INTERNATIONAL COMPARATIVE STUDY ON FIBER-REINFORCED-COMPOSITE RECYCLING PLANTS TOWARDS THE SUCCESSFULNESS OF CIRCULAR ECONOMY

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ABSTRACT: *The significant growth of fibre-reinforced-composites businesses in critical sectors creates a big challenge to the world sustainability matters in terms of massive waste that is generated. International pressure coupled with landfill restrictions has made recycling a must. However, recent data shows that only 2% of the composites waste is recycled in the UK and the recycling plant itself is very limited in number and operating capacity. This paper investigated the essential information and key features regarding the recycling plant as the integral factors to the success of recycling activities. The operational performance, plant capability, and investment data are studied based on the currently operating composite recycling plants internationally. A questionnaire survey was devised to capture the entire information from the key personnel at the recycling plant who is willing to cooperate before the descriptive statistical analysis was completed to present the finding in a meaningful way. The findings on the existing composites recycling plants' operation showed that the recycling of composites material is progressing well although presently those recycling plants are operating with limited capability at a commercial level. Based on the demand and supply and also the potential future expansion of the new recycling plants, better expertise might be available in a new location with a good capability that would significantly help to improve the recycling percentage of the composites waste. This study would be a reference case for the government, recycler, and related stakeholders in establishing the recycling technology in different regions that would help to achieve the goal of the circular economy.*

KEYWORDS: Composites Recycling; Recycling Plant; Selection Factors; International Comparison; Sustainability; Circular Economy

1.0 INTRODUCTION

A composite material can be defined as a combination of matrix or resin and reinforcement or fibres resulting in a material with superior properties [1]. They are rapidly gaining popularity in engineering production and usage due to their combined lightweight, stiffness, and strength features. Although it is difficult to find absolute statistics on the total global composite production, the composite market is projected to grow from £55 billion in 2016 to £87.47 billion by 2022 [2].

The increasing demand for composites has balanced effects on the generated wastes both nationally and internationally. Halliwell [3] reported that only 0.08% of composite waste is collected in Europe while only 2% at the United Kingdom (UK), a situation indicative of issues with a collection scheme that may not be well-designed or is affected by challenges in the waste post-treatment. There are two types of waste mainly associated with product output: manufacturing waste and end-of-life waste. Carbon Fibre Reinforced Plastic (GFRP) represents about 40% of the UK composite production by value but corresponds to only about 2% by volume since the vast majority is Glass Fibre Reinforced Plastic (GFRP) [4, 5]. Numerous researches has recently been conducted on CFRP recycling due to the cost differentials compared to virgin carbon fibres as well as the value of CFRP being ten times higher than GFRP.

The price for virgin GFRP and CFRP is in the range of £15.30-21.60 and £23.50-26.10 per kg respectively [6]. The Boeing Company estimates the cost of manufacturing virgin CFRP to be in the range of £22 to £44 per kg, while the price range of the recycled version is only £12-18 per kg [7]. Although there is a difference in price, these are still within the current market range in the UK. The ELG Carbon Fiber Ltd, UK compared prices between virgin and recycled CFRP materials and found the former to be £15/kg and the latter at £9/kg. Based on their limited capability, 2,000 tons of CFRP waste are recycled every year at the cost of £0.60/kg, pricing deduced from the electricity and gas costs involved [8]. The limited capacity has prevented many manufacturers from sending their composite waste to this centre although recent research recognized the recycling desirability potential of composites for recycling [9].

1.1. COMPOSITE RECYCLING PLANTS

Recycling is an important stage of a circular economy where the product or material is regenerated after its end of life. A circular economy is where the material is in use for as long as possible, extracts the maximum value from them whilst in use, then recovers and regenerates products and materials at the end of each service life [22]. Mechanical, thermal, and chemical recycling are the main recycling processes available for thermoset composites such as CFRP and are extensively used on GFRP [10]. Mechanical recycling is done by crushing composite waste into smaller particles before being separated into the form of resin and fibrous products. This is the simplest method; however, the downside to this is the method damages individual fibres thereby reducing the mechanical performance [1]. The recyclates from this process are usually used as powdered fillers and possible reinforcement products. Hambleside Danelaw Ltd in Scotland, Filon Products in England, Mixt Composite Recyclables in France, Reprocover in Belgium, and Eco-Wolf in the USA are among companies that utilize this approach [11]. There is an established commercial carbon fibre recycling plant in the UK able to process composite wastes. In terms of capacity, this recycling centre could only take up to 2,000 tons of waste annually. In addition to this, a processing plant able to process 60,000 tons of composite wastes per year was proposed in Germany [13]. The oxidation in the fluidized bed approach is possible for both CRFP and GFRC. The process consists of combusting the polymeric matrix in oxygen-rich airflow at 450-500°C [1]. A higher temperature than this could weaken the material strength. The composite scrap is reduced (about 25mm) into a bed of sand; as a result, it breaks down and vaporizes, releasing the fibres and fillers which are carried in the gas stream. An advantage of this method is its high tolerance of mixed and contaminated materials [14].

For thermal recycling, the processes involved are pyrolysis, oxidation in the fluidized bed, and chemical recycling [1]. In pyrolysis, composite waste is heated at 300-800°C in a non-oxygen environment which results in the polymeric resin being converted into a gas or vapour while the fibres remain inert and could be recovered later. The ELG Carbon Fiber Ltd in England is one such example of a UK recycling company practicing its patented thermal recycling method (Black, 2017). The recycled fibre is sold in milled, chopped, and pelletized forms [8]. Other companies with this approach are Carbon Conversions in the USA, Karborek in Italy, CFK Valley Stade Recycling GmbH and Hadeg Recycling Ltd in Germany and Recycle Industry Co Ltd (Japan) [12].

In chemical recycling, the polymeric resin is decomposed into oils which free the fibres for collection. For example, a solvolysis-based process utilizing the chemical treatment uses a solvent to degrade the resin. This method is however not commercially mature [11]. Of these methods, pyrolysis and solvolysis are the preferred established approaches for composite recycling.

Although the incineration and combustion methods are the other options, these are not classified under recycling technology since both do not involve any material recovery stages. Research and development, however, are rapidly evolving for composite recycling thus there is every possibility of new approaches such as biotechnology methods to be available as research is currently on-going in Germany [15] and high voltage fragmentation [16].

Sufficient amounts of composite scrap would also encourage investors to invest in processing plants and projects. Many parties have demonstrated willingness to invest in composite recycling technology – for instance, in the reuse of composite applications, the Washington-based Composite Recycling Technology Centre received seed money of about £8,000 to reuse carbon fibre for park benches [17]. The proposal to establish new recycling plants involves a considerable amount of investment; as an example, a composite recycling centre in the USA reportedly received £350,000 from IACMI-The Composite Institute as part of a one-year contract to design and build processing equipment for uncured aerospace carbon fibre scrap for high volume manufacturing applications [18]. In Germany, Zajons Logistics' Compocyle business on composite recycling invested about £5.5 million for the construction of a processing plant that is expected to recycle wind turbine blades [13]. A similar investment value of £5.5 million was invented by an inventor in Belgium's Reprocover to recycle fiberglass into useful products [19]. In 2013, Recycling Technologies utilized £3.6 million invested by 140 international backers to develop a pilot rig and laboratory for thermoplastic composite recycling; currently pre-revenue and employing 18, it has forecasted a turnover of £30 million by 2021 and hundreds of jobs as the manufacturer moves to mass-production and a full-fledged assembly plant [20].

The entire progress regarding the composites recycling plant is a positive indication that a large capacity composite recycling plant would soon be available to deal with big amounts of composite waste in the future. However, the important features, critical operational factors, and details information on the current recycling plants are not made known to the public or related stakeholders. Thus, there is urgency for the research to address these concerns to be carried out so the integral operational performance, crucial factors for the recycling centre, and other knowledge on the important elements could be unlocked to establish new recycling plants towards the successfulness of a circular economy.

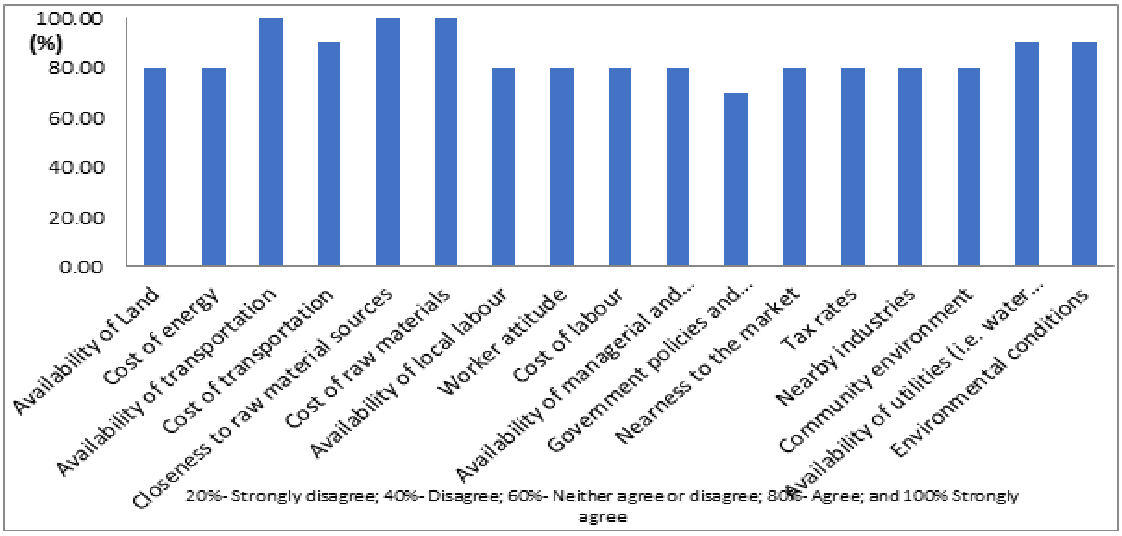

Figure 1: Factors for selecting composites recycling plant.

LOCATION SELECTION

Location selection is crucial to any recycling plant due to many factors. The first section of the questionnaire was related to the factors contributing to the selection of plant location and to what extent those factors are crucially based on the view of currently operating firms. Their previous experience in choosing the location of the existing recycling plant would be an advantage that strengthened the results. Among the factors that were thought to be useful for future development of composite recycling plants in the UK include: (1) cost and availability of land, (2) cost of energy, (3) availability of transportation, (4) cost of transportation, (5) closeness to raw material sources, (6) cost of raw materials, (7) availability of local labour, (8) worker attitude, (9) cost of labour, (10) availability of managerial and technical personnel, (11) government policies and incentives, (12) nearness to the market, (13) tax rates, (14) nearby industries, (15) community environment, (16) availability of utilities (i.e. water and electricity) and (17) environmental conditions [21]

2.0 RESEARCH MOTIVATION AND METHODS

The objective of this study was to identify and compare the critical factors (e.g. location selection factors, driving factors for composites recycling, and composites waste selection criteria) and operational performances (e.g. technology and operational methods, type of processed composite waste, international collaborators, expertise, plants operational capacity, investments, and plants future planning) of the recycling plants at the international dimensions. The research was done by approaching the higher level of management that have a high level of involvement in composites recycling commercially using the questionnaire survey. A five-point Likert scale questionnaire-based survey was chosen as the data collection method was proven reliable and successfully applied in the previous composites recycling research surveys [22, 23].

The questionnaire consisted of 46 questions divided into 11 sections and was aimed at the commercially available composites recycling plants in the United Kingdom, Europe, and Asia (e.g. ELG carbon fibre-the UK, Hadeg-Germany, CFK Valley Stade Recycling-Germany, Carbon Conversions-USA, and Karborek RCF-Italy). The questions made were embedded into the online software with interactive options. The completed online forms are sent to specific recipients with the access link. Only recipients with the access link could answer and return their responses. The returned questionnaires later were analysed using the descriptive statistical method where the results are illustrated in a graphical format to compare the findings between the recycling plants.

3.0 RESULTS

Of the contacted recycling plants, two recycling plants returned the questionnaire, which was completed by the plant's director. Although only two plants responded to the survey with about 33% of response rates this survey would be at a satisfactory level considering only six of the recycling plants are commercially visible in the world. In addition, the information regarding the plants is very difficult to be revealed or made public by the stakeholders due to know-how factors and confidentiality issues.

3.1 Factors in Deciding the Location for the Composite Recycling Plants

The respondents' feedback from the survey on selection factors for the recycling plant's location was summarized in Figure 1. Of all the 17 factors, availability of transportation, closeness to waste resources, and cost of raw materials was considered highly important with 100% of the agreement level. The cost of transportation, availability of utilities and

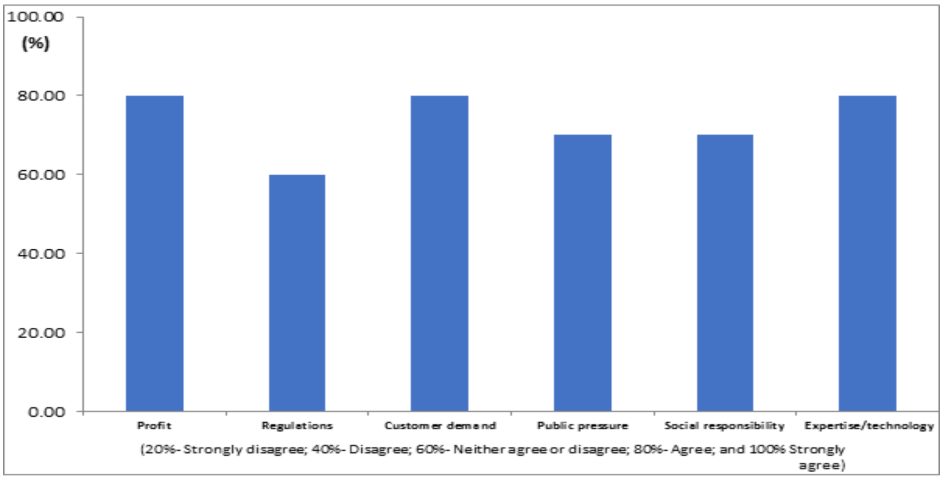

Figure 2: Driving factors for the existence of composites recycling plant.

environmental conditions were considered significantly important with 90% of the agreement level.

The other important factors with about 80% of agreement level for both companies were (1) community environment, (2) nearby industries, (3) tax rates, (4) nearness to the market, (5) availability of managerial and technical personnel, (6) cost of labour, (7) worker attitudes, (8) availability of local labour, (9) cost of energy and (10) the availability of land. The factor that was considered as not really influencing them was the government policies and incentives on recycling or waste disposal.

3.2 Driving Factors for Recycling Practices at the Composite Recycling Plants

The driving factors that lead to the existence of the composites recycling plant were recognized. Those factors were shortlisted as (1) profit from the recycling business, (2) regulation and environmental pressure, (3) customer demand, (4) public pressure, (5) social responsibility, and (6) availability of recycling technology. Of these driving factors (see Figure. 2), the profitability of the recycling firm from the operational activities (80%), the demand from the customer (80%), and the availability of the recycling technology (80%) were agreed to be equally important by both plants. The other three factors were identified as not significant features to drive the firm's effort to operate. The regulation and environmental pressure were ranked as the lowest among these factors.

3.3 Composite waste selection criteria for recycling

The crucial resources for composite recycling plants are waste reclamation. There is different waste acceptance or selection criterion set by the recycling firm depending on the waste stream and recycling technology that are available for the particular recycling plants. Figure. 3 shows that the continuous supply from the supplier of the waste (80%) and the ease of the process (80%) in recycling as the important criteria set by the recycling plants. On the other hand, the quality of the waste that is sent to the plant and the reclaimed material market value were not required by the plant in order to accept the waste for reprocessing. The continuous supply means the recycling firm could operate well and make a good profit while the ease of process eliminates the unnecessary operational cost (e.g. sorting, cleaning, and downsizing).

3.4 Technology operational method at recycling the plant

In order to perform the intended function of the recycling plant, the availability and accessibility of a good recycling technology are crucial. This section will address the operational method used at the recycling plant where both the recycling plants were recognized as operating under a combination of manual and automatic technologies. The advanced recycling technology is the efficient approach to processing the waste but the manual setting and other significant hands-on operations to reclaim the composites waste are still required. For both operations, skilled and competent workers are important to perform such tasks.

3.5 Type of waste processed at the recycling plant

There are different types of waste that were processed at the plant. The wasted resources could be from mixed waste which was sorted at the plant or clean waste which was sorted by the waste supplier beforehand. The former would require additional steps to separate the waste before the processing could take place while the latter would direct the waste to the processing stages. For the composite waste recycling, both recycling plants were accepting mixed waste for processing that was sorted in the plants.

3.6 Availability of local and foreign collaborators at the recycling plant

The recycling technology for composite is progressing at a different level in different countries. This scenario has opened a wide opportunity for companies to collaborate (e.g. technology, expertise, capital, etc.) with both local and/or international collaborators. Based on the survey there was a plant that was currently using both local and foreign collaborators and another plant had been utilizing its internal expertise.

The involvement of the collaborators would be an important feature that depends on the recycling plants' capability and local government policies. This most likely would not be an option for the plant with excellent in-house expertise and strong financial aid.

3.7 Involvement of foreign expertise at the plant

The results identified the availability of international expertise at both plants which includes working personnel, training, consultation, and also advanced recycling technology or types of machinery. The international expertise involved in the plant is not uncommon in the manufacturing sector but this is not the case for composites recycling although the technology is still developing. The know-how factor and novel approach in developing technology may be factors for both companies utilizing local expertise at the moment. Still, there are future opportunities for foreign expertise that may lead to a strong research bonding and contribute to good progress towards achieving better recycling results.

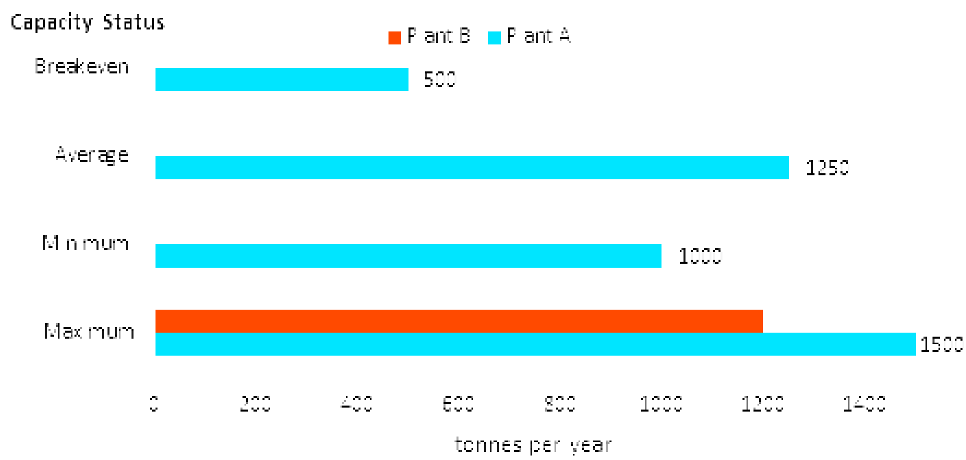

Figure 4: **Plant operating capacity (incomplete information was disclosed for Plant B).**

3.8 Plant's operation capacity

Figure 4 shows the information on the operating capacity of a composites recycling plant. The maximum operating capacity for plant A is 1,500 tons per year and 1,200 tons per year for plant B. As the rest of the information is applicable only to plant A, the average operating capacity is 1,250 tons per year, and the minimum operating capacity is 1,000 tons per year. The recycling plant is required to process a minimum of 500 tons per year to make a profit. Thus, by processing 1,000 tons per year as their minimum operating capacity, it is evident that the recycling plant is doing well economically.

3.9 Plant's investment value and future planning

The information on capital investment by the composites recycling plant was presented in this section. As the financial information of any plant is kept private and confidential, only limited details were provided by plant A. The initial capital investment was about $10 million. The total capital investment was not revealed by both companies. Plant A has proposed new plant development in America and Asia as their potential region for processing composites waste as future planning. No information was disclosed regarding the future planning by plant B.

4 CONCLUSION

The findings on existing composites recycling plants have yielded a significant understanding in terms of the factors that need to be considered by the stakeholders in developing a new recycling facility. The operational experience would help the decision-maker to decide and predict better towards efficiently operating recycling plant as many manufacturing waste companies were already in place to send their composite wastes for recycling. The main findings on composites recycling plants were summarized beneath:

- Availability of transportation, closeness to waste resources, and cost of raw materials were considered highly important for locating the recycling plants
- Profitability of the recycling firm from the operational activities, the demand from the customer, and the availability of the recycling technology were recognized as the crucial driving factors to practice recycling at both plants.
- The continuous supply from the supplier of the waste and the ease of the process in recycling as the important criteria set by the recycling plants.
- The advanced recycling technology is the efficient approach to processing the waste but the manual setting and other significant hands-on operations to reclaim the composites waste are still required at both recycling plants.
- Both recycling plants revealed that they were accepting mixed waste as the type of waste for reprocessing before it was sorted in the plants
- There was a plant that currently using both local and foreign collaborators and another plant had been utilizing its internal expertise. The involvement of the collaborators would be an important feature that depends

- on the recycling plants' capability and local government policies.
- The opportunity led to a strong research bonding among many research bodies internationally made the involvement of international expertise unavoidable and contributed to good progress towards achieving better recycling results but this is not the case for the recycling plants in this study due to knowing how expertise and confidentiality issues.
- As transportation and the distance-related substances to the recycling centre were revealed as important, these factors will be focused for the future research to develop a matrix that can be utilized as a decision model for the recycling plant's location selection
- The authors do not claim that this study is exhaustive as there could be other factors in examining the critical factors for composite recycling plants' operations and performances. Further research and engagements with the stakeholders are important but the current study was informed by first-hand information from the recycling plant directors.
- A study on the key elements of composites recycling plants' operation at the international level has revealed that new findings with critical information are captured (e.g. operating capacity, investments, and future expansion plan of the plants). These unique findings would be the first comparative study regarding the composites recycling plants ever reported and may serve as a vital guide for the stakeholders for the future technology and plant investments.

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