

Review

Feasibility of Recovering and Recycling Polymer Composites from End-of-Life Marine Renewable Energy Structures: A Review

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Abstract: Over the last few decades, several marine renewable energy (MRE) technologies, such as wave energy converters (WECs) and current energy converters (CECs), have been developed. As opposed to traditional materials such as metal alloys, the structure of these technologies is made up of polymer and polymer composite materials. Most structures have been made using thermoset polymer composites; however, since thermoset polymer composites are not recyclable and lack sustainability, and with recent innovations in recyclable resins, bio-based resins, and the development of additive manufacturing technologies, thermoplastic polymers are increasingly being used. Nevertheless, the methodologies for identifying end-of-life options and recovering these polymer composites, as well as the recycling and reuse processes for MRE structures, are not well-studied. Specifically, since these MRE structures are subjected to salinity, moisture, varying temperature, biofouling, and corrosion effects depending on their usage, the recyclability after seawater aging and degradation needs to be explored. Hence, this review provides an in-depth review of polymer composites used in marine applications, the hygrothermal aging studies conducted so far to understand the degradation of these materials, and the reuse and recycling methodologies for end-of-life MRE structures, with a particular emphasis on sustainability.

Keywords: marine renewable energy; sustainability; materials; composites; polymers; recycling; hygrothermal aging; end-of-life



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1. Introduction

The increasing global population, urbanization, and economic growth are projected to drive an excess of 25% growth in world energy demand, which is expected to reach around 206,000 TWh/yr by 2040. Additionally, the proportion of renewable energy in the global energy mix is increasing; by 2040, it is anticipated to account for more than 40% of total generation, up from 25% in 2017. Electricity demand is projected to grow from 22,200 TWh/yr to over 35,500 TWh/yr by 2040, making it the fastest-growing energy source [1]. While this shift offers significant environmental benefits, it also introduces a new set of challenges. The U.S. faces a substantial and rising energy demand of nearly 30,000 TWh/year. Combustion-based energy, which constitutes 80% of the U.S. supply, contributes significantly to human-driven climate change. Furthermore, fossil fuels are finite, underscoring the urgency of transitioning to clean, renewable energy sources [2].

Wind power and hydropower are key pillars of the renewable energy sector, harnessing natural forces to generate electricity with minimal environmental impact. Wind power, used since ancient times, has evolved significantly with modern technology to become a major contributor to sustainable energy. As the global wind industry grows, WindEurope, Cefic, and EuCIA have launched a platform to enhance wind turbine blade recycling. Currently, 85–90% of non-blade wind turbine components are recyclable, but blades, made from composite materials, are more challenging to recycle. Despite existing

technologies, blade recycling is not yet widely accessible or cost-effective. By 2023, approximately 14,000 blades (equivalent to 40,000–60,000 tons) could be decommissioned, making recycling an increasing priority. However, blade waste is expected to represent only 10% of the total thermoset composite waste by 2025, highlighting a broader cross-sector recycling challenge [3–5]. Figure 1 shows decommissioned blades across various landfills in the U.S. Although wind and tidal turbines share similar manufacturing processes and materials, they encounter different environmental stressors in service. As composite materials are used in tidal turbines and other waterpower technologies, it is essential to understand and prepare suitable end-of-life options for these composite structures.



Figure 1. Pictures of decommissioned blades (a) Discarded wind turbine blades in west Texas (photo by Eli Rosen) [6], (b) blade in Colorado landfills (photo by Andy Colwell) [7], and (c) shredded pieces of blades for recycling (photo from Veolia) [8].

1.1. Marine Renewable Energy Devices

As discussed earlier, the kinetic forces of both wind and water currents offer significant renewable energy potential. Marine energy, also known as marine and hydrokinetic energy (MHK) or marine renewable energy (MRE), is a renewable power source harnessed from the natural movement of water, including waves, tides, and river and ocean currents. These sources can be predictable and reliable in coastal regions. U.S. coastal waters hold 1168–1670 TWh/year in potential energy production, while offshore wind offers an additional 2000 GWh/year. However, offshore wind is less consistent than water current flow. A major challenge for both is their high levelized cost of electricity (LCOE), which is projected to remain non-competitive with combustion-based power for the next 20 years. The main cost factors are capital investment, installation, and maintenance, as wind and water power have no fuel expenses. Efficient turbine design focuses on maximizing energy output while minimizing maintenance needs, with rotor diameters now exceeding 200 m to capture wind energy more efficiently [9–15]. MRE resources like waves and tidal currents offer great potential for reliable, clean energy, and estimates suggest that MRE could significantly contribute to U.S. utility power generation [16,17]. Given the abundance and geographic distribution of these resources, MRE holds significant promise for producing utility-scale electrical power in the future. It is anticipated that MRE will be essential in the global low-carbon economy and in mitigating the effects of climate change.

In 2019, the Powering the Blue Economy (PBE) initiative of the U.S. Department of Energy (DOE) highlighted MRE devices, such as underwater turbines, as promising clean energy technologies. While wave energy technology benefits from wind turbine research and development, MRE technologies that harness energy from waves, tides, and currents are still under development and face challenges in durability, efficiency, and cost-effectiveness. The PBE report emphasized the need for more deepwater deployments and reliability demonstrations. For MRE turbines to reach commercialization, further investment is required to optimize designs capable of withstanding harsh subsea conditions [18,19].

MRE systems come in various forms, including tidal/ocean current turbines, crossflow turbines, wave point absorbers, and oscillating surge flaps. Figure 2 portrays a few of these MRE systems. Tidal current energy, which captures the kinetic energy of tidal currents using

turbines, is the most predictable and has reached early technological maturity. Like wind energy but partially or fully submerged in water, tidal energy is a promising renewable source. Research on ocean renewable energy remains crucial alongside conventional energy studies to further develop this reliable energy source [20,21].

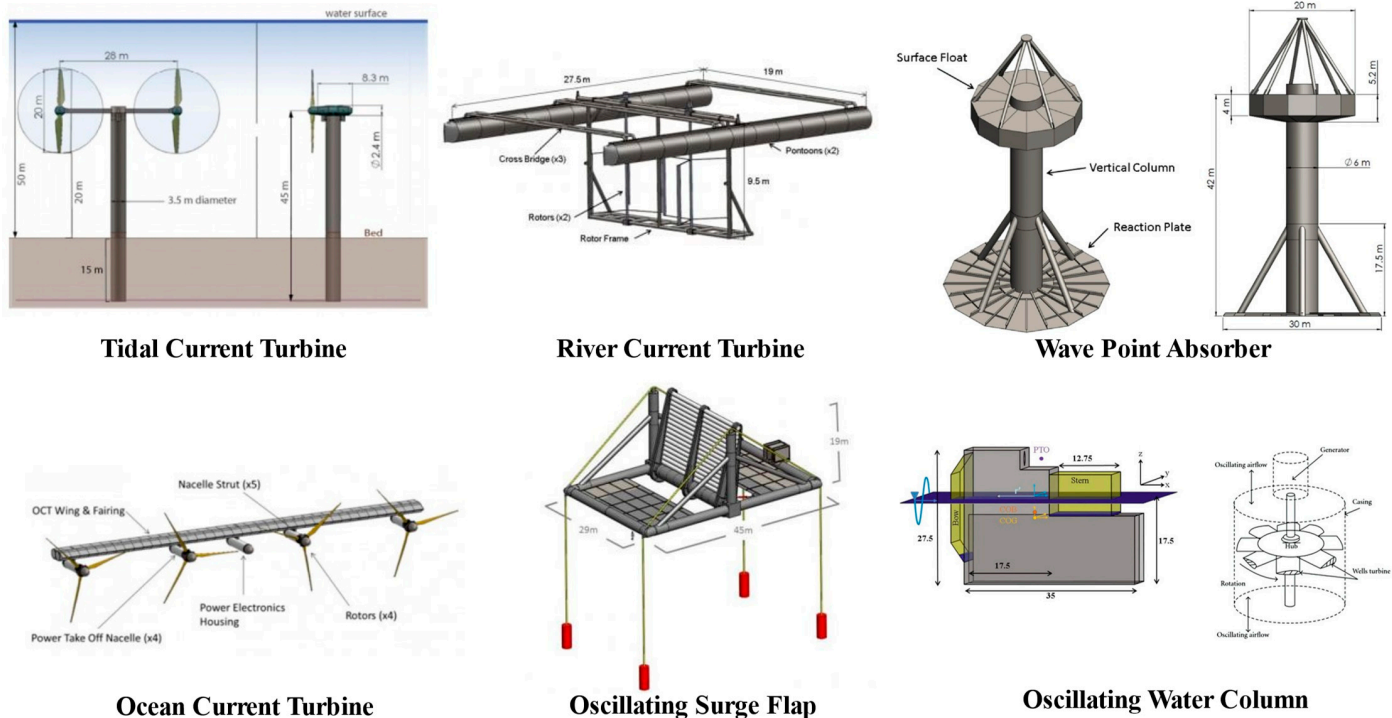


Figure 2. Marine renewable energy technologies (Figure adapted from PNNL Tethys) [22].

Until the last decade, MRE structures were primarily composed of metals. The technology readiness level (TRL) of the novel materials used in MRE devices has been low; however, with the new advancements in manufacturing technologies, material developments, and new recyclable resins, the MRE device industry has begun to use polymeric composites, with recyclable capabilities for their applications, replacing the traditional metals.

1.2. Polymer Composites in MRE Devices

The marine industry, especially boatbuilding, has seen rising demand, with 30 million recreational crafts owned worldwide. Over 80% of Norwegian pleasure boats are made from glass-fiber reinforced polymer (GFRP), which reduces boat weight by 30–40%, leading to lower costs and better fuel efficiency. Yet, a major challenge is managing end-of-life (EoL) boats. Around 140,000 recreational boats are expected to reach EoL each year, with traditional disposal methods (landfilling and incineration) facing stricter environmental regulations. This has accelerated the need for sustainable waste management and new design approaches, including bio-based resins and eco-friendly materials, although these still face durability and process limitations [23]. Example applications of MRE devices, including tidal turbines manufactured with polymer composites, are shown in Figure 3 [24–29].

Marine biofouling is a major issue for watercrafts, as submerged surfaces like ship hulls quickly attract various organisms, leading to significant economic and environmental problems. Traditional antifouling coatings, which rely on toxic metal ions and biocides, have proven harmful to non-target marine species and ecosystems. This has created an urgent need for environmentally friendly alternatives, driving increased research in this field [30]. Efficient antifouling coatings can help prevent marine biofouling, but challenges like seawater aging, fatigue, and hydrodynamic loads leading to blade failure require improved materials. Reusable and natural material-based composites offer alternatives to unrecyclable ones, potentially reducing waste. However, understanding the environmental

impact on these materials, especially regarding operation, maintenance, reliability, and safety, is crucial. Further research is needed to assess the effects of seawater and biofouling on these materials [31–33]. Table 1 below describes the MHK devices that are manufactured using composite materials.

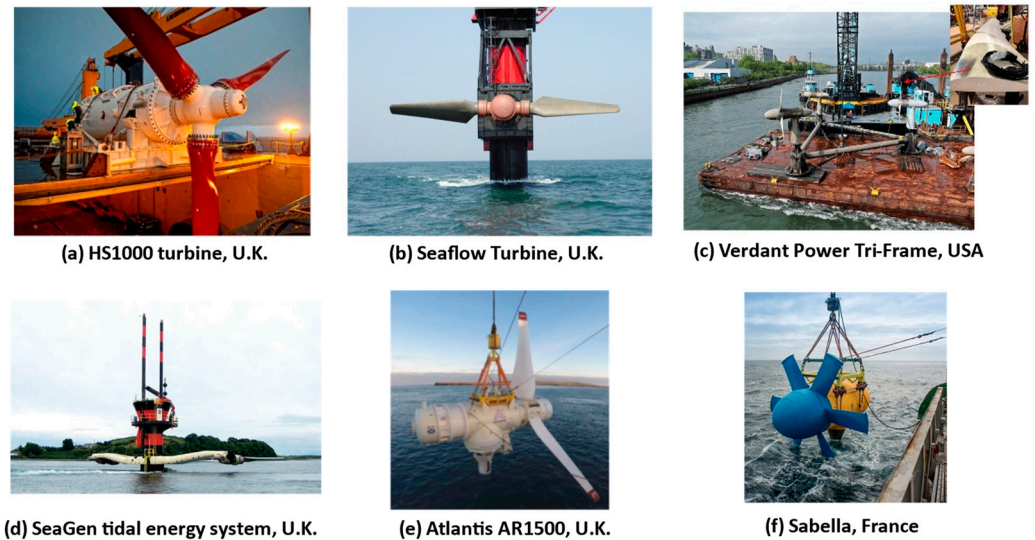


Figure 3. Tidal turbines made up of polymer composites: (a) HS1000 turbine in U.K. [24], (b) Seaflow turbine in U.K. [25], (c) Verdant Power Tri-Frame RITE project in USA [26], (d) SeaGen tidal system in U.K. [27], (e) Atlantis AR1500 in Scotland, U.K. [28], and (f) Sabella in France, Photo by: Balao [29].

Table 1. Composite structures used in MHK devices.

Materials	Application	Critical Information	References
Composite structure design	Wave Dragon, Denmark	Wave energy converter	[34]
Kevlar TM and rubber composite	Archimedes, AWS Ocean Energy, UK.	wave swing system	[35]
Three thermoset composite blades	RITE project, NY, USA	Tidal turbines	[36]
Thermoplastic Elium composite blades	RITE project, NY, USA	Tidal turbines	[37]
Carbon/epoxy blades	Sabella, Ushant Island, Brittany	500 kW turbine demonstrator	[38]
Composite (carbon and glass) blades	DeepGen Tidal Project, Tidal Generation Limited	500 kW tidal turbine	[39]
Kevlar TM 49 and chopped glass fibers in an epoxy matrix	Pelton turbine	22 buckets	[40]
Carbon + thermoplastic (3D printed)	Pelton turbine buckets	200 EUR composite vs. 300 EUR metal bucket	[41]
CF-reinforced thermoplastic	Small propeller-type turbine	Replacing stainless steel blades, similar peak efficiency; higher blade bending increases hydraulic head.	[42]
Composite blades	MeyGen project	Involves four 1.5 MW turbines	[43]
Recycled CF foils	CRIMSON project	Reduces capital and operating expenditures by 33% and 66%, respectively;	[44]

Table 1. Cont.

Materials	Application	Critical Information	References
GF composite (10 m long blades)	HS1000 Tidal power station by ANDRITZ Hydro	Installed near Hammerfest, Norway;	[45]
Carbon composite (11 m diameter)	SeaFlow tidal prototype	First sea trials in 2003, involved a 300 kW capacity;	[46,47]
GF composite tidal turbine blades	OpenHydro turbine	11 m diameter structure; interest in shrouds and other components;	[48]

The MHK devices are exposed to different environmental conditions such as extreme temperatures [49], water diffusion [50,51], absorption and swelling [52], osmosis and blistering [53,54], stress and stress corrosion [53,55], biofouling [56], and cavitation corrosion [57]. As these materials are traditionally recyclable, it is vital to understand the nature and feasibility of recycling after its use in marine applications, as the composites are susceptible to harsh environments in seawater. These external degradation mechanisms affect the properties of the materials and may cause serious issues, to the extent that they cannot be recycled, or their recycling may need extensive pre-processing steps. The key distinction between loads on MRE devices and those on other marine structures, such as pleasure boats or naval vessels, is the significance of fatigue loading. While conventional marine structures are seldom engineered to withstand fatigue, tidal turbine blades only cease to rotate during changes in tide direction. The loads experienced by these devices are influenced by three primary factors [58]:

- Tidal Currents: these drive the rotation that generates energy.
- Rotation: this leads to pressure variations caused by depth changes of up to 20 m.
- Waves: these impact underwater structures, particularly in shallow areas.

Material density and structural mass are of lower importance because the structures are submerged underwater where buoyancy forces offset gravity-induced forces. MRE structures are often filled with ballast such as concrete, epoxy slurry, or water to minimize buoyancy [21].

To assess the long-term performance of composites in a hygrothermal environment, researchers used the popular Arrhenius equation based on short-term data from accelerated aging studies. Paul et al. [37] studied the environmental aging at an ambient temperature of epoxy and Elixir composites, obtained from deployed tidal turbine blades. The authors aged full-size epoxy and Elixir composite blades for 11 months and the data produced were extrapolated to the full 20-year lifespan of the blade. Results indicated that after 20 years of equivalent time in the water, the epoxy blade absorbed less than 0.4% of its mass. Elixir blade data were difficult to interpret because of measurement errors, but pointed to close to full saturation with 20 years of equivalent aging.

To evaluate the recycling and reuse of the composites in MHK devices, it is vital to understand how these materials degrade and what options are available for the materials at the end of their service life. The pictorial representation of the life cycle of a sustainable MRE structure is shown in Figure 4. It illustrates the current lifecycle process, starting from raw materials to manufacturing and real-time applications, followed by operational exposures and end-of-life recycling options. The primary focus is to determine whether the material can be reused in the same application or repurposed for a new one.

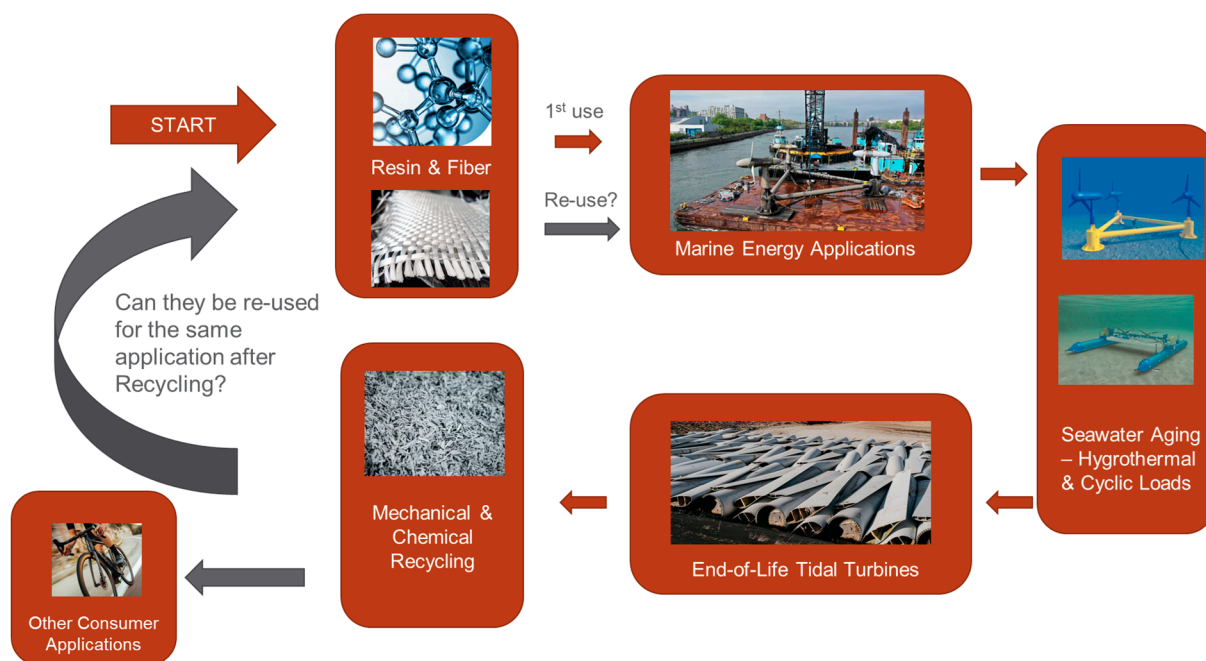


Figure 4. Life cycle of sustainable MRE structures.

2. Hygrothermal Aging and Property Degradation

The process of submerging polymer composites at an elevated temperature for an extended period until saturation is obtained is known as hygrothermal aging [59,60]. Reinforcing fabric architecture, the polymer matrix, the environment, and manufacturing processes are promising elements that affect the efficiency of composites in the hygrothermal environment. Several numerical modeling techniques, including classical laminate theory (CLT) and continuum damage mechanics (CDM) analysis, are utilized to forecast the mechanical responses of fiber-reinforced composites [61].

Fiber-reinforced plastics (FRPs) are favored for wind turbines and MRE devices due to their attractive mechanical properties relative to their density. However, their performance can be affected by environmental factors, particularly hygrothermal aging. Although the application of FRPs in such environments is not new, as seen in industries like marine, aerospace, and civil engineering industries, the diverse types of FRPs and their varying responses to hygrothermal conditions make this a relevant challenge in materials science and engineering.

The study of hygrothermal effects on composites involves three main areas: (1) understanding moisture diffusion into composites, (2) assessing changes in mechanical properties due to moisture, and (3) identifying the mechanisms behind these changes. While moisture diffusion in FRPs is well understood and predictable, the exact mechanisms of property degradation remain less clear. Such degradation is complex, influenced by various factors such as swelling, hydrolysis, interface degradation, and matrix plasticization, with the extent of these effects differing significantly among material systems [62].

The purpose of this section is to provide an overview of the present state of the art in the field as well as future directions for polymer composites in hygrothermal environments. This section explores the impact of the hygrothermal environment on composites, including moisture absorption and environmental factors that impact mechanical property degradation. The extensive evaluation offered in this work will help the composite industry and scientific society as a whole, with the latest developments in this sector leading to the development of improved composite materials for marine applications.

2.1. Impact of Hygrothermal Aging

N. Tual et al. [63] and M. Curto et al. [64] examined tidal turbine blades made from composites, highlighting their susceptibility to water absorption and hygrothermal effects with full submersion in seawater. These conditions can significantly degrade performance, especially under cyclic loads from ocean waves, making long-term structural reliability crucial for profitability. Water absorption follows a diffusion process, with seawater being more aggressive than humid air, leading to severe damage. C. de Zeeuw [65] warns that hygrothermal aging in marine applications is riskier than in wind turbine blades or aviation. Adhesive-bonded joints further increase vulnerability to humidity. The dynamic nature of tidal turbine operation, involving moving blades under mechanical loads, exacerbates creep behavior and reduces lifespan. The combined analysis of water diffusion and mechanical stresses is necessary to evaluate damage risk. Existing mechanical damage accelerates water diffusion, leading to further structural degradation and higher stress levels, as noted by J.Y. Ye and L.W. Zhang [66]. Environmental factors can significantly affect material longevity [67,68]. The polymer matrix of a fiber-reinforced polymer composite is more susceptible to humidity and elevated temperatures than the fiber [69]. Extensive research has been conducted on how aging affects the material characteristics of polymer composites [70–72]. Alterations to the material characteristics of polymer composites caused by moisture absorption may be reversible or they may be permanent [73,74]. Some hygrothermal aging effects, such as softening and plasticization, may be reversible when absorbed water is withdrawn and no chemical changes occur [75]. Extended environmental exposure leads to permanent property changes. The long-term performance of polymer matrix composites in hygrothermal conditions may be affected by various mechanisms, including residual curing, secondary cross-linking between polymer chains and water molecules, swelling, microcracking, leaching of low-molecular-weight segments (decomposition), plasticization, and polymer relaxation [69,73–76].

Polymer composites can experience various loading conditions during their use, leading to matrix damage, fiber failure, and delamination [77]. One of the primary causes of failure in composites is delamination, the separation of layers of fiber reinforcement within a composite, which can lead to catastrophic failure of a composite through deterioration of the mechanical strength and stiffness of the material [59,77]. Various fabric patterns have been developed to circumvent such issues with laminated composites. These consist of (a) woven fabric, with crimped yarn to increase impact resistance but decrease in-plane property resistance, and (b) non-crimped fabric (NCF), which is more effective at resisting delamination and impact and can be achieved using a variety of methods, including stitching, z-pinning, and weaving.

Bezzou et al. [78] studied the fracture propagation in biaxial non-crimp fabric ($\pm 45^\circ$) during hygrothermal aging and discovered multi-scale variations in NCF morphology. The scientists found three types of microcracks in NCF: Type-init (starts at stitching interface), Type-1 (occurs in fisheyes), and Type-2 (starts at fibrous area). In a study by Erklig et al. [79], woven S-glass composite laminates had a 33.9% loss in tensile characteristics when submerged in a humid environment. Mansouri et al. [80] found that aging significantly degraded the physical and mechanical characteristics of short fiber-woven composite laminates. Yong et al. [81] studied the mechanical properties of a carbon fiber-reinforced polymer (CFRP) using stacking sequences $[0]_{16}$, $[90]_{16}$, $[\pm 45]_{4s}$, and $[(+45/0/0/-45)_s]_s$ in a hygrothermal environment. They found a 15%, 28%, 63%, 46%, and 30% loss in tensile strength for composites, respectively, as depicted in Figure 5.

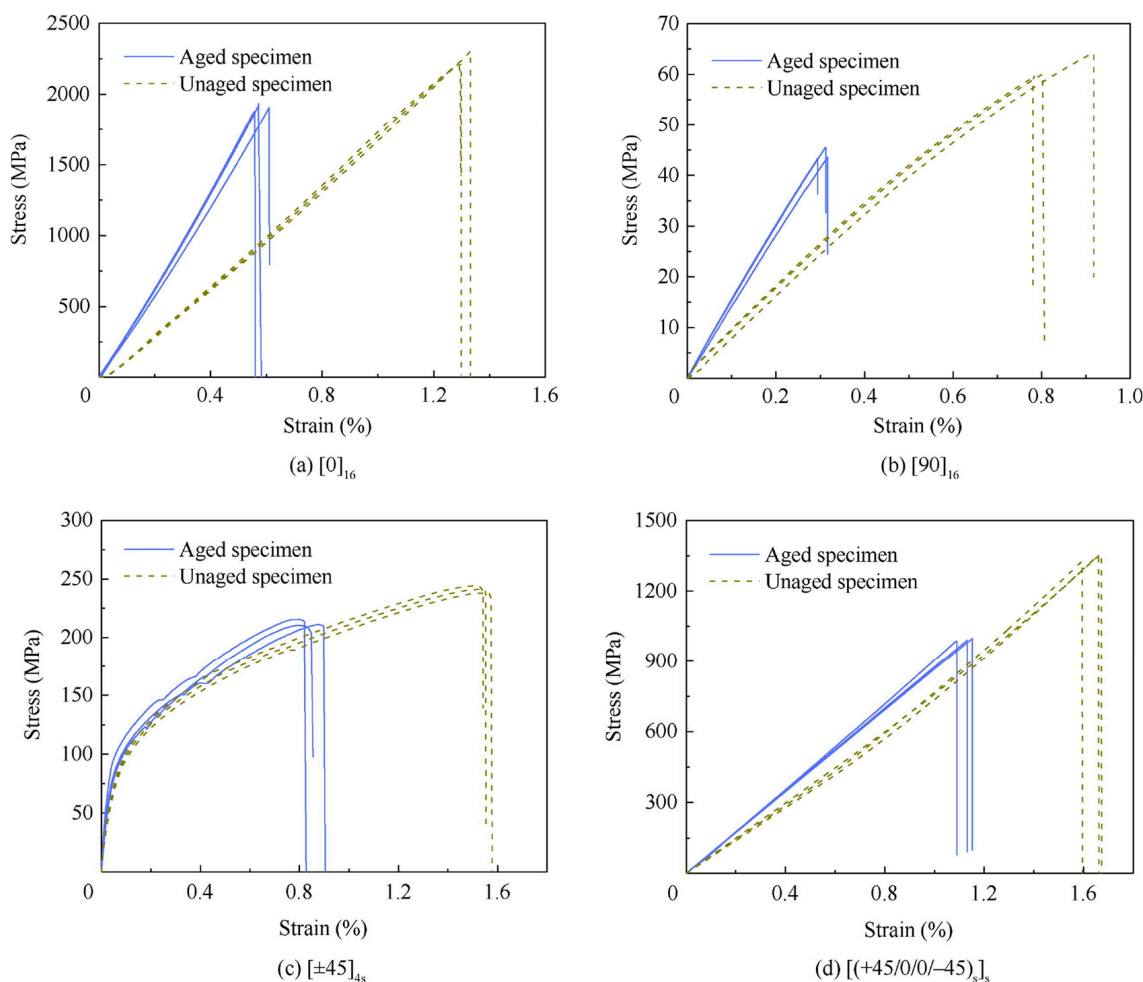


Figure 5. Stress–strain plot of carbon fiber composite (aged and unaged specimens) [81].

Stitched laminates have the potential to increase the mechanical properties of fabric. When Xiaoquan et al. [82] examined the behavior of unstitched and stitched composite laminates in hygrothermal circumstances, they concluded that unstitched laminates experience a faster transmission of delamination than stitched laminates. Stitching in laminates, however, inhibits delamination with the additional disadvantage of kink-band formation due to fiber misalignment. Ghabezi and Harrison [83] used indentation testing to examine how the elastic modulus and hardness of biaxial glass fiber (GF) and carbon fiber (CF) epoxy sheets degraded under hygrothermal conditions. The average drop in glass and carbon characteristics was determined to be 22.3% and 38.8%, respectively. Fabric structures such as woven, biaxial, and triaxial structures have a substantial impact on the degradation of composites because the water absorption differs in each type and has different structural failures impacting the matrix degradation on the failure. As a result, the fabric has an impact on the residual strength and is critical to sustaining the mechanical strength of the material in humid conditions. In a hygrothermal environment, unidirectional (UD), woven, and 3D-braided fabrics lose 64%, 3.4%, and 45% of their compressive strength, respectively. UD fabric experiences the greatest drop in compressive strength. UD fabrics have the biggest percentage reduction because of their open design and high porosity, resulting in increased water uptake when compared to weaved and 3D-braided fabrics [84–86]. UD fabric has great strength in just one direction, as the fibers are organized with gaps between neighboring threads, allowing water to easily infiltrate the fibers due to the lack of weaves. As a result, an in-depth knowledge of how fiber design influences fiber-reinforced polymer composite (FRPC) deterioration is required.

The polymer matrix used to make composites is another important factor in improving the efficacy of polymer composites in a hygrothermal condition. High stiffness, good adhesion to substrates, low strain failure, and low shrinkage during the curing process are all desirable properties of thermoset and thermoplastic polymers that are typically employed in marine environments. Composite materials subjected to adverse environmental conditions in humid conditions can experience degradation of mechanical properties through plasticization, swelling, and polymer matrix hydrolysis [86]. Composites in marine environments uptake moisture due to the free volume that exists between polymer resin molecules and polymer–water interactions. The molecular binding that disrupts polymer chains is the result of hydrogen bonds in a polymer matrix that attracts water molecules [87,88].

Guermazi et al. [89] studied the behavior of glass-reinforced epoxy and carbon-reinforced epoxy in a hygrothermal environment with distilled water as an aging medium. They found a substantial decrease in the mechanical properties of the composite with structure changes as the duration of immersion increased. Wang et al. [90] explored the potential impact of hygrothermal aging on the properties and structure of epoxy. The authors concluded that the tensile strength of epoxy decreases as water absorption reaches saturation. Nevertheless, tensile strength begins to recover because of a change in the molecular structure of the resin at a higher temperature and sufficient time. Mamalis et al. [59] stated that the hygrothermal aging of carbon fiber powder-reinforced epoxy results in matrix plasticizing, with a transition from brittle to ductile failure. Gobikannan et al. [91] reported that thermoplastic composites assimilate a lower moisture content than thermoset resins. At the same time, thermoplastics exhibit superior flexural strength in comparison to thermosets, which have a slightly lower modulus than epoxy resins, as depicted in Figure 6.

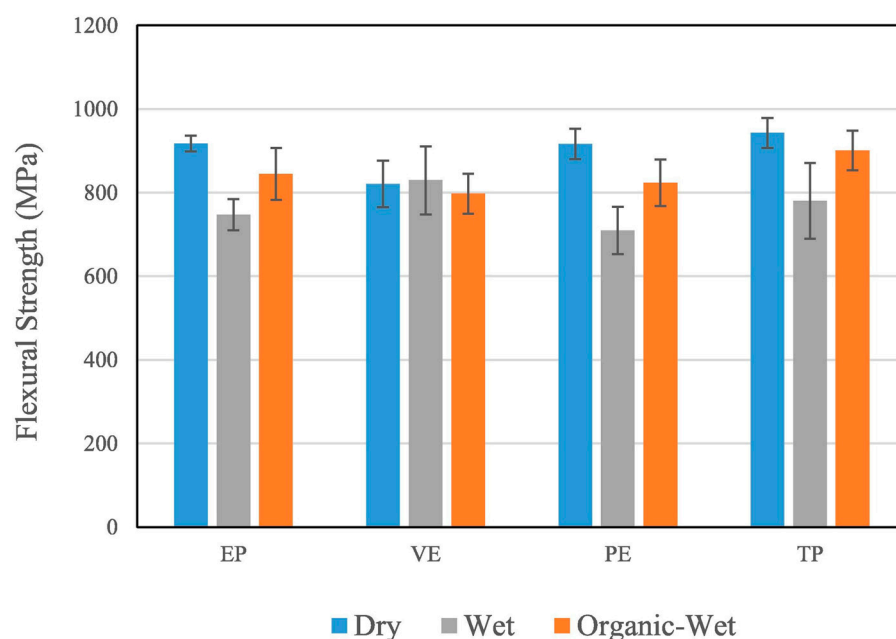


Figure 6. Flexural strength of the composite (aged and unaged) EP: epoxy, VE: vinyl ester, PE: polyester, TP: thermoplastic—Elium [91].

In a hygrothermal environment, moisture can affect the polymer matrix. The mechanical properties of composites are impacted by moisture absorption in the polymer matrix, leading to plasticization, swelling, matrix hydrolysis, matrix debonding, and other issues. In general, the duration of exposure and the surrounding environment have a major influence on the behavior of the polymer matrix. Because extended exposure times enhance plasticity, they also reduce the modulus, which in turn affects the mechanical strength of FRPCs. Fiber and matrix bond strength, which is susceptible to moisture exposure,

determines the mechanical strength of fiber-reinforced polymer composites. Water diffuses into the composites due to the capillary effect, which deteriorates the interface and increases water absorption. Mechanical characteristics of composites deteriorate further because of interface degradation [92]. Understanding how the characteristics of composites change in response to various hygrothermal aging media is therefore essential. The impact of aging media (seawater, tap water, distilled water, and deionized water) on the composite moisture diffusion phenomenon has been reported by numerous researchers. Because seawater and deionized water are corrosive and include salts, which contribute to the breakdown of composites, they induce damage more than other mediums [93].

Le et al. [94] investigated how the properties of glass-reinforced epoxy composites degraded at working temperatures of 32 °C, 50 °C, and 80 °C in a 5% brine solution. The authors found that the duration of exposure to brine directly correlates with the deterioration of composite mechanical properties. The impact of seawater on the deterioration of composites' mechanical properties has also been investigated by Bian et al. [95]. The authors concluded that composite tensile, flexural, and interlaminar shear strength dropped by 13%, 43%, and 50%, respectively. The immersion of the composite in seawater results in the debonding of the interface and both irreversible and reversible modifications to mechanical characteristics, which is the reason for the reduction in mechanical strength. Shan et al. [96] soaked specimens in three distinct media, tap water, seawater, and seawater, at 70 bar hydrostatic pressure to study the impact of moisture diffusion on the bending fatigue of composites. They observed that aged specimens failed at 80% ultimate flexural strength, as opposed to 90% of unaged specimens. Furthermore, the aging media has little effect on the specimen fatigue strength. Because of a confluence of edge and capillary effects, buckling-driven delamination is the cause of the induced failure.

Several researchers examined how composites behaved in various aging media, including seawater, distilled and deionized water, etc. The physical characteristics of composites are impacted by all types of water. The effect of water on mechanical properties is dependent on impurities and ions, since these substances react with composites to produce hydrolysis, which deteriorates the material mechanical properties. In addition, higher salinity in saltwater speeds up the aging process by increasing the conductivity of ions increasing the chemical reaction, which results in deterioration. Understanding the impact of aging media on the fiber composite's long-term durability requires understanding the impact of various aging media on composites.

A hygrothermal environment's temperature increases the pace at which moisture is absorbed, since higher temperatures result in a noticeable increase in the amount of moisture within the composite [81]. When composite materials are exposed to temperature ranges between room temperature and 70 °C, depending on the glass transition temperature T_g of the matrix, physical aging, a reversible phenomenon, takes place. In contrast, when temperatures rise over the glass transition temperature, composite materials experience irreversible chemical aging, which indicates chain scission [97–99] and irreversible degradation. Investigating the flexural behavior of pultruded glass fiber up to 80 °C, Haohui et al. [100] found that the flexural strength and flexural modulus deteriorate more rapidly at higher temperatures due to delamination, which is shown in Figure 7.

Juanzi et al.'s study [101] examined the interlaminar shear behavior of 3D-woven composites at 25, 90, 120, and 150 °C. These authors found that increasing the temperature degraded the resin and the fiber/matrix interface, which decreased the composites' ILSS. Mansouri et al. [80] analyzed the mechanical properties at 40, 60, and 80 °C, leading them to the conclusion that the elastic and stiffness properties of the woven composite are temperature sensitive. At moderate temperatures, the mechanical properties of the composite are changed in both longitudinal and plane directions due to the loss of bonding among the roving and fabrics, according to Haithem et al. [98].

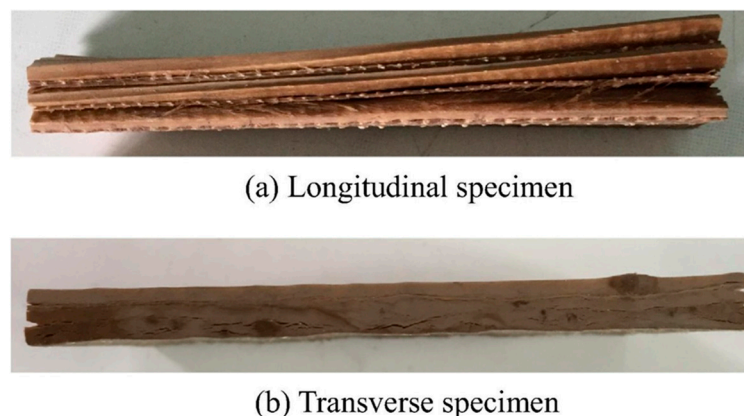


Figure 7. Failure mode in hydrothermal aged composite at 80 °C [100].

In conclusion, the mechanical characteristics of the composite are influenced by the hydrothermal aging temperature. High temperatures quicken the pace at which moisture absorbs into a material, resulting in polymer chain scission and thermal expansion of polymer composites that plasticize the substance. Higher temperatures cause composites to expand, which alters their overall performance. Overall, several factors, such as the kind of composite and the range of temperatures it is exposed to, influence the impact of hydrothermal conditions. To ensure that composites perform optimally and endure for an extended period in a variety of applications, it is imperative to have a comprehensive understanding of the impact of temperature on composites in hydrothermal environments. For composites to function at their best and last a long time in a variety of applications, it is therefore essential to have a thorough grasp of how temperature affects the composite in hydrothermal environments.

2.2. Degradation Mechanism of Polymer Composites by Hydrothermal Aging

Complex interactions between the composite matrix, fibers, and environmental variables often contribute to the degradation mechanisms of polymer composites aged in seawater. Figure 8 shows the degradation mechanism of a polymer-based composite aged in seawater [60].

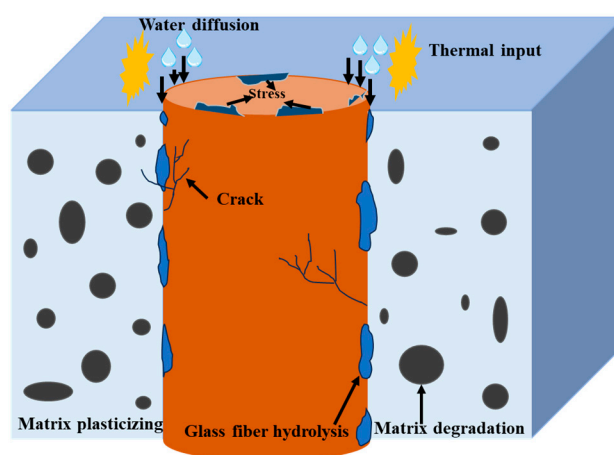


Figure 8. Schematic representation of degradation mechanism of polymer composites in seawater aging [60].

1. Diffusion and Absorption of Water

Over time, moisture seeps into polymer composites exposed to seawater, penetrating fiber/matrix interfaces, microvoids, and cracks. This process leads to plasticization, which reduces mechanical properties like stiffness and strength. Degradation is

exacerbated by elevated temperatures in hydrothermal conditions, which accelerate water diffusion. At higher temperatures, water molecules can penetrate the polymer matrix more deeply, altering the material's characteristics more significantly [81].

2. **Matrix Plasticization and Swelling**
As water is absorbed into the composite, the polymer matrix may swell, increasing the distance between polymer chains. This plasticization effect softens and makes the material more flexible, negatively impacting mechanical performance [86]. It results from a reduced cross-link density and increased chain mobility. Hydrothermal aging often lowers the matrix's glass transition temperature (T_g), decreasing thermal stability and stiffness at lower temperatures.
3. **Polymer Chain Hydrolysis**
Ester bonds in the polymer matrix may undergo hydrolysis when exposed to seawater and elevated temperatures, particularly in thermoset resins like epoxy. This chemical degradation breaks down the polymer backbone, weakening the composite structure and causing embrittlement [98]. Hydrothermal conditions accelerate hydrolytic degradation, which increases embrittlement and reduces molecular weight more rapidly.
4. **Leaching of Additives and Fillers**
Over time, exposure to seawater can lead to the leaching of plasticizers, fillers, and additives, altering the properties of the composite. This leaching effect can degrade mechanical, thermal, and surface properties, leading to increased surface roughness and reduced durability [76].
5. **Degradation of the Fiber/Matrix Interface**
Water intrusion damages the fiber/matrix interface, reducing interfacial adhesion and causing debonding. This decrease in load transfer efficiency can harm mechanical properties like tensile and flexural strength [60]. Due to ion interaction between glass and water, glass fibers in composites may deteriorate in seawater, resulting in surface pitting and strength loss.
6. **Delamination and Microcracking**
Thermal expansion and water absorption mismatches between the fibers and matrix may lead to the formation of microcracks within the matrix. These microcracks can propagate over time, causing delamination, further water intrusion, and accelerated degradation [96]. Hydrothermal aging increases the likelihood of microcracking due to cyclical stresses from thermal expansion and contraction, as well as differential swelling between the fiber and matrix.
7. **Osmotic Blistering and oxidation**
Salt and other solutes may become trapped within the composite when seawater infiltrates. Osmosis can cause pressure buildup in these areas under hydrothermal conditions, potentially resulting in blistering or swelling. This phenomenon may further erode the structure and create pathways for additional water intrusion. Oxidation can occur in the polymer matrix if oxygen is present, such as in surface or shallow marine applications, especially at elevated temperatures [99]. This oxidation of polymer chains can lead to further embrittlement and reduce the composite's lifespan.

3. Recycling Technologies and Their Properties After Recycling

Because of their excellent properties, fiber-reinforced polymer composites are a sought-after class of structural engineering materials. These materials are widely used in construction, automotive applications, aerospace industry, and energy sectors [102]. For the past 10 years, the United States has seen a steady increase in electricity produced by wind turbines, with a capacity of about 7.3 GW installed annually [103]. Fiber-reinforced polymers and balsa or foam cores are used to create wind turbine blades; disposing of turbine blades as waste adds a significant amount of composite material to landfills. According to one study, around 9.6 metric tons of composite are needed for every megawatt of installed capacity [104]. Such highly constructed material waste not only poses a risk to the

environment but also represents a loss of potentially recovered capital. Because composite waste landfilling is becoming more regulated, thermoplastic resins—which are naturally recyclable—may be a superior design alternative [105]. The 1999/31/EC Directive on Landfill Waste, a law issued by the European Union, forbids the discarding of large-sized polymer composite components like wind turbine blades. Anticipating the possibility of comparable legislation in the United States is wise. For this reason, a major goal of the Institute of Advanced Composites Manufacturing Innovation (IACMI) is to certify composite technologies in which 80% of the component materials are recyclable or reusable [106].

The market for composites is dominated by thermosetting resins like epoxy, vinyl ester, and polyurethane; the wind industry mostly employs these resins for the vacuum infusion of blades. Nonetheless, there is a growing interest in employing thermoplastic resins for the construction of blades and a trend toward their use in long-fiber composites beyond the wind sector [107]. When wind turbine blades reach the end of their useful lives, there are now a few alternatives for what to do with them: they can be burned with energy recovery, ground for use as aggregate in concrete, or deposited directly in a landfill [108–112]. Furthermore, a recent study [113] demonstrated that thermoset blades might be recycled by grinding them into building components. The meager profit margins of these recycling methods are evident from the fact that they are not widely used in the commercial sector. However, reintroducing recycled components into the supply chain to replace virgin materials is crucial to the sustainability of composite recycling [114]. This section quantifies and illustrates how material recovered and repurposed from a wind turbine blade component helps with the recycling of composite parts employing fiber-reinforced polymer composites. Three major methods of recycling are examined: mechanical recycling, chemical recycling, and thermal recycling. Table 2 provides a comparative summary of the various recycling methods, advantages, disadvantages, and their reuse applications.

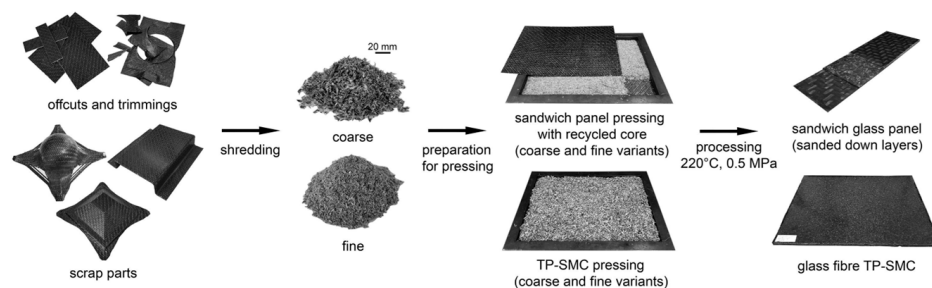
3.1. Mechanical Recycling of Polymer Composites

Mechanical recycling is suitable for FRPs, as it involves shredding to break down fibers [115–118]. This technology combines grinding and pulverization to convert FRPs into powder. Fine powders serve as reinforcements or fillers in novel composites [119,120]. Recyclates with different sizes can be recovered and isolated by sieving them into resin-rich powders and fibers of varying lengths that are impregnated in resin [121]. Typically, the production of short-fiber composites uses these recyclates as fillers. However, these recyclates have a low market value, which is associated with their limited reinforcement performance as a result of their diminished aspect ratio [112,122]. This method is ineffective for recovering glass fibers and carbon fibers because of the poor-quality surface generated by the shredding process. This treatment significantly degrades the fiber quality. To improve the quality of the recycled products, the chopped, discontinuous, and short recycled fibers were combined with virgin fibers. Figure 9 displays the mechanical recycling of PP-GF and PA6-CF composites.

Researchers explored the mechanical recycling approach and its effect on the mechanical characteristics of composites. Hu et al. [123] investigated the mechanical recycling of waste products in fly ash and ground granulated blast furnace slag (GGBFS)-based geopolymer composite. The findings revealed that both GGBFS and recycled aggregates enhanced the mechanical and physical characteristics of geopolymer composites.

Werken et al. [124] investigated the recycling of CFRPs which resulted in the loss of virgin fiber in small quantities. Furthermore, these composites retain excellent mechanical characteristics after recycling and can be used in high-end applications. Furthermore, when recycled, carbon fibers ranged in length from millimeters to centimeters and formed a tangled mass like cotton candy.

PP-GF recycling route



PA6-CF recycling route

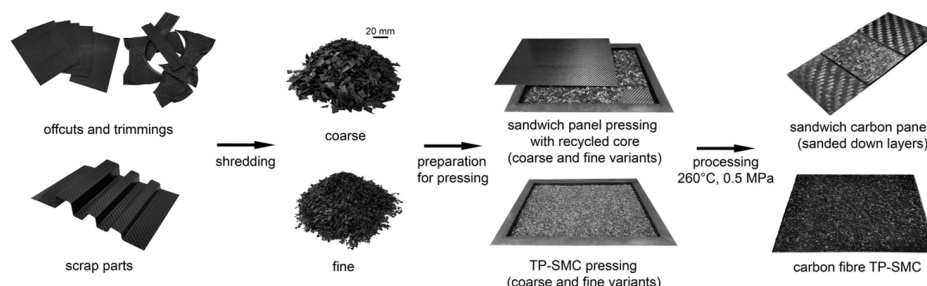


Figure 9. Mechanical recycling of polypropylene–glass fiber and polyamide 6–carbon fiber composites [116].

Colucci et al. [125] investigated the effect of mechanical recycling on the mechanical characteristics of PA66 composites incorporated with carbon fiber (30%). Commercially available pure PA66CF30 particles were molded into dog-bone shape specimens by the injection molding technique, and test examples were aged. Finally, the aged specimens were recycled with an RSP 15 open-type rotor grinder. Mechanical testing on virgin, aged, and recycled specimens revealed that aging lowered the elastic modulus and tensile strength by 14% and 16%, respectively. Recycling, on the other hand, had little effect on mechanical properties, save for a negligible reduction in tensile strength. It was observed that mechanical recycling could facilitate the efficient reuse of polymer composites in the automotive industry. Pietroluongo et al. [126] suggested the mechanical recycling of EOL automobile car radiator components made using PA 6.6 composites incorporated with 35.7% GFs. The author evaluated the mechanical characteristics of three recycled and remolded components of the reference material. The results showed that the mechanical properties continued to fall as re-molding and recycling increased, owing to the shortening of the glass fiber length during reprocessing. The short fiber length in EOL decreased from $253 \pm 107 \mu\text{m}$ to $124 \pm 65 \mu\text{m}$. Similarly, the modulus and strength of recycled samples were lowered by 23% and 29%, respectively. These results were nevertheless superior to the mechanical properties demonstrated by the virgin matrix. Recycled composites, such as unreinforced PA 6.6 or PA 6.6 with a small amount of GFs, can be used in automotive applications.

In another study, Stan et al. [127] evaluated the impact of mechanical recycling on low-density polyethylene/multi-walled carbon nanotube (LDPE/MWCNT) composites that had previously been produced by injection molding. LDPE/MWCNT-based composites were recycled and re-fabricated with MWCNT (0.1 and 5 wt%) via 3D filament extrusion and injection molding. The mechanical properties were compared to those of a virgin composite made under the same conditions. The mechanical properties of recycled composites were found to be higher than those of virgin composites after an injection molding process. The same trend was observed in the specimens developed using the 3D filament process.

3.2. Chemical Recycling of Polymer Composites

The chemical recycling of CFRP and GFRP-based thermoset composites generally involves depolymerization [128–130]. Chemical recycling of composites is performed using several reactive chemicals and mediums [131,132]. The primary goal of this technology is to recycle various fibers. However, this approach may be utilized to recycle a variety of polymers. Thermoset matrices are chemically decomposed in reactive media to recover fibers and biopolymers [133,134]. Solvolysis, a dissolution process, typically involves reactive media such as supercritical fluids and catalytic solutions [135,136]. Furthermore, chemical recycling has been successfully implemented for CFRPs. Chemical recycling has recently accomplished thermoset matrix breakdown utilizing solvent (solvolysis) or water (hydrolysis) [137]. Solvents are used in the solvolysis procedure to depolymerize or break down thermoset bonds. The solvolysis approach relies heavily on the reaction duration and solvent concentrations. Hydrolysis causes thermoset matrix breakdown by water and alcohol under supercritical circumstances [138,139].

The oligomers produced when polymeric resin breaks down can be recycled into raw chemical ingredients that are then used to recycle carbon fibers. Liu et al. [140] investigated the usage of CFRP-recycled material in epoxy resin and employed a moderate chemical recycling process for recovering the waste of CFRPs, exhibiting a glass transition temperature around T_g (>200 °C). The $ZnCl_2$ /ethanol catalyst was used to recycle CFRP waste. Figure 8 depicts the chemical recycling route. The new epoxy resin was then mixed with varying weights of the resultant decomposed matrix polymer. The mechanical characteristics of the neat epoxy and weight-decomposed matrix were compared. The findings showed that the decomposed matrix of 5 wt% had a flexural modulus and flexural strength that were approximately 14% and 13% greater, respectively, than plain resin, as seen in Figure 10. The chemical recycling process of fiber-reinforced polymer composites is depicted in Figure 11.

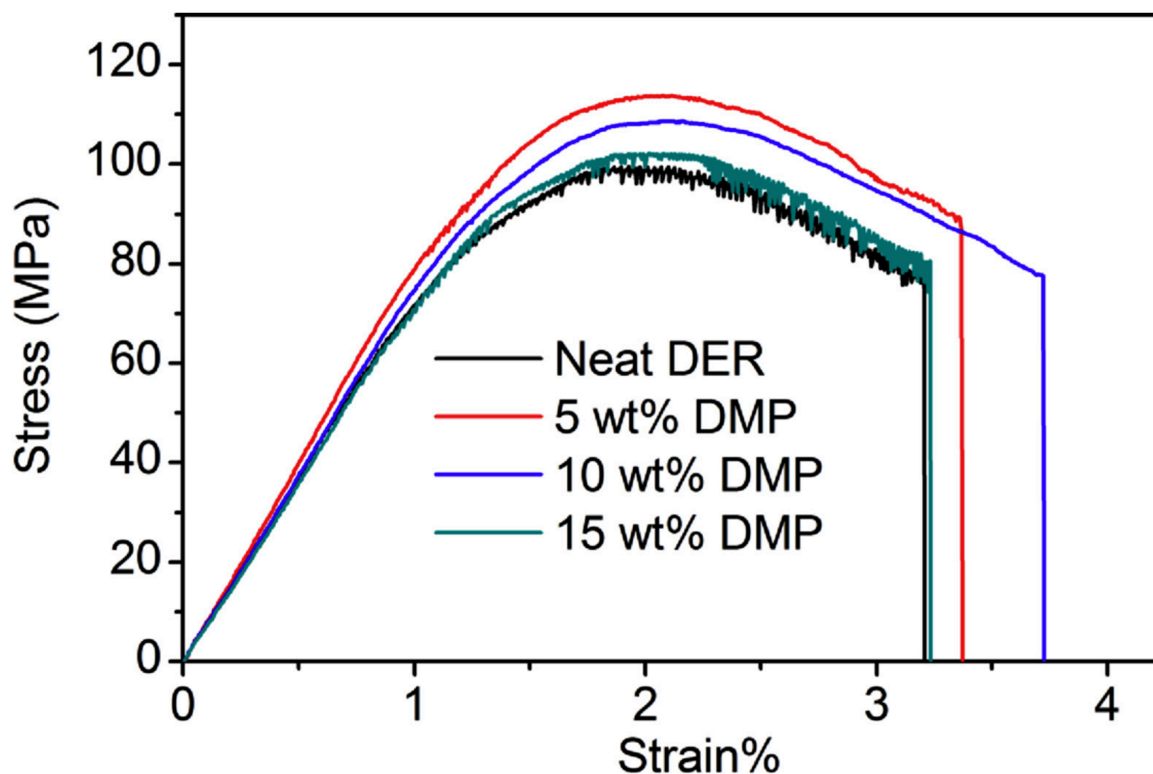


Figure 10. The stress–strain plot of the cured DER/NMA with varying quantities of DMP. DER—epoxy, nadic methyl anhydride, DMP—decomposed matrix polymer [140].

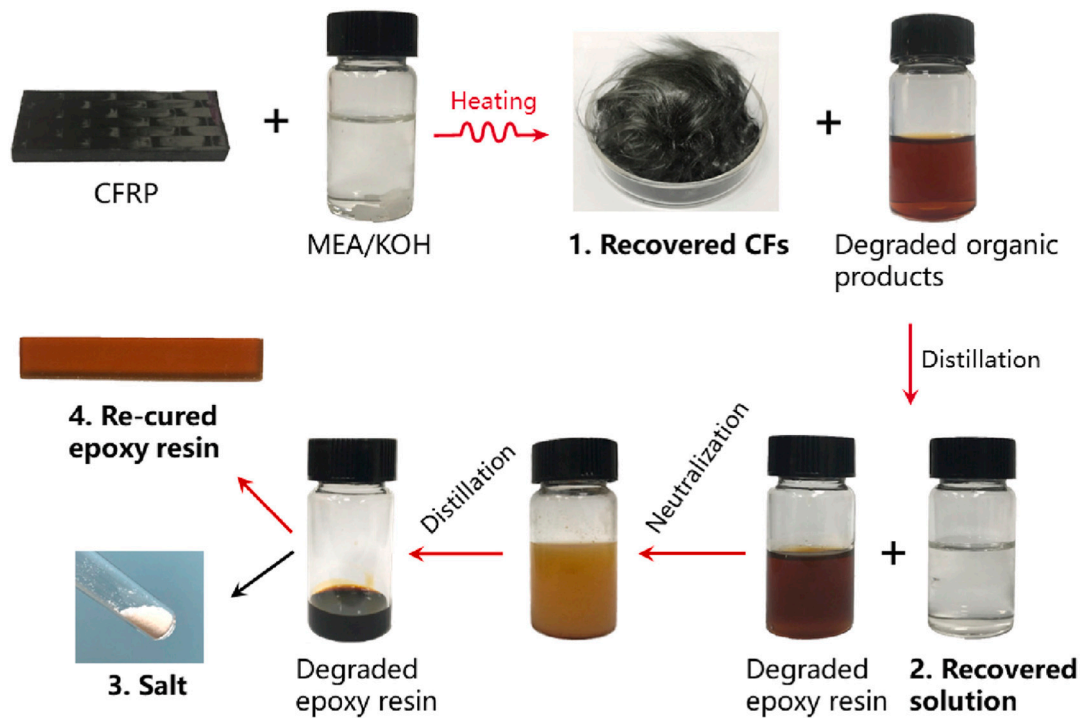


Figure 11. Schematic illustration of the chemical recycling of carbon fiber-reinforced epoxy composite [141].

A thermosetting carbon fiber/epoxy material, consisting of 60% carbon fibers and 40% resin, was obtained from the aerospace structure. Jiang et al. [142] carried out the chemical recycling process. As seen in Figure 12, fiber layers were separated using macrogol and nitric acid concurrently. Comparable surface characteristics of recycled fibers at a 95 wt% recycling rate were revealed by scanning electron microscopy (SEM). However, the mechanical characteristics were decreased to 3%, 5%, and 3%, respectively, for the elastic modulus, tensile strength, and percentage elongation. Due to these outcomes, the composite made of recycled materials is the most suitable for use in industry.

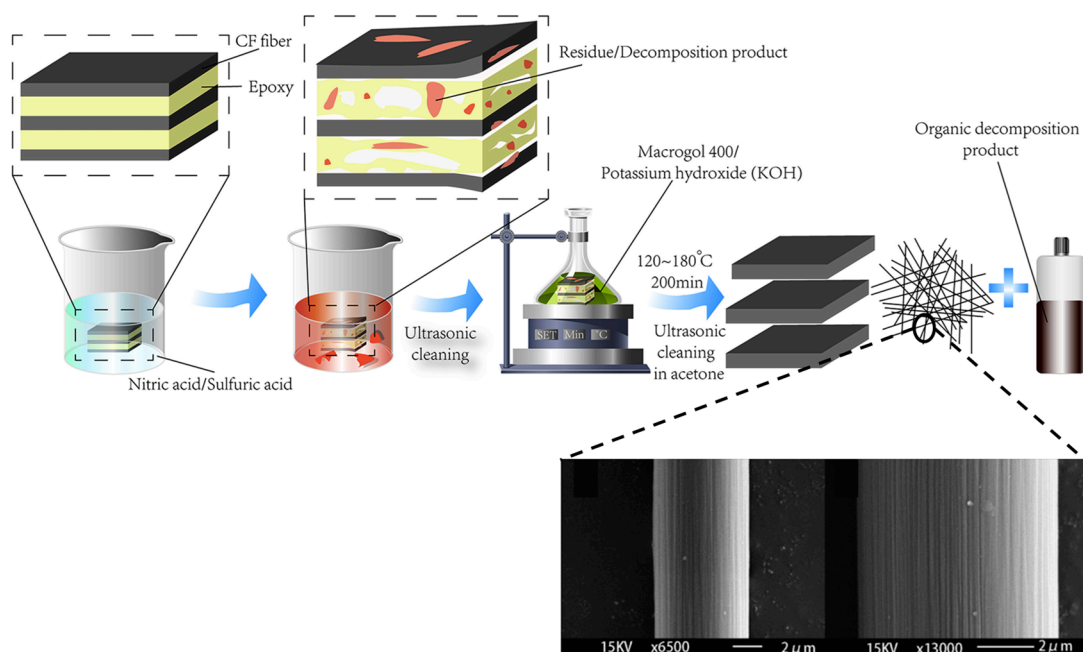


Figure 12. Decomposition process of carbon fiber epoxy composite and SEM images of recovered fiber [142].

Zabihi et al. [143] demonstrated a very economical and environmentally friendly method of recycling glass fiber from glass fiber composites using chemical recycling. As depicted in Figure 13a, 90% of the glass fiber was decomposed after the fractured composite had been soaked in TA/ H_2O_2 solvent and then microwaved for varying periods of time. Stress–strain curves were used to examine the mechanical characteristics of recycled fiber, as shown in Figure 13b. They compared the stress–strain plot of virgin glass fiber with those of recycled samples. The results revealed that the tensile strength, Young’s modulus, and strain of recycled glass fibers (RGFs) were significantly reduced, with values of 7.3%, 1%, and 1.3%, respectively. This technique also offers a low-energy approach in comparison to other chemical recycling processes that demand significant energy demands and time usage.

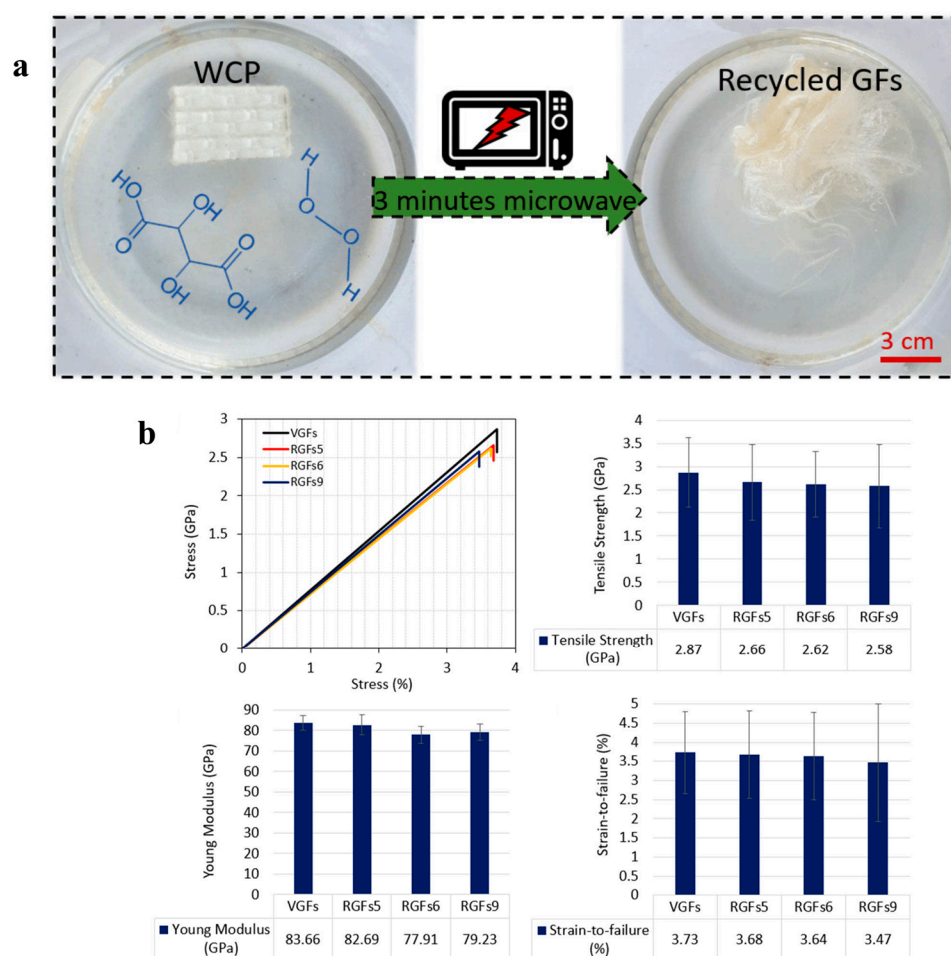


Figure 13. (a) Chemical recycling of glass fiber via microwave-assisted decomposition. (b) Comparison of stress–strain plot between recovered glass fiber and virgin glass fiber [143].

Rosa et al. [115] reported a novel technique for acquiring carbon fiber and thermoplastic epoxy from thermosetting carbon fiber composites by shredding them before the commencement of chemical recycling. The obtained thermoplastic is compounded with different percentages of carbon fibers, such as 10%, 20%, and 30%, to produce the composites, which are then put through an injection molding process. Tensile tests were performed on the dog-bone-shaped specimens, and the outcomes were compared with a virgin-obtained thermoplastic. The yield stress and elastic modulus of thermoplastic with 30% carbon fiber were found to have increased to 92.04 MPa and 12.29 GPa, respectively, and to be higher than those of the virgin thermoplastic. These findings demonstrate the economic viability and environmental sustainability of these recycled materials, in addition to their technological application in the commercial and industrial sectors.

3.3. Thermal Recycling of Polymer Composites

There are three categories for thermal recycling, but the fundamental idea is always the same: employ high temperatures to break down the polymer matrix and leave the fibers as residual material, as shown in Figure 14. To prevent the loss of important products or unwanted changes to the chemistry of the recovered fractions, thermal treatments require careful oversight over process parameters like temperature, atmosphere, and time [123,144,145]. Large volumes of ashes are inert waste that must be disposed of and the loss of valuable carbon fiber and polluting emissions result from thermal recycling, which is performed primarily for energy recovery. These processes also force the use of costly gas-cleaning equipment. On the other hand, clean recycled carbon fiber can be obtained as a solid residue by pyrolysis and fluid-bed methods [120]. For good quality fiber recovery, the residential time and temperature (450–700 °C) of the reactor are important. When the temperature is too low, poor matrix degradation results in an amorphous carbon layer (char) covering the fiber surface. These parameters vary depending on the polymeric resin to be treated. Re-impregnated carbon fiber has limited surface contacts, poor mechanical characteristics, and is stiff. On the other hand, excessive heat can cause the carbon fiber surface to partially oxidize, which lowers the diameter of the fibers and, as a result, its mechanical characteristics are lowered [146–148]. Pyrolysis is a well-known technique among all recycling processes that are used to recycle different kinds of carbon fiber-reinforced composites [149–151]. The polymer matrix composites are heated to temperatures between 350 °C and 800 °C in an inert atmosphere. Consequently, all organic material breaks down into gases and liquids. This method produces char, fumes, and oil due to matrix degradation [152–154]. Furthermore, post-treatment is needed for the fiber due to the presence of char on the fiber [155]. Different thermosets, such as epoxy macromolecules, are broken down into smaller molecules during thermal recycling in a furnace at temperatures higher than 350 °C [156,157].

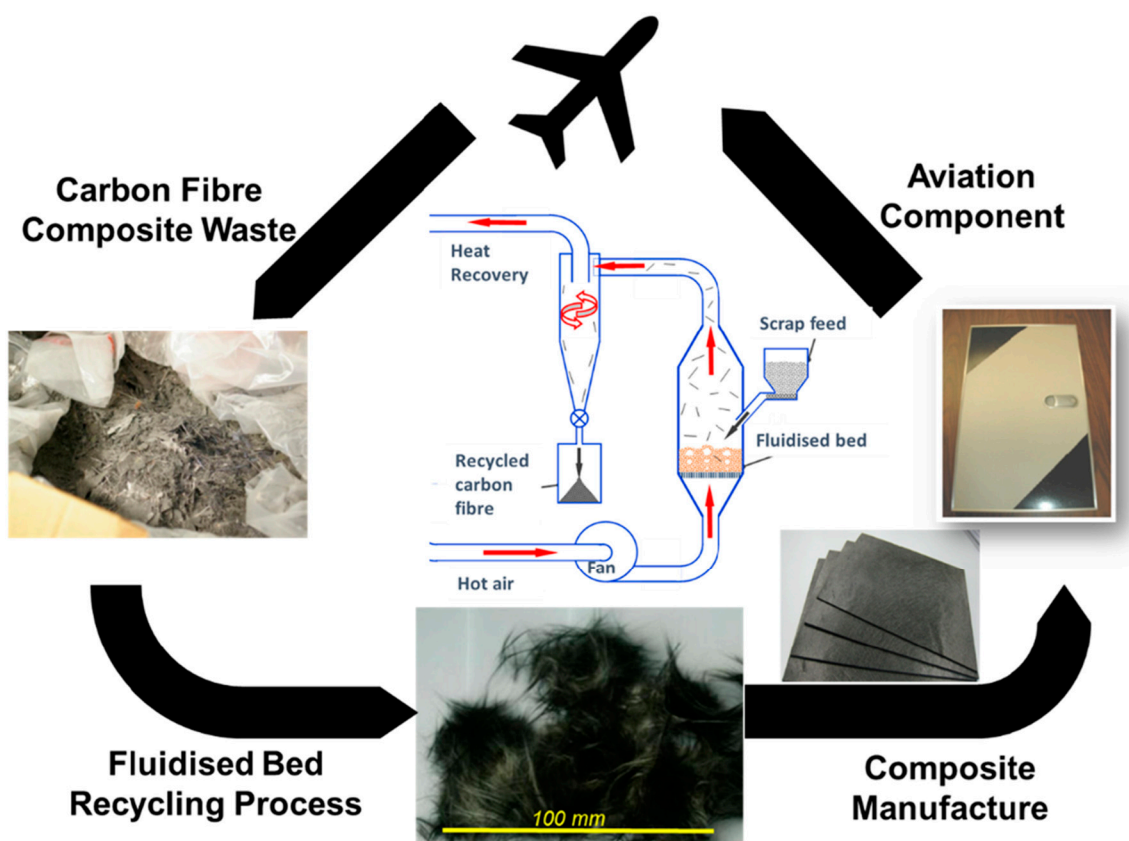


Figure 14. Schematic representation of recycling carbon fiber by thermal process [158].

Fluidized bed (FB) recycling is another thermal recycling method that works well for recycling composite materials [159,160]. Figure 15 shows an illustration of this method. Reclaimed fibers are short, distinct monofilaments that are generated by recovering composite waste. These days, both carbon and glass fibers are recycled using this method, but earlier, it was limited to recycling glass fiber only.

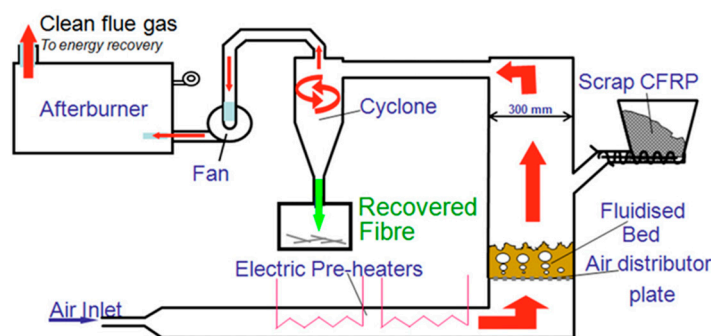


Figure 15. Illustration of the fluidized bed technique [161].

Pender and Yang [162] examined the impact of copper oxide (CuO) on the recycling of glass fiber composites by the fluidized bed technique. The goal was to decrease the recycling temperature of composites without affecting the mechanical characteristics of the composites. To accomplish this, wt% of 0, 1.5, and 5 wt% CuO were incorporated in PRIME 27 epoxy resin (Gurit, Wattwil, Switzerland). A thermogravimetric analysis (TGA) revealed that the inclusion of 5 wt% CuO caused a reduction in the total decomposition temperature of the epoxy to 60 °C. After subjecting the composites to recycling in the FB system, an improvement in yield efficacy was reported, ranging from 6% to 40%, when recycling was conducted using CuO at a concentration of 5 wt%. The tensile strength did not undergo considerable change, and the most favorable outcomes were obtained at a lower temperature for thermal recycling.

Fraisse et al. [163] performed a comparison of the mechanical properties of virgin fiber composites that were recycled thermally and re-fabricated unidirectional glass fiber thermoset composites. Hybon 2026 PPG glass fibers were incorporated with Huntsman 1568 epoxy resin (The Woodlands, TX, USA) to produce a virgin composite. The composite was subjected to a temperature of 565 °C to generate burned fibers, which were subsequently utilized in the re-fabrication of the composite. The results indicated a rise in the density of burnt fibers by 1% due to densification after thermal treatment. Moreover, the thermal treatment resulted in a reduction in the Young's modulus by 6% and 80% in the tensile stress. The mechanical characteristics of the original and re-fabricated composite were examined, revealing a decrement of 15% in the Young's modulus, 91% in the tensile strength, and 90% in the strain at maximum stress. The reduction in the mechanical properties was due to a decrease in the volume fraction of fibers and an increase in their stiffness, ultimately leading to a sudden fracture.

Meyer et al. [164] retrieved the carbon fiber from the carbon fiber composite of the airplane at the end of its lifespan. They enhanced the efficiency of the small-scale laboratory procedure to a semi-industrial pyrolysis technique. They may reproduce semi-industrial manufacturing processes by utilizing a larger oven. Although the amount of recovered carbon fiber was enough to replace virgin carbon fiber, an extra heating system was implemented to eliminate the remaining char. The outputs of the pyrolytic reactor can be significantly influenced by the regulation of the environment in which it operates. The carbon fibers obtained from this procedure present a promising opportunity to replace new carbon fibers in carbon fiber composite products, hence enabling the closure of the CFRP cycle.

Gopalraj and Kärki [165] conducted studies to assess the mechanical characteristics of glass fiber and carbon fiber-reinforced composites that have been thermally recycled.

Glass fiber and carbon fiber were recycled at a recovery rate of 80–82 wt% and 95–98 wt%, respectively, by the thermal recycling technique at 500 °C. After that, these fibers were compressed and molded to create glass fiber and carbon fiber composites. The results showed that the tensile strength, Young’s modulus, and impact strength increased by 12%, 34.27%, and 7.26%, respectively, with the ~20 wt% carbon fiber reinforcement, and by 75.14%, 12.23%, and 116.16%, respectively, with the ~20 wt% glass fiber reinforcement. These findings suggest that, while maintaining their structural integrity, carbon fiber composites and glass fiber composites can be thermally recycled several times.

Table 2. Recycling methods, advantages, disadvantages, and their reuse applications.

Recycling Method	Advantages	Disadvantages	TRL	Reuse and Application	References
Mechanical	High efficiency and throughput.	Lower-quality recyclates, high material waste (up to 40%), and limited large-scale applications.	Glass fiber: 9 Carbon fiber: 6/7	Composites with recycled short-fibers, random-oriented, and concrete-reinforced with crushed CFRP [M30-61,62] [M30-63–68]	[166,167]
Chemical Recycling (Solvolysis and Supercritical Fluid Methods)	Recovers full-length fibers and uses low-risk solvents.	High energy consumption, large solvent volumes, and decreased quality of carbon fibers.	5/6	Composites reinforced with recycled fibers, fuel gas	[168]
Thermal Recycling—(Pyrolysis, Microwave Pyrolysis, Fluidized Bed)	By-products used as energy or chemicals, scalable, and lower fiber damage.	Oxidation residue on fibers, strength loss, reduced fiber quality.	Pyrolysis: 9 Microwave: 4/5	Liquid fuels, pyrolytic gas/oil, composites with short recycled fibers, electromagnetic shielding, high-modulus composites	[166]

4. Research on Recycling Degraded MRE Structures

Otheguy, M.E. et al. carried out recycling efforts on thermoplastic materials from composite boats at the end of their life and compared the properties of the recycled materials with similar virgin unaged materials. The Atlantic 85 RIB boat was made up of Twintex T PP woven polypropylene glass fabric (Vetrotex Inc., Wallingford, UK). Additional samples using the same material were fabricated for validation. A mechanical recycling process was carried out. The properties of the recyclates (short fiber composites) seemed comparable to those of more widely used ‘short fiber’ materials. Balsa and paint have a negative effect on the elongation and strength of molded materials, thereby altering their properties. It is important to note that boats are only exposed to the upper layer of water and are not subject to any additional loads. Balsa and paint have a deleterious effect on molded strength and elongation to break the properties. However, boats are exposed to the top surface of the water only, and do not have any other loads acting on them [169].

As per the author’s knowledge, until now, no research has been performed on recycling the end-of-life or seawater-aged composites of MRE device materials; hence, the effect of seawater on recycling is unknown. To study this gap, in a recent work performed at Pacific Northwest National Laboratory (PNNL) (Richland, WA, USA), funded through the U.S. Department of Energy (DOE) Waterpower Technologies Office (WPTO) (Washington, DC, USA), the authors have compared the characteristics of virgin and recycled thermoplastic Elium-glass fiber composites, recycled through the mechanical grinding process. It was observed that the flexural strength and modulus decreased by 34.5% and 18.6%, respectively [60,170]. Based on this, the authors determined that it is important to study the

recycled material properties of unaged composite structures, and seawater-aged composite structures, through various recycling processes and determine the best process, based on future sustainability needs.

There has been a growing concern over selecting systems that meet current needs without jeopardizing the ability of future generations to meet theirs. However, many material selection choices are made based on opinion rather than validated evidence. Conducting a full quantitative life cycle assessment (QLCA) is crucial before mass-producing marine composites, covering all stages from design and manufacturing to marketing, use, and disposal [171,172]. Azapagic et al. [173] proposed a method for quantifying these burdens as environmental impact classification factors (EICFs). Additionally, land use, as noted in BS8905:2011 [174], presents another significant sustainability issue. Singh et al. [175] reviewed disposal options for composite boats and marine composites, highlighting concerns about thermoset composites, which are often deemed unsuitable due to limited disposal options and landfill restrictions. Conversely, thermoplastic matrix composites require higher manufacturing temperatures, potentially increasing global warming impacts. Further, with these higher costs involved in manufacturing, it is vital to study the costs and measures involved with recycling these seawater-aged degraded structures, by performing a QLCA and clarifying these sustainability challenges [58].

4.1. Reuse and Recycling of Composite Structures

Typically, during early signs of damage, composite structures are repaired [32]. Few researchers work on self-healing composites [176], where they sustain the degradation and damage, rejuvenating the composite structure. However, upon their failure during the end of their life cycle, an attempt to reuse and repurpose the composite structures with minor repair/modifications to their damage in alternative applications is needed. Figure 16 below shows an example of a reused wind turbine blade as a bike shed in Aalborg, Denmark. When the reuse and repurposing of the damaged composite structures from MRE is determined to be impossible, due to the amount of moisture content, biofouling effects, and other concerns, methods should be determined for the recycling of the structure and recovering the resin or fiber or obtaining grinded recyclates. The recycling process may be determined by the need.



Figure 16. A reused wind turbine blade—bike shed in Aalborg, Denmark. Reproduced with permission from Port of Aalborg [177].

4.2. Reuse of Recycled Fibers and Matrix

When reusing recycled fibers, it is important to differentiate between two approaches: direct reuse and the processing of fibers into semi-finished products. The direct reuse of ground or milled recycled fibers, such as in injection molding, offers cost-effective recycling but often leads to downcycling compared to virgin fibers due to issues like fiber

shortening, potential damage during recycling, and misalignment of fibers. Processing into semi-finished products presents greater potential to bridge the performance gap between composites made from virgin and recycled fibers. Achieving an optimal fiber orientation is crucial, and several methods exist for this purpose. Wong et al. [178] produced highly oriented filaments using rotational forces by a centrifugal process. Developed by Longana et al. [179], the HiPerDiF (Bristol, UK) method uses water fiber dispersion in a nozzle, achieving 67% fiber alignment at $\pm 3^\circ$ to the filament axis. Oliveux et al. [180] created a process by vibration and combing that produces 25 mm wide ribbons with up to 95% oriented fibers. The effectiveness of these semi-finished products has been demonstrated in applications like the manufacturing of staple carbon fiber surf fins.

Research on the recovery and reuse of matrix materials in composites is limited compared to that of fibers, primarily due to the lower economic value of the matrix. In mechanical recycling, matrix residues are often not separated from the fibers and reused together as filler. In thermal recycling, the matrix is primarily used as an energy source for the pyrolysis process, which can only be described as thermal utilization rather than recovery. However, laboratory-scale methods are exploring the use of pyrolysis gases and oils to recover low-molecular compounds for new chemical synthesis procedures. Chemical recycling is more common for recovering matrix components, as it allows for the extraction of more complex molecules, such as recovering polystyrene derivatives from unsaturated polyesters, which can then be processed into polystyrene-based thermosets. Despite these advances, achieving a complete recovery of the matrix or processing it to a comparable value as fibers remains challenging, making a closed recycling loop for matrix materials less feasible than for fibers, especially on an industrial scale [181].

In summary, it is vital to determine (1) the degradation of the composite structure upon the end of its life cycle; (2) the method of recycling based on expected reuse application; and (3) performing a life cycle assessment to determine if the recycling method chosen is beneficial and sustainable for the reuse application. Figure 17 below depicts the direction for research efforts to focus on evaluating the characteristics of recycled resins or fibers or composite structures.

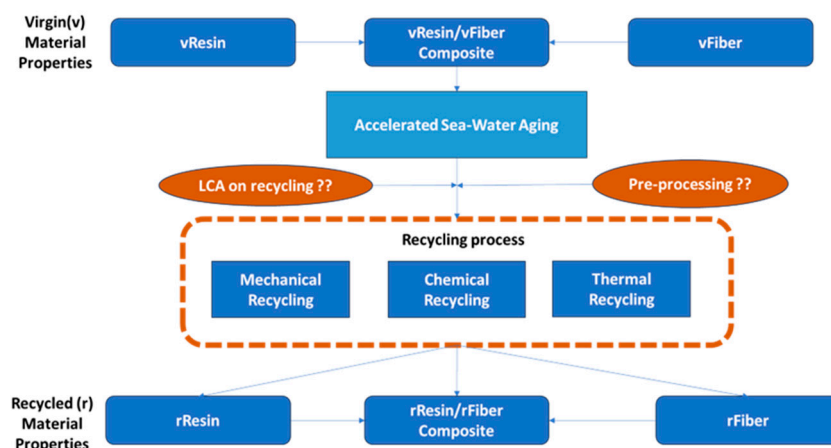


Figure 17. Framework for property evaluation of recycled composites at the end of their life cycle.

4.3. Economic Cost Analysis of Recycling the Composite

An economic analysis indicates that recovering materials from thermoplastic composites is financially viable if they can substitute virgin materials in the supply chain. Key factors for this include reducing labor costs, minimizing polymer losses, and maximizing glass fiber resale value [106].

To determine the economic viability of recycling polymer resins for large-scale composite manufacturing, several researchers have modeled the expenses of operating a recycling facility. Grinding requires 0.29 MJ/kg of energy, whereas thermal decomposi-

tion, dissolution/distillation, and dissolution/evaporation require 1, 20, and 4 MJ/kg, respectively [182].

Elum, as an acrylic polymer, has properties similar to PMMA (polymethyl methacrylate), a thermoplastic polymer with high manufacturing energy requirements (207.3 MJ/kg). This energy-intensive process raises the cost of PMMA to roughly USD 2.50/kg, making recycled materials more competitive in the market. Using recycled materials could help turbine manufacturers offset some blade production costs while also reducing embodied energy [182].

The economic analysis of a blade length of 61.5 m and a weight of 21,106 kg is explained below. Recycling consumes 15.3 MJ/kg for dissolution and 2.6 MJ/kg for devolatilization, with a typical blade having 5322 kg of resin. Total energy expenses are USD 2123 per blade. The facility charges include USD 3 million for equipment and 10% for installation and maintenance, while the building requires 1500 m² and costs USD 1.2 million. Operations require ten unskilled laborers, each paid USD 20 per hour, and each blade takes 48 h to process, costing USD 11,767 for facility operation. Recovered PMMA resin costs USD 2.50/kg with a 90% recovery rate, while fiberglass costs USD 4.00/kg with a 50% recovery rate from 12,077 kg per blade [106,183]. The cost of essential equipment, including a dissolving and evaporation tank, solvent recovery condensers, and an extruder, is estimated at USD 3 million. Operating costs, including labor and electricity, are based on projections for a similar wind turbine facility. The recycling facility may charge 60% of landfill costs for blade decommissioning [184].

The technique aims for a 90% polymer recovery rate, with 10% lost during separation. Due to structural complexity, only 50% of glass fibers are expected to be recovered, with unrecovered material incurring disposal fees. Recovered PMMA can be sold at USD 2.50/kg and fiberglass at USD 4.00/kg, with the breakeven point depending on price adjustments for recovered materials. Labor costs are the most sensitive operating expense, affecting feasibility at USD 960 per blade.

Wind turbine blade recyclability through dissolution depends on the quality of the recovered materials. While recovered polymers may retain high value, maintaining glass fiber quality is challenging. Recovered fibers could be used in compounding operations, although polymer compounding is more complex. Carbon fiber composites have better recycling economics, as carbon fiber costs USD 11–25/kg, significantly more than glass fiber. Thermoplastic carbon fiber composites offer economic benefits in recycling. Solvolysis, commonly used on carbon fibers, has rarely been applied to thermoplastics, but dissolution at lower temperatures may be a cost-effective recovery strategy. Current recycling technologies must advance from lab to commercial use, requiring more cost-effective and eco-friendly processes, as well as remanufacturing methods for high-performance products. Developing new sustainable blade materials—using natural fibers, modified thermosetting resins, and recyclable thermoplastics—can enhance the sustainability of water power technologies, promoting them as a truly clean energy source.

5. Knowledge Gaps

Based on the review conducted, it is necessary to allocate research funding to develop high-performance, recyclable materials for next-generation MRE devices. This includes supporting demonstration facilities to test sustainable materials and funding research into “smart” materials with integrated sensors for health monitoring and maintenance optimization. A full-scale demonstrator should be created to showcase how these innovations can extend the lifespan of polymer composite structures used in marine applications. Additionally, funding should be directed toward advancing recycling technologies, focusing on economic viability, and overcoming market barriers. Large-scale facilities should be established to scale up recycling processes, promote cross-sector collaboration, and integrate recycled materials into new manufacturing, such as composites. Expanding existing treatment methods and strengthening the composite waste recycling value chain are also crucial.

6. Conclusions

In conclusion, while MRE technologies have increasingly adopted polymer composites over traditional metal alloys for their structural components, the recyclability and sustainability of these materials remain underexplored. Recent innovations in liquid recyclable and bio-based resins, along with additive manufacturing technologies, offer promising solutions. However, the challenges posed by environmental degradation, such as seawater aging and biofouling, highlight the need for more comprehensive studies on the end-of-life management and recycling of these materials. Further research is essential to develop efficient reuse and recycling processes that ensure the long-term sustainability of MRE structures.

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