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Review

A Review of Recycling Methods for Fibre Reinforced Polymer Composites

Jawed Qureshi

School of Architecture, Computing and Engineering (ACE), University of East London, 4-6 University Way, Beckton, London E16 2RD, UK; j.qureshi@uel.ac.uk; Tel.: +44-20-8223-2363

Abstract: This paper presents a review of waste disposal methods for fibre reinforced polymer (FRP) materials. The methods range from waste minimisation, repurposing, reusing, recycling, incineration, and co-processing in a cement plant to dumping in a landfill. Their strength, limitations, and key points of attention are discussed. Both glass and carbon fibre reinforced polymer (GFRP and CFRP) waste management strategies are critically reviewed. The energy demand and cost of FRP waste disposal routes are also discussed. Landfill and co-incineration are the most common and cheapest techniques to discard FRP scrap. Three main recycling pathways, including mechanical, thermal, and chemical recycling, are reviewed. Chemical recycling is the most energy-intensive and costly route. Mechanical recycling is only suitable for GFRP waste, and it has actually been used at an industrial scale by GFRP manufacturers. Chemical and thermal recycling routes are more appropriate for reclaiming carbon fibres from CFRP, where the value of reclaimed fibres is more than the cost of the recycling process. Discarding FRP waste in a sustainable manner presents a major challenge in a circular economy. With strict legislation on landfill and other environmental limits, recycling, reusing, and repurposing FRP composites will be at the forefront of sustainable waste-management strategies in the future.

Keywords: FRP Recycling; glass fibre; carbon fibre; FRP waste; waste management; circular economy; sustainability

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1. Introduction

The construction sector produces about a third of global carbon emissions. Sustainable technologies and materials are needed to support the transition to net-zero carbon emissions through an energy-efficient and resilient building and construction sector [1]. Fibre reinforced polymer (FRPs) composites are eco-friendly materials with a lower carbon footprint than traditional materials, such as concrete, steel, masonry, and timber. FRPs have been used in various industries ranging from construction, aerospace, automotive, marine, and electronics to the wind energy sector. The key reasons for the growth of FRPs include their excellent mechanical properties, lightweight, mouldability, and corrosion resistance. With the growing use of FRP materials in the building and construction industry, recycling FRP waste materials is becoming a major environmental challenge. Sustainable tools and methods should be used for the effective disposal of FRP waste.

Fibre reinforced polymer (FRP) composite materials contain fibres placed in a resin matrix. Fibres provide strength and stiffness, and the resin acts as a binder for fibres. Generally, synthetic or man-made fibres are used in FRP composite parts. These include carbon, glass, and aramid fibres [2–4]. Currently, semi-natural basalt fibres made from basalt rock are undergoing experimentation for structural applications [5–9]. Academic research is available on natural fibres, such as hemp, sisal, flax, and bamboo fibres. However, commercial FRP products using natural fibres do not exist yet [5,9–12]. Thermoset resins, such as polyester, vinylester, or epoxy, are commonly used. Thermoplastic resins, though not widely used in structural engineering, also exist, primarily for use in aerospace engineering. Thermoset resins have cross-linked molecules; once set, they cannot be remoulded. It is hard to recycle thermoset-based FRP composites without the deterioration of the recovered fibres or resin [13]. Thermoplastic resins can be moulded, remoulded, and reshaped into any form due to their weak molecular bonds. They can be easily recycled and reprocessed [2,3,14–16]. As per the European Composites Industry Association (EuCia), in 2020, more than 90% of all FRPs materials were glass FRP composites [17]. The nature of the FRP composite industry controls the use of a particular resin. About 2/3 of all resins are thermoset, and 1/3 are thermoplastic [18]. Both glass fibres and thermoset resin are difficult to recycle.

By 2026, the global market for fibre reinforced polymer composites is expected to reach USD 375 billion, from USD 228 billion in 2019, with a compound annual growth rate of 7.3% [19]. FRP composites have applications in more than 15 industries, with an estimated production value of USD 100 billion and a volume of 12.1 million tonnes in 2021. The major growth will be in the construction, transportation, wind energy, aerospace, electrical, and electronics sectors [20]. The main challenges for the FRP industry in the future will be related to the handling and recycling of FRPs while meeting environmental limits and governmental legislation. In a circular economy, a closed-loop cradle-to-cradle approach is needed to turn the FRP composite waste into a valuable resource [19,21]. The waste is generated during production and end-of-life use. The estimated volume of FRP composite waste generated by various industries is shown in Figure 1. Construction is the largest contributor to FRP waste. To address this issue, a proper waste management hierarchy is needed, which is presented in the next section. The global market share and the size of FRP waste are estimated by market research organisations and should be used with caution. Different organisations provide different values. The author found no independent published journal papers to verify the claims made.

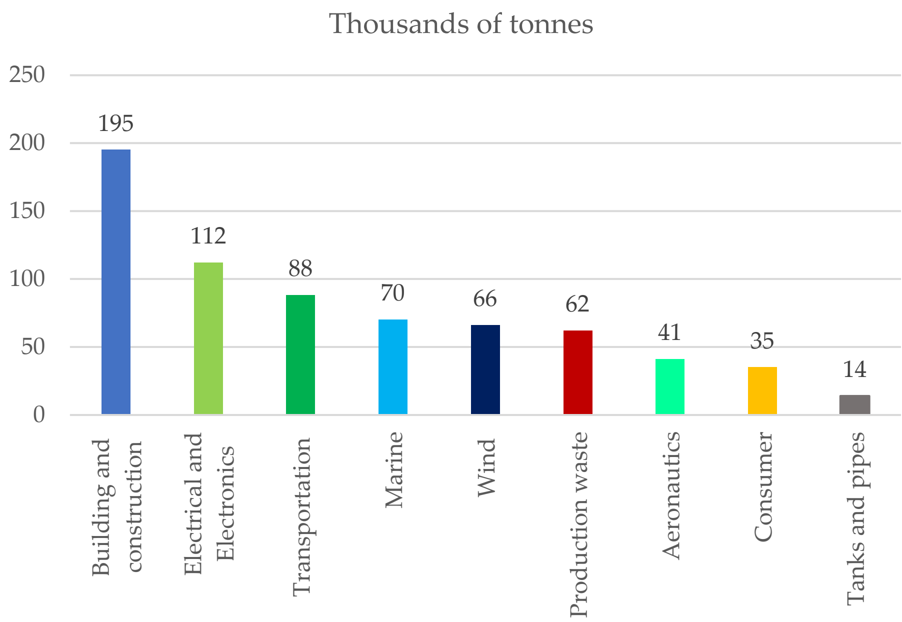

Figure 1. Estimated FRP waste in thousands of tonnes in 2025 (adapted from [22]).

The growing demand for FRP composites in various industries has led to increased waste. This waste should be discarded in a manner that is considerate to the environment. Furthermore, governmental legislation shapes public behaviour by promoting recycling rates and minimising landfill use. The European Union Directive 2018/850 on the landfill of waste [23] limits the municipal waste to landfill to only 10% by 2035 (article 5(5) of Landfill Directive, LFD). In future, there will be more and more focus on recycling FRP composite waste. Therefore, there is a need to explore different composite waste recycling/disposal routes that are environmentally sustainable and commercially viable. The relevant research conducted on FRP waste disposal routes is summarised in Table 1. Most papers are based on a single FRP recycling method, but some papers review all disposal options. The majority of research is on generic recycling methods at a small-scale while using laboratory experiments. FRP parts used in automotive, aerospace, and electrical/electronic industries are typically thin and small. Buildings, bridges, and wind turbines generally use thicker and bigger FRP components than the other FRP sectors. As per Figure 1, the building and construction sector is the major contributor to FRP waste. Recycling these large parts requires scalable recycling processes.

The novelty of this paper is that it critically reviews various FRP waste disposal routes for structural engineering applications and wind turbines. Prior research mainly focussed on the disposal of thin and small parts in other industries, such as aerospace, electrical, sports, marine, and automotive. The scope of this paper is limited to a review of the disposal routes for thermoset-based glass and carbon FRPs in the construction and wind turbine industries; thermoplastic FRPs are only briefly discussed. The recycling methods for thermoplastic FRPs are no different from thermoset FRPs. The reason for using only glass and carbon fibre composites is that most FRP applications use these fibres. More than 90% of all FRP products use glass fibres, and 66% of all composites use thermoset resin. The remaining FRPs mostly employ carbon fibres. This makes it worthwhile to study the recycling of glass and carbon fibres with thermoset resin. Other synthetic fibres, such as aramid fibres, are only used in less than 1% of FRP applications [17,18]. So, they are not included in this review.

This paper aims to review various FRP composite waste disposal pathways. Different FRP end-of-life disposal routes are discussed. These include waste minimisation or prevention, reuse or repurpose, recycling, incineration/co-incineration, and landfill. Mechanical, thermal, and chemical recycling routes are reviewed. Thermal recycling is again divided into fluidised bed and pyrolysis. Chemical recycling or solvolysis is again classed into sub- and supercritical temperature solvolysis. The paper is organised into eight sections. First, the introduction is presented, followed by a brief section on FRP waste disposal routes. The third section deals with waste prevention and the reuse of FRP composites. The fourth section reviews recycling pathways. The fifth section concerns other recovery and disposal routes. The energy demand and cost of different FRP waste disposal methods are presented in section six. Section seven relates to the limitations and future research requirements. Finally, conclusions are drawn, summarising the key points in section eight.

Table 1. Past research on review of recycling processes for FRP composites.

Researcher	Year	Content	Main Points
Schinner et al. [24]	1996	• Recycling of carbon-reinforced thermoplastic composites.	• Mechanical recycling of thermoplastic carbon FRPs. • Thermoplastic CFRP grinds used as a reinforcement in injection moulds.
Kouparitsas et al. [25]	2002	• Mechanical recycling applied to glass-, aramid-, and carbon-based thermoset composites.	• Recyclates were found to be of acceptable quality for use as reinforcement in new thermoplastic composite. • Tensile testing on new parts shows good response.
Halliwell [26]	2006	• Best practice guide for FRP waste disposal.	• Reuse, recycle, and other disposal methods discussed. • Legislation, life cycle, and best practice reviewed. • 98% FRP waste landfilled or incinerated; 2% recycled.

Table 1. *Cont.*

Researcher	Year	Content	Main Points
Conroy et al. [27,28]	2004/2006	• Composite waste-management options in the UK.	• FRP considered unrecyclable and ends up in landfill. • FRP waste used in wood/FRP composite, road asphalt, and concrete.
Various authors [29–84]	1995–2023	• Specific recycling and reusing methods for FRP waste.	• Only mechanical recycling is scalable to large scale. • Mechanical recycling is suitable for GFRP only. • Thermal and chemical recycling suitable for CFRP.
Pickering [85]	2006	• Recycling technologies for thermoset composites.	• Research on various recycling processes reviewed. • Prospects of commercial operation discussed.
Halliwell [86]	2010	• Challenges facing the FRP industry.	• Life-cycle assessment, embodied energy, material choice and end-of-life disposal options discussed.
Pimenta and Pinho [87]	2011	• Review of recycling methods for CFRP in Structures	• Pyrolysis (thermal recycling) was found to be at commercial scale, other methods only at lab or pilot scale • Recycling, re-making and market reviewed.
Bank et al. [15,88]	2014	• Reuse of mechanically recycled GFRP.	• Various disposal methods discussed. • Focus on use of ground recyclates in concrete.
Vo Dong et al. [80,89]	2015, 2018	• Environmental and economic impacts of FRP waste routes.	• Pyrolysis is attractive for CFRP recycling. • Grinding and incineration suitable for GFRP.
Ribeiro et al. [90]	2016	• Recycling methods and sustainability performance.	• Various recycling methods discussed. • Market outlook and potential for GFRP recyclates.
Naqvi et al. [21]	2018	• A review of pyrolysis (thermal recycling) for FRP waste.	• A review of pyrolysis method and reuse of reclaimed fibres.
Gharde and Kandasubramanian [16]	2019	• A review of recycling routes.	• Past research on mechanical, chemical, and thermal recycling reviewed.
Karuppannan Gopalraj and Karki [91]	2020	• A review of recycling techniques for GFRP and CFRP.	• Various recycling methods compared based on process outcomes, mechanical properties, ease of reuse, environmental impact, and cost-effectiveness.
Krauklis et al. [92]	2021	• A review of recycling methods and market analysis.	• Review of recycling routes, composite market, energy demand and Technology Readiness Level (TRL).

Table 1. *Cont.*

Researcher	Year	Content	Main Points
Bank et al. [93–96] and Leon [97]	2021–2022	• Use of wind GFRP turbine blades in structures.	• Review, analysis, and case studies for repurposing wind turbine blades in bridges, electric poles etc.
Utekar et al. [13]	2021	• A review of recycling routes for thermoset FRPs.	• Energy demand, recycling output and strength of reclaimed fibres reviewed.
Gonçalves et al. [22]	2022	• A review of GFRP recycling pathways.	• Recycling methods for GFRP reviewed. • Energy demand and recycling process cost analysed.
Arif et al. [98]	2022	• A review of FRP recycling methods	• High-voltage fragmentation (HVF) is a low-energy technique with high recycling rates

2. FRP Waste Disposal Routes

As per the four-tiered waste management hierarchy developed by The European Union's 2008/98/EC directive [99], as shown in Figure 2, the waste should be minimised to preserve valuable space in landfills. In order of preference, FRP waste disposal options are minimisation/prevention, reuse/repurpose, recycling, incineration with or without energy recovery, and dumping in a landfill [86,100]. The main focus is on either the minimisation or prevention of waste, followed by reuse, recycling, recovery, and disposal. It is essential to recycle, reuse, and repurpose FRP composite waste generated from production, usage, or end-of-life scrap. FRP waste material negatively impacts the local environment by contaminating the soil, air, and groundwater. It can spread infectious diseases as well [16]. Landfill and incineration are not recycling methods. The incineration route still leaves behind 50% of the waste material as ash, which still needs to be landfilled [101].

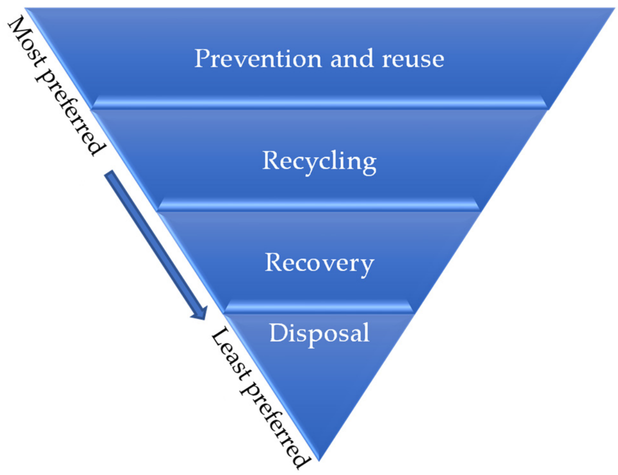

Figure 2. Waste management hierarchy as per The European Union's 2008/98/EC directive [99].

3. Waste Prevention and Reuse

FRP waste should be minimised as much as possible. The waste from production processes can be reduced by using automatic manufacturing methods. The end-of-life waste can be minimised by considering sustainable disposal routes at the conceptual design stage of the FRP composite part. Reusing and repurposing composite parts after their service lives should be the next preferred step in a sustainable waste management hierarchy.

3.1. Waste Minimisation or Prevention

The most eco-friendly option for waste disposal is to minimise waste. The production and manufacturing of FRP members and parts generate a considerable amount of waste. As much as 40% waste can be generated from the production of FRP parts [88]. FRP manufacturing techniques must be improved to reduce production waste. Most automatic methods, such as pultrusion and filament winding, are efficient and have limited production waste. The FRP waste generated from various manufacturing methods includes defective items, outdated moulds, trial runs, off-cuts, spray trimmings, trimming from vacuum infusion, trimming dust, and off-cuts [28].

FRP production waste (scrap) produced in highly efficient automatic processes, such as pultrusion, is in the range of 2–5%. In comparison, it can increase to 15% when using manual methods such as a hand layup. CFRP pre-preg scrap in aerospace production can reach as much as 40% [102]. The average FRP manufacturing waste or process waste/scrap is estimated to be 10% of the production volume [15]. Most FRP production waste, as seen in Figure 3, ends up in a landfill. Dumping this waste in a landfill may not be the best sustainable waste disposal solution, as there are now strict laws in some European countries for landfilling. Moreover, the space available in landfill sites may be limited in some countries.

Figure 3. FRP waste disposal [28].

FRP waste comes from production, usage, and end-of-life deconstruction. Production waste can be reduced by reviewing the manufacturing process and identifying the most efficient one. Most automatic processes result in less waste than manual methods. In construction, automatic processes can be used for structural profiles. However, free-form geometry may be required in bridge components, where manual methods are more suitable. Manual methods, such as pre-pregs and resin transfer moulding, dominate the FRP composite aerospace industry. Some automated hand-layups are also used in aerospace, but complete process automation is not feasible. Scrap pre-pregs can also be used as construction tiles. Trim allowances, normally 25–50 mm, can be reduced to minimise pre-preg scrap. Nesting composite parts for efficient material use in pre-pregs can also reduce waste.

3.2. Reuse or Repurpose

Reusing and repurposing FRP parts at the end of their service life should be the next priority if the waste cannot be prevented or minimised. Reusing means using the FRP parts after their end-of-life in the same industry in which the components were once used. Repurposing relates to reusing FRP parts at the end of their service for a different application, generally lower in value than the original application [103]. Deconstruction and reuse must be kept in mind when designing, constructing, and using FRP structures for intended future reuse. For example, FRP structures using bolted joints can be demounted at the end of their service life and can be reused. However, it might be challenging to re-calculate the strength and material properties of the reused pultruded FRP parts. This also depends on the type of FRP structure. FRP profiles are challenging to reuse, whereas FRP domes can be easily reused or repurposed. On the other hand, adhesively bonded joints are difficult to deconstruct and reuse at the end of their lives.

Many FRP products are specifically designed and constructed for a particular application with no intention of recovery or reuse after their usage. These applications include façade panels, FRP swimming pools, and pipes. However, FRP domes, chimneys, and clock towers can potentially be reused or repurposed. Structural profiles, such as I, W, channel, angle, and tubular sections, may be difficult to reuse, as the extent of deterioration and creep effects cannot be reliably determined. Equally, it is hard to assess the load-carrying capacity and material properties without prior knowledge of the fibre layup of the decommissioned composite part. Pultruded FRP profiles produced for one application are generally not suitable for reuse in other applications [28].

Glass FRP wind turbine blades can be repurposed into structural beams or columns. Repurposing is defined as remanufacturing and redesigning wind blades at the end of their service life and reusing them as structural elements in new structures, such as sound barriers, transmission poles, bridges, sea walls, and shelters [104]. A footbridge made from decommissioned wind turbine blades was installed in 2022 in Cork, Ireland, as shown in Figure 4. The bridge is 5 m long and 3.5 m wide and is supported on concrete abutments. The main girders are from two GFRP wind turbine blades. The joints, transverse beams and decks use structural steel. Wind turbine blades are designed for a service life of 20–25 years. Regardless of their condition, they are decommissioned at the end of life. Glass FRPs are very difficult to recycle. Repurposing these blades to new structural applications minimises the waste in a landfill [95]. Wind turbine blades are also proposed to be used in electric transmission towers [93,94,96], as seen in Figure 5. Wind turbine blades have also been employed in secondary applications, such as playgrounds and bus shelters in The Netherlands [97].

(**a**) (**b**)

Figure 4. Re-Wind Network's first footbridge in Cork, Ireland, constructed from decommissioned wind turbine blades in January 2022: (**a**) Front view of the blade bridge; (**b**) Side view of the footbridge, Photo Credit: Re-Wind Network [104].

Currently, only a small percentage of FRP composites are reused in the UK, 6% for glass fibre and 2% for carbon fibre [105]. There are two main barriers to the wide adoption of reusing and repurposing FRP composites. First is the difficulty in establishing the material properties of the decommissioned FRP part, and second is the high cost associated with reclaimed fibres, resin, and other ground FRP material. To address the first problem, non-destructive testing and structural health monitoring techniques can be used to estimate the material properties of the deconstructed part. The second problem can be solved by linking a suitable recycling route to the quality and value of the reclaimed material. For example, glass FRPs can be ground and reused in concrete or asphalt mixes; and carbon fibres can be recovered using more refined recycling processes—thermal or chemical recycling. The reclaimed carbon fibres can then be reused as a reinforcement in other FRP components. Recycling is discussed in detail in the next section.

Figure 5. Rendered Wind turbine blade utility transmission poles to be constructed in Kansas, USA [93], Photo credit: Re-Wind Network [104].

4. Recycling

There are three methods for FRP waste disposal: landfill, incineration and co-incineration, and recycling. Recycling is the most desirable disposal method for FRP waste material. The strengths, limitations, and key points of attention for these methods are presented in Table 2. Different FRP waste disposal pathways are summarised in Figure 6. There are three main recycling pathways: mechanical, thermal, and chemical recycling. Thermal recycling is again divided into three categories: pyrolysis, fluidised beds, and microwaves. Chemical recycling has two types: low-temperature solvolysis and sub–supercritical solvolysis [28,85–87,90,102].

4.1. Mechanical Recycling

Mechanical recycling involves breaking down FRP waste by using milling, grinding, shedding, or other similar mechanical processes into small-sized material. The resultant recyclates can be divided into two parts: a fibrous fraction containing mainly fibres and a fine powder fraction consisting largely of the resin matrix [25]. The recovered scrap material can be used as a filler material or reinforcement in other composite materials. It can also be used in the construction industry (for example, as fillers for artificial wood or asphalt or as a mineral source for cement) [28]. Mechanical recycling produces low-value products, and this is the reason it is mostly used for glass FRP waste. The low-value recyclates make them hardly competitive with virgin materials, such as calcium carbonate for cement production or virgin glass fibre. However, mechanical recycling is the most economically viable recycling method at the industrial scale, at least for thermoset-based glass FRPs. Glass fibres are cheaper than carbon and aramid fibres. A few applications of mechanical recycling are also found in thermoplastic FRPs and thermoset CFRPs. Mechanical recycling does not recover individual fibres; it just grinds the FRP parts into smaller materials [25,87,90,106].

Table 2. Pros and cons of various waste disposal methods for FRPs [16,22,103].

Disposal Route	Strengths	Setbacks	Points of Attention
Landfill	• Cost-effective and convenient.	• Dust and pollution to local environment. • Greenhouse gas emission, i.e., methane. • Toxic waste can pile up, causing health issues.	• Governmental legislations prevent or limit landfill use. • Limited space in landfill.
Incineration	• With or without energy recovery. • Efficient use of space. • Landfill space is reduced.	• No material recovered. • 50% waste left as ash. • Expensive to build, operate, and maintain. • Air pollution resulting from combustion.	• Non-recovery method. • Incineration of GFRP is not practical, as 50–70% is left as ash. • Gate fee charged.
Co-incineration or Co-processing in cement kiln	• Material and energy recovery. • Uses FRP waste as the main or extra fuel. • Highly efficient, fast, and scalable. • No ash left over. • Turns GFRP waste into energy and clinker.	• Loss of original fibre's shape. • Additional energy needed to reach high processing temperatures. • FRP waste needs to be reduced to a smaller size for use in kiln.	• Only suitable for glass FRPs. • Pollutants and particulate matter emissions.
Mechanical recycling or grinding	• Efficient and high output rates. • Scalable at industrial scale • No air pollution by gas emission or water pollution by chemicals. • Inexpensive equipment and no skilled labour.	• Health and safety concerns for risk of ignition during shredding process. • Low-value recyclates that are hardly competitive with virgin materials.	• No recovery of individual fibres. • Produces low-value products, used for GFRP only • Requires dedicated facilities with closed area to limit dust emissions.
Thermal recycling: pyrolysis	• The by-products (gas and oil) can be used as energy source. • Easily Scalable. • Already used at commercial scale for recycling carbon fibre composites.	• Recovered fibre may retain oxidation residue or char. • Low-quality reclaimed fibres. • Loss of strength of fibre due to high temperature. • Not economically viable.	• Potential leaks of gases from waste treatment chambers.
Chemical recycling: solvolysis	• Recovery of clean fibres with full length. • Recovery of resin that can be reused. • Low-risk solvents are used, such as alcohols, glycols, and supercritical water.	• Low efficiency and high cost. • High energy consumption due to the high temperature and high pressure. • Large amounts of solvents required.	• Human heath impact from greenhouse gases.

Mechanical recycling involves the initial cutting of the FRP composite part into smaller-sized particles, about 50–100 mm in size, and then grinding them into fine powder. The typical required equipment is as follows: (1) a basic granulator/hammer mill (rotary cutter or high-speed mill); (2) a pulveriser for crushing the ground material in powdered form and (3) a classifier (also known as cyclones and sieves or an electrostatic separator) for separating the coarse fibrous and fine powdered products. A flowchart showing various stages of mechanical recycling is presented in Figure 7. Generally, coarse products contain fibrous material and can be reused in bulk moulding compounds (BMC). The fine particles contained in the powdered fractions can be reused in sheet moulding compounds (SMC).

The BMCs and SMCs are glass fibre reinforced thermoset polymer moulds primarily used in the compression moulding process for automotive and electrical applications [16,25]. GFRP coarse and fine recycled aggregates have been used in polyester-based mortar and concrete. The aim is to compare the tensile, compressive, and flexural strengths of recycled concrete with traditional concrete using virgin materials [67–73,75–79]. The mechanical recycling of CFRP has been studied in numerous research papers [24,25,106].

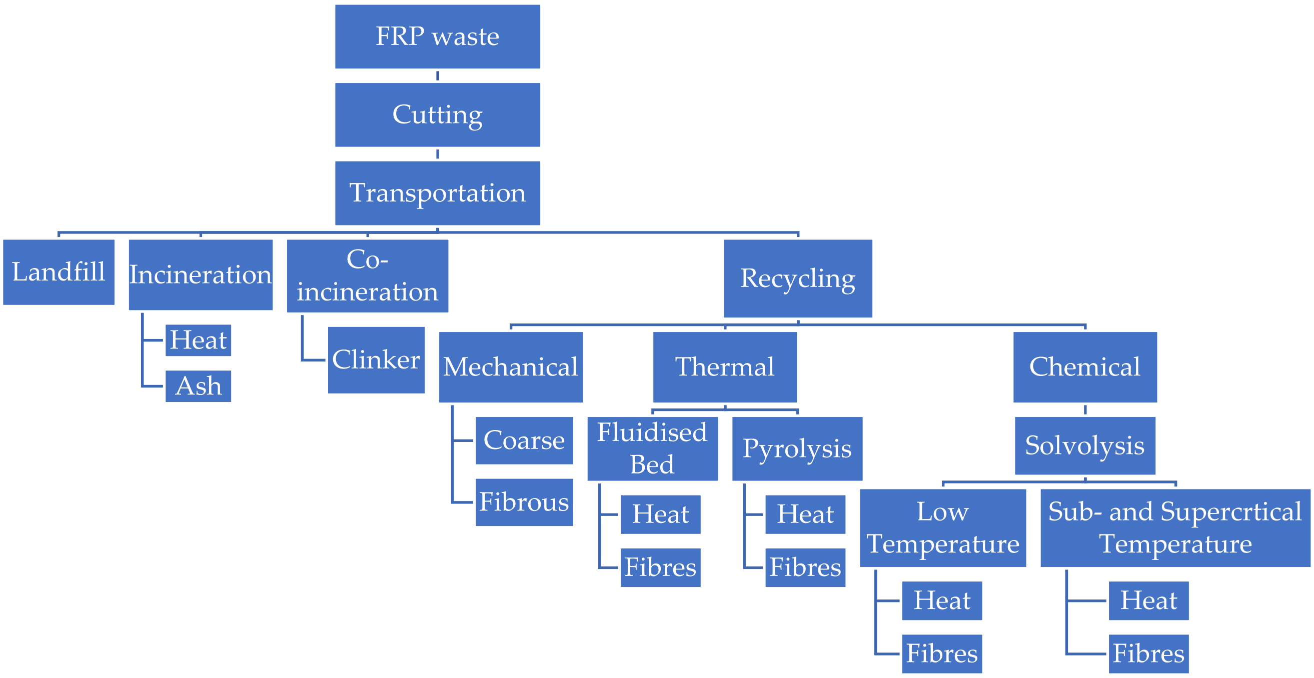

Figure 6. Various disposal techniques for FRP composite waste material [16,80].

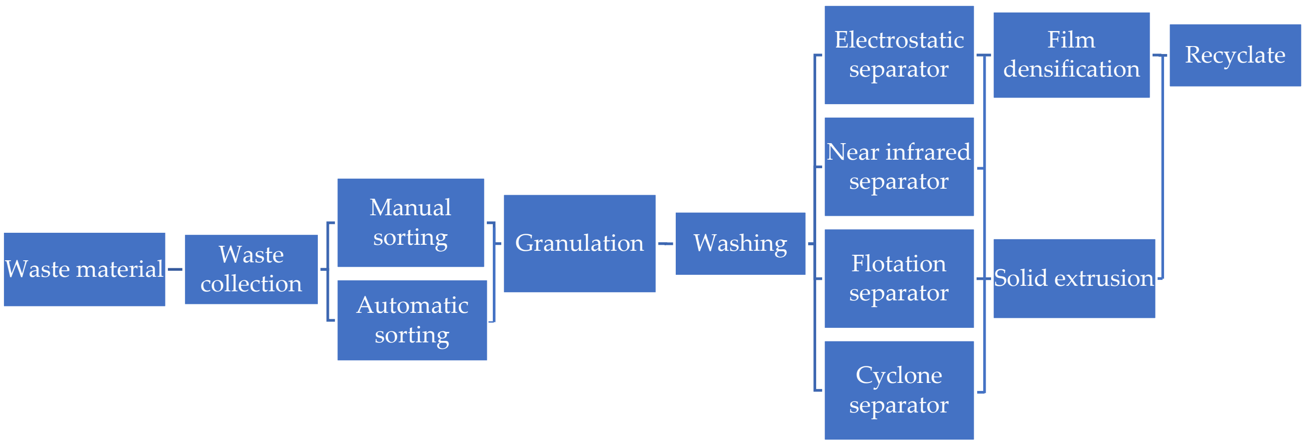

Figure 7. Schematic diagram showing mechanical recycling of FRP waste [16].

Many researchers used mechanically ground recyclates (fine powder and resin) in concrete and paints. Initially, Kojima and Furukawa [107] recovered fine powder from FTP (Fortified Tooling Prepreg) mouldings and used it to improve the tensile strength of paints. The ground material was also used as aggregates in concrete and was found to be useful. Ribeiro et al. [69] extracted coarse and fine aggregates from pultruded FRP products using mechanical grinding and used them in polyester-based mortar. Three sand filler replacement percentages, 4, 8, and 12% of weight, were tried. The use of the 8% replacement in mortar showed a 10% improvement in the flexural and compressive strengths compared with the pure polymer-based mortar. The authors also used a silane coupling agent (1% of resin weight) in a separate paper [71] but found no effect on the mechanical properties. The silane coupling agents are used to promote interfacial adhesion and improve the properties of composites. They create a chemical bridge between the inorganic reinforcement, such as glass fibre and organic polymer matrices. However, Meira et al. [73] found a marginal increase in the mechanical properties with the use of a silane coupling agent.

Asokan et al. [67,68] used 5, 15, 30, and 50% GFRP waste powder as a substitute for aggregates in concrete. They found more than a 20–60% reduction in concrete compressive strength at 28 days with water curing. However, at 180 days, the strength of the 5% and 15% waste was almost similar to the control specimen. García et al. [72] used 5% and 10% GFRP waste with the standard sand silica and natural limestone sand in the micro concrete part. The compressive strength decreased by 22% and 16% at 28 days for the 5% and 10% waste. Yazdanbakhsh et al. [75,76,78,79] used GFRP waste needles, bars, large-sized parts, and recycled wind turbine blades in concrete. They found that the compressive strength either decreased or remained unchanged, except with the turbine blade waste, where a 10% improvement was noted in the tensile and compressive strength. Dehghan et al. [77] used recycled glass fibres as a 5% coarse aggregate replacement in concrete. They found some increase in the tensile strength, but the compressive strength remained unaltered. In addition to its use in concrete, recycled GFRP waste has also been used in Sheet and Dough Moulding Compounds (SMC and DMC). Palmer et al. [108] used mechanical recycling to grind glass fibre reinforced SMC (Sheet Moulding Compounds) using a hammer mill. The recyclates obtained were used as 10% of the virgin-fibre replacement in the DMC (Dough Moulding Compounds). The mechanical properties of the composite part using 10% recyclate were not adversely affected. The authors suggested that a high level of recyclates can be used to reduce the cost of virgin materials.

Overall, the use of mechanically recycled ground FRP waste material in concrete showed either a reduction or no improvement in the compressive strength of concrete. Some marginal improvement in the tensile and flexural strengths of concrete was achieved. Less than 10% aggregate replacement in concrete was found to be the best proportion for keeping the compressive strength the same or slightly lower than the control concrete. Recycled GFRP waste is suitable as a filler material in other FRP components and aggregate in concrete. However, it should be used in non-load-bearing secondary structural applications. The ease, scalability, speed, and fewer environmental impacts mean that mechanical recycling is superior to other methods for glass-based FRP waste. However, the quality and value of the reclaimed material are lower than what you can obtain from other recycling routes.

4.2. Thermal Recycling

Fibres can be recovered from the resin by using thermal or chemical processes. The aggressive process breaks down the resin, resulting in fibre recovery and the release of energy from the resin. The resin matrix is typically a thermoset resin. Fibre reclamation (thermal or chemical recycling) is a suitable technique for carbon fibre reinforced polymer (CFRP) for three reasons: (1) carbon fibres have high chemical and thermal stability; (2) the mechanical properties of the recovered fibres are not largely degraded, and (3) extracting expensive carbon fibres justifies the high cost of thermal and chemical recycling. The recovered fibres are used in new resin to produce recycled CFRPs. The recycled carbon fibres have also been reused in non-structural applications. Thermal recycling uses heat to separate the fibres from the resin matrix. There are three thermal recycling techniques: (1) pyrolysis; (2) fluidised beds; and (3) microwave. Thermal recycling can recover both glass and carbon fibres from their composites with an operating temperature range of 450–700 °C [16,85,87,88]. Thermal recycling is still far away from becoming a large-scale industrial recycling method [90].

4.2.1. Pyrolysis

Pyrolysis is one of the most commonly used thermal recycling methods. It is based on the thermal decomposition of organic parts in the presence of nitrogen in a static pyrolysis reactor. The FRP parts are heated to 450–700 °C in the absence of oxygen. The matrix decomposition produces oily, solid (char) and gaseous products during the process. The oily and solid parts are of lower molecular substances. The gases consist of carbon monoxide (CO), carbon dioxide (CO_2), and other hydrocarbons [16,87]. The recycling of glass FRPs using pyrolysis was studied in papers [55–57,59]. Different temperatures were tried ranging from 300–800 °C. It was found that the tensile strength of the recovered fibre was about 65% at 500 °C, and it decreased beyond 650–800 °C.

The pyrolysis technique has been used to recycle CFRP in papers [54,60,61,64]. The researchers found that the recovered fibres had similar mechanical properties and surface characteristics to that of the original fibres. Most studies tried temperatures of 450 °C and 600 °C. Scanning electron microscopy (SEM) and energy dispersive spectrometry were used to study the superficial morphology and changes in the composition of the fibre. A thermal treatment lower than 450 °C was found to be suitable, with minimum damage to the fibre surfaces and reduction in mechanical properties. High temperatures, more than 600 °C, were found to cause severe damage to the fibres. Pyrolysis is a preferred recycling technique for CFRP, as the tensile strength and surface morphology of the recovered fibres are almost the same as the original fibres. The recovered fibres have 80–95% tensile strength of the virgin fibres [16]. Pyrolysis is also suitable for CFRP due to the high economic value of the recovered carbon fibre [90].

4.2.2. Fluidised Beds

Developed in the 1990s at the University of Nottingham, UK, oxygen in fluidised beds is another thermal process for FRP recycling [16,48,49,85,90]. It consists of burning the resin matrix in a hot and oxygen-rich flow. The recovered fibres are clean with no char deposits. However, degradation in fibre length and strength may happen during this process [90]. First, the composite waste is reduced to a 25 mm size and fed into a fluidised or silica sand bed. The bed is heated to 450–550 °C using a hot-air stream. Both fibres and resin are carried in the stream. The fibres are separated from the air stream by a cyclone, and the resin is fully oxidised in an afterburner, with energy recovery as heat.

The fluidised bed process has been used to recycle glass FRP scrap. It was a general consensus in past research that the thermal heating temperature affects the strength of the recovered fibre. The heating temperatures of 450 °C, 550 °C, and 650 °C led to a tensile strength reduction of 50%, 65%, and 90% in the recovered fibre compared to the virgin fibre [47,48,51,53]. Research studies [49,50] have been conducted on recycling CFRP waste using fluidised beds. The tensile strength of the recovered carbon fibre was reported to be about 75% of the virgin carbon fibre. Some drawbacks of the fluidised bed method include a reduction in the recovered fibre length, an unstructured or fluffy fibre architecture, and strength degradation between 25% and 50% [16,87].

4.2.3. Microwave

Microwave-based pyrolysis is an effective method for recovering glass and carbon fibre and disintegrating the resin into oil and gases. The main advantages of this technique are as follows: (1) The FRP waste material is heated to its core; (2) the fast rate of heat transfer; and (3) minimum heat loss to surrounding areas. The research paper by Åkesson et al. [62] uses microwave pyrolysis as a method of recycling glass fibre from the used blades of wind turbines. The recovered glass fibres only lost 25% of their tensile strength compared to the original fibres. The microwave was heated at 300–600 °C in a nitrogen atmosphere for 90 min to recover glass fibres and oil from the wind turbine scrap.

Research by Obunai et al. [65] compared three atmospheric conditions, air, nitrogen, and argon, to recover carbon fibres using microwave irradiation. The argon atmosphere was found to be the most effective for extracting carbon fibres. The tensile strength of the recovered fibres was either the same as the virgin fibres or at least comparable to the other recycling methods. However, the paper by Lester et al. [58] found a 25% reduction in the tensile strength of the recovered carbon fibres compared to the virgin carbon fibres using microwaves. The reason for this discrepancy in results in these three papers is due to the different atmospheres used in the microwave treatments. Åkesson et al. [62] and Lester et al. [58] used a microwave treatment under a nitrogen atmosphere; the results showed a 25% reduction in the tensile strength of the recovered carbon fibres. Conversely, Obunai et al. [65] used microwave irradiation under an argon atmosphere, which was found to be the most effective atmosphere in reclaiming fibres without flaws.

Recently, upcycling techniques have also been explored to extract better-quality carbon fibres than the original fibres. Upcycling means reusing the discarded material to create a product of higher quality or value than the original. Zhang et al. [109] proposed an upcycling method for CFRP waste to minimise environmental pollution. Microwave irradiation pyrolysis was used under a nitrogen atmosphere in this method. The authors believe that microwave plasma pyrolysis using graphene porous materials is the best solution for CFRP upcycling from abandoned aircraft, wind turbine blades, and sports equipment. The reclaimed carbon fibre produced by the upcycling method had better properties than the virgin carbon fibre. The new method can also save energy and reduce carbon emissions.

4.3. Chemical Recycling

Chemical recycling dissolves the resin matrix using a chemical product and a reactive medium (catalytic solutions and supercritical fluids) at a low temperature, usually less than 350 °C. The polymer resin matrix is decomposed and separated from the waste, leading to fibre collection and energy recovery from the matrix. The fibres remain inert during the chemical process. Chemical recycling can lead to negative environmental impacts if hazardous chemicals are used. Chemical recycling is also known as solvolysis. Chemical recycling is divided into two parts: low temperature (solvolysis) and supercritical fluid (solvolysis) [16,87,88,90].

4.3.1. Low-Temperature (Solvolysis)

Low-temperature (solvolysis) is carried out at low temperatures, less than 200 °C, under atmospheric pressure. It uses acid or solvents as a reactive medium, such as water, alcohol, ammonia, nitric, or sulphuric acid, to disintegrate the resin matrix from FRP composite scrap. Due to the low temperature, catalysts and additives need to be used. Recycling glass FRPs using solvolysis has been researched in papers [29,30]. The authors found that the mechanical properties and glass transition temperature of the reclaimed resin were better than the virgin matrix. The glass fibres could also be separated and recovered. Chemical recycling of CFRP waste using solvolysis has been studied in [30,32,33]. The nitric acid solution was used as a reactive medium to decompose an epoxy resin matrix. The mechanical properties of the reclaimed fibres and resin are almost the same as the virgin materials. The reclaimed carbon fibres are sold as chopped, or milled fibres, and the recovered resin is either used as fuel or chemical feedstock [87].

4.3.2. Sub or Supercritical Fluid (Solvolysis)

Chemical recycling using supercritical fluids enables a desirable reactive medium for the decomposition of the polymer resin. The method can recover high-quality fibres from both GFRP and CFRP. Supercritical fluids (SCF) are substances that are above their critical temperatures and pressure point. At this point, the distinct liquid and gas states do not exist. SCFs can pass through solids, similar to gases, and dissolve materials, similar to liquids. The SCFs are very useful in digesting the resin matrix in FRP waste. Sub- or supercritical fluid (solvolysis) is again divided into two categories: sub–supercritical water (solvolysis) and sub–supercritical alcohol (solvolysis). The alcohol can be methanol, ethanol, propanol, acetone, or glycols [16].

Research on chemical recycling solvolysis using sub- or supercritical water has been conducted by various researchers [31,34–37,42,46,74]. Using water as a solvent has generally led to the tensile strength of the recovered fibre to be 85–98% of the virgin fibre. A temperature lower than 350 °C resulted in the highest decomposition of the matrix and quality of recovered fibres. Several researchers [38–40,43–45,52,63,84] using sub-critical or supercritical alcohol techniques found almost no loss in the tensile strength and surface properties of the recovered fibre compared to the virgin fibre. Scanning electron microscope (SEM) has been used to confirm the surface morphology of the recovered fibre. Sub-critical or supercritical fluid solvolysis is more effective than low-temperature solvolysis and thermal techniques, such as fluidised bed and pyrolysis, in recovering high-quality fibres and extracting energy from the matrix. Sub-supercritical solvolysis does not use harmful and toxic chemicals compared to low-temperature solvolysis [16].

5. Recovery and Disposal

When FRP waste cannot be minimised, reused, or recycled, energy recovery through incineration can be considered. Co-incineration in a cement kiln to produce clinker (raw material for cement production) and partial energy recovery as fuel may also be a suitable disposal pathway. If none of the above methods is workable, dumping FRP scrap in a landfill should be the last resort.

5.1. Incineration and Co-Incineration

Incineration is a common FRP composite waste disposal method. It is based on burning the organic content in composite waste with or without energy recovery. Incineration with energy recovery could be a suitable disposal option due to the high calorific value of FRP waste. However, 50% of the combusted waste remains as ash after incineration, which ends up in a landfill [28,92,101]. The residual ash can contain hazardous materials. Moreover, the air pollution resulting from combustion is a setback of this method. As per European Union's Directive 2010/75/EU [110], the amount and harmfulness of the residues from incineration and co-incineration should be minimized and, where possible, recycled appropriately. Furthermore, the heat generated should be recovered, if practical, as energy to generate heat, steam, or power [90].

The incinerator operators usually charge more for accepting FRP waste, as it overloads the system due to toxic emissions and high calorific content. This means their capacity to process domestic waste is reduced. By accepting a small quantity of FRP waste for incineration, a large amount of domestic refuse must then be landfilled. The main business of the incinerator is to discard domestic refuse, not FRP waste [28]. Presently, incineration with energy recovery is considered a less cost-effective disposal method. The incineration of GFRP is not practical, as 50–70% of the material is mineral, which turns into ash after combustion and requires landfilling [111]. GFRP products usually contain 40% glass, 30% inorganic filler, and 30% resin. The glass and filler are mineral materials that do not burn. Together, glass and filler make up 70% of the composite part, which remains after incineration [26]. Incineration is also not suitable for large parts and glass fibre residue, as both can cause blockages in the process plant [101].

Co-incineration in a cement kiln is another disposal option for GFRP waste. It is also known as cement co-processing. It is slightly more cost-effective than incineration, as it offers both material and energy recovery. Co-incineration is used when the value of recovered material is higher than the cost of the disposal method. Co-incineration is not feasible for CFRP waste, as the cost of the carbon fibre is at least 10 times more than the glass fibre. As per "The Waste Incineration Directive in England and Wales" [112], the main purpose of a co-incineration plant is to generate energy and/or produce materials. The plant uses the FRP waste as the main or additional fuel. In a cement kiln, co-incineration turns GFRP waste into energy and clinker. The mineral part of the GFRP waste is converted into clinker, and the organic part, resin, is used as an alternative fuel for the kiln. No ash or residue is left behind in co-incineration, but the waste needs to be reduced to a smaller size for use in the kiln [90,101]. Co-incineration in cement kilns has been commercially successful in Germany [101]. While co-incineration is useful for recovering material and energy, it has some setbacks too. One major drawback is that co-incineration relies on GFRP waste meeting certain requirements as under [90]:

1. The waste should be smaller than 20 mm.
2. The toxic and heavy metals should be low in the waste.
3. It should not contain foreign material, including any metal fasteners.
4. It must not contain dust from pulverised fibreglass.
5. It should have a specific calorific value, usually higher than 5000 kcal/kg.

In addition, the total amount of fuel replacement by GFRP waste in a cement kiln is limited by the presence of the boron found in E-glass fibre reinforcement used in the composite product. More than 0.2% boron oxide increases the setting time of the cement and reduces the early strength of the cement. In practical terms, this means that not more than 10% of the fuel input can be replaced by combusting GFRP waste in the cement kiln [85,90].

5.2. Landfill

Dumping in a landfill site is the most common and cost-effective disposal option for thermoset-based FRP waste. Today, an estimated 90% of the UK's FRP composite waste goes to landfills [113]. Legislation, such as the EU landfill directive and the UK landfill tax, aims to discourage the use of landfill and encourage more eco-friendly disposal routes. Landfill tax in the UK currently stands at GBP 98.60 per tonne as of 1 April 2022. When gate fees and transport are included, the total cost of landfilling increases to about GBP 150 per tonne [114]. Germany and many other European countries have already banned landfill for FRP waste [115]. The cost of waste disposal in a landfill is set to increase, and the pre-treatment of waste will become mandatory in future. This will drive the need for alternative disposal routes for FRP composite waste [26]. These factors, including the increase in the price of landfilling, limited space in landfills, and waste management directives, will encourage recycling and reuse routes instead of simply discarding the FRP scrap in a landfill [90].

6. Energy Demand and Cost

The environmental impact of manufacturing synthetic virgin fibres and various recycling methods depends on the energy demand. Figure 8 shows the energy demand of various recycling processes and virgin carbon and glass fibres. Mechanical recycling is more suitable for recycling glass-based FRP products because the energy demand of the process is about 5 MJ/kg compared with virgin glass fibre (36 MJ/kg). Chemical and pyrolysis recycling methods are more useful for extracting carbon fibres, where the value of recycled carbon fibres is more than the cost of the recycling method. Chemical recycling has an energy demand in the range of 21–91 MJ/kg, and pyrolysis is more energy efficient, with an energy demand of 23–30 MJ/kg. Apart from mechanical recycling, the processing scale of the other recycling methods is not reported in the literature. Upscaling to commercial and industrial levels will reduce the energy demands of these recycling methods. Figure 8 shows that the recycling energy demand is about 10–20 times lower than the energy required to produce virgin fibres (glass: 13–32 MJ/kg and carbon: 183–286 MJ/kg) [115]. A specific recycling method should provide a suitable compromise between the energy consumed and the value and quality of the extracted fibres.

Figure 9 shows the cost comparison of different recycling methods in Euros per kg in 2018. Recycling routes are not cost-effective compared to incineration and landfill. In fibre recovery methods, chemical recycling is the most expensive and mechanical recycling and grinding is the least expensive. This makes chemical recycling the most suitable method for reclaiming carbon fibres, where the cost of the recovered fibres is higher than the processing cost. Chemical recycling and thermal recycling (pyrolysis) routes are used to reclaim high-quality carbon fibres from CFRP composites. In contrast, mechanical recycling can be useful for the recovery of glass fibres in GFRP composites. In non-recovery methods, landfill and incineration are the cheapest methods to dispose of FRP waste, with 0.1 Euro per kg. Despite no material recovery, landfill and incineration will continue to dominate FRP composite waste management due to economic reasons. With a cost of one Euro per kg, co-incineration instantly loses its economic viability when compared to incineration/landfill or even mechanical recycling. Co-incineration in a cement kiln produces clinker for cement production and partial energy to run the cement plant [89].

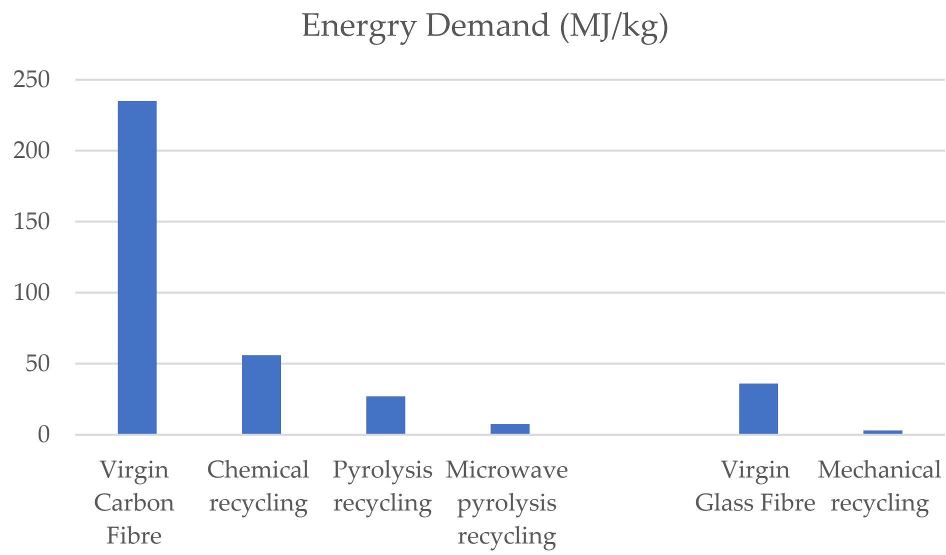

Figure 8. Energy demand of virgin fibres and recycling processes (adapted from [115]).

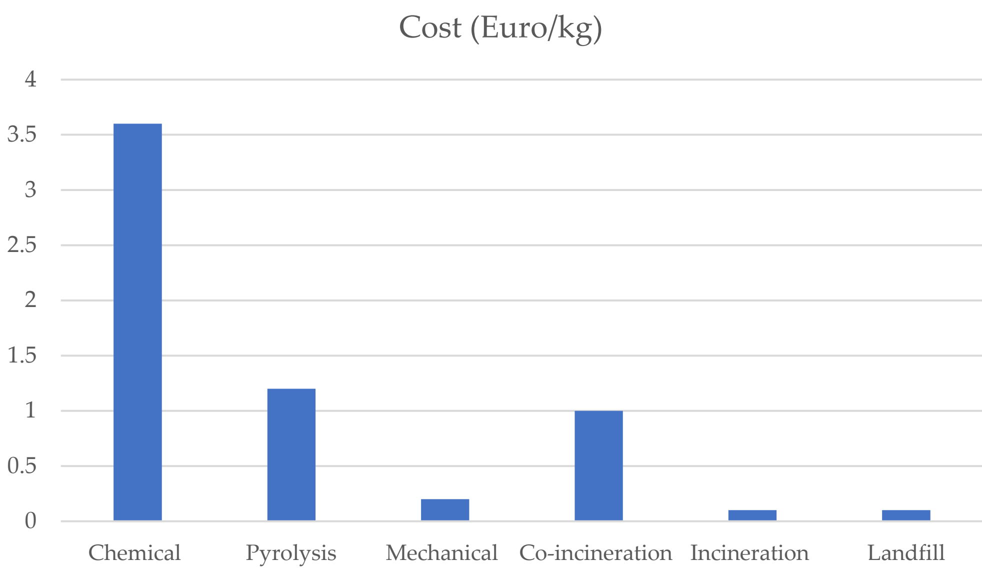

Figure 9. Average cost per kg of various recycling methods in 2018 (adapted from [16,89]).

7. Limitations and Future Research Requirements

Government policies shape waste-management strategies in the composite industry. The European Union has strict laws regarding landfill. Composite industry and academic research are focussed on reclaiming fibres fully. Partial fibre recovery can also be useful for secondary applications. Composite waste can be a valuable raw material. The major challenge is the scalability of recycling processes to an industrial-scale level. This is needed to reclaim a high proportion of fibres. The energy consumption of recycling routes is less than the manufacturing of virgin fibres.

With a slight compromise on the quality of fibres, recycled fibres can compete with virgin fibres. However, the cost of recycling will be a major factor in persuading the industry to recycle more. Levelling up recycling routes to an industrial scale will help reduce the cost. Alternative recycling approaches, such as high-voltage fragmentation, can be used to reduce environmental impact. Thermal recycling using microwaves, which saves half the recycling time, can also be employed. Electrochemical recycling approaches are still in their infancy at the laboratory-scale level. These three methods can be efficient and eco-friendly recycling routes when developed on an industrial scale. More research is also needed on upcycling techniques to reclaim fibres of higher quality and value than virgin fibres.

8. Conclusions

The paper provides a comprehensive review of existing recycling technologies and other disposal pathways for FRP composite waste. Despite being used for more than three decades, waste disposal and recycling routes for FRP composites are not fully developed yet. FRP waste consists of the production and end-of-life usage or decommissioning waste. Landfill is the cheapest and the most common method for discarding non-biodegradable FRP composite waste. Incineration recovers energy, but it still leaves behind 50% of the combusted waste as ash residue that ends up in a landfill. Co-processing or co-incineration in a cement kiln produces energy as a partial or full fuel for running the kiln and clinker for cement production. Co-processing is slightly more cost-effective than incineration as it recovers both energy and material. However, individual fibres are not reclaimed in co-incineration. Low-value glass FRPs are the most suitable waste material for co-processing. Co-incineration may not be cost-competitive as raw materials for clinker production, such as clay and limestone, might be cheaper than the clinker produced by the co-processing of FRP composite waste in a cement kiln.

The mechanical, thermal, and chemical recycling methods have been reviewed. Mechanical recycling simply grinds the FRP parts into powdered form. It produces low-value products, and this is the reason it is mostly used for glass FRP waste. The limited use of mechanical recycling for CFRP waste also exists. Mechanical recycling does not reclaim individual fibres. The quality of the recovered material is highly degraded. Industrial-scale mechanical recycling is only available for GFRPs. Mechanical recycling has not been utilised yet commercially for CFRP other than reducing the size of the CFRP parts before thermal recycling. Fibres can only be recovered from the resin by thermal or chemical recycling process. Thermal recycling is based on the decomposition of the organic part—resin via heat to recover fibres. Pyrolysis is the most common thermal recycling variant. Chemical recycling or solvolysis dissolves the resin using a chemical process leading to fibre and energy recovery. Thermal and chemical recycling are more suitable for CFRP than GFRP because the mechanical properties of the recovered carbon fibres are not degraded. The high cost of chemical and thermal recycling also justifies their use in reclaiming carbon fibres. The industry-scale application of both chemical and thermal recycling is yet to be realised. These processes should be scaled up from the laboratory scale to a commercially viable industrial level.

FRP composite structures using CFRP have a very long service life. Therefore, end-of-life FRP waste may not be available for long periods of time. The growth in the manufacture of CFRP outweighs the growth in the research on composite waste recycling. This creates a huge knowledge gap as the research in composite waste always lags behind the development of new FRP components. With potential limits on landfill and incineration, the future waste management agenda will highly encourage the repurposing, reusing, and recycling of FRP composite waste. The recovery of material and energy from FRP composite waste using circular economy approaches presents a major challenge in a sustainable society.

The United Nations adopted 17 Sustainable Development Goals (SDGs) in 2015 to balance social, economic, and environmental sustainability. It is a universal call to ensure that all people enjoy peace and prosperity by 2030. Goal No. 11 relates to sustainable cities and communities. Cities are responsible for more than 70% of global greenhouse gas emissions [116]. Minimising waste, reusing, and recycling FRPs will help reduce carbon emissions. These measures will assist in achieving the targets of the SDGs and ensuring sustainable cities. The key focus in future will be on handling and recycling FRP composite waste while meeting governmental legislation and addressing negative environmental impacts. In a circular economy, a closed-loop cradle-to-cradle approach is needed to turn the FRP composite waste into a valuable resource. This approach will help meet the UN's Sustainable Development Goal (SDG) related to sustainable cities and communities.

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