

Review

Waste Management of Wind Turbine Blades—A Review of Recycling Methods and Applications in Cementitious Composites

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Abstract: The decommissioned blades of wind turbines represent a contemporary challenge for waste management. The composites used in their construction, primarily thermosetting materials, as well as fiberglass and carbon fibers, present a range of challenges in terms of recycling these components. Depending on the region of the world, various legal regulations govern the disposal of these elements. One example of a ban is Germany, which, according to forecasts, is also expected to experience the highest accumulation of such waste in Europe. The article is based on a systematic review of the literature, including 59 sources, more than half of which were published in the last five years. The discussion covers the availability of common waste management methods, as well as examples of reusing these components in whole, in part, or after processing. The review emphasizes the need to explore solutions for utilizing wind turbine blades to minimize waste and reduce the consumption of natural resources by recycling waste material. Finally, the authors propose using mechanically shredded elements from wind turbine blades as an additive in cement mixtures.

Keywords: wind turbine blades; waste management; application



Academic Editor: Antonio Caggiano

Received: 30 November 2024

Revised: 26 December 2024

Accepted: 18 January 2025

Published: 21 January 2025

Citation: Jasińska, D.; Dutkiewicz, M. Waste Management of Wind Turbine Blades—A Review of Recycling Methods and Applications in Cementitious Composites. *Sustainability* **2025**, *17*, 805. <https://doi.org/10.3390/su17030805>

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1. Introduction

Wind energy is commonly perceived as a source of clean energy produced in an environmentally friendly way. However, it is important to consider the environmental impact comprehensively, also taking into account long-term effects such as end-of-life waste management of wind turbines. The main component of wind turbines are the wind blades. When these blades are decommissioned for different reasons, e.g., such as end of life or replacement with more modern ones, the question of their further management remains to be solved. When they are not able to be used any longer, the problem of managing this waste arises, which becomes a challenge due to the size and material structure of these components. Depending on the technical parameters of the wind turbine (e.g., turbine power) and the environment in which it operates, the lifespan of wind turbine blades ranges from 18 to 25 years. Refs. [1–6] The lifespan may be reduced in the case of failure or the need to increase the turbine's power output, leading to the replacement of components, known as repowering. At the end of the designed life, an inspection and analysis should be carried out to determine whether the turbine can continue to operate or can be repowered for less demanding farms. Ref. [3] There has been a perceived increase in the secondary sector market for the resale of removable turbines and distribution to less developed regions, for example, the sale of end-of-life turbine blades from Denmark to Eastern European

countries. Ref. [4] This is also connected with technological developments and increasing energy demand in more developed countries, which often allows new solutions to be installed at the end of their useful life.

Wind turbine blades that are no longer suitable for further use in wind energy are removed from the internal cycle, and even recovered materials cannot be reused in the industry, as they exhibit lower properties than those expected in wind engineering. One of the main challenges the world is beginning to face is the generation of large-volume waste (wind turbine blades), which is expected to exceed 40 million tons by 2050 [1]. This is related to the end of the lifespan of wind turbine blades, understood as the termination of their safe operational period. Other forecasts estimate 400,000 tons of waste annually by 2030, followed by 800,000 tons per year by 2050 [4]. As much as a quarter of this will accumulate in Europe [1]. Studies on the amount of waste in Europe, conducted in [5], predict 325,000 tons of waste annually by 2050, with a division of 76% from onshore farms and 24% from offshore farms. A growing trend in waste volume is expected year by year until 2045. The largest accumulations of waste from onshore wind turbine blades are expected in Germany, while offshore waste will mainly accumulate in the United Kingdom. According to forecasts, Poland ranks 8th (offshore farms) and 9th (onshore farms) in terms of wind turbine blade waste volume [5]. The development of wind farms is rapidly increasing each year. Considering the lifespan of turbine components, this creates a significant challenge in managing the vast amount of waste. This growth is documented in successive reports from the Global Wind Energy Council (GWEC). In 2023 alone, as stated in the report, 117 GW of new wind installations were created [6]. In relation to waste management, it is essential to analyze previous reports, which clearly indicate the very dynamic growth of wind installations over the past three decades. Observing the latest reports showing the increase in wind installations from 1996, when the total was 6 GW [7], to 2003—39 GW [8], 2013—319 GW [9], and 2023—1021 GW [6]. It is predicted that by 2030, the total number of wind installations will exceed 2 TW (200 GW) [10].

The issues of forecasting and further utilization of used materials are the subject of research by scientists. As indicated by [3], pioneers in this field are Liu and Barlow [1], who from 2014 to 2017 analyzed the consumption of materials from wind farms built since 1998, forecasting their use up to 2050, with a division into Europe, the United States, China, and other countries around the world. According to H. Albers, a significant amount of waste in Germany is expected after 2020, when 20 years of operation of subsequent wind installations will have passed [11]. In his publication, he also emphasizes the lack of standards and clear procedures for managing wind turbine blade waste. As reasons for their absence and the insufficient practical experience, Andersen et al. point to the relatively young age of wind turbine technology [4]. The authors also question the profitability of recovering materials from turbine blades, such as fiberglass, due to the harmful effects of dust and the substances accompanying these processes, as well as the generation of costs higher than the initial installation costs [4].

This article provides an overview of wind turbine blade waste management in the context of the author's research on the use of shredded wind turbine blades in cement composites.

The aim of the review is to achieve the following:

- Highlight the global significance of the issue of wind turbine blade waste management and its scale, covering the amount of waste and its growth trend.
- Consider the legal limitations related to managing composite waste.
- Discuss methods of managing wind turbine blade waste in whole or after shredding (recycling, reuse, material recovery).

- Discuss an original and innovative solution for the use of mechanically shredded wind turbine blades in cement composites.

The review begins by presenting the main legal regulations regarding the disposal and management of composite waste. It then focuses on presenting the structure of a wind turbine blade. The main focus is on waste management methods, such as recycling and reuse, presenting various approaches by scientists. Finally, a solution is proposed, which the author, after reviewing the literature, has deemed original and worth subjecting to experimental research.

The methodology of the review was based on a systematic literature review. The selection of materials was conducted in stages, taking thematic criteria into account. The initial selection of literature involved the analysis of titles and abstracts of publications. The next step of the analysis was the availability and in-depth content analysis of selected sources. During this process, particular attention was paid to thematic connections, and references identified within the texts were also analyzed. The thematic scope primarily concerns the issue of waste management related to wind energy, such as wind turbine blades. The cited sources analyse the issues of waste forecasting, blade reuse options, and recycling methods. Legal issues and regulations were also considered. A total of 59 sources of literature were analyzed. The time frame of the literature includes the years 2005–2024, with more than half of the analyzed sources dating from the last five years.

2. Waste Management

Waste management should be carried out in accordance with the currently applicable standards or legal acts [3]. Legislative provisions may vary between countries or even regions, introducing different restrictions. The first of these is the Waste Framework Directive (2008/98/EC) [12,13]. It requires Member States to develop waste management plans in accordance with the established hierarchy of solutions, which is presented in this article in the form of an inverted pyramid in Figure 1. Due to its formal scope covering nearly 60% of European countries, it is considered decisive in these considerations.

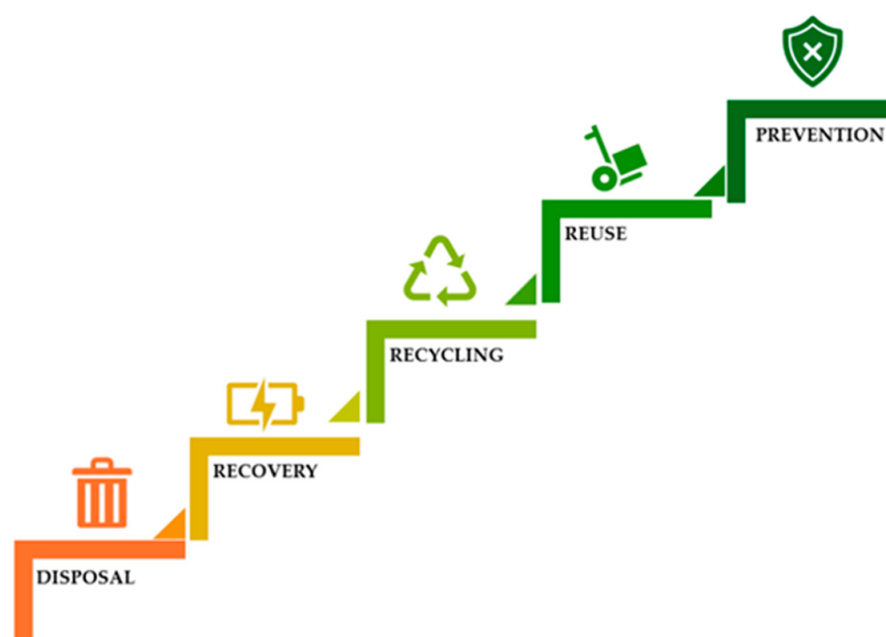


Figure 1. Waste management hierarchy [source: own work].

The most important aspect of waste management, according to the directive, is preventing their generation, for example, through design-stage analyses. Efforts should be made to ensure that this area is the most developed. However, their generation can be prevented by the next step in the hierarchy, which is reuse. The least beneficial and placed at the end of the classification are disposal processes, which should be avoided. This is not only due to the negative environmental impact but also because, in the case of retiring turbine blade components on a large scale, their storage or disposal may cause public disapproval and cast a negative view on wind energy [3,14].

Due to the material nature of the waste, an important perspective on this issue is provided by the European Sustainable Chemistry Platform (ESCP), which refers to composite materials and fibers [15]. National solutions in European countries align with the Resource Conservation and Recovery Act (RCRA) introduced in the United States [16]. This defines waste categories while suggesting solutions and requirements for managing them in accordance with a given classification. Based on these documents and legal provisions, wind turbine blades, which are largely made of composite materials with fibers, are classified as non-hazardous solid waste [3,16].

Waste management of wind turbine blades should focus on minimizing resource consumption and promoting their reuse. In this case, it is not possible to speak of a circular economy approach, as due to the diversity of wind turbine blade constructions, not every material can be fully recycled when retired from use.

As the diagram indicates, disposal should be the least expected procedure. A particular limitation is the legal regulations regarding the management of elements that have been withdrawn from use, such as those in Germany, which, since 1 June 2005, have prohibited the disposal of waste containing more than 5% organic components in landfills (KrW-/AbfG-Kreislaufwirtschafts- und Abfallgesetz-the Circular Economy and Waste Management Act). This is linked to the goal of reducing greenhouse gas emissions resulting from the decomposition of these substances [11,17]. In the UK, additional taxes have been imposed on the disposal of composites in landfills [5]. In the United States, where landfill disposal is permitted, the appropriateness of this solution is being debated due to limited space and the durability of wind turbine blades, which are not easily degradable or compressible. However, it has been concluded that there is no risk associated with the limited capacity of American landfills [18].

An important political tool enforcing the need to address the disposal of these composite wastes is the introduction of Extended Producer Responsibility (EPR). The introduction of this obligation for businesses to manage the waste they produce within the European Union was enabled by the Directive 2008/98/EC [12,13]. Extended Producer Responsibility imposes on the producer the obligation to accept products after they have been used, and it may include financial responsibility for actions related to the management of this waste. A less burdensome solution is the introduction of a public obligation to report the degree of further product reuse or methods of processing or disposal. Following this, French legislation introduced a requirement in 2022 that at least 35% of the mass of the rotor (including the blades) be recycled or reused, progressively increasing this to 45% in 2023 and 55% starting in 2024 [19]. China does not have specific legal regulations regarding the disposal and recycling of composite materials from wind turbine blades [20]. Existing legal acts aim to promote recycling and focus on minimizing landfill waste [21,22]. At the beginning of 2024, proposals for standards, such as a ban on landfill disposal and incineration, appeared; however, their legal validity is yet to be confirmed [23] (Table 1).

Table 1. Summary of the most important legal regulations mentioned in the text (by area of application).

<u>EU MEMBER STATES</u>	
●	Directive 2008/98/EC on waste (Waste Framework Directive)-Environment-European Commission
■	European Sustainable Chemistry Platform (ESCP)-Environmental impact of composite materials and fibers
<u>GERMANY</u>	
●	Ban on landfilling waste containing more than 5% organic components (1 June 2005)
●	KrW-/AbfG-Kreislaufwirtschafts- und Abfallgesetz-Circular Economy and Waste Management Act/Waste Disposal Act
<u>FRANCE</u>	
■	Requirement that at least 35% of the rotor mass (including the blades) be recycled or reused (45% in 2023 and 55% from 2024 onwards)
■	Arrêté du 22 juin 2020 portant modification des prescriptions relatives aux installations de production d'électricité utilisant l'énergie mécanique du vent au sein d'une installation soumise à autorisation au titre de la rubrique 2980 de la législation des installations classées pour la protection de l'environnement
<u>UNITED STATES</u>	
■	Landfill tax (mass-based or volume-based)
■	Resource Conservation and Recovery Act (RCRA)
<u>UNITED KINGDOM</u>	
■	Landfill tax (mass-based or volume-based)
<u>CHINA</u>	
●	No direct bans or requirements regarding the landfilling and recycling of waste
●	The China State Council. Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste
●	National Development and Reform Commission. Guiding Opinions on Comprehensive Utilization of Bulk Solid Waste during the Fourteenth Five-Year Plan,

3. Structure of Wind Turbine Blades

According to a detailed analysis of the material composition of wind turbine blades, the main components are fibers, polyurethane composite, balsa wood, and microfibers [24,25], as shown in Figure 2. The presented fragment of a wind turbine blade is part of the resources of the Research Laboratory of the Faculty of Civil Engineering, Architecture, and Environmental Engineering at Bydgoszcz University of Technology. The core is most often made of balsa wood, as well as PVC and PET. Another component is the thermosetting matrix in various variants. To reinforce the structure, fibers—most commonly glass, carbon, or basalt fibers—are used. Additionally, elements related to assembly or installations are made of metals such as steel or copper (e.g., bolts/wires) [26]. A single wind turbine blade can reach several tens of meters in length, changing its cross-section along its span, and may weigh several tons, which clearly illustrates the significance of the waste management issue once these components reach the end of their service life [27]. In [11], a graph showing the relationship between the blade's mass and the rotor diameter is presented. In [4], the mass of a wind turbine blade is correlated with its power, giving an example of 19.5 tons for a 2 MW turbine, with further assumptions of 10 tons per MW.

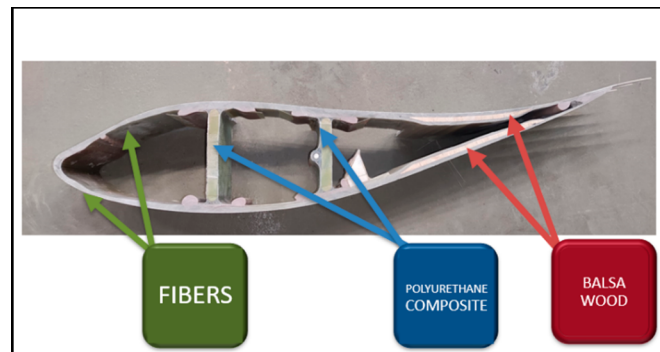


Figure 2. Structure of a wind turbine blade shown in cross-section [source: own work].

In the context of waste prevention or facilitating their recycling or reuse, the design of blades made from fully or partially biodegradable or bio-based materials, such as biocomposites, is being analyzed [3].

4. Recycling Methods

The waste generated by wind turbine blades presents a significant challenge due to their composition, which largely consists of composites, fibers, and a thermoset “sandwich” structure. The three-dimensional internal structure of thermoset composites requires more complex recycling methods compared to thermoplastic composites [28]. The proportion of composites in wind turbines represents about 8% of global composite material usage [18]. Research areas related to technical processes focused on the recovery of composite materials or fiberglass are not clearly defined, despite over 20 years of analysis by various researchers [3]. The issue of procedures or solution selection remains unsystematized, and the choice of method depends on many variables such as economic aspects, solution availability, waste scale, legal regulations, and socio-political attitudes.

Three main recycling methods are distinguished: chemical recycling, thermal recycling, and mechanical recycling [3].

Thermal recycling is based on thermal treatment in the range of 450–700 °C, typically using pyrolysis techniques, often multi-stage [29]. The result of these processes is the recovery of fibers and oil fractions. High temperatures may adversely affect the chemical structure of the fibers, reducing their properties compared to the original fibers [26,30]. The reduction in the mechanical properties of glass fibers occurs after exceeding 250 °C [4]. In [18], it was stated that the strength of glass fibers decreases by 50%. Carbon fibers have a smaller decrease in properties compared to their original values [18]. However, this type of recycling requires prior mechanical shredding of large wind turbine blades to prepare them for further processing. Thermal recycling is not a standalone process and requires mechanical shredding of the elements [31,32]. These aspects raise doubts about the financial feasibility of the solution. Economic unprofitability of pyrolysis is also indicated in [4], where concerns are raised about the cost increase and the reduction in properties compared to newly produced glass fibers. Pyrolysis processes are, however, commercially available in some countries such as the UK and Germany [29].

Chemical recycling is also not an independent process, as it requires shredding the wind turbine blade. It involves treatment using chemical agents under conditions necessary for conducting chemical reactions (e.g., appropriate pressure, heat supply), which limits its use to laboratory scale and reduces its applicability on an industrial scale [18]. Most often, solvolysis techniques are mentioned [3,26]. Chemical techniques are less degradative than thermal ones, as they take place at lower temperatures [30]. They allow for the separation of clean fibers in their full length. These fibers are purified from the matrix resin, which

is also recovered in these processes. Among chemical recycling methods, there is also a method based on the use of electric current, known as the electrochemical process.

On a larger scale, pilot studies are being conducted on methods utilizing high-voltage fragmentation and fluidized beds [29]. High-voltage fragmentation is based on methods for crushing rocks to extract minerals such as gold and is based on generating pulses of electrical discharge in a liquid, which generates a crash wave to a component placed in the liquid and ultimately allows the material to disintegrate [29].

The recycling methods described above required prior preparation through shredding, which is a form of mechanical recycling. This process occurs through cutting, grinding, crushing, or milling. The goal is to reduce the size of the waste with the intention of its further use [3,33]. The size and type of the applied mechanical recycling method depend on how the materials are intended to be used afterward. Therefore, it is one of the most commonly applied recycling methods. The shredded components can be subjected to sorting or sieving to separate the desired fractions or to isolate specific materials [34,35]. In the first phase, mechanical recycling can take place on-site during dismantling, which reduces the costs of large-scale transport [18]. The next step involves further fragmentation to a size of 50–100 mm. Two methods are used: slow, when there is metal in the composition, and fast, when it is absent [29].

Each recycling method affects the properties of the original material [36]. Depending on the chosen method, this may involve the degradation of the fiber geometry, the loss of the external matrix, or weakening of properties related to tensile strength. The properties of recycled fibers differ from those of the original “production” fibers. The paper [36] analyzed the properties of glass fibers obtained from grinding fragments of wind turbine blades and fibers recovered during the pyrolysis process, comparing them with primary fibers produced during manufacturing.

According to [37], mechanical recycling is considered the most interesting method due to the simplicity and availability of technology. However, as indicated in the same source, chemical recycling allows for the recovery of materials with properties closest to the original, making it more effective in terms of the quality of recovered raw materials.

A comparison of different recycling methods, including mechanical recycling, considering the quality of the recovered product, is described in [28]. The form of fibers recovered through the high-voltage fragmentation method had a compact structure visually similar to mineral wool. In contrast, mechanical recycling resulted in short fibers and flakes. The highest remaining resin residues, as observed through SEM analysis and burning, were found in the mechanical recycling process [28].

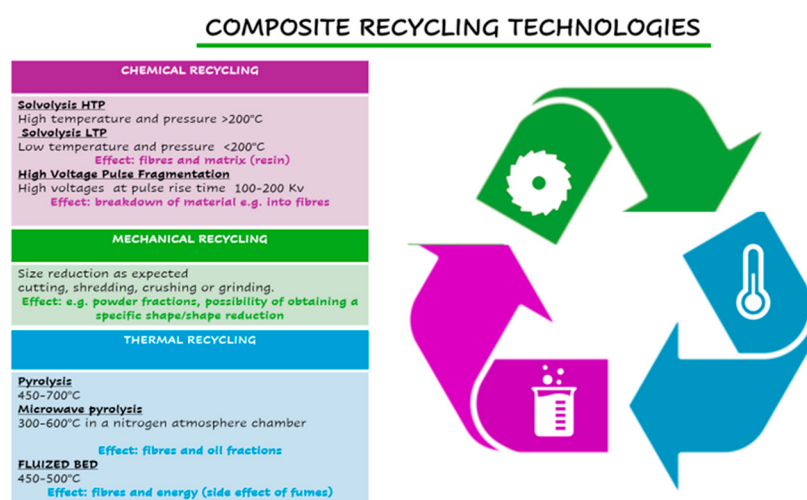


Figure 3. Methods of composite recycling [source: own work].

5. Reuse of Large-Scale Components

Wind turbine blades withdrawn from operation are considered large-scale waste due to their size, which can reach several dozen meters. In the literature, we can find solutions for reusing these elements either in their entirety or with minimal reduction in their value, such as through transverse cutting. An example of using cross-cut wind turbine blades could be their application as components for small geotechnical or architectural structures. The use of wind turbine blade components, additionally filled with concrete, as foundations or fences, can be found in [27]. Wind turbine blades have a cross-sectional shape that mimics a box-section (rigid, closed cross-section with internal transverse reinforcements), which serves as a lost formwork for these elements, simultaneously protecting the concrete from unfavorable environmental conditions. This solution also has potential for load-bearing applications [27]. Another solution involves using wind turbine blades in small architecture elements or furniture [38,39].

The use of wind turbine blades in construction is also an important issue. Considerations regarding their use as roofs, walls, bus shelters, and other everyday objects are explored in [40,41].

In Poland, the world's first pedestrian bridge made from upcycled wind turbines was built—the Footbridge over the Szprotawa River [2021]. The concept and design assumptions for the footbridge were developed in collaboration between Anmet and the Rzeszów University of Technology [42,43].

6. Reuse of Components After Shredding

The shredding of wind turbine blades provides numerous possibilities for further use. The forms of shredding can vary both in shape and material composition. Some solutions additionally involve sorting materials or sieving fractions. The shredded material can be used as a standalone fibrous or composite material for the production of new elements. Such solutions are implemented by companies like Thornmann Recycling, which produces sewer grates from the recycled wind turbine blade materials [44,45].

One of the most effective ways of utilizing wind turbine blades is using them as fuel in cement kilns, while simultaneously using the ash produced, which contains glass fibers, as a source of silica in the clinker production process [3,18,46]. This recycling technology helps reduce the exploitation of natural mineral resources and decreases the use of fossil energy sources. Additionally, it allows for a reduction of the carbon footprint in cement production by about 16%, supporting actions for sustainable development and a circular economy [28,37].

Shredded wind turbine blades are also used in cement and concrete mixtures, as discussed in the next section.

7. Shredded Wind Turbine Blades in Concrete

The use of recycled fibers in concrete or cement mixtures is already well-known. Examples include steel fibers recycled from car tires [47,48]. Another confirmation is polypropylene fibers recycled in concrete, which were recovered, for example, from disposable face masks [49,50]. There are also cases of recycled glass fibers used in cement floor screeds [51].

Shredded elements from wind turbine blades used as an additive to concrete mixtures are described in the works of V. Revilla-Cuesta et al. [52–54]. They studied elements in the form of fibers with a diameter smaller than 10 mm, segregated by sieving all the elements obtained after shredding. In the form of rectangular needles with a square cross-section of 6 mm and a length of 100 mm, the study was presented by Yazdanbakhsh et al. [55]. They used them as a replacement for coarse aggregate in concrete. Wind turbine blade

needles were also studied in [56], where elements with a cross-section of 6 mm and a length of 50 mm were analyzed. They, like in [55], served as a replacement for aggregate, but the authors decided to shorten the length to improve stiffness. The influence of a powdered form as a cement substitute, a cube form (20 mm) as an aggregate substitute, and a fiber form was presented by Baturnik et al. [57]. Two research series were distinguished, differing in the separation of wood fragments contained in the turbine blade composition. The series with separated wood was rated more favorably than the one that included it in its composition. The material from wind turbine blades in powdered form, used as a component of geopolymers, i.e., cement-free mixtures, was studied by the research team of Pławiecka et al. [58] (Table 2).

Table 2. Shredded wind turbine blades in concrete—literature summary.

SHREDDED WIND TURBINE BLADES IN CONCRETE-LITERATURE SUMMARY				
SOURCE	Form of the Material	Size [mm]	Application	Percentage Share in the Composite [as Reported by the Authors].
V. Revilla-Cuesta i in. [52–54].	Fibers	<10	Additive to the concrete mix	M1.5–1.5%
				M3–3%
				M4.5–4.5%
				M6–6%
Yazdanbakhsh i in. [55]	Regular needles (PLN) Grooved needles (GRV)	$6 \times 6 \times 100$	Coarse aggregate substitute	PLN-5–5%
				PLN-10–10%
				GRV-5–5%
				GRV-10–10%
Abdo, i in. [56]	Needles	$6 \times 6 \times 50$	Coarse aggregate substitute	FRP-RA-2.5–2.5%
Baturnik i in. [57]	Cubes	20	Coarse aggregate substitute	33% cubes
				66% cubes
				100% cubes
				33% aggregate
Baturnik i in. [57]	Powder	-----	Cement substitute	20%WWTB-GFRP
				40%WWTB-GFRP
				27%WWTB-GFRP
				54%WWTB-GFRP
				10% Powder
				20% Powder
				30% Powder
Sorathiya i in. [59]	Irregular elements resembling aggregates [“cubes”].	20–25	Coarse aggregate substitute	B1-20%
				B2-40%
				B3-60%
				B4-80%
				B5-100%

8. Material for Research

This article presents proposals for the use of shredded elements from wind turbine blades as an additive to cement composites. The research utilized shredded elements from “LM blade” wind turbines, which had previously undergone mechanical recycling processes. These elements were then manually separated to remove wooden fragments. This procedure aimed to maximize the positive impact of the components, referred to as fibers. Based on the literature, there was information about the potential weakening of properties if the balsa wood was not separated [57]. Preliminary studies were then conducted to confirm the validity of this approach. The next step was sieving the shredded turbine blade elements through sieves with mesh sizes of 0.5, 2, 4, and 8 mm. The elements from the largest and smallest sieves were excluded from further tests at this stage. The largest were discarded due to their overly large fragments, while the smallest were excluded due to their powder form. These processes are presented in Figure 3.

The originality of this approach lies in the form of the elements added to the mix. Unlike regular rectangular prisms or cubes, which are commonly found in the literature [57,59], or fibrous materials [52–54], the elements in this study are a direct result of mechanical recycling. No additional processes were carried out to give them a consistent, predefined shape. The only additional steps after obtaining the material were separating the wood fragments and sieving to standardize the size, eliminating the extremely large pieces and the dust. The material used is of varying dimensions, with elements resembling strips up to 1 mm thick, up to 5 mm wide, and with a maximum length reaching 40 mm (Figure 4). For the purposes of the research, this material was named “shredded wind turbine blade fibers” and was described as WT. There is no additional sorting by specific dimensions, and the selection of individual elements in the batch added to the mix is random. The advantage of this approach is the minimization of additional preparatory processes aimed at creating elements with a specific shape and size. It is also innovative to analyze the properties of cement mixtures with fibers from shredded wind turbine blades, as, based on the literature, it can be concluded that previous studies have focused on using this material in concrete mixtures. The material from wind turbine blades is used as an additive to the mix rather than as a replacement for aggregate or cement.

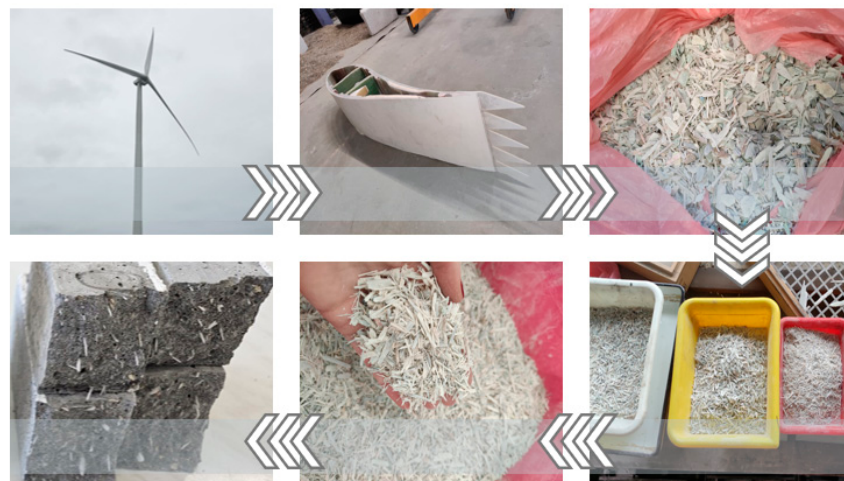


Figure 4. The cycle from wind turbine to application as fibers in cement composites.

9. Conclusions

Main conclusions:

- The management of wind turbine blade waste is of critical importance at a global level, especially in the context of the increasing volume of this waste and the projected increase in the future.
- According to predictions in the literature, the trend of increasing wind turbine waste is expected to continue until 2045 (up to 800,000 tons per year)
- There are no uniform regulations governing the management of wind turbine blade waste. There are different legal approaches to regulation, from landfill bans (Germany) to recycling purposes (France).
- The large size of the waste determines mechanical recycling as a more economical solution that does not require specialized laboratory facilities.
- The biggest challenges in turbine blade recycling are thermoset composites, as well as glass and carbon fiber.
- An innovative approach to the use of shredded wind turbine blades in cementitious composites is presented, which differs from traditional solutions such as cubes or fiber materials.

Recommendations for waste management also appear in the context of broader EU legal provisions, which require member states to introduce national regulations. Different countries approach these regulations in various ways. For example, Germany has introduced a landfill ban, while France has set a target for the proportion of a wind turbine blade that must be recycled. China has not yet introduced clear bans or mandates, but they do have guidelines for managing this type of waste. Other solutions include financial charges, such as taxes in the United States or the United Kingdom.

Mechanical recycling is a solution that requires less specialized preparation compared to other methods such as chemical or thermal recycling. These processes do not require strictly laboratory conditions and equipment, making it less costly overall. Fibers recovered through mechanical recycling have a rough surface, which improves their adhesion.

There are many ideas for large-scale uses of wind turbine blade waste, such as for formworks, benches, footbridges, roofs, or walls. However, there is significant potential in the further use of shredded elements from wind turbine blades. This includes utilizing recovered materials like fibers and incorporating shredded components, such as cubes, powders, strips, etc. Research on using these materials in concrete has been conducted by V. Revilla-Cuesta et al., Yazdanbakhsh et al., Abdo et al., and Baturnik et al. They used shredded wind turbine blade material as a replacement for aggregates, cement, and as an additive to mixtures. The properties of the resulting concrete composites show the potential of this solution. Each approach positively impacts the environment, as replacing raw materials reduces the demand for them, or when used as an additive, reduces the cement content per cubic meter and overall lowers the carbon footprint per cubic meter.

This review highlights the global significance of wind turbine blade waste management, pointing to the growing volume and projected increase. It also considers the legal restrictions related to composite waste management, which helps to fully elucidate the regulatory context of this issue. The literature analysis revealed different approaches by researchers to the use of elements, both whole and shredded, from wind turbine blades.

The final step was to present an innovative solution for using shredded wind turbine blades in cement composites. The originality of this approach lies in the unusual form of the elements added to the mix, which differ from the traditional cuboids, cubes, or fibrous materials described in the literature. The innovation also lies in studying the properties of cement mixtures, as previous research has mainly focused on their use in concrete mixtures.

Author Contributions: Conceptualization, M.D. and D.J.; methodology, M.D. and D.J.; validation, M.D. and D.J.; investigation, M.D. and D.J.; resources, M.D. and D.J.; data curation, M.D. and D.J.;

writing—original draft preparation, D.J.; writing—review and editing, M.D.; visualization, D.J.; supervision, M.D.; project administration, M.D.; funding acquisition, M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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