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Recycle potential of thermoplastic composites

Termoplastik kompozitlerin geri dönüşüm potansiyeli

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Abstract

Thermoplastic composite materials have become indispensable for the aerospace industry due to their processing and recycling potentials. The use of recyclable thermoplastic composites in aerospace manufacturing, offers a solution to the composite waste. It is a fact that a lot of waste convenient materials emerge every year. In this study, the advantages of thermoplastic composites being suitable for recycling and the benefits of recycling as a waste management in terms of environment, economy and energy were evaluated. Current outcomes indicate that thermoplastic composites are quite convenient for recycling and reshaping. In this context, the use of recyclable thermoplastics in production provides economic and environmental benefit by reducing the production of zero materials.

Keywords: Thermoplastic composites, Recycle, Composite recycle, Thermoplastic composites recycle, Thermoplastic wastes

Öz

Termoplastik kompozit malzemeler, geri dönüşüm potansiyelleri nedeniyle havacılık endüstrisi için vazgeçilmez bir seçenek haline gelmiştir. Havacılık sanayinde her yıl birçok atık malzemenin ortaya çıktığı kaçınılmaz bir gerçektir. Havacılık ve uzay araçları imalatında geri dönüştürülebilir termoplastik kompozitlerin kullanımı, kompozit atıklara bir çözüm sunmaktadır. Bu çalışmada, termoplastik kompozitlerin geri dönüştürülebilirliğinin avantajları ve atık yönetimi olarak geri dönüşümün çevre, ekonomi ve enerji açısından faydaları araştırılmıştır. Mevcut sonuçlar, termoplastik kompozitlerin geri dönüşüm ve yeniden şekillendirme için oldukça uygun olduğunu göstermektedir. Bu kapsamda geri dönüştürülebilir termoplastiklerin üretimde kullanılması sıfır malzeme üretimini azaltarak ekonomik ve çevresel kazanımlar sağlamaktadır.

Anahtar kelimeler: Termoplastik kompozitler, Geri dönüşüm, Kompozit geri dönüşüm, Termoplastik kompozit geri dönüşüm, Termoplastik atıklar

1 Introduction

Waste management is an important topic in the world. The increasing population and industrialization cause great problems for the environment and has negative outcomes for everybody in our world. One-sided approach is not possible to solve this problem. Waste prevention, waste reduction, recycling, recovery and disposal steps are implemented in the waste management process. As can be seen, the inability to solve the waste problem with a single step has led to the need for an integrated waste management hierarchy. The waste management steps aim to ensure environmental and economic sustainability. According to the hierarchy pyramid shown in Figure 1, the priority and desirability of the options increases from bottom to top.

16.000 commercial passenger and cargo planes have retired in the last 35 years and 700 jets each year where it is about 1260 planes per year [1]. The amount of waste is in just the aviation industry is unbelievable. To manage the waste, as it can be seen from the waste hierarchy triangle first options are prevent and reduce the amount of waste by using the materials with minimum waste through the production phase or the decrease the amount of waste created. Aircraft manufacturers are already pay great attention to this in terms of cost and weight are highly affected from this. Other option is to remove the reusable parts from the scrap aircraft and reuse them for other structures. For example, these parts can be used such as cables, avionics and engine parts in other structures. Recovery and disposal are the last and least favoured options in waste management. Recycle comes as the fourth option where top options of the pyramid are already applied or cannot be applied efficiently. In this aspect recycling is an important waste management method where it is highly developed in the aerospace industry through the years.

Figure 1. The waste hierarchy pyramid

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As the manufacturing methods and materials improved where also, new materials developed through the years, aerospace industry increased its production rates. Different types of materials from metals to composites have become the topic for application of recycle. In this study, as a new aerospace material thermoplastic composites will be investigated regarding to their recycling potential.

2 Recycling applications in the aviation industry

Owing to the research and new applications, the rates of recycling applications are increasing. Considering their recycling processes, a wide range of materials such as; titanium, aluminium, steel, plastic, cables, textiles, are used in building aircrafts. As a result of numerous scientific researches and applications following the completion of the life span of an aircraft, purification of the harmful liquids and radioactive components, disintegration, separation of reusable parts and recycling processes are carried out. Many new organizations and institutions have been founded for the applications. For instance, there is a global organization for the recycling of aircrafts, founded in 2006 by Boeing and 10 aviation companies: AFRA (The Aircraft Fleet Recycling Association). The organization's aim is to guide and promote the best environmental and cost-effective implementation of the recovery and recycling of parts of the aircraft, starting with disassembly. In line with this organization, the shredding and decomposition of a scrap is carried out as shown in Figure 2. This community provides an international perspective to assist the industry in the legal, regulatory, and technical issues of aircraft recycling.

Figure 2. Aircraft waste [2]

The life cycle of an aircraft can be studied in 6 stages: design, manufacture, operation, maintenance, parking/storage and end-of-life (EOL). In many cases, the end-of-life phase is neglected, but the reality of the increase in the number of aircrafts being retired, improvements in design are needed in order to optimize the lifecycle. A common practice at the end of the aircraft's lifespan has been to store it in aircraft graveyards. After being stored in these areas then they recycled. In addition to the end of life, another stage that needs to be considered is the production part. Recycling is very important not only for the retired aircrafts, but also for the management of waste that occurs during the production process of the parts.

Many new improvements are also being made to recycle as much material as possible. One of these improvements, in addition to existing recyclable materials, is the development of new composite materials, which has recently been a major innovation for the aerospace industry. This improvement is the initiation and development of the use of thermoplastic composites, instead of the currently used thermosetting composites, which are a challenge to recycle. Thermoplastics are made up of linear molecular chains, the chemical bonds where constituent the thermoplastics are weak so that, at room temperature they are in solid state then soften and become molten at high temperatures. Melted thermoplastics are extremely malleable and the process of shaping is reversible due to their chemical structure. Thermoplastic composites can be reshaped and recycled using various processes. These two characteristics are their primary advantages over thermoset composites. Usage of thermoplastic composites is revolutionary in terms of recycling in this field. Even though the studies and applications of recycling have not reached a definite method and result commercially, the possibility to recycle is one of the main motivations behind the use of thermoplastic composites in the aerospace industry.

Nowadays, many projects and researches in thermoplastic composites have been carried out due to this important status of thermoplastic composites in the aviation industry. One of them being, the Clean Sky program, which aims to clean up aerospace by producing less greenhouse gasses through aviation practices. In this context, Clean Sky carries out the ECOTECH project. The project to use fewer natural resources and reduce greenhouse gas emissions by recycling composite materials, including thermoplastics, and developing new technologies to achieve cleaner production cycles in the aerospace industry [3]. With their research on thermoplastic composites, Thermoplastic Composites Research Center (TPRC) and accordingly Thermoplastic Composites Application Center (TPAC) come to the fore with the projects they carry out. In 2016 in cooperation with GKN Fokker, scrap PPS thermoplastic material from the elevator and rudder of Gulfstream G650 was recycled and established as an access door panel which was used again in the G650 rudder as shown in Figure 3.

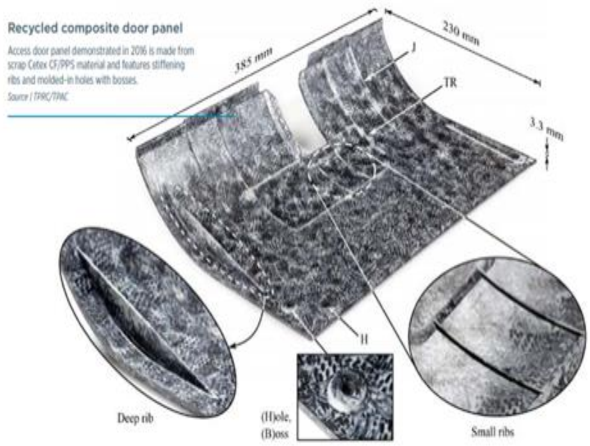

Figure 3. CF/PPS recycled door panel [4]

Likewise, under TPAC with different cooperation of other institutions, the TPC-Cycle project is on the run from 2015 with completed and ongoing projects about recycling of thermoplastic composites [5]. In addition, from Clean Sky, RESET Project which ran between 2016 and 2017, recycling solutions were developed for thermoplastics used in aircrafts. Focusing on carbon fiber PEEK and PPS, this project aimed to compare the properties of recycled thermoplastic with virgin counterparts. Furthermore, the development of new methods and comparison of recycling and production methods in environmental aspects, such as carbon footprint and mechanical properties, is aimed to be achieved [6].

3 Importance of recycling

In proportion to the growing world population, the materials and natural resources consumed for production of plastics and composites are increasing at an enormous scale. The usage of these materials has spread to a wide range of industries, including the aviation and transportation sectors, as well as the renewable energy sector and the products used daily. Mainly polymer-based composites are becoming everyday items to high engineering applications. This means that massive amounts of waste materials awaits to be managed properly. The accumulated composite wastes are much more in comparison to the new composites produced according to the needs. To give an example from the aviation industry, if no recycling is done, 23,360 tons of carbon fiber composite waste is expected to accumulate annually, until 2035, [7]. The increasing waste becomes a global environmental problem in many terms, and recycling is one of the most environmental solution. Traditional waste management methods or EOL which are used for composites are known as landfill and incineration except recycle. These methods are environmentally hazardous in many terms once compared to recycling.

Landfill is a waste management method based on the storage of wastes that are not used, in certain areas. As a result of the accumulation of wastes in landfills and the dissolution of its chemical components over time, a liquid that is very harmful to the environment called leachate is formed. This harmful liquid seeps in to the soil and water of the region around the landfill and causes pollution. Furthermore, since waste materials are not biodegradable, many wastes are mixed into the oceans as a result of the mishandling of landfills. These wastes, which decompose under the sun's rays, form micro plastics; which has serious consequences for animal life, and indirectly for humans; the accumulation of microplastics in to the body has serious repercussions on health [8]. In addition, the European Union (EU) has restricted the accumulation of wastes in landfills with the latest legislations and has subjected it to considerable taxes. According to the laws accepted in 2020, it is obligatory to evaluate and recycle all wastes, suitable for recycling in landfills, until 2030 and only 10% of the waste can be disposed at landfills until 2035 [9]. Laws and regulations lead us to recycle and use the potential of the composite waste. Moreover, thermoplastic and thermoplastic composites are materials suitable for recycling so the potential for recycling is great for these materials. It is incomprehensible that how, especially high-cost fibers and resins, accumulate in landfills and become harmful to humans and our environment. By recycling it is possible to reuse many thermoplastic wastes and to leave our naturepollution-free. From this point of view, recycling can be stated as one of the most environmentally friendly waste management method. Another traditional waste management method is incineration. This is a waste handling practice based on combustion of organic matters in the waste. Although this process provides energy recovery, most of the thermoplastic and composite materials still remain as ash and need to be landfilled. This procedure is highly restricted due to toxicity of the ash and needs to be managed carefully. First of all, burning the plastic or fibers in thermoplastic composites means waste of natural sources, since it is known that for production of a new material fossil fuels are used. Even though this procedure is used to gain energy still the energy and natural sources such as petrol and oil used for the production of the virgin material is lost as a consequence of this process. One of the biggest drawbacks of the incineration is production of chemicals due to the burning of wastes. These hazardous pollutants can be listed as CO_2, dioxins and some particulates which are toxic to health [8]. These toxic gasses are potential causes for air pollution which can result chronic diseases and indirect death. Furthermore, CO_2 is known as one of the greenhouse gasses.

Greenhouse gasses are found in our world naturally and due to human activities and create a glass effect over the world. The sun rays serve as a heat source for earth by providing heat thus warming the weather. Normally the warm air is expected to leave the earth and return back to space. However, greenhouse gasses form a layer in the atmosphere, preventing heat from leaving the world. This causes global warming which is one the biggest environmental problems of our world today. Global warming is an undesirable situation that our world has begun to observe especially after industrialization. Our world is getting warmer as a result of greenhouse gasses which is a result of burning fossil fuels. According to the data in 2020, CO_2 has the biggest portion in global warming, with a 48% increase since the industrialization [10]. So why is global warming undesirable? In fact, our world is naturally warming, and this is normal. Though, following the increasing industrialization, greenhouse gasses increased the heat of the world to high levels in a short time. The change in the temperature of the world causes the climate change that we are experiencing now and that will worsen gradually if precautions are not taken. Climate change is an important global environment problem in which many countries acted for prevention. Ever since 1992, the United Nations Framework Convention on Climate Change (UNFCCC) has organized climate summits. The first of these summits resulted in the Kyoto protocol signed in 1997. With the Kyoto Protocol the very first steps were taken worldwide to reduce greenhouse gas emissions to prevent climate change. According to the Paris Agreement signed in 2015, a limit which is 2°C put into global temperature rise and if it is possible keep it below 1.5°C [11].

As it can be seen, while our world is trying to cope with many problems, the indirect and direct effects of burning wastes to our environment cannot be denied. Also, by burning composite waste we directly disregard the potential of the materials. The production cycles need to be repeated which means more greenhouse gas emissions and more usage of natural sources. Thus, traditional and environmentally harmful waste management methods should be left behind and composite wastes should be evaluated by recycling. Thermoplastic composites come into prominence today because they are suitable for recycling in compare to other waste types. Therefore, recycling these wastes can be defined as the most valuable method for the environment. In Figure 4 comparison of traditional waste management methods over recycling in terms of environmental perspective is given. As it can be seen from Figure 4, environmental and health related factors are most badly affected by other methods whereas in recycling all the environmental and health related points are minimally affected.

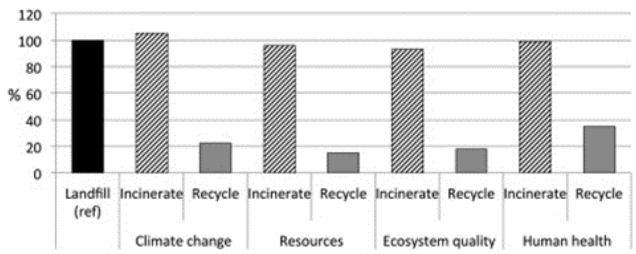

Figure 4. Comparison of the impact of waste management methods for composite waste [12]

Traditionally, thermoset matrix is used for composite applications but in recent years, thermoplastic matrix with the advantage of being environment friendly is getting popular in different industries such as aerospace and transportation. It may be a proper question to ask now, why are thermoplastics considered as environmentally friendly, and why is it important to be sustainable? Because thermoplastic polymers can be shaped again under temperature, recycling only by injection molding or extrusion methods is applicable for any type of materials such as scraps or end of life composite parts.

The growing problem of waste composite may be solved by the usage of recyclable thermoplastics. To give an example from the aerospace industry, the prepreg materials used based on thermoset matrices have a shelf-life and this limited time interval for consumption sometimes ends up with the scrap of the material. Also, the curing reactions for thermoset composites requires usage of autoclave in which throughout the process hazardous gas emissions occur. Similarly, it needs to be held in freezers which requires extra usage of energy [13]. Moreover, many of thermoset composites end up as scrap since they are not recyclable because during production many mistakes can occur and these cannot be undone. Increasing the amount of composite and plastic materials means to produce more products and the usage of natural sources such as petrol, oil and increasing the rate of CO_2 emissions which is one of the main environmental problems related to these materials. Because our world is one and only planet that we can live and there are not unlimited sources anymore. Also, carbon dioxide, methane and other greenhouse gasses cause global warming and climate change. By wasting materials and producing more, our environment is deeply affected. However, thermoplastic matrix theoretically provides unlimited storage duration and does not require special storage conditions which prevents materials to be scrapped even without using. Also, by faulty forming any mistake through production of these materials can be corrected without being listed as scrap.

By recycling and the recyclability of thermoplastics, the cycle of processes to produce virgin materials are eliminated so reduced scrap material and recycled composites means saving of natural sources and reduced carbon footprint to produce new materials. In Figure 5, CO_2 emission comparison of recycled and virgin thermoplastic polymers is given. As it is stated previously by recycling, environmental impacts of production cycles directly lower such as carbon footprint. Less CO_2 emissions mean less impact over global warming and climate change. Thus, it can be said that by recycling thermoplastic composites environmental benefits in many aspects are ensured, and it is necessary to recycle wastes before producing new materials for our environment.

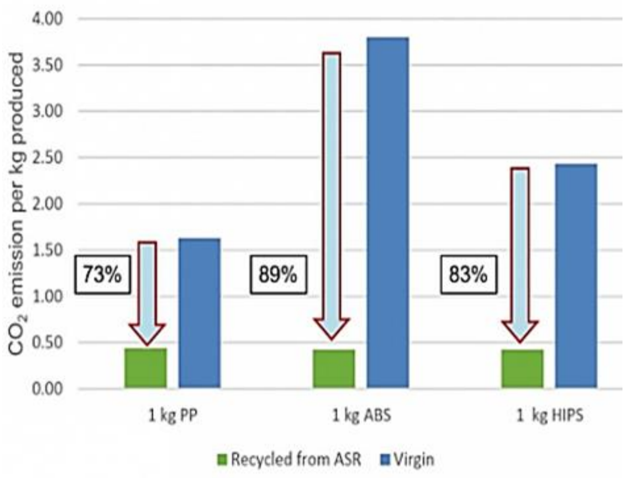

Figure 5. Carbon footprint comparison of recycled and virgin thermoplastic polymer [14]

Another main reason for recycling is energy. When examined with many different approaches, recycling leads to power savings. Since the amount of energy required for reprocessing is less than the energy required for production from original materials, it provides power savings. The concept of embodied energy is also included in the importance of recycling in this section. Embodied energy is the energy associated with the production of a product or service. This refers to the power used to complete a material's initial process, which includes the extraction and processing of raw materials, the manufacture of materials, transportation and distribution, assembly, and installation. As shown in Figure 6, while the energy requirement for the production of a virgin material is quite high, recycling processes require less, under all conditions, although the requirements vary according to the method chosen for recycling.

The concept of embodied energy through thermoplastics can be examined in two stages, from the extraction of the raw material to its transformation into thermoplastic resin and the energy required for the process of the part to be produced from the thermoplastic composite. First of all, thermoplastics consist of organic components. Petroleum, which is a raw material that must be extracted from the ground and processed to become a thermoplastic resin. Thermoplastic production starts with the distillation process that takes place in an oil refinery. In the process, the work of separating the heavy crude oil into lighter groups called fractions, is done. After distillation, components such as naphtha, LPG, and gas oil are formed.

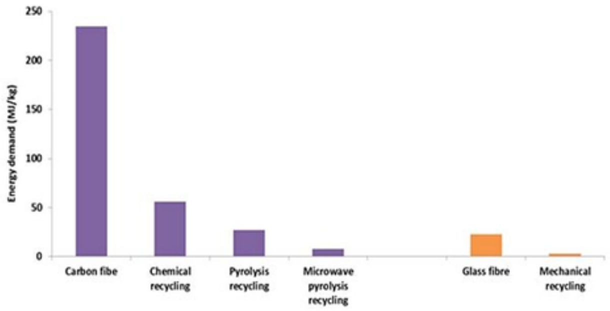

Figure 6. Comparison between average embodied energy of fiber production and potential recycling processes [15]

One of these fractions, naphtha, is the main material of polymers. Polymerization and polycondensation processes with certain catalysts are the two main processes used in polymer production. Monomers such as ethylene and propylene are linked together in the polymerization reactor to form long polymer chains. As a result of these processes, various polymers are formed depending on the type of monomer used. Thermoplastics are one of these polymers. For these processes, energy is needed at many stages such as drilling, heating, separation, and transportation. When the existing thermoplastic composite wastes are recycled, all this process and energy needed for virgin thermoplastic will be eliminated. Virgin thermoplastic production needs will decrease, and extra energy requirement for new material will be saved by recycling of thermoplastic materials.

With this approach, besides the energy required for thermoplastic production, the amount of crude oil used will be saved. Thus, energy and oil refinery will be transferred to other sectors and efficiency in the general industry will be achieved. The graph in Figure 7, arranged with reference to thermoplastics in the packaging industry, obviously shows the savings to be made from fossil fuel consumption. Approximate ratios are expected to be provided for other thermoplastics as well.

Secondly, when the embodied energy concept is evaluated in terms of the process of thermoplastic composites, it appears that unlike thermosets, there are no long curing requirements. Thermoplastic composites can perform the consolidation process, which they perform instead of curing requirements, in autoclaves and ovens in a shorter time. Accordingly, a significant amount of energy required for furnaces and autoclaves is saved in the production of thermoplastic composites.

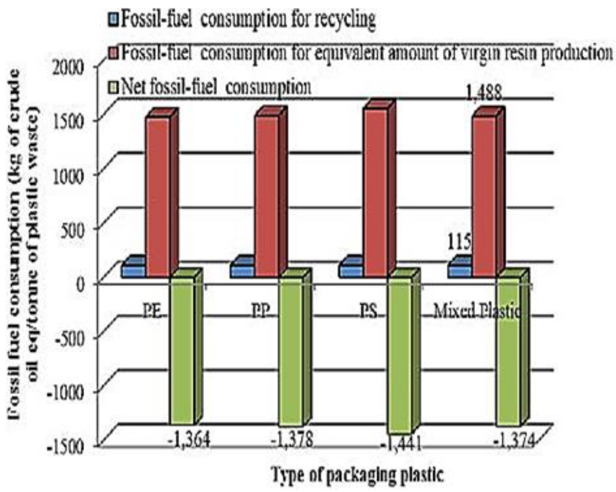

Figure 7. Comparison of virgin and recycled thermoplastics in terms of fuel consumption [16]

As seen in Figure 8, saving from the autoclave process, where the greatest energy requirement in production is experienced due to the short consolidation time, leads to an energy saving of around 75%. Considering the savings in autoclave and furnace time as different processes on the basis of the production of virgin thermoplastic materials, recycling processes and production of recycled materials, a serious energy saving is achieved.

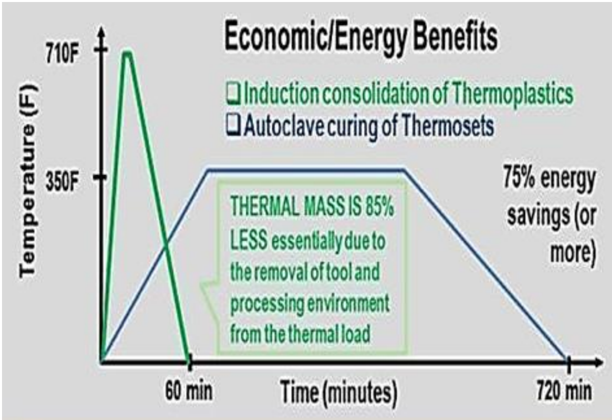

Figure 8. Comparison of autoclave requirements of thermoplastics and thermosets [17]

Composite materials have many advantages and are frequently used in various industrial fields. However, composite materials are economically expensive materials. For example, the cost to produce a steel pipeline is £3,000,000, while the cost of producing a composite pipeline of the same length is expected to be around £10,000,000 [18]. The composite parts are used in aviation, defence, automotive, rail, and construction industries. The highest production cost is seen in the aerospace and defence industries [19]. Due to the growing interest in composites and the increasing use in the future, the recycling of composites has become mandatory. The decrease in raw materials causes material prices to increase. In addition, some countries have a landfill tax and a landfill ban. These taxes are 3€ per ton to more than 100€ per ton depending on the type of waste [20]. The recycling of thermoplastic materials, which is one of the composite classes, is extremely important in order to conserve economically. The decrease in the use of natural resources and energy consumption contributes in considerable levels to the economy of the countries. One of the ways to manage economic income, is to obtain new products through recycling. By doing so, instead of throwing away waste, it is ensured that material value is brought back in the economy. The raw material obtained as a result of thermoplastic recycling can be evaluated by selling. It is also possible to transform the waste thermoplastic material into another product and with these products, extra income can be provided. Storing waste materials is also a costly process. As shown in Table 1, Boeing predicts that CFs can be recycled for roughly 70% of the cost of producing virgin fibers [21].

Table 1. Cost comparison of virgin and recycled carbon fiber [21]

	Cost to manufacture	
	Materials	Energy in kWh/kg (mj/kg)
Virgin carbon fiber	US$ 33-66/kg	55-165 (198-594)
Recycled carbon fiber	US$ 13-19/kg	2.9-9.9 (10.3-35.7)

To put in other words, the circular economy reduces waste and increases the maintainability of products. The circular economy is a production and consumption model that includes the reuse, repair, and recycling of thermoplastic material and reducing waste and increasing the maintainability of products. In this way, the life cycle of the products is extended and provides economic gains. In the linear economy model, natural resources are converted into thermoplastics and are destined to waste after use. Figure 9 shows why the global economic model is superior to the linear economy model.

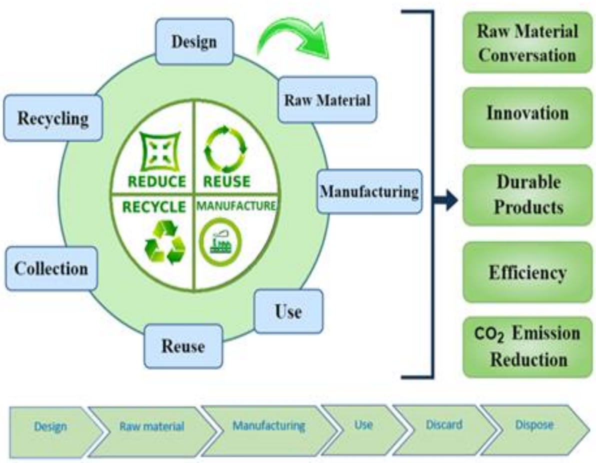

Figure 9. Circular and linear economy models

The economic efficiency also varies according to the selected recycling method, and the type of material to be recycled. It is necessary to choose a method suitable for the material. Recycling provides benefits in many ways. As shown in the Figure 9, the reprocessing of thermoplastics provides advantages in many aspects, such as obtaining raw materials for industry, reducing the environmental risk to living things because it is biodegradable, reducing incineration and storage problems, providing less energy consumption, and generating income by offering a new business opportunity for people.

4 Conclusion

Today, depending on the increasing usage of composites, waste generation has reached an incredible magnitude. On this basis, the aerospace industry has an important contribution with its increasing composite consumption. Waste management is an issue which its importance is being understood. Composite waste has become an important problem, and a huge burden on the environment and economy. Incineration or disposal of waste causes environmental pollution and loss of the potential of raw materials. The energy and raw materials lost through manufacturing of virgin materials increases the carbon footprint, the burning of wastes or the manufacturing of virgin materials processes increases the greenhouse gasses and causes irreversible environmental problems. One of the most important examples of this can be given as the problem of climate change. From this perspective, the recycling method in the management of composite waste has important environmental and economic advantages. The energy and resources that will be lost by the landfilling or incineration are evaluated and recycling provides great advantages to the environment and economy. Thermoplastic composites are materials that are suitable for recycling and reshaping due to their structure. Within this context, the use of recyclable thermoplastics in production provides economic and environmental gain by reducing the production of zero materials. Since their wastes can be reshaped, thermoplastic composites have taken their place in studies in the aerospace industry as potential materials that are highly suitable for recycling.

Conflict of interest

The authors declare that there is no conflict of interest.

Similarity rate (iThenticate): %5

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