microplastics

Review

End-of-Life of Composite Materials in the Framework of the Circular Economy

Georgia Chatziparaskeva [1], Iliana Papamichael [1], Irene Voukkali [1], Pantelitsa Loizia [1], Georgia Sourkouni [2], Christos Argirusis [2,3] and Antonis A. Zorpas [1,*]

1 Laboratory of Chemical Engineering and Engineering Sustainability, Faculty of Pure and Applied Sciences, Open University of Cyprus, Giannou Kranidioti 33, Latsia, 2220 Nicosia, Cyprus; georgia.chatziparaskeva1@ouc.ac.cy (G.C.); iliana.papamichael@gmail.com (I.P.); voukkei@yahoo.gr (I.V.); pantelitsa-loizia@hotmail.com (P.L.)
2 Centre of Materials Technology (CZM), Clausthal University of Technology, Leibnizstr. 9, 38678 Clausthal-Zellerfeld, Germany; cogsa@tu-clausthal.de (G.S.); amca@chemeng.ntua.gr (C.A.)
3 Laboratory of Inorganic Materials Technology, School of Chemical Engineering, National Technical University of Athens, I. Polytechneiou 9, 15773 Athens, Greece
* Correspondence: antonis.zorpas@ouc.ac.cy or antoniszorpas@yahoo.com; Tel.: +357-22-411-936

Abstract: Composite materials constitute an appealing choice in many industrial sectors, due to their unique composition and characteristics, such as low maintenance requirements, light weight, corrosion resistance, and durability. However, the sustainable management of end-of-life composite materials remains a challenge. Recovery strategies, design aspects, and their interconnection are currently largely unexplored, while technologies involved in the circular economy (reuse, reduce, recycle, refurbish, etc.) could be improved. The current paper provides an overview of the existing methods of composite material waste management, while presenting new circular economy prospects for end-of-life strategies and providing a brief roadmap towards circularity for industries. Finally, existing circular economy practices in regard to composites are presented in different European countries to present the applicability of composite material end-of-life waste management.

Keywords: composite materials; circular economy; end of life; waste management

Citation: Chatziparaskeva, G.; Papamichael, I.; Voukkali, I.; Loizia, P.; Sourkouni, G.; Argirusis, C.; Zorpas, A.A. End-of-Life of Composite Materials in the Framework of the Circular Economy. *Microplastics* **2022**, *1*, 377–392. https://doi.org/10.3390/microplastics1030028

Academic Editors: Nicolas Kalogerakis and Tony Robert Walker

Received: 3 June 2022
Accepted: 9 July 2022
Published: 20 July 2022

1. Introduction

Composite materials have been in the foreground of sustainability, supporting the efficient use of energy and materials through their specific chemical and mechanical characteristics. Their principle characteristic is the combination of two or more materials (reinforcing phase and matrix phase) with significantly different physical or chemical properties that do not interact with one another, but rather work together to give unique properties to the materials [1,2]. On a macroscopic scale, the phases are combined and indistinguishable from one another, while microscopically, the phases are separated and each phase exerts the properties of its original pure material [3]. Figure 1 illustrates some of the most commonly used materials in composite matrices and reinforcement [1,4]. Due to their high corrosion resistance, as well as high stiffness and light weight, composite materials have a long lifespan with low maintenance, while their unique structure allows composite materials to be used in automotive and aerospace infrastructures, as well in renewable energy, as they are commonly used in wind turbines and photovoltaic (P/V) panels [5].

Common materials used in the reinforced phase are glass, polymers, metals, ceramics, and graphite, with the most widely used being E-glass, which provides easy compatibility with matrix polymers and is low cost. For the matrix, common materials include metals, ceramic, and glass, while the most commonly used are polymers. The polymers used are divided into three different categories according to their physical properties: elastomers, thermosets, and thermoplastics. Thermosets and thermoplastics are the most commonly used polymers in the manufacturing of composite materials. The low viscosity and molecular weight of thermosets make them useful in low-cost processes, while when heated or activated by UV light, microwaves, or electron beams, thermoset resins undergo chemical reactions forming cross-linked polymers with a high molecular weight. On the other hand, thermoplastics are linear polymers with a high pre-existing molecular weight and are fully formed before the creation of a composite matrix. Contrary to thermosets, when heated (above their glass transition temperature), thermoplastics soften and exhibit low viscosity, with easy flow to cover the composite. They require much higher temperatures and pressure than thermosets to adequately melt and consolidate on the composite material, but at the same time, thermoplastics are much easier to recycle and reprocess [4]. According to Statista, concerning the market value of thermoplastic composites worldwide from 2019 to 2024 [6], thermoplastic composite materials are expected to have a total market of USD 36 billion by 2024 due to their applications in aerospace defense, consumer goods, and electronics, as well as transportation. Similarly, carbon-fiber-reinforced thermoplastics used in the automotive and aerospace sectors due to their light weight and strong impact strength will have a market value of USD 7.76 billion by 2025 [7].

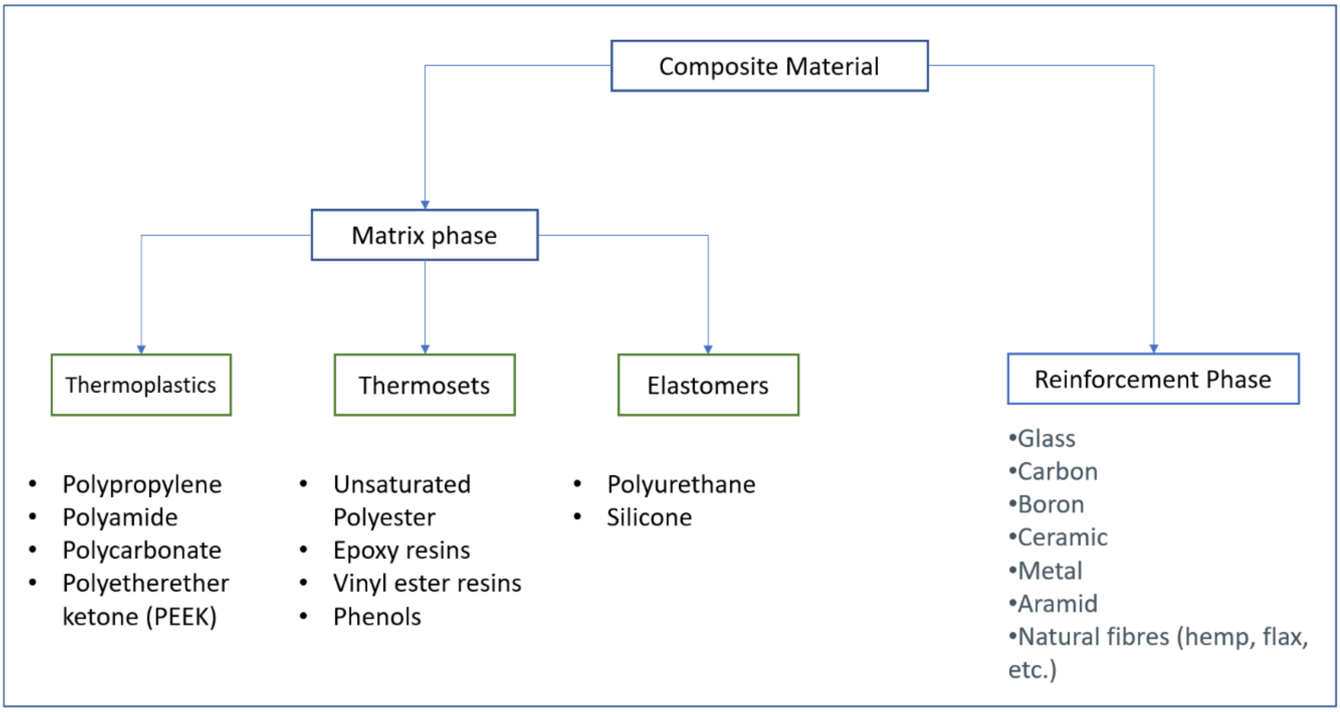

Figure 1. Some of the main components used for the production of composite materials in both the matrix and reinforcement phases.

The reinforced material is bound by a matrix enhancing the distribution of load across the composite. Their properties allow composite materials to be tailored to fit the loading requirements of structures in industrial architectural applications as well as in transportation and infrastructure, thus replacing traditional engineering technologies such as concrete. They can be tailored to twist when loaded in plain view and extend when bended. Many natural materials are classified as composites without requiring human intervention, such as wood (cellulose fibers and lignin matrix), bone, (hydroxyapatite and protein matrix), and even exoskeletons of insects (layers of fibrous chitin and protein matrix) [4].

Such usage has projected the value of composites in the market as, by 2026, the worldwide use of advance composite materials is expected to project to USD 59.6 and USD 144.5 billion by 2028 [8,9]. According to Statista [10], structure (USD 492 million), thermal protection (USD 382 million), and solar array panels (USD 328 million) are estimated to be among the highest valued composites. Furthermore, composite use in the space market is expected to grow in size from USD 846 million in 2020 to USD 2.9 billion by 2031 [10].

In order to benefit fully from the circularity potential of composites, attention must be given to their full life cycle. The most popular disposal method for composites is still landfilling. This represents a significant loss of high value materials terminating the opportunities to gain more value through circular thinking (i.e., recycle, reuse, reduce, etc.). This problem is particularly with thermoset structures used commonly in wind turbine blades. Composite manufacturers are increasingly adopting a sustainable development profile as the composite industry has seen the necessity for an increase in material efficiency due to the natural scarcity of natural resources. These efforts include extending the life of machinery, components, and spare parts, as well as constantly searching for new product innovations to replace previous products that consume larger quantities of raw materials. The main point of long-term material efficiency being adopted and sustained is to demonstrate that there is also a consumer benefit. The composite industry is committed to develop solutions that improve people's well-being while reducing the socio-environmental impact of composite products. This requires an approach from the cradle to the grave. There will always be a consumer demand for value-added products, with fewer negative effects on the environment. The composite sector is an active industry that secures a bright future for manufacturing and jobs. The size of the global composite market was USD 90 billion in 2019 and is expected to rise with a growth rate of 7.6%, reaching USD 160 billion by 2027 [11].

Nowadays, composite materials are increasingly replacing classic materials in a wide variety of fields, from household items to components for spacecraft or nuclear power plants. Sustainability is becoming an increasingly exciting argument in the materials selection process. Fiber-reinforced composites are strong, lightweight, and durable materials that are increasingly being adopted in transportation, construction, renewable energy, and many other markets. Sustainability in their use phase is often a key factor for the selection of composite materials over traditional materials. Composite constructions offer long service times combined with low maintenance requirements, and lightweight composites result in lower energy consumption throughout the life of a product [12].

Current methods of disposing composite materials involve mostly landfilling, cement clinker co-processing, recycling by matrix degradation (i.e., use of microorganisms, electrolytes, solvents), matrix decomposition by the fluidized air-bed method, high-voltage fragmentation, microwaves, and mechanical recycling [13,14]. As it is known, landfilling, especially of composite materials, represents a high loss of high-value materials and energy input for their production, as well as loss of opportunities for reusing composites in other investments. Therefore, there is a need for innovation regarding composite end-of-life disposal methods in order to integrate the materials into a circular economy mindset and increase value chain approaches by companies for high-quality recycled materials. At the same time, since the disposal of composite materials seems to be much more difficult than conventional materials, the replacement of some of them in their respective application and the search for alternative materials for lightweight products needs to be continued.

To date, there is limited legislation governing the treatment of composite waste or blade waste both nationally and at EU level. In general, authorities have different regulatory instruments to motivate the practice of recycling. These include landfill bans, increased taxes, legally binding targets, and requirements for Extended Producer Responsibility (EPR). This would probably be more efficient in developing a European blade waste recycling market. There would also be an agreement with other sectors of composite recycling. However, there is a clear impetus toward more circularity in general in the EU as shown by the new EU Circular Economy Action Plan (CEAP) (2020) [15]. The «European Strategy for Plastics in a Circular Economy» (2018) emphasizes that the low reuse and recycling rates of plastics at the end of their life cycle is a key challenge that must be addressed. The strategy also emphasizes that the private sector along with national and regional authorities, cities, and citizens will need to act to fulfill this vision. To date, it has not focused on composite waste. According to the European classification of waste [16] and WindEurope [17], the most common category of composite blade waste is plastic waste from constructions and demolitions with code 17 02 03. National authorities need to make certain that the correct and sustainable code is applied to blade waste. It is of utmost importance to ensure the methodical and efficient separate collection and sorting of composites and to assist in the identification of appropriately approved waste treatment options from separate collection and sorting.

The Sustainable Development Goals (SDGs) [18] launched by the United Nations (UN), especially goal number 12, deals with responsible consumption and production. In the long term, such an initiative could contribute to a more circular economy. Kirchheee et al. (2017) [19] defined CE as an economic system that replaces the concept of end of life by the reduction, alternative reuse, recycling, and recovery of materials in production, distribution, and consumption processes.

The current paper focuses on end-of-life composite materials from the aviation industry, solar panels, wind turbines, as well as challenges and opportunities regarding the circular economy of these materials after their use.

2. Methodology

The PRISMA statement of preferred reporting items for systematic reviews and meta-analysis was used for the identification of the **70** records (www.prisma-statement) (accessed on 25 April 2022) [20]. Inclusion and exclusion criteria were used to target the investigation and relation of composite materials and circular economy in regard to end-of-life disposal. Specifically, the inclusion and exclusion criteria are presented in Table 1.

Table 1. Inclusion and exclusion criteria for PRISMA statement.

Inclusion Criteria	Exclusion Criteria
Year of publication (2017–present)	Non-English papers
Reports and data (2010–present)	Insufficient data
Published in English	Irrelevant data
Including keywords	Duplicated records

Furthermore, primary data were collected through Statista and other reliable statistical sources and evaluated through specific criteria, such as accuracy and year of publication. The main database used was SCOPUS, while the keywords chosen were “Composite materials” AND “Circular Economy”, “Composites” AND/OR “end-of-life”, “Aviation waste” AND/OR “composites” AND “Circular Economy”, “Solar Panels” OR “Photovoltaic” AND “Circular Economy”, and “Wind turbines” AND “Circular Economy”.

At the same time, the methodology used for the recruitment of articles, reports, and records is illustrated in Figure 2. Using the PRISMA statement, the authors started off with the identification of 546 records using the keywords provided above. Through the exclusion and inclusion criteria, the number of records dropped to 166. Then, the authors manually excluded or included the records by first analyzing the abstract of the record and then the full article for eligibility. Through the process, 70 records were used in the study, which included 48 articles and 22 reports (official webpages, official reports).

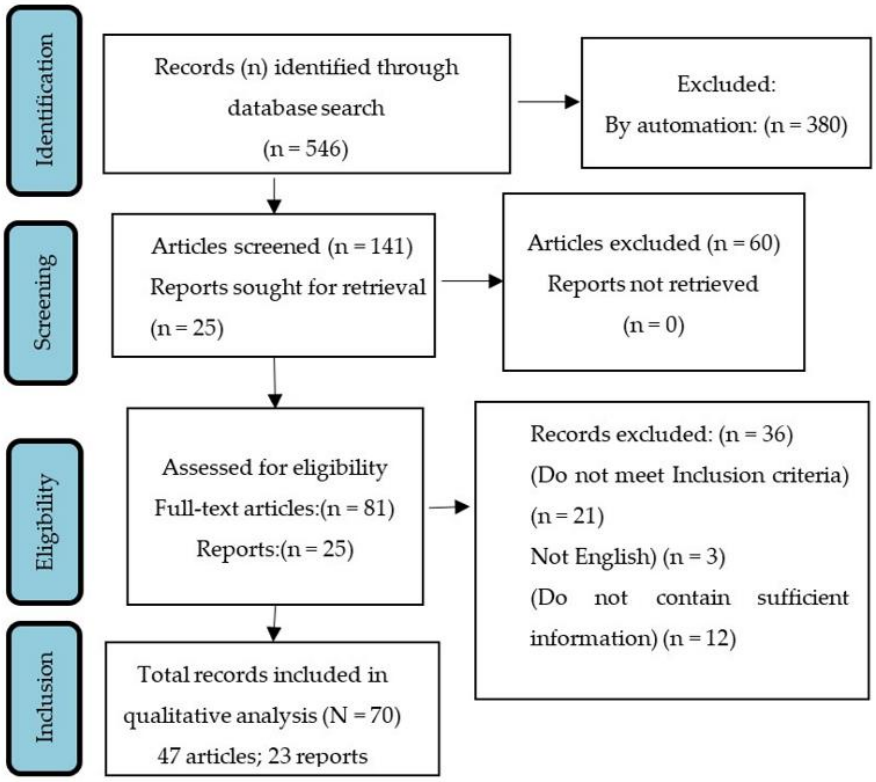

Figure 2. PRISMA statement of current study for recruitment of scientific records, reports, and articles.

3. Results and Discussion

3.1. Solar Panel Composite Waste

In recent years, any government that acknowledges the need for a transition towards a greener society, aversion from fossil fuels, and natural resource use, place renewable energy source installations as very high priority. EU strategies, such as the European Green Deal (EGD), encourage this transition, setting clear goals for clean energy production and decarbonization of energy systems until 2050 as the energy sector accounts for more than 75% of greenhouse emissions (GHGs) in the world. The goal of the EGD is the decrease in GHGs at least by 50% by 2030 compared to 1990 and to reach carbon neutrality by 2050 [18,21,22]. At the same time, the United Nations' (UN's) Sustainable Development Goals (SDGs) and specifically SDG 7 for affordable and clean energy support such logic, aiming to stabilize energy security and the transition towards renewable energy. Additional economic incentives are rapidly aligning towards green energy production encouraging customers and governments to install solar panels, wind turbines, etc. Even so, in an industry where circularity solutions remain an issue concerning composite materials integrated, for instance, in P/V panels, the large volume of waste after the end of life of the panels results in severe disposal issues [23,24].

Assuming the average lifespan of P/V panels is around 25 years, the accelerated growth of renewable energy use will also translate to accelerated end-of-life disposal issues of solar panels and extend to composite materials. Hitherto, solar panels have been simply manufactured, commercialized, used, and discarded in landfills [25]. In 2018, the installation of P/V represented about 2% of the world's electricity output [25], while according to Statista [26], the projection of P/V panel waste accumulation worldwide is estimated to reach 1.7 million metric tons by 2030 and 60 million tons by 2050. Solar panels vary in composition according to the manufacturer; however, they usual constitute of silicon solar cells; glass sheets; polymers, such as poly-methylmethacrylate (PMMA) also known as plexiglass; as well as metal frames. Such diversity in their composition complicates their disposal and implementation of circularity.

The most common methods of end-of-waste handling of P/V panels include recycling and reuse. the Recycling of P/V occurs mostly through physical separation or mechanical crushing, and less through thermal treatment. The recycled material can then be reused as filling in building constructions. More challenging recycling methods are chemical and thermal treatments [27]. Due to the variability of the solar panels, they are commonly selected according to a specific solar panel due to the difficulty of standardization. Most of the time, valuable rare elements are recovered, while the rest of the materials are incinerated. At the same time, implications through thermal treatment arise concerning the excursion of hazardous by-product emissions. Therefore, the incineration of composite materials is not commonly used [3,27].

Furthermore, the most desired waste-management practice is reusing solar panels in a form of solar cell recovery, therefore diminishing composite waste too. Even though desirable, this method has severe limitations, including the localization of the solar panel. Currently, in order to avoid the full disposal of the solar panel, the replacement of components to extend the life cycle is implemented [3].

Lastly, landfilling is still the less desirable option, but even more so for solar panel disposal as the energy loss and leaching toxicity issues of composites in landfills deem the method not only undesirable in terms of waste management, but also dangerous for human health and the environment [3]. There is a significant need for the circularity of solar panels with regard to innovations in reuse and recycle technologies for their incorporation in industrial practices. The composition of current P/V panel designs does not allow for advances in safe and sustainable disposal practices, and therefore provides low-value recycling results and landfilling. This does not only translate to environmental implications, but also Franco and Groesser (2021) [25] mentioned the loss of profitability in the industry resulting from non-adequate recycling processes. The low volumes of recycled composites as well as the high collection and transportation costs decrease the incentives of manufacturers to search and innovate in this regard.

3.2. Aviation Composite Waste

End-of-life aviation composite waste and aircraft structures create issues to be addressed. According to the International Air Transport Association (IATA) [28], until 2030, there will be a further retirement of approximately 11 thousand aircrafts. Since the COVID-19 pandemic limited air travel for three years, inevitably there will be an acceleration of this retirement, placing even more pressure on the end-of-life disposal of composites [2]. The use of carbon fiber composites in aircrafts and the aerospace industry is significantly high. In 2020, the revenue for the use of advanced space composites was around USD 846 million worldwide, while it is expected to rise to USD 2.9 billion by 2031 [10]. Taking as an example the Airbus line of aircrafts, according to the type of aircraft, the use of composite materials fluctuates approximately from 5–55% of the manufacturing materials used, for Airbus A350 composites constitute 53% in the outer flaps, nose, wing ribs, bulkhead, floor beams, and other significant parts [2].

The lifespan of a commercial aircraft is heavily decided upon economic and safety factors, and therefore it is influenced by maintenance and repair protocols. It also requires constant upgrades for compliance with the general health and innovation of the industry, as well as new safety regulations. General composite waste from the aviation industry is categorized into manufacturing waste and end-of-life waste. The main 'ingredients' in composite manufacturing are carbon-fiber-reinforced polymers (CFRP) and epoxy resins [14]. CFPRs constitute an ideal material for aerospace engineering applications due to their lightweight characteristics and weight-saving outcomes and temperature-change durability [29].

Even so, the waste disposal of them remains a difficult area of focus. For instance, a Boeing 787 aircraft contains around 18 tons of carbon fibers in its structure and 470 aircrafts are operating right now. When their life span ends, this means that approximately 8.4 ktons of carbon fibers could be recovered from around 13 ktons of composite waste [14]. Disposal issues arise in this regard as, for instance, the CFPR combination with hexavalent chromium primers does not allow for the recycling of these parts. Disposal in landfills is considered harmful as they are classified as hazardous waste. Classified as such, waste is able to affect human health and the environment (i.e., soil, air, and water). Therefore, carbon fiber composites coated with chromium primers may affect the quality of the environment by the leaching of toxic chromium into the soil. At the same time, the presence of epoxy and phenolic cross-linked molecule structures produces significant challenges for conventional disposal and recycling technologies [4,14]. The reason for this is that polymer matrices are usually thermoset materials and therefore cannot be remolded due to their cross-linked structures, compared to thermoplastic and elastomeric matrices. Furthermore, due to the different reactivities between compounds contained in composites, it is very difficult to handle and treat them in the same conditions. At the same time, the conventional recycling of such composites creates waste-management concerns due to liquified waste, such as acids, bases, surfactants, and solid waste [30].

3.3. Wind-Park Waste

Since the early 2000s, the wind-energy sector is one of the most important consumers of composite materials and one of the fastest growing sources of electricity generation in the world [31]. The total wind-power capacity installed at the end of 2016 was 153.7 GW, which was enough to cover 10.4% of the EU's total electricity consumption in a normal wind year [32]. Up until 2018, the total number of wind turbines installed in the EU was about 77,000, assuming a mean wind turbine power of 2 MW [33], with a combined power of 153.7 GW, and a project lifetime of 20 years. The EU's binding target by 2030 is to increase the share of renewable energy sources to 27% and to reduce GHGs by 80–95% by 2050 [32]. In addition, the EU has also set ambitious goals for renewable energies, with 32% of renewables energies consumed in 2030 [34], emphasizing the important role of wind energy in the future energy mix.

Liu and Barlow (2017) [35] predicted that, currently, the EU has to process more than 50 ktons of end-of-life wind turbine blades. However, a growing amount of wind turbines will be decommissioned considering that the standard lifetime of a wind turbine is 20–25 years and there are increasing repowering opportunities, i.e., replacing old components/models with newer and more efficient components/models [36].

Recent publications show several concepts, mainly, in one-off applications: housing [37], bridges [32], and power-transmission line poles [38]. Such studies demonstrate the feasibility of reuse but identify that the actual larger scale realization needs to be studied further in terms of logistics and costs, reprocessing technology, traceability of specifications' material quality, and social acceptance concerning the intended reuse application, as mentioned by Joustra et al. (2021) [39].

3.4. Circular Economy and Composite Materials

In order to integrate the use of composite materials more firmly into a CE mindset (other than reuse and recycle), all lifecycle perspectives of the materials must be investigated. Such an approach will have to demand changes throughout the life cycle of the materials, from product design to end of life, while a large portion of stakeholders (i.e., policy makers, government, customers, and academia) will have to be involved. Underlying principles, such as extended produced responsibility (EPR), along with similar policies, standards, and certifications will aid in shaping circularity in this regard [27].

In order to approach a circular thinking regarding the difficult end-of-life opportunities of composite materials, many R-strategies of circularity (i.e., reuse, reduce, recycle, refurbish, remanufacture, etc.) should be taken into account (Figure 3), namely [3,40–44], (i) ***reuse*** to extended the lifetime of composites to avoid disposal implications; (ii) ***repair***, maintain, and upgrade products to ensure efficiency and usability; (iii) ***recover*** products and increase the number of their cycles; (iv) ***remanufacture*** the structural elements while preserving material composition; (v) ***refurbish*** materials in another context of life construction; (vi) ***replace*** composites with other lightweight materials (i.e., integrate biocomposites) for easier waste management; and (vii) ***recycle*** materials to close the loop (i.e., recycled carbon fibers).

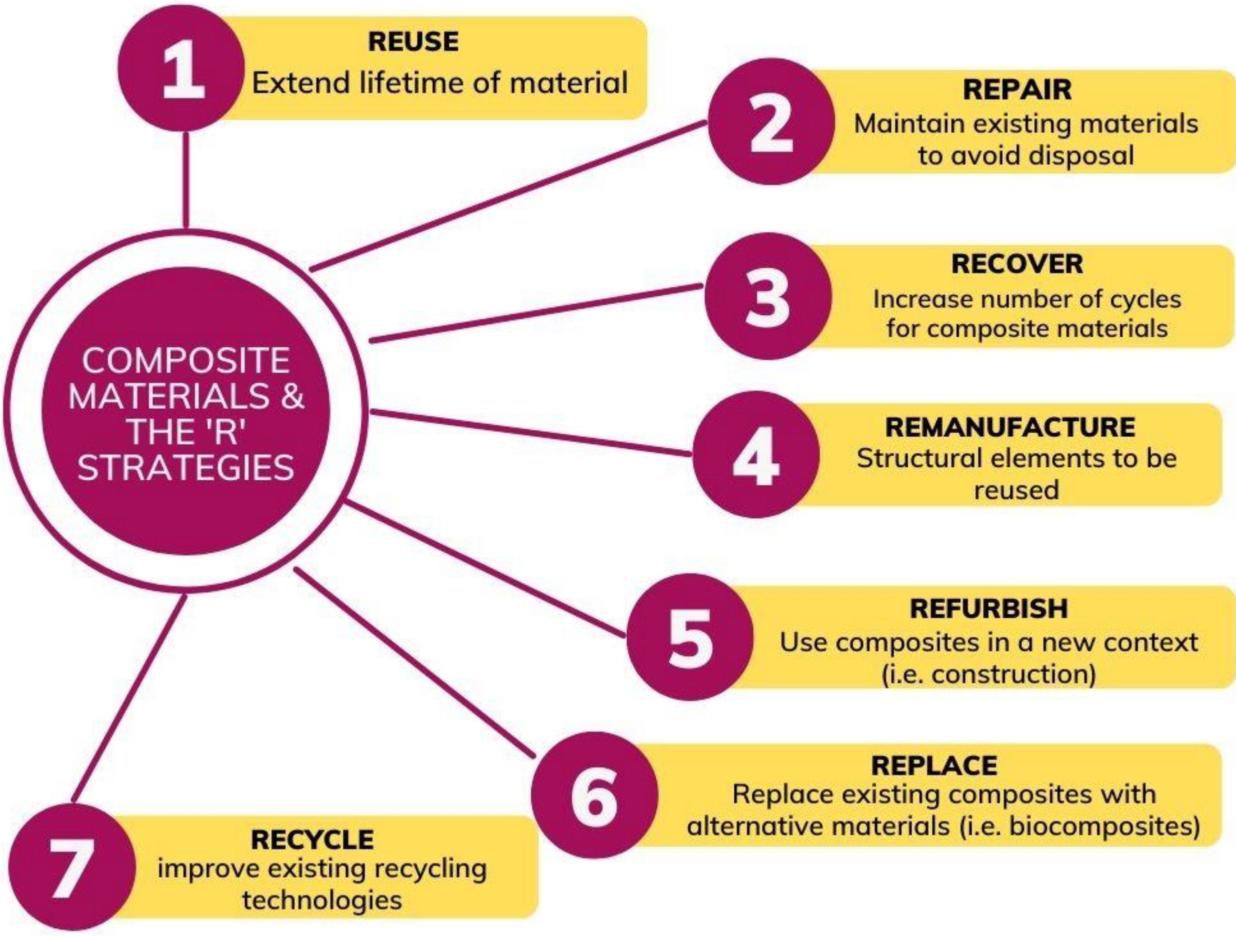

Figure 3. The use of the 'R' strategies for composite material waste management.

Nonetheless, recycling and recovery are of the highest priority concerning composite materials. Their high rank in the hierarchy comes also from the Waste Framework Directive, explaining that the most effective way of managing waste is the prevention of waste creation in the first place [45,46]. Recycling and recovery are the areas for which the most important technologies are developed. The motivation of industries to recycle multi-material composite waste arises from the cost of clean material production and environmental problems. The zero-waste production philosophy cannot only rely on recycling but should also entail reuse, remanufacturing and refurbishment as they are usually more profitable for the environment.

In order to enhance the development of innovation regarding the recycling of composites and to overcome the challenges, the development of new technologies and the optimization of existing ones should be a key area of focus along with proper law regulations and quality protocols for the end of life for such materials. For the smooth monitoring and reporting of any action implemented regarding the enhancement of CE concerning composites, quantifiable reports and data have to be obtained in order to inspect the environmental, social, and economic issues regarding circularity, but also to monitor the development of a new mindset [3]. These data can only be present by the use of Key Performance Indicators (KPIs), end-of-waste criteria (EWC) for the composite material according to their composition, material flow analysis (MFA) from design to manufacturing and disposal, and other common scientific tools (Figure 4) [21,40,47–50].

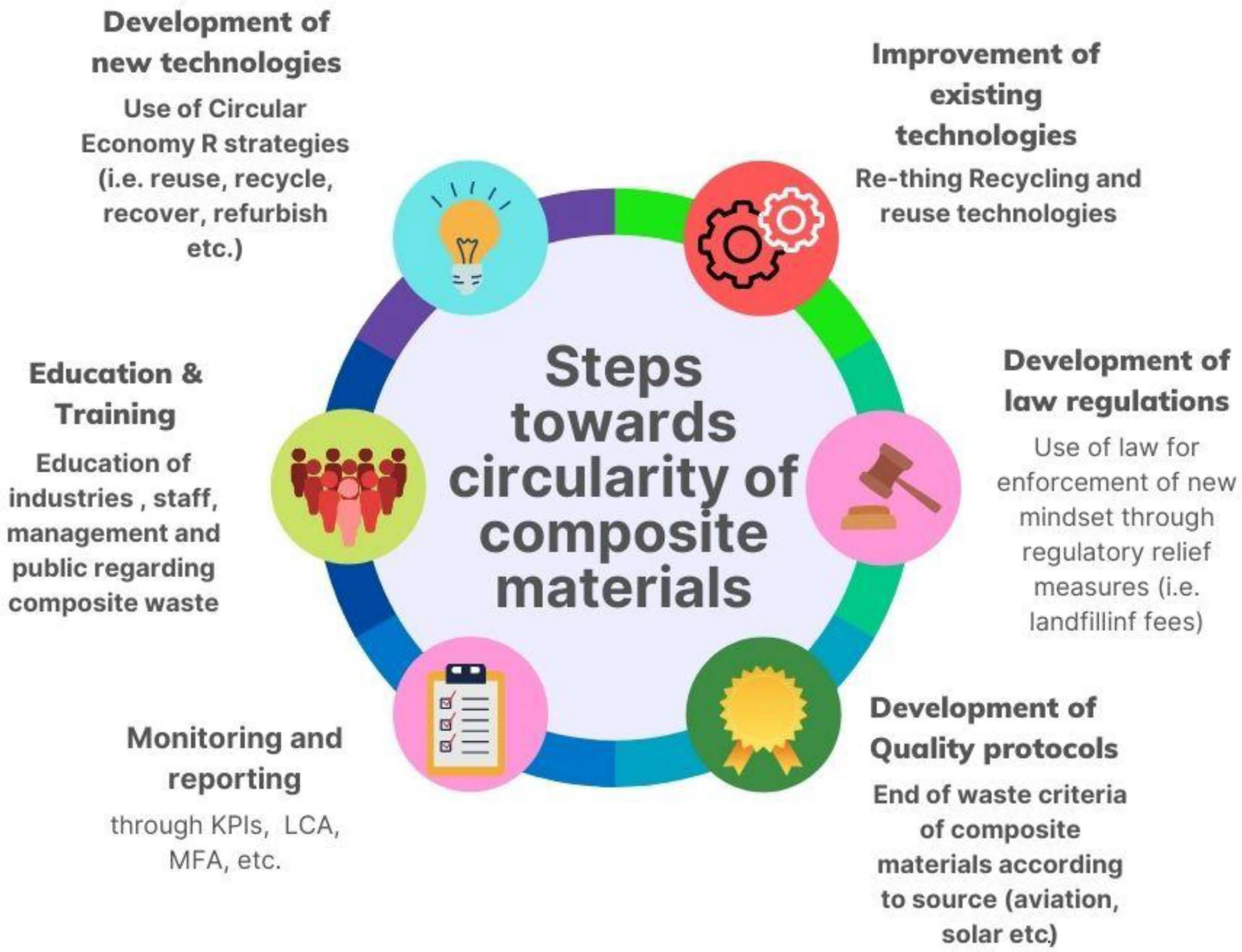

Figure 4. Steps towards the circular economy in regard to composite materials.

In this framework, biocomposites have gained increasing traction as environmentally friendly alternatives to synthetic composites. According to Statista [51], biocomposite production in the EU in 2020 was around 480 thousand metric tons, while by 2028 it is forecasted to reach 590 thousand metric tons. Unlike the non-degradable nature of conventional composite materials, biocomposites are bio-based polymers and fillers extracted from renewable natural sources (i.e., wood, palm-leaf sheath, apple pomace, bacterial cellulose, eggshells, shellfish shells, etc.). They are less environmentally harmful as they are recyclable and reusable [52–55]. At the same time, the most commonly used biopolymers in the development of biocomposites include (poly)lactic acid (PLA), (poly)hydroxyalkanoates (PHAs), cellulose esters, and starch-based plastics [56].

Hence, the development of biocomposites should be integrated within a CE model to ensure a sustainable production that is simultaneously innocuous towards the environment [57]. Most plastics are created from synthetic organic solids containing petrochemicals acquired from fossil-based fuel. According to Shanmugam et al. (2021) [58], the most important benefit from the use of biocomposites is the easier management of end-of-life products. At the same time, biocomposites can be used as fillers in plastic composites, therefore increasing their biodegradability, while simultaneously increasing the durability of the entire composite system. The use of biocomposites as bio-fillers with conventional plastic composites does not have a negative effect on the desirable characteristics of the overall material; instead, they provide increased tensile strength. Biocomposites as fillers can be used in domestic environments for the production of many different structures, such as fences, windows, and door frames, while, at the same time, some biocomposite materials can reduce domestic waste. For instance, the use of powder from walnut shells can be used as a biocomposite filler to decrease wood shortages in walnut-rich countries and lower the cost of biocomposite production. Similarly, chicken eggshells are considered an extensive environmental issue in egg-production industries, as eggshells have no added economic value to them and are therefore discarded in landfills. Nevertheless, they are considered an excellent potential calcium source and can be used for the production of polypropylene composites along with commercial talc and calcium carbonate [59].

The commercialization and more in-depth investigation of the further application of biocomposites will allow for the manufacturing, usage, and disposal of composite materials to increase their contribution to the circular economy. The CE's main goal is to maintain sustainability by reducing waste and preserving resources at their maximum value. Although the concept of CE is concerned with reducing the carbon footprint at every stage of a product's life cycle, one way to incorporate the concept is to use waste for the development of composites, which will help mitigate the take–make–use–dispose mentality that is so prevalent in today's society. Adapting the CE for biocomposites improves their recyclability and reusability, as well as their ability to convert biocomposite waste into useful products, energy, or secondary materials, potentially reducing biocomposite waste landfilling [58].

3.5. Countries Handling Composite Materials

At the national level, four countries make a clear and comprehensive reference to composite waste in their waste legislation. The countries are Germany, Austria, the Netherlands, and Finland, banning the landfilling or incineration of composite materials. In addition, various countries have implemented good practices that are described below.

3.5.1. Germany

A ban on directly landfilling waste with a total organic content higher than 5% came into force in 2009. Considering blades that contain an organic part, they therefore cannot be landfilled. In response to this regulatory constraint, a technical solution was developed for handling larger amounts of glass-fiber-reinforced polymer waste in northern Germany, which uses around 15 ktons of composite waste annually, 10 ktons of which comes from wind turbine blades. The plant has a total current capacity of 30 ktons per year. The cost is around EUR 150 per ton (gate fee). Recycling large amounts of glass-fiber-reinforced polymers has been challenging due to its thermosetting matrix. According to Gonçalves et al. (2022) [60], glass fibers can be extracted and repurposed for wind turbines, avoiding waste and landfilling. At the same time, mechanical recycling shows promising results and a lower energy demand. Reinforced fibers are recycled into fine powder or short fibers and used as fillers in new molding compound processes for the production of new composites [61]. Furthermore, a German company (Neocomp) found a way to recycle glass-reinforced fibers into additives for cement production by mixing them with paper-production residue, resulting in total recycling [62].

This presumes to potentially include specific elements of product responsibility for Original Equipment Manufacturers (OEMs), including (a) information and labeling obligations regarding the material composition of the rotor blades; (b) separate processing with the aim of quality assurance of recycled and substitute fuels; (c) obligation for high-quality recycling or guarantee of disposal safety; (d) inclusion of the manufacture's knowledge and processing technologies adapted to product-related technological change; and (e) cause-related allocation of disposal costs and organizational obligations during disposal [17].

3.5.2. The Netherlands

Under the third edition of the National Waste Management Plan, the landfilling of composite waste is banned «in principle». However, wind-farm operators can benefit from an exemption if the cost of alternative treatment is higher than EUR 200 per ton. According to a survey conducted by WindEuope, the cost of mechanically recycling wind turbine blades in the Netherlands ranges between EUR 150–300 per ton. This means landfilling is still practiced [17].

A popular example of repurposing composites at a large scale is the Wikado (Figure 5) playground in Rotterdam. The blades are considered safe to use in an alternative application. Wikado speaks for sustainable, circular solutions in terms of the reuse of materials and components. As Medici et al. (2020) [63] reported, the content of the CE is crucial to reconsider strategies regarding the reuse of resources and materials.

Figure 5. The Wikado playground. "Reproduced with permission from Guzzo D.; https://denisguzzo.com/projects/superuse/dortyart/, 2014" (accessed on 1 May 2022) [64].

3.5.3. France

France sets specific recycling rates for end-of-life wind turbines in a decree published on 22 June 2020, without detailing the responsible party. From 1 July 2022, a minimum of 35% of the rotor mass should be reused or recycled. For permits accepted after 1 January 2023, the recycling rate increases to 45% of the rotor mass. These requirements are further increased for permits accepted after 1 January 2025, where 55% should be reusable or recyclable [65].

3.5.4. Denmark

The re-wind research project looks into alternatives to unsustainable wind turbine disposal methods, while also exploring the potential to reuse blades in engineering and architecture aspects. The idea has already been implemented in the port of Aalborg in Denmark [66].

In a design case study by Joustra et al. (2021) [39], panels of a wind turbine were reused for a table (Figure 6), which served to explore barriers and opportunities for segmented reuse. The picnic table was created from construction elements cut from a wind turbine blade.

Figure 6. Picnic table prototype, "Reproduced with permission from Joustra J., Resources, Conservation & Recycling, published by Elsevier, 2021" [39].

Pyrolysis, solvolysis, and incineration with energy recovery (fuel, electricity, and heat) and waste by-products from blade waste all fall under the category of recovery. These waste-treatment technologies can also be referred to as tertiary recycling. A practical example is the production of insulating wood mats made from blade fibers via pyrolysis [67].

4. Conclusions

Even if composite materials offer great engineering opportunities, their integration in the circular economy remains challenging. This is due to their specific characteristics and properties of composites, as well as the limited availability of sustainable end-of-life waste-management technologies. There are several limitations when choosing to handle composite materials in a circular manner, concerning the limited known applications and lack of innovation. The key controversial areas for the usage and disposal of composite materials concern two of the main areas investigated: wind turbine blades and solar panels, which constitute methods of renewable energy production. Due to the increasing attraction towards clean and affordable energy, it is expected that these energy production technologies will increase their share in the energy mix in the subsequent years. The use of renewable energy will be raised in any case as the continuous use of fossil fuels is limited, no matter what materials are used for the construction of solar panels and wind turbines. If the use of composite materials continues in the present manner, until 2030, human beings will have a considerable problem concerning their disposal. Alterations from the 'business-as-usual' mindset by adopting the circular economy base pillars (reuse, recycle, recover, refurbish, remanufacture, replace, etc.) as well as the use of alternative materials (i.e., biocomposites) to replace or minimize the use of them in all areas is of the outmost importance and valuable for the diversion of waste from landfills. Regarding the composites, the development of a general circular business model is necessary, but also quality protocols concerning end-of-waste criteria of each individual mix of materials are needed. We consider the field of the reuse of composite components or, in the best case, of the whole composite material as very important as a basis for the production of novel materials using biotechnological methods in combination with surface activation methods, such as high-power ultrasounds, UV, and atmospheric plasma [68–70]. Furthermore, socioeconomic pressure for the development of sustainable composite recycling solutions will accelerate the replacement and/or alter the waste-management handling of these materials by banning landfilling options to reduce environmental impacts in the framework of the circular economy.

Author Contributions: Conceptualization, G.C., I.P., C.A. and A.A.Z.; methodology, G.C. and I.P.; validation, G.C., I.P., I.V., P.L. and A.A.Z.; formal analysis, G.C., I.P. and A.A.Z.; investigation, G.C. and I.P.; resources, G.C. and I.P.; data curation, G.C., I.P., I.V., P.L. and A.A.Z.; writing—original draft preparation, G.C. and I.P.; writing—review and editing, A.A.Z., G.S. and C.A.; visualization, A.A.Z.; supervision, A.A.Z., G.S. and C.A.; project administration, A.A.Z. and C.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the Open University of Cyprus (and the Lab of Chemical Engineering and Engineering Sustainability) for the financial support and research facilities. G.S. and C.A. declare that this study has been partly funded by the European Union´s Horizon 2020 research and innovation program under grant agreement number: 870292 (BioICEP).

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

References

1. Ngo, T.-D. Introduction to Composite Materials. In *Composite and Nanocomposite Materials—From Knowledge to Industrial Applications*; IntechOpen: Rijeka, Croatia, 2020; Chapter 1; ISBN 978-1-78985-461-9.
2. Krauklis, A.E.; Karl, C.W.; Gagani, A.I.; Jørgensen, J.K. Composite material recycling technology—State-of-the-art and sustainable development for the 2020s. *J. Compos. Sci.* **2021**, *5*, 28. [CrossRef]
3. Korniejenko, K.; Kozub, B.; Bąk, A.; Balamurugan, P.; Uthayakumar, M.; Furtos, G. Tackling the circular economy challenges—composites recycling: Used tyres, wind turbine blades, and solar panels. *J. Compos. Sci.* **2021**, *5*, 243. [CrossRef]
4. Udroiu, R.; Bere, P. Recycling of Polymeric Composite Materials. In *Product Lifecycle Management—Terminology and Applications*; IntechOpen: Rijeka, Croatia, 2018; Chapter 7; ISBN 978-1-78984-543-3.
5. Zabihi, O.; Ahmadi, M.; Liu, C.; Mahmoodi, R.; Li, Q.; Ferdowsi, M.R.G.; Naebe, M. A sustainable approach to the low-cost recycling of waste glass fibres composites towards circular economy. *Sustainability* **2020**, *12*, 641. [CrossRef]
6. Statista Market Value of Thermoplastic Composites Worldwide from 2019 to 2024. Available online: https://www.statista.com/statistics/1036597/global-market-value-thermoplastic-composites/ (accessed on 6 May 2022).
7. Statista Market Value of Carbon Fiber Reinforced Thermoplastic Composites Worldwide from 2014 to 2025. Available online: https://www.statista.com/statistics/1036742/global-carbon-fiber-reinforced-thermoplastic-composites-market-value/ (accessed on 6 May 2022).
8. Statista Sales of Plastic Apparels and Clothing Accessories in Europe in 2016. Available online: https://www.statista.com/statistics/830262/plastic-apparel-and-clothing-sales-europe/ (accessed on 29 April 2022).
9. Statista Market Value of Composite Materials Worldwide from 2015 to 2028. Available online: https://www.statista.com/statistics/944471/global-market-value-of-composites/ (accessed on 6 May 2022).
10. Statista Projected Global Advanced Space Composite Market Size in 2021 and 2031, by Component. Available online: https://www.statista.com/statistics/1289109/global-advanced-space-composite-market-size-by-type-forecast/ (accessed on 6 May 2022).
11. Wasilenkoff, C. Composites & Sustainability. Available online: https://www.sustainableplastics.com/news/composites-sustainability (accessed on 15 May 2022).
12. Emin, A. How Composite Materials Influence Sustainable Development. *Entrep. Perspect.* **2021**, *40*, 7–16.
13. Mativenga, P.T.; Sultan, A.A.M.; Agwa-Ejon, J.; Mbohwa, C. Composites in a Circular Economy: A Study of United Kingdom and South Africa. *Procedia CIRP* **2017**, *61*, 691–696. [CrossRef]
14. Wong, K.; Rudd, C.; Pickering, S.; Liu, X. Composites recycling solutions for the aviation industry. *Sci. China Technol. Sci.* **2017**, *60*, 1–10. [CrossRef]
15. European Commission Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions a new Circular Economy Action Plan. In Proceedings of the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions a New Circular Economy Action Plan new Circular Economy Action Plan for a Cleaner and More Competitive Eu, Brussels, Belgium, 11 March 2020; pp. 1–27.

16. Eurostat Guidance on Classification of Waste According to EWC-Stat Categories. Available online: https://ec.europa.eu/eurostat/documents/342366/351806/Guidance-on-EWCStat-categories-2010.pdf/0e7cd3fc-c05c-47a7-818f-1c2421e55604 (accessed on 14 May 2022).
17. WindEurope Accelerating Wind Turbine Blade Circularity. Available online: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf (accessed on 15 May 2022).
18. United Nations Transforming Our World: The 2030 Agenda for Sustainable Development. Available online: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (accessed on 30 March 2022).
19. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
20. Moher, D.; Shamseer, L.; Clarke, M.; Ghersi, D.; Liberati, A.; Petticrew, M.; Shekelle, P.; Stewart, L.A. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst. Rev.* **2015**, *4*, 1. [CrossRef]
21. Loizia, P.; Voukkali, I.; Zorpas, A.A.; Navarro Pedreño, J.; Chatziparaskeva, G.; Inglezakis, V.J.; Vardopoulos, I.; Doula, M. Measuring the level of environmental performance in insular areas, through key performed indicators, in the framework of waste strategy development. *Sci. Total Environ.* **2021**, *753*, 141974. [CrossRef]
22. Zorpas, A.A. Strategy development in the framework of waste management. *Sci. Total Environ.* **2020**, *716*, 137088. [CrossRef]
23. Harvard Business Review the Dark Side of Solar Power. Available online: https://hbr.org/2021/06/the-dark-side-of-solar-power (accessed on 8 July 2022).
24. European Environment Agency (EEA). BRIEFING Emerging Waste Streams: Opportunities and Challenges of the Clean-Energy Transition from a Circular Economy Perspective. Available online: https://www.eea.europa.eu/publications/emerging-waste-streams-opportunities-and (accessed on 14 May 2022).
25. Franco, M.A.; Groesser, S.N. A Systematic Literature Review of the Solar Photovoltaic Value Chain for a Circular Economy. *Sustainability* **2021**, *13*, 9615. [CrossRef]
26. Statista Projected Cumulative Volume of Solar Photovoltaic Panel Waste Worldwide from 2016 to 2050 (in 1000 Metric Tons). Available online: https://www.statista.com/statistics/565743/solar-pv-panels-waste-projection-worldwide/ (accessed on 14 May 2022).
27. Mulvaney, D.; Richards, R.M.; Bazilian, M.D.; Hensley, E.; Clough, G.; Sridhar, S. Progress towards a circular economy in materials to decarbonize electricity and mobility. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110604. [CrossRef]
28. International Air Transport Association (IATA). Helping Aircraft Decommissioning. Available online: https://www.iata.org/en/programs/environment/aircraft-decommissioning/ (accessed on 14 May 2022).
29. Weiland, J.; Hesser, D.F.; Xiong, W.; Schiebahn, A.; Markert, B.; Reisgen, U. Structural health monitoring of an adhesively bonded CFRP aircraft fuselage by ultrasonic Lamb Waves. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2020**, *234*, 2000–2010. [CrossRef]
30. Utekar, S.; Suriya, V.K.; More, N.; Rao, A. Comprehensive study of recycling of thermosetting polymer composites—Driving force, challenges and methods. *Compos. Part B Eng.* **2021**, *207*, 108596. [CrossRef]
31. Cooperman, A.; Eberle, A.; Lantz, E. Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. *Resour. Conserv. Recycl.* **2021**, *168*, 105439. [CrossRef]
32. The European Wind Energy Association. Wind in Power 2015 European Statistics. Available online: http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-Annual-Statistics-2015.pdf (accessed on 15 May 2022).
33. Jensen, J.P.; Skelton, K. Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. *Renew. Sustain. Energy Rev.* **2018**, *97*, 165–176. [CrossRef]
34. Eurostat. What Is the Share of Renewable Energy in the EU? Available online: https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-4c.html (accessed on 15 May 2022).
35. Liu, P.; Barlow, C.Y. Wind turbine blade waste in 2050. *Waste Manag.* **2017**, *62*, 229–240. [CrossRef]
36. WingEurope. Repowering and Lifelong Extension: Making the Most of Europe's Wind Energy Resources. Available online: https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-Repowering-and-Lifetime-Extension.pdf (accessed on 15 May 2022).
37. Bank, L.C.; Arias, F.R.; Yazdanbakhsh, A.; Gentry, T.R.; Al-Haddad, T.; Chen, J.-F.; Morrow, R. Concepts for Reusing Composite Materials from Decommissioned Wind Turbine Blades in Affordable Housing. *Recycling* **2018**, *3*, 3. [CrossRef]
38. Alshannaq, A.; Scott, D.; Bank, L.; Bermek, M.; Gentry, R. Structural Re-Use of De-Commissioned Wind Turbine Blades in Civil Engineering Applications. In Proceedings of the American Society for Composites: Thirty-Fourth Technical Conference, Atlanta, GA, USA, 13–15 September 2019. [CrossRef]
39. Joustra, J.; Flipsen, B.; Balkenende, R. Structural reuse of high end composite products: A design case study on wind turbine blades. *Resour. Conserv. Recycl.* **2021**, *167*, 105393. [CrossRef]
40. Agapios, A.; Andreas, V.; Marinos, S.; Katerina, M.; Antonis, Z.A. Waste aroma profile in the framework of food waste management through household composting. *J. Clean. Prod.* **2020**, *257*, 120340. [CrossRef]
41. Cao, J.; Sim, Y.; Tan, X.Y.; Zheng, J.; Chien, S.W.; Jia, N.; Chen, K.; Tay, Y.B.; Dong, J.-F.; Yang, L.; et al. Upcycling Silicon Photovoltaic Waste into Thermoelectrics. *Adv. Mater.* **2022**, *34*, 2110518. [CrossRef] [PubMed]
42. Levanen, J.; Uusitalo, V.; Harri, A.; Kareinen, E.; Linnanen, L. Innovative recycling or extended use? Comparing the global warming potential of different ownership and end-of-life scenarios for textiles. *Environ. Res. Lett.* **2021**, *16*, 054069. [CrossRef]

43. Zorpas, A.A.; Doula, M.K.; Jeguirim, M. Waste Strategies Development in the Framework of Circular Economy. *Sustainability* **2021**, *13*, 13467. [CrossRef]
44. Akbari, S.; Bahi, A.; Farahani, A.; Milani, A.S.; Ko, F. Fabrication and Characterization of Lignin/Dendrimer Electrospun Blended Fiber Mats. *Molecules* **2021**, *26*, 518. [CrossRef]
45. The European Parliament and the Council of the European Union. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. L 150. *Off. J. Eur. Union* **2018**, *61*, 109–140.
46. Official Journal of the European Union. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02008L0098-20180705&from=EN (accessed on 7 May 2022).
47. Voukkali, I.; Zorpas, A.A. Evaluation of urban metabolism assessment methods through SWOT analysis and analytical hierocracy process. *Sci. Total Environ.* **2022**, *807*, 150700. [CrossRef]
48. García-Sánchez, M.; Güereca, L.P. Environmental and social life cycle assessment of urban water systems: The case of Mexico City. *Sci. Total Environ.* **2019**, *693*, 133464. [CrossRef]
49. Pappas, G.; Papamichael, I.; Zorpas, A.; Siegel, J.E.; Rutkowski, J.; Politopoulos, K. Modelling Key Performance Indicators in a Gamified Waste Management Tool. *Modelling* **2022**, *3*, 27–53. [CrossRef]
50. Papamichael, I.; Pappas, G.; Siegel, J.E.; Zorpas, A.A. Unified waste metrics: A gamified tool in next-generation strategic planning. *Sci. Total Environ.* **2022**, *833*, 154835. [CrossRef]
51. Statista Production of Biocomposites in Europe in 2020, with a Forecast for 2028. Available online: https://www.statista.com/statistics/1282095/biocomposite-production-europe/ (accessed on 14 May 2022).
52. Ghasemi, S.; Sibi, M.P.; Ulven, C.A.; Webster, D.C.; Pourhashem, G. A Preliminary Environmental Assessment of Epoxidized Sucrose Soyate (ESS)-Based Biocomposite. *Molecules* **2020**, *25*, 2797. [CrossRef]
53. Dhir, D.K.; Rashidi, A.; Bogyo, G.; Ryde, R.; Pakpour, S.; Milani, A.S. Environmental Durability Enhancement of Natural Fibres Using Plastination: A Feasibility Investigation on Bamboo. *Molecules* **2020**, *25*, 474. [CrossRef] [PubMed]
54. Furtos, G.; Silaghi-Dumitrescu, L.; Pascuta, P.; Sarosi, C.; Korniejenko, K. Mechanical Properties of Wood Fiber Reinforced Geopolymer Composites with Sand Addition. *J. Nat. Fibers* **2021**, *18*, 285–296. [CrossRef]
55. Furtos, G.; Molnar, L.; Silaghi-Dumitrescu, L.; Pascuta, P.; Korniejenko, K. Mechanical and thermal properties of wood fiber reinforced geopolymer composites. *J. Nat. Fibers* **2021**, 1–16. [CrossRef]
56. Díez-Pascual, A.M. Synthesis and Applications of Biopolymer Composites. *Int. J. Mol. Sci.* **2019**, *20*, 2321. [CrossRef]
57. Ferri, M.; Vannini, M.; Ehrnell, M.; Eliasson, L.; Xanthakis, E.; Monari, S.; Sisti, L.; Marchese, P.; Celli, A.; Tassoni, A. From winery waste to bioactive compounds and new polymeric biocomposites: A contribution to the circular economy concept. *J. Adv. Res.* **2020**, *24*, 1–11. [CrossRef]
58. Shanmugam, V.; Mensah, R.A.; Försth, M.; Sas, G.; Restás, Á.; Addy, C.; Xu, Q.; Jiang, L.; Neisiany, R.E.; Singha, S.; et al. Circular economy in biocomposite development: State-of-the-art, challenges and emerging trends. *Compos. Part C Open Access* **2021**, *5*, 100138. [CrossRef]
59. Shaik, S.A.; Schuster, J.; Shaik, Y.P.; Kazmi, M. Manufacturing of Biocomposites for Domestic Applications Using Bio-Based Filler Materials. *J. Compos. Sci.* **2022**, *6*, 78. [CrossRef]
60. Gonçalves, R.M.; Martinho, A.; Oliveira, J.P. Recycling of Reinforced Glass Fibers Waste: Current Status. *Materials* **2022**, *15*, 1596. [CrossRef]
61. Zhang, Y.; Pontikes, Y.; Lessard, L.; Willem van Vuure, A. Recycling and valorization of glass fibre thermoset composite waste by cold incorporation into a sustainable inorganic polymer matrix. *Compos. Part B Eng.* **2021**, *223*, 109120. [CrossRef]
62. European Circular Economy Stakeholder Platform. Neocomp: Recycling Glass-Fibre-Reinforced Plastics. Available online: https://circulareconomy.europa.eu/platform/en/good-practices/neocomp-recycling-glass-fibre-reinforced-plastics (accessed on 2 July 2022).
63. Medici, P.; van den Dobbelsteen, A.; Peck, D. Safety and Health Concerns for the Users of a Playground, Built with Reused Rotor Blades from a Dismantled Wind Turbine. *Sustainability* **2020**, *12*, 3626. [CrossRef]
64. Guzzo, D. Wikado. Available online: https://denisguzzo.com/projects/superuse/dortyart/ (accessed on 28 May 2022).
65. Republic of France. Décrets, Arrêtés, Circulaires. Available online: https://www.legifrance.gouv.fr/download/pdf?id=DnpVIPYrAPUpgACFs1EL96_RnHomPM8tT8dp-lOuYrs= (accessed on 15 May 2022).
66. Designboom Denmark Is Repurposing Discarded Wind Turbine Blades as Bike Shelters. Available online: https://www.designboom.com/design/denmark-repurposing-wind-turbine-blades-bike-garages-09-27-2021/ (accessed on 15 May 2022).
67. Refiber Aps. We Develop Recycling Technology for Composites. Available online: https://www.refiber.com/technology.html (accessed on 15 May 2022).
68. Sourkouni, G.; Kalogirou, C.; Moritz, P.; Gödde, A.; Pandis, P.K.; Höfft, O.; Vouyiouka, S.; Zorpas, A.A.; Argirusis, C. Study on the influence of advanced treatment processes on the surface properties of polylactic acid for a bio-based circular economy for plastics. *Ultrason. Sonochem.* **2021**, *76*, 105627. [CrossRef] [PubMed]

69. Anucha, C.B.; Bacaksiz, E.; Stathopoulos, V.N.; Pandis, P.K.; Argirusis, C.; Andreouli, C.-D.; Tatoudi, Z.; Altin, I. Molybdenum Modified Sol–Gel Synthesized TiO_2 for the Photocatalytic Degradation of Carbamazepine under UV Irradiation. *Processes* **2022**, *10*, 1113. [CrossRef]
70. Anucha, C.B.; Bacaksiz, E.; Stathopoulos, V.N.; Pandis, P.K.; Argirusis, C.; Andreouli, C.-D.; Tatoudi, Z.; Altin, I. Preparation and Characterization of Supported Molybdenum Doped TiO_2 on α-Al_2O_3 Ceramic Substrate for the Photocatalytic Degradation of Ibuprofen (IBU) under UV Irradiation. *Catalysts* **2022**, *12*, 562. [CrossRef]