importance of upstream activities on the environmental footprint of wind energy systems.

The analysis shows that environmental impacts are not evenly distributed across the life cycle. Carbon-intensive material production, heavy logistics during construction and installation, site disturbances such as deforestation and soil erosion, and operational impacts on wildlife collectively form a multi-layered environmental burden.

While technological improvements have significantly reduced emissions during the operational stage, several impacts, including biodiversity loss, noise pollution, visual disturbances, and concerns about microplastics, remain prominent. Conversely, the relatively lower prominence of operational impacts in the ranking emphasizes that many popular criticisms are less significant than commonly perceived when assessed quantitatively.

A key contribution of this paper is the expert-informed cause-and-effect modeling, which identifies where policy, technology, and industry interventions can create systemic improvements. The findings reveal that improving circularity, scaling advanced material recycling, conducting ecological assessments, and implementing green logistics could help mitigate cumulative impacts. For the Global South, where regulatory enforcement is often weak, this study highlights pressing needs for stronger institutional capacity, long-term ecological monitoring, and transparent accountability mechanisms across the project life cycle. Overall, wind energy for achieving sustainability requires shifting from a narrow focus on operational-phase benefits to a holistic life-cycle perspective.

This study is not free from limitations. First, although fuzzy DEMATEL reduces uncertainty, the analysis still relies on a small pool of experts, leaving them to their subjectivity. Although we have diversified the pool selection based on their professional and geographic backgrounds, the possibility of bias may still influence the outcome. Second, the scope is limited to onshore wind energy, and only a few factors were considered. Third, potential cognitive biases in expert judgment, such as anchoring bias or availability heuristics, may influence responses. To mitigate this, experts were provided with structured definitions of each linguistic scale level and a calibration example prior to completing the questionnaire. Future research should focus on stage-specific environmental interventions across the wind turbine lifecycle in the Global South, including low-carbon material production, improved ecological assessments, sustainable construction practices, real-time operational monitoring, and scalable recycling supported by circular economy policies. Future research ought to (i) apply the same framework to offshore wind power to compare lifecycle impact profiles; (ii) include social and economic impact classes with environmental classes in order to determine sustainability;

and (iii) use multi-round Delphi validation with a larger panel of experts to lessen the subjectivity in fuzzy judgments.

Author contributions
Shambhu Sajith designed the study, conducted the analysis, and prepared the manuscript. Aswani RS contributed to methodology refinement, interpretation of results, and manuscript review.

Funding
Open access funding provided by Symbiosis International (Deemed University). This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability
All data generated or analysed during this study are included in this article.

Declarations

Ethics approval and consent to participate
The study was reviewed by the Institutional Research Ethics Committee of IILM University, Greater Noida, India, which determined that the study was exempt from formal ethics approval as it did not meet the criteria for human-subject research. The exemption was granted in accordance with institutional guidelines and relevant national regulations. Informed consent was obtained from all participants prior to data collection. Participation was voluntary, and respondents were informed about the purpose of the study, their right to withdraw at any time, and the anonymous use of their responses.

Consent to publish
Not applicable, as the study does not include any identifiable personal data or images.

Informed consent
All participants provided informed consent. No minors under the age of 16 were included in the study.

Competing interests
The authors declare that they have no known financial, professional, or personal conflicts of interest that could have influenced the work reported in this study.

Received: 19 November 2025 / Accepted: 25 May 2026

Published online: 03 June 2026

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