sustainability

Review

Waste Management of Wind Turbine Blades: A Comprehensive Review on Available Recycling Technologies with A Focus on Overcoming Potential Environmental Hazards Caused by Microplastic Production

Sara Taherinezhad Tayebi [1,2], Matteo Sambucci [1,2,*] and Marco Valente [1,2]

[1] Department of Chemical Engineering, Materials, Environment, Sapienza University of Rome, 00184 Rome, Italy; sara.taherinezhadtayebi@uniroma1.it (S.T.T.); marco.valente@uniroma1.it (M.V.)
[2] INSTM Reference Laboratory for Engineering of Surface Treatments, UdR Rome, Sapienza University of Rome, 00184 Rome, Italy
* Correspondence: matteo.sambucci@uniroma1.it; Tel.: +39-0644585647

Abstract: The 2020 targets for sustainable development and circular economy encourage global leaders and countries to legislate laws and policies on several critical hot topics to prevent further global warming: (1) the increased utilization of renewable electrical power (wind turbine implants, as an example); (2) waste transformation into high-added-value materials based on the European Green Deal for energy transition; and (3) material and energy recovery and circularity. Accordingly, scholars and researchers have predicted that, hopefully, installed wind power capacity is going to increase dramatically by 2050. However, our ecosystem will have to face and deal with an enormous amount of decommissioned turbine blades. The disposal of these wastes via conventional methods could not only raise the possibility of microplastic formation, but could also boost the probability of environmental issues such as air pollution, soil, water contamination, etc. Moreover, these hazards will endanger wildlife and humans. As a result, the waste management of these retired blades composed of multi-lateral composite materials through a sustainable, effective, and feasible single/or hybrid process is necessary. This review aims to summarize all of the information about turbines, introduce all the various recycling pathways used for their blades, and provide a comparative analysis of these methods as well. In addition, the paper defines the possibility of microplastic formation from this waste (especially end-of-life turbine blade scraps), points out potential risks for the Earth, and suggests actions to inhibit their build-up and to keep the environment safe.

Keywords: wind energy; EoL turbine blades; waste management; microplastics; environmental hazards

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1. Introduction

In the 21st century, the broad aims of "sustainability" and "circular economy" (CE) are found in every engineering sector, but primarily materials and environmental engineering. This vision has inspired many scientific communities, individual companies, and international country leaders to step forward and take action to minimize environmental damage. The fundamental challenge is addressing the problems at hand and protecting the ecosystem against further harm [1,2].

To begin with, let us define "sustainability" and CE and state what they mean. In 1978, the essence of all the definitions proposed for "sustainability" and "sustainable development" (SD) started [3]. In the "Our Common Future" report, published by the Brundtland Commission, these two expressions are described as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3–5]. Subsequently, other definitions state that working in balance and fairness with natural resources is essential while operating any business in our modern world.

These considerations guarantee a sustainable future for all creatures on Earth [6]. In other words, if humanity abuses the Earth's natural raw materials and its environment becomes unhealthy, it will be impossible for human society or business activity (economy) to flourish and blossom. Figure 1 illustrates this idea perfectly. When considering sustainability, the common understanding revolves around environmental, economic, and social aspects, emphasizing the importance of preserving natural resources for survival [7].

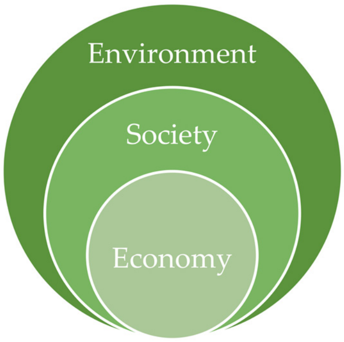

Figure 1. Nested circles of economy, society, and environment (authors' own illustration from reference [3]).

On the contrary, CE, which remarkably has been publicized lately, can be explained as "an alternative to "Linear economy" (LE) (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value for them while in use, then recover and regenerate products and materials at the end of each service life" [3–6,8]. Figure 2 depicts flowcharts of LE (Figure 2a) and CE (Figure 2b). Currently, most factories run their businesses in a linear path in which raw materials are extracted, refined, and processed into daily-needed products. However, in the past few decades, the LE has been questioned due to the warnings about Earth's resource depletion. Hence, academia, organizations, governments, and humanity seek an obligatory transition from LE to CE.

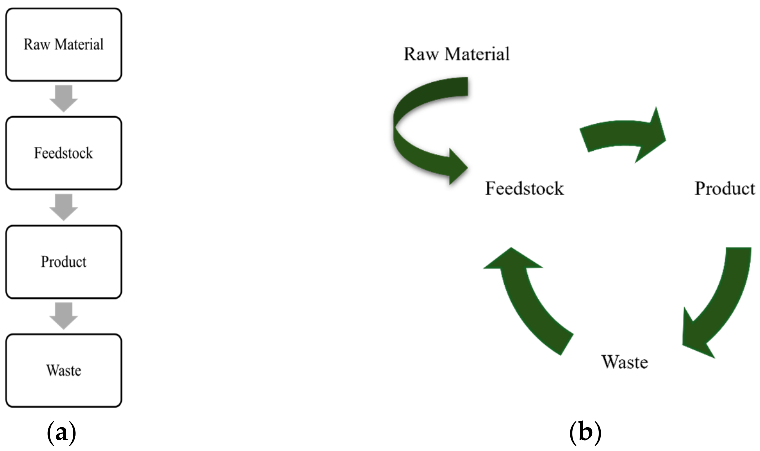

Figure 2. Moving from a (**a**) LE to (**b**) CE (authors own illustration from reference [3]).

Notably, the "United Nations Sustainable Development Goals" [9] and the Ellen MacArthur Foundation's "Circular economy" principles [10] are aligned with previous studies that have proven that enhancing wind power capacity as a green electrical resource, plus waste management and conversion into high-added-value secondary materials, can effectively improve adverse ecological issues, from "climate change" to microplastic (MP) formation and accumulation [11–13]. Consequently, our planet has the potential to serve humanity as a safe place to live for longer, in addition to offering all living beings long-term health and prosperity [3].

Wind energy is one of the most renowned forms of sustainable, cost-effective, and clean resources capable of generating electricity. By reviewing the energy market within Europe, it can be found that the wind energy industry has one of the highest cumulative energy sources, in second position after natural gas [14]. With an annual growth rate of 20%, its installed capacity in the EU grew from 24 GW in 2001 to 651 GW in 2019 [15]. At present, wind power supplies 15% of the EU's electricity demand. Optimistically, this share is expected to increase to 27% and 50% by 2030 and 2050, respectively, because of the EU's binding target and commitments to cut greenhouse gas emissions up to 95%. Hence, wind turbines (WTs) draw attention for their predominant role in the future of the energy mix [11,15,16]. Notably, the essential environmental benefit WTs bring us during their functional lifecycle is their independence from fossil fuels. However, the aforementioned forecasted calculations about wind power energy growth show that plenty of WTs will be decommissioned, considering their standard lifecycle and repowering opportunities [15]. In Europe, it has been forecasted that the total amount of EoL turbine blades will be around 325,000 tons, with 76% of this share accounted for by on-shore wind turbines and 24% accounted for by off-shore wind turbines [17]. This finding is in line with two other existing studies [18,19]. Waste management for these end of life (EoL) turbines will be urgently needed to proudly say that wind energy is eco-friendly. Based on research carried out by Wang et al., on-shore and off-shore WTs have different environmental impacts. Life-cycle assessments were used to estimate the life-cycle greenhouse gas (GHG) emissions of both on-shore and off-shore wind farms composed of 2 MW WTs. This study showed that GHG emission intensities for on-shore and off-shore wind are 0.082 and 0.130 kg CO_2 (eq)/Megajoule (MJ), respectively. No matter where the wind farm is located, the life-cycle GHG emission intensity is much smaller than in coal power plants [20].

Turbine blades, responsible for converting kinetic wind energy into mechanical energy, are generally made from multilateral composite materials. The major components of a typical WT, like the nacelle and the tower, except the blades, can be recycled easily. The average proportion of the blades' material composition fluctuates depending on their type and manufacturers, but fiber-reinforced polymeric thermoset composites always possess an outstanding share in all turbines [11,15]. The utilization of fiber-reinforced thermoset composites in blades boosts WT performance from different points of view, although their cross-linked structure makes recyclability and recovery complex. In other words, in thermoset composites, the long polymer chains are covalently bonded, forming a three-dimensional stable and irreversible network, consequently making it impossible for the material to undergo heating and cooling cycles. However, the structure of thermoplastic composites may alter from soft to hard if thermal cycles are applied to them [21,22]. Mostly, fiber-reinforced thermosets are utilized in applications where mechanical performance and durability are considered important characteristics, such as the automotive industry, WTBs, construction applications, etc. [23]. Precisely, these thermoset composites are mostly composed of glass fibers (GFs) and carbon fibers (CFs) as the reinforcement, and polyesters, epoxies, and vinylesters as the matrix [24]. Many scientists and companies have worked on blade waste transformation, but conventional disposal methods like landfilling and incineration are still commonly used. These traditional methods have been criticized by academia, industry, and governments over the past ten years due to the harmful environmental effects they create, from "global warming" to MP formation and accumulation [13]. As a result, a desirable pathway to take over the waste management of blades is a must.

Unfortunately, the first generation of WTs, installed during the 1990s with a standard 20–25-year lifetime, will soon reach the end of their service life. Simultaneously, as declared earlier in the above paragraphs, the predicted growing demand for wind energy production, one way or another, will also intensify the number of decommissioned turbines and, thus, the world will face massive amounts of blade waste [11,25]. Without waste management infrastructure, the usage of traditional disposal methods continues, in which blade litter is subjected to different degradation phenomena based on composite characteristics and environmental stimuli, such as heat, UV radiation, oxidation, biofouling, and mechanical forces. These processes result in the formation of small blade scraps, designated as MPs [13]. MPs, less than five millimeters in size, are significant pollutants threatening wildlife and the ecosystem.

Last but not least, this whole argument expresses that "sustainability", CE, "turbine blade wastes", and "MP formation and accumulation" are all related concepts that necessitate immediate efforts for recycling strategies moving toward a brighter and sustainable future. Unfortunately, microplastics are capable of absorbing heavy metals, pesticides, and polychlorinated biphenyls (PCBs). As a consequence, with the consumption of microplastics, humans may experience oxidative stress, cytotoxicity, neurotoxicity, and immune cell disruption [26,27].

This paper aims to explain WTs in depth and state how humanity is addressing the challenges associated with blades' different waste streams, then review how these litters can be handled according to the best available technologies. Afterwards, we discuss MP formation and accumulation, as well as their harmful effects on the Earth, and clarify their correlation between conventional disposal methods and EoL turbine blades. It is believed that blade litter can be subjected to different degradation phenomena based on its chemical composition and the environmental conditions it has been exposed to. On the other hand, it is not advisable to dispose of EoL WTBs through conventional methods such as landfills and incineration, because degradation occurs in these two situations. Therefore, establishing a pathway for the waste management of these materials must be taken into account.

2. Wind Turbines

Based on their design, WTs can be categorized into two groups (visit Figure 3): 1—horizontal-axis turbines (HaTs) (Figure 3a); 2—vertical-axis turbines (VaTs) (Figure 3b) [28–30].

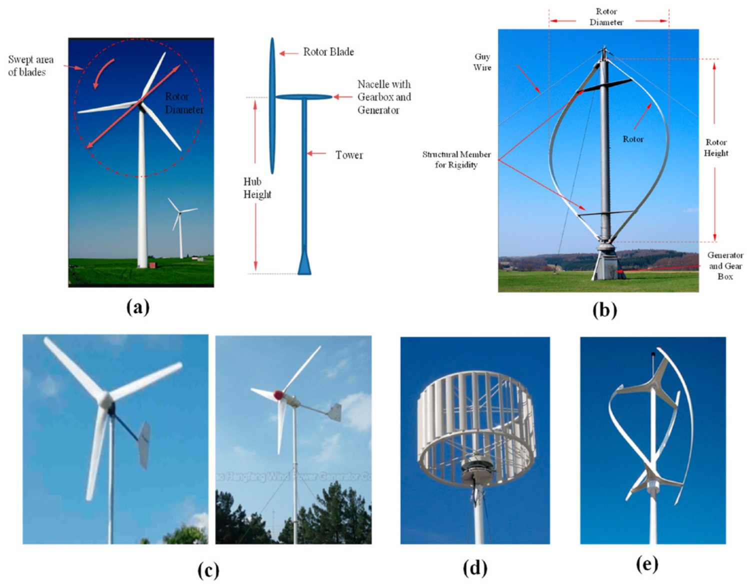

Figure 3. (**a**) Horizontal-axis turbines (HaTs), (**b**) vertical-axis turbines (VaTs), (**c**) domestic HaTs, (**d**) Savonius VaTs, and (**e**) Darrieus VaTs. Reprinted with permission from Ref. [30], 2023, MDPI.

HaTs can be defined as one of the most common forms of WT at present, and have a rotor shaft in the direction of the wind [30]. Based on the wind's direction, this kind of turbine is classified into upwind or downwind, but most in-use WTs are upwind HaTs. Additionally, these turbines can be single-bladed, double-bladed, three-bladed, or multi-bladed, although a remarkable percentage have three blades, similar to airplane propellers. It is good to note that the height of HaTs and the length of their blades are related to the electrical energy capacity generated by them. Therefore, the taller the turbines and the longer their blades, the greater the electrical energy produced [30]. In contrast to HaTs, VaTs are the other existing type of power-generating technology. They are typically small, and have a rotor shaft that rotates perpendicular to the wind direction. There are three kinds of VaTs: 1—domestic HaTs (Figure 3c); 2—Savonius VaTs (Figure 3d); and 3—Darrieus VaTs (Figure 3e) [30]. If the blades are built around the vertical shaft in a helix format, like DNA, the figure will be called Savonius. However, the shape of Darrieus VaTs is more or less similar to an eggbeater, with long and wide wings attached to the upper and lower joints of the rotor, providing a maximum swept area [30]. Historically, it has been proven that VaTs lag behind their HaT counterparts in terms of their electric power production efficiency, according to scientists measuring their power coefficients [30].

Finally, yet importantly, owing to HaTs' figure, their blade design, and their capability to capture vigorous wind for effective power production, nearly all in-service turbines are upwind HaTs around the globe [28–30]. Therefore, this manuscript will only describe the upwind three-bladed HaT as a standard model for further discussion.

2.1. Structure of Wind Turbines

As declared before, among all alternative designs for WTs, upwind HaTs with three blades play a significant role in the wind industry sector. Figure 4 represents a typical upwind HaT with three blades and highlights every component of this form of WT [31,32].

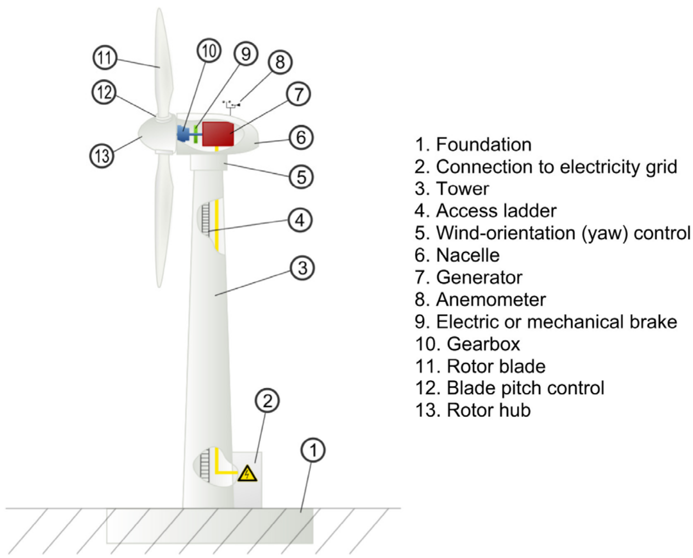

Figure 4. Standard figure of upwind three-bladed HaT. Reprinted with permission from Ref. [31], 2016, Elsevier.

As illustrated in Figure 4 above, upwind HaTs usually have a large central tower, a rotor hub, a nacelle, and blades as the main parts. Even though each of these chief pieces can hold other specific components with a particular function and character, they all assist upwind HaTs in power generation and performance. Nevertheless, the principle of wind energy conversion to electricity is elementary. Wind energy moves the blades around the WT's rotor hub, which is connected to the main shaft responsible for spinning the generator to create green electricity [30]. An overview of these parts, the characteristics correlated to each, and their tasks are written in Table 1 with more detail, and wind turbine blades (WTBs) will be described in detail in the next section.

Table 1. WTs' main components and their functions (table drafted from reference [33]).

Component	Material	Function
Tower	Steel, concrete	Supporting the structure
Rotor hub	Cast iron, GFRPs	A central part connecting blades; allows blades to rotate
Blades	GFRPs, CFRPs, wood or foams, adhesives, metals	Responsible for extracting wind energy; convert the pressure of the working fluid to kinetic energy
Gearbox	Steel (98%), aluminum (1%), copper (1%)	Increasing the rotation speed of the blades
Generator	Steel (65%), copper (35%)	Converting mechanical energy to electrical energy
Nacelle	Steel (85%), aluminum (9%), copper (4%), GFRPs (3%)	Holding key components of WTs, including gearbox and generator
Foundation	Concrete, steel reinforcing bars	Supporting the entire turbine and forces acting on it

2.2. Structure of the Blades, Material Composition, and Properties

Figure 5 depicts a lateral cut of a regular WTB [34]. WTBs are multilateral composite structures comprising various materials with different properties. Although the material composition of WTBs may differ from one manufacturer to another, generally speaking, they are composed of the following elements described in Figure 5, as we also stated earlier in the introduction part (see Table 2).

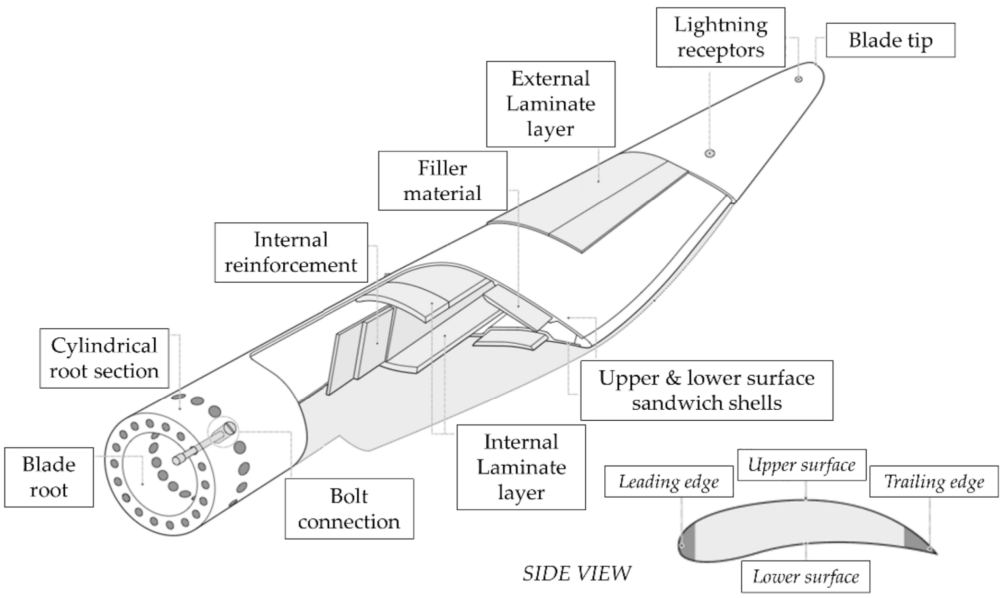

Figure 5. Main components of a typical WTB. Reprinted with permission from Ref. [34], 2022, MDPI.

It can be concluded from Table 2 that thermoset polymeric composites are used the most compared to the rest of the materials. In thermoset polymeric composite manufacturing, more than two constituents will usually be mixed to acquire new products with superior physical and/or chemical properties compared to each component alone [35]. So, as the scope of this project is on thermoset polymeric composites, they can be classified by reinforcement type and subdivided into (1) particle-reinforced composites and (2) fiber-reinforced composites [36]. As a reminder, the formula that makes turbine blades is polymeric resins plus fabric reinforcements, known as FRP composites [35–37]. In this case, 50% of the thermoset composite comprises fiber; the rest is the resin content. FRP thermoset composites can be manufactured from a numerous variety of polymeric resins and fiber reinforcements by many processing operations, with tailored engineering properties paving the way for them to play a crucial role in most high-tech industrial markets, such as the automotive, aerospace, construction, and marine sectors, and so on [14,36,38] (see Figure 6). These advanced composites offer low density, corrosion resistance, good insulation, and high strength and stiffness [14]. The wind energy sector is ranked as one of the available markets for FRP thermosets [14,39].

Table 2. Material composition of a turbine blade (table drafted from reference [14]).

Materials	Percentage (wt%)
Thermoset FRP composites: 1—Fiber reinforcements (glass, carbon, aramid, or basalt); 2—Thermoset resins (epoxy, polyester, vinylester).	93%
Core materials: Balsa wood or foams such as polyvinyl chloride or polyethylene terephthalate.	4%
Adhesive coatings: Usually polyethylene, polyurethane, or other materials (for example, metal copper wiring, steel bolts).	3%

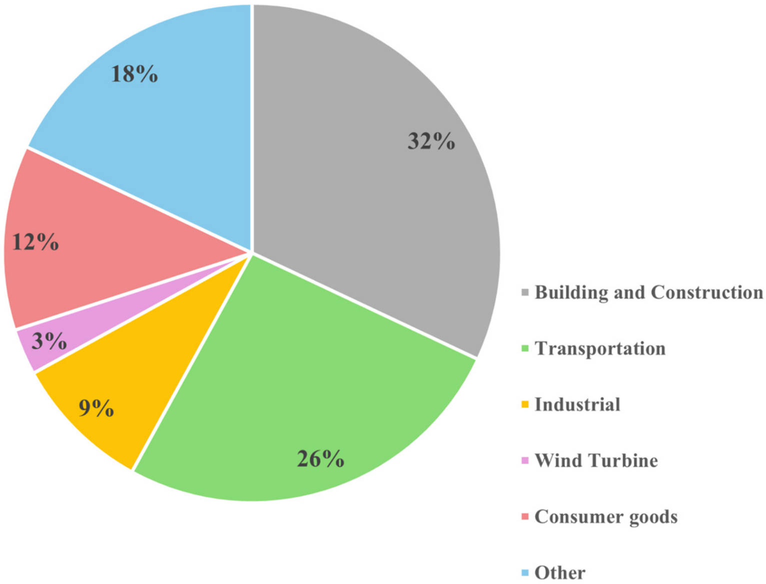

Figure 6. The main applications of GFs: automotive, alternative energy, aerospace, transportation, building, sports, and others (authors' illustration from Ref. [39]).

When it comes to the reinforcements used, GFs, CFs, and hybrid mixtures of both take the top spots as being the most utilized due to their versatility and the various properties they propose.

Glass-Fiber-Reinforced Composites

In the current decade, composite materials containing GF surround us in society. A straightforward example of such goods is WTBs. GFRPs dominate the turbine blade market because they have the potential to bring necessary properties at a meager cost [35–37]. GF composites find themselves the best candidate compared to CF composites due to some characteristic weaknesses, from low damage tolerance, ultimate strain, and compressive properties to drastic cost [35–37]. Furthermore, from the early advent of WTs until now, several kinds of GFs have been implemented in academia and the market for diverse targets. Since it has been verified that blade lengths may differ based on the output of turbine power production [40,41], blades with lengths of 15–25 m^2 only contain GFs, but longer lengths comprise a mixture of GFs and CFs. For wind repowering, E-glass fiber called "electric glass" is the most common form of reinforcement due to its high electrical resistance [42].

2.3. Material Utilization per Blade

Jensen and his colleague gathered aggregated data from fourteen original equipment manufacturers and showed the relationship between average blade mass and unit of rated power (t/MW) [11,40]. It is visible in Figure 7 that there is a slight increase in the ratio until the 5 MW power rate for turbines. Mass reduction is detected in longer and larger blades for more efficient designs, lower safety factors, lighter materials, and improved processing techniques.

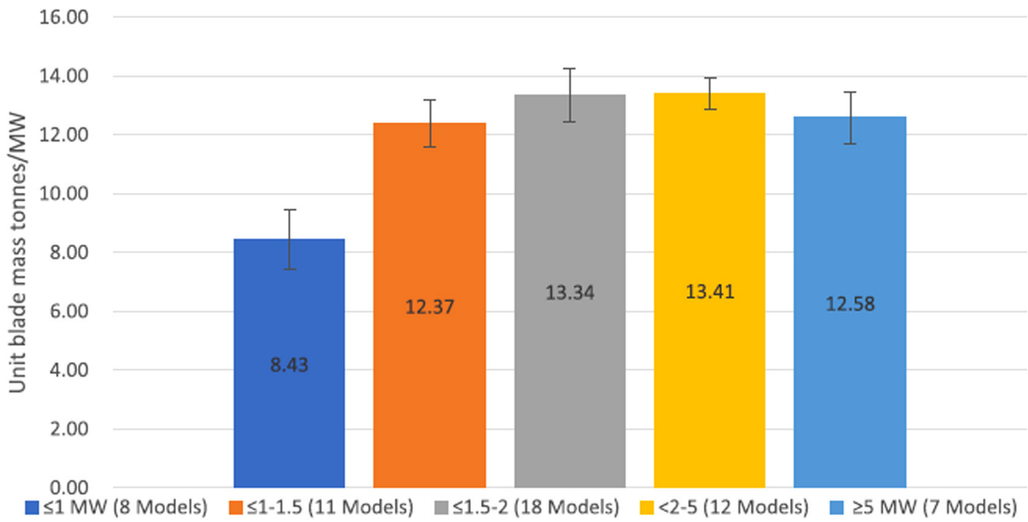

Figure 7. Blade mass per unit of rated power for the different turbine sizes. Reprinted with permission from Ref. [11], 2018, Elsevier.

2.4. Sources of Blade Waste

Waste streams of blades can be divided into three major groups: EoL waste, manufacturing waste, and service waste [11,14]. Waste from EoL blades contributes to the most considerable fraction of composite waste from the wind energy industry. Normally, blades have a life span of 20–25 years. Meanwhile, other waste streams, for instance dry fiber cut-offs, cured composite cut-offs from blade edges and root ends, as well as grinding dust during the finishing process, also arise during composite fabrication. Minor amounts of blade litter come from tested blades, accidental damage, and defects after installation [11].

2.5. Global Blade Material Quantification

2.5.1. GF and CF Composite Production

According to the statistics and market analysis of German associations AVK and CCeV, GFRPs' volume production in Europe reached 1069 million tons in 2015, corresponding to 25% of the world's total volume production. In addition, 34% of Europe's production is associated with the construction sector, and the wind energy industry is also included in this category [11]. Compared to GFs, the global CF demand was 53,000 tons, with only 14% growth in recent years. This share is related to the construction sector, and wind power represents only 14% of this amount (7400 tons) [8]. Based on the EU's binding target for increasing green energy, Figure 8 shows the projected trends and use of GFRPs in WTBs until 2030 [11].

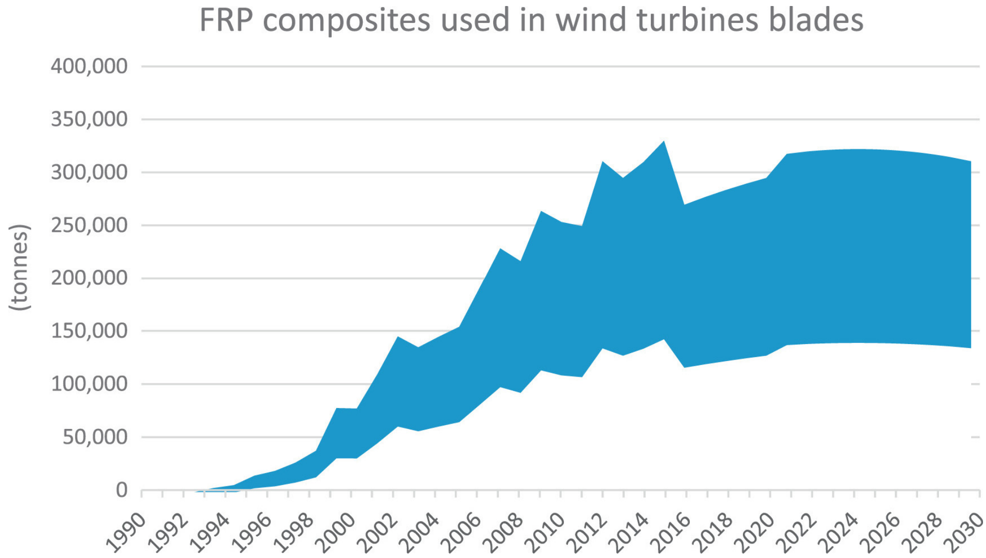

Figure 8. The trend for the annual growth of GFRP utilization in blades. The blue trend exhibits the annual amount of composite material used until 2030, assuming 12–15 tons per MW thermoset composite material. Reprinted with permission from Ref. [11], 2018, Elsevier.

2.5.2. GF and CF Composite Waste Streams

The annual amount of waste from each litter stream group in wt% can be estimated by calculating the amount of waste from WTBs. In this way, a project published by [14,19] proposed a median for composite material used per MW. The project collected data from 14 WT producers. Their findings, in line with other studies, indicated that somewhere between 8 and 13.4 tons of composites may be used per MW [14]. In agreement with [43], the blade mass per unit of rated power tends to be between 12 and 15 tons/MW, suggesting that based on the specific number of established WTs within Europe, 160,000 tones/year of WTs must be handled [14,43]. The European Composites Industry Association (EuCia) projections designate around 66,000 tons of thermoset composite waste will originate from WTs in 2025 [37]. An overview of blade litter sources from a life-cycle perspective is given in Table 3.

Table 3. Composite waste streams from a life-cycle perspective (table drafted from reference [11]).

Life Cycle Phase	Manufacture	Operation	Upgrade/Retrofit	EoL
Contributing causes to blade waste	- In-process waste - Blade testing - Defective blades	- Routine service - Accidental damage	- Exchange of blades (due to failure or upgrade to larger rotor diameter)	- Turbines decommissioning
Estimated waste amount	~ 10–18% of total blade weight	~ 3% of total blade weight	~ 5% of total blade weight	~ 5% of total blade weight

3. Waste Management of Wind Turbine Rotor Blades

Currently, a lot of products in our society are made from composite materials, especially FRP thermoset composites. Considering this reason and the goals set out in 2020, environmental regulations necessitate the proper recovery and recycling of all engineering materials, such as composites [44,45]. In 2008, the EU provided a directive on managing litter and EoL materials. The 2008/98/EC directive suggested a hierarchy of six subcategories (see Figure 9). In this specific directive, no ban on using conventional disposal routes is mentioned, but instead, there are proposed solutions to tackle environmental issues and diminish them [44]. However, these directives have a direct impact on the way each European country treats its litter. For example, Germany and the United Kingdom have abandoned GFRP landfills [46,47]. In this context, the current situation in the UK requires more specific discussion regarding the relationship with EU directives following Brexit. Despite leaving the EU, the UK government has stated that this has not changed its world-leading ambitions for the environment and its commitment to moving towards a CE by preserving resources as long as possible, achieving maximum value from scrap materials, minimizing wastage, and promoting resource efficiency. For this reason, it is unlikely that the United Kingdom will ignore the regulations and commitments it signed up to with the EU before Brexit, including the Paris Agreement on climate change and the EU Waste Framework Directive on circular economy [48].

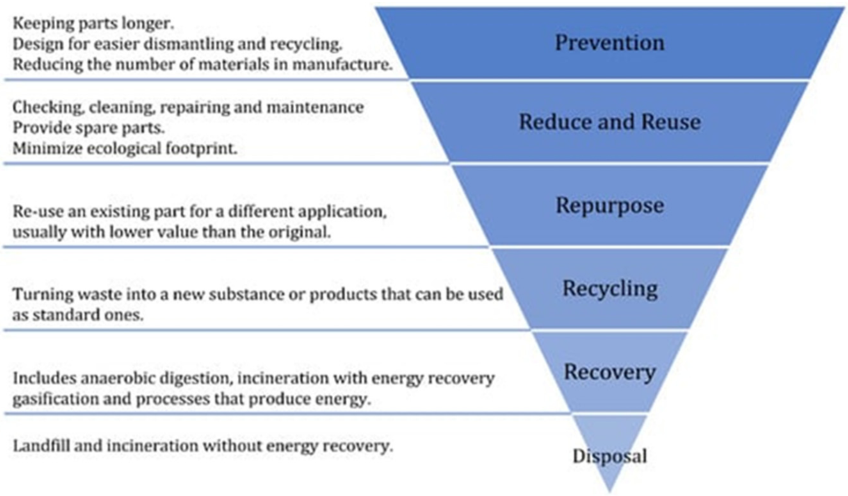

Figure 9. The waste management hierarchy. Reprinted with permission from Ref. [44], 2022, MDPI.

To extend the discussion on the management of EoL wind turbines to a global scale, the following are the main practices and policies in place in some countries with a key role in wind energy generation, including the United States (U.S.), China, and India. According to the survey by Korey et al. [49], the U.S. are prone to favor a linear approach in the management of waste turbines. Currently, wind turbine blades are most commonly landfilled after being decommissioned. As supported by Cooperman et al. [50], the recovery of energy or material from EoL turbines would not be energy-effective or cost-effective compared to the disposal of blades in large segments or through grinding, discouraging circular practices for waste management. In recent years, mechanical recycling has been spreading as a post-decommissioning strategy to tackle the negative impact of landfilling. EoL turbine blades are grinded into small particles which can be used as feedstock for concrete aggregate, cement production (co-processing), or as filler for strand board panels [49]. China account for the largest wind power capacity globally, making up 37% of the total installed capacity. To address the future growth of EoL turbines, China established regulation and financial incentives (China Solid Waste Law) aimed at implementing waste handling and recycling methods varying from cement kiln co-processing, mechanical recycling, and thermal recycling (pyrolysis and fluidized bed process) to chemical recycling. Similarly to the Sustainable Development Goals defined by the EU, the target is to reach peak emissions before 2030 and carbon neutrality by 2060. However, China's scenario is very uneven. There are significant differences in wind resource distribution, development progress, power policies for wind energy, and waste management practices across regions [51]. India has strongly maintained fifth place in the world for installing wind energy, after China, the U.S., Germany, and Spain. The Indian government established a specific ministry for renewable energy named the Ministry of New and Renewable Energy (MNRE), which is responsible for planning and applying policy frameworks for renewable energy. The MNRE introduced incentive schemes to provide financial support for every unit of generation up to ten years [52]. Regarding the management of EoL wind turbines, the available literature provides scarce information on the Indian context. Woo and Whale [53] state that repowering is the most active option in India, where the Wind Repowering Policy for turbines 1 MW and below is in force.

This project studies the most recognized and discussed waste management options viable today. Based on this information, a diagram is given in Figure 10, and a brief description for each possible method is noted.

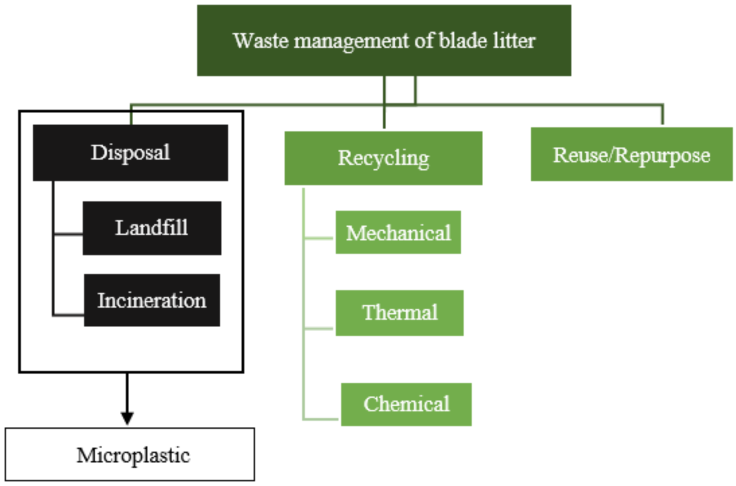

Figure 10. Feasible remediation techniques for EoL waste WTBs (authors' own illustration).

3.1. Landfilling

Landfills are engineered sites designed for the disposal of waste material by burial. For composite materials, i.e., turbine blades, this method is one of the typical disposal routes available globally. Despite their widespread use, they lead to several environmental challenges, including soil and groundwater contamination [14,44]. As a matter of fact, landfill is not recommended at all. Also, it is prohibited due to the laws and regulations connected to CE infrastructures in some European countries like Germany because of material and energy losses [44]. In other countries, including Belgium, the Netherlands, and the United Kingdom [54], governments require high taxes for such disposal techniques to avoid them [44,55]. For instance, the "Flemish Landfill Tax" was introduced in the 1990s in Belgium to discourage waste landfilling and incineration and promote more eco-friendly practices to handle waste and recycle scrap materials. At the beginning of the 2000s, the law laid out a tax of 64 EUR/ton to 75 EUR/ton depending on the type of waste stream. From July 2015, all environmental taxes were multiplied by a factor of 1.5 [56].

3.2. Incineration

As a disposal method, incineration involves burning waste materials under a specific processing condition [44]. While it is responsible for various environmental and human health issues, like landfills, it is another commonly used solution to manage composite waste. Several reasons can be pointed out for its harmful effects. Incineration can release toxic gases and pollutants, such as heavy metals, dioxins, and furans, into the atmosphere [35]. Although modern incinerators are equipped with pollutant-scrubbing technologies, there is still an inherent risk associated with the emissions, especially for thermoset polymeric composites. Another drawback worth considering is that the calorific value of GF/CF-reinforced materials is lower than that of traditional fuels, making them less efficient to burn as an alternative. Unfortunately, incineration necessitates residue management due to ash and slag production. Along with these limitations, many regions and countries restrict the incineration of composite materials, just like landfills, because of their hazardous effects [11]. Therefore, it is not considered a first option for managing the WTB waste stream.

3.3. Recycling

3.3.1. Thermal Recycling

Heating is a way to break down the polymeric part of composite structures in thermal recycling methodologies. The temperature of the procedure depends on the type of resin used to manufacture the composite. Usually, the temperature fluctuates between 450 and 700 °C, and because of the high operating temperature, the polymeric resin will likely burn, and only the fibers will remain [14,44]. It is worth noting that EoL blades need pre-mechanical recycling to enhance efficiency. Three types of thermal decomposition are currently used (Table 4).

Table 4. Thermal recycling methodologies comparison (table drafted based on reference [14,44,55]).

	Thermal Recycling Type	Description	Benefits/Drawbacks
1	Pyrolysis	Composite's organic part combusted in an inert high-temperature atmosphere (450–700 °C).	+ The organic part can be recovered as gas/oil and used as an energy resource or as new monomers for resin production. + Low CO_2 emissions. – Fibers with char contamination face property loss. – Long processing time. – The process can only be undertaken for large quantities of waste.
2	Microwave Pyrolysis	Microwaves are utilized to decompose the organic part of composite waste into a low-molecular-weight substance (gas/oil), specifically in a nitrogen chamber atmosphere (300–600 °C) by microwave radiation.	+ Minimal degradation of the fibrous part due to the lower processing temperature. + Shorter reaction time. + Recovery of the resin as a secondary energy resource.
3	Fluidized bed	A scalding stream of air is employed to fluidize the waste on a silica bed for the resin decomposition and fiber retrieval.	+ Energy or monomer recovery through resin decomposition. – High degradation of the reinforcement part due to the abrasive condition of the process.

The recovered fibers are cleaned, and can potentially be reused in new composite materials. Despite all the benefits counted, one drawback is that the high temperature involved can damage the fiber phase, particularly in the case of GF recovery [14]. Indeed, thermal recycling results in a remarkable loss of recovered fiber strength (50–90%) [1]. Ge et al. studied the isothermal pyrolysis of the primary component of waste WTB composites (epoxy resin, thermoplastic polyethylene, CF, and GF). The results showed that the mass loss rate for the resins reached 90%, and certain amounts of CO_2 and CO were emitted. However, the reinforcing component barely reacted, and the reported mass loss for each yielded approximately 1%. As a result, the removal of the matrix along with fiber structure retainment via pyrolysis was successful [57]. Huang utilized a closed-loop solvothermal recycling process for CF-reinforced vinyl ester resin. Degradation of the matrix resin to 99.96% was achieved with minimal damage to the recycled fibers under mild reactive conditions. Surprisingly, flexural strength and flexural fracture surface observations implied that better mechanical properties could be achieved with recycled CFs owing to the more robust interface that could form [58].

3.3.2. Chemical Recycling

Solvolysis, the most common form of chemical recycling, is another promising technique to depolymerize the matrix and liberate the reinforcement. Normally, the chemical structure of the polymeric resin dictates the suitable solvent and chemical for the process [33]. Various solvents, such as water, alcohols, glycols, and ketones, are used to break down the crosslinked bond between polymer chains and decompose the resin into basic monomers to create energy sources for other processes or to synthesize new polymers. In the meantime, the intact fibers for re-utilization remain [14]. In this process, the reactive solvent diffuses into the matrix at a specific temperature and pressure and breaks particular bonds, abolishing the bond between the resin and the fibers. By this method, both GF and CF separations can be performed. However, at high temperatures, the property loss of the separated GF is a lot. Chen et al. [55] reviewed the effect of chemical recycling on the residual mechanical properties of the recovered polymers and fibers. Depending on the recycling technology and the process parameters implemented, recycled fibers suffer a loss of strength between 2% and 10% compared to virgin fiber. The recovery yields of the polymeric fraction (epoxy or phenolic resins) range from 70% to 95%, with loss in tensile strength between 12% and 17%. Therefore, solvolysis can be divided into two categories based on the temperature and pressure (Table 5) [14]:

- High temperature and pressure (>200 °C) (HTP).
- Low temperature and pressure (<200 °C) (LTP).

Table 5. HTP and LTP differences (table drafted from reference [14]).

	Solvolysis Type	Advantages	Disadvantages
1	HTP	- Environmentally friendly due to the usage of water and alcohol as solvents.	- High energy consumption. - Expensive.
2	LTP	- Secure recovered fiber properties due to the safe temperature and pressure conditions.	- Aggressive solvent usage. - Environmentally hazardous. - High energy consumption. - Expensive.

3.3.3. Mechanical Recycling

Mechanical recycling is the only feasible method currently employed to manage EoL turbine blades. According to the literature, a variety of machines, such as shredders, crushers, millers, and grinders, can be utilized based on the target and end product. In the first step, the EoL blades will be subjected to a physical size reduction to produce smaller, more manageable units and separate the impurities while making transport easier [14,44,59]. Then, with the help of different millers/grinders, the pre-cut units are further crushed into even smaller and finer pieces. The particles can be characterized into two materials: 1—fiber-rich particles; 2—resin-rich particles [55]. The hammer mill granulator is an impressive piece of processing equipment for composite materials to fabricate ready-to-use recyclates for various applications [44,60]. As a result of this type of recycling, a mixture of resin and fibers with different aspect ratios that may have to be further sieved will be available. The following table (Table 6) presents the advantages and disadvantages of this recycling procedure.

Table 6. Mechanical recycling methodologies comparison (table drafted based on reference [14,44]).

Recycling Method	Advantages	Disadvantages
Mechanical recycling	- Cost-effectiveness. - On-site processing. - Low environmental effect. - High technology readiness/option of running this method commercially.	- Low added value for recyclates. - Loss of mechanical integrity and property compared to virgin fibers. - Only short fibers or powders are obtainable.

Another approach similar to mechanical recovery is High-Voltage Fragmentation (HVF). Both methods are used as recycling methods to reduce the size of waste. However, in the HVF process, the EoL turbine blades are decomposed into small fragments through high-voltage pulses (100–200 kV) in an aquatic medium. In contrast to mechanical recycling, cleaner and longer fibers can be achieved, but the energy consumption to operate this process is higher [35,61]. As with chemical recycling, discussed above, mechanical processing leads to a downgrading in the mechanical characteristics of the recovered materials (fiber and polymer), inducing a more significant strength degradation than the chemical route. Tahir et al. [62] found that the tensile strength of recovered GF from grinding was up to 48% lower than that of virgin fiber. Powder residues (thermoset-resin-rich) cannot be reprocessed for new polymer products, but are usually implemented as fillers or reinforcements for cement, concrete, or other building materials [55].

Co-Processing in Cement Kilns

Co-processing provides a sustainable and circular solution to recycling EoL composite materials with GF while simultaneously tackling environmental issues. The outputs of mechanical recycling can be re-utilized in cement co-processing where the resin content of the composite's waste is combusted as a secondary fuel energy resource, and the fibrous content of the waste provides minerals to the feedstock, as it is rich in silica (Si), calcium (Ca), and alumina (Al) [14,44,63]. This kind of recycling technology not only helps us reduce natural raw mineral material extraction and replace fossil energy resources, but also reduces the carbon footprint of cement production by 16%. Due to the presence of boron in the composite material, which slows cement's curing time, only 10% of the feedstock can be substituted with waste, which may hinder the application of this recycling method [64,65]. The enhancement of co-processing as a recycling option for managing EoL turbine blades also clashes with other critical issues. Firstly, the processing of solid waste can increase the amount of toxic persistent organic pollutants (dioxins and furans released from cement kilns), leading to scientific/public skepticism and serious concerns about this practice [66]. However, Yang et al. [67] state that the concentration of these organic pollutants emitted by kilns co-processing solid waste is lower than by other industrial plants (i.e., metallurgical smelters and waste incinerators). The high temperatures (>1000 °C) and very alkaline environment involved in cement kilns inhibit the reactions for dioxin-like compound generation. Another issue is related to kiln plant maintenance. Low levels of oxygen in combination with high concentrations of chlorine (Cl) from organic burning may cause the corrosion of the kiln machinery, limiting cement plant stability. The corrosion mechanism can be ascribed to several reactions: alkali chlorides react with metal oxides and hydrochloric acid (HCl) is oxidized, forming Cl_2, which reacts with the iron metal shell. These products are oxidized and hydrolyzed, forming metal oxides and HCl [68].

3.3.4. A Comparative Analysis of Recycling Technologies

Based on the cost of operation, energy consumption to run the process, and Technology Readiness Levels (TRLs) (presented in Table 7 and Figure 11 below), recycling methodologies are compared here. The color legend in Figure 11 categorizes the reported recycling methods into three groups—low, middle, and high—based on the properties of the various processes, outputs and TRLs, but specifically on the residual material value.

Table 7. Overview of current recycling strategies (table drafted from reference [14]).

	Recycling Strategies	TRL	Material Output
1	Mechanical	9	GF/CF
2	Co-processing	7–8	GF
3	Pyrolysis	7–8	GF/CF
4	Microwave-assisted Pyrolysis	4	GF/CF
5	Fluidized Bed	4/5	GF/CF
6	Chemical	5/6	GF/CF
7	HVF	5	GF/CF

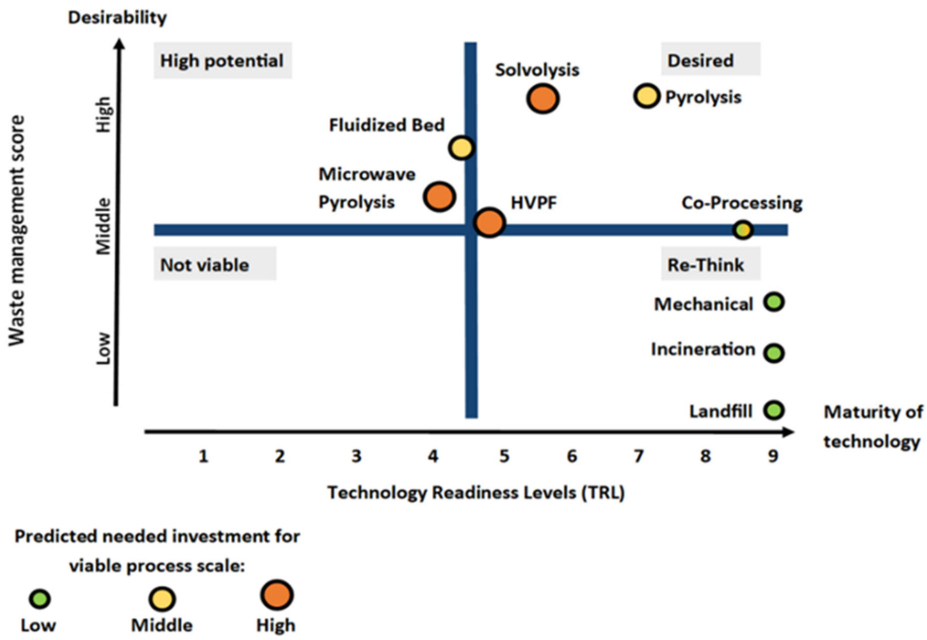

Figure 11. TRL comparison of recycling processes. Reprinted with permission from Ref. [14], 2021, MDPI.

First of all, TRL is a scale to estimate and measure the maturity of a technology and rank it from 1 to 9 [14].

- TRL 1–4: Lab scale.
- TRL 5–7: Pilot scale.
- TRL 8–9: Commercial scale.

It is obvious that, currently, mechanical recycling and co-processing are indicated as the most interesting operations. Among the "desired" waste management practices, pyrolysis and solvolysis protocols are in different stages of development. Pyrolysis seems to be the most mature and well-developed technology for fiber recovery. However, as discussed above, the quality of the recovered material is lower than in chemical recycling. Solvolysis, which better preserves the characteristics of the recovered fibers, can be implemented with a variety of chemicals and process conditions, providing many options for recycling solutions. However, the method has a very uneven level of maturation. Research on CF recovery is focused at the laboratory scale, while some projects on GF are closer to proof of concept [69].

From an energy-demand point of view, generally, it is predicted that 111.88 MJ/kg is required for the fabrication of a piece of composite material. This number consists of fiber production, resin production, the pultrusion process, and additive energy requirements [70]. According to a study, it has been concluded that the energy demand of recycling methods is comparatively 10 to 20 times lower than the energy demand of new material production. It is stated that the production of virgin GF needs 13–32 MJ/kg of energy, whereas virgin CF consumes 183–286 MJ/kg [70–72]. Figure 12 compares the individual processing energy demands of various recycling procedures. It is important to note that most recovery methods use mechanical recycling as an initial pre-treatment to downsize the blades into manageable scraps. For the amounts of energy mentioned in the diagram, no pre-processing or energy-intensive operations are included.

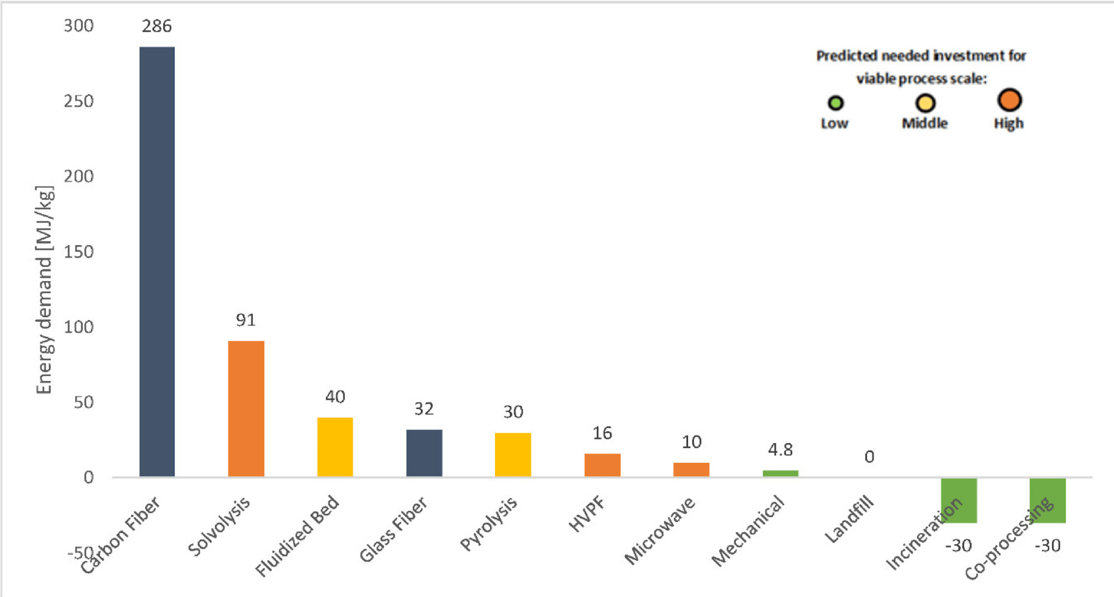

Figure 12. Energy demand of recycling methods and fiber production. Reprinted with permission from Ref. [14], 2021, MDPI.

The relative cost and value of different recycling technologies are shown in Figure 13. The amount and size of the bars are quantitative, and may vary between recycling companies due to the diversity of process parameters such as output rate, capacity, temperature, and pressure [44]. However, it is crystal clear that the co-responding figure outlines for GF recovery, mechanical grinding, and co-processing are preferably cost-effective.

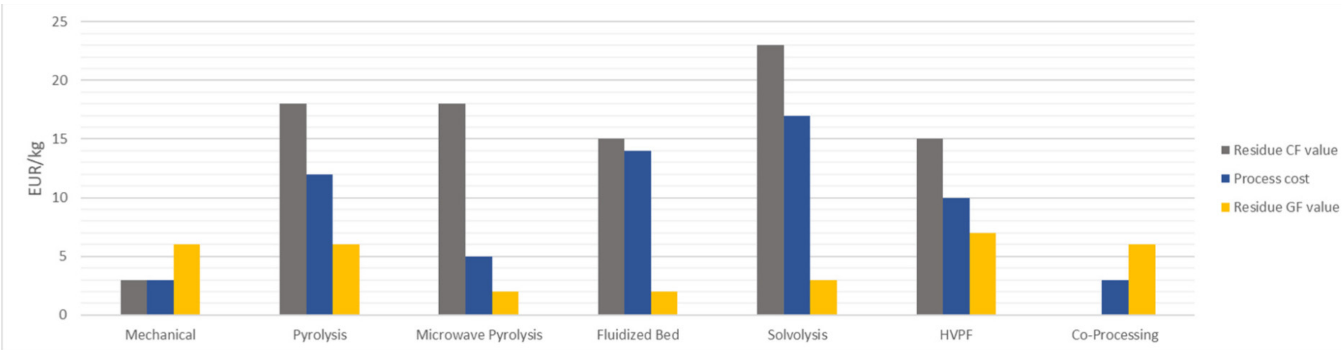

Figure 13. Processing cost evaluation. Reprinted with permission from Ref. [14], 2021, MDPI.

3.4. Prevention

As a first step, design and material selection in each process should consider the overall sustainability of the materials, as this will influence their recovery and recyclability, and how recycling methods must be updated in the future. Furthermore, the other possibility is to keep the blades in service as long as possible before waste management with the help of routine maintenance and repair. On the other hand, this criterion suggests the utilization of bio-based components or thermoplastic polymers to fabricate new composite materials suitable for the wind energy sector. Moreover, sandwich structures made from multiple layers and various polymeric matrixes and fibrous reinforcements could exhibit desirable properties that can be attained easily through engineered material design [11].

3.5. Reuse/Reduce/Repurpose

For this outlook, it is better to monitor the service life and the properties of decommissioned blades to check their function in different applications, rather than ones in use. Prior to this action, some repairs can be performed to fix the weaknesses of damaged blades. In the past few years, multiple attempts have been made in this area to repurpose EoL service blades in a variety of applications. For instance, blades have been reused in northern Europe as pieces of small city furniture or for playgrounds, bike shelters, parking roofs, and elements to construct bridges and sidewalks [11,14,44].

4. Microplastics and EoL Turbine Blades

As we stated previously in the introduction, MPs are polymeric waste particles with an average size of 0.1–5000 µm [73,74]. The EU produces 16% of global plastic production, which is predicted to double by the next decade. In addition, it has been reported that over 80% of marine litter consists of plastic [13]. A study revealed that the highest MP concentrations can be observed in the West Tropical North Pacific Ocean (249–349 particles/m^3), the Mediterranean, and the Gulf of Cadiz (180–307 particles/m^3) [75]. During the "International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris" held in 2008, MPs were classified into two categories: primary MPs and secondary MPs.

Primary MPs are produced either intentionally to be utilized directly, or as precursors for fabricating other materials with various applications and geometries, such as cosmetic goods with microbeads, microflakes, etc., in different shapes and forms [13,73]. Alternatively, the same primary MP terminology has been exploited for particles derived from plastic and polymeric product abrasion throughout manufacturing, usage, and maintenance [13,76].

In contrast, polymeric fragments created in the environment because of giant polymeric object decomposition are known as secondary MPs [13,73]. These discharged secondary MPs can face several degradation and deterioration phenomena based on their polymer physio-chemical characteristics and the environmental conditions they are exposed to (see Tables 8 and 9 for thermoplastic and thermoset polymers, respectively). Although thermosets are preferred in the construction of wind turbine systems, there is a growing trend in the implementation of thermoplastic resins for the design of new blades. Thermoplastic composites provide some advantages over thermosets, such as higher toughness, faster production, and their recyclable nature [77]. Temperature (thermal degradation), light (photodegradation), oxygen (oxidation), mechanical forces (mechanical degradation), various chemicals (chemical degradation), and biological factors (biological degradation) are the so-called environmental conditions under which plastic degradation can occur [13,73]. Notably, these ecological conditions can also release processing additives, such as plasticizers, stabilizers, antioxidants, etc., in addition to causing polymer degradation [13,73]. On the other hand, these conditions could have a synergic/or antagonistic effect on each other, which raises the possibility of the further fragmentation and degradation of MPs into smaller components, i.e., nanoparticles (NPs) with sizes between 1 and 100 nm [13,73,78]. However, a limited understanding of NPs' ecological risks is accessible at this moment [13,79]. In Figure 14, all the details mentioned here about MPs are depicted.

Table 8. MPs obtained from thermoplastic polymers degraded in the environment (table drafted based on reference [80–86]).

Polymer	Degradation Method	Effects	Rate of Degradation (µm/Year)	
Polyethylene (PE)	Photodegradation [80]	Introducing oxygen functional groups on the surface; specific surface area increase [80].	On land (un.acc): HDPE: 1.0. [82] LDPE: 11. [82]	In marine environments (un-acc): HDPE: 4.3. [82] LDPE: 15. [82]
	Chemical degradation [81]	Fragmentation [59].	On land (acc): HDPE: 1.3. [82] LDPE: 22. [82]	In marine environments (acc): HDPE: 9.5. [82] LDPE: 10. [82]

Table 8. *Cont.*

Polymer	Degradation Method	Effects	Rate of Degradation (μm/Year)	
Polypropylene (PP)	Photodegradation [83]	Volume reduction in MP particles [83].	On land (un.acc): -	In marine environments (un-acc): 7.5. [82]
	Biological degradation [84,85]	Polymer mass reduction; structural and morphological changes [84,85].	On land (acc): 0.51. [82]	In marine environments (acc): 4.6 [82]
Polystyrene (PS)	Biological degradation [86]	Changes in surface morphology, weight loss, and decreased carbon content [86].	On land: -	In marine environments: -

Table 9. MPs derived from thermoset polymers (table drafted based on reference [87,88]).

Polymer	Degradation Method	Effects	Time (Year)	References
Polyester resin (Vinyl ester)	Aging in the natural environment: (room temperature 22 °C, pH = 7).	Mechanical integrity loss	3	[87]
Epoxy resin	Aging in the natural environment: (temperature −6.3–31 °C, humidity: 74.3%).	Mechanical integrity loss	5	[88]

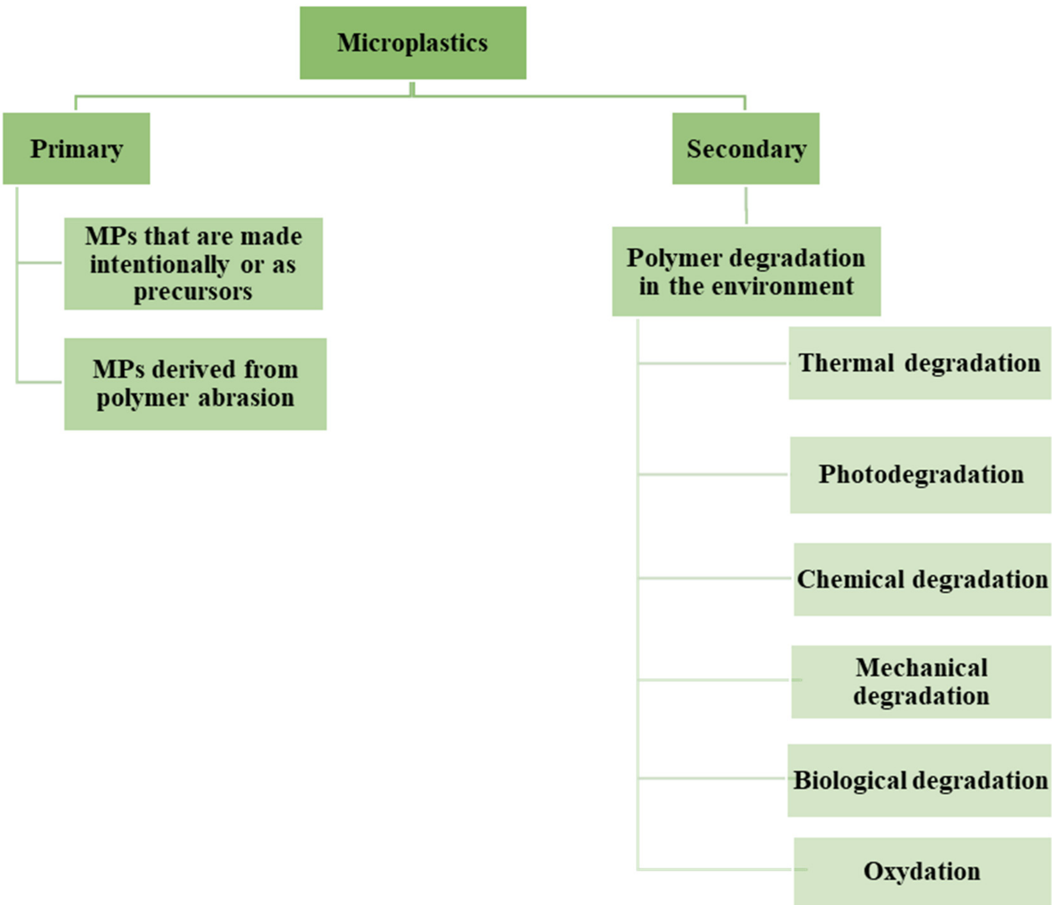

Figure 14. MP classification (authors' own illustration).

The growth of both primary and secondary MP formation and build-up, as an emerging hazard of the current century for living beings and the Earth, is a crucial global concern, as their potential side effects on humans, animals, and our planet have remained vague till now [13]. Therefore, we can say that, unfortunately, there must be some inherent characteristics of MP particles that give them this opportunity to aggravate and worsen life on planet Earth. High bioavailability and large surface area are the intrinsic aspects behind all the issues that arise from MPs [13]. For instance, it has been shown that MPs can alter ecological factors and the parameters of their surrounding environment, such as the qualities and properties of soil, water and wastewater, air, etc. [73,89]. Along with this fact, as formerly specified by scientists and environmentalists, their generation and accumulation potentially threaten a variety of species' life, with issues for both aquatic and terrestrial living beings due to the adverse outcomes they cause in nature [13,73]. They can travel for kilometers, quickly entering and contaminating the food and beverage chain [73]. Last but not least, unfortunately, this process will even pave the path to endanger the health of humans and animals and enhance the risk of diseases from mutation, immune reactions, cancers, and inflammation, leading to respiratory and neurodegenerative diseases [13,73].

As explained in the second section, we considered two waste streams of turbine blades. One of them is EoL turbine blades, which represent the most considerable fraction of waste. Waste originating from manufacturing processes, installation, maintenance, and repair is the other expected waste stream. Hence, from this point of view, both primary and secondary MPs will be derived from blades' waste in a short period. Finally, the proper waste management of turbine blades will inhibit the hazards caused by MPs either by formation or accumulation [89].

5. Future Perspectives

The visions for the "Waste Management of WT Blades" are promising, as scientific communities from around the world are gathering and making efforts to come up with appropriate solutions for a clean environment. These future perspectives are highlighted in the following paragraphs.

Obviously, fabrication processes and their machines will become so well established and high-tech that less manufacturing composite waste will be generated. Hence, the production rate of this waste stream will decrease [45].

In addition, due to the scarcity of natural resources such as oil, petroleum, minerals, etc., developing a single or hybrid optimized process to recycle and recover valuable derivatives such as resins and fiber reinforcements will take place. This optimized recycling procedure will help us to produce recyclates with higher economic added value and satisfactory mechanical performance for fabricating new materials accepted by the market [44,45,90,91].

Presumably, academia will soon shift its research attempts toward "bio-based composites" to initiate the mass production of brand-new rotor blades and accelerate their recovery [13,45]. On the other hand, scientists will also try different thermoplastic resins and mixtures to create a new generation of blades that fulfil the needed characteristics of adequate mechanical properties and ease of recyclability.

It is noteworthy that the chain of success for blades' waste management is also dependent on international firm regulations and huge governmental investments against harmful traditional methods to promote industrial companies and their owners to build a "green" mindset and move towards "sustainability" and a CE by supporting all recycling efforts [45,91].

Finally, it is crystal clear that all noted future perspectives will hinder MP accumulation and facilitate solving the environmental hazards that arise from them.

6. Conclusions

Green energy consumption and establishing proper waste management infrastructure have been set as global goals worldwide. By keeping these visions in mind, hopefully, law legislation by leaders, international associations, and governments will facilitate us to alter the world's current environmental issues, from climate change to microplastic hazards, to achieve sustainability and CE. Research completed in the recent past revealed that wind power, as one of the most efficient renewable energy sources, has the ability to generate green electricity. Therefore, based on the statistics and assumptions related to the increment in wind energy being installed up to 2050, an appropriate pathway to deal with the upcoming tide of decommissioned WTBs must be considered. From another point of view, using traditional disposal routes such as landfill and incineration for handling this massive amount of litter could not only boost the probability of ecological hazards, but could also act as a threat to the life of all creatures. As a result, the waste management of retired blades composed of multi-lateral thermoset composite materials through a sustainable, practical, and feasible single or hybrid process is necessary. Overall, of the mentioned methods, co-processing could be one of the most cost-effective, eco-sustainable, and feasible recycling routes suggested until now for fiber-reinforced composite materials, simultaneously enabling material and energy recovery to ensure microplastic prevention to preserve our ecosystem as a safe place to live. Finally, this paper aimed to address future research efforts towards the establishment of networks between material producers/suppliers, the wind energy industry, and recyclers to mark this sector as sustainable not only in terms of energy production, but also in terms of material valorization and environment protection. Once the optimal disposal strategies have been identified, the next steps to mitigate the impact of MPs will involve a possible upgrade of recycling plants through the implementation of advanced methods for the detection and quantification of microplastics. This approach could be conducive to rigorously monitoring the degradation mechanisms of plastics during the recycling route, promoting material selectivity.

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