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Review

From Waste to Renewables: Challenges and Opportunities in Recycling Glass Fibre Composite Products from Wind Turbine Blades for Sustainable Cement Production

Sandra Bulińska [1,*], Agnieszka Sujak [1] and Michał Pyzalski [2]

[1] Department of Biosystems Engineering, Faculty of Environmental and Mechanical Engineering, Poznań University of Life Sciences, Wojska Polskiego 50, 60-627 Poznan, Poland; agnieszka.sujak@up.poznan.pl
[2] Faculty of Materials Science and Ceramics, AGH University of Krakow, Al. Mickiewicza 30, 30-059 Cracow, Poland; michal.pyzalski@agh.edu.pl
* Correspondence: sandra.bulinska@up.poznan.pl

Abstract: The progress of civilization, driven significantly by the widespread adoption of electricity, has impacted various aspects of life, from household operations to industrial activities. Consequently, there has been a notable increase in waste production across different sectors of the economy. Among used materials, composite products reinforced with glass fibres stand out due to their prevalent use in numerous industries. While offering strength and durability, they pose disposal challenges due to their complex composition, making recycling difficult and contributing to waste accumulation in landfills or to environmental contamination. Industrialised nations wrestle with balancing economic growth and environmental sustainability, aiming to reduce the ecological footprint of industrial activities. Efforts to promote recycling, develop alternative materials, and improve waste management practices are crucial for mitigating the environmental impact of civilisation's progress. This article presents methods of disposing of post-operation wind turbine blades, focusing on recycling glass and glass fibre as secondary raw materials. We discuss technological, normative, and economic challenges and emphasise the need for ongoing research and innovation in waste management practices. We examine the use of glass and glass fibres in cement production and advocate for sustainable principles in the renewable energy industry, aligning industrial endeavours with ecological sustainability for a greener future.

Keywords: wind turbine blades; post-operational waste; sustainability; waste treatment; special cement production

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1. Introduction

The development of civilisation is closely linked to the increase in energy consumption and the generation of waste in virtually all sectors of the economy. Industrially developed countries are characterised by a high level of polymer waste generation, among which we can distinguish fibre-reinforced composite products, which are formed by the destruction of materials in the process of their normal use. This waste has the highest global production due to its wide use in various areas of everyday life, such as sports equipment, construction, aerospace, and the automotive industry. Their popularity is due to their unique physical and chemical properties [1], which include high mechanical strength, lightweight [2], durability, and high flexibility. The above properties determine the use of composite materials as an alternative to steel [1]. Composites are everywhere in many areas of life; however, the aerospace and defence industries stand out for producing most of them. Another sector in which they are used is the renewable energy sector, particularly wind power [3]. On the one hand, intensifying global warming and, on the other, reducing negative environmental impacts and achieving zero greenhouse gas emissions in line with the principles of the European Green Deal [4] and maintaining energy security are directly linked to national political issues [5]. Waste management worldwide is a significant environmental problem, mainly in protecting the environment and mitigating the effects of climate change, which are exacerbated by inappropriate waste treatment [6]. Growing public awareness contributes to people's involvement in the fight against environmental threats.

European Union authorities are taking steps to manage waste effectively by introducing closed-loop systems and promoting resource efficiency through appropriate end-of-life management [7]. The management of waste generated by modern systems can be problematic due to the use of recent, innovative products that, until now, have not required end-of-life management; hence, no infrastructure has been developed to enable their proper recycling. One such product is wind turbines, specifically wind turbine blades, which become waste at the end of their life [8,9].

It is their management that is beginning to pose quite a challenge, due to the imminent end of the operation of the first wind turbines developed on the globe. The inadequate knowledge gathered to date adds to the interest in the creation of an appropriate infrastructure that will enable such a large amount of composite materials to be processed with appropriate environmental care. According to estimates made by the European Union, more than 500 Mt of glass-fibre-reinforced plastic (GFRP) waste and almost 20 Mt of carbon-fibre-reinforced thermosetting polybenzoxazine resin (CFRP) waste are expected to be generated between 2020 and 2030 [2,7]. Renewable electricity generation involves the generation of waste materials, such as glass and glass fibre from decommissioned turbine blades. The lack of efficient waste management systems and storage space can lead to environmental pollution. Processing this type of waste into secondary raw materials requires advanced recycling technologies. Some types of glass may contain chemicals or layers that can hinder the recycling process. It is therefore necessary to develop efficient separation and purification methods, as well as to study their physical, chemical, and mechanical properties and adapt production processes to ensure their quality.

Waste glass in the form of fibres and cullet from wind turbines can potentially be an additive used in Portland cement or aluminous cement. However, the use of these secondary raw materials requires the development of appropriate recycling technologies, an analysis of their technical properties, and a guarantee of their market acceptance and economic viability. Despite the potential environmental and technical benefits, the usage of waste glass and glass fibres from wind turbines as secondary raw materials may meet resistance from the construction industry and consumers. Also, the costs associated with the collection, segregation, processing, and distribution of secondary raw materials have to be balanced by the savings and environmental benefits of reduced consumption of natural resources and reduced CO_2 emissions.

Solving these problems requires collaboration between industry sectors, research institutions, regulatory authorities, and local communities to create a sustainable, closed-loop economy model that minimises waste and maximises the use of recyclable materials.

Managing wind turbine blade waste is important for various reasons, as listed below.

- Environmental protection: Effective management of wind turbine blade waste helps to reduce the negative impact on the environment. Avoiding uncontrolled disposal or improper waste treatment reduces the risk of soil, water, and air pollution.
- Sustainability: Proper waste management can help promote sustainable development by using technologies and strategies that minimise environmental impacts and promote the efficient use of resources.
- Innovation and technological development: The search for methods to effectively manage wind turbine blade waste stimulates innovation and technological development in the renewable energy and waste management industries.
- Economic benefits: Effective waste management can lead to identifying new business opportunities and creating new markets, which can bring economic benefits to wind turbine manufacturing and maintenance companies and companies specialising in recycling and waste treatment.

This review paper will describe the techniques used to date for the management and treatment of waste wind turbine blades as part of a sustainable development strategy, benefiting the environment, the economy, and society as a whole. Other ways of utilising waste wind turbine blades will be proposed.

In this review article, we focus on analysing the issue of recycling glass and glass fibre from wind turbines as secondary raw materials, discussing the technological, normative, and economic challenges associated with their efficient use. By identifying these challenges and providing perspectives on the way forward, this article aims to highlight the importance of further research and innovation in the field of waste management and to promote sustainable practices in the renewable energy industry.

2. Construction of Wind Turbine Blade vs. Recycling Possibilities

Wind turbine blades are the basic building block of a turbine and are the key part responsible for converting the kinetic energy of the wind into mechanical energy. Their construction depends on the turbine model, as each blade differs in its quantitative chemical composition. The literature data indicate that the average blade is composed of composite materials accounting for approximately 93%; 2% is separately made up of PVC and balsa wood, and the last 3% is metals, paint, and putty. The main components of the blade are the reinforcing fibres (glass (GF), carbon (CF), basalt or aramid (AF)), the polymer matrix (thermoplastic or thermosetting plastics, among which can be distinguished epoxies, polyesters, vinyl esters, polyurethane), and a layered core made of balsa wood or foam (polyvinyl chloride (PVC), polyethylene terephthalate (PET)). Coatings are often made of polyethylene (PE) or polyurethane (PUR). An important component of wind turbine blades is the metals from which the wires (copper) and the screws (iron in the form of steel) are made [9]. The composites used are made of inorganic fibres embedded in polymer matrices [10]. Most commonly, a thermosetting resin reinforced with fillers is used, among which calcium carbonate or aluminium trihydrate can be found accompanying glass or carbon fibres. It is this combination that makes it possible to obtain a reinforced propeller mould [11], otherwise known as glass-fibre-reinforced polymer (GFRP) or carbon-fibre-reinforced polymer (CFRP) [12].

Due to the use of multiple materials, wind turbine blade waste has a complex physicochemical composition [7]. Blades of different lengths require different designs and technologies, so they may have different relative contents of individual materials [3]. The design of wind turbine blades is difficult to describe unambiguously, as each manufacturer uses its own unique materials with different physicochemical compositions [12]. Two of the largest wind turbine manufacturers in Europe, Vestas and Siemens Gamesa Renewable Energy, use glass-fibre-reinforced polymer (GFRP) as the main material for rotor blade construction. However, Vestas uses a combination of glass and carbon fibre to reduce weight while maintaining high strength, allowing it to produce shorter blades without sacrificing power. The decrease in weight is due to the significantly different density of CFRP compared to GFRP [7]. The basic blade structure consists of an inner beam, leading edge, and trailing edge (Figure 1). The beam is constructed of unidirectional, biaxial laminates and polyvinyl chloride (PVC). Unidirectionality allows for bending moment, while biaxiality allows for shear load transfer. The trailing and leading edges are made up of biaxial and triaxial laminates bonded to balsa and PVC to create the correct external shape while maintaining the proper geometry and allowing the wind turbine blades to increase their shear load capacity [12].

According to Liu and Barlow (2017), each 1 kW of wind power requires 10 kg of blade material (10 kg/kW or 10 t/MW). The amount of material to be recycled between 2029 and 2033 is expected to be around 400,000 tonnes. Waste from wind power can be divided into production, service, and post-operational waste [8]. The production stage is generally fibre cuttings, composites, resin residues, etc. The service stage includes waste generation during the maintenance or replacement of turbine components. The end-of-life stage involves the greatest amount of waste, as wind turbines are dismantled in their entirety, including foundations and underground cables [8]. It is estimated that the global annual amount of waste will be 2 million tonnes by 2050, and the cumulative amount by 2050 will be more than 43 million tonnes. China will be the largest contributor to the waste generated, with about 40% of the total waste mass, followed by Europe (25%), which will be the earliest to face the problem of managing wind turbine blade waste [13].

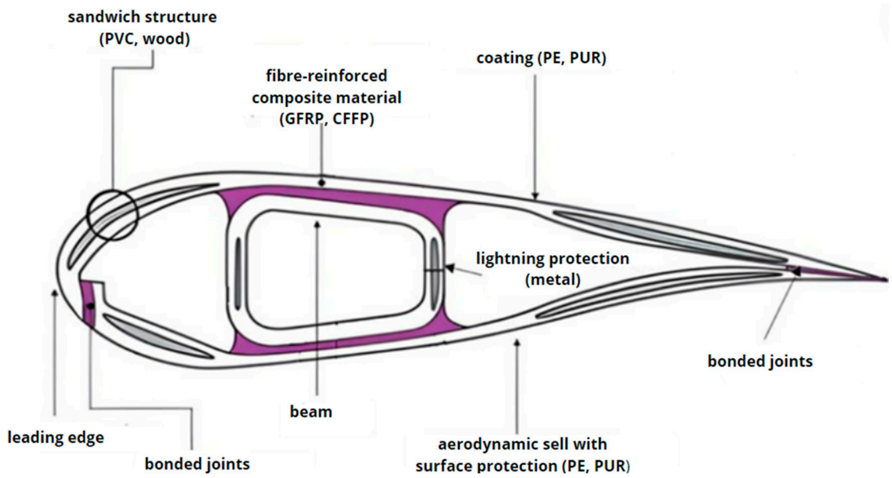

Figure 1. Construction of a wind turbine blade [11]; bonded joints in purple.

3. Possibility of Managing Tailings from Wind Turbine Blades

As wind turbine blades are a three-dimensional cross-linked structure of thermoset composites, it is impossible to melt the waste and re-mould it, as is the case with thermoplastic composites [14]. The different technical properties of fibres influence the need for appropriate treatment. Carbon fibres have electrical conductivity, as well as resistance to thermochemical processes, while glass fibres have a low melting point [7,15]. Composite waste treatment technologies are mainly thermal, mechanical, chemical, electrical, biotechnological and electrochemical processes [14], landfilling, incineration with heat recovery, mechanical recycling, fluidised bed recycling and pyrolytic recycling processes [12], co-processing in cement kilns, furniture manufacturing and bridge manufacturing [16], and diversion [13]. Due to the rapidly growing wind energy industry, the number of end-of-life wind turbine blades is expected to increase significantly, so a systematic process for identifying and managing end-of-life waste from wind turbines needs to be developed [17]. This is primarily due to increasingly rigorous European Union directives, which indicate high anticipation of moving to carbon neutrality by 2050 due to the current handling of this waste [18]. Due to the size of wind turbine blade waste, it needs to be pre-shredded before most of the available methods can be applied, to fit into the machines or chambers used for recycling [14]. Among the available methods for the treatment of European wind turbine blade waste, the following can be distinguished in order of hierarchy:

- disposal by landfill or incineration without energy recovery;
- recovery, the key end product of which is fuel, heat, and energy;
- recycling, which aims to transform waste into new substances or products;
- the reuse of an existing part for a different application;
- the reuse of remanufactured components;
- prevention, which aims to minimise the use of materials during design and production and to ensure the least possible amount of waste after use [19].

According to the waste hierarchy (Figure 2), published by the National Climate Change Centre, focusing on reducing waste generation, the higher we place activity in the hierarchy, the greater the positive impact it has on the environment, as well as on human life and health. Within this hierarchy are several key categories such as waste prevention, reuse, recycling (which includes repurposing), resource recovery, and disposal.

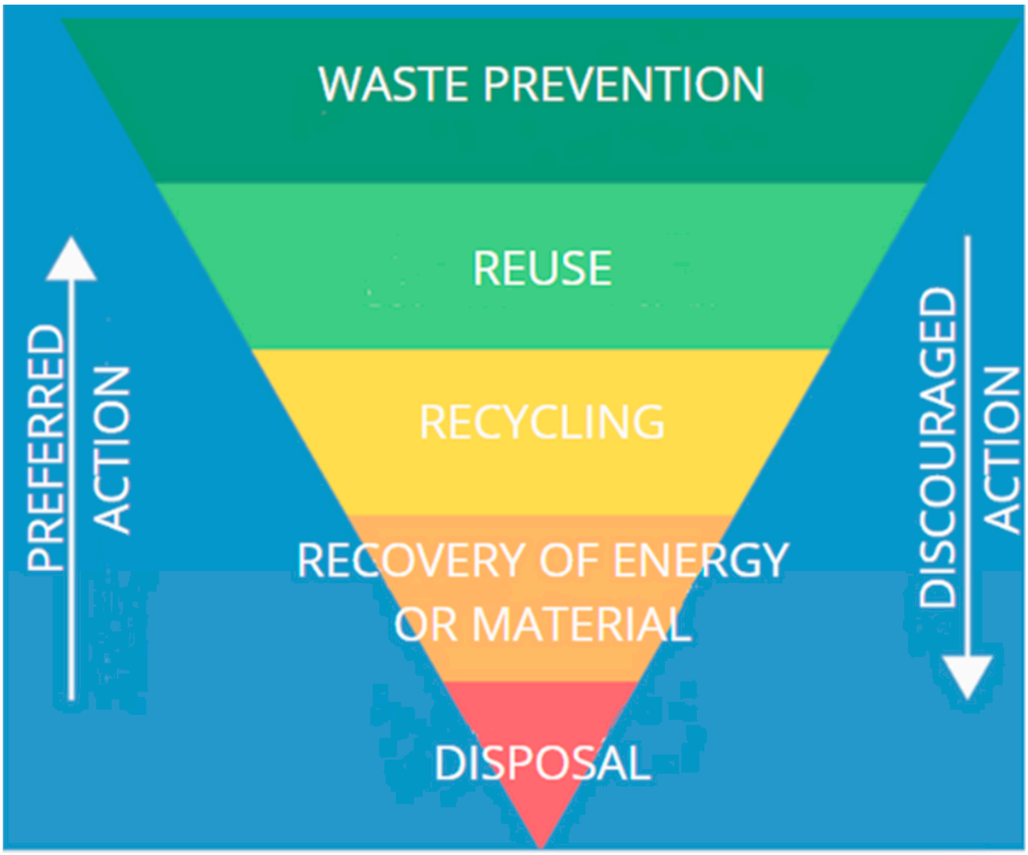

Figure 2. CLE pyramid (closed-loop economy) according to the National Climate Change Centre [20].

To optimise the disposal of wind energy waste, processes must be managed efficiently while considering technical progress, legal regulations, and environmental and economic aspects, which depend on the amount, location, and direction of the waste stream generated along with the flow of materials. Due to the complexity of the processing of waste containing composite materials, it is important to establish responsibility and co-operation of supply from production through collection to disposal [21].

4. Strategies and Treatment Methods for Wind Turbine Waste

4.1. Waste Prevention

To prevent wind turbine blade waste and meet European Union restrictions, so-called 'eco-design' should be used to help minimise the amount [22]. In an attempt to reduce the huge amount of planned waste from the wind energy sector, a waste prevention initiative has been launched from the design and construction stage of wind turbines. Eco-design initiatives involve replacing traditional materials, which represent a huge disposal project, with materials of biological origin that are biodegradable, which translate into a streamlined and easier recycling process. Among biobased materials, polymer composites containing a single natural component can be distinguished and are divided into biobased polymers and petrochemical polymers.

There have already been first studies of biocomponents made of hemp fibre with vinyl ester, flax with polyester or epoxy resin, bamboo fibre with epoxy resin, or wood with epoxy resin [23,24]. In addition to the examples indicated, researchers are exploring a variety of other materials for use in turbine blade construction. One promising approach is basalt fibres, which have similar mechanical properties to carbon fibres. Basalt is a volcanic rock with a chemical composition similar to silver and is the natural raw material for the production of these fibres. Its chemical composition is mainly composed of silica and aluminium, supplemented by numerous other oxides (CaO, Fe_2O_3, MgO, K_2O, Na_2O, and TiO_2), whose proportion depends on the geographical location of extraction. The production of the fibres is comparable to that of glass fibres. Volcanic rocks in a fused state (1500 °C–1700 °C) are extruded using filters.

However, unlike glass fibres, the production of basalt fibres uses less energy and requires no additives. Basalt fibres exhibit mechanical properties similar to E-type carbon fibre. They are also characterised by good thermal and chemical stability. As a result, basalt fibres offer an alternative to glass fibres. They can be used for organic (thermoplastic or thermosetting), metallic, and ceramic matrix composites. During the fibre manufacturing process, one of the organic layers, called 'ensimage', is placed on the surface of the fibre to facilitate handling and cutting operations. Located at the level of the fibre/matrix interface, this layer plays an important role in the mechanics of the composite material. Its presence can lead to a weakening of the interface and a reduction in the mechanical properties of the composite. Therefore, if it is not compatible with the composite material, a destructive process (chemical or thermal) may be carried out during the manufacturing phase of the composite [25].

4.2. Reuse

Wind turbines pose a major challenge when it comes to managing post-operational waste due to the limited potential for re-use. More than 85% of the entire turbine can be properly recycled or reused in another sector. From the perspective of the technology of many appliances, including wind turbines, their reuse by remanufacturing components is not attractive as there is a continuous performance improvement, which affects the limited demand for older remanufactured wind turbines. It is the limited options for remanufacturing that influence the recycling, recovery, and disposal of blades to become very important and necessary to maintain adequate environmental protection. While the recycling of towers and foundations is not a problem, rotor blades, due to the technology used, present a challenge that is difficult to tackle and research on the subject is still being conducted [7].

Decommissioned wind turbines can be reused in new facilities such as wind farms, demonstration projects, and training installations. There are several companies involved in the decommissioning and resale of end-of-life wind turbines. Blades can also be repaired, repainted, and balanced. Re-use seems technically and economically affordable for older generations of wind turbine blades, which are relatively small and may have a significant remaining lifespan. However, for larger and newer wind turbine blades, transportation can be challenging and costly. The design of newer blades is based on design expertise that allows for material savings and improved design life.

This leads to a reduced remaining service life, which may prevent them from being reused. Developing methods to assess the damage condition and determine the remaining life of wind turbine blades at the end of their life can enable more blades to be safely reused. The reuse of end-of-life wind turbine blades reduces the overall environmental impact of the wind turbine throughout its life cycle, as it reduces the amount of newly manufactured turbine blades or fragments of other alternative sources of electricity generation. The low level of reprocessing associated with such a solution and the value of the blade make such a reuse system economically attractive. On the other hand, reuse may not be possible in all cases due to the damaged condition of the blade, the demand for a given blade model in the aftermarket, or the dimensions of the blade. To help estimate and track the number of decommissioned and reused wind turbine blades, it is necessary to assess the market for second-generation wind turbine components [26].

4.3. Recycling

As the useful life ends and the wind industry improves year on year, wind turbine owners face the challenge of wind turbine disposal. Most materials can be recycled without too much trouble in the traditional way, although blades built from composite materials pose major problems for the world as they cannot be recycled through traditional management methods [27]. Recycling, in its broadest sense, is the process by which end-of-life material is processed in order to put some of its components back into circulation. Among the available techniques for dealing with polymer composites, we distinguish between chemical, mechanical, and thermal recycling processes.

4.3.1. Mechanical Recycling

Mechanical recycling can start as early as the dismantling stage of wind turbines to reduce waste transportation costs by reducing the size of dismantled blade pieces [28].

A distinction can be made between the following:

- Water jet cutter—a method using high-pressure water or a mixture of water and abrasive substances. This cutting is characterised by low emissions of dust into the atmosphere; however, it requires high water consumption.
- Wire saw—a steel wire with diamond teeth that is continuously cooled by water is used for cutting. The process is time-consuming but reasonably environmentally friendly due to low dust and noise emissions. The only limitation of this method is the length of the steel wire.
- Circular saw—a method using manual or hydraulically driven diamond circular saws, which can be up to 2 metres in diameter. The big advantage of this is that cuts can be made in all directions, making it possible to separate the laminates from the wood. However, this increases the amount of dust generated.
- Jaw cutter—a hydraulically driven jaw cutter, which is the most common method of cutting blades. This method requires the use of water mist, due to the possibility of crushing the material as it is cut [9,29].

4.3.2. Chemical Recycling

Chemical methods are used to degrade the composite matrix, and each has a different way of achieving the bond breakage occurring in composites. They are based on the application of higher temperatures and pressures and the use of solvents including water, alcohol, or acid, which results in the breaking of bonds between the matrix. Electrochemistry takes place using an electric current that is passed through an electrolyte. In contrast, biotechnological treatment of waste involves the use of microorganisms to degrade polymer matrices.

To recover fibres and resin or liquid chemicals from composite materials using chemical processes, chemicals, heat, and pressure must be used to dissolve the material matrix. The process temperature is lower than for thermal recycling, which has the positive effect of not forming charred layers on the recovered fibres. However, it must be remembered that this method of recycling is very expensive, which contributes to the low popularity of this process.

As with thermal recycling, glass fibres recovered by solvolysis show reduced mechanical properties, mainly strength. The reuse of recovered glass fibres is unsatisfactory due to their poor properties and high cost compared to their original counterpart. The applications of the recovered resin are not very clear; for some types of resin, it is possible to reuse it as a matrix material, while this seems to be more difficult for other resin systems. Currently, there are no commercial applications of solvolysis processes for decommissioned wind turbine blades, and scaling up the process to an industrial scale to treat fibre-reinforced polymer composites has not yet been carried out.

The advantages of chemical recycling include the ability to recover pure glass fibres and, to some extent, matrix material in liquid form. The challenge remains the quality of the recovered materials. As with thermal recycling, recovered glass fibres are brittle and have lower mechanical properties compared to their original counterparts, limiting their applications. Chemical recycling also requires a reduction in the size of wind turbine blades so that they can be introduced into the recycling process. The use of chemical solvents, which can be expensive and lead to toxicity issues in the event of occupational exposure and/or release to the environment, and the difficulty of recycling them remain issues to overcome.

Therefore, due to the required process temperatures and pressures, the use of solvents, and the low quality of recovered glass fibres, chemical recycling is currently not economically viable for glass-fibre-reinforced thermoset plastics [30]. This method is used to chemically depolymerise, using a solvent composed of catalysts, the cross-linked bonds present in thermoset materials. After such recovery, the resulting fibres can be used to build BMW bodies, and the recyclates are used as a filler or a method to reinforce new composites [31].

Solvolysis is a chemical process in which a solvent breaks down resins, i.e., epoxy and polyester used in plastics thermosetting plastics. It can be carried out at different temperatures and with different solvents but usually does not require high temperatures like pyrolysis. The temperature and pressure of solvolysis depend on the catalyst, with the addition of potassium hydroxide reducing the temperature and pressure [30].

4.3.3. Thermal Recycling

The aim of thermal recycling is to subject materials to thermal treatment to separate fibres from the matrix, thus enabling the recovery of fibres, some oil fractions, and energy, for example, from waste incineration. However, it is important to note that recycling does not involve energy recovery or the use of waste as an energy carrier. Therefore, for wind turbine blade recycling, methods such as pyrolysis, fluidised bed pyrolysis, and microwave pyrolysis are employed. Pyrolysis has been used for many years in the processing of biomass, solid municipal waste, tires, and carbonaceous materials, including coal and wood, to recover energy and valuable compounds. It is considered a thermal decomposition method for polymer materials under anaerobic conditions and high temperatures [31]. Successful attempts have been made to process composite waste containing carbon fibres, from which not only energy but also useful carbon fibres have been recovered for reuse. Subjecting waste to the pyrolytic process causes composites to undergo thermal degradation and transform into three different forms: oil fraction, gas fraction, which can be used as an alternative fuel and chemical raw material, and solid residue fraction [32].

One way to recover carbon and glass fibres from wind turbines is semi-batch pyrolysis, which allows for the preservation of the mechanical properties of fibres obtained from recovery compared to primary fibres. In the literature, among many methods of reusing recovered carbon fibres, one can find compression moulding and vacuum moulding. However, fibre recovery is not promising for producing new blades because the bonds between secondary fibres and resin are much weaker than those of primary fibres [31]. Another method is fluidised bed pyrolysis, which involves passing a reduced-size composite through a bed of quartz sand with a stream of hot air. This method allows for easy and rapid heating of the composite material, facilitating the release of fibres by wearing down the resin [31]. Another method for traditional pyrolysis is microwave pyrolysis, which has so far been limited to plastic waste. This method relies on heating the material using microwave radiation, resulting in moderate temperatures, thus preventing the thermal decomposition of the glass fibre [33].

The use of different pyrolysis methods has had a positive effect on the recycling efficiency of many types of resins used in wind turbine blades, which include unsaturated polyester and epoxy resin, through thermal treatment. Due to the use of styrene as the main chemical compound of the unsaturated polyester fraction, many wind turbine blade manufacturers continue to use this type of resin [34].

4.3.4. High-Voltage Fragmentation (HVF)

A high-voltage electrical pulse method of up to 200 kV can be used to disintegrate wind turbine blade materials by immersing a blade fragment in water between electrodes that discharge their electrical potential between each other, creating a high-pressure shock wave along the plasma channels that break down the material [28]. HVF uses repeated pulsed electrical discharges in a dielectric liquid medium, usually water, to disintegrate a solid material. Pulses are discharged in a very short time between two electrodes. The solid material is held in the gap between the electrodes. When using high voltages (100–200 kV) with a pulse rise time of less than 500 ns, the breakdown strength of solid materials is lower than that of water. The discharge creates a spark channel that travels between the internal boundaries of the material and weak areas such as external interfaces and pre-existing cracks. The spark channel generates an intense shockwave with high pressure (approximately 10^9–10^{10} Pa) and temperature (above 10^4 K), inducing internal mechanical stresses that exceed the tensile strength of solid materials. Ultimately, this leads to material disintegration. It can be observed that recycled materials recovered using a small number of impulses (500 and 1000) contain poorly separated parts. A higher number of impulses allows for material processing with greater energy, thereby releasing a larger amount of material. Recycled materials from mechanical recycling take the form of short fibres, flakes, and powdered fractions. The main power source for mechanical and HVF methods is direct electrical energy [14].

4.3.5. Change in Application

When extending the lifespan of wind turbines is not feasible, and if the turbine blades have not been significantly damaged by extreme weather conditions during operation, they can be refurbished and repurposed as replacement parts for other types of turbines that have not reached the end of their service life. Due to decreasing demand for used wind turbine components, an alternative has emerged for turbine blades, enabling the utilisation of such specific waste as amenities in urban settings, in the leisure and recreation sector, such as benches and playground equipment [28], bus shelters in architecture, outdoor and indoor furniture, and building materials. However, due to their exceptional weather-resistant properties, they are also used in furniture production, roofing, windows and doors, road infrastructure including bridge structures, and acoustic materials [16] and can be used to manufacture beams or sound-absorbing panels. Unfortunately, giving a second life to such waste is still not as popular as landfilling, which requires practically no energy input. Examples of wind turbine blade applications are shown in Figure 3.

Figure 3. Practical use of blades in the Wikado playground and as public benches REwind Willemsplein [9].

4.4. Recovery of Energy or Material

4.4.1. Incineration

During the thermal treatment process in the form of incineration, there is the generation of heat and electricity, which allows the energy contained in the waste to be recovered. The recovered heat allows for a certain positive environmental impact, as 10 tons of thermally treated composite waste can generate the same heat as 6 tons of coal. However, there is still the storage of ash generated as a by-product of combustion [16]. For the material to be burned, it has to be prepared and cut into smaller fragments, which are placed in furnaces at 800 degrees Celsius. The organic matter is burned and converted into non-flammable material, flue gases, electricity, and heat. The resulting ash can be used as an aggregate substrate in other applications or stored.

4.4.2. Co-Processing in Cement Kiln

Waste from wind turbine blades can be used in cement kilns to produce cement. This involves adding composite waste, replacing the original raw material, to other raw materials used in cement kilns [16,35] According to Nagle, Delaney, Bank, and Leahy (2020), carbon polymer replaces fuel, while glass fibres can replace some of the raw materials found in cement (lime, iron oxide). To be able to use waste wind turbine blades in cement kilns, they need to be shredded into smaller pieces and mixed with fuel, which is a mixture of dry secondary raw materials (SRF). To make full use of the blades, its polymer part is best used as a fuel to raise the temperature. At a temperature of about 1450 °C, calcium carbonate and glass fibre aluminium borosilicate are calcified, and these compounds are converted into alumina, silica, and calcium oxide, which are the main components of Portland cement [19]. The shovels can be destined for thermal combustion in cement. The latest solution is mechanically processed fibres for concrete [36]. Currently, this is one method that allows 100% of composite waste to be recovered in the form of energy (about 33% used as a substitute for fossil fuels) and raw materials, resulting in the recovery of mineral material of about 67%, which is integrated into the clinker [37].

4.4.3. Fused Filament Fabrication

To recover reinforced fibres for modelling and 3D printing, mechanical grinding must be integrated with mechanical screening. With this method, a scheme combining the recycling of used wind turbine blades and 3D printing has been developed. Their properties make it possible to obtain strong and rigid raw materials for additive manufacturing [38].

4.5. Disposal—Landfilling

Among the many methods of waste disposal, landfilling is at the bottom of the hierarchy according to the EU Waste Directive. It is one of the methods allowing for the rapid disposal of the resulting wind turbine blade waste; however, landfilling is prohibited in Germany, Finland, and Austria. It is anticipated that other EU countries will also be required to use another method of waste disposal, which is very challenging today [16]. Landfilling involves dividing the shovels into pieces of appropriate size and placing them in the nearest landfill. This method of waste disposal prevents the recovery of material, heat, and electricity.

5. Economic Costs of Wind Turbine Blade Disposal

The costs associated with the management of wind turbine blade waste are not clearly defined, as it all depends on the recycling method chosen, the size of the blades, the logistics of transportation, the labour costs of the workers, and the regulations in the country concerned. Presently, the most eco-efficient solution is to dispose of this waste by landfilling or incineration, and the barrier to recycling is the lack of financial justification due to high operating costs and the lack of a proper treatment scheme and a designated recycling site and method [21].

To compare, the costs associated with the energy-intensive production of carbon fibre are 198–595 MJ/kg, versus the recovery of carbon fibre, the cost of which is approximately 15% of the price of virgin fibre and can be around USD 5/kg [5]. According to [22], disposal costs by landfill or incineration will range from USD 150 to USD 200 per tonne, while recycling costs depend on the technology used: mechanical from USD 500 to USD 1000 per tonne and chemical, or pyrolysis, which can be more expensive, from USD 1000 to USD 3000 per tonne [22].

Given the EU's strong focus on sustainability and innovation, sponsoring turbine blade disposal is a logical step. It aligns with the EU's environmental goals and could drive advancements in recycling technologies, supporting the circular economy and creating economic opportunities. However, this initiative should be part of a broader strategy that includes funding for R&D, fostering public–private partnerships, and ensuring effective regulatory frameworks across member states.

By taking a proactive stance, the EU can mitigate the environmental impact of turbine blade disposal while positioning itself as a leader in sustainable energy solutions.

Turbine blade shredding is a complex and specialised process due to the materials used in the blades and their unique shapes and sizes. Often made of superalloys, titanium, or composite materials, blades are designed to withstand extreme conditions, making their disposal or recycling a challenge. Available turbine blade shredding techniques include mechanical shredding, cryogenic shredding, plasma arc cutting, and water jet cutting [4,39].

5.1. Mechanical Shredding

This method involves the use of high-powered industrial shredders equipped with robust cutting mechanisms to break turbine blades into smaller, easier-to-handle pieces. The blades are fed into the shredder, which uses rotating blades or hammers to cut, tear, and shred the material. Industrial shredders such as scissor shredders, hammer mills, and granulators are commonly used. This technique wears out equipment a lot due to the hardness of the blade materials. Initial investment costs range from USD 50,000 to more than USD 500,000 for industrial shredders, while operating costs range from USD 100 to 500 per ton, including maintenance and wear parts.

5.2. Cryogenic Shredding

The technique involves freezing wind turbine blades with liquid nitrogen to make them brittle and easier to break. Once frozen, the blades are fed into a shredder or crusher [4]. Due to high operating costs, this is not a popular technique; the price depends on the use of liquid nitrogen and is USD 500 to USD 1500 per ton, including liquid nitrogen and maintenance. The cryogenic crushing plant itself costs about USD 200,000 to more than USD 1,000,000 for cryogenic systems and crushers.

5.3. Plasma Arc Cutting

It uses a plasma torch to precisely cut wind turbine blades. The plasma arc melts and cuts metal, which can then be further processed. It is classified as a slow technique that generates dangerous fumes and requires proper ventilation [40]. The price of plasma cutting machines ranges from USD 10,000 to over USD 100,000, with operating costs of USD 50–300 per hour of operation, depending on the energy consumption and consumables.

5.4. Water Jet Cutting

High-pressure water jets, often mixed with abrasive materials, are used to cut turbine blades, the high-velocity jet eroding the material. A major advantage is the lack of heat generation, thus avoiding warping of the material [41]. However, it is a slow process with a high financial overhead of USD 15–50 per hour of operation, plus the cost of water, electricity, and abrasives. The purchase of machinery ranges from USD 50,000 to over USD 400,000.

5.5. Other Methods of Mechanical Waste Management

Using mechanical recycling techniques provides various options for recycling and repurposing waste wind turbine blades. The choice of the appropriate technique mainly depends on factors such as the type of material, the desired end product, operational scale, and cost considerations. Each method has its advantages and trade-offs, and often a combination of techniques is used to achieve the most efficient and sustainable results. Beyond shredding, there are several other mechanical utilisation techniques for turbine blades, particularly for recycling and repurposing. These methods aim to maximise the value of the materials and components extracted from used or end-of-life turbine blades [4].

5.5.1. Laser Cutting and Ablation

This technique uses concentrated laser beams to cut or ablate material from turbine blades, which are directed at the blades to vaporise or melt the material. This allows precision cutting, especially for complex shapes and hard materials such as blades and allows high precision with minimal mechanical stress [42]. However, operating a bush cutter requires skilled operators and great precautions, which also requires a financial outlay. Costs can vary widely depending on the equipment, scale of operation, and specific material requirements. The purchase of suitable machinery alone is hugely expensive, ranging from tens of thousands to several million dollars, depending on the complexity and scale of the machinery. Operating costs vary according to energy consumption, consumables (such as abrasives or chemicals), labour, and maintenance.

5.5.2. Crushing and Pulverising

This involves the use of mechanical crushers and pulverisers to break turbine blades into coarse and fine particles. The blades are fed into crushing machines, which apply a compressive force to break and pulverise the material. This technique makes it possible to prepare the material for further recycling processes or direct use in production. The main disadvantage of this solution is the generation of noise and dust.

5.5.3. Milling and Grinding

This technique involves using milling and grinding machines to break down by grinding and crushing turbine blades into fine particles or powders. The resulting powders can be used for a variety of industrial applications, including as raw material for new alloys or as additives in other manufacturing processes. The technique produces fine particles that can be easily handled and recycled, although it may require multiple processing steps to achieve the desired particle size.

5.5.4. Chemical Milling

The technique uses chemical solutions to selectively remove material from blades by immersing them in a chemical bath, effectively reducing them to smaller, easier-to-machine pieces. It is used to prepare material for further machining or to recover valuable components. It allows precise, controlled removal of material while working with hazardous chemicals, generating chemical waste.

5.5.5. Electrochemical Machining (ECM)

This is categorised as a non-traditional machining process that removes material from blades by electrochemical dissolution using an electrolytic solution and electric current. It is used in particular to remove hard materials and blades with complex geometries while maintaining high precision and ensuring no thermal or mechanical stresses.

6. Secondary Processing of Binding Materials

6.1. Characteristics of Portland and Aluminate Cements

Cement is a finely ground inorganic material that, when mixed with water, forms a plastic paste, then undergoes highly complex hydration processes (setting and hardening), resulting in a loss of plasticity and increasing strength. Cement is a hydraulic binder, meaning it hardens and does not lose strength when stored in water [43–48].

6.1.1. Portland Cements

The invention of Portland cement is credited to Joseph Aspdin, who obtained a patent for its production in 1824. The name comes from the colour of the resulting cement, which resembled the colour of rocks found in Portland, England. In Poland, Portland cement was first produced at the Grodziec cement plant near Będzin as early as 1857 [43,44].

The main component of Portland cement is Portland clinker. It is obtained by calcining, at a temperature of about 1450 °C, a properly prepared raw material mixture rich in CaO, SiO_2, Al_2O_3, and Fe_2O_3. It typically consists of a mixture of grayish-green porous granules ranging in diameter from a few to several tens of millimetres. After cooling, the clinker is ground along with a certain amount of dihydrate gypsum ($CaSO_4 \cdot 2H_2O$) into a fine powder, resulting in the final product in the form of cement [43–49]. The typical quantitative mineral composition of Portland clinker expressed as a percentage is shown in Table 1.

Table 1. Typical quantitative mineral composition of Portland clinker (weight %).

Phase Composition	Weight %
C_3S	58
β-C_2S	22
C_4AF	10
C_3A	9
CaO and MgO	4

The basic components of Portland clinker are four minerals, which are also responsible for the binding properties of cement:

- Alite—Tricalcium silicate—C_3S;
- Belite—Dicalcium silicate—β-C_2S;
- Tricalcium aluminate—C_3A;
- Brownmillerite—C_4AF.

The silicates present in clinker, and thus in cement, are not pure compounds but contain several impurities, with which they form solid solutions. These impurities have a significant impact on the hydraulic properties of the silicates.

Portland cements are typically produced by three technological methods:

- Dry method (the grinding and homogenisation of raw materials occur after drying);
- Semi-dry method;
- Wet method (the grinding and homogenisation of raw materials occur in a water suspension).

However, due to economic factors, the most commonly used method of cement production at present is the dry method. The chemical composition of typical Portland cements is shown in Table 2.

In addition to Portland clinker, cement may also contain the following:

- Calcium sulfate—added to cement to regulate setting time;
- Minor components—specifically selected inorganic materials, the proportion of which does not exceed 5% of the total composition;
- Additives—used to improve manufacturing or cement properties. The total amount of additives should not exceed 1% [50,51].

Table 2. Chemical composition of typical Portland cements [52].

Oxides Content	Weight %
CaO	62–68
SiO_2	18–25
Al_2O_3	4.0–8
Fe_2O_3	2.0–4
MgO	0.5–4
SO_3	0.5–4
Roasting losses	<5

6.1.2. Aluminate Cements

Aluminate cement is a rapidly hardening, hydraulic binding agent obtained by grinding aluminate clinker, obtained by melting or sintering a properly prepared raw material mixture. The composition of the raw meal should be chosen so that high-basic calcium aluminate dominates the finished product. These cements belong to high-strength binders, characterised by very rapid initial strength growth dynamics. Already after several hours, they achieve strengths enabling their use. A significant advantage of these cements is also their resistance to high temperatures and high frost resistance. They also exhibit satisfactory durability in waters rich in various mineral salts. They are relatively resistant to weak acids, waters rich in CO_2, and industrial wastewater. The disadvantage of these cements is their weak resistance to alkaline solutions.

Aluminate cement was first produced in France. Currently, the main producers of these cements are the USA, France, the United Kingdom, Germany, and Japan. Significant quantities of aluminate cement are also produced in Hungary [44,45]. Aluminate cement with elevated iron content deserves special attention, as the available technical literature has not yet clearly explained the influence of iron on hydration processes and, consequently, on the properties of the produced cement.

The primary components commonly used in the raw material mixture for the production of aluminate cement are high-grade limestone and bauxite. The suitability of bauxite depends on the SiO_2 content in the clinker, which should not exceed 6%, and in exceptional cases, 8%. Generally, bauxites are used where the SiO_2 content, calculated on an ignited substance basis, does not exceed 5%. The Fe_2O_3 content in smelted cement can be high, and therefore, bauxites with Fe_2O_3 content up to 30% are used in the technology. The main component of bauxites is aluminium hydroxide, occurring in the form of hydrargillite $Al(OH)_3$, boehmite, or diaspore AlOOH. Bauxites also contain iron compounds (oxides, hydroxides, silicates), silica, titanium compounds, as well as certain amounts of calcite and dolomite. Trace compounds include sulfur, phosphorus, sodium, and potassium compounds. Meanwhile, limestone, which is a much cheaper raw material, should be distinguished by high purity. The limestones used typically contain more than 50% CaO, and the SiO_2 content should not exceed 1.5%, while MgO should be limited to 1% [45,53].

The chemical composition of "classic" aluminate cement varies widely and depends mainly on the production method and the purposes the produced cement is intended to fulfil (Table 3) [54].

Table 3. Chemical composition and phase composition of aluminate cements.

Oxides	Weight %	Phase Composition	Weight %
Al_2O_3	35 ÷ 70	CA_2	25 ÷36
CaO	30 ÷ 45	CA	30 ÷ 65
SiO_2	5 ÷ 10	$C_{12}A_7$	1 ÷ 5
Fe_2O_3 + FeO	5 ÷ 15	C_2AS	2 ÷ 15
MgO	0.5 ÷ 2	C_2S	<10
TiO_2	0.5 ÷ 2	-	-
SO_3	<1	-	-
$Na_2O + K_2O$	1	-	-

The phase composition of aluminate cements can be assessed based on their ternary system CaO-Fe_2O_3-SiO_2. The primary component of most aluminate cements is monocalcium aluminate $CaO{\cdot}Al_2O_3$ (CA). Furthermore, these cements contain $CaO{\cdot}2Al_2O_3$ (CA_2), $12CaO{\cdot}7Al_2O_3$ ($C_{12}A_7$), gehlenite $2CaO{\cdot}Al_2O_3{\cdot}SiO_2$ (C_2AS), and β- $2CaO{\cdot}SiO_2$ (β-C_2S), solid solutions from the series $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$—$2CaO{\cdot}Fe_2O_3$ (C_4AF-C_2F) which also include Fe^{2+} ions, Fe_3O_4, $6CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3{\cdot}SiO_2$ (C_6AFS), as well as periclase MgO and $6CaO{\cdot}4Al_2O_3{\cdot}MgO{\cdot}SiO_2$ (C_6A_4MS). The titanium present in the raw material blend incorporates into phase structures, typically substituting silicon Si^{4+} ions [55]. In the case of cements with elevated iron content, the ternary system CaO–Fe_2O_3–Fe_2O_3 plays a significant role.

In this system, the series of solid solutions stretching from C_2F to 6CaO·2Al_2O_3·Fe_2O_3 (C_6A_2F). (C_6A_2F) are of the highest importance. These are solid solutions of 2CaO·Fe_2O_3 (C_2F) with a hypothetical 2CaO·Al_2O_3 („C_2A”). The composition of the alumina-ferritic phase in such cement mainly depends on the alumina modulus. For high values (2.2 to 2.3), it approximates 6CaO·2Al_2O_3·Fe_2O_3 (C_6A_2F); for medium values, it corresponds to 4CaO·Al_2O_3·Fe_2O_3 (C_4AF), and for low values (Al_2O_3/Fe_2O_3 < 1), it approaches 6CaO·2Al_2O_3·Fe_2O_3 (C_6AF_2). Solid solutions from the series 2CaO·Fe_2O_3 (C_2F)—2CaO·Al_2O_3 („C_2A are stable up to 70 mol% “C_2A”.

The ferritic phase in equilibrium with the solid solution Fe_2O_3 in 3CaO·Al_2O_3 (C_3A) and CaO contains ns 48 mol% “C_2A”, thus having a composition close to 4CaO·Al_2O_3·Fe_2O_3 (C_4AF) [56]. The phase composition of “classic” aluminate cement is highly variable and depends mainly on the chemical composition, with iron playing a significant role, as well as on the kiln atmosphere—oxidising (rotary kilns) or reducing (large kilns and “L” type kilns)—and therefore on the ratio of Fe^{2+}/Fe^{3+}. The content of individual phase components varies widely [56].

Additionally, small amounts of corundum (from a few to several percent) are sometimes introduced during the grinding of clinker to cement, as well as certain amounts of sulfides, especially in the production in blast furnaces. Due to their adverse effects, the presence of these sulfides is undesirable. Another undesirable component in cement is alkalis, which typically occur in raw materials, with concentrations ranging from 0.1 to 0.3%, usually concentrating in the glassy phase.

Considering the phase composition, aluminium cements can be divided into three basic groups:

- Ordinary cement, mainly containing CA (up to 60%), $C_{12}A_7$, C_4AF, and small amounts of C_2AS, C_2S, and wustite;
- White cement, mainly containing CA and in smaller amounts CA_2 and α-Al_2O_3;
- Iron-rich cements, containing significant amounts of iron-bearing phases such as $C_xA_yF_z$.

Cements belonging to the first group are characterised by a high mechanical strength and short setting time. On the other hand, white cement, with low impurities, primarily iron oxides and silica, is known for its high refractoriness and is mainly used in the production of special refractory concretes. The third group of cement exhibits lower refractoriness and reduced heat of hydration. Due to their high iron content, these cements show higher resistance to aggressive environments. Aluminum cement are produced by melting or sintering a mixture of limestone with bauxite or aluminum hydroxide, as well as with other additives, depending on the allowable level of impurities in the product. With a high content of Fe_2O_3, sintering becomes very difficult, so the most common method for producing aluminum cement worldwide is melting. In the melting method, various types of electric arc furnaces, “L” type furnaces, rotary kilns, and others are used, allowing temperatures to reach approximately 1400 °C to 1700 °C [43,45,48]. The melting temperature of the raw material mixture depends on the content of SiO_2, Fe_2O_3, Al_2O_3, and CaO. The higher the content of SiO_2 and Fe_2O_3, the lower the melting temperature. Conversely, increased Al_2O_3 and CaO content leads to an increase in the melting temperature of the raw material charge.

In the sintering method, aluminum clinker is fired in rotary or shaft kilns at temperatures ranging from 1300 to 1600 °C. The raw material mixture can be prepared either wet or dry. Mainly, high-purity bauxites and limestone containing small amounts of MgO, SiO_2, and Fe_2O_3 are used as raw materials. However, maintaining the appropriate temperature poses some challenges. The difference between the sintering and melting temperatures of the mixture often does not exceed 100 °C; therefore, even a slight temperature exceedance can lead to kiln fouling.

Aluminate cements are high-strength binders. Mortars and concretes obtained from them exhibit very rapid initial strength development. Already after several hours from mixing with water, they achieve strengths allowing for their use. After 1 day of hardening, they reach 80–90% of their 3-day strengths, which range from 30 to 70 MPa [43,45,48]. The brand of aluminate cement provides the strength of the prepared mortar after 3 days, not after 28 days as in the case of Portland cement. The strength of aluminate cements increases with the increase in CA content and the decrease in the content of silicate and ferrite admixtures.

The setting time of mortars made with aluminate cements is shorter than that of mortars made with Portland cements and usually does not exceed half an hour. Therefore, aluminate cements belong to the category of slow-setting cements but quick-hardening ones. The slow setting is caused by the formation of AH_3 gel, which likely reduces the rate of ion diffusion in the solid phase, and the addition of CH, leading to the formation of hexagonal aluminates, significantly shortens this period.

Due to the high heat of hydration (usually above 300 kJ/kg after the first day of hydration), aluminate cements are commonly used for work performed in winter conditions. However, excessive heating of the mixture negatively affects its strength.

Aluminate cements are characterised by high resistance to high temperatures and high frost resistance. They also exhibit good durability in waters rich in various mineral salts. They are relatively resistant to weak acids, waters rich in CO_2, and industrial wastewater. Thanks to the formation of protective hydroxide coatings during hydration on the crystals of hydrated calcium aluminates, aluminate cements have higher resistance to the action of sulfate waters than normal cements. However, they are not resistant to the action of alkaline solutions, which is related to the solubility of aluminum hydroxide in aqueous solutions of sodium and potassium hydroxides, with which calcium aluminates also react.

The production cost of aluminate cement is several times higher than that of Portland cement. Therefore, their use is conditioned by the special properties of these cements. Aluminate cements are mainly used for quick repairs and emergencies, for road repairs, bridges, and dams, for construction work carried out in winter conditions, and for the construction of channels, and culverts exposed to the action of acidic waters and industrial wastewater. Aluminate cements have also found wide application in the production of refractory concretes and mortars. High-alumina cements (with an Al_2O_3 content of about 80%) despite their high price, are increasingly used for the installation of monolithic linings of various thermal devices, enabling rapid repairs and renovations while simultaneously increasing the durability of refractory masonry [53]. On the other hand, refractory concretes made from white aluminate cement with the addition of suitable aggregates (e.g., corundum) can operate even above 1600 °C [53].

Aluminate cements are also used in the production of expansive cement, whose technology is based on the phenomenon of increasing the volume of compensating shrinkage. One of the reactions leading to the increase in the volume of the cement paste is the formation of ettringite. In the reaction of ettringite formation, aluminate phases present in aluminate cement play a significant role as a source of aluminate ions. Among them, CA and hydrated calcium aluminates obtained during the hydration of aluminate cement are of the utmost importance. They usually consist of a mixture of hexagonal aluminates, mainly C_2AH_8, and regular C_3AH_6. All of these phases, upon reacting with sulfate ions derived from gypsum ($CaSO_4 \cdot 2H_2O$) and a small addition of $Ca(OH)_2$, which prevents the formation of $Al(OH)_3$, form ettringite, which compensates for drying shrinkage [57].

$$CAH_{10} + 2Ca(OH)_2 + 3(CaSO_4 \cdot 2H_2O) + 14H_2O = C_3A \cdot 3CaSO_4 \cdot 32H_2O$$

Another solution concerning expansive cements was introduced by Klein, who used calcium sulfoaluminate as a source of aluminate ions for the formation of ettringite. This compound, with the formula $C_4A_3\hat{S}$, is referred to as the Klein complex. It behaves similarly to calcium aluminates and, upon reaction with $CaSO_4 \cdot 2H_2O$ and $Ca(OH)_2$ in an aqueous environment, forms ettringite:

$$C_4A_3\hat{S} + 6Ca(OH)_2 + 8(CaSO_4 \cdot 2H_2O) + 74H_2O = 3(C_3A \cdot 3CaSO_4 \cdot 32H_2O).$$

Additionally, aluminate cement is used in the production of non-shrinkage cement.

6.2. The Use of Waste Glass and Glass Fibres in Cement

6.2.1. Potential for the Use of Glass and Glass Fibres as Additives in Portland and Aluminous Cements

Waste glass and glass fibres from wind turbines represent significant sources of potential secondary raw materials that can be used in the production of construction materials, using Portland cement or alumina cement. The potential for utilising waste glass from photovoltaics and glass fibres from wind turbines as additives to Portland cement and alumina cement is significant for several reasons:

- The addition of waste glass and glass fibres can significantly improve the mechanical properties of mortars, grouts, and consequently concrete, contributing to the improvement of its durability and structural stability;
- The use of these materials can reduce the extraction of natural resources, such as sand and gravel, which will have a positive impact on the environment;
- Glass is resistant to chemical corrosion, which can increase the resistance of structures to atmospheric conditions and chemical corrosion;
- Glass fibres can improve the mechanical properties of mortars, grouts, and concrete, mainly in terms of flexural strength, contributing to savings in the use of reinforcing steel, thereby reducing energy consumption and limiting steel production to the construction sector. The benefits may also be related to improving safety and work comfort.

As a result, the utilisation of waste glass as additives to Portland cements and aluminate cement has significant potential to improve the efficiency, durability, and sustainability of building structures, while simultaneously contributing to environmental protection. Furthermore, such materials will enhance the mechanical strength of hydrating cement and reduce the consumption of natural aggregates. The incorporation of these waste materials as additives to cement aligns with the concept of sustainable development. Recycling these materials enables a reduction in waste volume and negative environmental impact, while also contributing to the enhancement of the quality and durability of building structures. The valuable potential of these materials as additives to Portland cement and aluminate cement emphasises the importance of further research, technological innovations, and the development of norms and standards to promote their widespread application in the construction industry.

6.2.2. Waste Glass

According to experts, greenhouse gas emissions in Europe are expected to reach climate neutrality by 2050 [58,59]. This fact indicates that cement with reduced Portland clinker content will become increasingly popular. Such cement may contain various mineral additives, including granulated blast furnace slag, silica fume, and fly ash, as well as limestone [60]. Multi-component cements account for over half of the production of such binders in many countries [61]. The mechanism of commonly used mineral additives, such as granulated blast furnace slag or silica fume, and their impact on the microstructure and properties of cement composites have been thoroughly studied and described in the literature [62,63]. Their use in cement and concrete technology is considered safe, and the durable characteristics of the finished products are predictable. The positive effect of these additives on the durability of mortars and concretes in contact with chemical corrosion is particularly valued. This effect results from limiting their permeability by increasing the density of the microstructure and reducing the content of calcium hydroxide in the cement matrix—a substance most prone to corrosion due to hydration. However, these resources are becoming increasingly difficult to access. Moreover, the closure of long-standing steel mills is leading to a reduction in the production of granulated blast furnace slag [64–66].

Furthermore, waste glass cullet contains a significant amount of reactive silica, similar to traditional mineral additives. Its chemical composition may vary depending on the source and previous use of the glass [67]. In the alkaline environment present in cementitious pastes (pH > 11), ground waste glass in the presence of sodium and potassium hydroxide can react with aggregate containing non-crystalline silica, leading to the formation of expansive gel [68]. This results in the appearance of cracks in the microstructure and a decrease in the material's mechanical strength [69]. These observations over the years have created a common belief that the use of waste glass cullet in concrete production carries a high risk of expansion [70]. Further research has found that an appropriate degree of grinding of waste glass inhibits the alkali-silica reaction, and the material obtained as a result begins to exhibit pozzolanic properties [68]. Based on the cited studies, it is difficult to unequivocally determine the critical grain size above which the reaction of reactive silica with aggregate containing sodium and potassium hydroxides occurs, as the reactivity of a specific aggregate also depends on its chemical composition [68]. Most authors refer to studies where the critical grain size is reported to be 0.350 mm [68]. However, there are also studies where the use of larger grain size aggregate, for example, up to 1 mm, has been considered safe. There is no doubt that the higher the specific surface area of the glass powder, the greater its pozzolanic activity. An analysis of scientific studies has also shown that the addition of finely ground glass powder with a specific surface area of 0–0.079 mm causes, similar to the addition of slag, fly ash, or silica fume [71], a reduction in the shrinkage of mortars and concretes compared to reference samples without additives. The indicated specific surface area of the powder also limits material destruction in cases where the sample contains reactive aggregates. Additionally, resistance to chemical corrosion, including chloride corrosion, is improved [72]. In terms of performance, ground glass behaves similarly to fly ash—its introduction in place of part of the cement leads to a worsened consistency of mortars and concretes and a decrease in early compressive strength. Scientific research [73] has shown that, after longer periods of hydration reaction, the strength with pozzolanic additives is greater than that of reference samples. Depending on the percentage content of the additive and the type of binder or aggregate used, this increase ranges from 7 to 67%. The pozzolanic reaction can also be accelerated by curing samples at elevated temperatures. Some studies suggest that cement containing pozzolan experiences a decrease in compressive strength over longer maturation periods, especially when the additive replaces Portland cement in an amount greater than 10% of the cement mass [74]. Experimental studies on concrete conducted by Shayan revealed that concrete samples containing 20% rock powder in the binder exhibited compressive strength approximately 18% lower than the reference sample after 90 days [73]. However, after a year, the trend changed—the strength of the concrete in this series increased by about 10% compared to the reference sample, reaching close to 70 MPa. When thirty percent of the cement was replaced with glass powder, the compressive strength after 90 days was approximately 30% lower than the standard value, and the final value after a year was 40 MPa.

6.2.3. Glass Fibres

Glass-fibre-reinforced polymer (GFRP) is a type of composite material made from resins (such as epoxy resin, butyl resin), glass fibres, and auxiliary materials such as calcium carbonate, magnesium carbonate, or talc [1]. The physicochemical properties obtained from the combination of these components, including high mechanical strength, ease of shaping, and excellent resistance to chemical and biological corrosion [49–51], have made this composite an indispensable material in the production of wind turbine blades, storage tanks, ship hulls, and other laminates of this kind. It is estimated that the global production of industries producing such materials exceeds several million tons annually [75]. At the same time, it generates a significant amount of waste due to its high proportion [76]. The waste generated by the aforementioned industry remains persistent for 200–300 years, thus causing enormous nuisance and posing significant challenges in waste management, as traditional disposal methods are being rejected by many countries. Some scientists have developed economically unfeasible recycling methods, which, for the reasons mentioned above, have not been translated into industrial practice. These methods include pyrolysis, solvolysis, and biodegradation [1]. Given these facts, there is a significant challenge in the sustainable recycling of waste from the wind turbine production industry. Currently, these wastes are increasingly being removed using energy-intensive mechanical recycling techniques, in which waste product dimensions are progressively reduced through cutting, crushing, and grinding processes. They are primarily recovered in the form of powder, aggregate, and broken fibres. These components have found application as fillers in concrete and mortar to supplement the growing shortage of natural aggregates and improve mechanical properties [25]. Studies have shown that such ground waste containing 95% powder and 5% fibres can lead to increased mechanical strength and improved resistance to concrete tearing. However, the workability of the concrete mix was significantly reduced due to the large surface area of the ground waste, requiring the addition of surface-active substances to the concrete mix in amounts exceeding 2%, which represents a five-fold increase compared to self-compacting concretes (SCCs) [77]. Correia et al. [78], by replacing a portion of the aggregate with 5% of discarded glass fibre powder, caused an increase in water demand and a significant decrease in compressive and tensile strength. The authors in [79] found that the tensile strength of concrete increased with the addition of fibres used (0.02 mm < length < 20 mm). García et al. [25] replaced 1% of sand in concrete with fibres measuring 5–6 mm, and with this addition, they increased compressive and flexural strength by 22.0% and 16.0%, respectively. In another study, the addition of fibres measuring 4.75 mm and 9.5 mm reduced both the compressive strength and flexural strength of concrete [80]. The authors attributed this fact to fibre agglomeration during the mixing process and the introduction of contaminants such as spherical particles and dust.

Rodin et al. [81] categorised waste fibres from wind turbine blades using the following nomenclature: large fibre, medium fibre, small fibre, and powder. They replaced sand in concrete with the obtained material from 1 to 5%. The research revealed that a fibre measuring 2.38 mm increased the compressive strength and flexibility of concrete, while the other components worsened the mechanical properties of concrete. As indicated by studies on the impact of waste glass fibres on the functional properties of concrete described in the literature, there is significant disparity among them.

This fact can be attributed to the following variables:

- Variability in the chemical composition of waste;
- Variable physicochemical properties of components originating from mechanically recycled raw materials;
- Harmful effects of contaminants, including fibres, particles, clumps, and dust;
- Lack of homogeneity in waste fibres [76].

Further information regarding the durability of recovered fibres in the alkaline environments of cementitious pastes is scarce [50,51]. Hence, there is a need for a systematic assessment of the impact of fibre content, dimensions, and chemical composition on the mechanical properties and microstructure of cementitious materials.

7. Conclusions

Overcoming the challenges of wind turbine blade disposal is essential for the sustainable development of wind energy systems. The following conclusions can be drawn:

- Wind turbines are crucial for wind energy systems, but their blades pose significant disposal challenges at the end of their lifespan.
- Traditional methods like landfilling and incineration are financially viable but do not meet increasingly stringent legal regulations.

- New, efficient disposal methods are being explored, including reusing blades in public facilities, utilising the pyrolysis process, and processing blades in cement kilns, which can also reduce fossil fuel use in cement production.
- The increasing number of decommissioned wind turbine blades necessitates continued research and development to find effective disposal methods.
- Waste from wind turbines, such as glass and glass fibre, can be used as additives in Portland and aluminate cement, improving concrete's mechanical properties, durability, and structural stability.
- Using wind turbine waste materials in concrete production reduces the need for extracting natural resources, positively impacting the environment and supporting sustainable development by reducing waste, improving construction quality, and mitigating negative environmental impacts. Further research is needed to determine the optimal use of these materials.

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