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Research Article

Towards Sustainable End-of-Life Management of Wind Turbine Blades Through Circular Economy Strategies: The Case Study of Indonesian Wind Farms

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Abstract: Indonesia's transition to renewable energy, highlighted by the operation of Sidrap and Tolo 1 wind farms, faces a significant challenge: managing the end-of-life of wind turbine blades. These blades, primarily composed of Glass Fibre-Reinforced Plastic (GFRP), are challenging to recycle due to their composite structure. A circular economy framework must be developed to address this issue, focusing on material recirculation and waste reduction. This study explores upcycling strategies as a core component of the framework, aiming to repurpose decommissioned blades into functional products while minimising environmental impact. Using secondary data and Life Cycle Assessment (LCA), three upcycling scenarios are assessed: turning blades into pedestrian bridges, housing foundations, and fishing vessels. Each scenario shows considerable potential for reducing CO_2 emissions by replacing traditional materials like steel, concrete, and wood with repurposed blade components. The results highlight the practicality and environmental advantages of applying circular economy principles to Indonesia's wind energy sector. Developing a strong framework for blade upcycling not only encourages sustainable infrastructure but also strengthens Indonesia's dedication to renewable energy systems. This approach provides a scalable model for other regions encountering similar challenges in renewable energy waste management.The system boundaries are limited to the material substitution phase and exclude upstream and downstream processes such as blade cutting, transportation, installation, and maintenance. This simplification is intended to isolate the environmental benefits of material replacement and align with similar comparative studies. However, it is acknowledged that these excluded processes, especially for large, heavy blade sections, can contribute significantly to the overall environmental impact. Their omission represents a limitation of this study and may lead to an underestimation of total emissions. Future research should incorporate these phases for a more comprehensive assessment.

***Keywords*:** circular economy, wind turbine blade, Life Cycle Assessment (LCA), waste management

1. Introduction

The circular economy is an approach to eliminating waste and regenerating natural systems by keeping materials and products in circulation through reuse, refurbishment, and recycling processes [1]. It is particularly crucial for the renewable energy sector, as it is currently in high demand, to mitigate environmental impacts [2]. The linear "take-

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make-waste" model for renewable energy could contribute to greenhouse gas emissions and resource depletion as currently renewable energy rapidly expands [1], [2]. These challenges can be addressed by adopting circular economy principles, which include reducing demand for raw materials, extending product lifespans, minimising waste, and creating new business opportunities [1].

The Circular Economy provides a principled framework to mitigate such waste, focusing on closing material loops. A pertinent example is the integration of Circular Economy and Life Cycle Assessment (LCA) for virtual water management in food consumption across Iran, which demonstrates how embedded resource flows can be quantified and redirected to reduce environmental burdens [3]. Similarly, this study applies LCA to manage the embedded energy, carbon, and material value within wind turbine blades, treating them not as waste but as a resource to be circulated, thereby preventing new resource extraction and reducing the overall environmental footprint of Indonesia's energy transition.

The Water-Energy-Food (WEF) nexus provides a critical lens for understanding the interconnected impacts of renewable energy systems on broader sustainability goals. Wind energy, while low in water consumption compared to thermal power generation, influences land use and infrastructure planning, which in turn affects agricultural productivity and water access. End-of-life management of wind turbine blades intersects with these systems by introducing waste streams that may compete for land, disrupt ecosystems, or divert resources from food and water infrastructure. By embedding circular economy strategies into wind energy planning, such as upcycling blades into bridges or housing, this study contributes to integrated solutions that support resilient energy, water, and food systems. Literature by Albrecht et al. [4] and Endo et al. [5] emphasises the importance of cross-sectoral approaches in achieving sustainability targets within the WEF nexus.

The Indonesian Ministry of Energy and Mineral Resources, through The Asean Post [6], emphasises that Indonesia has great potential for renewable energy, especially wind energy. The country's total wind power potential is estimated to be 155 GW, including offshore and onshore. However, despite this significant capacity, wind energy utilisation in Indonesia is currently only 131 MW, accounting for about 0.1% of the total potential. To address this, the government's Green Electric Power Supply Business Plan (*Rencana Usaha Penyedia Tenaga Listrik (RUPTL)*) aims to substantially increase the wind energy capacity, with a target of installing up to 597 MW by 2030 [7].

Furthermore, the transition to renewable energy must be pursued in tandem with managing other critical resource constraints, particularly water and food security. The interconnectedness of these systems is evident in regional studies, such as the assessment of climate change impacts on agriculture using the SWAT model and HWA method in a critical region of Iran, which highlights how shifts in energy policy can influence agricultural productivity and water availability [8]. Similarly, a system dynamics analysis of the Water-Energy-Food nexus in the Ardabil Plain demonstrates how resource sustainability requires integrated planning across sectors [9]. These studies underscore the complexity of resource management and the importance of systemic approaches to sustainability, which directly informs the need to address the waste footprint of new energy infrastructures like wind farms.

The inauguration of the Sidrap wind farm in South Sulawesi marked a significant milestone in Indonesia's wind energy journey. This utility-scale project, developed by UPC Renewables, is the largest wind farm in Southeast Asia. It utilises 30 Siemens Gamesa 2.5 MW turbines expected to generate 75 MW of electricity and deliver power to around 70,000 households [6]. As Indonesia has established an ambitious energy target with a 23% renewable share by 2025, Siemens Gamesa has also secured its second project in Indonesia for the 'Tolo 1' wind power plant in Jeneponto, South Sulawesi, following the success of the Sidrap wind farm [10]. Figure 1 displays the two currently operational wind farms in South Sulawesi, Indonesia.

Despite the promising growth of wind energy infrastructure, challenges emerge over the sustainable management of the blades, particularly at their end-of-life stage. Liu et al. [11] highlight that although wind turbines are mainly clean during operation, in their end-of-life stages, they release emissions and consume significant energy for disposal. As wind turbine blades are primarily constructed from Glass Fibre-Reinforced Plastic (GFRP), the recycling process is challenging due to their composite nature and is economically challenging to recycle. Current practices often result in the landfilling or incineration of decommissioned blades, contributing to waste accumulation and environmental concerns.

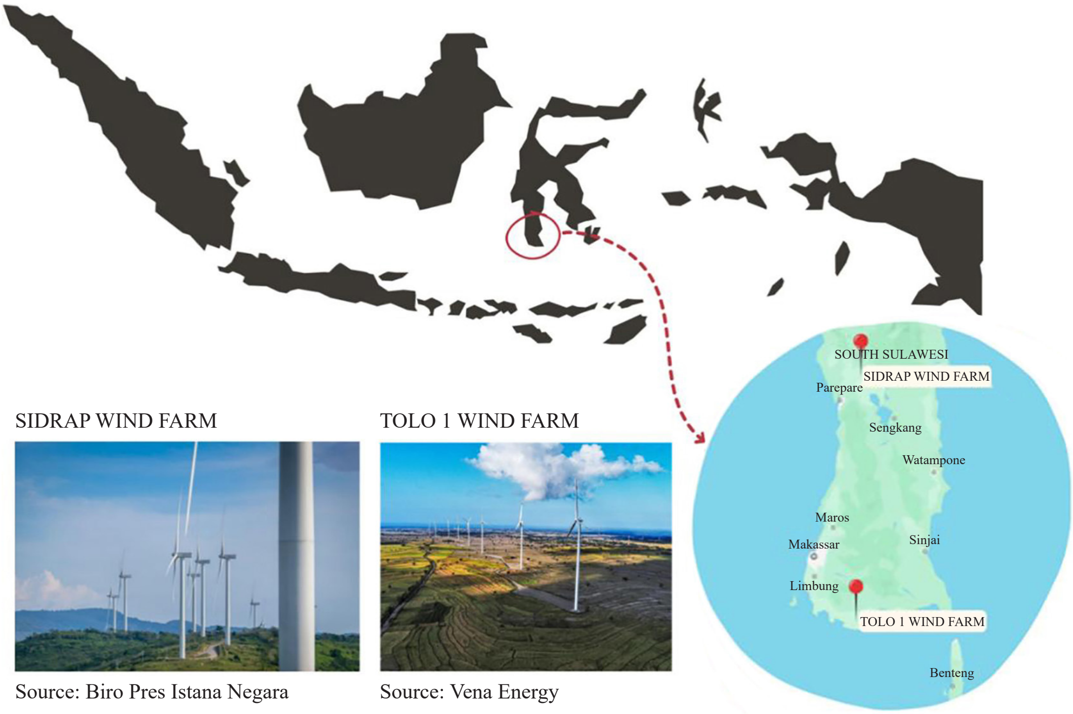

Figure 1. Wind Farms in South Sulawesi, Indonesia

As Indonesia strives to accelerate its wind energy development, it is crucial to address the sustainability of the end-of-life management of wind turbine blades. Moreover, the Indonesian government, through the 2020-2024 National Medium-Term Development Plan (*Rencana Pembangunan Jangka Menengah (RPJMN)*), has stated that it will adopt a circular economy with particular attention to the green economy [12]. Several companies have also adopted circular economy principles in their business processes due to the development plan. Therefore, the following research questions arise:

a. What are the most feasible circular economy strategies for managing end-of-life wind turbine blades in the context of Indonesian wind farms?

b. What are the environmental impacts of implementing different circular economy strategies for wind turbine blades in Indonesian wind farms, particularly regarding CO_2 emissions?

This paper aims to explore the sustainable end-of-life management of wind turbine blades in two Indonesian wind farms by prioritising upcycling strategies within a circular economy framework. Unlike traditional recycling or downcycling, which often result in a loss of material value and quality, upcycling offers the potential to transform wind turbine blades into high-value products, extending their lifespan and reducing environmental impacts. By analysing the challenges and opportunities associated with wind turbine blade disposal in Indonesia, this research seeks to develop innovative upcycling solutions that contribute to a more circular economy while mitigating the environmental consequences of wind energy generation.

2. Literature review

2.1 *Wind turbine blade recycling and upcycling technologies*

The concept of circular economy focuses on minimising waste and maximising resource efficiency through the reuse and recycling of materials. According to Robertson-Fall [2], cited by the Ellen MacArthur Foundation, transitioning towards circular economy models, especially in renewable energy, is essential to mitigate environmental impact at the end-of-life stage and achieve sustainability goals. The Ellen MacArthur Foundation's Butterfly Diagram [13] also serves as a guiding framework for identifying circular economy opportunities in end-of-life management strategies for wind turbine blades. In addition to the Butterfly Diagram, the LCA is a valuable tool for assessing sustainability in environmental contexts. Yildiz et al. [14] utilise LCA methodology to evaluate different end-of-life scenarios for wind turbine blades, highlighting the environmental impacts of mechanical recycling, incineration, and landfill disposal. A holistic framework for implementing the circular economy in large-scale infrastructure projects has been proposed by Alotaibi et al. [15], emphasising the integration of material flow analysis, sustainability metrics, and policy mechanisms to support circular transitions in the construction sector.

Recent advancements in wind turbine blade recycling include mechanical recycling, pyrolysis, and solvolysis. Mechanical recycling involves shredding blades into smaller particles for use in cement or filler materials, but often results in degraded fibre quality and limited reuse applications [11]. Pyrolysis, a thermal decomposition process, can recover fibres but is energy-intensive and emits greenhouse gases [16]. Solvolysis, which utilises chemical solvents to break down resins, offers higher-quality fibre recovery but faces challenges in terms of cost, solvent recovery, and scalability [17].

2.2 *Global case studies for end-of-life management of wind turbine blades*

There are significant challenges in the end-of-life management of wind turbine blades due to their composite material structure and large-scale disposal requirements. Studies by Liu et al. [11], Morini et al. [16], and Jensen & Skelton [17] show the complexities of the wind turbine blade disposal process, including energy consumption, carbon emissions, and landfill accumulation. The lifespan of wind turbine blades typically ranges from 20 to 30 years [14], [15]; thus, practical strategies for sustainable end-of-life management are necessary. To address these challenges, circular economy strategies like repurposing and recycling offer promising solutions. Liu et al. [11] explore opportunities through mechanical and chemical recycling techniques to repurpose blades and minimise waste. Similarly, Morini et al. [16] highlight the importance of exploring alternative disposal methods beyond landfill, such as mechanical recycling and incineration. Jensen and Skelton [17] suggest innovative approaches, such as material conversion and secondary applications, to foster a continuous flow of blade composite materials within circular economy frameworks.

Several global initiatives have demonstrated the feasibility of repurposing wind turbine blades. The BladeBridge project in Ireland repurposed 13-meter blade sections as bridge girders, replacing imported steel and reducing emissions [18]. In the Netherlands, decommissioned blades have been transformed into playground structures, showcasing creative reuse in urban design [19]. Other applications include public benches, bike shelters, and architectural installations, highlighting the versatility of blade materials in second-life uses.

2.3 *Circular economy opportunities in South Sulawesi, Indonesia*

Some potential opportunities for a circular economy in South Sulawesi include building bridges, primarily due to the region's numerous rivers. According to Kumparan News [20], students in Luwu Regency risk their lives crossing a rope bridge to attend school. The 30-metre suspension bridge was the main link connecting several villages until it was destroyed by floods in July 2020, washing away the wooden planks and leaving only the ropes behind. As a result, students and villagers must use the precarious ropes suspended over the river to reach school and travel between villages in their daily lives. The damaged bridge highlights the infrastructure challenges in South Sulawesi, putting children's safety at risk as they pursue their education.

Despite promising reuse strategies, significant economic and logistical barriers persist. Transporting and processing large, heavy blades is costly and requires specialised equipment, often unavailable in developing regions [19]. Additionally, the absence of financial incentives and regulatory frameworks for structural reuse limits widespread adoption. Safety certification and engineering validation are also necessary hurdles, particularly for load-bearing applications like bridges and housing [15].

3. Methodology

3.1 *LCA*

LCA is a comprehensive methodology that evaluates the environmental impacts of all stages of a product's life cycle, from raw material extraction through manufacturing, transportation, use, and end-of-life treatment or disposal methods [14], [21], [22]. The LCA process involves collecting data on inputs (materials, energy, etc.) and outputs (emissions, waste, etc.) throughout the entire life cycle, quantifying and assessing the potential environmental impacts of these inputs and outputs, such as carbon emissions, energy consumption, and resource depletion [21], [22].

LCA facilitates opportunities to reduce environmental burdens at various stages of the life cycle by substituting materials, improving processes, and evaluating alternative end-of-life scenarios such as recycling, incineration, or landfilling [14], [21], [22]. The methodology defines goals and scope to develop a life cycle inventory, conducts impact assessments, and provides results to support decision-making towards more environmentally sustainable products, processes, or services, aligned with circular economy principles [21], [22]. Overall, LCA offers a comprehensive and quantitative cradle-to-grave assessment of a product or system's performance, enabling the identification of improvement opportunities and supporting sustainability objectives [14], [21], [22].

The shift to wind energy is a key sustainable source of electricity essential for mitigating climate change. However, the issue of blade waste from end-of-life wind turbines presents a significant challenge [21]. Repurposing decommissioned blades into second-life applications through upcycling and downcycling is gaining popularity as an alternative to costly recycling [22]. Karavida and Peponi [21] propose a conceptual framework integrating circularity principles, suggesting downcycling blade waste for cement co-processing and upcycling it for architectural projects aimed at urban regeneration.

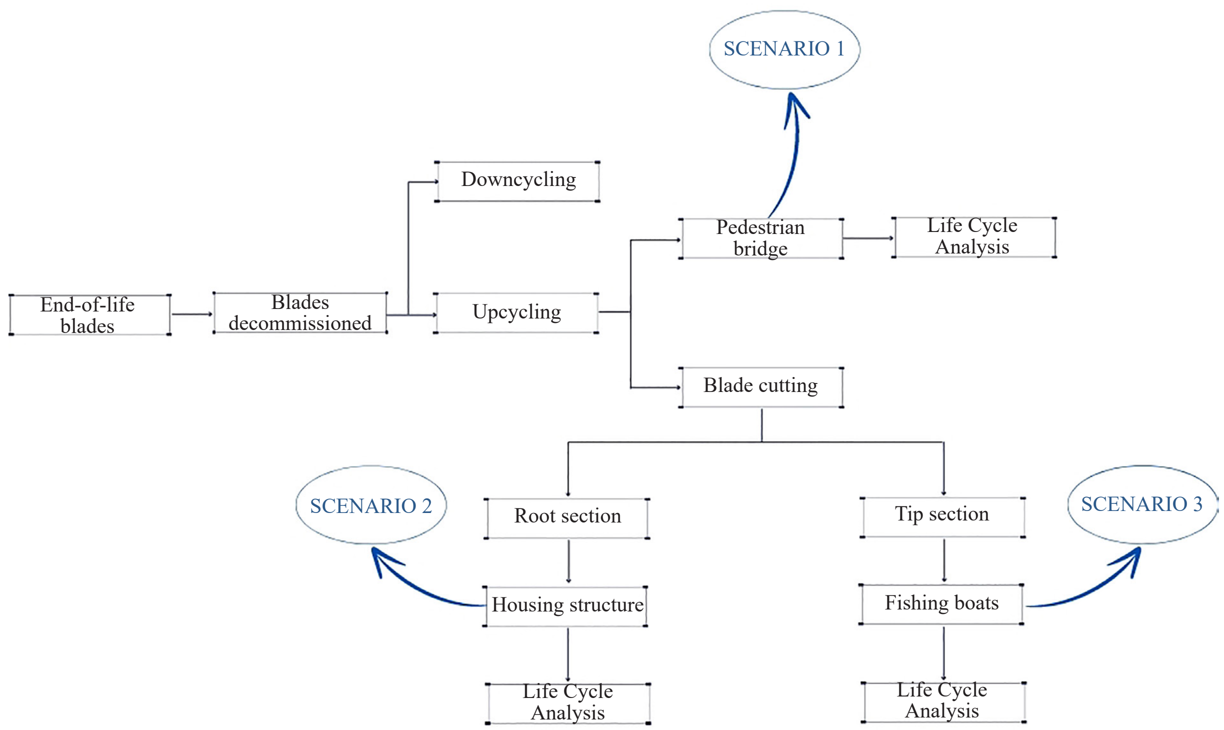

Figure 2. Methodology diagram for end-of-life wind turbine blade

Furthermore, upcycling involves repurposing decommissioned wind turbine blades for new uses while preserving their physical shape rather than breaking them down. It is less expensive and produces lower emissions than downcycling methods that dismantle the blades. Examples include pedestrian bridges using blades as girders, blade bridges on greenways for pedestrians and cyclists, utility poles made from blade sections, affordable housing projects in areas prone to harsh weather, public furniture such as benches and playground structures using blades, towers, sculptures, and small constructions like bike sheds, animal passages, and lamp posts created from repurposed blades [21].

Therefore, the LCA in this study will utilise OpenLCA software with the OzLCI2019 database to analyse three different upcycling scenarios: pedestrian bridges, housing foundations, and fishing vessels. Figure 2 illustrates the methodology diagram for end-of-life wind turbine blades across these three upcycling scenarios.

This study follows the ISO 14044 standard for LCA. The LCA was conducted using OpenLCA software and the OzLCI2019 database. The goal is to evaluate the environmental benefits of upcycling wind turbine blades in Indonesia, and the scope is limited to material substitution. The density of galvanised steel (25 kg/m) is based on Nagle et al. [22], who used this value for bridge girder replacement. The concrete mix specification (20 MPa) reflects the K-225 mix commonly used in Indonesian residential construction [23]. Teak wood was selected as the baseline for fishing vessels based on its traditional use in Indonesian boatbuilding [24]. While these datasets are Australian, they were selected due to the lack of region-specific Indonesian LCA data and are considered a reasonable proxy for comparative analysis.

4. Results, data analysis and discussion

4.1 *Scenario 1: Pedestrian bridge*

4.1.1 *End-of-life scenario*

Scenario 1 targets the Sidrap wind farm, which uses Siemens Gamesa G114/2500 wind turbines, each with a power output of 2.5 MW. There are 30 turbines installed on-site, and each blade is 56 metres long, made of fibreglass reinforced with epoxy [25]. One idea is to repurpose the blades into pedestrian bridges, especially considering the Sidrap wind farm's proximity to several rivers. According to the Central Statistical Agency for Luwu Regency (*Badan Pusat Statistik Kabupaten Luwu*), as reported by Tribunnews [20], there are 40 rivers spread across 13 subdistricts in Luwu Regency. A recent article from Tribunnews [26] reported that a bridge in Salu Paremang village, connecting Kamanre village and Salu Paremang village, has been damaged. The iron support of the bridge foundation has almost collapsed and shifted from its original position, and the wooden bridge base has also rotted. According to the Central Agency of Luwu Regency, the widest river is 50 metres wide. As a solution, the decommissioned blades from the Sidrap wind farm's turbines could be utilised to build bridges over rivers in high demand. A study by Nagle et al. [22] found that the middle section of wind turbine blades is being repurposed as girders for pedestrian bridges. In the south of Ireland, a 13-metre section of the blades is being used for this purpose, replacing galvanised steel U-beams previously imported from the UK. Additionally, the BladeBridge project demonstrates the structural reuse of decommissioned wind turbine blades in pedestrian bridge applications, providing design options and engineering validation for 18.5-meter spans using 53-meter blades [27]. This supports the feasibility of similar applications in Indonesia. This methodology will also be employed for the Life Cycle Assessment of Scenario 1, which involves constructing a pedestrian bridge across rivers in Luwu Regency, South Sulawesi. The study will compare the weight of steel replaced by end-of-life blades and the reduction in CO_2 emissions achieved by replacing the conventional steel bridge with one made from end-of-life blades. The proposal suggests using two 56-metre blades as a single bridge girder. Figure 3 outlines the proposed scenario for the bridge construction, utilising Siemens Gamesa G114/2500 turbines with 56-metre blades as bridge girders. Thus, the functional unit for scenario 1 is defined as 1 meter of bridge girder replaced with a wind turbine blade section.

- Blade Segmentation and Structural Design

The full 56-meter blade is segmented into two 28-meter sections to accommodate typical pedestrian bridge spans. The middle section of the blade, which has the most uniform cross-section and structural integrity, is used as the primary load-bearing girder. The aerodynamic profile is retained to minimise material weakening.

- Connection Techniques

Each blade section is mounted onto reinforced concrete abutments using custom-fabricated steel end plates bolted through the blade's internal shear web. Additional lateral bracing is installed beneath the deck to prevent torsional movement. The walking surface is constructed using lightweight composite panels anchored to the blade's upper surface with adhesive bonding and mechanical fasteners.

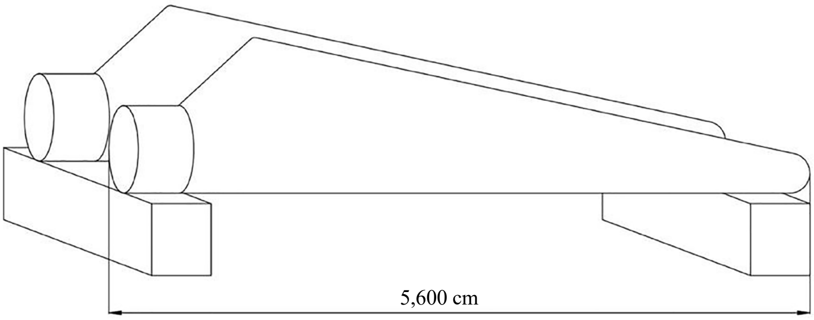

Figure 3. Proposed pedestrian bridge from Blades Upcycling (measurement in cm)

4.1.2 *Life cycle assessment*

The LCA for Scenario 1 aims to assess the environmental impacts of replacing the girders of a pedestrian bridge with end-of-life wind turbine blades. The assessment involves comparing this substitution material to galvanised steel, which would have been used to construct the same girders. This method follows the study by Nagle et al. [22], in which the system boundaries only permit a direct comparison of the materials and do not consider environmental impacts across the entire production and transportation processes involved in constructing the pedestrian bridge. Additionally, this study utilises OpenLCA software with the OzLCI2019 database.

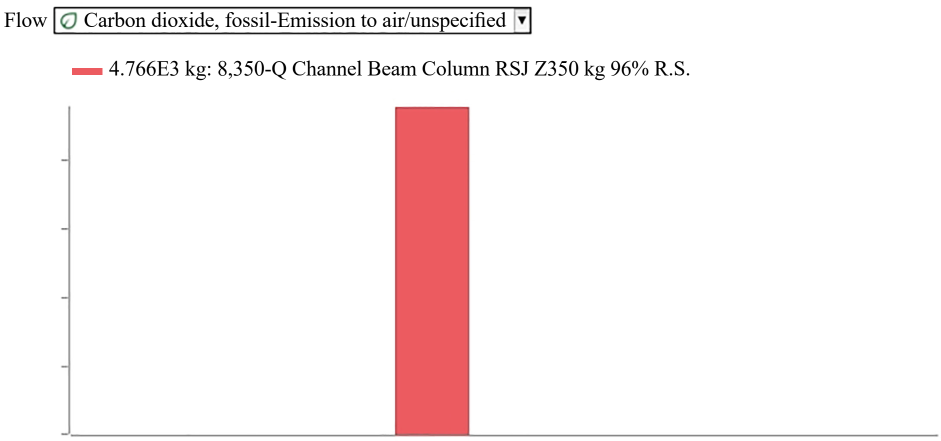

Figure 4. CO_2 emission of conventional pedestrian bridge (OpenLCA, 2024)

Figure 4 shows the results of the LCA for a conventional steel bridge with galvanised steel used for the bridge girders. The assessment indicates that using galvanised steel for 50-metre-long girders emits 4,766 kg of CO_2. The evaluation was carried out using OpenLCA software and the material from the OzLCI2019 database.

The assessment used a galvanised steel weight calculated at a density of 25 kg/m [22]. Nagle et al. [22] based this density on the replacement material of galvanised steel for the middle section of the blades, which were used to construct a 13-meter pedestrian bridge. The same method is applied to calculate each bridge in Luwu Regency. Table 1 provides detailed information for each river in Luwu Regency, South Sulawesi, and estimates the galvanised steel requirement by calculating the weight using a density of 25 kg/m, along with the CO_2 emissions in kg CO_2 equivalent employing the same LCA method for each bridge. The analysis covered 39 rivers out of 40 in Luwu Regency; one river was excluded due to an unknown width. The total weight of galvanised steel used is 27,500 kg, replaced by 78 blades.

This substitution resulted in a total CO_2 emission reduction of 52,432 kg CO_2.

Table 1. Steel weight and CO_2 emissions for steel bridge construction in Luwu Regency

Sub Regency	River	Width (m)	Quantity of blades	Weight of galvanised steel (kg)	CO_2 emission (kg CO_2 e)
South Larompong	La'loa	15	2	750	1,430
South Larompong	Temboe	15	2	750	1,430
South Larompong	Salusana	15	2	750	1,430
South Larompong	Sampano	12	2	600	1,144
South Larompong	Malewong	8	2	400	763
South Larompong	Riwang	10	2	500	953
South Larompong	Rante belu	15	2	750	1,430
South Larompong	Minanga	10	2	500	953
Larompong	Komba	15	2	750	1,430
Larompong	Lalento	15	2	750	1,430
Larompong	Larompong	16	2	800	1,525
Larompong	Binturu	12	2	600	1,144
Larompong	Redo	9	2	450	858
Larompong	Buntu sawa	8	2	400	763
Larompong	Liang	8	2	400	763
Larompong	Lamaring	12	2	600	1,144
Larompong	Garegge	8	2	400	763
Larompong	Keppe	N/A	N/A	N/A	N/A
Suli	Suli	20	2	1,000	1,906
Suli	Lempopacci	20	2	1,000	1,906
West Bajo	Bone	15	2	750	1,430
West Bajo	Suso	50	2	2,500	4,766
West Bajo	Kompi	30	2	1,500	2,860
Bajo	Tallang Bulawang	8	2	400	763
Bua Ponrang	Salu Paremang	40	2	2,000	3,813
South Ponrang	Mamumba	12	2	600	1,144
Basse Sangtempe	Matarin	8	2	400	763
Basse Sangtempe	Ojo	15	2	750	1,430
Basse Sangtempe	To'long	15	2	750	1,430
Basse Sangtempe	Bolu	10	2	500	953
North Basse Sangtempe	Pantai	10	2	500	953
South Ponrang	Pancobe	5	2	250	477
South Ponrang	Laminanga-nanga	5	2	250	477
South Ponrang	Bassiang	6	2	300	572

Table 1. (cont.)

Sub Regency	River	Width (m)	Quantity of blades	Weight of galvanised steel (kg)	CO_2 emission (kg CO_2 e)
Ponrang	Kaiyang	15	2	750	1,430
Ponrang	Tanjong	5	2	250	477
Kamanre	Kamburi	8	2	400	763
Bua	Kandoa	15	2	750	1,430
Bua	Bua	15	2	750	1,430
Walenrang	Battang	20	2	1,000	1,906
		TOTAL	78	27,500	52,432

4.2 *Scenario 2: Housing structure*

4.2.1 *End-of-life scenario*

The Tolo 1 wind farm utilises Siemens Gamesa SWT-3.6-130 wind turbines, each with a power output of 3.6 MW. There are 20 turbines installed on site, each blade measuring 64 metres in length and made of fibreglass reinforced with epoxy [28]. After use, blades can be repurposed by cutting them into root, middle, and tip sections to create various applications. One method involves converting the blade root sections into housing structures.

According to a study by Bank et al. [18], housing in the Yucatán province of Mexico is constructed using both intact and dissected blade roots. Blade roots improve the structural integrity of these buildings. Previously, housing in Mexico's Yucatán province was built with low-quality masonry blocks, making it vulnerable to hurricanes and severe flooding.

Bank et al. [18] describe how wind turbine blade roots are integrated into housing structures and present a strong case for reusing these materials. Blade roots can significantly strengthen building foundations, especially in earthquake-prone areas. For example, one-metre-high platforms with blade root sections serve as foundation platforms for a standard rectangular masonry house measuring 7 metres in length, 5 metres in width, and 2.7 metres in height, with the interior filled with rubble. The final houses are lifted off the ground using the blade roots as the foundation platforms [18].

Given the similar vulnerability to natural disasters, it is worth considering the adoption of such a strategy for the coastal regions of South Sulawesi. The area has a history of earthquakes, highlighting the urgent need for resilient housing solutions. According to the National Disaster Management Agency (*Badan Penanggulangan Bencana Nasional (BNPB)*) [29], 230 houses were damaged in Selayar, South Sulawesi, due to a magnitude 7.4 earthquake in East Nusa Tenggara. Muhari reported in Detik News [29] that residents' concrete fence structures were damaged, based on visual observation. Additionally, there were at least 15 aftershocks following the 7.4 earthquake [29]. Therefore, reusing blade roots as housing structures could be a viable measure to reduce damage caused by frequent earthquakes.

4.2.2 *Life cycle assessment*

The LCA for Scenario 2 evaluates the environmental impacts of using discarded blade root sections instead of traditional concrete for housing foundation construction. This assessment is similar to the study by Bank et al. [18], which does not include the entire production and service process but focuses on directly comparing material substitution.

The assessment utilises information from the studies by Rinaldi et al. [30] and Marwati [31] regarding the construction of stilt houses in the earthquake-prone islands of Indonesia. These houses are designed to be resistant to earthquakes. According to Rinaldi et al. [30], the traditional stilt house of the Besemah Clan from South Sumatra has proven to be earthquake resistant. Similarly, Marwati [31] conducted a study on the safety system of earthquake-resistant buildings in the stilt houses of Woloan Manado in North Sulawesi. A stilt house can use a pillar foundation made of concrete, where each pillar must be tied to the others with a cross connection, in which the pillar's base in contact with the ground is reinforced concrete to distribute the load evenly [31].

The dimensions of the concrete base, which measures 80 × 80 cm with a depth of 15 cm, and the concrete pillar, which has a height of 60 cm [23]. In addition, each pillar is reinforced with sloof concrete measuring 15 × 15 cm, with lengths of 7 meters (2 points) and 5 meters (3 points) [31]. The assessment in OpenLCA uses 20 MPa reinforced concrete, as studied by Limanto et al. [23], and utilises K-225 concrete, equivalent to 20 MPa concrete, to calculate CO_2 emissions. Table 2 provides a detailed description of the structure dimensions for a house measuring 7 meters in length and 5 meters in width, as well as CO_2 emissions. Thus, the functional unit for scenario 2 is defined as the concrete foundation for a 7 m × 5 m stilt house.

Table 2. Concrete requirements and CO_2 emissions for a 7 × 5 meter housing structure

Housing structure	Strength	Volume of concrete (m^3)	CO_2 emission (kg CO_2 e)
Concrete base foundation 80 × 80 cm, depth 15 cm (6 points)	20 MPa	0.576	184.74
Concrete pillars 15 × 15 cm, depth 60 cm (6 points)	20 MPa	0.081	25.98
Concrete reinforcement 15 × 15 cm, length 7 m (2 points)	20 MPa	0.315	101.03
Concrete reinforcement 15 × 15 cm, length 5 m (3 points)	20 MPa	0.3375	108.25
1 Blade Root replacement		13.095	420
20 Blade Roots replacement		26.19	8,4

- Blade Segmentation and Structural Design

The root section of the 64-meter blade, typically 3-4 meters in diameter and made with dense composite material, is cut into 1-meter-high cylindrical segments. These segments serve as elevated foundation piers for stilt houses, especially in flood-prone or seismic regions.

- Connection Techniques

The blade root segments are anchored to the ground using reinforced concrete footings. Steel rebar is inserted through pre-drilled holes in the blade root and embedded into the concrete base. The house's wooden or concrete superstructure is then bolted to a steel flange mounted on top of the blade root, ensuring vertical load transfer and lateral stability.

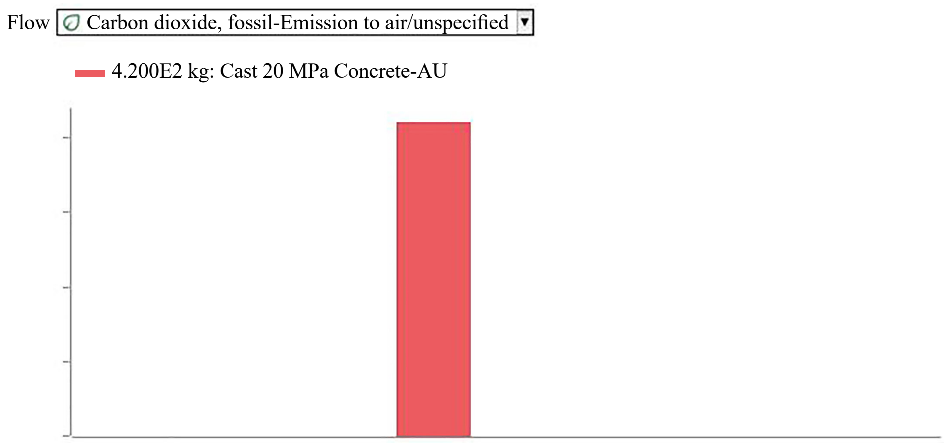

Figure 5. CO_2 emission of conventional housing structure (OpenLCA, 2024)

In Table 2, the calculation demonstrates that by using one blade root section for the housing foundation platform, it is possible to replace 1.31 m^3 of concrete. Calculations from OpenLCA indicate that using one blade root section can reduce 420 kg of CO_2 for every house built, as demonstrated in Figure 5. Scaling this up, using twenty blade root sections for building foundation platforms can replace approximately 26.19 m^3 of concrete and reduce 8,400 kg of CO_2 emissions for twenty houses in total.

4.3 *Scenario 3: Fishing vessels*

4.3.1 *End-of-life scenario*

Scenario 3 utilises the blade middle sections from the Tolo 1 wind farm Siemens Gamesa SWT-3.6-13. One possible strategy is to cut the blade middle sections into several pieces and repurpose them into fishing vessels, considering that Jeneponto is located on the south coast of Sulawesi Island, where fishing is the primary occupation for local residents.

In a study conducted by Joustra et al. [19], it was shown that blade sections have the potential to be repurposed for various applications. Joustra et al. [19] anticipate that transforming large blades into practical construction elements could open up diverse potential applications. This could increase demand, as construction elements are widely used in building, construction, infrastructure, and furniture industries.

4.3.2 *Life cycle assessment*

The LCA for Scenario 3 assesses the environmental impacts of utilising discarded blade middle sections to construct fishing vessels, thereby replacing traditional teak wood. The study identifies significant environmental benefits by substituting teak wood with blade middle sections. The primary environmental benefit stems from the reduced need for logging and processing teak wood, which is associated with high CO_2 emissions and deforestation impacts.

A study by Kurniawati et al. [24] shows that the construction of fishing vessels in Indonesia has traditionally relied heavily on wood as the primary material. This dependence has resulted in numerous challenges, including the depletion of forest resources. The increased demand and limited wood supply have led to higher costs and reduced availability of suitable timber for building vessels [24]. Halid, et al. [32] also support the idea of a limited wood supply for constructing fishing vessels. They propose integrating fibreglass material into traditional fishing vessel construction as a promising solution to address these issues, whereby applying fibreglass coatings to wooden hulls, fishermen can enhance the durability and longevity of their vessels and reduce maintenance requirements. Additionally, Sunardi et al. [33] also agree with the fibreglass integration into fishing vessels and found that this approach has effectively mitigated issues related to water damage, leaks, and the overall lifespan of fishing vessels.

The fishing industry in Indonesia still relies on wood to build vessels. This wood material poses challenges in sustainability, efficiency, and durability [32], [33]. Fibreglass technology offers a promising solution to address these issues by increasing strength and durability. Furthermore, a study by Sunardi et al. [33] reveals that fibreglass is a composite material that is strong, weather-resistant, and easily formed.

Interestingly, the materials used in wind turbine blade construction share the characteristics required for sturdy fishing vessels. De Simone et al. [34] highlight that fibreglass-reinforced composites used in constructing wind turbine blades are preferred for their strength, flexibility, and lightweight properties. These material overlaps suggest a potential circular economy approach that could address the material challenges the fishing industry faces on wood resource depletion while also contributing to blade waste reduction.

Research conducted by Pramoda and Apriliani [35] under the Indonesian Marine and Fisheries Socio-Economics Research Network has determined that small-scale fishers in Indonesia primarily require vessels with a Gross Tonnage (GT) of a maximum of 5 GT. A typical vessel in this category measures approximately 10 meters in length, 1.2 meters in width, and 0.9 meters in height.

Given the dimensions of the 64-meter wind turbine blade used in Tolo 1 wind farm, there is potential to repurpose these materials into multiple fishing vessels, specifically from the middle sections. While precise calculations would require a detailed analysis of blade dimensions and material properties, initial estimates suggest that at least two fishing vessels could be constructed from a 64-meter wind turbine blade.

- Blade Segmentation and Structural Design

The middle section of the blade is cut into 8-10 meter curved panels, which are then trimmed and joined to form the hull of a 5 GT fishing vessel. The blade's inherent curvature is advantageous for hydrodynamic performance, reducing the need for extensive reshaping.

- Connection Techniques

The blade panels are joined using marine-grade epoxy resin and fibreglass tape, forming a watertight hull. Internal ribs made from recycled composite or aluminium are added for structural reinforcement. The deck and cabin are constructed using lightweight composite panels, and stainless steel fittings are used for attaching the engine, rudder, and other marine hardware.

The calculation from OpenLCA above, shown in Figure 6, indicates that constructing a single 5 GT conventional wood fishing vessel emits 3,590 kg of CO_2. This calculation uses 5 m^3 of teak wood with a density of 486 kg/m^3 to construct one 5 GT fishing vessel. Scaling this up, using twenty-blade middle sections for building 5 GT fishing vessels can substitute approximately 200 m^3 of teak wood and reduce CO_2 emissions by 143,600 kg for 40 fishing vessels. Thus, the functional unit for scenario 3 is defined as one 5 GT fishing vessel constructed using blade middle sections.

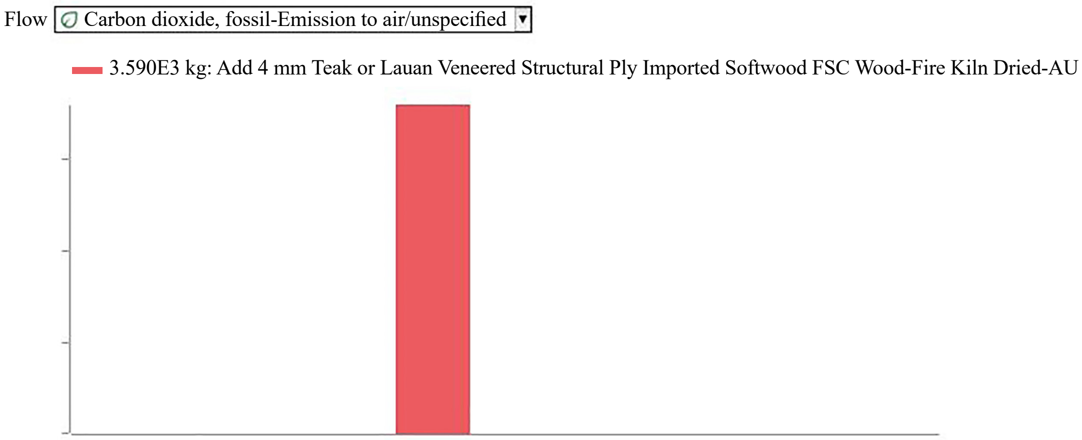

Figure 6. CO_2 emission of conventional fishing vessels (OpenLCA, 2024)

4.4 *Comparative analysis and discussion*

The comparative results highlight that all three upcycling scenarios offer substantial CO_2 savings by substituting conventional materials with decommissioned wind turbine blades. As shown in Table 3, the fishing vessel scenario appears to yield the highest CO_2 savings per blade, primarily due to the high emissions associated with teak wood harvesting and processing. However, this scenario may face greater implementation challenges, including the need for marine-grade certification, design adaptation, and community acceptance.

Table 3. Comparison of CO_2 savings per blade for each scenario

Scenario	Blade Section Used	CO_2 Savings per Blade (kg CO_2 e)	Notes
Pedestrian Bridge	Full Blade (56 m)	672.2	Based on 78 blades replacing 27,500 kg of steel (52,432 kg CO_2 total)
Housing Foundation	Blade Root	420	Based on 1.31 m^3 of concrete replaced per blade
Fishing Vessel	Blade middle section	1,000-1,200 (estimated)	Based on the teak wood substitution, the exact LCA values should be clarified

The pedestrian bridge scenario, while offering slightly lower per-blade savings (672.2 kg CO_2), is highly scalable and aligns with urgent infrastructure needs in South Sulawesi. It also benefits from existing precedents like the BladeBridge project, making it practically feasible with moderate engineering adaptation.

The housing foundation scenario provides moderate CO_2 savings (420 kg per blade) and addresses disaster-resilient housing needs in earthquake-prone regions. Its feasibility is enhanced by the modularity of blade roots and their structural integrity, though logistical challenges in cutting and transporting blade roots remain.

5. Conclusions and limitations

5.1 *Conclusions*

The main goal of this study is to explore how circular economy principles can help tackle the challenges of managing wind turbine blades at the end of their life in Indonesia, emphasising upcycling strategies. The findings suggest that repurposing these large composite structures into useful products such as pedestrian bridges, housing foundations, and fishing vessels is achievable, especially in South Sulawesi, Indonesia. Using LCA is essential as it offers a thorough evaluation of the environmental impacts associated with a product or system throughout its entire life cycle. By analysing inputs and outputs, LCA identifies potential environmental burdens and opportunities for improvement. This supports the broader aims of the research, which are to evaluate the environmental effects of various upcycling strategies for wind turbine blade end-of-life management. Incorporating upcycling concepts into the LCA framework is crucial for understanding the environmental benefits of repurposing wind turbine blades. The analysis in this study shows considerable potential for reusing wind turbine blades in different applications, particularly in addressing infrastructure issues in regions like South Sulawesi, Indonesia. It highlights the importance of reusing these large composite materials through three different upcycling scenarios: pedestrian bridges, housing foundations, and fishing vessels. While this research offers valuable insights into the feasibility and environmental advantages of upcycling, further investigation is needed to realise the full potential of this strategy. By aligning blade upcycling strategies with broader sustainability frameworks such as the Water-Energy-Food nexus, this study underscores the potential for circular economy interventions to generate co-benefits across sectors. Additional research should focus on optimising design and construction processes, assessing the economic viability of these applications, and examining the long-term performance of repurposed blade components. Future research should also explore how renewable energy waste management can be integrated into regional planning for water and food security.

5.2 *Limitations*

While this study demonstrates the environmental potential of upcycling wind turbine blades in Indonesia, several limitations must be acknowledged:

- Simplified LCA System Boundaries

The Life Cycle Assessment focused solely on material substitution and excluded upstream and downstream processes such as blade cutting, transportation, installation, and maintenance. These activities can contribute significantly to overall emissions and environmental impact, and their omission may lead to an underestimation of total lifecycle burdens.

- Data Uncertainty and Regional Relevance

The study relied on the OzLCI2019 database, which is based on Australian manufacturing data. While these datasets offer robust benchmarks, they may not accurately reflect Indonesian-specific production methods, energy mixes, or material sourcing. This introduces uncertainty into the CO_2 emission estimates and limits the precision of regional applicability.

- Technical and Structural Feasibility

The proposed upcycling designs, such as blade-based pedestrian bridges, housing foundations, and fishing vessels, require further engineering validation. Long-term durability, load-bearing capacity, connection details, and compliance with safety standards must be assessed through field trials and structural modelling to ensure viability.

- Economic Viability and Market Acceptance

The economic feasibility of blade upcycling depends on factors such as transportation costs, labour availability, and local demand for repurposed products. Market acceptance may be influenced by aesthetic preferences, cultural perceptions, and regulatory approval. Without targeted incentives or public-private partnerships, scaling these solutions may face resistance.

- Health and Safety Risk

Potential exposure to glass-fibre dust and microplastics during blade processing and use poses occupational and community health concerns. These risks require further assessment and mitigation strategies.

- Techno-Economic and Policy Gaps

The study does not include a full techno-economic analysis or evaluate policy tools like green procurement or Extended Producer Responsibility (EPR), which are critical for scaling up.

While this study estimates CO_2 emissions reductions based on material substitution by mass and length, it does not include mechanical validation of the repurposed blade components. Specifically, equivalence in strength, stiffness, fatigue resistance, and long-term durability compared to conventional materials (e.g., steel, concrete, teak wood) has not been demonstrated. The absence of Finite Element Analysis (FEA), coupon-level testing, and component/joint validation means that the reported environmental benefits should be interpreted as preliminary and indicative rather than definitive. Future research should incorporate structural testing and compliance assessments with relevant engineering codes to ensure the feasibility and safety of these upcycling applications.

This study's LCA focuses exclusively on the material substitution phase, comparing the environmental impacts of conventional materials with repurposed wind turbine blade components. It does not account for additional lifecycle stages such as blade cutting, transportation, re-manufacturing, installation, in-service maintenance, or eventual end-of-life treatment of the upcycled products. These exclusions are acknowledged as limitations and may influence the overall environmental impact results. Future research should incorporate these stages to provide a more comprehensive and realistic assessment of the sustainability performance of blade upcycling strategies.

5.3 *Policy implications and future work*

The findings of this study suggest several actionable policy directions to support sustainable end-of-life management of wind turbine blades in Indonesia:

- Develop national guidelines for blade upcycling

The Indonesian government should establish technical and safety standards for repurposing blades into infrastructure, housing, and marine applications. This includes engineering validation protocols and certification pathways for reused composite materials.

- Incentivise circular economy initiatives

Financial incentives, such as tax breaks, subsidies, or public procurement preferences, can encourage companies to invest in blade reuse technologies and infrastructure projects that utilise upcycled materials.

- Integrate blade waste into regional planning

Local governments in wind farm regions, such as South Sulawesi, should incorporate blade reuse into their infrastructure development plans, particularly for bridges, disaster-resilient housing, and coastal livelihoods.

- Support pilot projects and public-private partnerships

Demonstration projects for blade-based bridges, housing platforms, and fishing vessels can validate technical feasibility and build public trust. Collaboration between energy firms, universities, and local communities will be key.

Building on this study, future work should:

- Conduct full cradle-to-grave LCAs, including cutting, transport, and installation phases.
- Develop region-specific LCA datasets to improve accuracy.
- Perform structural and durability testing of blade-based designs under Indonesian climate and load conditions.
- Explore community perceptions and market acceptance of upcycled products.
- Assess the scalability and cost-effectiveness of blade reuse across other renewable energy regions in Southeast Asia.

These steps will help translate the environmental potential of blade upcycling into practical, scalable solutions aligned with Indonesia's green economy goals.

Conflict of interest

The authors declare no competing financial interest.

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