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Life-Cycle Environmental Assessment and Comparative Recycling Pathways of Wind Turbine Blades: Toward Circular Design and Sustainable Decommissioning

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ABSTRACT. Wind energy is vital to achieving carbon neutrality, yet the growing retirement of wind turbine blades poses emerging environmental challenges. This study establishes a localized life-cycle assessment (LCA) framework to quantify the environmental impacts of wind turbine blades across four stages — manufacturing, transportation, operation, and end-of-life management. Eight impact categories, including global warming, particulate matter formation, eutrophication, and ecotoxicity, were evaluated, and three recycling pathways — mechanical, pyrolysis, and chemical — were compared. Results show a pronounced "front-end concentration" pattern, where environmental burdens are predominantly aggregated in the upstream manufacturing stage, it dominates over 95% of total impacts in all categories, mainly due to the production of glass and carbon fibers with high embodied energy and emissions. Among recycling routes, mechanical recycling exhibits the lowest overall environmental burden, while chemical recycling shows higher energy use and toxicity potential. The findings highlight that decarbonizing the manufacturing process and advancing recyclable composite materials are essential to improving the sustainability of wind turbine blades. The proposed framework provides scientific support for circular design and policy formulation under China's dual-carbon goals.

Keywords: circular design, environmental impact analysis, life-cycle assessment, recycling pathways, wind turbine blades

1. Introduction

Against the backdrop of global energy transition and climate change mitigation, wind energy has become a key driver toward carbon neutrality due to its clean, renewable, and scalable nature. According to the International Renewable Energy Agency (IRENA), the global cumulative wind power capacity surpassed 900 GW by the end of 2022, with China leading at 365 GW — over 40% of the total (Shi and Zhao, 2025). Under the "dual-carbon" strategy, China's wind industry is expanding rapidly, supported by a complete value chain covering manufacturing, installation, and maintenance. However, as early wind turbines approach their 20-year design life, decommissioned scientists to readily calculate the main fluxes of Net Ecosystem units will increase sharply, and the disposal of large composite blades has become a critical environmental challenge. Global cumulative blade waste is projected to exceed 43 million tonnes by 2050, with China being the most affected country (Liu and Barlow, 2017).

While towers and nacelles are mostly metallic and exhibit recycling efficiencies above 90%, wind turbine blades pose a unique challenge. These blades are typically composed of glass- or carbon-fiber-reinforced thermoset composites, which are lightweight and durable but inherently difficult to recycle. Consequently, they are often termed 'industrial fossils' due to the complexity of separating their cross-linked polymer matrices (Oliveux et al., 2015). Once cured, thermoset composites cannot be remelted, making landfill and incineration the dominant EoL options, both inconsistent with wind energy's sustainability principles (Lund and Madsen, 2024). LCA studies have consistently shown that blade manufacturing contributes 70 ~ 80% of total environmental burdens, primarily due to glass fiber production and epoxy resin synthesis (Haapala and Prempreeda, 2014; Das and Nandi, 2025). As blades evolve toward larger and lighter designs, the use of carbon fiber — despite its mechanical advantages — further amplifies embodied energy (183 ~ 286 MJ/kg) and carbon intensity (Song et al., 2009; Meng et al., 2017). Consequently, the manufacturing phase remains the dominant carbon hotspot in the blade life cycle.

Over the past decade, research on wind blade life-cycle im-

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pacts has matured significantly. Early assessments relied on static averages, whereas more recent works incorporate dynamic energy mixes, transport distances, and recycling scenarios to improve realism (Alavi et al., 2025). Although transportation and maintenance stages contribute relatively less, their associated NO_x and particulate emissions can be significant for offshore or remote installations (Verma et al., 2022). Modern LCAs now extend beyond greenhouse gas metrics to include acidification, eutrophication, particulate matter formation, and toxicity indicators (Spini and Bettini, 2024). EoL management strategies can be broadly classified as mechanical, thermal, and chemical recycling (Gopalraj and Kärki, 2020; Naqvi et al., 2020; Morici and Dintcheva, 2022). Mechanical processes such as cutting and shredding offer low-cost disposal but yield downgraded products like fillers and cement additives (Howarth et al., 2014). Thermal recycling (pyrolysis) decomposes resin at 400 ~ 600 °C under inert gas to recover fibers and fuel gases, though it involves high energy use and partial fiber degradation (Zhang et al., 2024; Kumar et al., 2025). Chemical recycling (solvolysis) employs acids, alcohols, or amines under moderate temperature and pressure to depolymerize resins, enabling the recovery of intact fibers and resin monomers (Protsenko et al., 2023; Shen et al., 2023); yet, solvent consumption and waste-liquid treatment remain challenges.

An emerging solution to wind blade end-of-life challenges is design for recyclability. The adoption of recyclable thermoplastic resins — such as Elium® — enables wind turbine blades to be remelted and reprocessed after decommissioning. For example, the ZEBRA project demonstrated the feasibility of producing fully recyclable blades using Elium®, with successful modeling and polymerization studies for thick composite parts (Denis et al., 2023), and validated infusion techniques for large components.

Similarly, researchers have manufactured and tested smaller thermoplastic blades, confirming that Elium®-based composites offer comparable mechanical performance to conventional epoxy blades, while allowing solvent-based recycling of both resin and fibers (Carnicero et al., 2022). At the U.S. National Renewable Energy Laboratory (NREL), a 9-meter thermoplastic blade using Elium® and recycled PET foam was successfully fabricated, highlighting the resin's potential for reduced cycle time, thermal welding, and recyclability (Murray et al., 2017). These advances reflect a shift from post-use waste management to circular material strategies in blade design, aligning with broader sustainability goals in the wind energy sector.

Despite notable progress in recent research, several critical limitations remain. Current studies often fail to integrate all stages of the blade life cycle into a unified analytical framework, and few attempts have been made to couple environmental, economic, and resource efficiency assessments. Moreover, most existing evaluations rely on foreign datasets and lack adaptation to China's industrial and energy contexts. In addition, the majority of analyses still focus narrowly on carbon emissions, overlooking broader environmental indicators such as toxicity, eutrophication, and particulate matter formation.

Based on the above research gaps, it is necessary to establish a more comprehensive and localized analytical framework. Specifically, the main objectives of this study are threefold: (1) To develop a life-cycle-based environmental assessment system that covers the entire process of blade manufacturing, transportation, operation, and recycling, systematically identifying environmental hotspots; (2) To conduct a comparative analysis of major recycling routes — including mechanical recycling, pyrolysis, and chemical depolymerization — within a unified platform, incorporating multiple environmental indicators such as acidification and toxicity beyond carbon emissions; (3) To integrate China-specific industrial data to ensure the modeling reflects local realities. Through this approach, the study reveals key environmental pressures and provides scientific evidence for selecting optimal recycling pathways, supporting the development of a closed-loop recycling system for wind turbine blades in China.

2. Methodology

2.1. Overview of the Wind Turbine Blade Life Cycle

The life cycle of a wind turbine blade is a complex and systematic process encompassing the entire chain from raw material extraction to end-of-life (EoL) management. In this study, the blade life cycle is categorized into four interrelated stages — (1) manufacturing, (2) transportation, (3) operation and maintenance, and (4) decommissioning and recycling — each characterized by distinct technological features, resource inputs, and carbon emission sources (Sphera (GaBi) n.d., n.d.). This framework enables a comprehensive identification of environmental hotspots and provides the foundation for life-cycle assessment (LCA) modeling.

2.1.1. Manufacturing Stage

The manufacturing stage represents the most emission-intensive phase of the life cycle. Carbon dioxide (CO_2) emissions primarily originate from the production of turbine blades and other major components such as transformers, cables, and transmission towers. These emissions are influenced by material composition, processing techniques, and manufacturing efficiency (Merugula et al., 2012). The production of composite materials — particularly glass-fiber and carbon-fiber reinforced polymers — accounts for the majority of embodied energy and carbon emissions in this phase. Accurate identification of material constituents and process parameters is therefore essential for emission quantification.

2.1.2. Transportation Stage

The transportation stage is another significant contributor to CO_2 emissions, mainly driven by the combustion of fossil fuels such as diesel, gasoline, or natural gas during logistics operations. As a key preparatory activity for wind-farm construction, transportation consolidates materials and components at the project site. The total emission magnitude depends on both the transport mode (road, rail, or air) and the distance involved. While the transport mode determines the emission factor intensity, the transport distance directly affects total carbon output.

Accordingly, identifying accurate emission factors and transport distances is critical for modeling this stage.

2.1.3. Operation and Maintenance Stage

During the operation and maintenance (O&M) phase, carbon emissions arise mainly from component replacement and the use of lubricants and auxiliary materials to ensure stable performance. Bearings, gearboxes, and pitch-control systems require periodic lubrication, while inspection and maintenance activities consume additional materials and energy. Blades operate in harsh conditions and face multiple degradation mechanisms, including sand erosion, lightning strikes, ultraviolet exposure, and hail impact. These stresses lead to characteristic damage modes such as leading-edge erosion (reducing aerodynamic efficiency by 5 ~ 30%), transverse cracking near the root, and porosity-induced moisture ingress. Maintenance practices generally include visual or drone inspections, non-destructive testing (infrared thermography, ultrasonic scanning), and targeted repair (crack reinforcement, resin injection). These maintenance-related processes must be included in the carbon accounting of the O&M phase.

2.1.4. Decommissioning and Recycling Stage

The final stage occurs when blades reach their design life of approximately 20 years or are retired early due to technological upgrades. Large-scale blade decommissioning has emerged as a major environmental challenge (Gennitsaris et al., 2023). By 2030, China alone is expected to retire approximately 34,000 blades, generating around 720,000 tonnes of solid waste (Yang et al., 2023). Current end-of-life options include landfilling, incineration, and recycling. Landfilling remains the dominant approach but faces tightening restrictions; incineration provides partial energy recovery but involves pollution risks; recycling technologies — mechanical, thermal, and chemical — are rapidly evolving under policy incentives such as the Administrative Measures for Wind-Farm Retrofit and Decommissioning.

2.2. Environmental Impact Assessment Methodology

To quantify the environmental performance of wind turbine blade recycling, this study employs a life-cycle assessment (LCA)-based approach using midpoint impact indicators, following the CML 2001 baseline methodology (Margni and Curran, 2012). Additionally, two benefit indicators — carbon emission reduction benefits and green electricity benefits — are introduced to evaluate the environmental gains of recycling activities. Eight environmental impact categories are considered: freshwater ecotoxicity potential (*FEP*), marine aquatic ecotoxicity potential (*MAEP*), global ecotoxicity potential (*GEP*), global warming potential (*GWP*), ozone depletion potential (*ODP*), particulate matter formation potential (*PMFP*), water eutrophication potential (*WEP*), and marine acidification potential (*MAP*). The corresponding calculation methods are described below.

2.2.1. Freshwater Ecotoxicity Potential (*FEP*)

The *FEP* is calculated using the toxicity characterization factor (*CF*) method. Based on the life-cycle inventory (LCI), the emission amounts of toxic substances (e.g., heavy metals, organic pollutants) released to freshwater environments during blade recycling are obtained. Each emission m_i is multiplied by its corresponding freshwater characterization factor $CF_{i,freshwater}$ from methods such as CML2001, and the results are summed to obtain total freshwater ecotoxicity:

$$FEP = \sum m_i \times CF_{i,freshwater} \tag{1}$$

where m_i represents the emission amount of pollutant i released to freshwater environments, and $CF_{i,freshwater}$ denotes the freshwater toxicity characterization factor of substance i derived from midpoint impact assessment methods such as CML2001. The summation extends over all n toxic substances considered in the life-cycle inventory (LCI).

2.2.2. Marine Aquatic Ecotoxicity Potential (*MAEP*)

The same characterization approach is applied to emissions affecting marine ecosystems. Using the LCI data for substances released into the marine environment, each emission m_i is multiplied by its marine characterization factor $CF_{i,marine}$, and the total marine aquatic ecotoxicity is computed as:

$$MAEP = \sum m_i \times CF_{i,marine} \tag{2}$$

where, m_i is the emission of pollutant i entering marine waters, while $Cf_{i,marine}$ is the marine ecotoxicity characterization factor representing the relative toxicity of each substance toward marine organisms such as fish and plankton.

2.2.3. Global Ecotoxicity Potential (*GEP*)

GEP integrates the ecotoxic effects on multiple environmental media, including terrestrial, freshwater, and marine ecosystems, by applying a multimedia toxicity factor method. For each pollutant, toxicity impacts on different ecosystem types jare first calculated, and then aggregated:

$$GEP = \sum \sum m_i \times CF_{ij} \tag{3}$$

where, m_i denotes the mass of emitted pollutant i, and CF_{ij} represents its toxicity characterization factor for environmental medium j (air, water, or soil). The summations extend over all n pollutants and m environmental compartments considered.

2.2.4. Global Warming Potential (*GWP*)

The *GWP* is determined using the IPCC characterization factors (Yu et al., 2010), with carbon dioxide (CO_2) as the reference gas. Based on the LCI, the emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) are obtained. Each emission is multiplied by its global warming potential relative to CO_2 over a 100-year time horizon, and then summed:

$$GWP = m_{CO_2} + m_{CH_4} \times GWP_{CH_4} + m_{N_2O} \times GWP_{N_2O} \tag{4}$$

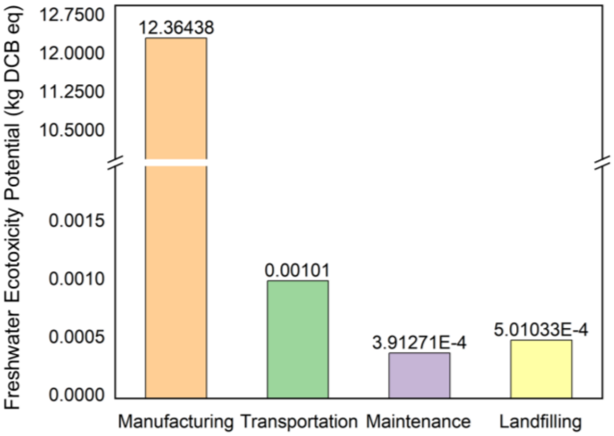

Figure 1. The impact of four stages in the full life cycle of wind turbine blades on the toxicity to freshwater aquatic ecotoxicity.

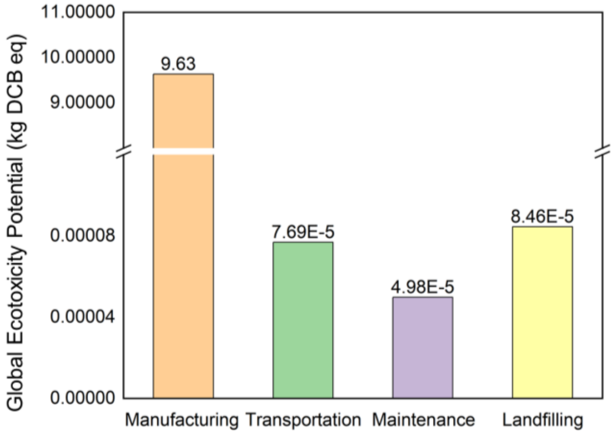

Figure 2. The impact of four stages in the full life cycle of wind turbine blades on the toxicity to global ecotoxicity potential.

where, m_{CH_4}, and m_{N_2O} are the life-cycle emissions of carbon dioxide, methane, and nitrous oxide, respectively. GWP_{CH_4} and GWP_{N_2O} are the 100-year global warming potential factors of CH_4 and N_2O relative to CO_2, as recommended by the IPCC.

2.2.5. Ozone Depletion Potential (*ODP*)

The *ODP* is calculated with trichlorofluoromethane (CFC-11) as the reference substance. The emissions of ozone-depleting compounds (e.g., chlorofluorocarbons and halons) are multiplied by their respective *ODP* values and summed:

$$ODP = \sum m_i \times ODP_i \tag{5}$$

where, m_i is the emission of ozone-depleting compound i, and ODP_i is its ozone depletion characterization factor relative to trichlorofluoromethane (CFC-11).

2.2.6. Particulate Matter Formation Potential (*PMFP*)

The *PMFP* is assessed using the particulate matter precursor method. From the LCI, emissions of direct particulate matter ($PM_{2.5}$ and PM_{10}) and precursors (SO_2, NO_x, and VOCs, etc.) are identified. Each emission m_i is multiplied by its particulate formation characterization factor $Cf_{i,particulate}$, and the results are summed:

$$PMFP = \sum m_i \times CF_{i,particulate} \tag{6}$$

where, m_i refers to the emission of pollutant i contributing to particulate formation, including direct $PM_{2.5}$ and PM_{10} particles as well as precursors such as SO_2, NO_x, and VOCs. $Cf_{i,PM}$ denotes the particulate formation characterization factor of each pollutant.

2.2.7. Water Eutrophication Potential (*WEP*)

The eutrophication potential is estimated using the nutrient characterization factor method. Emissions of nitrogen and phosphorus compounds (e.g., ammonia and phosphates) are obtained from the LCI, multiplied by their corresponding eutrophication factors $CF_{i,eutrophication}$, and aggregated:

$$WEP = \sum m_i \times CF_{i,eutrophication} \tag{7}$$

where, m_i denotes the emission of nutrient compound i, typically including ammonia, nitrate, and phosphate, while $Cf_{i,eutrophication}$ represents its eutrophication characterization factor.

2.2.8. Marine Acidification Potential (*MAP*)

SO_2 is used as the reference substance for acidification. Acidic substances such as sulfur dioxide and nitrogen oxides are identified from the LCI, and each emission m_i is multiplied by its relative marine acidification potential MAP_i:

$$MAP = \sum m_i \times MAP_i \tag{8}$$

where, m_i is the emission mass of acidic substance i, such as SO_2 and NO_x, and MAP_i is its acidification characterization factor relative to sulfur dioxide.

3. Results Analysis

3.1. Life-Cycle Environmental Impact Assessment of Wind Turbine Blades

This section systematically presents the life-cycle environmental impact assessment (LCA) results for wind turbine blades, covering the four stages of manufacturing, transportation, maintenance, and final disposal. By quantitatively evaluating multiple environmental dimensions — including ecotoxicity, global warming potential, and water-related chemical impacts — this analysis aims to identify the major contributors to environmental burdens and determine critical stages where mitigation efforts should be prioritized.

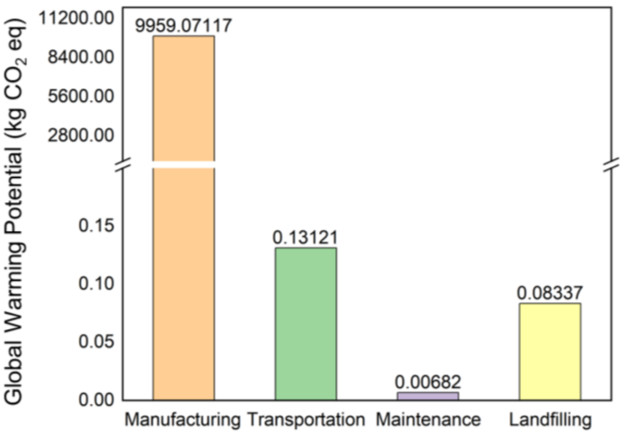

Figure 3. The impact of four stages in the full life cycle of wind turbine blades on the toxicity to global warming potential.

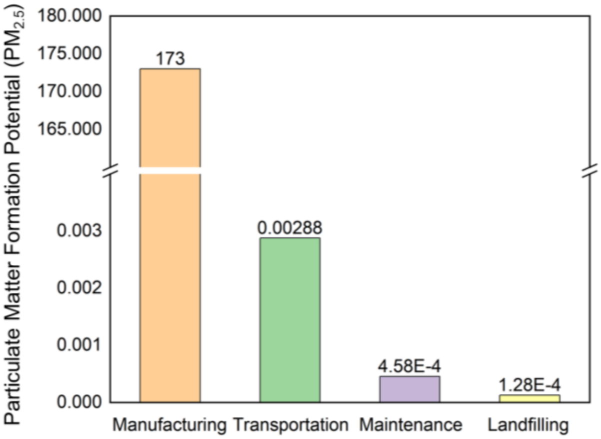

Figure 4. The impact of four stages in the full life cycle of wind turbine blades on the toxicity to particulate matter formation potential.

3.1.1. Ecotoxicity Potential Analysis

Ecotoxicity potential is a key indicator that measures the potential harm of pollutants released by industrial processes to both aquatic and terrestrial ecosystems. The results of this study consistently indicate a single dominant finding: The manufacturing stage overwhelmingly dominates the overall ecotoxicity impact of wind turbine blades, far exceeding the contributions from transportation, maintenance, and end-of-life disposal stages.

In terms of freshwater ecotoxicity, the manufacturing phase exhibits an extraordinarily high impact value of 12.36438, accounting for over 99.98% of the total life-cycle contribution (Figure 1). In contrast, the combined contribution from the other three stages — transportation, maintenance, and landfilling — is less than 0.02%, nearly negligible on a graphical scale. This pronounced disparity reveals the inherently pollution-intensive nature of blade manufacturing. The primary sources of such impacts include the upstream production of aluminum alloy components, the synthesis of polymeric materials such as epoxy resin and glass fiber, and subsequent coating and surface treatment processes. These industrial operations inevitably generate wastewater containing heavy metals (e.g., Pb and Cr) and persistent organic pollutants (e.g., PAHs), which, once discharged into freshwater environments, can cause long-term toxic accumulation and chronic ecological damage to fish and plankton populations.

Similarly, the global ecotoxicity potential, which integrates the impacts on terrestrial ecosystems, exhibits a nearly identical pattern (Figure 2). The manufacturing stage reaches an impact value of 9.637, representing approximately 99.997% of the total. The remaining stages collectively contribute only about 0.002%. This dominance is largely attributed to emissions of volatile organic compounds (VOCs) and heavy-metal-based pigments during coating and curing processes, which contaminate soils through atmospheric deposition. Moreover, raw material extraction activities disrupt vegetation and contribute to soil pollution, further amplifying terrestrial ecotoxic impacts. In contrast, the transportation, maintenance, and disposal phases exert negligible influence on terrestrial ecosystems due to their relatively enclosed operational environments, low frequency of activity, and standardized environmental controls (e.g., sealed transport containers, and engineered landfill liners).

Taken together, these findings clearly demonstrate that the manufacturing stage is the critical leverage point for mitigating ecotoxicity across the blade life cycle. Reducing emissions from this stage through upstream material substitution, cleaner production technologies, and improved wastewater treatment is essential for minimizing the overall ecological risk of the wind power sector.

3.1.2. Global Warming and Atmospheric Impacts

This section focuses on greenhouse gas (GHG) emissions and their potential impacts on the global climate and atmospheric environment. The results once again reinforce the dominant role of the manufacturing stage: both in terms of global warming potential (GWP) and particulate matter formation (PMFP), the production process overwhelmingly contributes the majority of environmental burdens.

As shown in Figure 3, the GWP of the four life-cycle stages differs by several orders of magnitude. The manufacturing stage exhibits an impact value of 9,959.07117, while transportation (0.13121), maintenance (0.00682), and landfilling (0.08337) are drastically lower — approximately five to six orders of magnitude smaller, representing a difference of 7.6×10^4 to 1.46×10^6 times. This indicates that raw material extraction, energy consumption, and industrial processes such as component fabrication and final assembly are the principal sources of greenhouse gas emissions across the life cycle. Consequently, optimizing raw material selection, energy efficiency, energy sourcing, and emission control technologies during manufacturing is crucial for carbon mitigation.

The transportation stage, with an impact value of 0.13121, is the second-largest contributor but accounts for only 0.0013% of the total, suggesting that the logistics-related carbon footprint

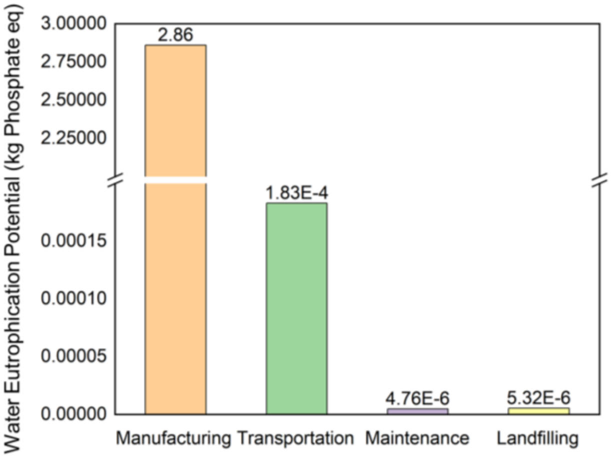

Figure 5. The impact of four stages in the full life cycle of wind turbine blades on the toxicity to water eutrophication potential.

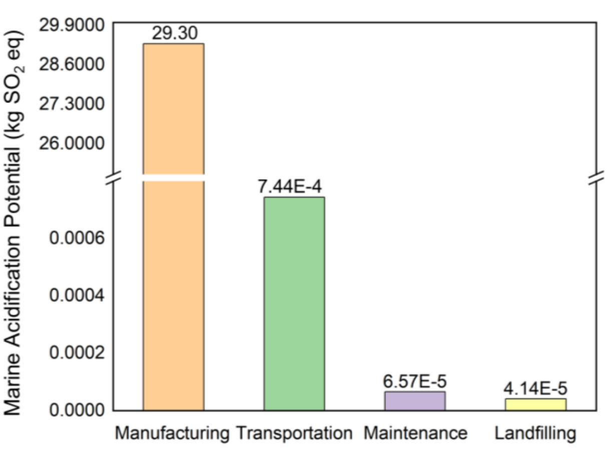

Figure 6. The impact of four stages in the full life cycle of wind turbine blades on the toxicity to marine acidification potential.

is minimal — likely due to relatively short transportation distances or efficient logistics systems. The maintenance stage (0.00682) represents the smallest contribution, implying that regular servicing, lubrication, or minor component replacement during turbine operation has negligible influence on GWP. The landfilling stage (0.08337) contributes slightly more than maintenance and transport but remains insignificant in absolute terms (only 0.00084% of manufacturing). This minor contribution may be associated with methane (CH_4) generation during the decomposition of organic materials in landfill sites. Overall, these results confirm that the manufacturing phase dominates the life-cycle carbon footprint, and efforts to reduce global warming potential should primarily target improvements in material production and energy use during this stage.

The pattern is similar for particulate matter formation potential (PMFP), as shown in Figure 4. The manufacturing stage records an impact value of 173, accounting for approximately 96% of the total potential impact. The transportation stage contributes only 0.00288, far lower than manufacturing but slightly higher than maintenance (4.58×10^{-4}) and landfilling (1.28×10^{-4}). The dominance of the manufacturing stage is again evident — its impact is roughly 60,000 times greater than transportation, 378,000 times greater than maintenance, and 1.35 million times greater than landfilling. Together, the latter three stages contribute less than 0.003 in total, compared with 173 for production.

This extreme contrast highlights that particulate emissions during manufacturing are the principal bottleneck for air quality impacts. They are primarily associated with material processing, resin curing, surface coating, and energy-intensive operations that release particulate precursors (SO_2, NO_x, and VOCs). Although transportation and end-of-life processes have minimal impacts, continuous monitoring and preventive measures remain necessary to mitigate long-term exposure and health risks. In sum, both GWP and PMFP analyses clearly identify the manufacturing stage as the dominant contributor to atmospheric and climate-related burdens.

3.1.3. Water-Related Chemical Impacts

This section analyzes the impacts of the wind turbine blade life cycle on water eutrophication potential (WEP) and marine acidification potential (MAP). The results are consistent with previous indicators, showing that environmental burdens are highly concentrated in the manufacturing stage, while the contributions from transportation, maintenance, and landfilling are negligible.

As illustrated in Figure 5, the manufacturing stage exhibits a WEP value of 2.86, making it the primary source of eutrophication-related emissions. This result suggests that pollutants containing nitrogen and phosphorus — such as ammonium and phosphates — are released during raw material extraction, composite material processing, and resin production. These emissions promote nutrient enrichment in water bodies and can lead to algal blooms and oxygen depletion. In contrast, the transportation (1.83×10^{-4}), maintenance (4.76×10^{-6}), and landfilling (5.32×10^{-6}) stages contribute negligibly to eutrophication, together accounting for less than 0.01% of the total. Thus, eutrophication impacts are almost exclusively driven by manufacturing-phase wastewater and material residues, emphasizing the need for upstream pollution control and wastewater treatment system upgrades in composite material production.

A similar pattern is observed in marine acidification potential (MAP) (Figure 6). The manufacturing stage records a MAP value of 29.30, overwhelmingly higher than transportation (7.44×10^{-4}), maintenance (6.57×10^{-5}), and landfilling (1.15×10^{-5}). This clearly indicates that the production process — particularly glass fiber and resin synthesis, energy consumption, and acid gas emissions — serves as the major source of acidification precursors. The extremely small values of other stages imply that emissions of acidic substances (e.g., SO_2 and NO_x) during transport, maintenance, and disposal are well controlled, likely due to advancements in vehicle fuel efficiency, environmentally friendly maintenance practices, and regulated landfill management.

Overall, the water-related chemical impact assessment reveals a “single dominant–multiple minor” distribution pattern, where the manufacturing stage overwhelmingly dictates environmental performance. To effectively mitigate life-cycle contributions to eutrophication and acidification, strategic emphasis should be placed on green process innovation and low-carbon material substitution in production, such as adopting bio-based resins, improving energy efficiency, and minimizing wastewater discharge. Meanwhile, other stages — although minor contributors — should continue to improve operational efficiency and pollution prevention to maintain long-term environmental sustainability.

This differentiated impact pattern provides a scientific basis for targeted mitigation strategies across the wind turbine supply chain: Prioritizing high-impact stages for technological breakthroughs while maintaining continuous improvement in low-impact phases, thereby promoting the transition of the wind turbine industry toward a low-carbon and sustainable future.

3.2. Comparison between different recycling technical frameworks

3.2.1. Ecological Impacts

Figure 7 present the environmental impact results of three recycling technologies — pyrolysis, mechanical (physical) recycling, and chemical recycling — across three ecotoxicity dimensions: Freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestrial/global ecotoxicity potential. The detailed analysis is as follows. In the freshwater aquatic ecotoxicity dimension, as shown in Figure 7a, pyrolysis exhibits the highest impact, with a value of 185.79639, indicating a substantial release of toxic substances into freshwater environments. This suggests that pyrolysis has a strong disruptive influence on freshwater ecosystems such as plankton, fish, and aquatic plants, potentially altering ecological balance and degrading water quality. Mechanical recycling, with a value of 0.0113, records the lowest impact among the three, indicating minimal toxicity and wastewater generation — demonstrating its relative environmental compatibility. The chemical method, with a value of 0.07918, ranks between the two: While far lower than pyrolysis, it still poses moderate freshwater toxicity, likely resulting from chemical reagent use and minor toxic discharges during processing.

In the marine aquatic ecotoxicity dimension, as shown in Figure 7b, chemical recycling stands out with an exceptionally high value of 2,865.31668, indicating severe ecological risk to marine organisms such as coral reefs, marine fish, and plankton. This may stem from residual chemical reagents or reaction byproducts discharged into the marine environment, leading to potential ecosystem disruption and biodiversity loss. In extreme cases, such pollutants can bioaccumulate along the food chain and pose indirect threats to human health via seafood consumption. Mechanical recycling shows a much lower value of 966.31543, suggesting a moderate but controllable influence, possibly associated with fine particulate emissions or small pollutant leakage. Pyrolysis shows the lowest value (0.30877), reflecting minimal marine ecotoxicity due to the closed and controlled nature of the process, which limits the release of harmful substances into the ocean.

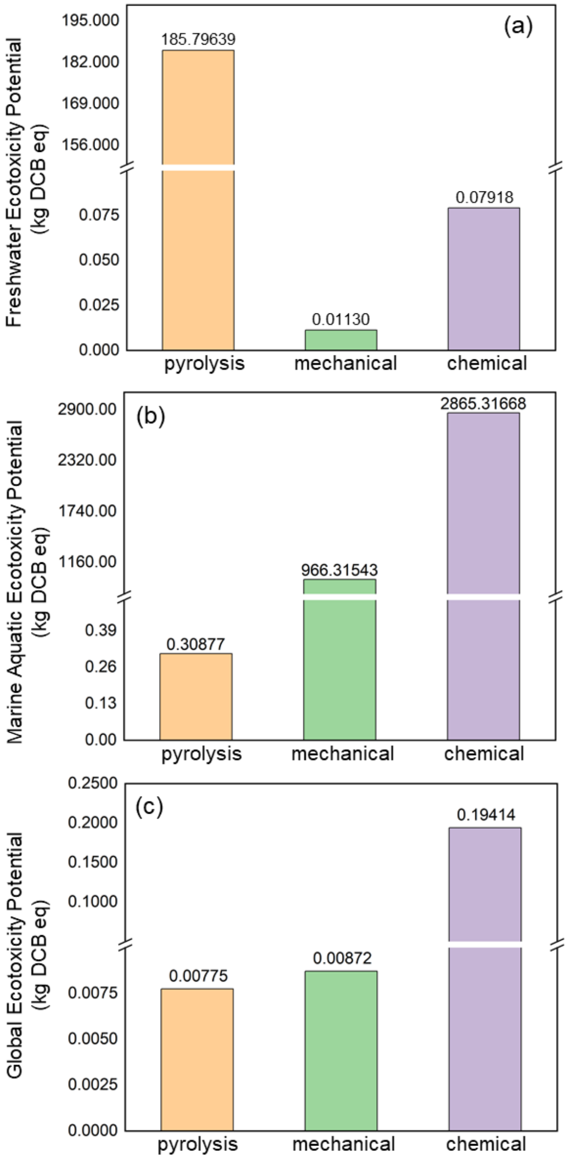

Figure 7. Comparative ecotoxicity potentials of different recycling pathways: (a) freshwater ecotoxicity potential (FEP) in kg DCB eq; (b**)** marine aquatic ecotoxicity potential (MAEP) in kg DCB eq; (c) global ecotoxicity potential (GEP) in kg DCB eq.

For the global ecotoxicity potential (Figure 7c), chemical recycling again presents the highest value (0.19414), implying that toxic substances generated during this process may persist and disperse across multiple environmental media — air, water, and soil — causing long-term ecological risks. Mechanical recycling shows a low impact value (0.00872), indicating limited but nonzero accumulation of pollutants in global ecosystems. Pyrolysis performs best, with the lowest value (0.00775), demonstrating its relatively mild global ecotoxic effects and lower long-term risks to terrestrial ecosystems.

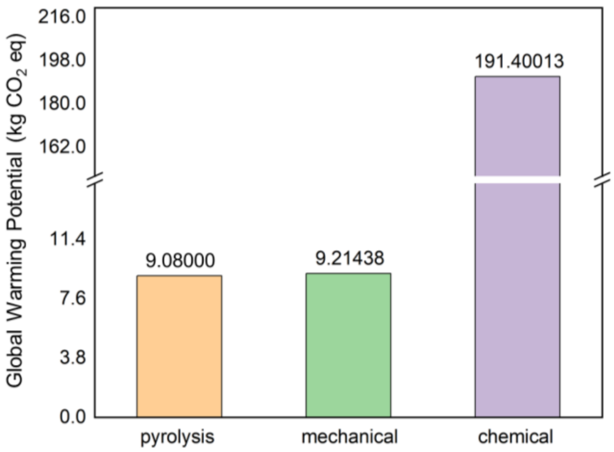

Figure 8. The impact of wind turbine blade recycling and disposal methods on the toxicity to global warming potential.

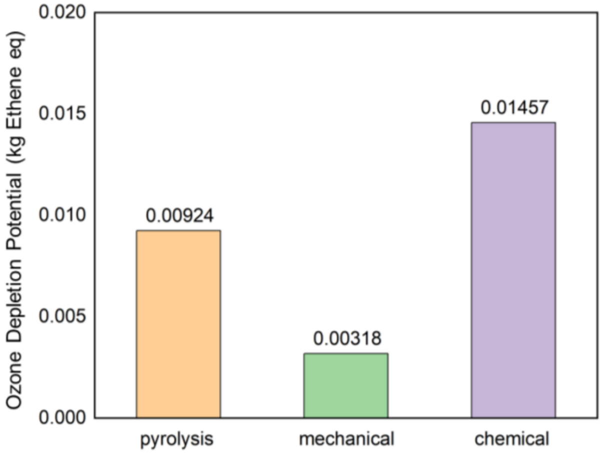

Figure 9. The impact of wind turbine blade recycling and disposal methods on the toxicity to ozone depletion potential.

Overall, these results suggest that chemical recycling carries the greatest risk of ecological toxicity — particularly to marine systems — while mechanical recycling remains the most environmentally friendly option among the three, and pyrolysis exhibits moderate performance with relatively controllable impacts.

3.2.2. Global Warming and Photochemical Ozone Formation

Figures 8 and 9 illustrate the results of the three recycling methods in two atmospheric impact dimensions: Global warming potential (GWP) and photochemical ozone creation potential (POCP). In terms of global warming potential, chemical recycling records a remarkably high value of 191.40013, indicating that this process produces substantial greenhouse gas emissions (e.g., CO_2 and CH_4), which significantly exacerbate climate change. In contrast, pyrolysis (9.08000) and mechanical recycling (9.21488) exhibit similar and much lower values, demonstrating that both processes emit relatively small amounts of greenhouse gases. The large disparity highlights that energy-intensive chemical reactions, combined with reagent production and waste treatment, make chemical recycling the most carbon-intensive pathway, whereas pyrolysis and mechanical recycling are more climate-friendly options. For photochemical ozone creation potential, chemical recycling again shows the highest impact (0.01457). Elevated POCP values indicate that volatile organic compounds (VOCs) and other precursors released during chemical recovery are prone to photochemical reactions under sunlight, forming near-surface ozone. High tropospheric ozone concentrations can harm human respiratory systems, damage vegetation, and degrade air quality. Mechanical recycling, with a POCP of 0.00318, demonstrates the lowest impact, reflecting its minimal emission of photochemically active substances. Pyrolysis records an intermediate value (0.00924), suggesting moderate ozone formation potential. Overall, the chemical method has the strongest atmospheric impact due to its reagent use and emissions, while mechanical recycling remains the cleanest route.

3.2.3. Human Toxicity Potential

Figure 10 shows the human toxicity potential (HTP) results for pyrolysis, mechanical recycling, and chemical recycling. Combined with the previous ecotoxicity and atmospheric indicators, a comprehensive assessment reveals distinct patterns of health-related risks across recycling routes. Pyrolysis has the highest HTP value (7.9274), indicating the greatest potential for adverse health impacts. This suggests that during pyrolytic processing, toxic substances such as heavy metals and hazardous organic compounds are released, which may enter the human body through air, water, or soil exposure pathways. These substances pose risks to the respiratory, hepatic, and renal systems, and may even exhibit neurotoxic or carcinogenic effects, particularly for plant operators and nearby residents. Mechanical recycling exhibits the lowest HTP value (0.82839), demonstrating minimal impact on human health. Its relatively simple process generates fewer toxic byproducts, and potential exposure routes (inhalation, dermal contact, ingestion) are well controlled, resulting in low occupational and public health risks. Chemical recycling presents a moderate HTP value (3.01641), indicating measurable but intermediate toxicity potential. The use of chemical reagents and associated reaction products may release harmful components, leading to certain health risks; however, compared with pyrolysis, the magnitude of exposure and toxicity is substantially lower.

In summary, pyrolysis poses the highest potential threat to human health due to the release of hazardous emissions during high-temperature treatment; chemical recycling presents a moderate risk associated with chemical reagent handling and waste treatment; mechanical recycling remains the safest and most environmentally benign method. These findings underscore the importance of balancing environmental efficiency and health safety in developing sustainable blade recycling technologies.

3.3. Comparison of Recycling Pathways

To facilitate a systematic evaluation of the trade-offs between different recycling technologies, Table 1 summarizes the detailed environmental performance across all assessed indica-

Table 1. Comprehensive Quantitative and Qualitative Comparison of Environmental Impact Indicators and Trade-Offs among Pyrolysis, Mechanical, and Chemical Recycling Pathways

	Pyrolysis	Mechanical	Chemical
Freshwater aquatic ecotoxicity	The highest impact value is 185.79639, which will release a large amount of toxic substances into the freshwater environment.	The impact value is 0.01130, the lowest among the three technologies.	The impact value is 0.07918, which is between.
Marine aquatic ecotoxicity	The minimum impact value is 0.30877, which is closed and controllable.	The impact value is low at 966.31543, and the impact is moderate and controllable.	It stands out with an unusually high score of 2,865.31668, posing a serious ecological threat to marine life such as coral reefs, marine fish and plankton.
Global ecotoxicity potential	The best performer, with the lowest ecological impact value of 0.00775.	The ecological impact value is only 0.00872.	It tops the list with a value of 0.19414, which means that the toxic substances produced by this process may exist for a long time and spread to various environmental media such as air, water and soil, thus causing long-term threats to the ecosystem.
Global warming potential	The impact value is 9.08.	The impact value is 9.21488.	A significantly high value of 191.40013 indicates that the process generates significant greenhouse gas emissions.
Ozone depletion Potential	The impact value is 0.00924, indicating that its ozone formation potential is moderate.	The impact value is 0.00318, showing the lowest impact, reflecting its extremely low emissions of photochemically active substances.	The highest impact value is 0.01457, because the use and emission of reagents have the greatest impact on the atmosphere.
Human toxicity potential	The highest impact value is 7.92740, indicating that it has the greatest potential to adversely affect health.	The lowest impact value is 0.82839, indicating that it has the smallest impact on health.	The medium impact value is 3.01641.
In summary	Due to the release of harmful substances during high-temperature processing, it poses the greatest potential threat to human health.	The safest solution with minimal environmental impact.	Involve the operation of chemical reagents and waste disposal, the risk level is medium.

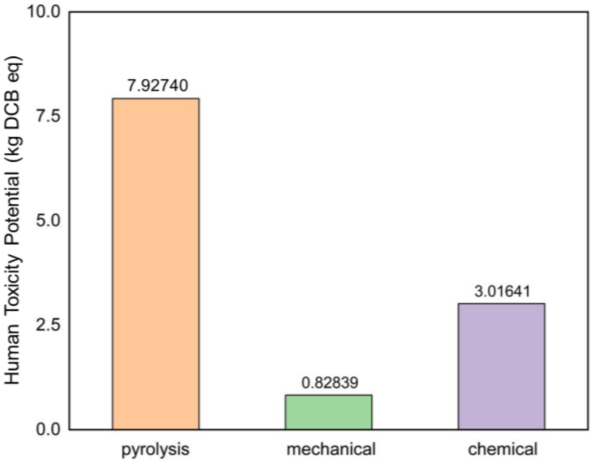

Figure 10. The impact of wind turbine blade recycling and disposal methods on the toxicity to human toxicity potential.

tors, including GWP, ODP, and various toxicity potentials.

As detailed in Table 1, mechanical recycling emerges as the safest solution with minimal environmental burden, achieving the lowest scores in freshwater ecotoxicity (0.0113 kg DCB eq) and human toxicity potential (0.8280 kg DCB eq). Pyrolysis, while effective for fiber recovery, is the ‘best performer’ only in global ecotoxicity but suffers from high freshwater toxicity and moderate global warming impacts. Chemical recycling stands out with distinct disadvantages, notably its unusually high marine aquatic ecotoxicity (2,865.3100 kg DCB eq) and significant global warming potential (191.4000 kg CO_2 eq), largely due to the use of chemical reagents and waste liquid generation. This summary clearly indicates that while chemical and thermal methods offer material recovery advantages, they currently entail severe environmental trade-offs compared to mechanical recycling.

4. Conclusion and Discussion

This study quantitatively evaluated the full life-cycle environmental impacts of wind turbine blades and compared three recycling pathways using eight environmental indicators. The results consistently demonstrate that environmental burdens are overwhelmingly concentrated in the manufacturing stage, which accounts for over 95% of total impacts across all categories, including ecotoxicity, global warming, and acidification. This dominance arises mainly from the production of glass and carbon fibers, which are energy- and emission-intensive processes. In contrast, transportation, maintenance, and disposal stages contribute marginally to overall impacts.

Among recycling options, mechanical recycling exhibits the lowest overall environmental burden, followed by pyrolysis and chemical recycling. The latter shows notably higher global warming and human toxicity potentials due to high energy use and solvent consumption. These findings highlight a clear "front-end concentration" and "pathway differentiation" pattern across the life cycle. Therefore, effective mitigation should focus on greening material production through renewable energy integration, resin substitution, and clean manufacturing, while scaling up mechanical recycling as the most viable circular solution.

A deeper discussion of these findings reveals the fundamental drivers behind this imbalance. The dominance of the manufacturing stage originates from the intrinsic energy- and chemical-intensive characteristics of conventional blade production technologies. Processes such as glass fiber drawing, epoxy resin synthesis, and large-scale mold curing require substantial energy input. When this energy demand is predominantly met by fossil-fuel-based power systems, the resulting indirect emissions of CO_2, SO_x, and NO_x escalate sharply, explaining the high global warming and acidification potentials observed in the assessment. In parallel, the extensive use of chemical reagents and materials — from metal alloy smelting to resin systems, curing agents, and coatings containing volatile organic compounds (VOCs) and heavy metals — constitutes the main source of ecotoxic and human toxicity risks.

In contrast, the subsequent stages — transportation, operation, and landfilling — appear relatively "quiet" in terms of direct emissions. Yet this quietness should not be mistaken for insignificance. Their challenges are of a different nature: Dispersed, long-term, and systemic. The core issue of land- filling, for instance, is not its immediate emission intensity but its irreversible loss of high-embodied-energy composite materials, representing a failure of circular economy principles and an unsustainable end-of-life pathway.

Despite these clear insights, this study acknowledges several limitations. The assessment reflects a static snapshot based on specific technological and database conditions, which may not capture the evolving environmental performance of emerging manufacturing or recycling technologies. Furthermore, the analysis did not include a comprehensive comparison of alternative end-of-life management routes — particularly advanced recycling technologies, which are gaining industrial attention. Regional differences in energy structures and environmental regulations may also limit the generalizability of certain numerical results.

Based on these findings, promoting the green and sustainable transition of the wind power sector requires coordinated efforts between industry and policymakers. For the industrial sector, priority should be given to front-end emission reduction, including the adoption of renewable electricity, environmentally friendly materials, and "design-for-recyclability" concepts that enable high-value recovery from the outset of product design. At the same time, active investment in physical, thermal, and chemical recycling technologies is essential to transform retired blades from "environmental liabilities" into urban resources.

For policymakers, the urgent task is to strengthen extended producer responsibility (EPR) frameworks to ensure stable funding for collection and recycling systems, and to implement LCA-based green procurement and subsidy mechanisms that incentivize circular product design. Establishing quality standards for recycled materials and cultivating secondary markets will also be critical to bridging the final gap in the recycling chain.

Ultimately, the "clean" nature of wind power cannot be defined solely by its zero-emission electricity generation. This study reveals the hidden environmental reality behind that label: The manufacturing stage remains the core environmental bottleneck. The future of wind power must therefore be driven by a dual strategy — technological innovation and supply-chain decarbonization to create truly "green" blades at the source, and the establishment of efficient, high-value recycling systems to ensure their sustainable rebirth at the end of life. Only through such cradle-to-cradle transformation can the wind power industry genuinely fulfill its role as a cornerstone of global clean energy transition.

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