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Technology readiness level assessment of composites recycling technologies

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ABSTRACT

Composite materials made of glass and carbon fibres have revolutionised many industries. Demand for composites is experiencing rapid growth and global demand is expected to double. As demand for composites grows it is clear that waste management will become an important issue for businesses. Technically composite materials evoke difficult recycling challenges due to the heterogeneity of their composition. As current waste management practices in composites are dominated by landfilling, governments and businesses themselves foresee that this will need to change in the future. The recycling of composites will play a vital role in the future especially for the aerospace, automotive, construction and marine sectors. These industries will require different recycling options for their products based on compliance with current legislation, the business model as well as cost effectiveness. In order to be able to evaluate waste management strategies for composites, a review of recycling technologies has been conducted based on technology readiness levels and waste management hierarchy. This paper analyses 56 research projects to identify growing trends in composite recycling technologies with pyrolysis, solvolysis and mechanical grinding as the most prominent technologies. These recycling technologies attained high scores on the waste management hierarchy (either recycling or reuse applications) suggesting potential development as future viable alternatives to composite landfilling. The research concluded that recycling as a waste management strategy is most popular exploration area. It was found mechanical grinding to be most mature for glass fibre applications while pyrolysis has been most mature in the context of carbon fibre. The paper also highlights the need to understand the use of reclaimed material as important assessment element of recycling efforts. This paper contributes to the widening and systematising knowledge on maturity and understanding composites recycling technologies.

1. Introduction

Composite materials have revolutionised many industries, predominately aerospace, marine, construction and automotive industries (Sims and Bishop, 2001; Jiang, et al., 2007; Bai, 2010). The possibility of combining mechanical strength, design flexibility, reduced weight and low system cost, make composites the material of choice in transportation allowing unique design and functionalities in combination with high fuel efficiency. For instance, Airbus A350X Wide Body design is dominated by composites; by aircraft weight, the A350 XWB will be 53% composites, 19% Al/Al—Li, 14% titanium and 6% steel.

The UK carbon fibre composite production represents around 2130 tonnes (36% for aerospace and defence and 33% wind energy), the rest being mostly in automotive, marine and sports goods (Materials KTN, 2011). In comparison, the glass fibre reinforced plastics (GFRP) production represents 144,000 tonnes in UK and it was estimated at approximately 1053 million tonnes in Europe in 2010 (Materials KTN, 2011). As composites materials in a form of carbon fibre-resin/glass fibre-resin matrix are relatively new in commercial use, the commercially available recycling processes of these materials are still under development (Job, 2010). Waste management of composites has started showing on the government agenda (BIS, 2009). There are several European Directives and regulations that impact polymer waste management, collection and recycling, e.g. 99/31/EC on Landfill of Waste; 2000/53/EC on End-of-life vehicles; 2004/35/EC on Environmental Liability. Manufacturers across Europe need to pay to dispose their production

Abbreviations: EPSRC, Engineering and Physical Sciences Research Council.
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waste if it goes to landfill, including a climate change levy. The incineration of scrap is also restricted due to directive 2000/76/EC that prevents air, water and soil pollution by limiting emission levels. This has significant cost and operational implication for the future waste management of the composites in many industries (Witik, 2013), but currently the most affected will be aerospace, construction, marine and automotive industries (Sims and Bishop, 2001; Jiang et al., 2007; Bai, 2010). It is estimated that by 2015 end-of-life composite waste will reach 251,000 tonnes and production waste will achieve 53,000 tonnes (Simth, 2009). Also, the *Lifting Off* report (BIS, 2013) acknowledges that substantial growth within the aerospace sector over the next 20 years will involve step-change increases in aerospace production volumes.

In order to be able to respond to these changes, the industry needs to understand its own waste management capabilities and the recycling options available. Understanding the level of recycling technologies and their potential legislation implications allow industry to identify opportunities for viable waste management solution for composites. The aim of this research is to define the maturity and potential desirability of composites recycling technologies through using technology readiness level assessment and waste management hierarchy frameworks for evaluation.

2. Related research

This section explores the research related to composites waste management options.

The increased use of composites across different industries will lead to creation of heterogeneous waste, either end-of-life or manufacturing waste (Yang, 2012). As composite materials have heterogeneous nature, the diversity of different production variables makes is very difficult to find recycling routes (Yang, 2012). Further, lack of infrastructure and market are the difficulties in funding commercial scale applications (Conory, 2006).

EU Waste Framework Directive defines the different types of waste processing and provides a view on desirability of the different strategies along with definitions of their meaning for industry (Conory, 2006; Council directive 2008/98/EC; Pickering, 2006). The framework has guided waste practice classification for many industries and provides the scale of desirability in waste management from the legislation perspective. EU Waste Framework demonstrated in Fig. 1 outlines five broad waste management strategies, starting from most desirable to the least these are: prevention, preparing for reuse, recycling, recovery and disposal.

Current waste management practices in composites are dominated by landfilling (WRAP, 2013), which still is a relatively cheap option for industry in comparison to alternatives. However, it is the least preferred option by legislation (Council directive 2008/98/EC). It has also been recognised that landfilling will become unviable for industry mainly due to legislation-driven cost of disposal increases (Pickering, 2006). From 1998 the standard landfilling rate increased from £7 per tonne to £64 per tonne in 2012 on average increasing £4 annually. From 2013 that annual increase has risen to £8, making the 2014 landfilling rate to be £80/tonne and in 2015 it is declared to be 82,60/tonne (HM Revenue and Customs, 2015).

When considering waste management of composites the efforts of researchers predominantly focus on the recycling technologies that process the scrap material to a form which significantly decreases the value of material (Correia, 2011; Chen, 2006; Turner, 2010). This falls mostly into recycling but sometimes covers recovery and reuse stages in the Waste Management Hierarchy.

There have been several classifications of composites recycling technologies. Yang (2012) recognises thermal, chemical and mechanical recycling for thermo-set matrix composites. Also, Job (2010) has summarised research that has been done around recycling efforts in glass fibre reinforced- (GFR) and carbon fibre reinforced (CFR) composites. The study describes five recycling processes: mechanical grinding, pyrolysis, cement kiln route, fluidised bed and solvolysis. Microwave heating is also discussed (Lester, 2004). Pickering (2006) provides detailed review of recycling technologies along with the graphical illustration of each technology. Key recycling technologies are described below. Mechanical grinding is a process of using hammer mill or similar tools where waste is milled to the level of powder (Job, 2010) or fibrous product that could have some reinforcement properties Correira (2011). Pyrolysis is a thermal recycling process where composite material is heated to a temperature between 450 °C to 700 °C in the absence of oxygen (Lester, 2004). This process is mostly used for carbon fibre (CF) composites (Marsch, 2008) and produces fibres of reduced strength and fillers (Pickering, 2006). Cement kiln is identified as a method where the organic fraction is combusted to generate energy and the inorganic fraction is incorporated into cement (Job, 2010). Fluidised bed process is a thermal recycling process that aims to recover high grade glass and carbon fibre reinforcement from scrap glass and carbon fibre reinforced

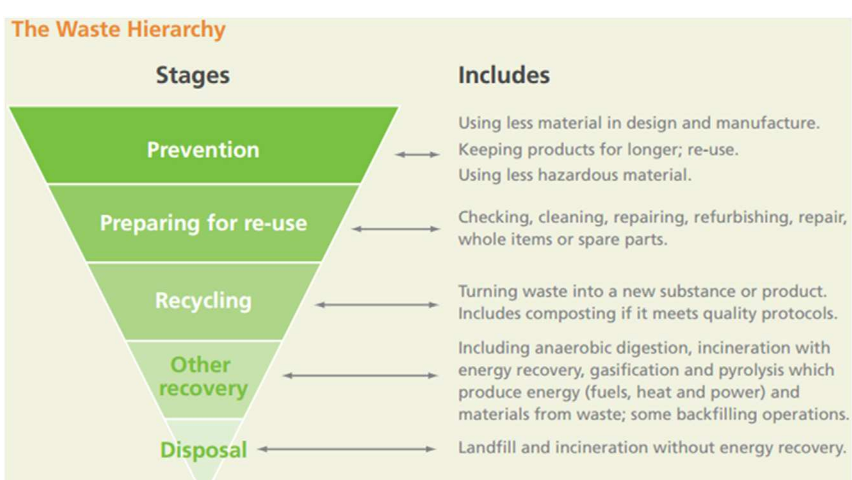


Fig. 1. EU Waste Framework, source: DEFRA (2011) Government Review of Waste Policy in England 2011.

composites (Marsh, 2008; Packering, 2000). The fibre composites are cut and fed into the silica sand bed and are treated with hot air at temperatures between 450 and 550 °C. Fibre-size and filler-size are separated from each other to be used for different purposes (Correia, 2011). Microwave heating is another thermal recycling method where the fibres are heated directly through the use of microwaves to achieve fibre separation. Lester (2004) has published a technical feasibility study of this method; however there is very limited research in this area. Solvolysis is a method of recycling through various chemicals that decompose composites into chemicals and fibres (Liu, 2012). Variable results have been achieved depending on the chemical selected and the experimental conditions. All the above lead to reduced strength properties of fibres (Bai, 2010; Jiang et al., 2009; Piñero-Hernanz, 2008; Xu, 2013; Oliveux, 2013; Kao, 2012; Yuyan, 2009).

As the value of glass fibre (GF) type composites is small, the process of recycling needs to reflect the potential profits that could be achieved. So far mechanical grinding is considered a commercially viable strategy although on a small scale (Filon publications). Due to large volumes of GF scrap available, the demand for viable recycling of GF is increasing. However, BIS (2009) reports that ever increasing end-of-life composite waste does not have sufficient infrastructure and facilities in place for recycling.

CF recycling is predominantly driven by tightening legislation around its disposal. As the value of CF is much higher than GF, there is opportunity for more expensive technologies to be applied in recycling (Pickering, 2006). So far, pyrolysis (thermal recycling process) has been developed to a commercial scale (Wood, 2006), however it still is limited in capacity as the supply of waste is discontinuous due to the small volumes available and lack of infrastructure facilitating waste flows (Pickering, 2006). In the case of CF, the issue of recycling is the devaluation of the material after recycling.

For composites waste management it is important to establish process or processes that could compete with the cost of disposal. This is going to become more attractive as the landfill tax increases (Conory, 2006). Understanding the maturity of the recycling technologies will enable industry to assess the options available and explore the capabilities required to facilitate composite recycling. So far no context landscaping has been done for the composites recycling industry although many efforts of classification of recycling technologies have been proposed in the past (Conory, 2006; Pickering, 2006; Correia, 2011). This is the first attempt, however to look at the maturity of composites recycling technologies with the use of landscaping to build understanding of capabilities requirements.

3. Methods

As the purpose of this research paper is to evaluate recycling technologies, it is key to review the relevant and significant research and to evaluate recycling technologies in the new contexts (Saunders, 2007). Therefore, this paper focuses on literature review of recycling technologies available and its evaluation on two-dimensional scale – maturity and sustainability as waste management option.

Inductive approach in the literature review is applied (Saunders, 2007) to take into account the need for organising data into the relevant context. The waste management hierarchy and technical readiness level frameworks are used as assessment scales for the technologies. The technologies are assessed on the scale and cross-validated with several experts from materials and recycling environments. Finally, the recycling technologies are displayed in two-dimensional graphs to demonstrate its maturity landscape. The graphical representation of the methods used is presented in Fig. 2.

These methods allow coverage of the wide research scope needs: understanding the state of current composites recycling technologies as well as defining the requirements of industry and academia to inform future research in developing commercial composites recycling technologies and systems.

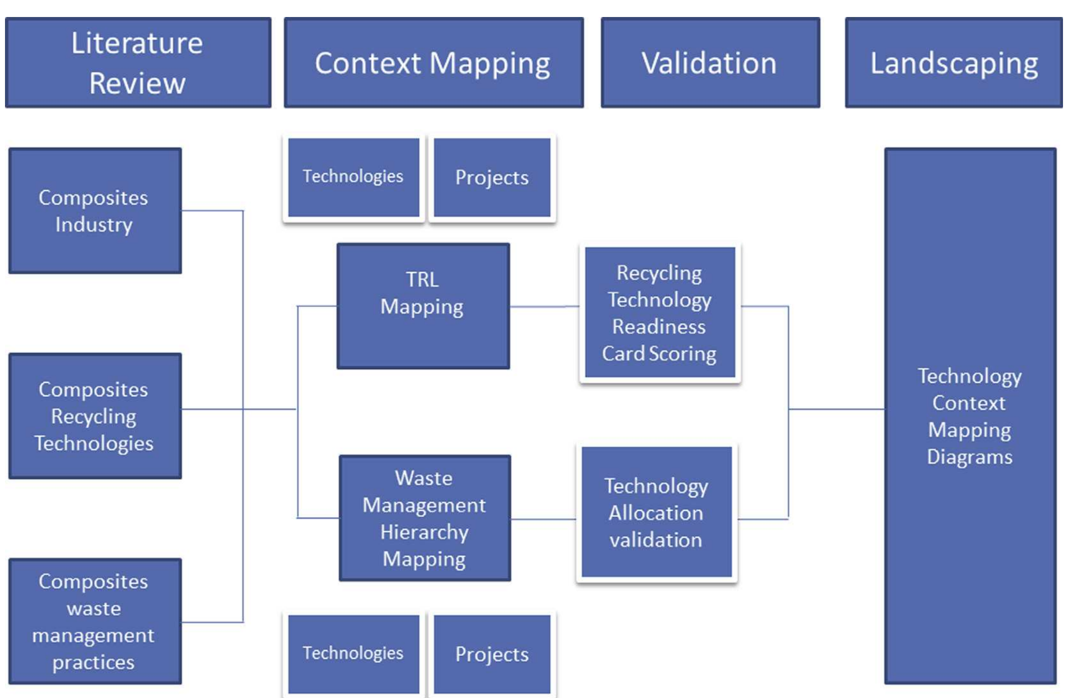


Fig. 2. Research methods.

3.1. Literature review

As this research look at the technical readiness level of technologies not only academia but industry sources had to be considered in this study. State of the art in composites recycling in industry has been investigated to understand the magnitude of composites waste management impact on business. This work supported understanding of what technologies are commercially available today. Further, literature review of different processes of composites waste management has been researched in order to identify the types of recycling and processing available. In order to understand the scale of composites recycling and identify arising trends, reviews of journals, white papers and company publications have been carried out. The journals search has been carried out in SCOPUS database whereas the white papers have been identified on the interest group networks (i.e. Materials KTN) and company publications have been found directly on company websites. Fifty six projects and publications on composites recycling processes have been identified. The search key words were selected to ensure consistency of themes covered in the context of waste management strategies conveying: composite, CRFP, GFRP, reuse, recycling, recovery, disposal, and incineration. The investigation of the technologies focused on what type of waste management strategies are explored in composites, whether there is a difference between glass- and carbon-fibre composites waste management, and what recycling strategies have received most interest.

3.2. Context mapping

The 56 projects have been classified on the TRL and on the Hierarchy of Waste Management frameworks in order to develop a landscape of these technologies in the relevant context. TRL classification enabled identification of technological maturity of the current developments and Waste Management hierarchy allowed to understand the potential legislation-driven desirability of the technologies.

3.2.1. TRL scale assessment

Technology Readiness Level (TRL) is a framework that has been used in many variations across industries to provide a measurement of technology maturity from idea generation (basic principles) to commercialisation (Nakamura, 2012). TRL can also be adapted to support understanding of capabilities and resources required to develop technologies at different stages of development. Conrow (2011) provides description of the TRL stages in terms of the development adopted in NASA. The TRL stages are summarised in Table 1.

There were two allocation stages to the TRL framework. First stage allocation was adopted from Yang (2012) where TRL 1–3 were defined as lab scale, TRL 4–6 as pilot scale and 7–9 as commercial scale. This first allocation was performed to identify the range within the three scales. Following that the second run of allocation was performed; the description of the processes used in each of the 56 research projects have been compared with the TRL level descriptions from Williamson (2011). This activity provided specific information that allowed allocation to one stage on the TRL level. The whole process is demonstrated in Fig. 3.

Table 1
Technology Readiness Level (TRL) framework. Adapted from Williamson (2011).

TRL	Description
9	Actual system "flight proven" through successful mission operations
8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
7	System prototype demonstration in a space environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed/reported

3.2.2. Hierarchy of Waste Management

The assessment of technologies in terms of waste management level has been performed on a basis of matching the technology outputs to the definition in the Waste Management Hierarchy (DEFRA, 2011). The mapping of these technologies is discussed further in the Results section.

3.3. Validation

The maturity of the technologies has been evaluated through expert evaluation sessions with 10 experts from the University of Birmingham, University of Manchester, Exeter University, Cranfield University and the Materials KTN (Knowledge Transfer Network) in the UK. The evaluation has been conducted by asking the experts to allocate the recycling technologies to TRL levels represented by the technology cards. The cards are presented in Fig. 4. The cards characterised the technology application detailing: the process description, specified material and its different forms that could be treated through the process, process outputs, potential applications, and identification of organisations and projects that implemented the process in their work/company. The experts were asked to provide their view on the technology maturity. This findings were then compared to the original assessment.

3.4. Landscaping

The crosslinking between TRL levels and Waste Management Hierarchy allocations were registered on two dimensional diagram. These data were then analysed to gain an understanding based on desirability of the Waste Management Hierarchy maturity of technology. Fig. 5 demonstrates how the scatter diagram sections are divided and their respective explanations.

The technologies that fall above the 0X axis are more desirable to implement from the legislation perspective, whereas the projects below could have limited or negative impact on future waste

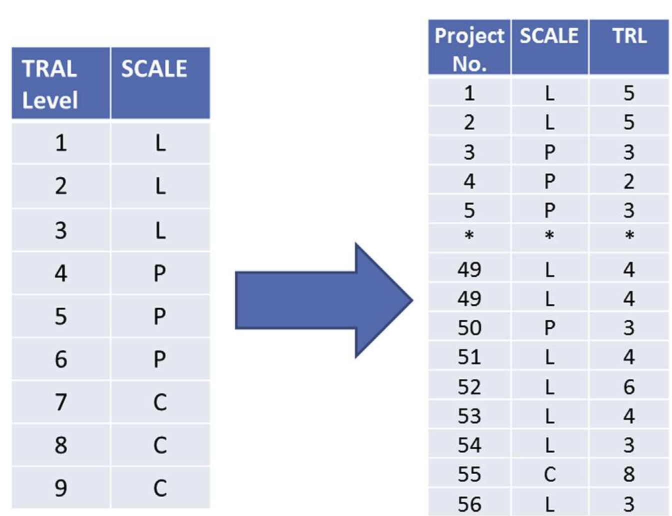


Fig. 3. TRL scale allocation to 56 research projects: Table A Yang TRL scale allocation: L- Lab; P- Pilot; C- Commercial.; Table B TRL level scale allocations stage two.

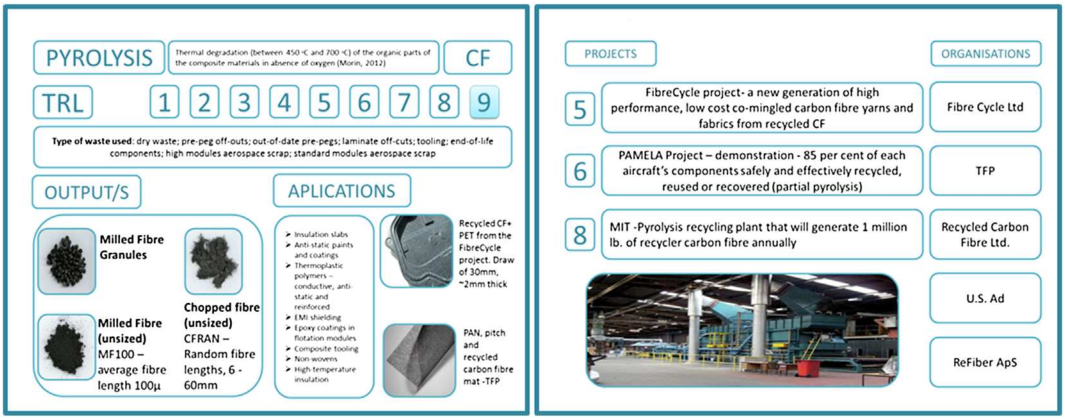


Fig. 4. Technology cards developed for TRL evaluation.

management strategies. The low TRL scores (projects on the left side of the 0Y axis) suggests that the amount of work required by industry for adapting the technology to business needs requires more effort than the technologies on the right (with high TRL score). These require less effort and are therefore easier to uptake. Fig. 5 provides four technology allocation categories: 'desired', 'high innovation potential', 're-thinking needed' and 'not viable'.

4. Results

The results form review of the papers is presented in this section. The allocation of the composites recycling practices in a context of Waste Management Hierarchy and TRLs is discussed and it is followed with by material and by technology breakdowns.

4.1. Composites recycling practices in a context of waste management hierarchy

Fig. 6 presents a summary of composites recycling processes captured using the Waste Management Hierarchy framework. Landfilling falls under the 'disposal' category, Incineration falls under as 'recovery', as it allows burning for energy. 'Recycling' strategies are represented by waste processing technologies: solvolysis, microwave heating, pyrolysis, mechanical grinding 'Reuse' strategies focus either on options where change to the manufacturing processes or supply chain is required; these are rather bespoke to individual production lines. Finally, 'prevention' as a strategy is looking at a system approach and aims to minimise the composite waste in the first place. From a technology development perspective, the areas of recycling and recovery allow the trailing and testing of individual recycling technologies. When looking at waste from manufacturing, 'reuse' and 'recycling' categories are seen to spur research interest.

From the review of 56 papers on composites recycling and allocation of these technologies in the Waste Management Hierarchy, it was possible to detect what types of waste management strategies have been researched in the past. Fig. 7 demonstrates that recycling of composites (45%) followed by reuse of composites (38%) are research areas that received most interest from researchers accounting for 83% of the research undertaken in the area

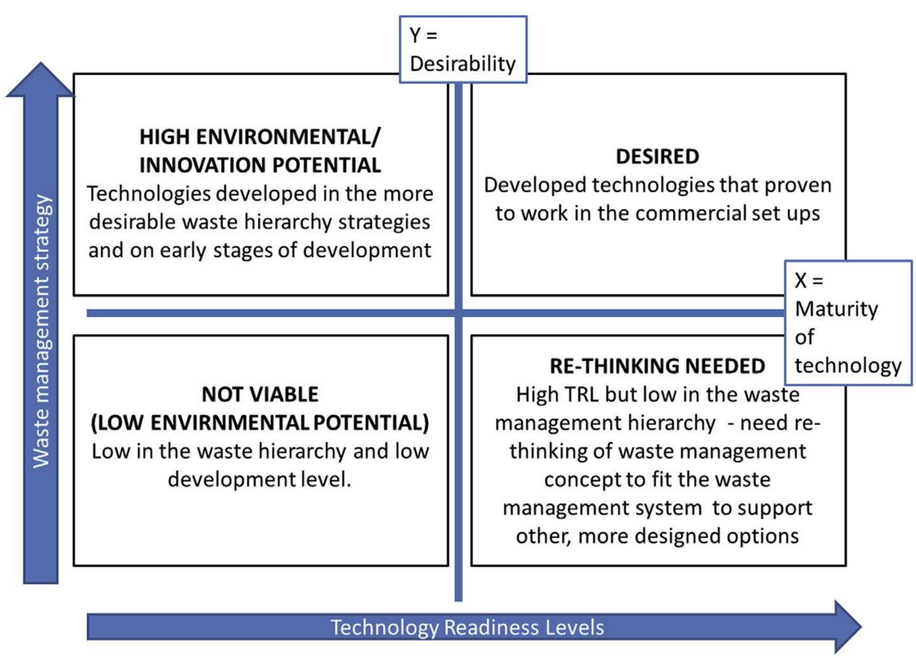


Fig. 5. Explanation of the context-relevant technology analysis.

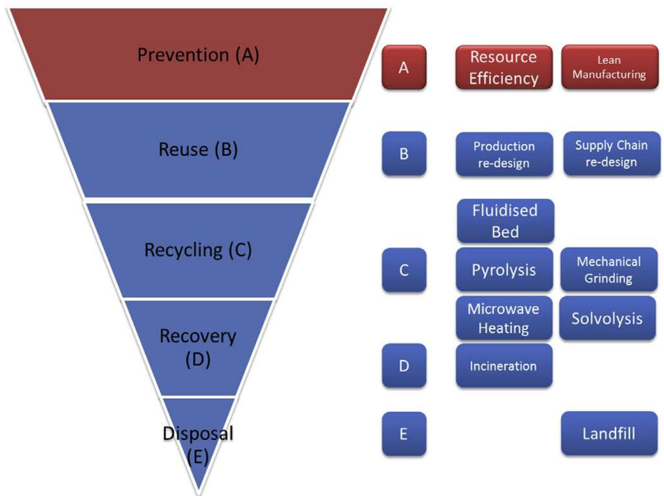


Fig. 6. Composites waste management strategies allocated on the Waste Management Hierarchy.

of composites waste management. Disposal of composites through landfilling has not been researched.

In terms of focus on types of materials researched in composites recycling carbon fibre (CF) is accounting for 53% and glass fibre (GF) for 34% of the research. This is outlined in Fig. 8. This however might not be entirely representative as for 11% of research in composites recycling it was not possible to identify the type of composites material used.

In order to explore how composites recycling evolved in relation to the type of material used the comparisons of glass- and carbon fibre recycling research has been compared with the time of its publication. There is an increasing trend to publish composites recycling. GF recycling has been published more than CF recycling between 2000 and 2009, however only in the last three years of the last decade carbon fibre recycling has shown not only a 360% increase from the last decade, but has also outgrown glass fibre research. This might be due to the increase in funding available for

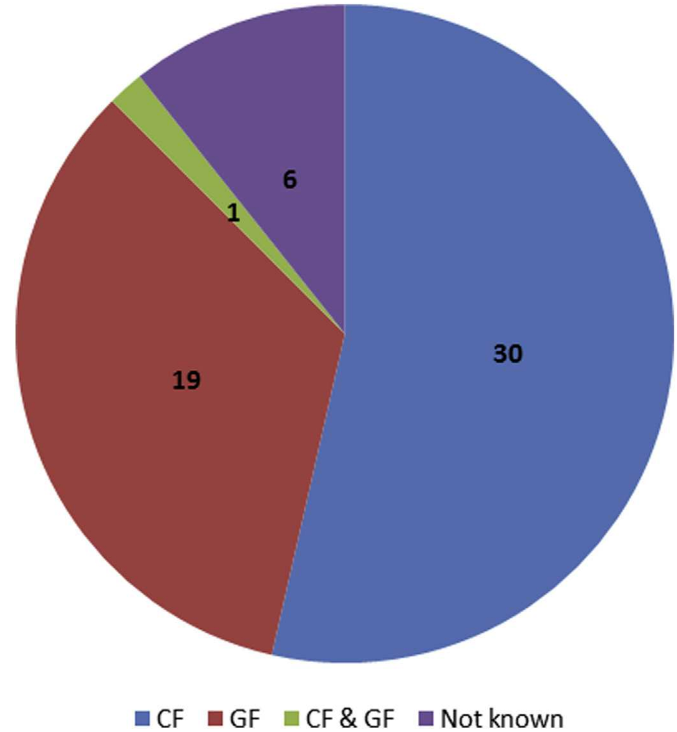


Fig. 8. Waste management strategies by material (based on 56 projects identified from journals and white papers).

research in materials recycling in the UK as well as building of research expertise in the UK universities is leading to greater publication development. Fig. 9 summarises this trend.

Fig. 10a and b shows the waste management strategy breakdown for composites recycling of GF and CF, respectively. Recycling seems to be a dominating area of research interest for both types of materials accounting for over half of the research- 57% for GF and 51% for CF. Reuse is the second most popular area covering 33% for GF and 32% for CF research. CF recovery (14%) seems to be handled more than GF recovery (5%).

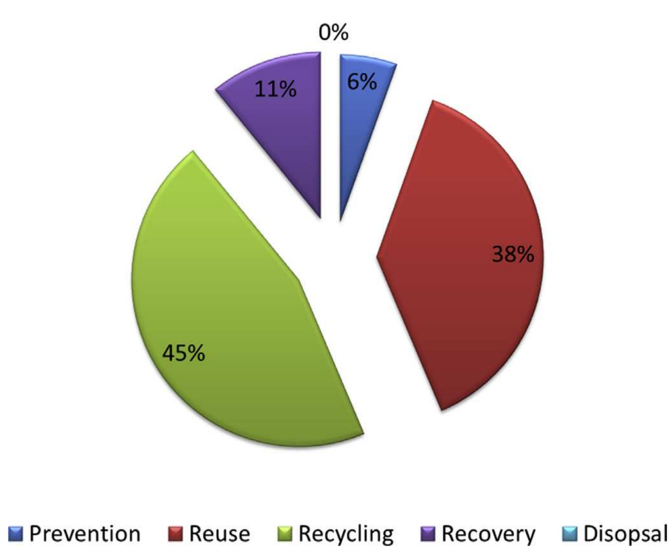
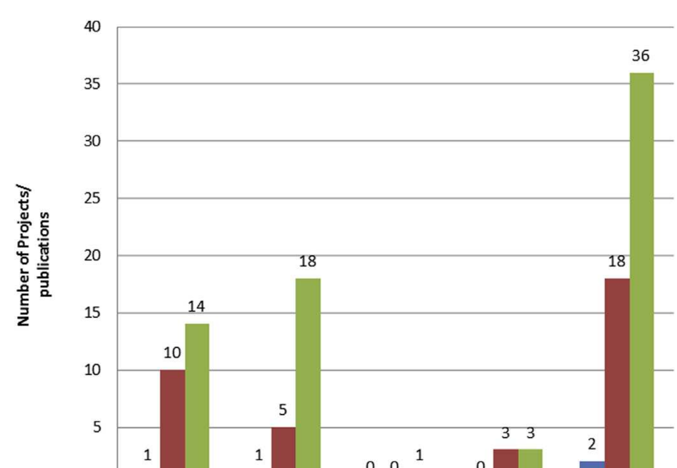


Fig. 7. Number of research projects by type of composites waste management strategies (based on 56 projects identified from journals and white papers*).
*As some papers covered more than one strategy, the total number of identified entries is 56.



	Glass Fibre	Carbon Fibre	Both	Not Known	Total
>2000	1	1	0	0	2
2000-2009	10	5	0	3	18
<2010<	14	18	1	3	36

Fig. 9. Composites recycling research uptake by material.

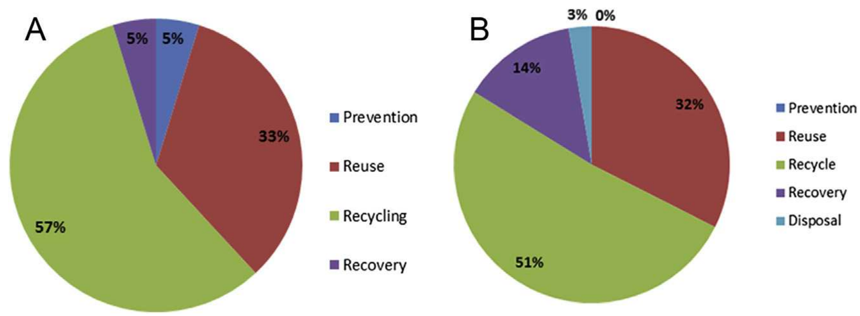


Fig. 10. (a) Glass fibre projects breakdown by waste management strategy (b) Carbon fibre projects by waste management strategy.

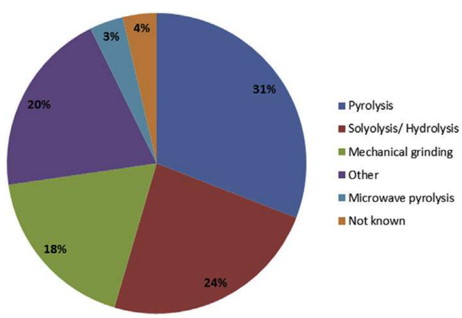


Fig. 11. Composites recycling projects by recycling technique.

Fig. 11 demonstrates the breakdown of recycling technologies explored by research and industry. Solvolysis (24%), pyrolysis (31%) and mechanical grinding (18%) stand out with the most uptake. 20% are technologies defined as 'other'. Fluidised bed has been allocated to pyrolysis as they are closely related. In this area it was not possible to identify the processes falling into one category, but usually a combination of different techniques and activities were identified.

Fig. 12 introduces the findings from the literature review analysed through the TRL scale allocations combined with the expert evaluation based on the technology card scoring. The scoring was based on average and median scores for each recycling technology.

Incineration and landfilling are assumed TRL 9 as a system currently in place. Pyrolysis for carbon fibre and mechanical grinding for glass fibre applications scored averages of 8.3 and 8.2 and a median of 8 which places it on a TRL 8. Pyrolysis for glass fibre and mechanical grinding for carbon fibre has achieved average scores 6.25 and 6.3 with a median of 7. Fluidised bed pyrolysis and solvolysis process has achieved average scores of 4.2 and 2.24 and median of 4. Finally, microwave heating had average of 3.2 and median of 3.

Fig. 13 presents the waste management strategies allocation on the TRL scale of individual projects researched in this study. Research in 'recycling' of composites seems to cover the whole

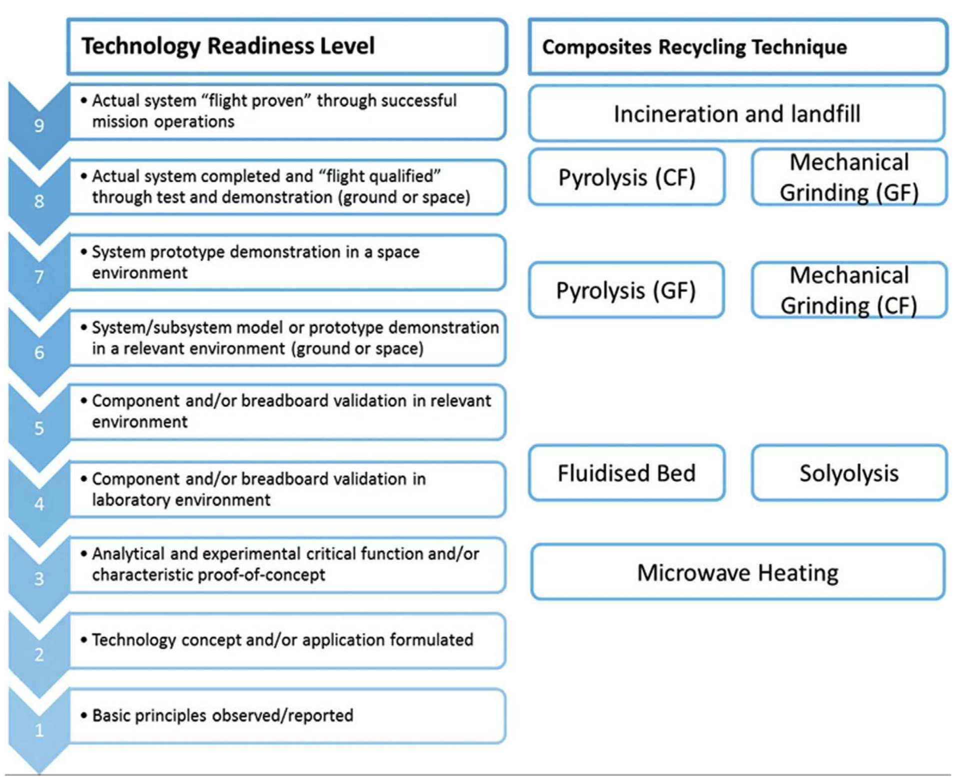


Fig. 12. Allocation of composites recycling technologies on TRL scale.

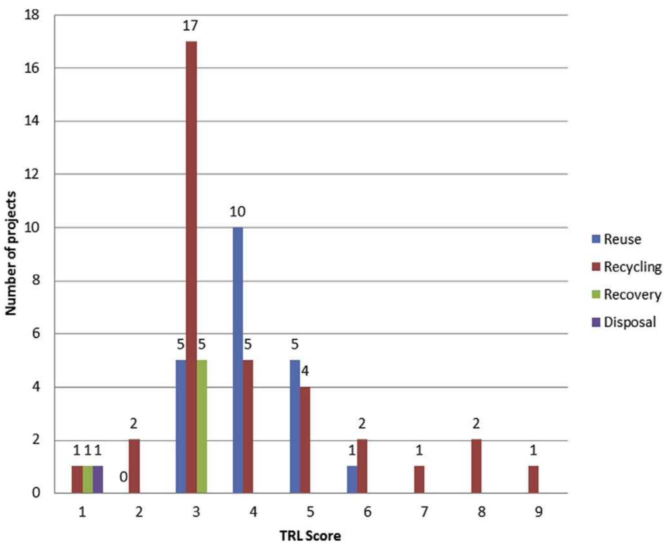


Fig. 13. TRL of composites recycling projects categorised by waste management strategies (based on 56 projects identified from journals and white papers*).
* Some publications covered more than one strategy; therefore total number of waste management strategies identified is 64.

spectrum of TRL scale. This implies that research within composites recycling is consistently developing. 'Reuse' activities cover TRLs 3 to 6 suggesting that the research in this area has consistently evolved from lab to pilot scale. 'Recovery' and 'disposal' cover lower TRLs. This may reflect the low interest in these areas from the new product development and legislation perspective.

The TRL allocation was analysed for CF and GF allocation (shown in Fig. 14a and b) and it is very clear that there is less research in GF recycling, a trend that is consistent across the TRL spectrum, whereas CF recycling is covered well from TRL 1 to 6 which suggest a clear development trend towards commercialisation.

4.2. Recycling technology landscaping

The three main recycling technologies defined in this research — pyrolysis, mechanical grinding, solyolysis have been plotted on Figs. 15, 16 and 18 to evaluate their environmental impact and technological readiness recognition. The diagrams show the disposal to reuse stages of the Waste Management Hierarchy on the Y axis and TRLs on the X axis. Projects that have used a composites recycling technology have been positioned on the diagrams. The definition of the Waste Management Hierarchy Stages meaning is represented in the context of recycling technologies analysis. 'Reuse' stage represents where the recycled material has found reuse application in a new product; 'recycling' means that material has recycled but it is not been proven to reuse beyond its reclamation value; 'recovery' focus on recycled materials trailed to be burnt for energy; and 'disposal' intrudes project where reclaimed material has been tested and disposed when considered as invaluable. Fig. 15 shows the specification of materials types and key symbols used in different projects.

4.2.1. Pyrolysis

Fig. 16 demonstrates how pyrolysis is plotted on the TRL/waste management strategies matrix. Most of the pyrolysis processes are used in CF research. This is a process that allows recycling of material (although it downgrades its value and currently has limited recyclate application), and fits in recycling and reuse sections depending on the purpose of recyclate use after processing. In terms of technological development, the projects in the laboratory scale are well developed with a strong trend of moving into commercial applications. The technology maturity suggests that there is viable opportunity in developing this technology further.

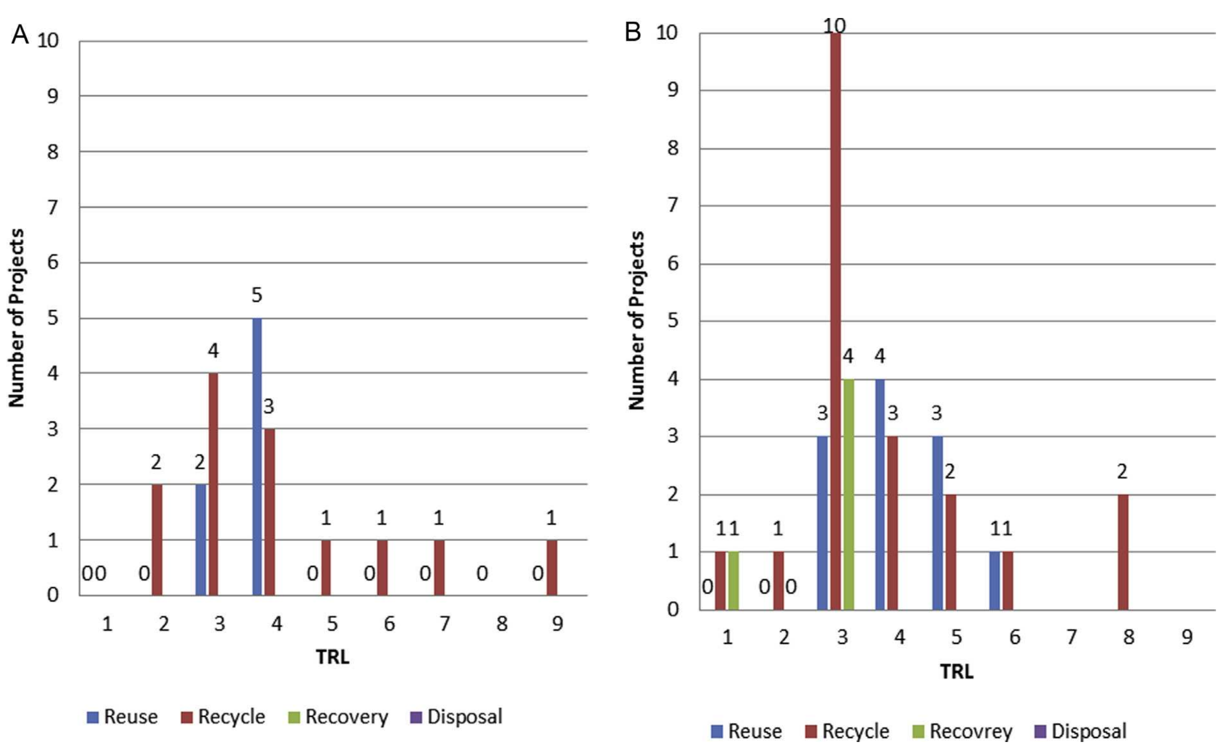


Fig. 14. (a) Glass fibre recycling by TRLs (b) Carbon fibre recycling by TRLs.

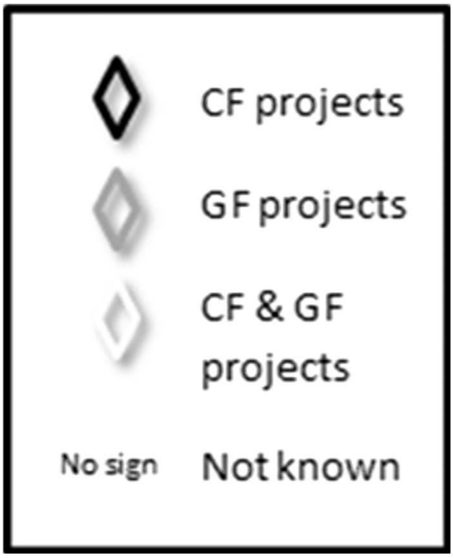


Fig. 15. Landscaping activity legend.

4.2.2. Solvolysis

For solvolysis there is a clear split between CF and GF research projects in terms of technological maturity. This is presented in Fig. 17. GF projects still reside in laboratory scale operations, whereas CF projects are moving towards the pilot scale and demonstrators. Both CF and GF solvolysis research covers a wide spectrum in terms of waste management strategies due to the different use of the end product. The recovery projects cover incineration after solvolysis processing whereas reuse projects describe the reuse of the recyclate in different applications.

4.2.3. Mechanical grinding

From summary of mechanical grinding technologies in Fig. 18 it is clear that mechanical grinding processing is primarily used for GF recycling applications. This might be due to the low cost of processing in comparison to the more expensive solyolysis and pyrolysis routes. The mechanical grinding process allows for reuse of the material in different ways, and is therefore positioned high on the waste management strategy hierarchy. It is also clear that there are two areas of development for GF recycling through mechanical grinding: there are recycling projects moving towards pilot scale development; and mature technologies that are reaching commercial scale. This suggests mechanical grinding can provide a viable option for recycling. CF recycling through mechanical grinding does not seem to get similar attention, only one project that uses GF as material has been identified. Two reasons for that were mentioned in literature and by experts: CF material is difficult to grind and was often leading to failure of grinding equipment; and value of CF recycled through mechanical grinding becomes too low for the process to be viable.

5. Discussion

As established by the results in Fig. 7 composites recycling research demonstrates a growing trend. This reflects the view that the industry recognises the changing conditions of composites waste management.

In terms of specific material recycling, CF research seems to span to a variety of technologies and processing options due to the material value reclaiming potential. On the other hand, GF research predominantly focuses on recycling options where volume is a more significant factor than retaining value of the fibres. As suggested in the literature, the main UK composites production capabilities lie in CF for aerospace industry and in GF structural applications for the automotive and construction industries. This suggests that recycled fibres, in order to be reused will require respective similar fibre qualities. This is currently not achievable with the recycling technologies available. It can be concluded that currently reclaimed fibres will need to be used in applications that use lower value fibres and have less quality requirements. The potential for fibre reuse requires understanding of composites supply chain that is beyond the scope of this paper. From comparisons between glass and carbon fibre research, it is evident that CF research has increased within the last decade. This might be due to the change in focus of funding for research into composites. A

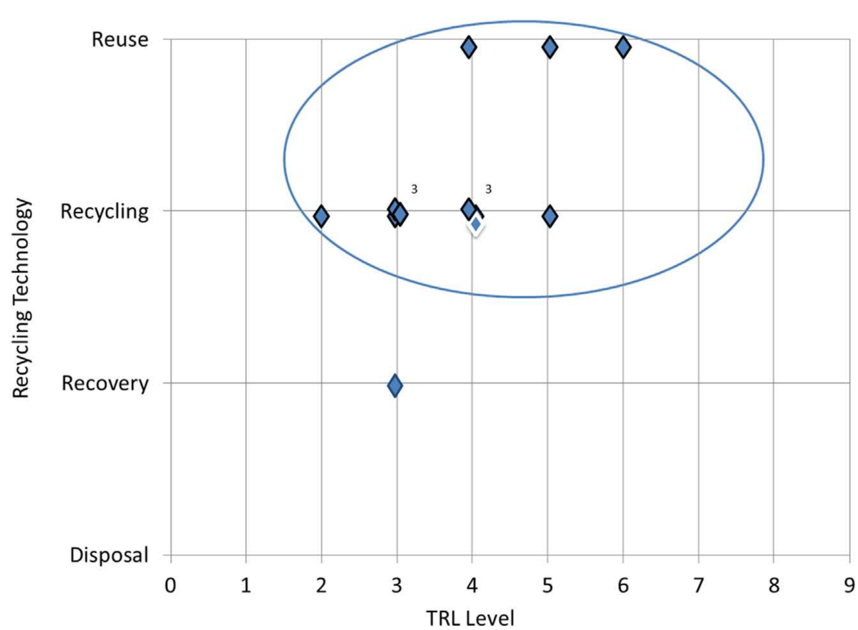


Fig. 16. Landscaping of pyrolysis process in the context of Waste Management Hierarchy index and technology readiness level.

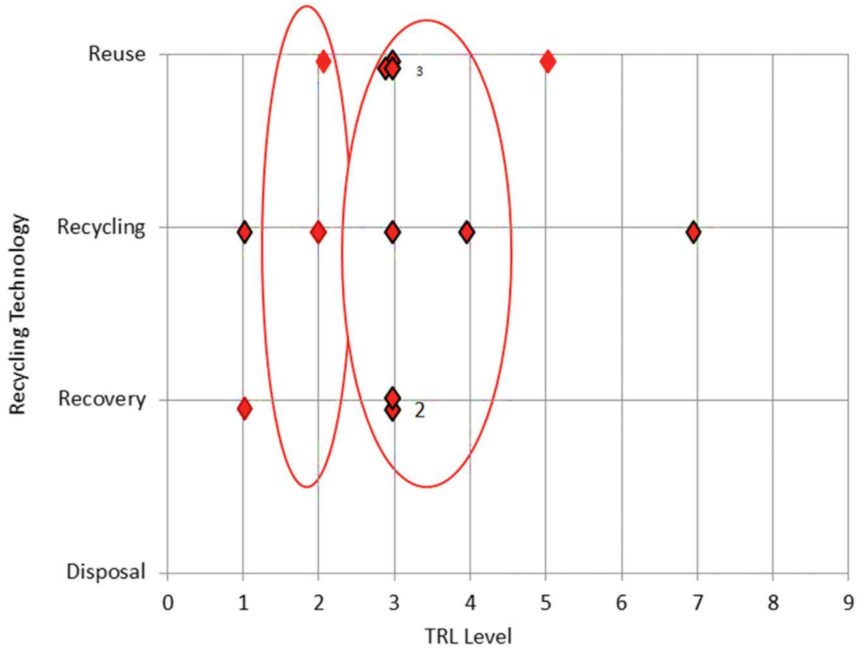


Fig. 17. Landscaping of solvolysis process in the context of Waste Management Hierarchy index and technology readiness level.

change that may be driven by the increase in composites demand and tightening of legislation around waste management.

The landscaping activity aims to provide an understanding of current state of composites recycling in the context of legislation and technological development. Waste Management Hierarchy (WMH) has been chosen as a framework to allocate different recycling projects. The framework allowed the demonstration of technologies' future desirability from the legislative and business model perspective. It was identified that the majority of composites waste management effort addresses 'recycling' and 'reuse' stages of WMH.

Technology Readiness Level (TRL) framework allows to understand the advancement of technologies. The TRL allocation, preformed on the 56 projects in composites recycling, showed that TRL level 3–4 is the most common stage of research. This suggests that the research still requires further development and investment for commercialisation.

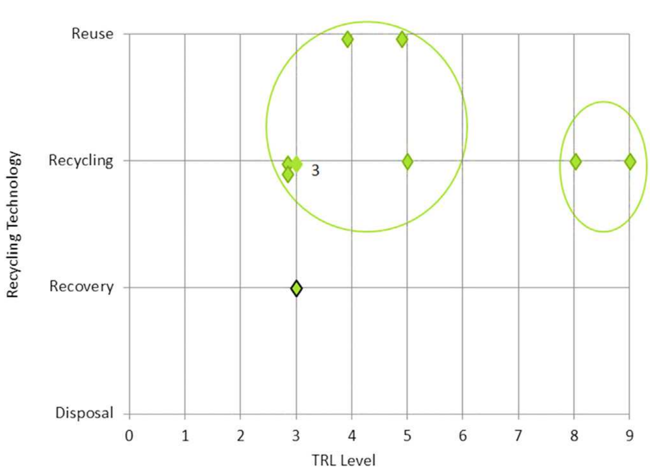


Fig. 18. Landscaping of mechanical grinding process in the context of Waste Management Hierarchy index and technology readiness level.

Three composites recycling technologies cover 75% of the total research activity: pyrolysis (31%) and solvolysis (22%) and mechanical grinding (18%). These three technologies dominate the picture of recycling, however in many instances combining mechanical grinding with another technology took place. Also, 20% of technologies were identified as 'other' suggesting that there is a host of niche technologies unexplored in this paper: recycling with use of injection moulding, chemical recycling with use of phenol and potassium hydroxide.

The landscaping activity demonstrated that GF recycling is dominated by mechanical grinding and it appears to reach high TRL levels; an observation also confirmed in the literature (Job, 2010). Currently, the Resource Efficiency Action Plan (REAP) study focuses on GF recycling due to the increasing volume of production. This may lead to new recycling opportunities.

For CF recycling, pyrolysis and solvolysis research are on the different stages of development. The most mature technology seems to be pyrolysis. Pyrolysis is defined high on the Waste Management Hierarchy and is a well-developed technology. Pyrolysis as a process can be developed in different configurations and it is reflected by diversification of projects on different development stages. This variety of recycling options in pyrolysis creates a variety of development opportunities for organisations as it is still relatively a new area of research, but proves to be commercially viable. There is one company officially registered to recycle CF by pyrolysis and has bases in the UK and Germany.

As a recycling process, solvolysis can be performed with diversity of chemicals and in a variety of conditions. This provides many options for recycling solutions and hence many applications are defined around TRL 3. For solvolysis, there is a clear diversification of technological maturity between GF and CF applications. It seems that CF research is focussed at the laboratory scale, whereas GF research is closer to proof-of-concept. However, there are isolated projects where the TRL stages are higher than the trend, for both GF and CF, which suggests that applications for commercialisation are possible.

Mechanical grinding as a recycling method predominantly is used in GF recycling. This method of composites recycling has reached high TRL level. This suggests that GF recycling is potentially viable in the current market. Also, mechanical grinding has been identified for use in CF recycling in conjunction with an additional technology to size the material.

This research was based on a database search, and it only covers the work that has been published, either as a journal or a white paper publication. The commercial work that has been done in this area is not included due to commercial sensitivity and lack of availability. This means that non-academic research or commercial applications of recycling technologies may not be captured, and therefore the landscaping activities might not represent the full picture of composites recycling research.

6. Conclusions

The manufacturers and users of composites need to take into account waste management as the legislation is increasingly impacting on this industry. The recycling of composites will play a vital role in the future for sectors like aerospace, automotive, construction and marine. These industries will require different recycling options for their products that will be complaint with current legislation and support their business models.

This paper details the research trends in the research on composites waste management options as well as provides context-mapping to landscape of the recycling technologies based on technological readiness levels. Fifty six research articles were used to identify growing trends in composites recycling technologies, and showed that pyrolysis, solvolysis and mechanical grinding as the most uptaken recycling practices.

In terms of opportunity development, individual technologies were analysed based on technology readiness level and Waste Management Hierarchy to establish current maturity status and potential opportunities for the development of viable strategies for the future. The aforementioned recycling technologies have been identified to have high Waste Management Hierarchy positioning (either recycling or reuse applications) suggesting potential for future development as a viable alternative to composites landfilling. These technologies reached different TRLs of which mechanical grinding for glass fibre application was considered as the most advanced and pyrolysis most advanced for carbon fibre application.

The landscaping activity has also led to conclusion that not only process used for recycling but the reclaimed material use has significant impact on its identification on the waste hierarchy. Although pyrolysis seems to be the most advanced technology for CF and mechanical grinding is most mature for GF, it is important to further evaluate the value and impact of applying these waste management strategies in the context of the recovered materials use. This suggests that it is required to consider a wider perspective when selecting recycling technologies, taking into account design the system to accommodate the materials reuse.

This paper contributes to the widening and systematising of knowledge on maturity and understanding composites recycling technologies. This research hopes to inform industry and research organisations on current recycling technology landscape to support decision making for industry-led recycling technology development. The findings from this research are applicable as guidance on potential waste management options to the industries relying on composites material currently and in the future in hope to make informed and sustainable decisions.

For the future research a full LCA (attributional, consequential and impact assessment) could be carried out to reinforce this papers conclusions. It is also important to note the advancements in zero waste research programmes that are cannibalising the area of composite materials recycling by diverting the waste as valuable materials. Therefore widening of scope into considering system level transformation could be additional research consideration and landscaping not only technologies but strategies could be assessed.

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Enquiries for access to the data referred to in this article should be directed to researchdata@cranfield.ac.uk

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