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**TOWARDS A SUSTAINABLE FUTURE:
Exploring methods, Technologies, and Applications
for Thermoset Composite Recycling**

Centria University of Applied Sciences

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1 INTRODUCTION

Composite materials are engineered substances composed of two or more distinct constituents, each possessing varying physical and chemical properties (Chawla 2019). These constituents, referred to as the matrix and the reinforcement, combine to form a novel material exhibiting enhanced properties not inherent in the individual components alone.

Polymer composites represent materials comprising two or more distinct components: a polymer matrix and a reinforcing phase. The polymer matrix is a continuous medium enveloping and bonding with the reinforcing phase, consisting of fibers, particles, or flakes. This reinforcing phase significantly enhances the composite material's mechanical, thermal, or electrical properties.

Various materials, such as glass, carbon, aramid, nanoparticles, or natural fibers, can serve as reinforcing phases in polymer composites. The choice of these materials depends on the composite's desired properties and intended application. Moreover, the polymer matrix can be fabricated from a wide array of polymers, including thermosetting resins (e.g., epoxy, polyester, or phenolic resins) or thermoplastic polymers (e.g., polypropylene, polyamide, or polyethylene). A classification of polymer composites based on materials can be seen in Figure 1.

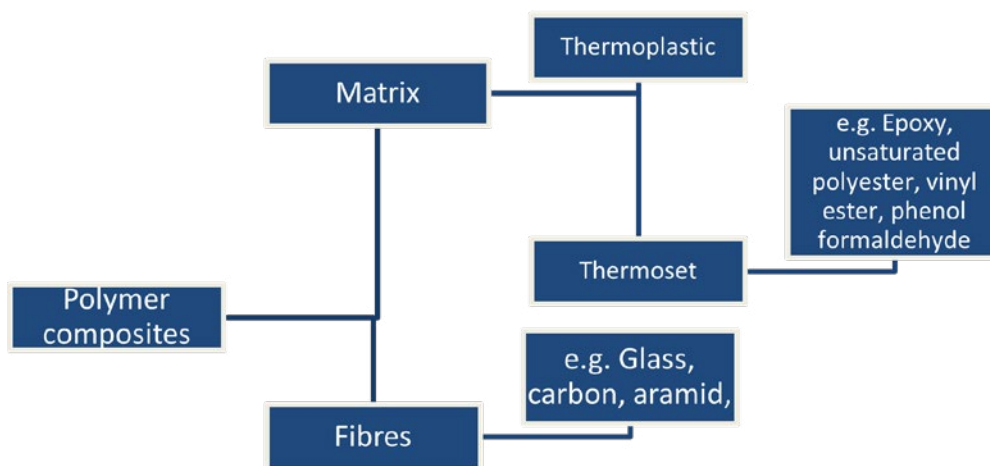


Figure 1. Classification of polymer composites based on materials.

Polymer composites find widespread applications across various industries, encompassing aerospace, automotive, construction, electronics, sports equipment, and numerous other sectors. Within these domains, polymer composites are the foundational material for crafting lightweight and durable components, including aircraft components, automotive body panels, wind turbine blades, boat hulls, and sporting equipment. The distinctive properties and performance characteristics of polymer composites are adaptable through meticulous adjustments in composition, processing methodologies, and design parameters, thus facilitating alignment with the specific requirements of the intended application.

The core objective of this report is to deliver an all-inclusive depiction of the existing recycling alternatives available for thermoset composite materials. Within this scope, it shall assess the technological readiness level of these recycling methods while concurrently evaluating their present feasibility in the context of composite material recycling. Furthermore, the report shall define a forward-looking perspective, shedding light on the potential benefits and difficulties of the prevailing approach in thermoset composite recycling.

1.1 MARKET SHARE - THERMOSET COMPOSITES

In 2022, the global composites market achieved a total volume of 12.7 million tonnes, signifying a notable 5% upswing compared to the preceding year, 2021, during which it had amounted to 12.1 million tonnes. Conversely, European composite production experienced a noticeable contraction, declining by 6.1% in the same year, 2022. This diminished the European composites market from 2962 kilotons (kt) in 2021 to 2781 kt (Elmar & Volker 2023). Europe's share in the global market stood at approximately 22%, mirroring the market share of America. In sharp contrast, the Asian composites market has held a considerably higher global market share, reaching an impressive 50%. The European thermoset composite market by areas of application and by country is shown in Figure 2 excluding carbon fibre-reinforced plastic (CFRP).

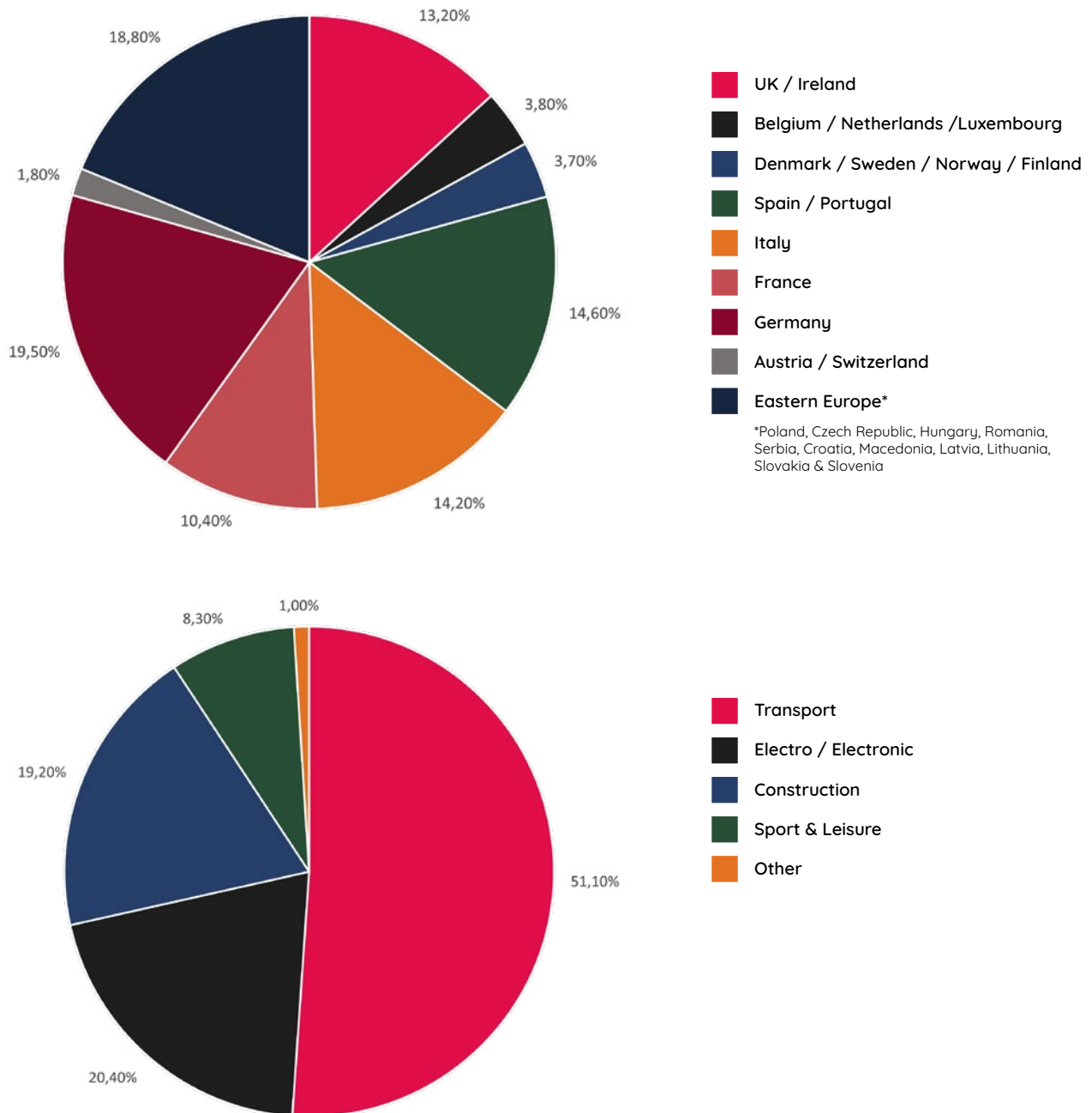


Figure 2. European thermoset composite market by areas of application and by countries (excluding CFRP) (Adapted from Elmar & Volker 2023)

In 2022, the collective production volume of thermoset composites (excluding CFRP) amounted to 1,138 kilotons, reflecting a decrease from the previous year's figure of 1,250 kilotons. Consequently, this category of materials constituted 41.8% of the overall European market share. Simultaneously, 2022 witnessed a notable surge in the market volume of CFRP, with a remarkable growth rate of 9.6% compared to the preceding year. The total market volume for CFRP in Europe expanded to 57,000 tonnes, signifying a substantial upswing within this market segment. Nevertheless, compared to the market volume of glass fibre reinforced plastic (GFRP), the market size of CFRP remains relatively modest, estimated to represent only approximately 5% of the total thermoset composites market.

1.2 CIRCULAR ECONOMY AND POLYMER COMPOSITES

The circular economy concept has a long history but attracted significant attention in the late 1970s. At its core, the circular economy strives to rebuild economic, natural, and social capital while harnessing the potential of renewable energy sources. It underscores the pivotal role of the economy in achieving optimal functionality across all levels, ranging from individuals to expansive organizations and enterprises, both within local and global contexts. The circular economy rests on three foundational principles:

1. Eliminating waste and pollution through design: This principle prioritizes the proactive design of products and systems to restrict waste generation and prevent pollution.
2. Promoting product and material reuse: Central to the circular economy concept is the maximization of product and material utility, aiming to prolong their lifespan. This principle champions strategies such as repair, refurbishment, and collaborative sharing models to extend the usability of products.
3. Regenerating natural systems: Acknowledging the importance of restoring and rejuvenating natural systems, the circular economy advocates for employing regenerative processes and renewable resources to promote environmental sustainability.

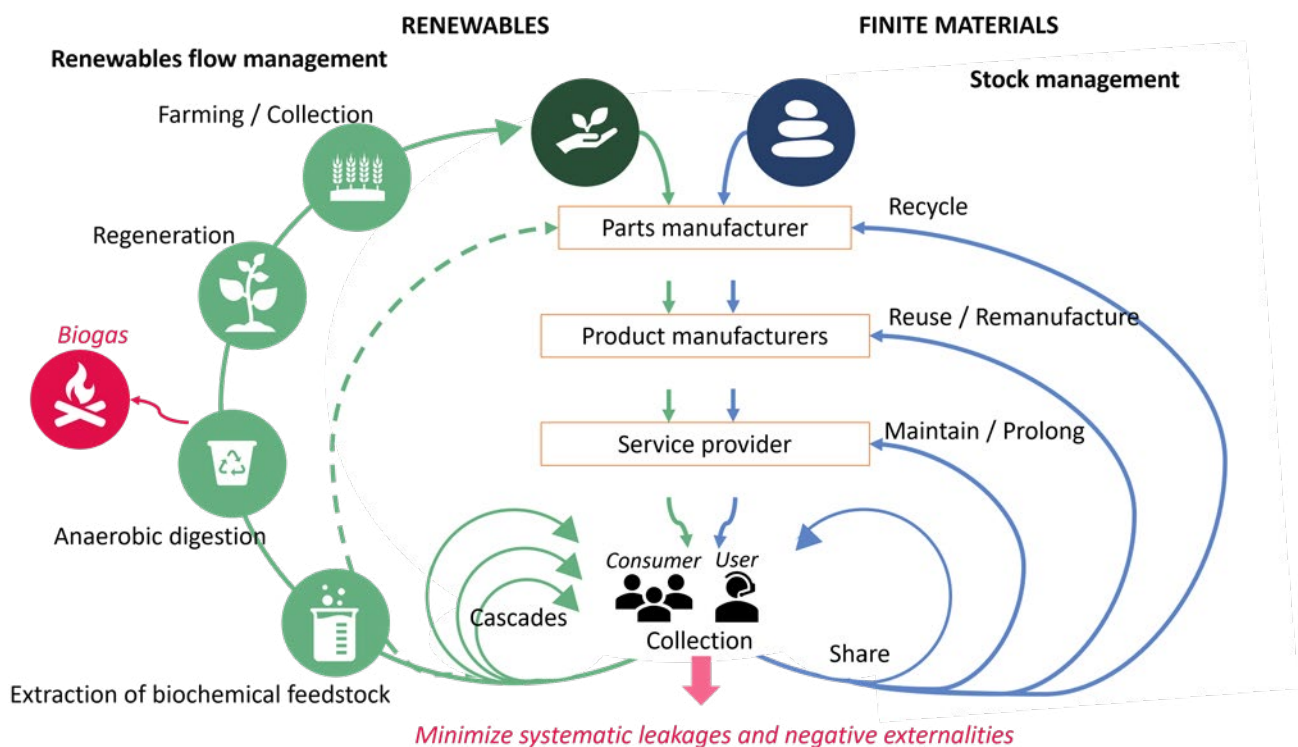


Figure 3. Circular economy butterfly diagram (Adapted from Ellen MacArthur Foundation 2013)

The schematic representation seen above, often referred to as the butterfly diagram (Figure 3), illustrates the fundamental concept of the circular economy. It showcases how this model fosters continuous and augmented cycles of goods and services by enabling the seamless cycling of materials through both technical and biological cycles.

Within the context of the circular economy framework, considering composite materials becomes crucial. It is vital to recognize that these materials must possess the capacity to circulate similar to any other material within this framework. Without this recognition, composite materials cannot integrate into the circular economy, regardless of their sustainable advantages, such as weight reduction and fuel efficiency. The challenge inherent in facilitating the movement of composite materials through these cycles resides in the intrinsic complexity of separating embedded fibers and fillers from the resin matrix. Thermoset composites in a circular value chain is illustrated in Figure 4.

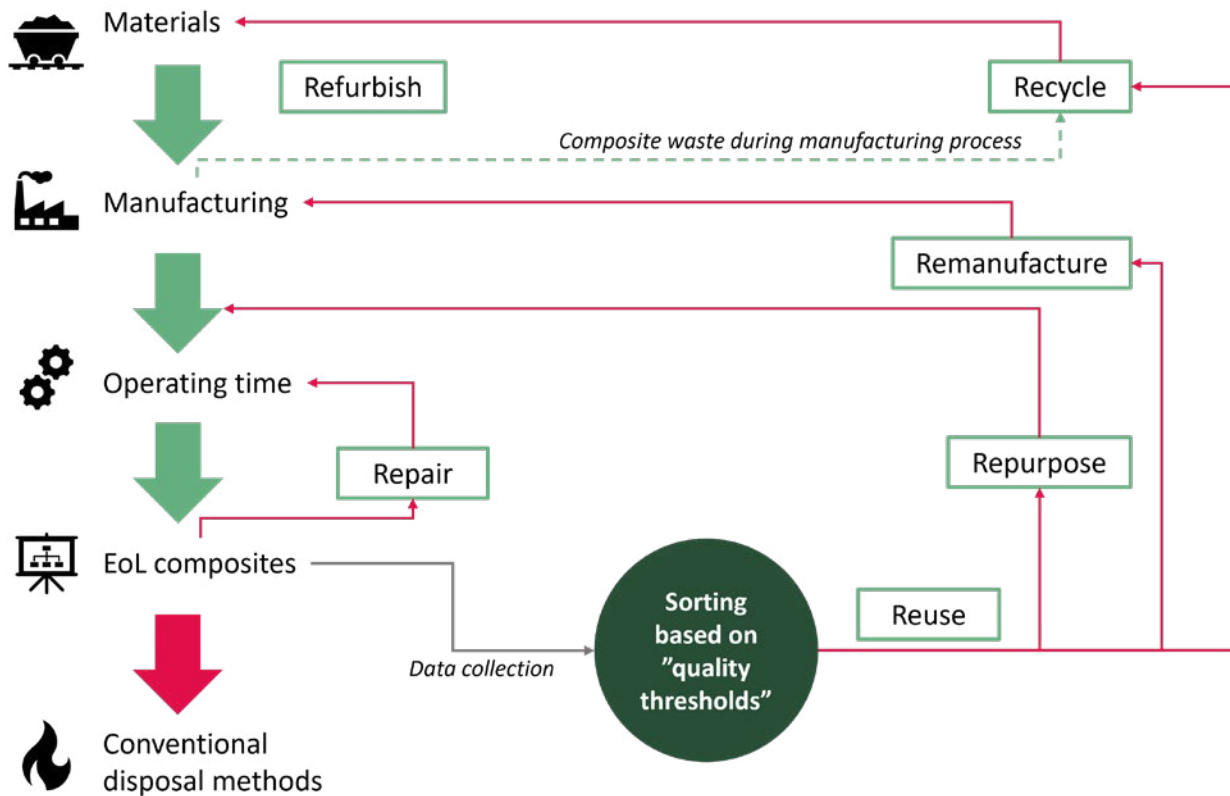


Figure 4. Thermoset composites in a circular value chain (Adapted from Johst, Kucher, Schulz, Knorr, Kupfer & Böhm 2022)

The management of thermoset composite waste poses distinct challenges within the framework of the circular economy, primarily due to its inherent recyclability limitations. Nonetheless, concentrated actions are currently in progress to align thermoset composite waste management with the principles of the circular economy. A key strategy in this endeavor involves adopting a ‘design for the circular economy’ approach, which strongly emphasizes enhancing recyclability by integrating end-of-life considerations into the product design process.

Simultaneously, ongoing research initiatives are delving into advanced recycling technologies tailored to break the crosslinked structure of thermoset composites. This type of research seeks innovative methods to effectively recycle and reintegrate these materials into the production cycle.

Waste minimization is another pivotal facet of waste management in this context, which centers on reducing waste generation through optimizing manufacturing practices. By adopting more efficient and sustainable production methods, the goal is to limit waste generation from the beginning.

Table 1. Waste management for composites prioritized in the context of circular economy.

Priority	Waste management method	Examples in the European context
1	Prevention and Minimization: The priority in the circular waste hierarchy is to prevent or minimize waste generation. This can be achieved by promoting sustainable design and manufacturing practices that minimize the use of thermoset composites or optimize their lifespan.	By incorporating lightweight thermoplastic composites that are easier to recycle and repair, BMW minimizes waste generation and promotes sustainable material choices
2	Reuse: The second priority is to explore opportunities for reusing thermoset composites. This involves identifying ways to extend the lifespan of composite products, such as through refurbishment, repair, or repurposing. Reusing thermoset composites in their original form helps retain their value and reduces the need for additional resources.	ReFibre Asp is a Danish company that specializes in repurposing decommissioned wind turbine blades. They transform the blades into sustainable building materials, such as noise barriers for highways, sound-absorbing panels, and structural components for construction.
3	Recycling and Material Recovery: If reuse is not feasible, the next priority is to focus on recycling and material recovery. Although thermoset composites pose challenges in terms of recycling, research and development efforts are underway to find innovative recycling technologies and processes. These may include pyrolysis, solvent-based recycling, or other advanced recycling methods to break down the crosslinked structure of thermoset composites and recover valuable materials.	Composites Evolution, a UK-based company, has developed a recycling process called "EcoPrep," which involves mechanically grinding or shredding thermoset composite waste to produce recycled carbon fibre materials. These recycled carbon fibres can be used in various applications such as automotive parts, sporting goods, or aerospace components.
4	Energy Recovery: If recycling is not technically or economically viable, the next option is energy recovery. Thermoset composites can be used as an energy source through incineration, where the calorific value of the material is harnessed to generate heat or electricity.	Holcim, a global cement manufacturer, has implemented co-processing methods where thermoset composite waste is used as a replacement for traditional fossil fuels in cement kilns, simultaneously reducing CO2 emissions and utilizing the energy content of the composites

Furthermore, exploring alternative applications for thermoset composite waste and harnessing it for energy recovery represents crucial components of circular economy objectives. This entails identifying and developing new avenues for utilizing waste materials, which not only minimizes waste but also contributes to the generation of valuable resources. Waste management for composites prioritized in the context of circular economy is listed in Table 1.

Ultimately, the success of these actions relies heavily on collaborative efforts between industry stakeholders, research institutions, and policymakers. Such collaborations are instrumental in driving the advancement of sustainable waste management strategies and fostering the development of innovative solutions to address thermoset composite waste within the overarching framework of the circular economy.

1.3 DRIVING FACTORS FOR RECYCLING

There exist three primary drivers motivating the recycling of waste from thermoset polymer composites. The first motivation is rooted in the economic perspective, focusing on the substantial costs of producing virgin fibers. The second motivation revolves around environmental concerns, particularly regarding the adverse environmental impacts of landfill disposal practices (Nkwachukwu, Chima, Ikenna & Albert 2013; Maheshwari & Deswal 2017). The third motivation is related to legislative requirements.

The impetus driving environmental considerations is deeply rooted in a commitment to sustainable development, as initially defined by the Brundtland Commission (Keeble 1988). This commitment entails meeting present needs without compromising the ability of future generations to meet their own needs. Evaluating this impact entails comprehensive assessments, including metrics such as global warming potential (Cherrington, Goodship, Meredith, Wood, Coles, Vuillaume, Feito-Boirac, Spee & Kirwan 2012). While primarily an intrinsic motivation, it is also a valuable tool for promotional and brand positioning endeavors.

Therefore, exploring the utilization of waste derived from thermoset composites as a secondary resource for producing recycled fibers becomes imperative. This approach is paramount, primarily due to the exorbitant energy consumption and costs of producing virgin fibers. Notably, Pimenta and Pinho's research revealed that the energy consumption for producing virgin fibers ranged from 183 to 286 MJ, which is significantly higher than the energy required for steel production, exceeding it by 14 times (Pimenta & Pinho 2011). Furthermore, producing virgin carbon fibers results in greenhouse emissions that surpass those associated with steel manufacturing by a factor of ten. In contrast, recycling offers a twofold solution by effectively managing waste while generating substantial financial value by recovering carbon fibers.

The United Kingdom, in line with the European Union (EU) end-of-life directive (2000/53/EC), has enacted a landfill tax as a fiscal disincentive to promote the diversion of composite waste away from landfill disposal and towards alternative treatment methods like recycling. This directive mandates that vehicle waste materials must be reusable or recyclable to an extent of 85% by weight, starting from 2015, with a comprehensive recovery target of 95%, which encompasses incineration. Consequently, only 5% of vehicle waste can be disposed of in landfills, while 10% can be allocated for energy recovery. The EU Landfill Directive (1999/31/EC) imposes stringent restrictions on the permissible amount of organic material designated for landfill disposal (Anane-Fenin & Akinlabi 2017).

The abundance of waste materials stemming from the composite industries presents notable opportunities for enhancing sustainability among suppliers, manufacturers, and prospective users. Thermoset recycling technologies have experienced less commercial success when compared with thermoplastic recycling technologies. Nevertheless, channeling efforts toward recycling thermoset composites holds the potential to stimulate economic growth and foster job creation.

By employing diverse recycling techniques tailored for polymer composites, it becomes feasible to recover the reinforcement fibers. These recycling processes can effectively extract valuable materials, including glass fibers, carbon fibers, and residual matrices. Generally, recycled materials derived from polymer composites exhibit a greater cost-effectiveness than virgin composite products, except glass fiber recovered from glass fiber-reinforced composites.

1.4 CHALLENGES IN RECYCLING THERMOSET COMPOSITES

Annually, a substantial volume of thermoset composites, amounting to thousands of tons, is manufactured globally to cater to specialized applications. While these composites effectively bolster various products, challenges loom when they reach their end-of-service life. Numerous scholars and experts have duly recognized the complex hurdles associated with the recycling of polymer composites, which can be briefly summarized as follows and listed in Table 2: (1) irreversible curing; (2) lack of re-formability; (3) fiber-matrix bonding; (4) contamination; (5) limited recycling technologies; and (6) economic viability (Pimenta & Pinho 2011), (Xue, Liu, Zhang, Wang & Xiao 2022; Morici & Dintcheva 2022).

Addressing these formidable challenges necessitates concentrated efforts and technological innovations. These endeavours encompass the development of novel recycling techniques, exploring chemical processes to facilitate the breakdown of thermoset materials, and pursuing innovative applications for recycled thermoset materials.

Table 2: Major challenges in the recycling of thermoset composites

Challenges	Description
Irreversible curing	Thermoset composites undergo a chemical curing process, resulting in a rigid and durable structure. This irreversible curing makes it challenging to break down the material for recycling.
Lack of re-formability	Unlike thermoplastics, thermoset composites do not soften when heated, making them resistant to traditional melting and reshaping methods used in recycling.
Fibre-matrix bonding	Thermoset composites typically bond strongly between the reinforcing fibres (e.g., carbon or glass) and the polymer matrix. Breaking this bond without damaging the fibres is challenging and affects the quality of the recycled material.
Contamination	Thermoset composites often contain other materials, such as coatings, adhesives, or metals, which can complicate recycling. Removing these contaminants is time-consuming and requires additional processing steps.
Limited recycling technologies	Compared to thermoplastics, there are fewer established recycling technologies for thermoset composites. The lack of efficient and cost-effective methods hampers large-scale recycling efforts.
Economic viability	Recycling thermoset composites is often more expensive than producing new materials. The high collection, sorting, and processing costs can make recycling economically unfeasible.

2 RECYCLING METHODS FOR THERMOSET COMPOSITES

Thermoset composites undergo recycling through various methods, primarily mechanical, thermal, and chemical approaches. According to the literature, the mechanical method has the lowest energy consumption, followed by moderate energy consumption for thermal recycling and the highest for chemical recycling. It is noteworthy, however, that these recycling techniques, despite their energy requirements, significantly outperform traditional landfilling and incineration methods in terms of energy efficiency (Rani, Choudhary, Krishnan & Zafar 2021). Moreover, these recycling techniques exhibit the added benefit of yielding remarkable net energy recovery. This section of the report will briefly overview the recycling methods commonly employed for thermoset composites. Each of these methods will be examined in terms of their respective advantages, disadvantages, and energy consumption profiles.

2.1 MECHANICAL RECYCLING

The initial stage of recycling composite scrap mostly involves mechanical treatment, primarily owing to the considerable disparity between the size of industrial parts and the capacities of recycling reactors. When mechanical grinding and fragmentation are employed, the bulky composite components undergo further processing, wherein they are crushed or ground into smaller fragments to yield recyclable materials (Oliveux, Dandy & Leeke 2015).

This section will explore into the specifics of two mechanical recycling approaches: mechanical grinding and high-voltage pulse fragmentation.

2.1.1 Mechanical grinding

Mechanical grinding constitutes a systematic approach aimed at disintegrating composite scrap into smaller fragments, thereby facilitating the separation of fiber and resin constituents (Figure 5). Extensive research has been dedicated to exploring this technique, particularly concerning its application to both glass and carbon fiber-reinforced composites, with a notable emphasis on glass fiber (Pickering 2006). The energy requisites for mechanical grinding span a spectrum from 0.1 to 4.8 MJ/kg, contingent upon the machinery employed and the scale of the recycling process. It is important to emphasize that optimal energy efficiency is attained when the granulator or hammer mill drive motors operate at their maximum capacity, as these motors account for the lion's share of the energy demand. Notably, the energy-intensive phases of the recycling process are predominantly intense in the actual recycling step. In contrast, the pre- and post-recycling stages, encompassing activities such as shredding and sieving, are comparatively less energy-intensive (Job, Leeke, Mativenga, Oliveux, Pickering & Shuaib 2016).

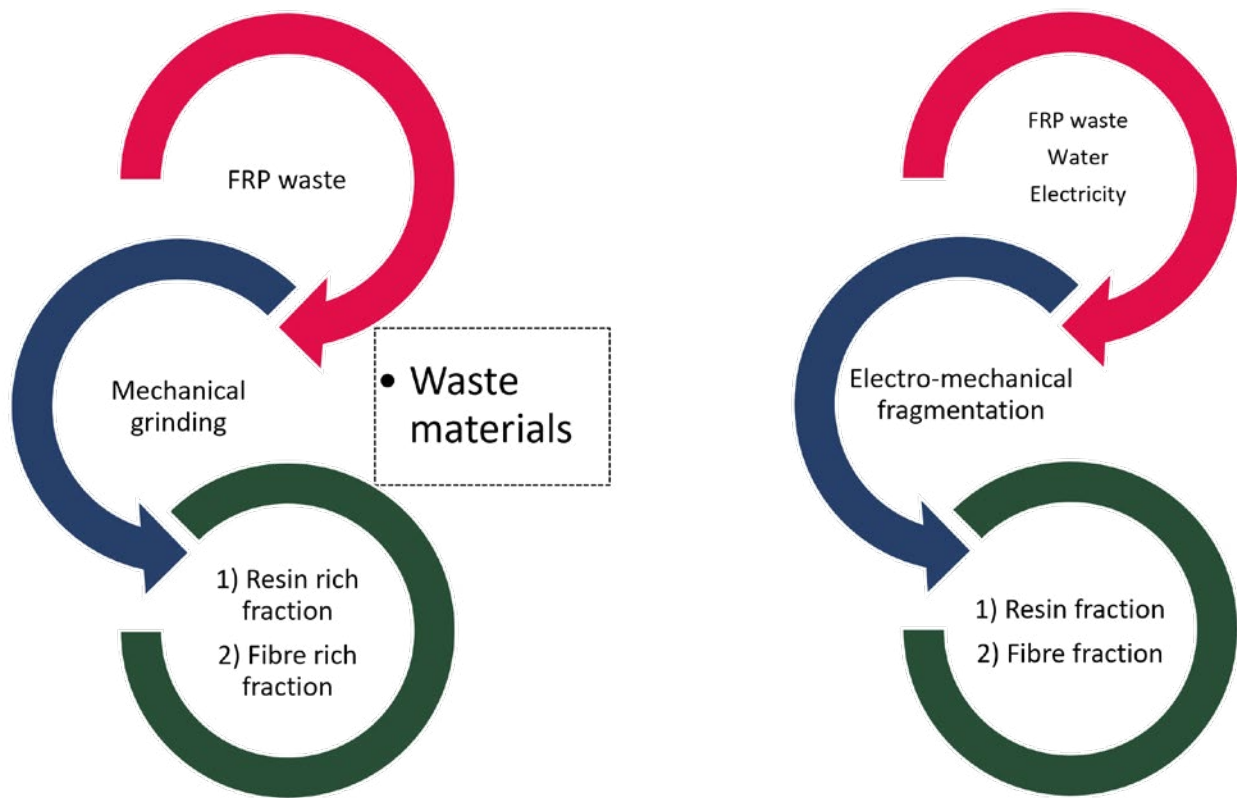


Figure 5. Overview of mechanical recycling methods

PROCESS: The recycling process commences with the initial step of shredding the material into manageable 50-100mm chunks. This crucial phase serves the dual purpose of facilitating the removal of any embedded metal inserts and, when conducted at the waste site, reducing the material’s volume for more convenient transportation. Subsequently, the chunks undergo further reduction, being ground down into fragments ranging from 10 mm to 50 µm in size, a task accomplished through the utilization of cutting or hammer mills (Pickering 2006).

It is relevant to recognize that each type of mill confers specific advantages: cutting mills yield a more uniform distribution of fiber lengths and produce longer fibers, whereas hammer mills offer the distinct advantage of avoiding the need for blade sharpening, thereby reducing wear and increasing output. Notably, concerning the resin content found within the recyclate, no significant difference is distinguished between the two methods (Schinner, Brandt & Richter 1996). In the final phase, the fragments undergo separation based on their contents and size, facilitated by the deployment of cyclones and sieves (Pickering 2006). Nevertheless, it is worth noting that complete separation of the two constituent materials is seldom achieved, as the fragments typically remain comprised of mixed materials. The summary of mechanical grinding is presented in Table 3.

OUTPUT: Following the mechanical grinding process, the resultant recyclate is a composite mixture comprising resin, fiber, and filler components. Within this recyclate, two primary fractions are identified: the fine fraction, which is enriched in resin and filler, and the coarse fraction, distinguished by its prevalence of fibers. In particular, the fine fractions manifest as powders with a higher resin and filler proportion relative to the original composite composition. Conversely, the coarser fractions predominantly exhibit a fibrous nature, containing a greater concentration of fibers (Pickering 2006).

Table 3. Summary of mechanical grinding method

Mechanical grinding

Merits	Demerits	TRL level	Energy required
- Efficient and high throughput rates	- Currently not competitive with the use of virgin raw materials - Recyclates quality compromised due to the high content of other materials - Approx. 40% waste generated during processing	GF:9 CF:6/7	0.1–4.8 k(MJ/Kg) (Utekar, V K, More & Rao 2021)

2.1.2 High voltage pulse fragmentation

Process: High voltage pulse fragmentation, initially introduced in the early 1960s (Bluhm, Frey, Giese, Hoppé, Schultheiß & Sträßner 2000), has conventionally found application in the field of rock mining. Its primary objective is to disintegrate rocks into parts, thereby facilitating the extraction of valuable minerals and crystals. This technique entails the repetitive discharge of electrical pulses within a dielectric liquid environment, typically employing water. By applying high voltages, typically within the range of 100–200 kV, characterized by a pulse rise time of less than 500 ns, the breakdown strength of solid materials becomes lower than that of the surrounding water medium.

This discharge initiates the creation of a spark channel that traverses through the material, adhering to internal boundaries, external interfaces, and pre-existing cracks. As this spark channel propagates, it generates a formidable shockwave characterized by high pressure, typically in the order of 10⁹–10¹⁰ Pa, and elevated temperature exceeding 10⁴ K. The culmination of these effects results in the generation of internal mechanical stresses that exceed the tensile strength of the solid material (Bluhm et al. 2000). Ultimately, this process leads to the disintegration and fragmentation of the material.

The process's energy efficiency depends upon several factors, with the number of pulses and processing rate playing pivotal roles. Mativenga et al. (Mativenga, Shuaib, Howarth, Pestalozzi & Woidasky 2016) conducted experiments and observed an average process efficiency of 18% for processing rates ranging from 0.15 to 0.04 kg/hour. Specific energy demands were determined, revealing values of 17.1 MJ/kg, 35.6 MJ/kg, 60.0 MJ/kg, and 89.1 MJ/kg for 500, 1000, 1500, and 2000 electrical pulses, respectively. It was determined that employing fewer pulses yielded better energy demand and efficiency; however, this approach came at the expense of fiber quality (Mativenga et al. 2016).

Table 4: Summary of high voltage pulse fragmentation

High voltage pulse fragmentation

Merits	Demerits	TRL level	Energy required
<ul style="list-style-type: none"> - The potential for scalability exists, enabling the treatment of substantial quantities of waste - Better quality fibres compared to mechanical grinding 	<ul style="list-style-type: none"> - Currently, only laboratory- and pilot-scale equipment is available - Only short fibres recovered - Decrease in fibre quality compared to the original fibre - Energy intensive compared to mechanical grinding 	CF: 6	CF:4.3 (MJ/Kg) (Weh 2015) GF: 17-89 (MJ/kg) (Mativenga et al. 2016)

OUTPUT: In both mechanical grinding and high-voltage pulse fragmentation processes, the average length of the recovered fibers measured approximately 2 mm, with most fibers falling below the 5 mm mark. In contrast, electro-mechanical fragmentation yielded a maximum fiber length of up to 9 mm, surpassing the 5 mm limit achieved in mechanical grinding (Mativenga et al. 2016). This notable difference, coupled with the enhanced purity of the fibers, suggests that recyclates obtained through high-voltage fragmentation would offer superior reinforcement capabilities in new composite materials when compared to those derived from mechanical grinding. The summary of the process is seen in Table 4.

2.2 THERMAL RECYCLING

Figure 6 illustrates the critical distinctions among thermal processes based on their primary characteristics. The pivotal differentiating factor is the presence or absence of oxygen. In conditions lacking oxygen, the process is known as pyrolysis. When excess oxygen is present, the process transforms into combustion or incineration. It's important to clarify that while incineration and combustion represent separate processes, they are occasionally used interchangeably. For this report, incineration specifically denotes the complete combustion of waste at elevated temperatures, producing only ashes, which is classified as recovery rather than recycling. Conversely, combustion signifies a controlled burning process at lower temperatures to recover fibers and fillers from composite waste.

Method	Pyrolysis	Combustion	Incineration
Temperature	Thermal decomposition of polymers in inert atmosphere at 300-800 °C	Controlled burning at 450-600 °C	Complete burning at temperature >850 °C or <1100 °C
Air	No oxygen	Excess oxygen	Excess oxygen
Output	Tars, hydrocarbons, char, fibres, fillers	CO ₂ , H ₂ O, fibres, fillers, recovered energy equivalent to approx. 30 MJ/kg	CO ₂ /fuel gas, H ₂ O, ash, solid residue, recovered energy equivalent to approx. 30 MJ/kg

Figure 6. The key difference between pyrolysis, combustion and incineration

Pyrolysis acknowledged as the most established thermal technique for reclaiming fibers and reusing the matrix resin, typically operates in an environment devoid of oxygen. Nevertheless, in practical applications, a small quantity of oxygen is introduced during pyrolysis to reduce char formation, as previously discussed (Oliveux et al. 2015; Job et al. 2016).

PROCESS: The temperature range for pyrolysis varies depending on the resin type, typically falling between 450°C and 700°C. For polyester resins, complete decomposition occurs at temperatures ranging from 400°C to 450°C, while higher temperatures of 500°C to 550°C are necessary for epoxy resin. (Cunliffe, Jones & Williams 2003; Job et al. 2016; Oliveux et al. 2015).

Classical pyrolysis involves transferring composite waste through a furnace under carefully controlled temperature and atmospheric conditions. Commercial pyrolysis operations commonly utilize a chain conveyor (Job et al. 2016) or rotary kilns (Chen, Yin, Wang & He 2014). During this process, the waste is initially conveyed into a furnace at approximately 500-800 °C. The resulting solid waste, which includes fibers, fillers, and char, is collected at the furnace's end to undergo further separation. Meanwhile, the flue gases are directed to a condenser, which cools down to approximately 50°C. Then, the precipitated gases from pyrolysis oil are collected. The remaining gases are conveyed to the afterburner, where they undergo combustion at temperatures ranging from 1100°C to 1200°C. The resulting high-temperature gases are subsequently utilized for heat recovery in a boiler, which operates at approximately 900°C or directly combusted in the furnace. Following filtration, the remaining purified gases are released into the atmosphere (Dorigato 2021).

A fluidized-bed pyrolysis method has been developed to accelerate the heating process of materials. This technique involves passing the waste material, which has been reduced in size, through a bed of silica sand that is fluidized by a hot air stream. As a result, the resin undergoes thermal degradation and attrition, releasing fibres (Job et al. 2016; Oliveux et al. 2015). Within the fluidized bed, various types are employed, such as stationary or bubbling beds, circulating beds, and vibratory fluidized beds. Different flow regimes, including slugging, boiling, channelling, and spouting, can also be utilized.

OUTPUT: The pyrolysis procedure generates three main substances: a fuel gas, liquid oil products, and a solid residue. This solid residue comprises inorganic fibres, fillers, and char residue. The specific amounts of these products vary depending on the composite type and resin content. It can be stated that the solid portion comprises the most significant proportion, ranging from 50 weight percent to over two-thirds. Then, liquid products contain 0 to 50 weight percent, and gas products constitute 5 to 15 weight percent (Yang, Boom, Irion, van Heerden, Kuiper & de Wit 2012). The summary of pyrolysis method is listed in Table 5.

Table 5. Summary of pyrolysis method

Pyrolysis			
Merits	Demerits	TRL level	Energy required
<ul style="list-style-type: none"> - Given the capability to handle mixed and polluted waste, the significance of waste pre-treatment is diminished. - Possible to recover both fibers as well as chemical feedstock from the polymer resin - Already used at a commercial scale for recycling carbon fiber composites 	<ul style="list-style-type: none"> - Fibre product may retain oxidation residue or char - Loss of strength of fiber due to high temperature 	Pyrolysis: 9 Microwave/ pyrolysis: 4/5	Pyrolysis: 23-30 (MJ/Kg) (Job et al. 2016) Microwave pyrolysis: 5-10 (MJ/kg)

2.3 CHEMICAL RECYCLING

Solvolysis is a chemical treatment method that breaks down resin using an appropriate solvent. Due to its commercial viability, it is a commonly employed recycling process for recovering fibers from carbon fiber-reinforced polymer composites (CFRP). Water is widely used as a solvent in this process, often combined with other co-solvents such as alcohol, phenol, and amine. Commonly utilized alcohols in solvolysis include methanol, acetone, glycols, and propanol. Alkaline catalysts like sodium hydroxide (NaOH) or potassium hydroxide (KOH) are typically employed to catalyze the reaction. This method can be further classified depending on the specific solvent used. For instance, water as a solvent is used in hydrolysis, while glycols are used in glycolysis. Similarly, acid can be employed in a treatment known as acid digestion.

Recovery of glass fibres has limited commercial worth and is susceptible to chemical treatment degradation primarily due to their fragility when subjected to high temperatures, acidic, and alkaline conditions (Job et al. 2016; Oliveux et al. 2015). Additionally, fibers recovered by solvolysis require the resizing of glass fibers to enhance their adhesion with the matrix when used in composite manufacturing. Consequently, for solvolysis to be effective for glass fiber composites, enhancements such as gentler solvolysis conditions involving lower temperatures and pressures are necessary.

PROCESS: A reactive solvent, sometimes combined with a co-solvent or co-reactive solvent, permeates the composite material and selectively breaks certain bonds within the resin. This process allows for the recovery of the fibers and the resin monomers. Moreover, it prevents the accumulation of char residues on the fibers. While water has been predominantly utilized as a solvent in testing, alcohols have also been employed (Oliveux et al. 2015). The advantage of using water or alcohol is that they are relatively environmentally friendly and can be separated from the dissolved solution through processes such as evaporation (for water) or distillation (for alcohol) (Yang et al. 2012). The solvent can exist in various forms, such as vapor, liquid, biphasic, or supercritical, depending on the solvent present and the temperature. An overview of solvolysis method is presented in Figure 7.

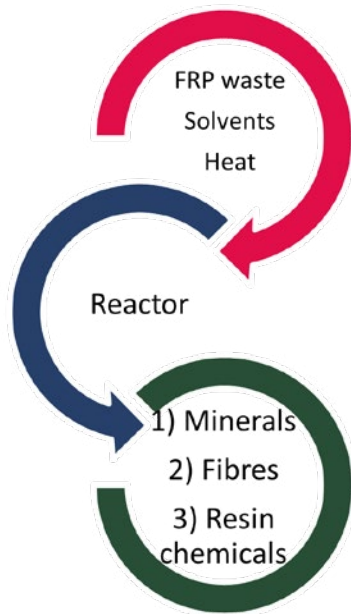


Figure 7. Overview of the solvolysis method

High temperature and pressure solvolysis:

The use of supercritical conditions in solvolysis has garnered interest due to the significant changes in solvent properties that occur from subcritical to supercritical states. Supercritical fluids possess characteristics that lie between those of liquids and gases, offering advantages such as low viscosities, high mass transport coefficients, and high diffusivities (Hyde, Lester, Kingman, Pickering & Wong 2006). Consequently, supercritical fluids have superior penetration capabilities into materials, making them suitable for breaking down larger composite structures, which is particularly advantageous for scaling up the process. By manipulating pressure, it is possible to control the properties of the solvent and the reaction rates and selectivity of the process (Roek, Kremer, Roberts, Chateaufneuf & Brennecke 1999; Wu, Klein & Sandler 1991).

This adaptability renders the process highly versatile. In testing supercritical fluids for recycling carbon fibre reinforced composites, temperature ranges of 250-400°C and pressures of 4-27 MPa were employed for water, while temperatures of 300-450°C and pressures of 4-17 MPa were used for alcohol.

Low temperature and pressure solvolysis:

Low temperature and pressure solvolysis are typically conducted at temperatures below 200°C and atmospheric pressure. Due to the low temperature, catalysts and additives are required to facilitate resin degradation, and stirring may also be necessary (Qureshi 2022). Acidic mediums, such as nitric, sulfuric, and acetic acids, have been predominantly utilized in this method, in contrast to high temperature and pressure solvolysis, which primarily employs alkaline conditions (Oliveux et al. 2015).

OUTPUT: Through the solvolysis process, it is possible to regenerate clean fibres and fillers compared to mechanical and thermal recycling methods. Polymerised matrix components in the form of monomers or petrochemical feedstock are also recovered (Yang et al. 2012). The generation of gases during solvolysis has not consistently been addressed or analyzed in research studies (Oliveux et al. 2015). The summary of solvolysis method is tabulated in Table 6.

Table 6. Summary of solvolysis method

Solvolysis			
Merits	Demerits	TRL level	Energy required
<ul style="list-style-type: none"> - Lower temperatures to degrade the polymers (compared to pyrolysis) - Potential to reclaim chemicals from the resin is higher, and it can lead to cleaner fibres with no char formation - Low risk solvents are used such as alcohols, glycols and supercritical water 	<ul style="list-style-type: none"> - High energy consumption due to high temperature and high pressure of some processes - Very difficult to use when treating mixed post-consumer composite scrap - Cost analysis showed that the recycled glass fibre would be more expensive than virgin fibre due to the treatment costs 	3-4	21-91 MJ/kg (Job et al. 2016)

2.4 OTHER METHODS

In the Chapter, some of the methods other than the ones discussed above is discussed. It will cover methods such as cement co-processing which has been proven to be best method for recycling GFRP and other pilot phase or commercial methods are covered.

2.4.1 Cement co-processing

Currently, the predominant method of recycling composite waste is accomplished through cement co-processing, which is alternatively referred to as the cement kiln route. Co-processing entails utilizing waste as both a raw material and an energy source, serving as a substitute for natural mineral resources and fossil fuels within industrial operations. When composite waste is co-combusted within a cement kiln, the fibers and fillers in the waste material serve as feedstock for the cement production process. Although the cement co-processing method is applicable for recycling both glass and carbon fiber-reinforced composites, it is not considered optimal for carbon fiber composites due to their high value, which makes them unsuitable for such applications. An overview of cement co-processing is seen in Table 7.

PROCESS: During the co-processing of composite materials in a cement kiln, the components undergo size reduction and are combined with other solid-recovered fuels to be introduced into the kilns. They are fed similarly into the kiln system to traditional raw materials. However, there are alternative entry points for bulk fuel, such as the transition chamber at the inlet end of the rotary kiln (Ziegler, Schimpf, Dubach, DEGRÉ & Mutz 2006). Within the cement kiln, temperatures range from 1050 to 2000 °C. At these temperatures, the fibers are transformed into ashes and mix with clinkers, while the resin is converted into organic matter, serving as a source of energy for the combustion process (Vijay, Rajkumara & Bhattacharjee 2016).

Table 7. Overview of cement co-processing (cement clinker)

Cement co-processing			
Merits	Demerits	TRL level	Energy required
<ul style="list-style-type: none"> - Exceptional efficiency, rapidity, and scalability - Possible to process substantial amounts - Potential to decrease CO2 emissions from cement manufacturing by as much as 16% - No ash left over 	<ul style="list-style-type: none"> - Fiber shape of the glass is lost and hence cannot be used in other composite applications 	9	-

OUTPUT: Co-processing is a practical approach to extract value from non-combustible materials, such as reinforcing fibers and fillers since they contain minerals that can be integrated into cement production (Pickering 2006). Any calcium carbonate calcines present are transformed into calcium oxide, an essential constituent of Portland cement. Additionally, alumina and silica possess cementitious characteristics in an alkaline condition.

2.4.2 Thermo-cyclic pressolysis

Pressolysis (DEECOM®) method employs supercritical steam and alternating cycles of compression and decompression to target the surface area of organic material, resulting in a physical disruption or fracturing of the polymeric structure. Doing so effectively disrupts the bonding between the fiber and matrix. The entire procedure occurs within a pressurized container that contains superheated steam. The behavior of the polymer varies based on its type, and temperatures exceeding 200°C can result in either melting or softening of the polymer, accompanied by some hydrolysis. Under pressure, steam infiltrates the cracks and crevices within the polymer, condensing within them. During decompression, the condensed steam rapidly boils, leading to the immediate fragmentation of the polymer chain and carrying away monomers, oligomers, and polymer fragments from the outer surfaces.

As the process primarily affects the resins rather than the fibers, it has shown the capability to restore waste composites' format, length, and structure from post-industrial or end-of-life sources, regardless of whether they are cured or uncured. Although the energy consumption can be relatively high due to prolonged cycling periods at high temperatures and pressures, it is still expected to be significantly lower than the energy required for manufacturing virgin carbon fiber. The ability to recover long tows in their entirety yields notable advantages. The technique applies to CFRP (carbon fiber-reinforced polymer), and ongoing research explores the potential of extending its use to GFRP (glass fiber-reinforced polymer).

2.4.3 Electro-dynamic and electro-hydraulic fragmentation

Electro-dynamic fragmentation (EDF) and electro-hydraulic fragmentation (EHF) are methods used for size reduction by fragmentation of composite scrap. While they share some similarities to high-voltage pulse fragmentation (HVPF), these techniques have distinct differences in the context of the mechanism, energy input, and how they interact with the material.

While HVPF and EDF utilize high-voltage electrical pulses, the fragmentation mechanisms differ. HVPF directly relies on the intense electric fields created by the pulses, while EDF emphasizes the formation of high-stress zones through the electric fields. These differences in mechanisms result in variations in the fragmentation process and control over the size and distribution of fragments. In contrast, the EHF method involves the interaction of shockwaves generated by high-voltage electrical discharges with a conductive fluid medium and the material to be fragmented. It relies on both electrical and hydraulic mechanisms.

3 COMMERCIAL THERMOSET COMPOSITE RECYCLING TECHNOLOGIES

Recycling holds significance in the effective management of composite waste and in enhancing the concepts of circular economy and sustainable technologies. The sustainable development goals (SDGs), established by the United Nations in 2015, serve as crucial objectives for society.

The global issue of end-of-life composite waste is a legitimate concern due to the challenges involved in reshaping thermoset matrices for future applications, and these matrices typically lack biodegradability. Additionally, to enhance the feasibility and cost-effectiveness of recycling processes for composites, it is essential to develop methods that can effectively recycle high-quality synthetic fibers and thermoset resin.

The chapter will list the active recycling companies involved in composite recycling and discuss the economic viability and overall status of composite recycling.

3.1 COMPANIES INVOLVED IN RECYCLING

In the past two decades, the establishment of Carbon Fiber Reinforced Polymer (CFRP) recycling companies has seen significant growth in Europe, the USA, and Japan. Several companies are involved in the composite recycling business in Europe, as seen in Table 8.

Currently, the predominant method for carbon fiber recovery is pyrolysis due to its well-developed nature, versatility across various stages of composite manufacturing, and commercial viability. Mechanical recycling methods followed by energy recovery and co-processing are employed for GFRP.

The companies believe that utilizing recycled carbon fibers (CFs) is among the most effective approaches to minimize waste from carbon fiber-reinforced polymers (CFRPs). Recycling CFs typically requires 96% less energy than the energy expended in producing new CFs. Pyrolysis is the primary method for carbon fiber recovery due to its maturity, versatility, and economic viability. The pyrolysis process for carbon fibers has achieved a Technology Readiness Level (TRL) of 9, indicating its advanced stage of development.

Table 8. List of companies active in composite recycling (EUROPEAN COMPOSITES RECYCLING SOLUTIONS - EUCIA - Google Sheets n.d.)

Company Details		Waste Type	Fibre Type		Recycling Process		
Company	Country	Dry, Prepreg, Semi-Cured, Cured Composites	Glass	Carbon	Mechanical	Thermal	Chemical
Reprocover	Belgium	TS waste EoL and production waste	X		X		
Miljosarm	Denmark	TS waste EoL and production waste	X		X		
ReFiber ApS	Denmark						
U-composites	Denmark	Glassfiber production waste	X		X		
Finnsementti Oy	Finland	Crushed/shredded material	X	X			
Kuusankoski Oy	Finland	Waste from composite industry, EoL	X	X	X		
Extractive	France	Cured composites		X		X	X solvolysis
Recycling Carbon	France	CF EoL Composites		X	X	X	
Techtera (MC4 Project)	France	GF and GF EoL	X	X	X		X
ALTEX Textile recycling GmbH & Co. KG	Germany	Dry GF	X	X	X		
C.A.R.Fibertec GmbH	Germany	Clean CF recycling		X	X		
Hadeg Recycling GmbH	Germany	The fibres are dried, shredded and the ground by us. (max. with a 2.0 mm screen)		X	X		
Roth International	Germany	All TS composites	X	X	X		
Curti Energy	Italy			X			
GEES	Italy	EoL FRP recycling	X	X	X		
Karborek Recycling Carbon Fibers	Italy	Cured		X		X	
RYMYC SRL	Italy	CF composites recycling		X		X	
Composite Recycling	Switzerland	TS composites	X			X	
i-was concepts	Switzerland	TS composites EoL	X		X		
B&M longworth	UK	DEECOM eqpt to process GF & CF waste	X	X			
Gen2Carbon Limited	UK	Produce rCF mats & dabrics from dry, prepreg, semi-cured and cured composites		X		X	
Gen2Plank	UK	GRP waste to make into new GRP panels	X		X	X	
Sigmatex Limited	UK	Produce rCF fabrics		X			
V-Carbon	UK	CF prod and EoL waste		X		X	X

Solvolytic technologies are emerging as alternatives for producing higher-quality recycled carbon fibers while minimizing energy consumption and environmental impact. However, despite the advantages of solvolysis, achieving a positive profit margin using this chemical recycling method remains challenging. Solvolysis currently possesses a TRL of 3-4, placing it at the ‘technology development’ stage.

Notable efforts toward market penetration can be observed in the aerospace industry, where the first material supply chain between ELG and Boeing was established in early 2019. This milestone marked the deployment of recycled CFRP composite materials in aerospace applications. Additionally, the automotive sector is making strides in adopting recycled composite materials, as demonstrated by BMW and Volkswagen, which increasingly incorporate recycled CFRPs into their products (Zhang, Chevali, Wang & Wang 2020).

Various recovered carbon fiber products are being developed to create higher-value recycling routes, including nonwoven mats, aligned short fiber mats, and carbon fiber yarns. Likewise, recycled composite products such as compounded thermoplastic pellets for injection molding, 3D printing filaments, and discontinuous fiber-reinforced thermoplastic sheets are under development. For instance, the collaboration between Shocker Composites and R&M International has yielded densified recovered carbon fibers and thermoplastic/recovered CFRP pellets, enabling large-scale 3D printing with results similar to virgin CFRP products but at a lower cost (Amaechi, Agbomerie, Orok & Ye 2020).

3.2 ECONOMIC VIABILITY OF RECYCLING

A recent study analyzing costs and market prospects for recycled carbon fibers in the automotive sector revealed that pyrolysis could retrieve fiber for \$5 per kilogram or lower. This finding considers various process factors, such as a plant capacity ranging from 500 to 6000 tons per year. Moreover, recycled carbon fibers constitute roughly 15% of the expense incurred for new carbon fibers (Meng, McKechnie & Pickering 2018). Hagnell et al. (Hagnell & Åkermo 2019) listed the mechanical properties and representative costs of fiber materials and grades from various sources (Table 9).

Table 9. Mechanical properties and corresponding costs for commonly used reinforcements

Reinforcement type	Young’s modulus (GPa)	Cost (€/kg)
High-modulus carbon	400	60
Intermediate-modulus carbon	300	30
High strength carbon	250	20
Ideal lignin carbon	172	4
Lignin carbon	120	4
S-glass	89	20
E-glass	80	2.5

For a smaller production capacity of 100 tons per year, recycled carbon fibers must attain a market value of \$15 per kilogram to be economically feasible. The investigation further revealed that recycled carbon fiber-reinforced plastics (CFRPs) offer substantial weight reductions compared to steel while exhibiting similar mechanical properties at a similar cost. Notably, aligned recycled CFRPs can significantly enhance financial competitiveness by reducing costs by over 35%, thanks to their superior mechanical properties and lower density, resulting in lighter structures (Meng et al. 2018).

An additional economic evaluation indicates a significant opportunity for recycled carbon fibers to replace virgin and glass fibers (Vo Dong, Azzaro-Pantel & Cadene 2018). Through the mechanical grinding process, recycled carbon fibers can achieve a cost of 1€ per kilogram with a plant capacity of 1000 tons per year. However, for advanced recycling technologies to compete with virgin carbon fibers and recycled carbon fiber produced from

more cost-effective recycling technologies, higher recycling production capacities, and increased carbon fiber recovery rates are necessary.

Glass-fiber reinforcements typically offer a cost-effective solution and exhibit moderate stiffness levels. For recycling to be economically feasible, the reclamation of materials must be inexpensive due to the low cost of the fibers. When subjected to pyrolysis at temperatures exceeding 400°C, glass fibers experience a reduction of up to 50% in their mechanical properties. The combination of diminished mechanical properties and the affordability of virgin glass fiber renders extensive material reclamation of GFRP economically impractical. Nevertheless, reclaiming the entire composite materials and transforming them into chemical building blocks is a promising and feasible approach. A report (WindEurope 2020) published by cefic, windeurope, and EuCIA has provided estimated relative costs and values of composite recycling technology, as seen in Figure 8.

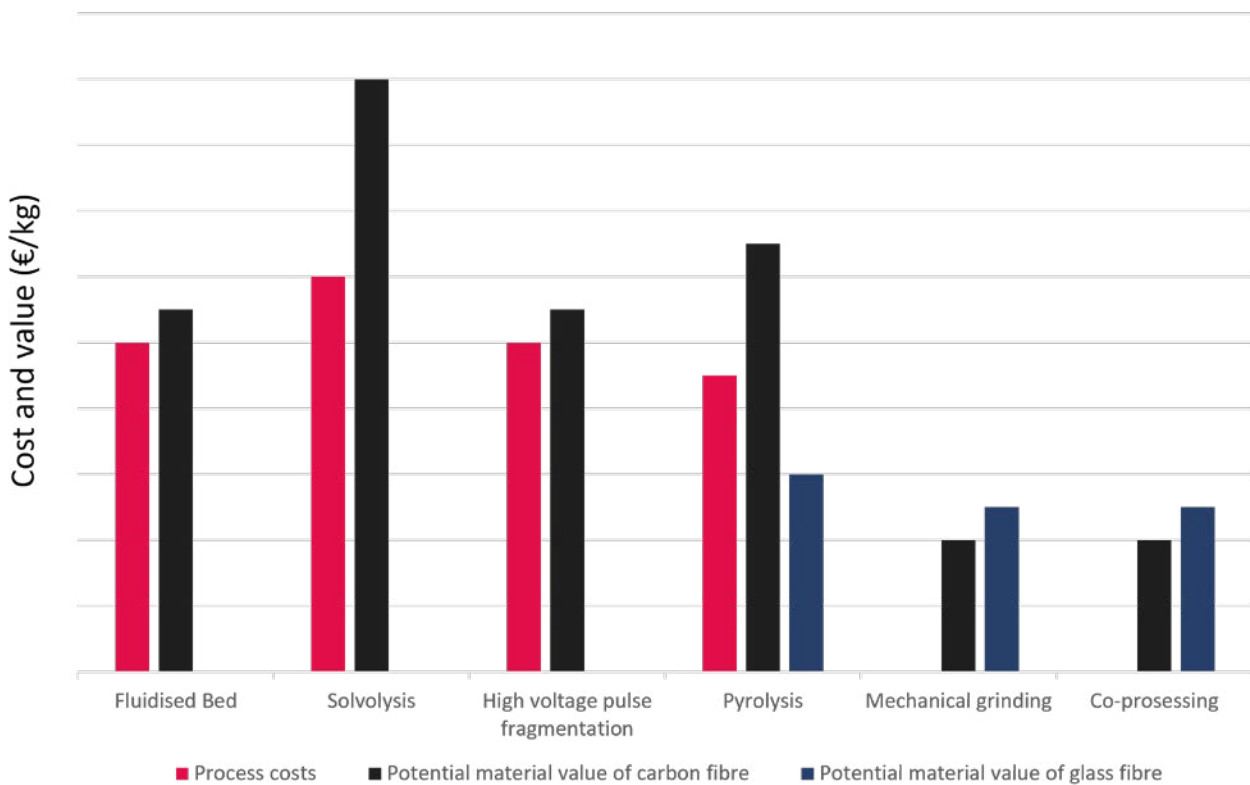


Figure 8: Relative costs and values of composite recycling technologies (Adapted from: WindEurope 2020)

3.3 STATUS OF COMPOSITE RECYCLING IN EUROPE

As composite materials gain broader acceptance in various industries, the significance of tackling the issues related to end-of-life (EOL) management is gaining prominence. Despite the limited quantity of composite waste, its future volume is projected to increase, emphasizing the need to seek circular economy-aligned solutions. Associations such as the European Composites Industry Association (EuCiA) advocate for minimizing the disposal of composites through landfilling or incineration, and there is a growing requirement to identify and support the development of circular solutions. To attain complete circularity for composites, the relevant stakeholders and the authorities at the European, national, regional, and local levels must address several barriers, as described in Table 1.

During the past decade, the industry has dedicated efforts to enhancing composite's circularity. While prioritizing the reuse of composite parts, which maintains their inherent properties, it is often impractical for individual situations. As an alternative, the industry has explored the co-processing of composites into cement. This approach effectively utilizes the glass fibers and fillers as raw materials for cement production, while the resin serves as a fuel source, replacing traditional fossil fuels. Co-processing offers the advantage of reducing energy consumption and CO₂ emissions in cement manufacturing while replacing mined raw materials.

Another existing technology involves mechanically grinding or shredding composites for reuse in new composite products. However, this process may result in a loss of properties, such as reduced tensile strength, limiting the application of the by-products to a restricted range of reinforcement applications or as fillers.

Furthermore, the composites industry, independently or with support, is actively researching, developing, and testing several other circular solutions. These solutions encompass product design, strategies to optimize product lifespan, the reuse of composite products in alternative applications, and the exploration of novel recycling processes to enhance the value retention of composites. However, these recycling solutions require further scaling up and market development and are not expected to be widely accessible in the short term.

4 APPLICATIONS OF RECYCLED MATERIALS

Oliveux et al. (Oliveux *ym.* 2015) suggest that the utilization of recycled fibers or resin in industrial applications is infrequent due to a lack of trust in the performance of recycled fibers, as well as the fact that a batch of recycled composites typically originates from various manufacturers and comprises different fiber grades. Consequently, it becomes challenging to effectively manage recycled fibers in terms of length, length distribution, surface quality, and origin.

However, it does not imply that there are no viable uses for the reclaimed materials. For instance, recycled carbon fibers are used to produce automotive parts, such as body panels, hoods, and interior components. Companies incorporated recycled carbon fiber materials in their vehicles to reduce weight and improve fuel efficiency. For example, BMW's i3 electric car features a carbon fiber-reinforced plastic (CFRP) passenger cell made from recycled carbon fiber (BMW Group 2013).

For instance, Boeing, a prominent aircraft manufacturer in the aerospace industry, has implemented recycled carbon fibers in their aircraft production. As a demonstration, Boeing tested the acoustic properties of recycled carbon fiber composites, resulting in reduced aircraft weight and improved fuel efficiency (Gardiner 2021). Recycled carbon fibers are employed in the manufacturing of wind turbine blades. Companies like General Electric (GE) have developed wind turbines using recycled carbon fiber materials to construct longer, more efficient blades.

The sporting goods industry uses recycled carbon fibers to produce equipment like bicycles, tennis rackets, and hockey sticks. JUC Surf, an Australian company, has manufactured surfing boards made from recycled carbon fiber (Gurit 2021). The University of Bristol has developed a HiPerDif (high-performance discontinuous fiber) process to recover fibers from damaged or retired carbon fiber components used in sports equipment. This innovative process realigns the fibers and transforms them into unidirectional prepreg tapes. These tapes are then supplied to alliance members, including Wilson Sporting Goods, SCOTT Sports, and OneWay. The manufacturers within the alliance reuse the material to produce new sporting equipment (Hoodin 2022).

Recycled glass fiber finds diverse applications across multiple industries. In construction, it reinforces structures, increasing tensile strength and crack resistance. With ongoing advancements in sustainable materials and processes, the applications of recycled glass fiber continue to expand, showcasing its versatility and environmental benefits.

While still an emerging technology, depolymerized thermoset resins have the potential for various industrial applications. One notable application is in the production of adhesives and sealants. Additionally, depolymerized thermoset resins can be used as coating materials. It is essential to acknowledge that the commercial implementation of depolymerized thermoset resins is still in its early stages, with limited specific examples. Ongoing research and development efforts aim to explore and expand their potential applications further.

5 CONCLUSIONS

The management of thermoset composite waste and its hierarchy plays a crucial role in advancing the principles of the circular economy. Thermoset composites present unique challenges due to their crosslinked structure, but efforts are being made to align their waste management with circular economy principles. The hierarchy of waste management methods, including prevention, reuse, recycling, and energy recovery, provides a framework for optimizing the circularity of thermoset composites. While complete recyclability remains a challenge, innovative solutions are being developed. Designing for the circular economy focuses on improving recyclability and minimizing waste generation. Reuse and repurposing of thermoset composites, such as in noise barriers or architectural designs, offer alternative applications. Recycling methods like mechanical grinding, shredding, and co-processing into cement enable the recovery of valuable materials. Energy recovery processes contribute to minimizing waste and reducing environmental impact. By embracing the circular economy concept and implementing the waste hierarchy, the industry is progressing towards a more sustainable and resource-efficient approach to managing thermoset composite waste, contributing to a circular and regenerative economy.

The recycling of thermoset composites presents unique challenges, but significant progress has been made in developing effective recycling methods. While thermoset composites are known for their excellent properties, their crosslinked structure makes them less readily recyclable than thermoplastics. However, various recycling methods have been explored and implemented to address these challenges. Mechanical grinding or shredding processes allow for the reuse of thermoset composites in limited reinforcement applications or as fillers. Co-processing, where composites are integrated into cement production, offers the dual benefit of utilizing composite components as raw materials while reducing energy consumption and CO₂ emissions.

Additionally, research efforts are underway to explore innovative recycling technologies such as chemical degradation and pyrolysis. The circular economy concept serves as a guiding principle, emphasizing the importance of resource preservation, waste prevention, extended product lifecycles, and value retention. Through ongoing research, technological advancements, and collaboration among stakeholders, the recycling of thermoset composites continues to evolve, enabling progress towards a more sustainable and circular approach to composite materials.

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TOWARDS A SUSTAINABLE FUTURE:

Exploring methods, Technologies, and Applications for Thermoset Composite Recycling

This review commences with an introduction to the market share of thermoset composites, emphasizing their significance in various industries. The concept of the circular economy and its relevance to polymer composites is explored, highlighting the potential for recycling these materials. The driving factors behind the need for thermoset composite recycling are examined, considering environmental concerns, resource conservation, and regulatory frameworks. The challenges associated with recycling thermoset composites, such as their complex structure and inherent durability, are addressed.

The subsequent section explores the different recycling methods available for thermoset composites. Mechanical recycling, a widely utilized recycling process, is discussed in detail, including mechanical grinding and high-voltage pulse fragmentation, which aim to break down the composites into smaller components for reuse. Thermal recycling methods like pyrolysis and incineration to recover valuable resources from thermoset composites are briefly explained. Chemical recycling methods such as solvolysis and glycolysis, which utilize chemical reactions to break down and recover monomers or oligomers from thermoset composites, are also presented. Other emerging methods, like cement co-processing, thermo-cyclic pressolysis, and electro-dynamic or electro-hydraulic fragmentation, are introduced as potential alternatives for recycling thermoset composites.

The study examines the current status of commercial thermoset composite recycling technologies. It highlights companies actively involved in recycling thermoset composites and evaluates the economic viability of these technologies, considering factors like cost-effectiveness and scalability. Furthermore, the status of composite recycling in Europe is presented as an overview of recycling technologies and ongoing efforts in the region. Finally, the study explores the various applications of recovered materials from thermoset composites. Carbon fiber, a valuable resource recovered from recycled composites, finds applications in multiple industries, including automotive, aerospace, and sporting goods. Glass fiber, another commonly used reinforcement material, can be reclaimed and utilized in construction and consumer goods. The study also explores the applications of depolymerized compounds derived from matrix resin during recycling processes.

In conclusion, this study provides a comprehensive overview of thermoset composite recycling. It examines various recycling methods, assesses the commercial viability of recycling technologies, and explores the applications of recovered materials. The findings of this study contribute to the understanding and advancement of sustainable practices within the thermoset composites industry.

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