Economic Aspects of Fiber Reinforced Polymer Composite Recycling

Chiemela V Amaechi, Lancaster University, Lancaster, United Kingdom and Standards Organisation of Nigeria, Abuja, Nigeria
Charles O Agbomerie, Continental, ContiTech Industrial Fluid System, Dunlop Oil and Marine Limited, Grimsby, United Kingdom
Etim Offiong Orok, Coventry University, Coventry, United Kingdom and Standards Organisation of Nigeria, Abuja, Nigeria
Stella Job, Composites UK, Berkhamsted, United Kingdom
Jianqiao Ye, Lancaster University, Lancaster, United Kingdom

Glossary

Biocomposites A composite material formed by a matrix (resin) and a reinforcement of natural fibers.
Bulk molding compound (BMC) Polyester resin/glass fiber premix, for injection or transfer molding, also known as dough molding compound (DMC).
Carbon fiber Reinforcing fiber known for its light weight, high strength and high stiffness.
Composite A material made up of resin and reinforcement (usually fiber).
Fiber reinforced polymer (FRP) A general term for composite materials or parts that consist of a resin matrix that contains reinforcing fibers such as glass or fiber and have greater strength or stiffness than the resin. FRP is most often used to denote glass fiber reinforced polymer.
Fiber A unit of matter of relatively short length, characterized by a high ratio of length to thickness or diameter.
Glass fiber Reinforcing fiber made by drawing molten glass through bushings. The predominant reinforcement for polymer composites, it is known for its good strength, processability and low cost.
Impregnation Saturation of reinforcement with liquid resin.
Polymer A long-chain molecule, consisting of many repeat units.
Recyclates The raw material, collected, taken to and processed in a waste recycling plant or materials recovery facility which will be used in the manufacturing of new materials.
Recycling The process of converting waste materials into new materials, products and objects.
Reinforcement Key element added to resin (matrix) to provide the required properties; ranges from short fibers and continuous fibers through complex textile forms.
Resin Polymer with indefinite and often high molecular weight and a softening or melting range that exhibits a tendency to flow when subjected to stress. As composite matrices, resins bind together reinforcement fibers.
Scanning electron microscope (SEM) A type of electron microscope that is used to produce enlarged images of a sample by scanning the surface with a focused beam of electrons, like reinforced CFRP samples. When the samples are placed under the microscope, the electrons mix with the constituent atoms within the composite sample. This will produce different signals that contain information about the surface topography and composition of the sample.
Sheet molding compound (SMC) A flat prepreg material, comprising thickened resin, glass fiber and fillers, covered on both sides with polyethylene or nylon film, ready for press-molding.
Thermoplastic A plastic that softens each time it is heated.
Thermoset A plastic that flows and then sets permanently on first heating, as a result of setting up a three-dimensional cross-linked molecular structure, and subsequently will not soften or dissolve.

Introduction

People have the tendency to use resources rather than to reuse or recycle these resources. Recycling has not always been treated as important until recent decades. From building and road construction materials like concrete (Khalid *et al.*, 2017; Letelier *et al.*, 2017; Liu *et al.*, 2013) to composite polymers (Ogi *et al.*, 2007; Wei *et al.*, 2018; Ignatyev *et al.*, 2014), recycling is economically viable. There is an increase in the study of recycling of composite 77polymers (Knight *et al.*, 2012; Oliveux *et al.*, 2015; Ignatyev *et al.*, 2014), plastic waste (Jaivignesh and Sofi, 2017; Siddique *et al.*, 2008; Rebeiz and Craft, 1995), composite wastes (Halliwell, 2006; Kratz *et al.*, 2017; Meng *et al.*, 2017a,b) and nanocomposites (Hasan *et al.*, 2019). However, there are limitations and issues to recycling composites, particularly the fiber reinforced composites. Historically, the use of composite materials is dated back to about 3000 years ago in ancient Egypt. Natural fiber straws were used as reinforcements to build walls. Over the years, more durable materials were developed and today we have fiber reinforced composites that can also be produced in large scales. In the 1960s, glass fibers were used in large scale production of by mixing glass fibers and very rigid resins. However, in an attempt to save weight of the composite materials, and reduce the cost of composite materials, recycling of composites have been the trend in the past two decades (Brower, 2000; Oliveux *et al.*, 2015; Vieira *et al.*, 2017).

FRPs have great advantages that can be harnessed due to their corrosion resistance and high strength-to-weight ratio (Amaechi *et al.*, 2019a; Xu *et al.*, 2013; Yang *et al.*, 2014; Asmatulu *et al.*, 2014). These materials are applied in offshore applications, automobiles, sports, wind energy, automobiles, and wave energy converters (Zhang *et al.*, 2019; Doyle and Aggidis, 2019; Amaechi *et al.*, 2019b). The need for more sustainable materials led to development in composites. Economically, CFRP

 doi:10.1016/B978-0-12-803581-8.10738-6

Fig. 1 Wastes from an engineering department workshop showing composite wastes. Courtesy: Lancaster University.

composites contribute to the decrease of greenhouse emissions by reduction in fuel consumption as they are used to manufacture lighter bodies of cars and airplanes. There are also some health, safety, and design requirements during the production of composites generally (Amaechi, 2017; Ye, 2003; Murray, 2018; Job, 2015). According to Hopkins *et al.* (2014), composites are expensive, and the case study of a composite pipe is anticipated to cost approximately £10,000,000 compared with approximately £3,000,000 for the equivalent steel pipe. However, savings arise from the reduction in buoyancy tank size as well as the reduction in the lower riser assembly and upper riser termination assembly sizes. It is anticipated that the biggest cost saving would be as a result of simplifying the installation process as the reeled pipe and the smaller buoyancy tank would require less offshore installation time and smaller installation vessels. That being stated, there is no obvious argument to adopt composites based on cost alone, even with the better performance. The author concluded that the composite pipe cost is comparative to a steel option in the single leg hybrid riser configuration considered.

Currently, there are different classes of composites – Both thermosets and thermoplastics. Due to the need for better mechanical properties of these materials and the need to save some project costs, thus the use of recycled composites. These recycled composites have improved strength properties and other material properties (Wei *et al.*, 2018; Meng *et al.*, 2017a,b; Babafemi *et al.*, 2018). Some of these are due to the fiber orientations been aligned in multidirections and the methods used in manufacturing these recycled composites. The most common method for the recycling of fiber reinforced composites is by pyrolysis. GFRP is mostly considered during recycling because it uses a thermoset resin. Currently, it is not economical to recycle thermoset (CFRP using pyrolysis. Wastes can be generated in factories, workshops, schools, houses and they are collected, sorted, and then recycled. Wastes are generated from manufacturing factories, engineering workshops, scrap yards and all collected for recycling. **Figs. 1** and **2** show images of wastes at an Engineering Department workshop and an automotive scrap yard, showing high composite waste materials contents that can be recycled.

Presently, FRP composite recycling has been a current debate in both the composite material industry, and the renewable and sustainable materials industry. This is as a result of the economic impact of the FRP wastes generated from both production and utilization of the FRP material. This is expected, considering the growing demand for more sustainable materials, with regards to the timeline of composite materials, as shown in **Fig. 3**. The application of FRP composites has risen globally in the production of materials for automobiles, households, airplanes, and in the offshore industry. There is also an increase in the researches on recycling FRP composites. Despite the availability of different types of thermoset composites, there are BMC and SMC readily available. These compounds account for the highest percentage of thermoset composite waste due to their greater applications in different forms. In the automobile industry, the use of BMCs and SMCs has increased to attain lighter cars, which will be more fuel saving.

By definition, reinforced plastics are combinations of polymer resins and reinforcing fibers, including short fibers, cut fibers, chopped fibers, and fabric reinforcement (Osmani and Asokan, 2010; Osmani and Pappu, 2010; Kamaruddin *et al.*, 2017). Generally, FRP composites are known to have increased corrosion resistance, increase strength, improved fire resistance, and are able to form complex shapes, have lighter weight, and ease design due to its functional integration. They can also be made of carbon, glass or fiber, while their matrix can be either thermoset matrix or thermoplastic matrix. Leblanc *et al.* (2015) investigated the recyclability of fiber reinforced thermoplastic composites that are randomly oriented. The authors opined that ROS that have high fiber volume fractions (> 50%) have very high formability and attractive mechanical properties, when compared with long or continuous fiber composites. Thus, these properties help to increase the strength of recycled FRP composites as they have good

Fig. 2 Wastes from an automotive scrap. Courtesy: Stella Job.

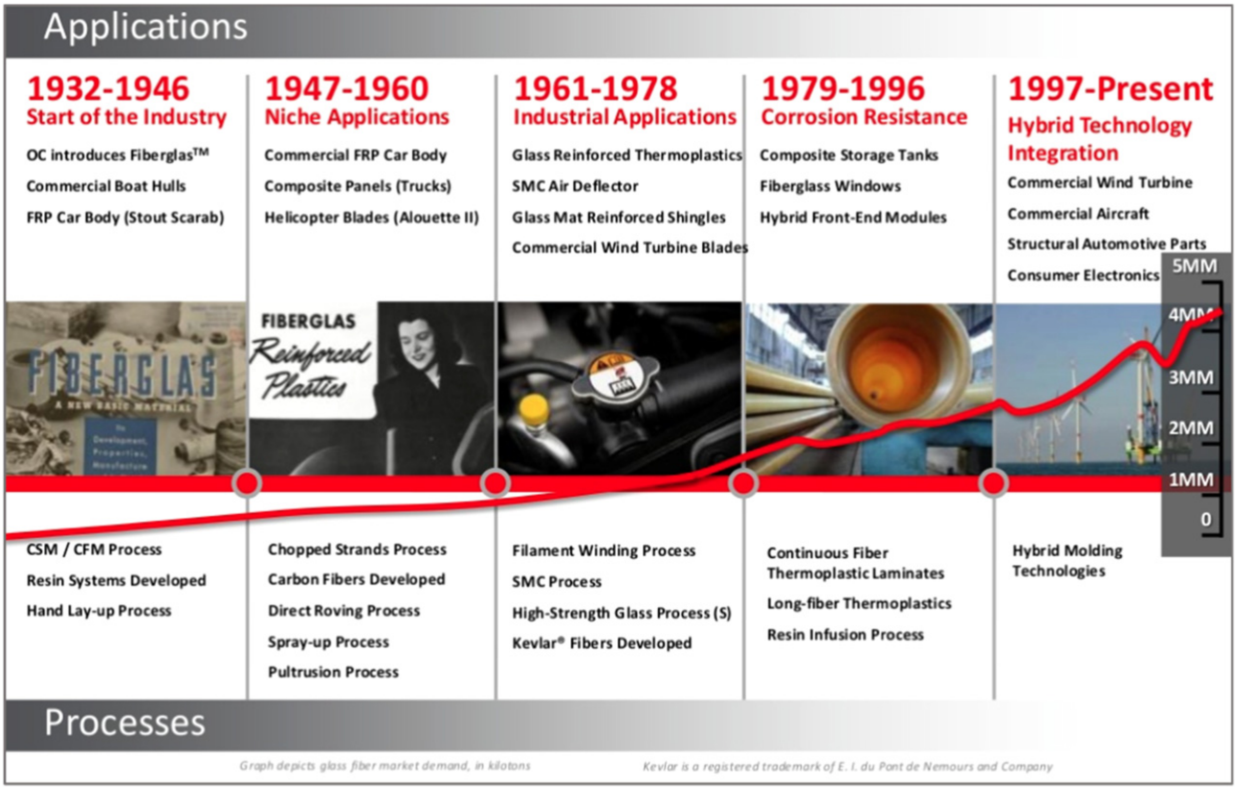

Fig. 3 Timeline on composite applications and processes. Courtesy: Hartman, D., 2014. Advances in reinforcement materials (glass fiber materials). In: Proceedings of the Composites and Advanced Materials Expo (CAMX), October 13-16, 2014, pp. 1–25. Orlando, USA: CAMX.

capabilities in compression molding of complex parts of smaller sizes. Thus, this allows the ease of adjusting the parameters such as tight diameter, wall thickness, and rib. According to Lauzé (2001), the best recycling technique available today is the thermal process called conventional pyrolysis, since it generates recyclate of excellent quality while being contamination tolerant, highly energy saving, and thus the best option economically. This is quite debatable as the thermal process takes down the fiber molecules and disorientates them. Today, there is no or a restricted deposit (or very few) of carbon fibers from aircraft, at the EOL,

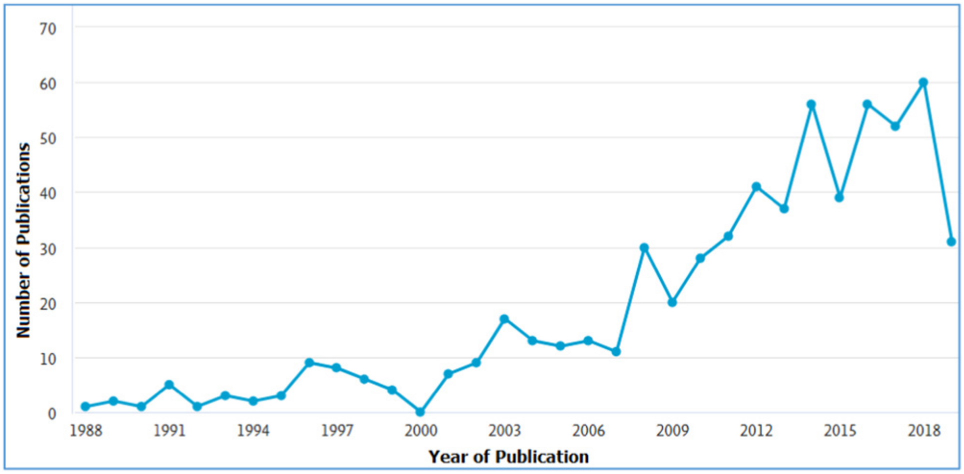

Fig. 4 Number of scientific publications on fiber reinforced polymer composite recycling. Data obtained from SCOPUS database (accessed on 12.06.19).

as aircraft that integrate such materials are only being constructed at the point and will later become waste (Prinçaud *et al.*, 2014). Connora argues that resin and fiber (e.g., carbon, glass, Kevlar) can be retrieved from epoxy composite goods produced using its Recyclamine hardeners using a "patented, low-energy recycling method." The parts that are recovered from the epoxy and fiber can be sold, reused, redirected, or repurposed.

"X-Ray" on Recycling Fibre Reinforced Polymer Composites

From a thorough search on peer-reviewed literature on FRP composite recycling was carried out. Major article databases and search engines include Google Scholar, Science Direct, Web of Knowledge, and Scopus. The focus was on publications within the recent years with current developments. Results obtained from Scopus are presented in **Fig. 4**. It shows that there is an increase in research on recycling of composite materials, which rose from 2000 to the current date. In the context of this encyclopedia, we will examine some issues on recycling fiber reinforced polymer (rFRP) composites based on certain popular questions on the subject. These questions will be answered within the body of this article: Can FRP composites be recycled? Why is it difficult to recycle many composite materials like FRP composites? Can epoxy composites be made 100% recyclable? What is the difference between FRP and fiberglass? How can plastics reinforced with carbon fiber be recycled? Is it more environmentally sustainable recycling than producing virgin carbon fibers? Can carbon fibers recycled from aircraft (or from aircraft and automotive waste) mechanically replace most of the carbon fibers presently used in the industrial, recreational, and sports sectors, given that recycling can be accomplished cost-effectively and that recycled fibers will not be used by the aeronautical sector? What is the role of FRP composites in sustainability? What are the economic and environmental benefits of reinforced FRP composites? What are the waste volumes of FRP composites that can be recycled? What are the best methods to collect and recycle these FRP composites? Are there safety and health concerns in saving cost during the recycling of FRP composites? What are the major applications of recycled FRP composites? What are the major issues facing the science of recycled FRP composites?

Global Market on Composite Materials

The increase in the use of composites – particularly recycled composites – has led to more developments in the application of recycled FRP composites. The market for composite products globally is anticipated to achieve an estimated \$40.2 billion by 2024 and from 2019 to 2024 it is anticipated to expand at a compound annual growth rate (CAGR) of 3.3%. It is anticipated that the worldwide market for end product composites will reach an estimated \$114.7 billion by 2024 (Wood, 2019). There is an increase in the projection for composite market globally including recycled FRP composites. According to another report, the estimated projection is from \$72.58 billion in 2016 to \$115.43 billion by 2022, at a CAGR of 8.13% from the year 2017 to the year 2022 (Markets and Markets, 2017). This implies that application of different sectors is increasing by harnessing the properties of recycled composites. These properties include increased building capacity, reduced weight, increased sustainability, and increased strength capability. This projection stated was from a survey carried out with most of the top leading composite companies: Victrex (UK), Gurit (Switzerland), SGL Group (Germany), Solvay (Belgium), Hexcel Corporation (U.S.), Owens Corning (U.S.), Toray Industries, Inc. (Japan), Teijin Limited (Japan), etc., against that of different secondary sources, such as such as Factiva, Hoovers, Manta, etc. **Fig. 5** shows the use of composites in the following sectors: Automobiles, aerospace, defense, renewable energy, transportation, marine (pipes, risers, and tanks); construction & infrastructure industries. In an earlier publication, the global market forecast was to grow to £75 billion by the year 2015 (Hinton, 2017).

Fig. 5 UK market opportunity for composites. Reproduced from Hinton, M., 2017. Bristol composites institute launch and ACCIS 10th anniversary conference. In: Proceedings of the ACCIS 10th Anniversary Conference. Bristol, UK: Bristol University. Available at: http://www.bris.ac.uk/media-library/sites/composites/documents/Bristol Composites Inst Launch 151117v4.pdf.

Table 1 US fiber reinforced polymer composites demand (million pounds)

Items	*Year*			*% Annual growth*	
	2007	*2012*	*2017*	*2007–2012*	*2012–2017*
FRP composite demand	3586	3455	4345	–0.7	4.7
Motor vehicles	864	1025	1380	3.5	6.1
Construction	1071	890	1235	–3.6	6.8
Electrical & electronic	502	550	550	1.8	–
Consumer durables	418	360	405	–2.9	2.4
Others	731	630	775	–2.9	4.2

Abbreviation: FRP, fibre reinforced polymer.
Courtesy: Freedonia, 2017. Fiber Reinforced Plastic Composites Market by Fiber, Product and Market in the US. thirteenth ed., Cleveland: The Freedonia Group. Available at: https://www.freedoniagroup.com/Fiber-reinforced-Plastic-Composites-Market-In-The-Us.html.

However, there is a global challenge to bring down greenhouse gas emissions, reduce dependence on fossil fuels, and increase the use of renewable materials. To this end there is a challenge with using composites, considering that EOL management of composites, particularly the disposal and recycling pathways have not been extensively uncovered. According to the Composites Industry Market report, around 1.141 million tons of composite materials for GFRP were produced in Europe in 2018 (Witten *et al.*, 2018). In the United States, demand for FRP was expected to increase to nearly 2 million tons in 2017 as shown in **Table 1** (Holmes, 2019). In another report by Freedonia (2017), US demand for composites of FRP is projected to increase by 4.7% annually to 4.3 billion pounds in 2017, estimated at nearly $23 billion, and will increase to 3.9 billion pounds in 2020 at an annual rate of 3.1%. Presently, the demand finally has recovered from the mild decreases encountered during the recession-impacted era 2007–2012, when possibilities were limited by a sharp decline in building activity, decreased output of motor vehicles, and decline in production of FRP boats, yachts, and recreational small ships. **Fig. 5** shows the UK market opportunity as potentially having growth. In composite part production, it potentially increased. According to a study by Lucintel LLC, there is an increase in the global market for composite products and this is expected to reach $96 billion by the year 2020, following an increase of 40% as seen from the year 2014 as shown in **Figs. 6** and **7**. The case study of the UK Composite Market shows that there are opportunities available in UK for composites, particularly the recycled FRP composites.

In another study, it was revealed that the annual output of GFRP was approximately 55,000 t in the United Kingdom alone, with an anticipated annual manufacturing increase of 10% in 2010 (Yazdanbakhsh and Bank, 2014). Most of the production and

EOL waste in the UK is landfilled, and up to 90% of the GFRP waste is landfilled (Brown *et al.*, 2018; Osmani and Asokan, 2010; Yazdanbakhsh and Bank, 2014). Different researches have been carried out using recycled composites and cement. In an attempt to improve quality of building materials, different composite and recycled debris have been introduced into concrete (Li and Kaewunruen, 2019; Ge *et al.*, 2011; Yin *et al.*, 2013).

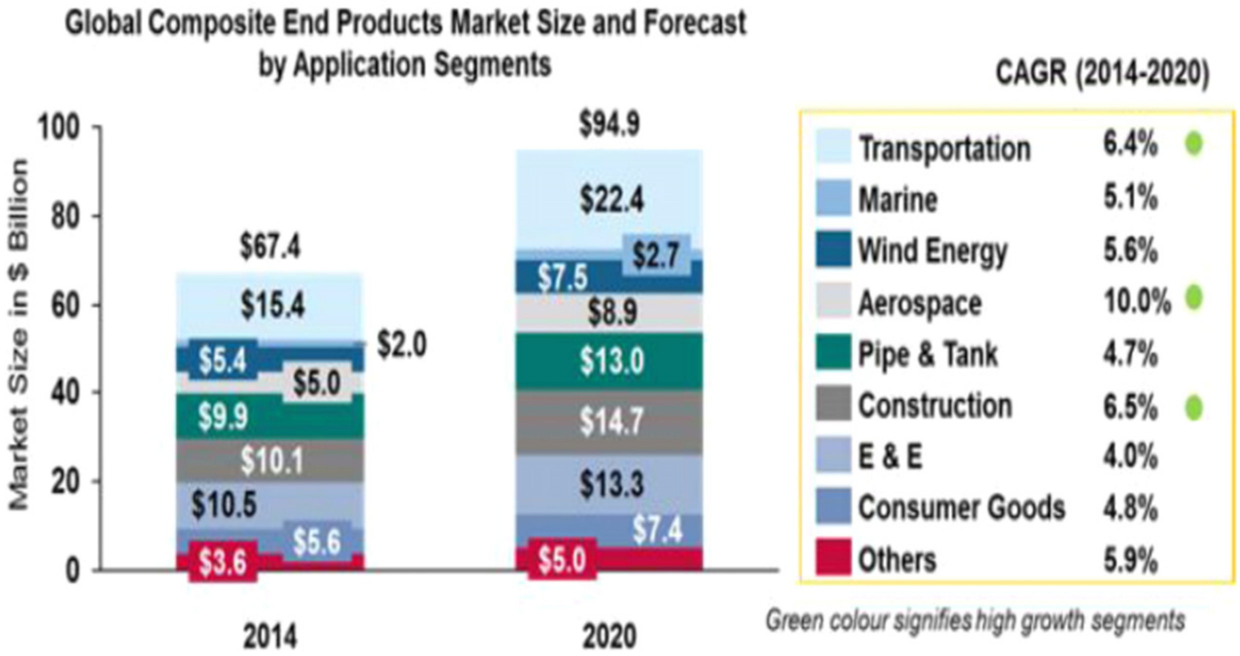

Fig. 6 Global composite end products market size and forecast by application segments. Courtesy of Lucintel LLC.

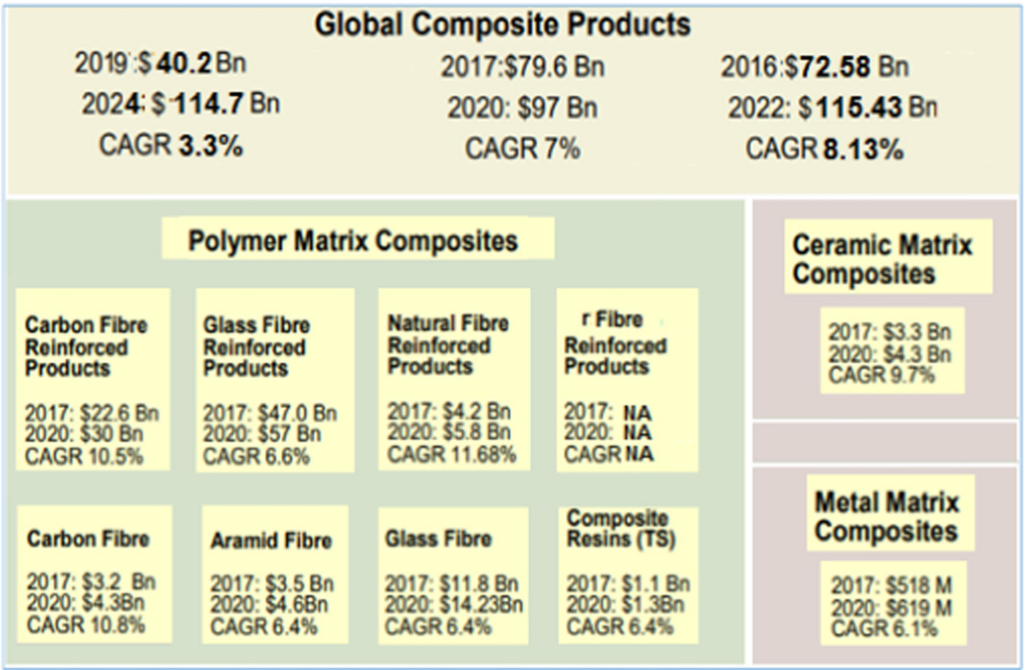

Fig. 7 Global composite products. *Source*: Markets and Markets, 2017. Composites Market by Fiber Type (Glass, Carbon), Resin Type (Thermoset, Thermoplastic), Manufacturing Process (Layup, Filament Winding, Pultrusion), Application (Transportation, Aerospace & Defense, Wind Energy), Region – Global Forecast to 2022, UK. Available at: https://www.marketsandmarkets.com/Market-Reports/composite-market-200051282.html.

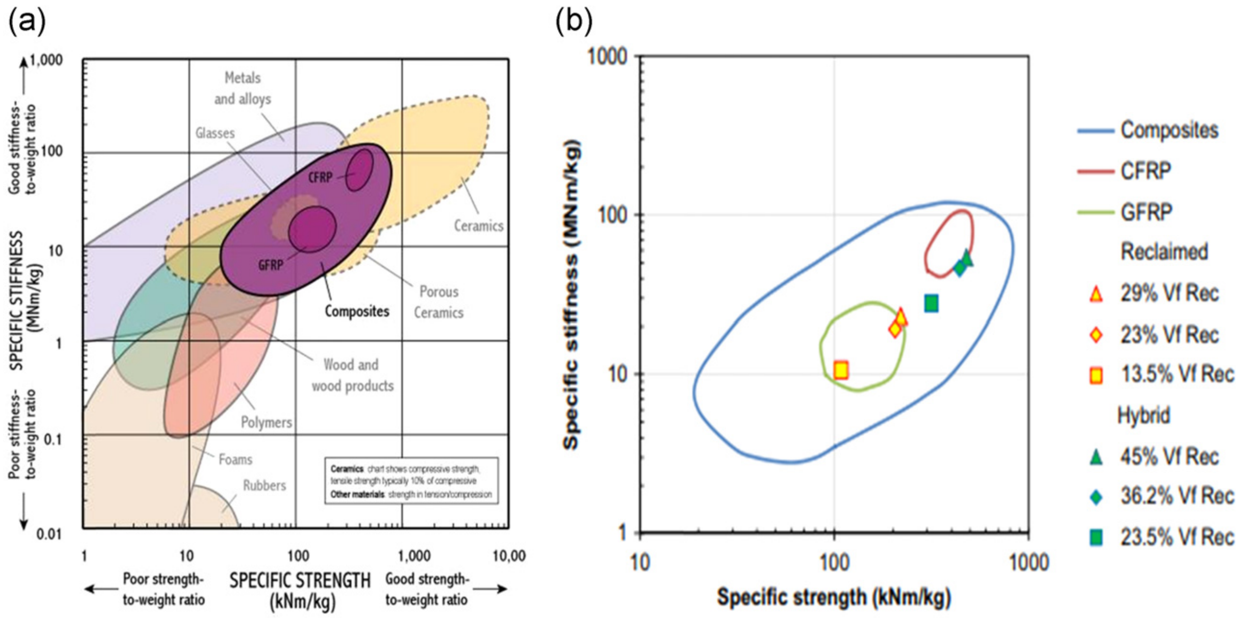

Fig. 8 Specific stiffness and specific strength of fiber reinforced polymer composites against: (a) other materials (b) reclaimed and hybrid carbon fiber laminates. Courtesy: (a) Ashby, M., Shercliff, H., Cebon, D., 2007. Materials: Engineering, Science, Processing and Design. first ed., Oxford: Butterworth Heinemann. (b) Kratz, J., Low, Y.S., Fox, B., 2017. Resource-friendly carbon fiber composites: Combining production waste with virgin feedstock. Advanced Manufacturing: Polymer and Composites Science 3 (4) 121–129. doi:10.1080/20550340.2017.1379257. University of Cambridge, 2011. Specific stiffness – Specific strength. University of Cambridge – Materials Group Interactive Charts, pp. 1–2. Available at: http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/spec-spec/basic.html (accessed 08.06.19).

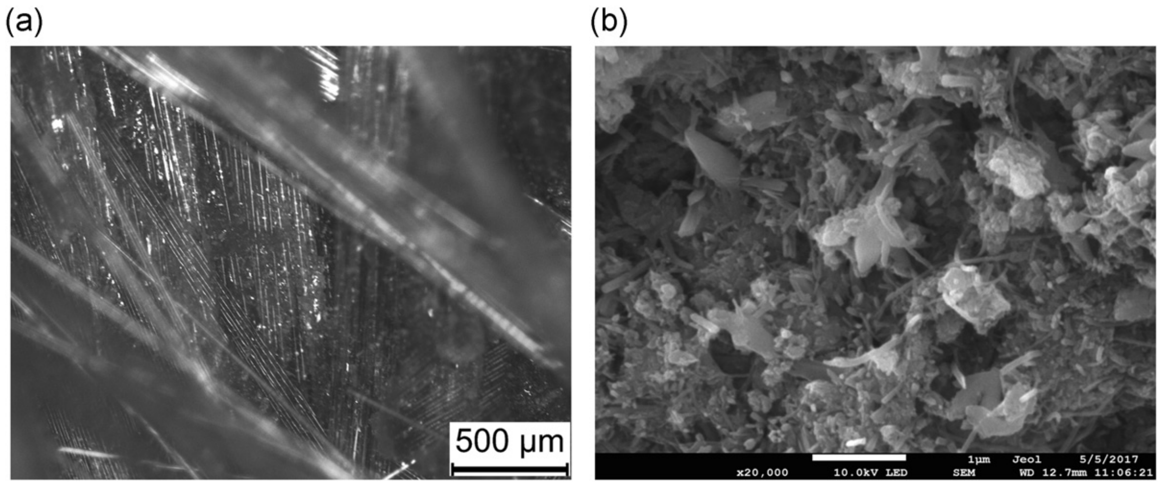

Fig. 9 Images of fibers of composites taken under scanning electron microscope, for (a) glass fiber specimen, and (b) composite using beetroot on cement.

Characteristics of Recycled Fibre Reinforced Polymer Composites

The characteristic behavior of recycled FRP composites has shown that the main properties of composites are exhibited, as in **Fig. 7**. Further studies on the and behavior under increasing temperature, and the wave scattering properties as carried out by Yin *et al.* (2013). Images of composite fibers and composite specimens with beetroot taken under the SEM show the characterization of the fibers (Hasan *et al.*, 2019) and could be used in bioengineering the recycled composites and biocomposites, as presented in **Figs. 8** and **9**.

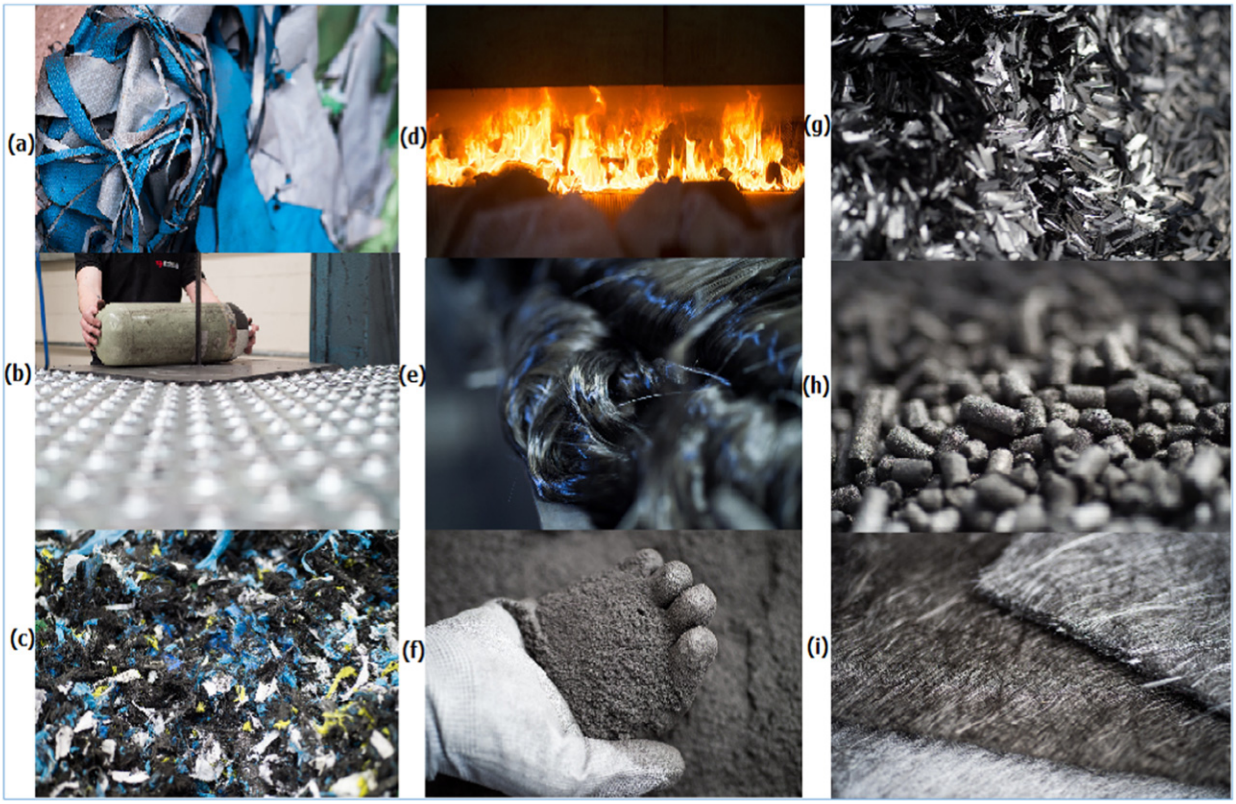

Fig. 10 Steps (a)–(i) involved in the carbon fiber recycling process. Courtesy: ELG Carbon Fibre, 2017. Why Recycle Steel? Coseley, West Midlands, UK. Available at: https://www.recycle-more.co.uk/why-recycle-/why-recycle-steel-.

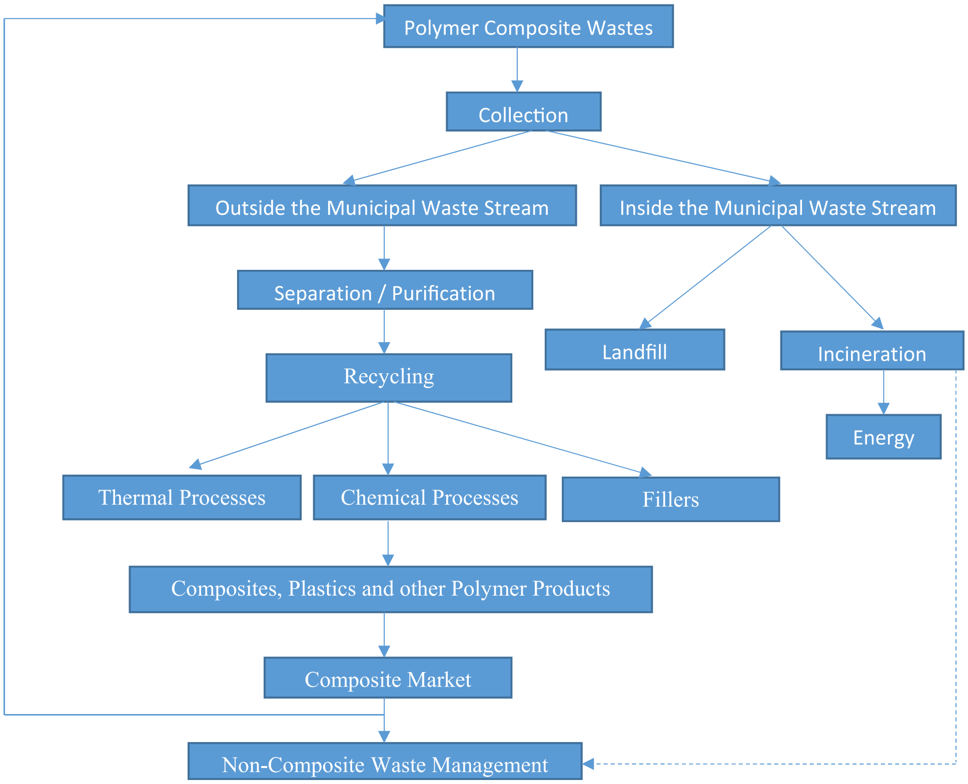

Fig. 11 Flow chart of a polymer composite waste management process.

Review on Recycling Pathways and Technologies

Due to the advantages of FRP recycling, it is pertinent to identify recycling pathways for recycling composites. Fig. 10 is used to show the steps that are undertaken in carbon fiber recycling. From collection to combustion with the resin all involves some energy and depends on the type of recycling process considered. A flow chart of a polymer composite waste management process is presented in Fig. 11. It was developed using the concept by Rebeiz and Craft (1995) on plastic waste management. Energy can actually be saved through recycling. Different researches on the recycling pathways have been carried out on FRP composites (Yang *et al.*, 2012; Vo Dong *et al.*, 2015, 2018), however the crunch of it requires funding support, collaborations, and monetization of the recycling concepts.

Issues on Commercializing Recycled Fibre Reinforced Polymer

There have been different projects carried out globally on recycling FRP. Reports have also been presented on different viable options and techniques used in recycling, reclaiming, and reusing the recycled fiber reinforced carbon fibers in different products. Despite these breakthroughs, there are challenges facing these rFRP composites. Bringing both these recycling processes and the recycled products to the composite market has been difficult. Fig. 12 shows the economic advantage of recycled composites from materials to products. During the economic recession in 2009, there was a big hit on many manufacturers, particularly in the composites industry. Due to the economic downturn that occurred, most of these manufacturers now try to keep their companies by just simply having business survival and less on sustainability. However, over these past 10 years, there has been a shift of interest to sustainability and the use of recycled materials in the composites industry and other industries. There is also an increase into the growth phase and the attention to recycling has been heated up.

To overcome these challenges, there is need to carry out more extensive tests that are economically costly but will assist in the development of standards for these products to be qualified and accepted as products with the recycled contents. To this end, there are still issues with the waste volumes generated per location, management of the waste volume to ensure there is constant supply of waste, provenance, and the amount of money that these waste will cost and the debate about companies' willingness to pay for these wastes. They are other issues with health and safety of rFRP composites, the most effective waste management system to adopt for recycled fiber reinforced composites, the requirements for waste management licenses, having a comprehensive understanding of the requirements for the health and safety of rFRP composites and the relate new processes involved in the recycling, the time for adoption of these new processes in the composites industry. Despite that all these are time consuming, it is important to get the required investment needed or the right niche company that can use the raw materials and obtain good finished products, although the recycled finished product may have low profit marginally (Job *et al.*, 2016). There is also the issue of not having enough trained personnel on recycling of composites, as not many composites manufacturers are keen on recycled composites.

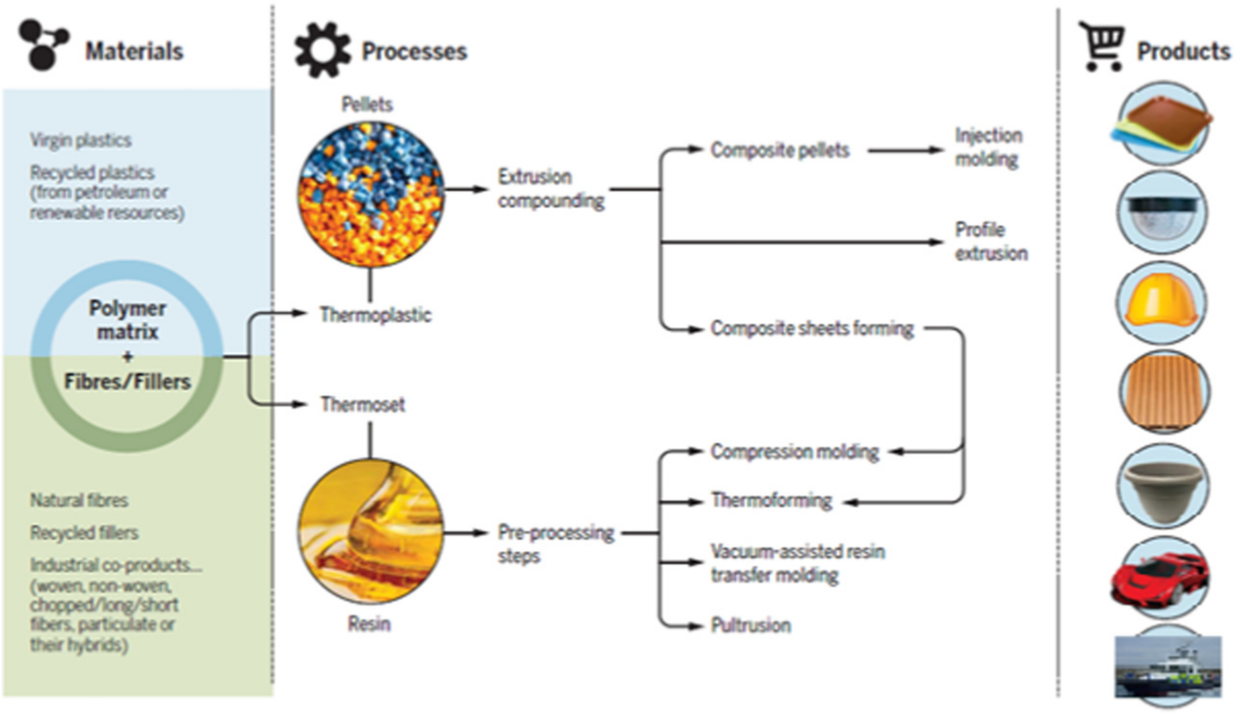

Fig. 12 Economic advantage of recycled composites from materials to products.

GFRP are seen to be recycled in cement kilns, reclaimed from landfills and mechanically recycled. The FRP wastes have economic value in energy recovery. Normally, energy is recovered from the resin, which is the mineral feedstock for cement (from the fibers and fillers). As a result of them been reinforcing fibers, they also determine the magnitude of reclamation or recycling of that will be achieved. To that note, different disposal options will have to be considered. The major disposal routes for reinforced FRP composites are landfills, mechanical recycling, cement kilns, and EfW. With respect to the EU Waste Framework Directive, it is pertinent to state that not all disposal options currently meet the requirements. The EfW incinerator bottom ash does not meet the requirements of recycling with respect to this Directive. However, both the cement kiln and the EfW are considered recycling routes that are also used in energy recovery, because the mineral content can be recycled into clinker and aggregate, respectively (Brown *et al.*, 2018). The cost of disposing the FRP wastes using landfills, cement kilns, and EfW are comparatively around the rate of £140 per t, because the waste management businesses almost have the same charge for the composites wastes, without regard to the route of disposal. In the UK, the capacity of EfW is increasing currently. With respect to this increase, the cost charged on EfW should potentially reduce as older plants have already made returns on investments and covered the capitals costs, maintenance costs, and running costs.

On the other hand, there has also been an increase in the commercialization of recycled CFRP. This increase in progression is actually in an order of magnitude been of more value than glass fiber. In addition, some large aerospace primes encourage carbon fiber recycling initiatives while an equivalent encouragement for GFRP has never been attained. In the UK, carbon fiber recycling using pyrolysis processes was first established by Milled Carbon in the West Midlands, now known as ELG Carbon Fiber since it was purchased by ELG Haniel in 2011. Currently, carbon fiber recycling based on pyrolysis is active in USA, Germany, Italy, and Japan. In the UK, recycling of glass reinforced polymer (GRP) composites is done at a very low scale, which is basically in-house activity production volume (Job *et al.*, 2016). In January 2019, ELG and Boeing formed the first material supply relationship between a carbon fiber recycler and major aircraft original equipment manufacturer. This kind of collaboration means that recycled FRP composites can be deployed in the aviation industry.

Issues on Supply Chain of Recycled Fibre Reinforced Polymer

The global demand for carbon fiber is estimated to more than double to be between 150,000 t and 180,000 t by 2020. With the manufacturing techniques used today, there is approximately 30% of the overall demand for carbon fiber becoming waste both during the conversion phase and component manufacturing phase of the recyclates. The remaining fiber is added into the finished parts, which will be disposed of later at the EOL. With the increase in the application of CFRP composites in components with shorter service lives, the EOL will range between 2 and 40 years, depending on the frequency of its usage (ELG Carbon Fibre,

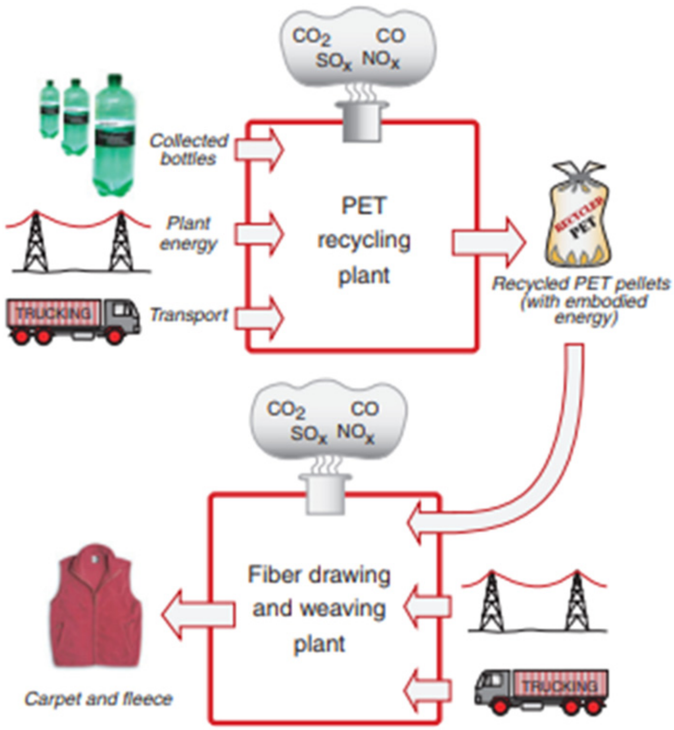

Fig. 13 Input–output sketch for the recycling process used to recover polyethylene terephthalate. *Source*: Ashby, M., Shercliff, H., Cebon, D., 2007. Materials: Engineering, Science, Processing and Design. first ed., Oxford: Butterworth Heinemann.

2017). Fig. 13 shows a simplified supply chain diagram for recovery process for plastics and composites, with a case study of PET from plastics. The input–output sketch for the recycling process is used to recover PET, for lower-grade products such as fleece.

The market drivers that determine the best disposal solutions of wastes from FRP composites are the market forces of demand and supply, the increasing cost of landfills, the increase in awareness on circular economy thinking, the markets for recycled products, government policies, and legislations on recycled FRP composites. However, the most important driver on commercial viability of rFRP composites is the breaching of new markets (Brown *et al.*, 2018). With the increase in more composite recyclates, there is also an effect on the existing composite manufacturers, and their sources of raw materials. Currently, automobile manufacturers like BMW and VW are also researching on increasing the use of composites on their cars and also using recycled composites and biocomposites (Das *et al.*, 2016; Bharath and Basavarajappa, 2016; Mohanty *et al.*, 2018). This will also increase the economic viability of rFRP composites in the automobile industry. There is need to create more circular recycling on FRP composites, create higher value recycling routes to explore other areas of the market, and increate more economic exchanges and businesses both within the composites industry and with other industries such as the mainstream aviation industry, automobile industry and construction industry.

There are four main drivers that influence the supply chain of recycling carbon fibers. They are the affordability, security and legislative policies, and environmental responsibility. The economic conversion of both the raw wastes from manufacturing and EOL components into different recycled carbon fiber shapes, forms and component designs is very important. This material product, can then be used technically for different applications, making these lightweight carbon fiber composites less expensive. With respect to the security of the supply chain, the application of recycled carbon fibers controls any supply side capacity risk by bringing in high tonnes of carbon fiber from existing production capacity, thus buffing it up. Legislation plays a very great role, as these policies are what guide the manufacturers and the end-users about the product and its circulation in the market. The need for environmental responsibility cannot be overemphasized. In the automotive industry, EU legislation requires 85% of a vehicle to be recyclable. Carbon fiber waste can be recovered and converted to new products using less than 10% off the energy required to produce the original carbon fiber, fulfilling legislative and sustainability targets (ELG Carbon Fibre, 2017).

Issues on Environmental Aspects of Recycled Fibre Reinforced Polymer

Composite wastes could be an environmental concern too, as well as reinforced FRP composites. They could be fine ground into powder form or solid form in product or sheet material form. Composite wastes are also generated in factories, homes, schools, etc., and in different forms as shown in Fig. 14 (a)–(c). Generally, there are environmental aspects too that should be looked at in recycling of FRP composites. Just like the economic aspects of rFRP composites, the environmental aspects are also driven by same factors that affect the breaching of new markets using viable recycling routes. Environmental aspects of these reinforced FRP composites are dominated by the replaced content of the recyclates, particularly the mechanical strength from the recycling process of the virgin fiber and combusting the resin. This process contributes to energy generation and there is a transformation of energy from combustion using coal as fuel in the process.

In a study carried out in line with ISO 14040 (ISO, 2006) by Brown *et al.* (2018), three case studies were analyzed to represent the typical GFRP composite materials. They are the SMC, the continuous composite sheet, and the infused composite materials. The SMC as is often used in automobile and construction applications, assumed 30%/23%/47% resin/glass fiber/filler. The continuous sheet, as used in rooflights, or hand lay GFRP, is used for a large number of applications and is the largest process by

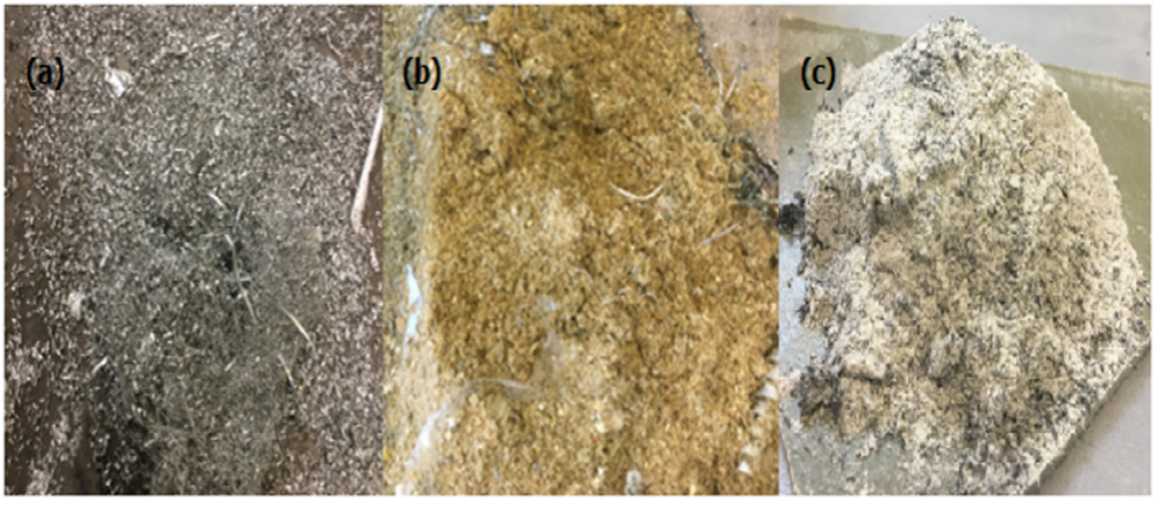

Fig. 14 Different forms of wastes for recycling (a) metal waste, (b) wood waste, (c) composite waste.

volume, with comparable constituents, assumed 65% resin, 35% glass fiber (CS/HL). The infused composite materials uses infusion in producing products like wind turbine blades, work boats, and leisure boats, assumed 40% resin, 60% glass fiber.

The environmental aspects of processing reinforced FRP composites are dominated by energy demand. Source of energy is the key factor considered in any manufacturing and recycling processes. In most cases, the main source of power for the energy usage is electricity. During these processes, this takes over greater percentage of the energy footprint. Reduction of energy demand is key in improving sustainability as well as the reduction of collateral damage caused by excessive energy put in by the system.

Issues on Energy Demand Aspects of Recycled Fibre Reinforced Polymer

According to Brown *et al.* (2018), the energy demand in a mechanical recycling process, for instance, is used to hammer the mill machine or to power the motor of the granulator. However, the power requirement is subject to the type of machinery. Any decrease in the energy demand will be beneficial in improving its sustainability. It can also be beneficial in decreasing the collateral damage due to excessive energy input. From **Fig. 15**, the composite recycling processes and the corresponding specific energy demand is summarized, as carried out by Composites UK, however there is still need to clarify the issue of the nonequality between the recycling processes with respect to the energy demand. Some studies in the EXHUME project reported the energy demand to be around 0.17–0.27 MJ/kg for the

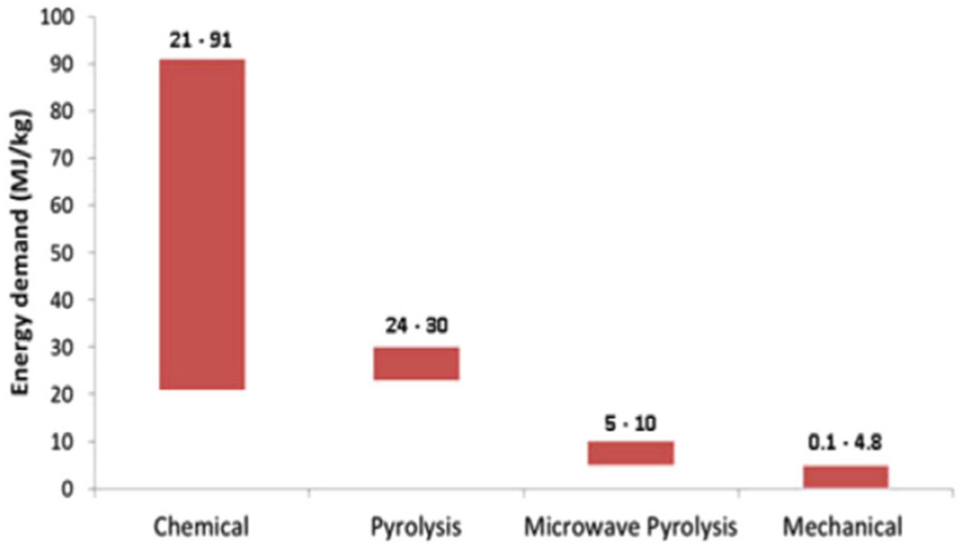

Fig. 15 Energy demand in composite recycling methods. Courtesy: Composites UK.

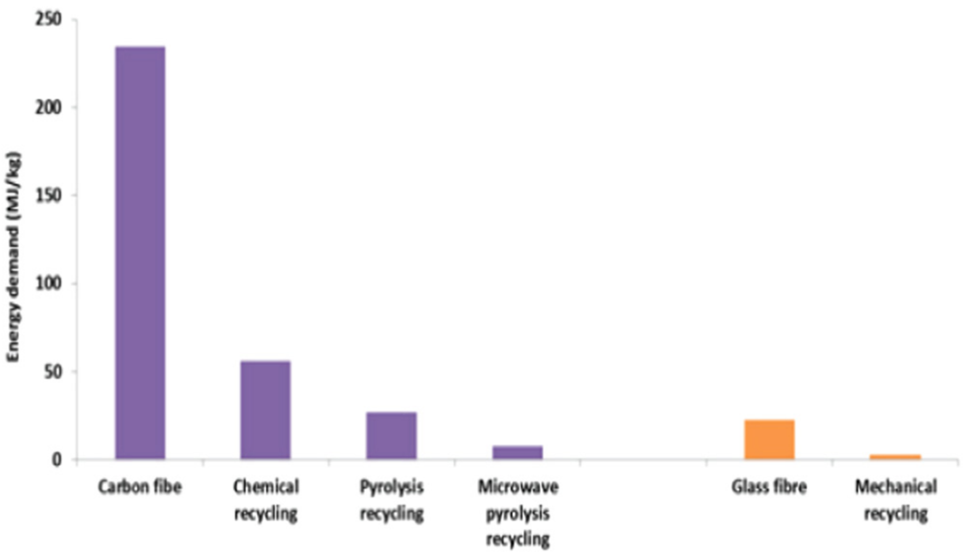

Fig. 16 Average comparison on embodied energy of fiber production and potential recycling processes. Courtesy: Composites UK.

Wittmann ML2201 granulator running at maximum capacity of 150 kg/h and about 0.35 MJ/kg for the Wittmann MAS1 granulator (at 30 kg/h). The Eco-Wolf grinder Model GM-2411-50 and IIT Ltd M300 machine respectively have the energy demand of 0.14 MJ/kg (800 kg/h) and 4.75 MJ/kg (around 29 kg/h). They also reported that prerecycling and postrecycling stages, for instance, shredding and sieving, are not as energy intensive as the actual recycling processes. It is noteworthy to state that the specific energy demand for each of the mechanical recycling processes is dependent on the process throughput with the most minimal lowest value when operating at its maximum machine capacity. During this stage of processing, the basic power requirement of the machine drive motors can be maximized with care thereby subsequently reducing the specific energy demand.

Fig. 17 Level crossing panels including recycled glass reinforced polymer and phenolic from car parts. Courtesy: Reprocover.

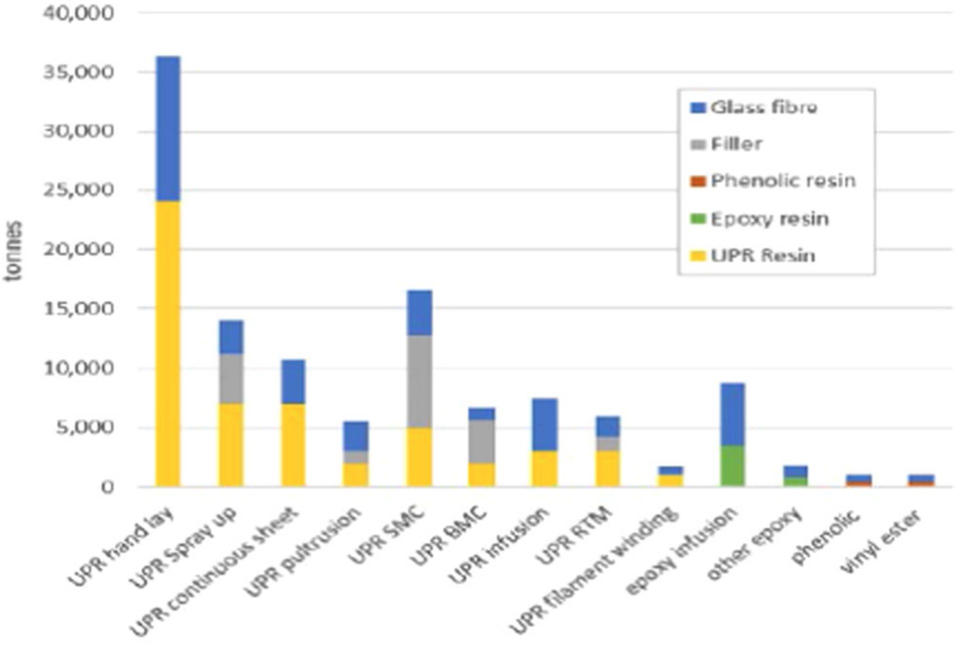

Fig. 18 Estimated quantities of glass fibre reinforced polymer produced in the UK by processes and their quantities. Reproduced from Brown, S., Forsyth, M., Job, S., *et al*., 2018. FRP Circular Economy Study: Industry Summary – August 2018, UK. Available at: https://compositesuk.co.uk/system/files/documents/FRP CE Report Final_0.pdf.

Table 2 UK glass fibre reinforced polymer estimated typical constituents and volumes by resin and process

	Total	*UPR hand lay*	*UPR Spray up*	*UPR continuous sheet*	*UPR pultrusion*	*UPR SMC*	*UPR BMC*	*UPR infusion*	*UPR RTM*	*UPR filament winding*	*Epoxy infusion*	*Other epoxy*	*phenolic*[a]	*Vinyl ester*[a]
% resin (including combustible additives)		66	50	65	36	30	30	40	50	60	40	44	50	50
% glass fiber		34	20	35	46	23	15	60	30	40	60	56	50	50
% filler (noncombustible)		0	30	0	18	47	55	0	20	0	0	0	0	0
Resin supplied to this process (t)	59,300	24,000	7000	7000	2000[b]	5000	2000	3000	3000	1000	3500[c]	800	500	500
GFRP composite produced (t)	117,757	36,364	14,000	10,769	5556	16,667	6667	7500	6000	1667	8750	1818	1000	1000
Process waste (%)		6	3	12	7	4	4	3	3	3	3	10	5	5
Process waste (t)	6216	2182	420	1292	389	667	267	225	180	50	263	182	50	50
Calorific values (MJ/kg)		20	15	20	11	9	9	12	15	18	12	13	15	15
Typical fiber length (mm)		50	50	50	Long	25	25	Long	Long	Long	Long	Long	Varies	Varies
% containing halogenated FRs		5	5	80	70	1	1	5	5	0				
Factor to EOL		0.5	0.5	0.9	0.8	0.8	1.5[d]	0.6	0.6	0.4	0.2	0.6	0.7	0.7
EOL products	75,659	18,182	7000	9692	4444	13,333	10,000	4500	3600	667	1750	1091	700	700

[a]For phenolic and vinyl ester resins, a nominal figure of 500 t resin has been assumed in each case, with 50/50 fiber and resin, as volumes are relatively small.

[b]Pultrusion value allows for imported pultrusions used in UK manufacturing.

[c]70% of the epoxy infusion value is for offshore wind blades, much of which has recently started in manufacturing.

[d]BMC EOL factor increased to allow for imported BMC parts.

Abbreviations: EOL, end of life; FRs, fibre resins; GFRP, glass fibre reinforced polymer; UPR, unsaturated polyester resin.

Note: % resin, fiber, filler are by mass. Blue rows indicated calculated values. The estimated data is anecdotal, based on interviews with experienced industry professionals.

Note: Brown, S., Forsyth, M., Job, S., *et al*., 2018. FRP Circular Economy Study: Industry Summary – August 2018, UK. Available at: https://compositesuk.co.uk/system/files/documents/FRP CE Report Final_0.pdf.

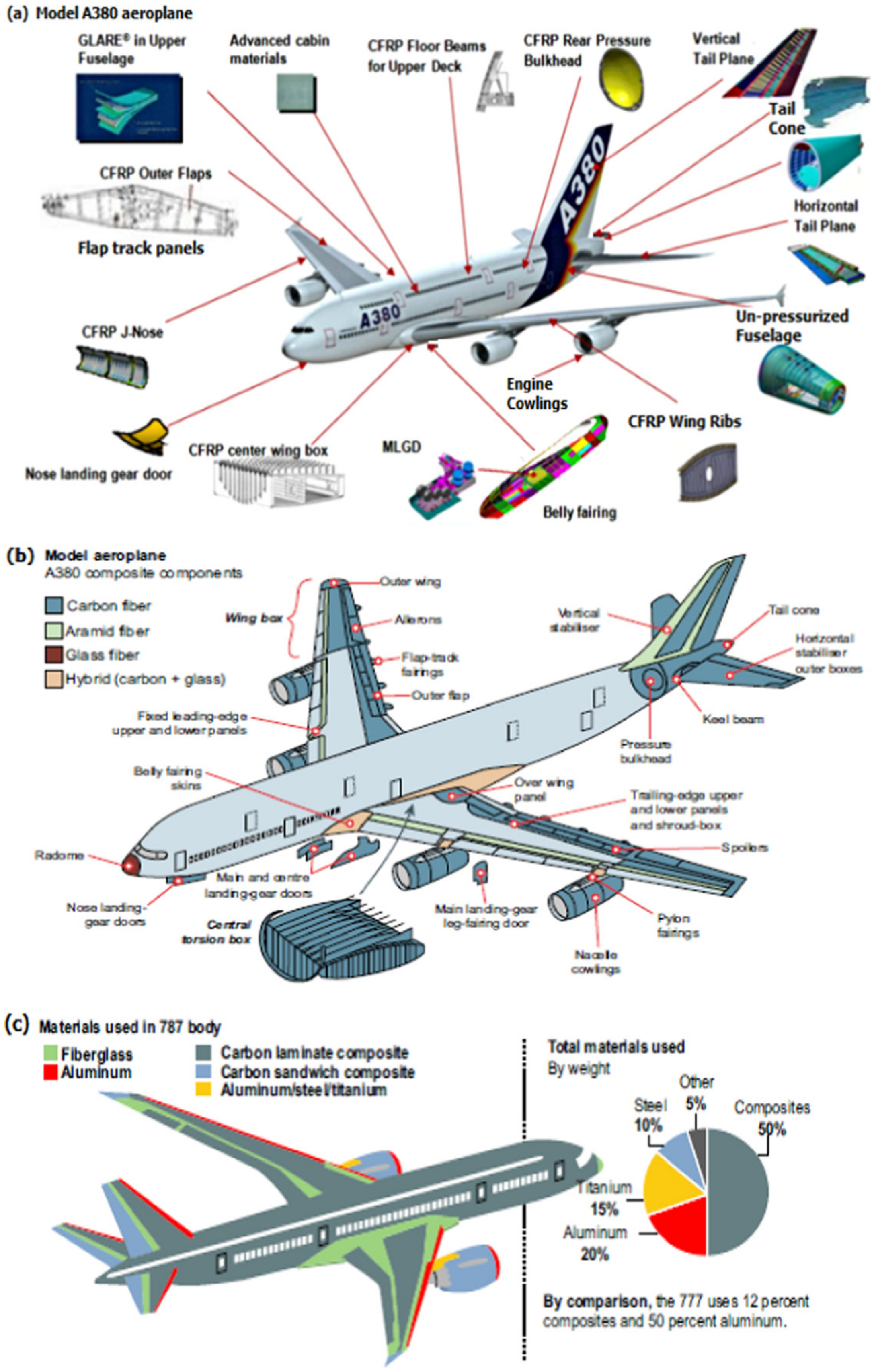

Fig. 19 Application of composites in airplane models (a)–(b) Airbus 380, (c) Boeing 787 "Dreamliner," by Airbus Industry and Boeing Industry respectively.

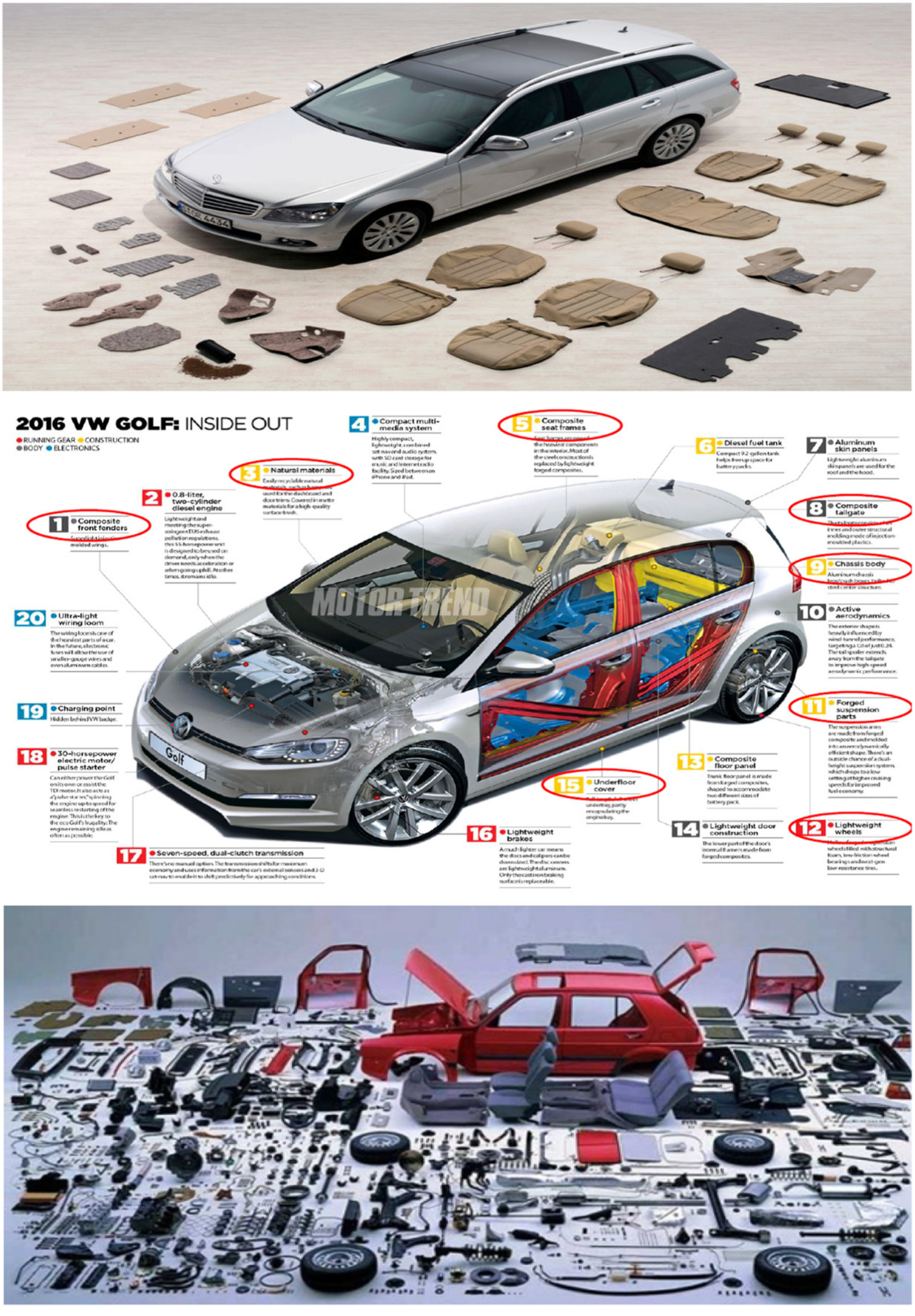

Fig. 20 Application of composites materials and other materials in VW Golf cars. Courtesy: Daimler and Motor Trend.

Today, pyrolysis and chemical processes exist commercially, as large scale recycling processes available for carbon fiber composites. From a literature review carried out by Composites UK, the average energy demand for a conventional pyrolysis process reported to be within the range of 23–30 MJ/kg but no information on processing scale is included. Microwave pyrolysis is reported as more energy efficient compared with the conventional pyrolysis due to fast and selective heating – With estimated energy demand about 5–10 MJ/kg. Also, organic by-products can be retrieved for energy or chemical feedstock from these processes. However, synthesis and refining steps may escalate the process energy demand even further. Hitachi Chemical (Japan), developed a chemical recycling process for epoxy based tennis racquet with energy demand between 63–91 MJ/kg and maximum processing capacity of 17,000 racquets per month. The solvent dissolution and water distillation steps dominated the process energy footprint. A pilot scale chemical recycling process at the University of Birmingham used a mixture of acetone and water to recycle 300 g of RTM6 CFRP plate. The process took around 3.5 h (0.085 kg/h) and had an electricity energy demand (for heating) around 21 MJ/kg. Optimization and upscaling the process will enable higher processing rate and lower specific energy demand. **Fig. 15** shows that the recycling energy demand is relatively lower (10 to 20 times lower) compared with embodied energy of production for virgin glass (13–32 MJ/kg) and carbon (183–286 MJ/kg) fibers. Environmental credits from avoidance of virgin material can be realized through cross sector applications of the recyclate (Brown *et al.*, 2018). An instance is using glass fiber thermoset waste in railway products can avoid production of virgin or new concrete material, by Reprocover as shown in **Fig. 16**. By avoiding production of high embodied energy material (such as fibers or polymer based material), major environmental benefits can be successfully achieved (**Fig. 17**).

End-of-Life Waste of Reinforced Fiber Reinforced Polymer

Wastes generated from the manufacturing of FRP composite and at the EOL. Currently, an estimated 1600 CFRP production waste and about 100 t of CFRP EOL. There are also an estimated 6200 t of GFRP production waste and 75,000 t of GFRP EOL waste is generated yearly in the UK. In a study by Brown *et al.* (2018), the constituent materials were broken down and it was found that at least 11,000 t of E-glass fiber waste comes from the early stages of the supply chain of FRPs. **Fig. 18** and **Table 2** show the constituents and the estimated quantities of GFRP wastes generated in the UK, as recorded in Brown *et al.* (2018).

With the increase in the application of renewable energy, wind turbine blade waste has a high tendency to increase to over 10,000 t per year in 2030, except for challenges in the lifting, relifting, and hoisting of wind farms. In addition, there is the tendency for the value of recycled CFRP that is recycled through sylvolysis and pyrolysis to increase. An example is the simplified

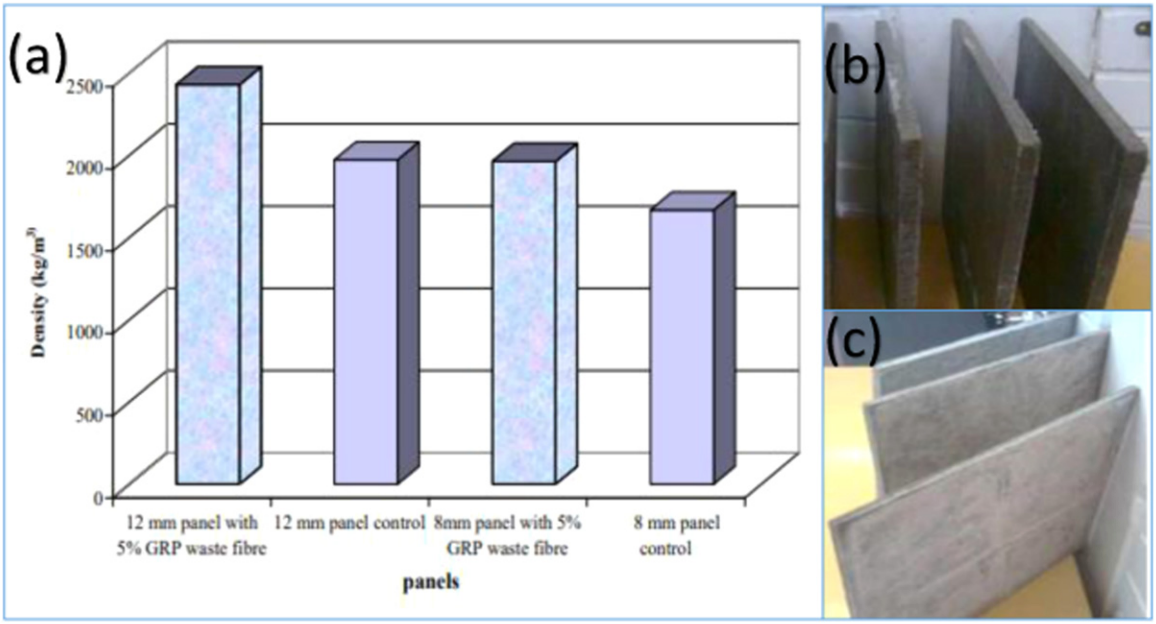

Fig. 21 Glass reinforced polymer waste fiber on architectural cladding panel showing (a) the effect on panel density, (b) 12-mm-thick panels and (c) 8-mm-thick panels. Courtesy: Osmani, M., Asokan, P., 2010. An assessment of the compressive strength of glass reinforced plastic waste filled concrete for potential applications in construction. Concrete Research Letters 1 (1), 1–5. Osmani, M., Pappu, A., 2010. Utilisation of glass reinforced plastic waste in concrete and cement composites. In: Proceedings of the 2nd International Conference on Sustainable Construction Materials and Technologies, pp. 1127–1137. Ancona, Italy. Available at: http://www.claisse.info/2010papers/m45.pdf.

input–output diagram for the recycling of plastics to recover PET, for lower-grade products such as fleece. Thus, this will enable a corresponding increase in the amount of tonnes of aircraft CFRP EOL waste by the year 2030. For FRP wastes, they also have potential application to replace aggregates present in cementitious materials using fillers, but by partially replacing them (Yazdanbakhsh and Bank, 2014).

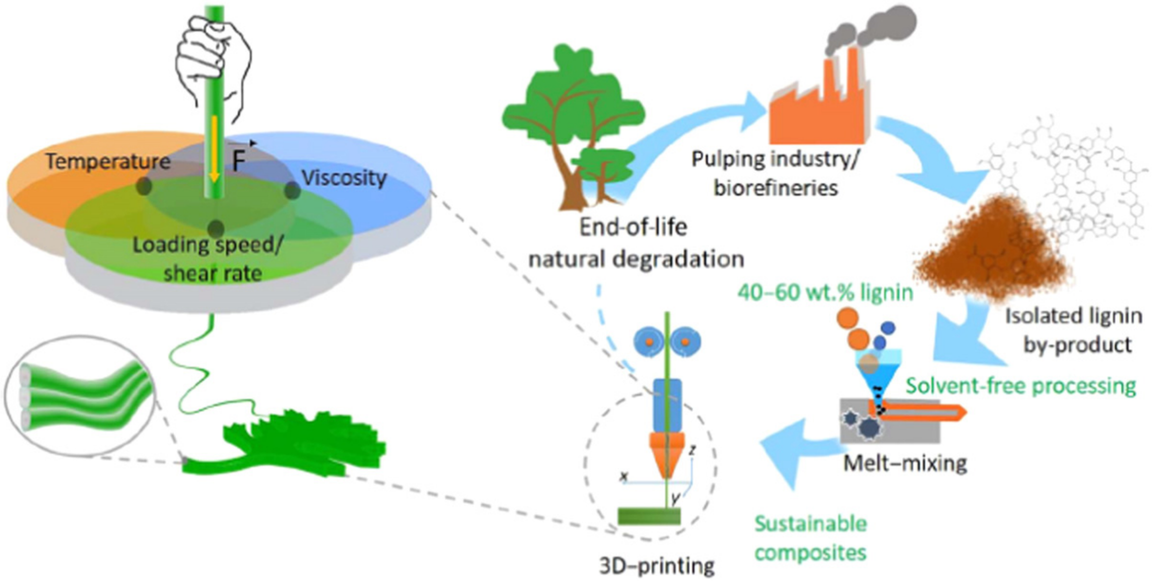

Fig. 22 Printability of renewable composites. *Source*: Nguyen, N.A., Barnes, S.H., Bowland, C.C., *et al.*, 2018. A path for lignin valorization via additive manufacturing of high-performance sustainable composites with enhanced 3D printability. Science Advances, 1–16. Available at: http://advances.sciencemag.org/cgi/content/short/4/12/eaat4967.

Table 3 Biocomposites in automotive, packaging, and other applications

Manufacturer	*Resin*	*Filler*	*Applications*	*Reference*
Ford	PP	Coir fiber	Load floor, package shelf	(Malnati, 2018)
	PP	Cellulose fibers	Console armrests	
	TPE	Powdered coconut shells, shredded tires	Structural guards	
	TPO	Powdered coconut shells, shredded battery cases, magnesium silica fibers	Rear deck lid applique brackets and side-door cladding	
Hyundai	ABS	Cork	Veneer	
Mercedes Benz	Epoxy	Flax/Sisal fiber mats	Interior door panels	(Akampumuza *et al.*, 2017)
Toyota	Bio-nylon 6,10	Short glass fiber	Radiator end tank	
Volkswagen	Polyurethane	Flax/Sisal fiber mats	Door trim panels	
Mitsubishi Motors and Fiat SpA	Bio-PBS	Bamboo fiber	Interior vehicle components	
Toyota – Lexus	Bio-PET	–	Luggage compartment liner	
Club Coffee	Biodegradable polymer blend	Coffee chaff	Coffee pods	(Ackrill, 2018)
Competitive Green Technologies	PP	BioC	Additive/coloring agent	(Bali and Tiessan, 2018)
Zespri	PLA	Kiwifruit skin	Biodegradable spoon-knife	(Graichen *et al.*, 2017)
Scion	Aliphatic polyesters	Grape pomace	Biodegradable net clip for vineyard	
Tecnaro	Natural resins	Lignin and natural fibers	Construction, electronics, furniture, headphones	(Kun and Pukánszky, 2017)

Abbreviations: ABS, acrylonitrile butadiene styrene; PBS, polybutylene succinate; PET, polyethylene terephthalate; PLA, polylactides; PP, polypropylene; TPE, thermoplastic elastomer; TPO, thermoplastic olefin.
Source: Mohanty, A.K., Vivekanandhan, S., Pin, J.-M., Misra, M., 2018. Composites from renewable and sustainable resources: Challenges and innovations. Science 362 (6414), 536–542.

Application of Recycled Fiber Reinforced Polymer Composites

Due to the different environmental conditions for the applications of recycled FRP composites, their manufacturing and testing are slightly different. However, they make up a great number of applications in use today. The current usage of composite materials is highly driven by the aerospace, marine, and automobile industries. As can be seen in **Fig. 19**, the large proportion of the airplanes are made up of composite materials. In **Fig. 20**, composite materials are used in making automobiles. The parts of cars are made up of different materials like metals, alloys, steels, and composites. With the increase in the researches on recycled composites, recycled fiber reinforced composites are next to be seen on airplanes and on cars. There is limitation on the offshore application on large scale for recycled composites. Offshore structures like cylindrical floating production storage and offloading, paired column semisubmersibles (Odijie and Ye, 2015; Odijie, 2016; Odijie *et al.*, 2017a,b; Odijie, 2015), submarine hoses (Amaechi *et al.*, 2019b,c), composite risers (Amaechi *et al.*, 2019a; Amaechi and Ye, 2017; Gillett, 2018), and other structures require extensive design and material checks. Composites have been an enabling technology in the offshore industry, as seen in wind turbine blades and oil wells with deeper risers. However, while the standards allow small boats, leisure boats, and work boats to be built using composites, the International Maritime Organization Safety of Life at Sea regulations restrict the use of composites and greatly prohibit the structural use of composites due to reasons like combustibility (Job, 2015, 2014).

In the automobile industry, one of the objectives is to have fuel-efficient cars and also lightweight cars. Application of CFRP in car parts reduces the weight of the 30% of a standard car. In another study, it was observed that GRP waste fibers can be used to strengthen the bending in architectural cladding panels and also reduce the propagation of cracks with the cement composites, as shown in **Fig. 21**.

In another report by Job *et al.* (2016), the work on continuous FRTP or long FRTP is limited, but more work has been carried out using the thermoset resins. In contrast, the thermoplastic resins are reprocessed and remelted for reuse as recycled FRP composites (Pimenta and Pinho, 2011; Rebeiz and Craft, 1995; Moothoo *et al.*, 2017; Leblanc *et al.*, 2015). There are glass fiber reinforced thermoplastics that have been recycled from automobile wastes and reprocessed into new compounds. On the other hand, the glass fiber reinforced thermoset resins could be degraded thermochemically, thereby helping to recover the organic atoms with low molecular weights.

Job *et al.* (2016) stated that the properly prepared and smoothened carbon fiber reinforced PEEK molded and then injected into virgin PEEK resin and pressed up to 50 wt%, producing recycled composites with mechanical characteristics. There was also the direct recycling process without grinding was also successfully performed but has not applied to EOL composite materials. It is noteworthy that thermoset resins are highly durable, can survive high temperature and have excellent mechanical behavior. However, they can be replaced by thermoplastic resins. Some commercially available thermoset epoxy resins are easier to recycle, as developed by Connora Technologies and Adesso. These thermoset composite resins can be decomposed chemically under low temperature conditions to free up the fiber molecules, and degraded resins that can be used as recycled thermoplastics and as adhesives. Using lignin, recycled composites can also be printed using 3D printing, as shown in **Fig. 21**. Sustainable 3D-printed products are made from 40 to 60 wt % lignin containing polymeric materials formulated by a solvent-free process and exhibiting appropriate processability constrained by an optimum window of temperature, shear rate and/or filament feeding rate, and viscosity (Graichen *et al.*, 2017; Nguyen *et al.*, 2018) (**Fig. 22**; **Table 3**).

Conclusion

There are more economic aspects to be achieved from the recycling of FRP composites. As discussed here, state-of-the-art applications of composites in different industries show a growing demand for composites, and thus the need increases too. The trend in recycling also increases and will be beneficial in the near future based on the current recycling processes and regulations to support recycling in the composite industry. Despite challenges with the application of recycled FRP composites, due to strength issues not highly validated in large scale structures, it is still an enabling technology in some products and can be harnessed. Application of recycled FRP composites in large scale in offshore and marine applications will be one of the key challenges. Economically, it will be successful with small-scale production like remotely operated vehicle handles but will have issues with vibration requirements. Considering the different environmental conditions for oil explorations, such as those that may be harsh, benign, or squall, will also be an issue. There can be more optimization of the impacts by reclaiming fibers very well for reuse as recycled FRP composites and using the leftover resin powder in cement kilns to replace coal, with a large scale, centralized operation to reduce energy impacts. However, technical and logistical advances would be needed before a business model to support this could be proven in a circular economy.

Acknowledgment

The authors wish to acknowledge the Engineering Department, Lancaster University, and Niger Delta Development Commission, Nigeria (NNDC). We also thank the authors whose images we have used for the permissions obtained, such as Composites UK, ELF Carbon Fiber and Daimler.

References

Ackrill, S., 2018. The simple solution that consumers want for single serve waste. Coffee Talk 5. Available at: https://coffeetalk.com/ctmagazine/05-2018/57083/.

Akampumuza, O., Wambua, P.M., Ahmed, A., Li, W., Qin, X.-H., 2017. Review of the applications of biocomposites in the automotive industry. Polymer Composites 38 (11), 2553–2569.

Amaechi, C.V., 2017. Health, Safety and Biohazards in Construction, first ed. Germany: Lambert Academic Publishing.

Amaechi, C.V., Gillett, N., Odijie, A.C., Hou, X., Ye, J., 2019a. Composite risers for deep waters using a numerical modelling approach. Composite Structures 210, 486–499.

Amaechi, C.V., Wang, F., Hou, X., Ye, J., 2019b. Strength of submarine hoses in Chinese-lantern configuration from hydrodynamic loads on CALM buoy. Ocean Engineering 171, 429–442. doi:10.1016/j.oceaneng.2018.11.010.

Amaechi, C.V., Ye, J., 2017. A numerical modeling approach to composite risers for deep waters. In: Proceedings of the International Conference on Composite Structures (ICCS20). Paris, France: Societa Editrice Esculapo.

Amaechi, C.V., Ye, J., Hou, X., Wang, F.-C., 2019c. Sensitivity studies on offshore submarine hoses on CALM buoy with comparisons for Chinese-lantern and lazy-S configuration. In: Proceedings of the 38th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2019-96755), June 9–14, 2019. Glasgow, Scotland, UK: ASME.

Asmatulu, E., Twomey, J., Overcash, M., 2014. Recycling of fiber-reinforced composites and direct structural composite recycling concept. Journal of Composite Materials 48 (5), 593–608.

Babafemi, A.J., Šavija, B., Paul, S.C., Anggraini, V., 2018. Engineering properties of concrete with waste recycled plastic: A review. Sustainability 10 (11).

Bali, A., Tiessan, M., 2018. Bio-carbon from biomass. Bioplastic Magazine. 13 (14). Available at: https://www.bioplasticsmagazine.com/en/online-archive/data/20180114.php.

Bharath, K.N., Basavarajappa, S., 2016. Applications of biocomposite materials based on natural fibers from renewable resources: A review. Science and Engineering of Composite Materials 23 (2), 123–133.

Brower W.D., 2000. Natural fibre composites in structural components: Alternative applications for sisal? In: Proceedings of the Seminar held by the Food and Agriculture Organization of the UN (FAO) and the Common Fund for Commodities (CFC): Alternative Applications for Sisal and Henequen, Rome Technical Paper No. 14, pp. 1–6. Rome: FAO and CFC. Available at: http://www.fao.org/3/Y1873E/y1873e0a.htm.

Brown, S., Forsyth, M., Job, S., *et al*., 2018. FRP Circular Economy Study: Industry Summary – August 2018, UK. Available at: https://compositesuk.co.uk/system/files/documents/FRP CE Report Final_0.pdf.

Das, O., Sarmah, A.K., Bhattacharyya, D., 2016. Biocomposites from waste derived biochars: Mechanical, thermal, chemical, and morphological properties. Waste Management 49, 560–570. doi:10.1016/j.wasman.2015.12.007.

Doyle, S., Aggidis, G.A., 2019. Development of multi-oscillating water columns as wave energy converters. Renewable and Sustainable Energy Reviews 107, 75–86.

ELG Carbon Fibre, 2017. Why Recycle Steel? Coseley, West Midlands, UK. Available at: https://www.recycle-more.co.uk/why-recycle-/why-recycle-steel-.

Freedonia, 2017. Fiber-Reinforced Plastic Composites Market by Fiber, Product and Market in the US, thirteenth ed. Cleveland: The Freedonia Group, Available at: https://www.freedoniagroup.com/Fiber-reinforced-Plastic-Composites-Market-In-The-Us.html.

Ge, Z., Sun, R.J., Zheng, L., 2011. Mechanical properties of concrete with recycled clay-brick-powder. Advanced Materials Research 250–253, 360–364.

Gillett, N., 2018. Design and Development of a Novel Deepwater Composite Riser (BEng Thesis). Lancaster University.

Graichen, F.H.M., Grigsby, W.J., Hill, S.J., *et al*., 2017. Yes, we can make money out of lignin and other bio-based resources. Industrial Crops and Products 106, 74–85. doi:10.1016/j.indcrop.2016.10.036.

Halliwell, S., 2006. End of life options for composite waste: Recycle, reuse or dispose? National Composites Network. 1–41. Available at: https://compositesuk.co.uk/system/files/documents/endoflifeoptions.pdf.

Hasan, H., Huang, B., Saafi, M., *et al*., 2019. Novel engineered high performance sugar beetroot 2D nanoplatelet-cementitious composites. Construction and Building Materials 202, 546–562. doi:10.1016/j.conbuildmat.2019.01.019.

Hinton, M., 2017. Bristol composites institute launch and ACCIS 10th anniversary conference. In: Proceedings of the ACCIS 10th Anniversary Conference. Bristol, UK: Bristol University. Available at: http://www.bris.ac.uk/media-library/sites/composites/documents/BristolCompositesInstLaunch151117v4.pdf.

Holmes, M., 2013. US demand for fibre reinforced plastic composites to rise. In Reinforced Plastics; Oxford, UK: Elsevier, October Series. Available online: http://www.materialstoday.com/composite-industry/news/us-demand-for-fibrereinforced-plastic-composites. (accessed on 12.04.19).

Hopkins, P., Saleh, H., Jewell, G., 2014. Composite pipe set to enable riser technology in deeper water. In: Proceedings of the MCE Deepwater Development Conference. 2H Offshore.

Ignatyev, I.A., Thielemans, W., Vander Beke, B., 2014. Recycling of polymers: A review. ChemSusChem 7 (6), 1579–1593.

ISO, 2006. ISO 14044:2006 Environmental Management – Life Cycle Assessment – Principles and Framework. Switzerland: The International Standards Organisation, Available at: http://www.springerlink.com/index/10.1007/s11367-011-0297-3.

Jaivignesh, B., Sofi, A., 2017. Study on mechanical properties of concrete using plastic waste as aggregate. In: Proceedings of the ICCIE 2017 IOP Conference, 80.

Job, S., 2014. Recycling composites commercially. Reinforced Plastics 58 (5), 32–38. doi:10.1016/S0034-3617(14)70213-9.

Job, S., 2015. Why not composites in ships? Reinforced Plastics 59 (2), 90–93. doi:10.1016/j.repl.2014.12.047.

Job, S., Leeke, G., Mativenga, P.T., *et al*., 2016. Composites Recycling: Where are We Now? p. 11. Available at: https://compositesuk.co.uk/system/files/documents/RecyclingReport2016_1.pdf.

Kamaruddin, M.A., Abdullah, M.M.A., Zawawi, M.H., Zainol, M.R.R.A., 2017. Potential use of plastic waste as construction materials: Recent progress and future prospect. IOP Conference Series: Materials Science and Engineering 267 (1).

Khalid, F.S., Azmi, N.B., Sumandi, K.A.S.M., Mazenan, N., 2017. Mechanical properties of concrete containing recycled concrete aggregate (RCA) and ceramic waste as coarse aggregate replacement. AIP Conference Proceedings 1891 (2017).

Knight, C.C., Zeng, C., Zhang, C., Wang, B., 2012. Recycling of woven carbon-fiber-reinforced polymer composites using supercritical water. Environmental Technology 33 (6), 639–644.

Kratz, J., Low, Y.S., Fox, B., 2017. Resource-friendly carbon fiber composites: Combining production waste with virgin feedstock. Advanced Manufacturing: Polymer and Composites Science 3 (4), 121–129. doi:10.1080/20550340.2017.1379257.

Kun, D., Pukánszky, B., 2017. Polymer/lignin blends: Interactions, properties, applications. European Polymer Journal 93, 618–641. doi:10.1016/j.eurpolymj.2017.04.035.

Lauzé, M., 2001. Recycling Carbon Fibre Reinforced Composites: A Market and Environmental Assessment. McGill University, pp. 1–13.

Leblanc, D., Landry, B., Jancik, M., Hubert, P., 2015. Recyclability of randomly-oriented strand thermoplastic composites. In: Proceedings of the 20th International Conference on Composite Materials ICCM20, pp. 19–24. Copenhagen, Denmark: ICCM. Available at: http://iccm-central.org/Proceedings/ICCM20proceedings/papers/paper-3409-1.pdf.

Letelier, V., Tarela, E., Moriconi, G., 2017. Mechanical properties of concretes with recycled aggregates and waste brick powder as cement replacement. Procedia Engineering 171, 627–632.

Liu, F., Yan, Y., Li, L., Lan, C., Chen, G., 2013. Performance of recycled plastic-based concrete. Journal of Materials in Civil Engineering 27 (2), A4014004.

Li, D., Kaewunruen, S., 2019. Mechanical properties of concrete with recycled composite and plastic aggregates. International Journal of GEOMATE 17 (60), 231–238.

Malnati, P., 2018. Recycled waste products get new life as lightweight, cost-effective auto parts. Plastics Engineering 74 (6), 18–25. Available at: http://read.nxtbook.com/wiley/plastics_engineering/june_2018/recycled_waste_products_get_n.html.

Markets and Markets, 2017. Composites Market by Fiber Type (Glass, Carbon), Resin Type (Thermoset, Thermoplastic), Manufacturing Process (Layup, Filament Winding, Pultrusion), Application (Transportation, Aerospace & Defense, Wind Energy), Region – Global Forecast to 2022, UK. Available at: https://www.marketsandmarkets.com/Market-Reports/composite-market-200051282.html.

Meng, F., McKechnie, J., Turner, T.A., Pickering, S.J., 2017a. Energy and environmental assessment and reuse of fluidised bed recycled carbon fibers. Composites Part A: Applied Science and Manufacturing 100, 206–214. doi:10.1016/j.compositesa.2017.05.008.

Meng, F., McKechnie, J., Turner, T., Wong, K.H., Pickering, S.J., 2017b. Environmental aspects of use of recycled carbon fiber composites in automotive applications. Environmental Science and Technology 51 (21), 12727–12736.

Mohanty, A.K., Vivekanandhan, S., Pin, J.-M., Misra, M., 2018. Composites from renewable and sustainable resources: Challenges and innovations. Science 362 (6414), 536–542.

Moothoo, J., Garnier, C., Ouagne, P., 2017. Production waste management of thermoplastic composites using compression molding. In: Proceedings of the ICCM International Conferences on Composite Materials, pp. 20–25. Xián, China: ICCM. Available at: http://iccm-central.org/Proceedings/ICCM21proceedings/papers/4235.pdf.

Murray, J., 2018. Improving safety through communication. E&P Magazine 2. Available at: https://www.hartenergy.com/exclusives/improving-safety-through-advanced-composite-technology-176873.

Nguyen, N.A., Barnes, S.H., Bowland, C.C., *et al.*, 2018. A path for lignin valorization via additive manufacturing of high-performance sustainable composites with enhanced 3D printability. Science Advances, 1–16. Available at: http://advances.sciencemag.org/cgi/content/short/4/12/eaat4967.

Odijie, A.C., 2016. Design of Paired Column Semisubmersible Hull (PhD Thesis). Lancaster: Lancaster University.

Odijie, A.C., Quayle, S., Ye, J., 2017a. Wave induced stress profile on a paired column semisubmersible hull formation for column reinforcement. Engineering Structures 143, 77–90. doi:10.1016/j.engstruct.2017.04.013.

Odijie, A.C., Wang, F., Ye, J., 2017b. A review of floating semisubmersible hull systems: Column stabilized unit. Ocean Engineering 144, 191–202. doi:10.1016/j.oceaneng.2017.08.020.

Odijie, A.C., Ye, J., 2015. Effect of vortex induced vibration on a paired-column semi-submersible platform. International Journal of Structural Stability Dynamics 15 (8).

Odijie, C., 2015. Understanding fluid-structure interaction for high amplitude wave loadings on a deep-draft paired column semi-submersible platform: A finite element approach. In: Proceedings of the International Conference on Light Weight Design of Marine Structures, November 09–11, 2015. Glasgow, UK: The Corinthian Club.

Ogi, K., Nishikawa, T., Okano, Y., Taketa, I., 2007. Mechanical properties of ABS resin reinforced with recycled CFRP. Advanced Composite Materials: The Official Journal of the Japan Society of Composite Materials 16 (2), 181–194.

Oliveux, G., Dandy, L.O., Leeke, G.A., 2015. Current status of recycling of fiber reinforced polymers: Review of technologies, reuse and resulting properties. Progress in Materials Science 72, 61–99.

Osmani, M., Asokan, P., 2010. An assessment of the compressive strength of glass reinforced plastic waste filled concrete for potential applications in construction. Concrete Research Letters 1 (1), 1–5.

Osmani, M., Pappu, A., 2010. Utilisation of glass reinforced plastic waste in concrete and cement composites. In: Proceedings of the 2nd International Conference on Sustainable Construction Materials and Technologies, pp. 1127–1137. Ancona, Italy. Available at: http://www.claisse.info/2010 papers/m45.pdf.

Pimenta, S., Pinho, S.T., 2011. Recycling carbon fiber reinforced polymers for structural applications: Technology review and market outlook. Waste Management 31 (2), 378–392. doi:10.1016/j.wasman.2010.09.019.

Prinçaud, M., Aymonier, C., Loppinet-Serani, A., Perry, N., Sonnemann, G., 2014. Environmental feasibility of the recycling of carbon fibers from CFRPs by solvolysis using supercritical water. ACS Sustainable Chemistry and Engineering 2 (6), 1498–1502.

Rebeiz, K.S., Craft, A.P., 1995. Plastic waste management in construction: Technological and institutional issues. Resources, Conservation and Recycling 15 (3–4), 245–257.

Siddique, R., Khatib, J., Kaur, I., 2008. Use of recycled plastic in concrete: A review. Waste Management 28 (10), 1835–1852.

Vieira, D.R., Vieira, R.K., Chain, M.C., 2017. Strategy and management for the recycling of carbon fiber-reinforced polymers (CFRPs) in the aircraft industry: A critical review. International Journal of Sustainable Development and World Ecology 24 (3), 214–223. doi:10.1080/13504509.2016.1204371.

Vo Dong, P.A., Azzaro-Pantel, C., Boix, M., Jacquemin, L., Domenech, S., 2015. Modelling of Environmental Impacts and Economic Benefits of Fibre Reinforced Polymers Composite Recycling Pathways. Elsevier. doi:10.1016/B978-0-444-63576-1.50029-7.

Vo Dong, P.A., Azzaro-Pantel, C., Cadene, A.L., 2018. Economic and environmental assessment of recovery and disposal pathways for CFRP waste management. Resources, Conservation and Recycling 133, 63–75. doi:10.1016/j.resconrec.2018.01.024.

Wei, H., Nagatsuka, W., Lee, H., *et al.*, 2018. Mechanical properties of carbon fiber paper reinforced thermoplastics using mixed discontinuous recycled carbon fibers. Advanced Composite Materials 27 (1), 19–34. doi:10.1080/09243046.2017.1334274.

Witten, E., Mathes, V., Sauer, M., Kühnel, M., 2018. Composites Market Report 2018: Market Developments, Trends, Outlooks and Challenges. AVK & Carbon Composites. (accessed 08.06.19) Available at: https://eucia.eu/userfiles/files/20181115_avk_ccev_market_report_2018_final.pdf.

Wood, L., 2019. Global Composites Market Report 2019: $40.2 Billion Market Trends, Forecast and Competitive Analysis 2013-2018 & 2019-2024, Dublin. Available at: https://www.globenewswire.com/news-release/2019/04/12/1803326/0/en/Global-Composites-Market-Report-2019-40-2-Billion-Market-Trends-Forecast-and-Competitive-Analysis-2013-2018-2019-2024.html.

Xu, P., Li, J., Ding, J., 2013. Chemical recycling of carbon fiber/epoxy composites in a mixed solution of peroxide hydrogen and N,N-dimethylformamide. Composites Science and Technology 82, 54–59. doi:10.1016/j.compscitech.2013.04.002.

Yang, P., Zhou, Q., Li, X.-Y., Yang, K.K., Wang, Y.-Z., 2014. Chemical recycling of fiber-reinforced epoxy resin using a polyethylene glycol/NaOH system. Journal of Reinforced Plastics and Composites 33 (22), 2106–2114.

Yang, Y., Boom, R., Irion, B., *et al.*, 2012. Recycling of composite materials. Chemical Engineering and Processing: Process Intensification 51, 53–68.

Yazdanbakhsh, A., Bank, L.C., 2014. A critical review of research on reuse of mechanically recycled FRP production and end-of-life waste for construction. Polymers 6 (6), 1810–1826.

Ye, J., 2003. Laminated Composite Plates and Shells: 3D Modelling. London: Springer.

Yin, S., Rabin, T., Mark, C., *et al.*, 2013. Mechanical properties of recycled plastic fibers for reinforcing concrete. In: Proceedings of the Fibre Concrete 2013. Prague, pp. 1–10. Czech Republic. Available at: https://researchonline.jcu.edu.au/29588/1/oral_29_Full_YIN_Shi.pdf.

Zhang, D., Shi, J., Si, Y., Li, T., 2019. Multi-grating triboelectric nanogenerator for harvesting low-frequency ocean wave energy. Nano Energy 61, 132–140.

Further Reading

Gerdeen, J.C., Lord, H.W., Rorrer, R.A.L., 2006. Engineering Design with Polymers and Composites. Boca Raton: CRC Press.

Ye, J., 2003. Laminated Composite Plates and Shells: 3D Modelling. London: Springer.