

Abstract

Rubber recycling is a growing industry, as the demand for recycled rubber products increases. However, the current rubber recycling process is not without its challenges. One of the biggest challenges is the high energy consumption required to granulate rubber. This is due to the fact that rubber is a tough material that is difficult to cut.

In this study, we investigated the effects of modifying granulator settings on the quality of crumb rubber produced. We found that by adjusting the speed of the rotor, the size of the knives, and the air flow rate, we were able to produce crumb rubber with a more consistent size distribution. We also found that the modified granulator settings resulted in a lower energy consumption, which is a key factor in the economic viability of rubber recycling. Overall, our findings suggest that modifying granulator settings can be a promising way to improve the energy efficiency of the rubber recycling process. This could lead to significant cost savings for rubber recyclers and help to make rubber recycling more sustainable.

We also discussed the future developments like digital twins that can help in the rubber recycling process further helping in reducing the carbon footprint and move towards a sustainable world.

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Chapter 1: Introduction

The growing concerns over environmental sustainability have prompted increased attention towards recycling and waste management practices across various industries. As the global community strives to mitigate the adverse effects of climate change and reduce the burden on natural resources, it becomes imperative to examine and optimize recycling processes in diverse sectors. This dissertation focuses on a significant aspect of the sporting goods industry: the recycling of table tennis rubber rackets and sponges in the United Kingdom.

Despite the relevance of recycling in modern waste management strategies, there exists a scarcity of comprehensive research on the recycling of table tennis rubber rackets and sponges. With the UK's commitment to achieving ambitious climate change goals and enhancing resource efficiency, understanding the current state of recycling practices for these materials becomes critical. This research aims to fill this gap by investigating the effectiveness of existing recycling processes and exploring opportunities for improvement in the context of environmental benefits and economic potentials.

Used tyres, rubber pipes, rubber belts, rubber shoes, rubber technical items, and rubber waste generated during the manufacture of rubber products are all examples of rubber waste. A sizeable portion of all waste rubber products are used tyres. Currently, over 15 million tonnes of natural rubber are consumed annually, and over 31 million tonnes of rubber products are produced globally (ETRMA, European Tyre & Rubber Manufacturers' Association, 2019). However, processing such large amounts of garbage is a major problem everywhere. Additionally, due to environmental issues and high recovery costs, several current options for the disposal of old tyre debris, such as landfilling or incineration, are becoming less and less practical.

Additionally, the limited reuse of tyre waste permitted by the present recycling processes for used-tyre trash makes other solutions necessary. Devulcanization and reuse of rubber to

create new industrial goods is the most effective choice in terms of protecting the environment (Dobrotă and Dobrotă, 2018, Amza et al., 2008, Mishra and Siddiqui, 2014).

1.1. Objectives of the study

The primary objectives of this dissertation are as follows:

- To research and analyze the current state of rubber racket and sponge recycling in the UK.
- To identify challenges faced in the recycling industry and opportunities for enhancing the recycling process.
- To evaluate the environmental impact of recycling table tennis rubber rackets and sponges, particularly in terms of reducing hazardous waste and conserving resources.
- To explore potential economic opportunities associated with improved recycling practices in the UK.
- To consider the feasibility of creating a digital twin to optimize and streamline the recycling process

1.2. Scope of the Study

This research will focus specifically on table tennis rubber rackets and sponges used in the United Kingdom. The study will involve a comprehensive review of existing literature, data collection from recycling facilities, and analysis of environmental impact assessments. The economic opportunities arising from recycling these materials will be assessed, and the feasibility of implementing a digital twin for process optimization will be explored.

Chapter 2: Organisation of the report

- Chapter 1: Introduction
Introduces the research topic, its significance, and the objectives of the dissertation.
Provides the rationale for the study and the specific project outcomes to be achieved.
- Chapter 2: Organisation of the Report
Outlines the overall structure of the dissertation and explains the purpose of each chapter.
- Chapter 3: Background
Covers a brief background about Racket composition. Conducts an in-depth review of existing literature related to table tennis rubber racket and sponge recycling.
Explores the current state of recycling practices, environmental impact, challenges, and opportunities.
- Chapter 4: Methodology
Describes the research methodology employed in the study, including research design and process.
- Chapter 6: Discussion
Clarifies the approach used to evaluate the effectiveness of current recycling processes and explore improvement opportunities.
Discusses the implications of the using Digital Twins in recycling process, linking them to the research objectives and the broader context of environmental benefits and economic opportunities.
- Chapter 7: Conclusion
Summarizes the key points and contributions of the dissertation.
Restates the significance of the research outcomes and their alignment with the project objectives.
- Acknowledgements

Acknowledges individuals, organizations, or institutions that provided support, guidance, or assistance during the research process.

- References

Includes specific references cited within the dissertation following the appropriate citation format.

- Appendices

Contains additional materials, data, or information that supports the findings but is not included in the main body of the dissertation.

Chapter 3: Background

Table tennis, also known as ping-pong, is a widely popular sport enjoyed by millions of enthusiasts around the world. The rubber racket and sponge play a pivotal role in determining the game's speed, spin, and control, making them essential components for every player. However, the disposal of these materials at the end of their life cycle poses environmental challenges, with potential hazardous waste entering the ecosystem and contributing to landfill accumulation.

The table tennis racket is composed of three parts: the bottom plate, the rubber and the sponge. The reasonable combination of the three determines the quality of a racket.

Wooden pat: The quality of softness and hardness will be different due to the difference of wood. The slightly harder wood is suitable for fast attack players, and the slightly softer wood is suitable for loopers and slicers.

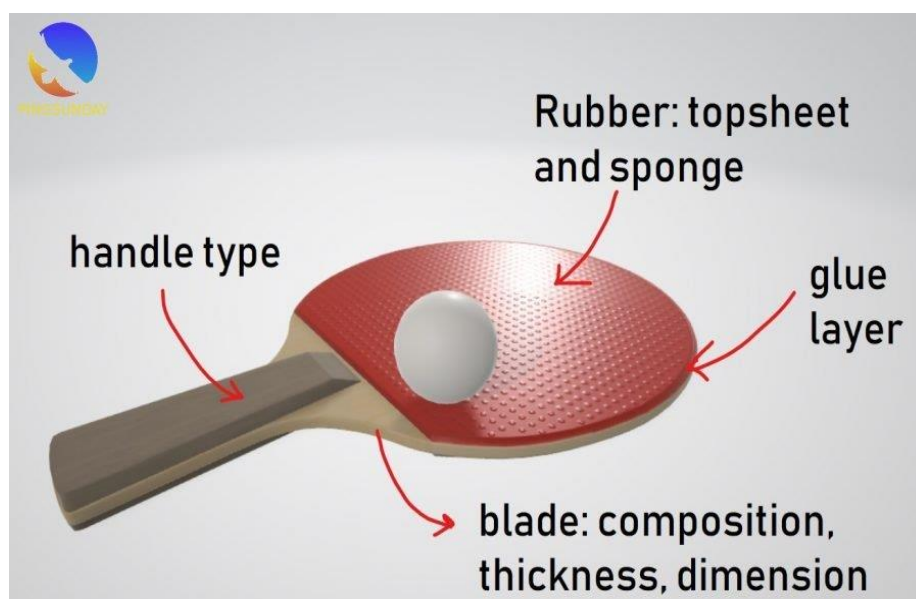


Figure 1: Material Composition of Table tennis racket

Rubber: There are two types of positive stickers and reverse stickers (long stickers are one type of positive stickers).

Sponge: There are thickness and soft and hard points. Thick sponges will be faster than thin sponges. Due to the different feel of each person, when choosing the softness and hardness

of the sponge, it depends on the personal feeling. Generally speaking, there are fewer users of sponges that are too hard, and junior golfers are more suitable for using slightly softer sponges, which can improve the feel of the hand when hitting the ball.

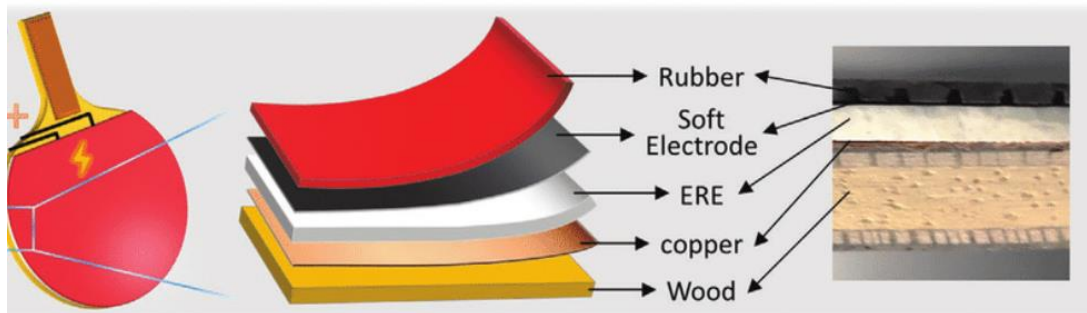


Figure 2: Detailed description of the layers of racket

The wooden sandwich panel used in table tennis rackets is covered with rubber and sponge, and it has proven to be an amazing design for the game. Athletes may easily defend themselves thanks to the rubber and sponge dampening component on the hardwood plate, which delivers elastic force for quick offence. Rubber can be thought of as acting as the "bodyguard" for wood and bamboo due to its unique benefits of high compressive performance, low moisture absorption, good damping vibration attenuation, excellent energy absorption, characteristically large elastic deformation, better sound insulation, good durability, abrasion resistance, anti-caustic and anti-rot properties.

As a result, the rubber-wood-bamboo hybrid composite laminates would possess many functionalities and have a great deal of potential for other applications (container soleplate, train car flooring, manufactured building, etc).

3.1. History of Rubber recycling

Industrial rubber recycling is almost as ancient as industrial rubber production. Charles Macintosh required more rubber in 1820 after he began using rubberized fabric to make raincoats than he could import. His research partner Thomas Hancock came up with a solution. He created a device that can ground up rubber scraps left over from creating raincoats. These leftovers were then ground up into bigger rubber blocks that could be used

again during production. The device used for this task was known as a "masticator" or "pickle" because it effectively chewed the rubber scraps into tiny pieces.

The days of simple rubber recycling, meanwhile, were brief. Rubber recycling is made more challenging by the vulcanization process that enabled most of the contemporary rubber industry. Rubber cannot be melted down again and moulded into a new product after it has been vulcanised. This is due to the process of vulcanization, which joins all the molecules in a rubber product into a single, large molecule that will not readily separate.

Due to the high cost of rubber, whether natural or synthetic, recycling was still a sound short-term financial decision in the 20th century. In 1910, the price of an ounce of rubber was equal to that of an ounce of silver. That is one of the reasons why all rubber goods had an average recycled content of over 50% long into the 20th century. However, by 1960, just 20% on average of rubber goods were made using recycled materials. This is as a result of decreased production costs brought on by imports of cheap oil and rising synthetic rubber use. By the 1960s, steel-belted radial tyres had nearly put an end to the rubber recycling business. This is due to the fact that it made it extremely expensive to slice and grind tyres for rubber.

3.2. Literature Review

Industrially rubbers are manufactured at a low cost through an efficient but irreversible process called vulcanization. Vulcanization can be defined as the creation of three-dimensional crosslinked network between rubber macromolecules via irreversible reactions, in the presence of curing agents (sulphur, peroxides), activators (stearic acid, zinc oxide), accelerators (thiazoles, sulphonamide), retarders (*N*-cyclohexylthio phthalimide) and other additives (Luna et al., 2020; Junkong et al., 2020). The sulphur vulcanization creates strong chemical bonds, and the sulphur content strongly dictates the resulting structural and physical properties of the rubber vulcanizates (Sienkiewicz et al., 2017; Yangthong et al., 2020).

In contrast to thermoplastics, rubber goods like tyres are therefore difficult to reprocess since they are insoluble and infusible (Sienkiewicz et al., 2012). Global industrialization is also causing the automobile industry to rapidly expand, which in turn is increasing the manufacturing of tyres, which now totals around 1.5 billion units annually (Czajczyska et al., 2017; Simon-Stger and Varga, 2021). As a result, a lot of end-of-life tyres are produced since they take millennia to naturally disintegrate (Gupta et al., 2012; Liu et al., 2020).

Traditional waste tyre disposal and unregulated burning are serious risks to people and the environment, drawing international attention (Ghosh et al., 2020). There is no known efficient method to totally recover elastomeric waste monomers, unlike thermoplastic waste that is utilised to create new products with additional value (Adhikari et al., 2000). This reduces the recycled rubber's commercial viability. Thus, the environment's conservation is altered by the large-scale disposal of such elastomeric materials. However, incorporating the GTR into thermoplastic matrices to create blends is a commendable alternative method of repurposing worn-out tyres (Simon-Stger and Varga, 2021). This strategy is gaining traction in scientific studies since it is the most simple method for recycling rubber. It is affordable, simple, and kind to the environment. Furthermore, according to Karger-Kocsis et al. (2013), it utilises a sizeable amount of waste rubbers in the form of GTR. More crucially, the eco-sustainability goals are supported by the renewability and recycling of thermoplastic matrices (Nuzaimah et al., 2018; Ramarad et al., 2015; Sanusi et al., 2020, 2021a).

3.3. Rubber recycling in UK

The success of the UK's tyre recycling programme, which allowed the nation to consistently meet the requirements of the EU's Landfill Directive, was cited at the Tyre Recovery Association annual forum in 2011 as being critically dependent on the combination of successful partnerships, participation, and proactive involvement from many organisations across the tyre and reprocessing industries. The attendees of this meeting were told that in 2009, the UK was able to reuse almost 480,000 tonnes of scrap tyre materials. This

contrasted quite positively with the rest of the EU, where Germany, which has a larger automotive sector, recycled around 570,000 tonnes more tyres in the same year.

The European Tyre & Rubber Manufacturers' Association (ETRMA) has released statistics that break down what happened to these discarded tyres in the UK. According to this data, of the 480,000 tonnes, 8.5% of the tyres were retreaded, 45.1% were processed again to create new goods and materials, 24% were utilised as a source of energy, and the remaining materials were exported or used again in some other way .

The main tyre companies in Europe have established "Producer Responsibility" organisations to collect and recycle their used tyres, and they pay for this operation up front using a fee added to their customers' bills. Because not all tyres and tyre brands are covered by these initiatives, there are issues. This price then funds a nationwide free recovery network.

The automobile industry, together with the transportation industry as a whole, is thought to account for around 70–75% of all rubber products manufactured, according to a piece of EU law that has had a significant influence on encouraging rubber recycling. This legislation, known as the End-of-Life Vehicle Directive (2000/53/EC), set escalating targets for the recycling of car components, culminating in a final target of 95% for all car components, to be achieved by the first of January 2015. This was done in recognition of the significant contribution that end-of-life vehicles make to the use of landfill space.

Other significant initiatives are also being undertaken in this regard, such as the collaboration between Ford, General Motors, and Chrysler known as the Vehicle Recycling Partnership, which aims to find the most effective method of disassembling and recycling automobile parts.

3.4. Current State of Rubber Recycling

Over 25 distinct varieties of rubber are typically available, including natural rubber (NR), styrene-butadiene rubber (SBR), nitrile, ethylene-propylene-diene monomer (EPDM) rubber, fluorocarbon rubber, silicon, and many more, which are used to make a variety of goods. The trash produced by this rubber includes scrap tyres, inner tubes, rubber gloves that are discarded or rejected, balloons, rubber bands, shoe bottoms, mattresses, hoses, seals, gaskets, diaphragms, and more.

Only 1.7 million tonnes of the 9.2 million tonnes of rubber trash generated were determined to be recyclable. Taking into account simply the quantity used for landfills and energy recovery, this statistic represented only 40% of the total tyre trash produced. In 2018, 7.2% of rubber waste was burned for energy recovery and 3.4% was disposed of in landfills. In addition to tyres and home appliances, 30% of the rubber market is made up of consumer products including shoes, toys, sporting goods, and leisure items as well as general rubber goods like belting, hoses, and tubes. However, there is currently relatively little effort put into recycling the trash produced by the general rubber products business.

Only 1.5% of the trash produced is recycled or reused from typical rubber products. The lack of industrial interest in recycling trash from ordinary rubber items has a variety of causes. These factors are also restricting the use of circular economy in the field of rubber goods in general.

It is generally known that polymer biodegradation takes a long time and has negative consequences on the environment. Therefore, the disposal of polymer wastes is a significant environmental concern. The majority of the rubber in tyres comes from polymeric polymers. About 26.7 Mtons of rubber materials were produced worldwide in 2017—12.31 Mtons of natural rubber and 14.46 Mtons of synthetic rubber. Waste rubber goods come in many different forms, including old belts, shoes, and rubber pipes. The primary use of rubber (65%

of worldwide output, however, is in the tyre industry, which also produces the most rubber waste. Consequently, recycling rubber is sometimes referred to as recycling tyres.

Currently, 1.5 billion tyres per year are wasted globally, and up to 90% of those tyres include vulcanised rubber that is difficult to recycle (reprocess) because of its intricate crosslinking . Since these thermoset materials can withstand extreme mechanical and thermal conditions and do not vary with temperature, vulcanised rubbers are utilised in the production of tyres. Tyres' mechanical behaviour and longevity are influenced by their chemical makeup.

The vulcanised rubber compounds are made resistant to biodegradation, photochemical breakdown, chemical reagents, and thermal degradation by using various additives like stabilisers, antioxidants, and anti-ozonants. The tyre industries are faced with a significant challenge as a result of this complicated formulation: effective, affordable solutions for recycling used tyres. The simplest method for getting rid of used tyres is to place them in a landfill. There are, however, a number of negatives. For instance, impermeable used tyres might retain water for a long time and serve as breeding grounds for mosquito larva, which are responsible for illnesses like dengue and malaria. End-of-life tyre recycling for pyrolysis and energy recovery has been the subject of several studies.

The traditional approaches to waste management mostly concentrate on gathering, burning, and disposing of the garbage (open dumping, landfills). These practises have stifled the development of integrated waste management strategies that try to decrease trash at the source, such as recycling and resource recovery. Industrial and consumer rubber waste are separate categories. Cleanliness and separation of the produced trash are essential for effective waste management because they make it simple to identify the industrial waste scrap for further waste treatment. However, with consumer waste, this is not the case. The most popular disposal techniques, regardless of the kind of rubber waste produced, are, however, open dumping, landfilling, burning, and grinding the rubber waste into powder.

Tyres and other disposable rubber debris serve as a breeding habitat for several mosquito species that transmit illnesses including malaria, dengue fever, and chikungunya. Snakes and rodents that spread diseases reside in waste tyres. These techniques are inherently incapable of reducing rubber waste, which leads to large dumpsites where the rubber is piled high. These waste sites run the danger of starting a fire that would burn for days or perhaps weeks. Tyre fires are also exceedingly difficult to put out because, even after being put out from the exterior, they keep burning within and are easily re-ignited.

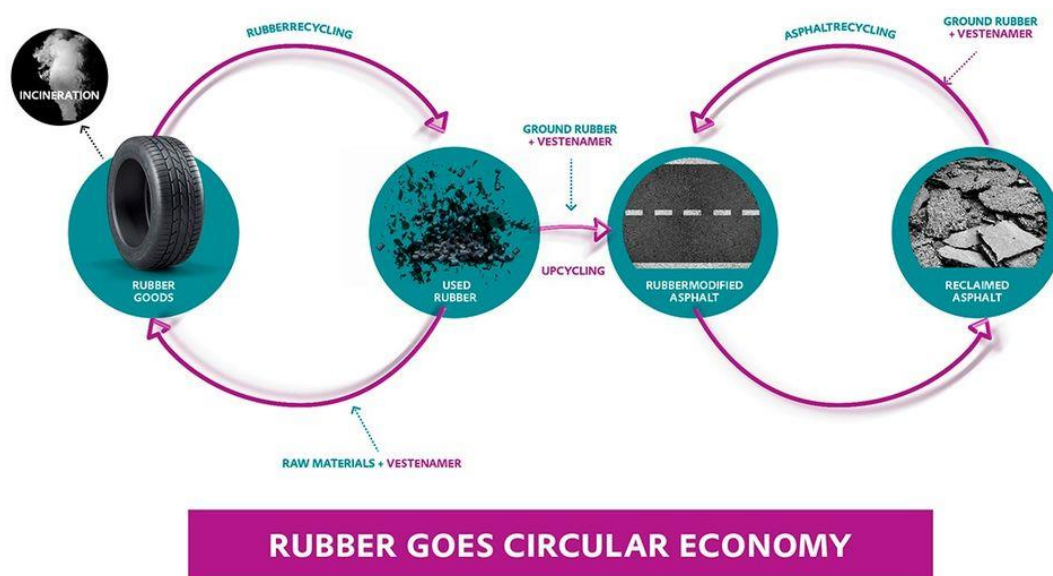


Figure 3: Circular economy of rubber

However, a wealth of research demonstrates that the sustainable treatment of waste rubber has advanced significantly. Reuse, recycling, recovery, and pyrolysis are significant steps performed by the researchers to ensure sustainable management of these rubber wastes. Tyres may be reused by simply being retread and put back into use. Utilising the rubber in various ways, such as in marine conservation programmes (as an artificial reef, erosion control, breakwaters, and floating devices), counts as recycling waste rubber.

In addition, the waste rubber can be ground up and the resulting particles added to matrices like concrete or polymer for use in civil engineering, or they can be made into entirely new products like playground surfaces and athletic tracks, or they can be used as filler in

rubberized composite, among other things. In addition, recovery is a technique that uses waste rubber as a fuel source for high-temperature processes like steam generation, electrical energy production, cement kilns, and so on. While pyrolysis breaks down rubber components like steels, gas, oil, and its filler like carbon black to produce the fundamental compounds in rubber waste.

Waste tyres have been utilised for energy recovery since they contain more than 90% organic components and have a heat value of 32.6 MJ/kg (coal has a heat value of 18.6-27.9 MJ/kg). For instance, using scrap tyres as a fuel source in cement kilns is more ecologically beneficial than burning coal. The manufacture of steam, electricity, pulp, paper, lime, and steel all require scrap tyres as fuel. However, burning tyres as fuel only recovers 25% of the energy required for the manufacturing of rubber and produces harmful pollutants . In addition, the rubber component of scrap tyres is broken down during pyrolysis to yield carbon black, zinc, sulphur, steels, lubricants, and gas.

The widespread use of this technology is however constrained by the high running expenses of the pyrolysis plants. Triboelectric separation, froth flotation, and laser-induced breakdown spectroscopy are a few processes for recycling that are ecologically acceptable. These techniques are pricey, though, and the recycled rubbers that are produced differ in terms of quality, size, form, and surface topography. Vulcanised waste rubbers may be employed as suitable fillers in the creation of composite materials, despite the fact that they are challenging to recycle.

3.5. Process of rubber recycling

Recycling scrap rubber tyres entails turning them into components that may be used to make new goods. The practise of recycling old tyres from cars that can no longer be utilised on them owing to wear and tear or irreparable damage is referred to as recycling waste rubber tyres. Among the most problematic and difficult sources of solid waste are old, used tyres. The processes for recycling used rubber tyres are as follows:

Step 1 :- Collection of waste rubber tires

The first step is gathering your unwanted rubber tyres for recycling. These components occasionally arise from landfills. People may dump it and send it to the recycling facility.

Step 2 :- Shredding of waste rubber tires

Making minor cuts to them is the following step. To make tyre material that can be handled easily, tyres are shredded to minimise their size. Additionally, there are two ways that tyres can be processed: mechanically or cryogenically.

Mechanical shredding of waste rubber tire: At room temperature, the mechanical device shreds used tyres into smaller bits. The trash may be chopped into smaller and smaller bits as the fibre is removed, depending on the intended use of the recovered rubber. The finished product, known as "crumb rubber," is available in a range of sizes based on the size of the crumbs.

The crumb gets smaller as the mesh size increases. because producing larger grit crumbs requires more grinding.

Cryogenic shredding of waste rubber tire: The process is called 'cryogenic' because the temperature here can go as low as -80 degree Celsius to -120 degree Celsius. Shredded or the whole tire is cooled to -120 degree Celsius and it becomes glass hard and brittle. It is crushed or grounded to a fine size of 50-250 mm in special mills. Compared to the standard

procedure, this one uses less apparatus and energy. Using this method makes it simpler to separate steel and fibre from the rubber, giving us a cleaner end result.

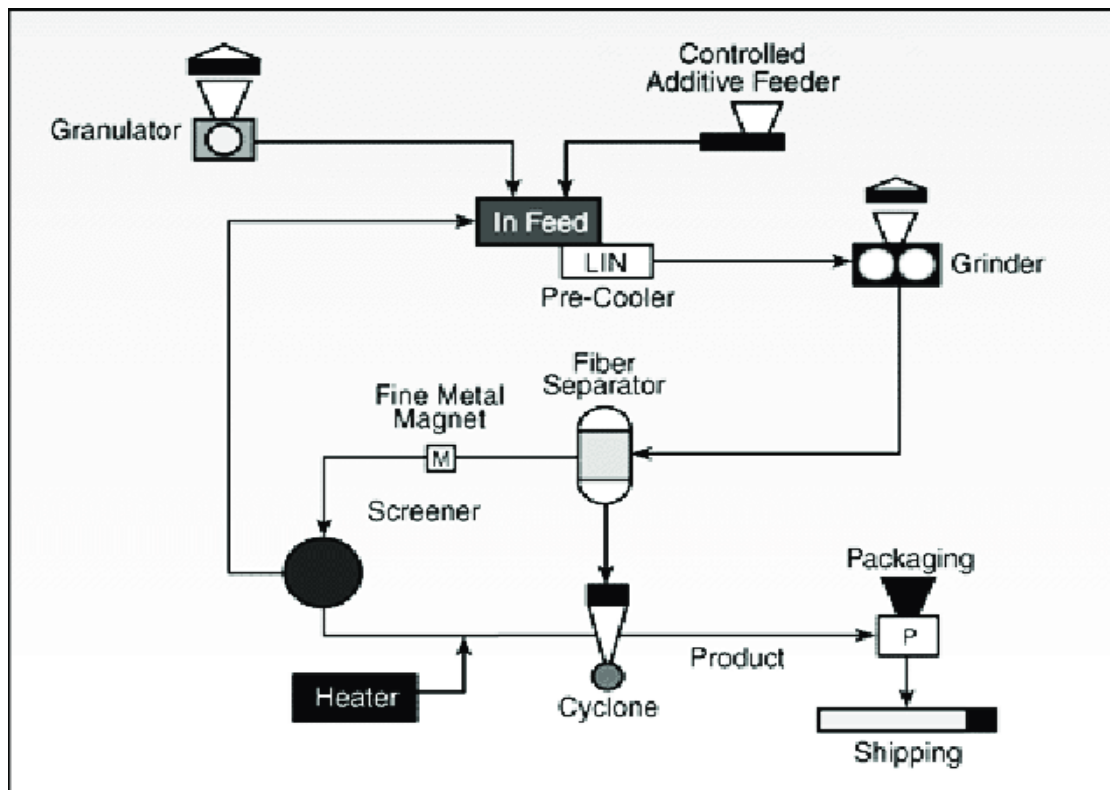


Figure 4:Traditional process of rubber recycling

Step 3 :- Sorting

It requires removing steel and textile filaments from the shredded rubber. Typically, this occurs after the shredding process. The technique makes use of magnets. The steel fibres are removed from each and every one of them by these magnets. On the other hand, polyester fibres may be removed using modern technologies. Examples of this include wind sifters, low vacuum suction, and shaking screens. Remember that this phase is important since they make up 30% of the overall group.

Step 4 :- Screening

Screening comes after removing the rubber from the wires. The purpose of screening is to carefully inspect the rubber to make sure there is no remaining steel. In essence, you will sort and screen enormous quantities of wireless rubbers into different sizes. Additionally, it entails the removal of any undesirable elements and the scaling down of huge rubbers.

Step 5 :- Cleaning

The screened rubber must be well cleaned to do this. To get the desired result, several cleaning chemicals and water are used here.

Step 6 :- Packaging & Transportation

After going through the cleaning process, the clean rubber is packaged and shipped to industries who require it as a raw material for their facilities. Rubber shoe and playground turf makers are only a couple of examples of these firms.



Figure 5: Stages of Rubber recycling

3.6. Methods of Rubber Recycling

Shredding/grinding used tyres into tyre rubber (GTR) and using the material (different particle sizes) as fillers in thermosets, virgin rubbers or thermoplastics (especially recycled resins) to produce thermoplastic elastomer (TPE) compounds is the easiest and most environmentally friendly method. Less than 500 m is the most practical rubber particle size for blending with thermoplastic resins because smaller rubber particles are more effective in enhancing the mechanical strength of TPE.

TPE combines the facile processing of thermoplastics with the combined mechanical capabilities of thermoplastic/elastomers. The three types of recycled rubber particles that are most frequently utilised for melting and combining with thermoplastics to create TPE materials are styrene-butadiene rubber (SBR), ethylene propylene diene monomer (EPDM), and natural rubber (NR). Melting scrap rubber and recycled plastic together is an ecologically clean and sustainable method that has the added benefits of being more cost-effective and environmentally friendly. The poor mechanical characteristics of TPE are

caused by limited compatibility and weak interfacial adhesion between rubbers and thermoplastics.

At greater rubber concentrations (over 50% wt.%), poor interfacial adhesion between the rubber and thermoplastic predominates, which severely degrades the blends' mechanical characteristics (particularly elongation at break and toughness). So, in order to create recycle-based TPE compounds with the desired characteristics, modification approaches are needed. It was discussed here how to modify rubber surfaces using oxidising agents, the reclamation/devulcanization process, and radiation-induced modification, as well as non-reactive and reactive ways employing chemical agents (copolymer/nanoparticles, NP).

Additionally, solution treatment with more eco-friendly (green) solvents is an option. Enhancing the interfacial adhesion between rubber particles and thermoplastic matrices is the major goal of these modification approaches in order to produce TPE compounds with the necessary mechanical and morphological qualities.

Given these factors, it is essential to develop technical solutions that enable effective used tyre waste recycling in order to lower environmental pollution and create a successful circular economy. The primary analytical tools for rubber goods must be reviewed in order to achieve efficient circularity and avoid unfavourable outcomes (for instance, big energy-intensive recycling procedures that might cause environmental pollution must be examined). Thus, resource conservation and used tyre deposit reduction are required to create a sustainable circular economy. Therefore, it is essential to discover methods that will guarantee improved use of secondary materials from worn tyres, increasing the likelihood that such trash would be recovered under these circumstances and guaranteeing a successful circular economy.

Table 1: Methods of Rubber Recycling

Methods	Description	Advantages	Disadvantages
Ambient (0.3 mm rough, irregular)	Repeated grinding following shredder, mills, knife, granulators, and rolling mills	High surface area and volume ratio	Temperature could rise up to 130 °C Oxidation on the surface of granulates Cooling needed to prevent combustion
Wet ambient (100 µm rough, irregular)	Grinding suspension of shredded rubber using grindstone	Lower level of degradation on granulates	Requires drying step and shredding of tires before grinding
Water jet (rough, irregular)	Water jet of >2000 bar pressure and high velocity used to strip rubber	Environmentally safe, energy saving, low level of noise, and no pollutants	Requires high pressure and trained personnel
Berstoff's method (rough, irregular)	Combines a rolling mill with a specially designed	Small grain size, large specific area, and low humidity	Not disclosed

	twin screw extruder in a line.		
Cryogenic (75 µm sharp edge flat/smooth)	Rubber cooled in liquid nitrogen and shattered using impact type mill	No surface oxidation of granulates and cleaner granulates	High cost of liquid nitrogen High humidity of granulates

The parameters Life Cycle Assessment (LCA) and Material Circulation Indicator (MCI) were examined in the literature. According to studies, extending tyre life by including recycled materials into the construction of a tyre enhances the circulation indicator of the tyre's components but has little to no effect on ecosystems or human health (Lonca et al., 2018).

3.7. Economic Implications of Improved Recycling

Due to challenges with waste management brought on by current trash production, some emerging economies have adopted the extended producer responsibility (EPR) environmental policy idea, following the lead of OECD nations. While the implementation of EPR for tyres frequently places additional financial and operational burdens on tyre producers and importers, it is still not yet able to set criteria that will ensure that all economic agents complete their assigned duties and obligations.

It has been demonstrated that EPR has improved the amount of tyres collected, however the materials from the recycled tyres cannot be utilised effectively. To encourage innovation in the area of recovering old tyre trash, it is required to introduce additional economic tools

and complementing policies in these circumstances. Thus, we can improve the circularity of rubber products by implementing new EPR directions for the recovery of shredded rubber waste, such as the incorporation of rubber waste particles into concrete structures, thereby obtaining greener concrete by partially replacing aggregates and cement (Park et al., 2018).

It is more advantageous to stop the manufacturing of unsustainable items in order to foster a circular economy for that product than it is to apply a later treatment that makes it simpler to recycle those products. In certain cases, the processes utilised to turn the raw materials into tyres are not environmentally friendly, polluting, and expensive (Ruiz-Penalver et al., 2019).

While becoming trash at the end of a product's lifespan, natural rubber and synthetic elastomers are anticipated to continue playing a crucial part in commercial and residential applications. Rubber degrading has been extensively researched and refined over the last few decades using a variety of techniques. The rubber produced as a result of devulcanization has a less carbon impact. It may be frequently incorporated into the creation of brand-new goods, enhancing their cost-effectiveness, sustainability, and environmental impact.

The circular economy of tyres, one of the main rubber products, is now being quickly formed in industrialised nations but has not yet been established in other nations throughout the world. On the other hand, there is hardly any evidence of a circular economy for everyday rubber items. For a healthy management of rubber waste and the formation of the circular economy, better sorting, collection, and efforts for nontire and general rubber items are urgently required. According to the state of the environment right now, used tyres and other rubber goods shouldn't be viewed as waste or pollution, but rather as a cheap source of raw materials for creating new products.

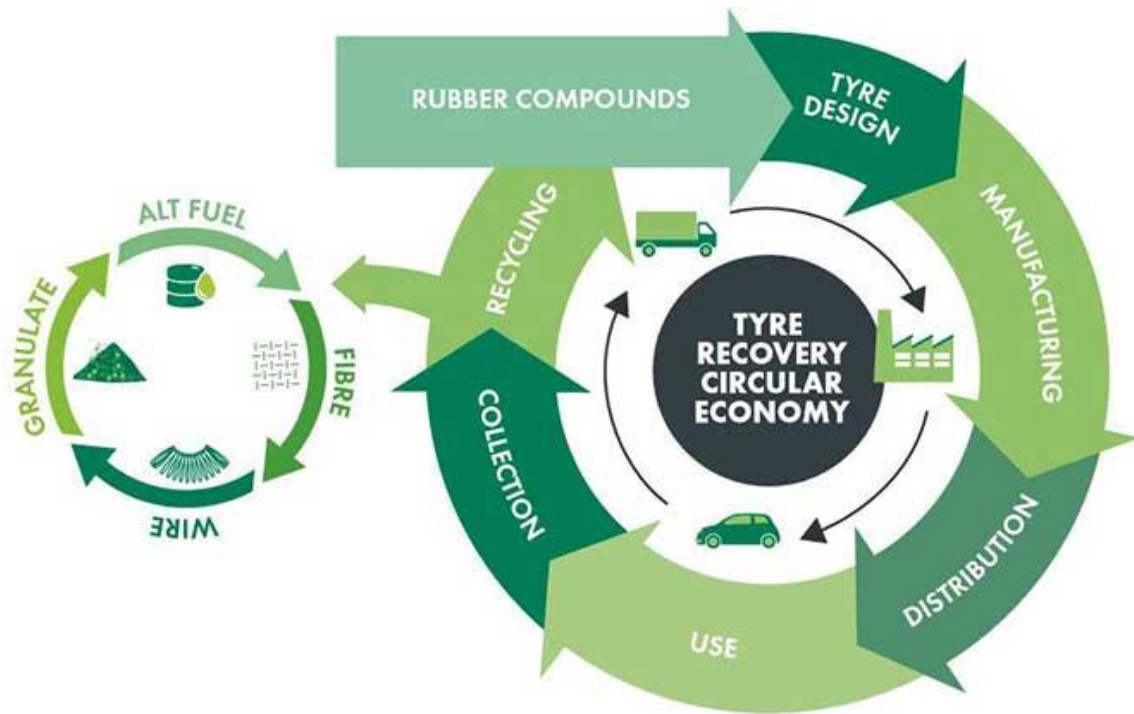


Figure 6: Circular life-cycle of a tyre

Through a variety of available grinding procedures, tyres and other rubber goods may be reduced in size to get ground rubber. The most used shrinking technique is grinding since it is the most economical. The produced ground rubber may be utilised as filler in many different products, including playground mats, rubberized asphalt, shock absorbers, and new tyres. Recycling used rubber will be the subject of additional study and development in the near future as a viable strategy for enhancing rubber's sustainability and circular economy.

3.8. Applications of waste rubber tires recycling

Recycling waste rubber is beneficial from both ways i.e., economically and environmentally. Other than these benefits, rubber recycling has some other benefits as well. Some of them are listed below:

- **Medical Industry**

In manufacturing of hospital floors and surgical gloves to provide comfort for medical professionals and patients.

- **Metal Industry**

Steel mills can use tires as a carbon source, replacing coal or coke in steel manufacturing

- **Sports Industry**

Infill for synthetic turf , indoor and outdoor running tracks, and fitness mats – broadening sports and fitness opportunities across the country

- **Construction Industry**

Rubberized asphalt on roadways providing surface durability while reducing traffic noise.

- **Fashion Industry**

Recycled rubber can be used in the making of sandals

Chapter 4: Methodology

Since the racket rubber and sponge waste does not amount to huge quantity, small level recycling can be used such as grinding. Also there is a lack of dedicated recycling process for the racket rubber recycling in UK. The research will be focusing on the use of a granulator to recycle the rubber.

This concerned research will be trying to improve the rubber recycling process by making adjustments in the granulator settings to optimise its performance.

Granulation

Rubber granulation is used extensively in mixing, extruding, and dissolving operations. Unvulcanized rubber, which can be a compound or a raw material, might be utilised in these procedures. Additionally, methods exist for producing rubber for secondary use and material reclamation utilising a variety of size reduction tools.

Granulated rubber, commonly referred to as crumb rubber or ground rubber, is a substance created by grinding up used or recycled auto tyre rubber and fusing the pieces with resin and other adhesives. Using a screen or mesh, the granules are further reduced in size. Granulated rubber, which originally came from tyres, is a post-consumer recycled material that diverts millions of pounds of rubber from landfills and puts it to use in new goods. This is especially true for flooring products like sheet or tile, either on their own or as a base for other flooring products.

4.1 Research Design

The design for the process of the recycling was prepared keeping the complex nature of the rubber rackets. The main challenge in the design is dismantling the rubber racket from the sponge and further processing the rubber from the granulator. The design requires a combination of manual as well as mechanical work since there are no dedicated mechanism or machinery to undertake the racket recycling.

Figure show the research design for the recycling of table tennis rackets.

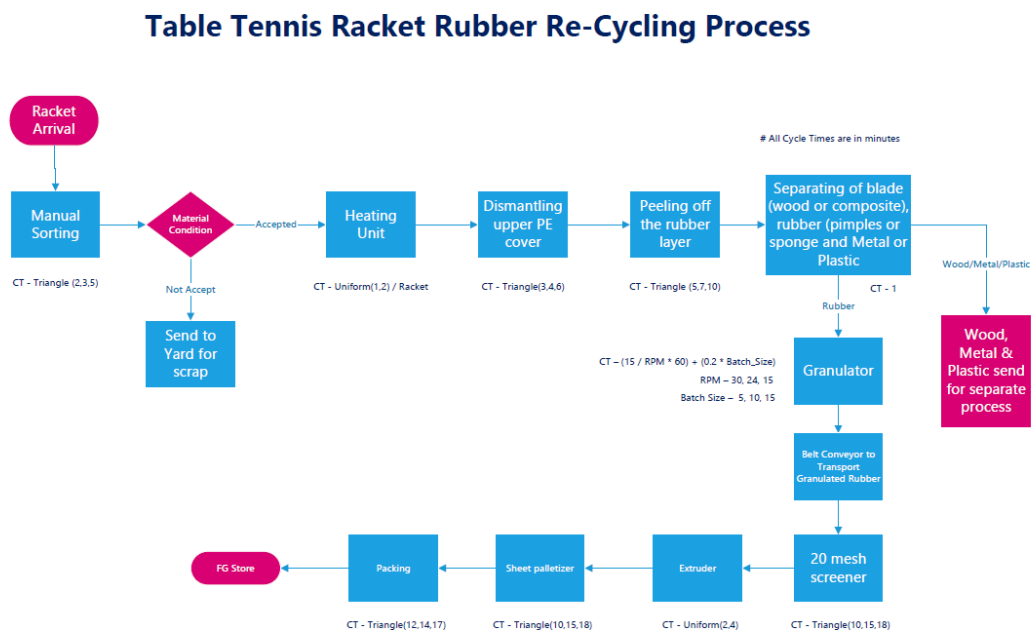


Figure 7: Design of the process of tennis rubber recycling

Further we also run a simulation of the model design to check for its usability. WITNESS SOFTWARE is used for the simulation.

A computerised simulation system called WITNESS was created to simulate industrial processes. It makes use of high-level components, a graphical user interface, and menus to make it easy for non-specialist users to construct, validate, and experiment with models fast.

The manufacturing processes are represented by pre-defined element types in WITNESS using a fully interactive, visual modelling technique. Building a WITNESS model involves the Define, Display, and Detail steps in that order. The user can switch to the Run mode at any time throughout the model-building process and run the recently produced section of the model. The user can exit the Run mode and continue to edit or contribute to the model with equal ease. At any time, WITNESS may alter in any way. In the Define step, elements for WITNESS modelling are produced.

Element placement on the computer screen happens during the Display phase. The modeller fills up templates in detail to explain how elements function and how they relate to one another. The simulation is carried out in Run. The model is animated as statistics are simultaneously obtained. Once the model is running, interactions may be utilised to gain more knowledge about it.

4.2. Research process

1. **Manual Sorting:** Once collected, the rackets need to be sorted based on their materials. Table tennis rackets typically consist of multiple components, including the blade (wood or composite), rubbers (sponge and topsheet), and handle (usually made of wood, plastic, or metal). Each of these components may require different recycling methods.
2. **Heating Unit:** In general, the racket is not designed for easy disassembly, it may need to heat before the dismantled manually to separate the various components. For this step specially used the heating oven and it is autoclave type oven and continuously can feed from inlet and take out from outlet door with respect to the defined heating cycle.
3. **Dismantling PE cover:** This step can be labor-intensive and may require specialized tools to remove PE cover available in the racker.
4. **Peeling off the rubber layer:** To begin the process, the table tennis racket needs to be dismantled, which means removing the rubber part from the blade. This can be done by carefully peeling back the edges of the rubber, exposing the wood or composite surface of the blade. Using Solvents (Optional): In some cases, players or technicians might use a solvent to help loosen the adhesive used to attach the rubber to the blade. This can make the peeling process more manageable and reduce the risk of damaging the rubber or blade. However, it's essential to use the right type of solvent and exercise caution, as some solvents can damage the rubber or be harmful to the environment. Peeling off the Top sheet: Once the rubber has been adequately loosened, the top sheet can be peeled off from the sponge. It's crucial to do this slowly and gently to avoid tearing the rubber or leaving remnants of the topsheet on the sponge. After removing the topsheet, the sponge may have some adhesive residue or bits of rubber left on its surface. Technicians will carefully clean the sponge to ensure for contaminations.

5. **Separating process:** After dismantling, the different materials must be separated to facilitate recycling. Considering our process, focused rubber components can be recycled separately, while the blade and handle might be processed differently based on their materials (not focused on the model).
6. **Granulator:** A granulator is a machine commonly used in recycling processes to break down materials into smaller granules or particles. In the context of table tennis racket rubber part recycling, a granulator could potentially be used to process the rubber components, such as the top sheet and sponge, into smaller pieces for further recycling or repurposing. Here's how a granulator involved in the recycling process. Before feeding the rubber components into the granulator, the table tennis racket rubber parts need to be collected and separated from other racket components (e.g., blade, handle). If the rubber parts include both the top sheet and sponge, they might need to be separated during the sorting process. This separation can be done manually or through automated methods. The rubber components, either the top sheet or sponge, are then fed into the granulator machine. The granulator contains rotating blades or knives that shred the rubber into small granules or particles.



Figure 8: Granulator

7. **Screening:** After granulation, the rubber particles may pass through a screen to ensure uniform particle size. This step can help produce consistent granules suitable for further processing or reuse. Once the rubber has been granulated, the resulting granules can be processed further depending on the intended recycling or reuse method.

8. **Extruder:** In the context of table tennis racket rubber part recycling, an extruder can play a crucial role in reprocessing the granulated rubber material obtained from the previous steps.



Figure 9: Extruder

An extruder is a machine that takes raw material in the form of granules, powders, or flakes and converts it into a continuous, uniform shape. The basic principle of an extruder involves applying heat and pressure to soften or melt the material and then forcing it through a specially shaped die to produce the desired product. In the context of table tennis racket rubber part recycling, the extruder is used to shape the granulated rubber into new rubber sheets that can be used as the top sheet for table tennis rackets. The extruder ensures that the recycled rubber material is processed into a continuous and uniform sheet foam, ready for further activities.

Using an extruder in the recycling process has several advantages, including:

Ability to process various materials: Extruders can handle a wide range of materials, including rubber, plastics, and other compounds.

Consistent and efficient processing: Extruders can produce a continuous output of shaped material with uniform dimensions and properties.

9. **Customization:** The die design can be tailored to produce different shapes and sizes, allowing flexibility in the end product.

It's important to note that the specifics of the extruder used in table tennis racket rubber recycling may vary depending on the type of rubber being processed, the desired end product, and the available equipment at the recycling facility. However, the general extrusion process remains consistent, providing an effective method for shaping recycled rubber into new usable forms.

10. **Sheet palletizer:** Sheet palletizing is the process of stacking the newly extruded rubber sheets onto pallets in an organized and efficient manner. This step is essential for easy storage, transportation, and handling of the rubber sheets.

Once the rubber sheets come out of the extruder and have been cooled and solidified, they are collected and cut into standard sizes, typically matching the dimensions of a table tennis racket.

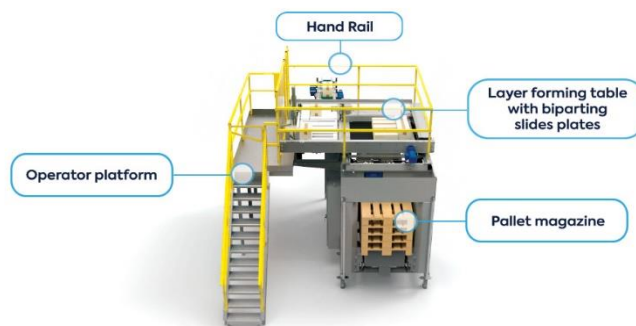


Figure 10: Sheet palletizer-front

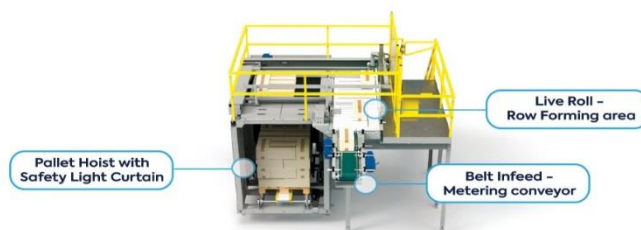


Figure 11: Sheet palletizer-back

These cut rubber sheets are then placed on a pallet, which is a flat, sturdy platform used for stacking and transporting goods. The number of sheets placed on each

pallet may vary based on factors like sheet thickness, pallet size, and shipping requirements.

To ensure stability during transportation, the sheets are usually stacked in a neat and uniform manner. In some cases, they may be interlocked or secured using strapping or wrapping materials to prevent movement or damage during transit.

11. Packing:

Packing is the process of preparing the palletized rubber sheets for shipment or distribution. Proper packing ensures that the rubber sheets remain protected during transportation and storage until they reach their final destination.

Once the rubber sheets are palletized, the entire pallet is prepared for packing. The pallet may be wrapped in plastic shrink wrap or stretch film to secure the sheets in place and protect them from dust, moisture, and other environmental factors. For additional protection, especially during international shipping or long-distance transport, the palletized rubber sheets may be placed in sturdy cardboard boxes or wooden crates. The boxes or crates are labeled with relevant information, including product details, destination address, handling instructions, and any necessary markings or symbols required for shipping compliance. The benefits of this process is follow:

Proper sheet palletizing and packing ensure that the rubber sheets remain in good condition during transit, minimizing the risk of damage.

Organized palletizing makes it easier for warehouse personnel and distributors to handle and distribute the rubber sheets efficiently.

Appropriate packing materials protect the rubber sheets from external factors that could potentially affect their quality.

It's important to note that the specific sheet palletizing and packing methods can vary based on the scale of the recycling facility, the volume of rubber sheet production, and the distribution channels involved. Additionally, environmental considerations should be considered, and sustainable packing materials may be used wherever possible to reduce waste and promote eco-friendly practices.

Chapter 5: Results

The granulator is identified as the bottleneck machine in the rubber recycling process, it means that its capacity or efficiency is limiting the overall throughput of the recycling system. To improve the situation and increase the overall process efficiency, we consider an Optimize Granulator Settings. Fine-tuning the granulator settings can make a noticeable difference in its performance. Adjusting the rotor speed, blade configuration, and screen size can impact the processing efficiency and reduce the bottleneck effect. Through this study we are focusing on the rotor speed vary by adjusting the Amp value.

The relationship between motor amp (current) and RPM (revolutions per minute) for a granulator in a rubber recycling process can vary depending on the specific equipment used, its design, and the load it's handling. Here we are model general three relevant trends,

1. **No Load Condition:** When the granulator is operating with no load, meaning it is not processing any rubber material, the motor amp draw will typically be relatively low. In this condition, the motor is not working against any resistance, so the amp draw is minimal. (Machine Idle time in the Model)
2. **Low RPM and High Load:** As the granulator starts processing rubber material and the RPM is relatively low, the motor will need to work harder to crush and grind the rubber. Consequently, the motor amp draw will increase as it exerts more effort to process the rubber.
3. **Optimal Processing:** There is usually an RPM range at which the granulator operates most efficiently. Within this range, the motor amp draw will likely be at a moderate level, indicating the optimal operating condition for the machine.
4. **High RPM and Low Load:** If the granulator is operating at high RPM but with a low load, the motor amp draw may still be relatively high. This could happen if the machine's load fluctuates, or if it's not properly adjusted for the current processing requirements.

Considering the durability of the motor, it's essential to monitor the motor amp draw and RPM during the operation of the granulator to ensure it's working optimally and not being subjected to unnecessary stress or potential damage.

$$\text{Total Process Time} = \frac{15}{\text{RPM}} \times 60 + \text{Loading \& Unloading time}$$

Where:

Processing Cycle Time is the total time taken to complete one full processing cycle, including any additional processing time, in minutes.

RPM is the number of Revolutions Per Minute.

Additional Processing Time is the extra time required for loading and unloading processes that add to the total processing cycle time.

By incorporating the additional factor, the formula becomes more adaptable and can better represent real-world scenarios where factors impact the processing cycle time

Chapter 6: Discussion

Automation works well with rubber granulators. Rubber racket can be depalletized onto an infeed conveyor manually, using a power assisted lifting equipment, or by a robot. The length of the unmanned operation will depend on the conveyor's length and the rate of granulation. To guarantee that no stray metal reaches the granulator, a metal detector may be placed if necessary on the conveyor. The noise level inside the working area will be reduced to the necessary legal limits with a sound-attenuating enclosure that is designed properly.

A cycle drives the granulator's operation. The necessary output, particle size, kind of rubber, and partitioning agent are all factors that affect cycle time. A racket rubber entering the feed hopper starts the cycle. The infeed conveyor and partitioning agent are then controlled by this. A volumetric screw feeder is used for dry powders, while a pressurised dispensing system is utilised for liquids.

An ideal lean phase pneumatic extraction method is used for granule take-off. It has the benefit of pulling air through the granulator in addition to carrying the material. This results in a cooler material, more output, and more uniform granule size. When a liquid partitioning agent is employed, the material is transported into an air separator by a fan. If powder is introduced, an indirect approach is used, with a rotary valve used to discharge granules from the air separator. The collected powder can then be utilised again once the exhaust air and extra powder are passed through a filter device. One granulator at floor level can feed numerous dissolving tanks or storage containers with the right conveying system. The system is sequenced, timed, and monitored by a programmed controller when there are several pieces of interconnected equipment. Experience has demonstrated that a system for granulating rubber of this kind can deliver with just one operator in four hours what a traditional guillotine and granulator might provide with two operators in eight hours.

The rackets must be size reduced into granules or powder for nearly any form of processing in order to obtain quicker dissolving, kneading, and mixing times, greater conveyability, and

a continuous manufacturing process. Depending on the need for rubber preparation and the desired final particle size, various preparation procedures are utilised for size reduction. Granulation is classified as either one step or two steps. The granulating process may frequently be completed in a single stage for common rubber size granule particle sizes under 10 mm. A dusting agent must, however, be applied for various varieties of rubber.

The rubber rackets are immediately granulated to the necessary final size after being fed by hand or on a conveyor belt. The size of the screen mesh installed in the knife mill determines the particle size. In order to convey the grains and remove heat generated during the granulating process, a pneumatic aspiration system is placed downstream from the rubber granulator. The mill can be equipped with a bale cutter built into the infeed chute to reduce the size of rubber rackets that are challenging to granulate.

The benefits of an internal operation when utilising the most recent granulating technology are:

- * A reduced processing fee;
- * Material is only granulated when necessary, reducing storage and agglomeration issues;
- * enhanced material utilisation as a result of less waste; and
- * the incorporation of a thorough materials management system into the granulation process, enhancing overall production control and product quality.

Granular rubber is now employed mostly in the production of paints, oil lubricants (which enhance viscosity index), modified bitumen, and modified polymers (such as high impact polystyrene), as well as adhesives and sealants. Granular feedstock can be fed into extruders for compounding, injection moulding, or profile extrusion. A continuous mixer (like MVX) needs a granular feedstock for mixing; this feedstock can also be used for open or internal mills.

Future Developments

Regarding equipment design and use in the manufacturing environment, granulating technology has made significant advancements. The rubber industry is currently faced with the difficulty of improving automation while utilising the advantages of granular rubber in its operations.

In order to improve the flexibility and scalability of manufacturing systems using information technologies, physical and virtual environments are being combined (Dassisti and De Nicol, 2012; Pirola et al., 2020). The design and implementation of digital twins, which constitute a body of information about the actual processes, are necessary for the current digital transformation of organisations (Panetto et al., 2019; Dassisti et al., 2019a). The goal of the digital twin (DT) is to develop highly accurate virtual representations of each physical thing that can evaluate, optimise, and anticipate their states and behaviour.

The idea of utilising "twins" was first introduced by NASA's Apollo programme, which produced two identical spacecraft to enable mirroring of the spacecraft's circumstances during the voyage. In 2003, University of Michigan Professor Grieves introduced the idea of a "Digital Twin" in Product Life Cycle Management (PLM) classes (Grieves and Vickers, 2017). The term "digital twin" describes a comprehensive, digital engineering perspective that includes product design and development as well as production planning, production engineering, manufacturing, and related services (Product Life cycle Management). The DT may be created to fulfil several duties throughout each stage of the product life cycle (Dassisti and Semeraro, 2018).

The setup and validation of probable future scenarios may be completed more quickly when the digital twin is used in the design phase (Brettel et al., 2014). The DT can aid decision-makers in accurately evaluating market demands and customer preferences, claim Semeraro et al. (2019b). DT may make it possible for the simulation—and subsequently the decision maker—to evaluate the interdependent behaviours among production elements

during the manufacturing phase by collecting data from the order, design, purchasing, production planning, manufacturing, and product consumption phases. The DT can help with real-time process and production planning optimisation and assessment. DT estimates the remaining usable life of components or products throughout the service stage using virtual activities like maintenance and real-time status monitoring. (2018) Lee and Kim.

Digital twins along the product lifecycle

Based on the literature we determined that a product's lifespan may be separated into four different, succeeding periods.

Phase 1: System conception and design.

Phase two: manufacturing and production.

Phase 3: operational/use.

Phase 4. End-of-life/disposal.

Although there are research describing applications of DTs in each stage of the product lifecycle, the bulk (64%) of these studies, according to Lo et al., concentrate on the production stage.

To more accurately classify the use of the digital twin during each of these phases, a detailed list of these applications is recommended for each phase. Based on a careful assessment of the industrial uses of digital twins across the product lifecycle, it created a taxonomy of applications. In the context of this study, Liu's classification will be used as a first step to calculate the proportion of each application of digital twins in the current literature. The next step is to examine the type of digital twins that have been utilised for each of these applications.

As a digital twin, a granulator can be produced virtually. Throughout the product's lifecycle, it will use real-time data from sensors to simulate behaviour and monitor activities. We can track a granulator's performance with the use of digital twin technology, identify potential issues, and make wiser maintenance and lifecycle decisions.

Benefits of digital twins

- Improved performance Digital twins' real-time data and insights allow you optimise the operation of your machinery, plant, or facilities. Problems may be resolved as they arise, ensuring that systems operate at their best and minimising downtime.
- Capabilities for prediction
- A comprehensive visual and digital picture of the recycling process is possible with digital twins. Smart sensors keep an eye on each component's output and alert the user when problems or malfunctions arise. Instead of waiting until a piece of equipment entirely fails, action may be performed at the first hint of issues.
- Remote control and monitoring are made possible by the virtual nature of digital twins. Less workers are required to check on potentially hazardous industrial equipment thanks to remote monitoring.
- Faster production times
- By creating digital duplicates, the production of goods and buildings that have not yet been built may be sped up. By running scenarios, it is possible to observe how a facility or product responds to errors and make the required adjustments prior to beginning actual production.

Working of a Digital Twin

A physical object's functionality, features, and behaviour are digitally replicated in the virtual environment to create a digital twin of the actual asset. Smart sensors that gather data from the product are used to produce a real-time digital depiction of the asset. The representation may be used throughout an asset's lifespan, from initial product testing through actual operation and decommissioning.

Digital twins receive data from various sensors monitoring the real-world twin. In a manufacturing setting, for example, sensors can measure a wide range of information, such as performance outputs (number of holes drilled, energy consumed and so forth) or environmental information (weather conditions, for example). This information is then analysed with the help of machine learning and artificial intelligence (AI).

A digital model of an asset is provided by digital twins using a variety of methods. These are some of them::

- **Internet of Things**

The term "Internet of Things" describes a broad network of interconnected gadgets as well as the technology that makes it possible for gadgets to communicate with one another and with the cloud. We now have billions of devices connected to the internet because low-cost computer processors and high-bandwidth telephony become available. IoT sensor data is used by digital twins to transfer information from real-world objects into their digital counterparts. You may watch data updated in real time by using a software platform or dashboard where the data is input.

- **Artificial intelligence**

Artificial intelligence (AI) is the area of computer science that focuses on finding solutions to cognitive issues like learning, problem-solving, and pattern recognition that are frequently linked to human intelligence. By using statistical models and

algorithms, machine learning (ML) is an AI approach that enables computers to carry out tasks without explicit instructions by relying on patterns and inference. Machine learning algorithms are used in digital twin technology to analyse the massive amounts of sensor data and find data trends. Data insights on efficiency, maintenance, emissions outputs, and performance optimisation are provided by artificial intelligence and machine learning (AI/ML).

- **Digital twins compared to simulations**

Although both digital twins and simulations are virtual model-based simulations, they have several significant variations. Typically, simulations are used for design and, in certain circumstances, offline optimisation. Designers modify simulations to test different hypotheses. On the other hand, digital twins are intricate virtual worlds that you can engage with and change in real time. Their scope and scope of use are greater.

The twin is made to be able to use data collected by sensors from a physical counterpart. As a result, the twin can accurately replicate the original object in real time and offer information about how it functions and any potential problems. The twin's design may have been influenced by the physical counterpart's prototype; in this instance, the twin might provide feedback while the product is being created or even function as a prototype before the physical counterpart is built.

Eniram, a business that develops digital twins of the enormous container ships that transport a large portion of global trade, describes the procedure in some depth in this article. This type of digital twin application is exceedingly sophisticated. The amount of data you utilise to create and maintain a digital twin, though, will decide how well you're imitating a physical thing. A digital twin may be as complex or as straightforward as you wish. For instance, this lesson shows how to create a straightforward digital replica of an automobile that computes mileage using only a few input variables.

Digital Twin helping in Recycling sustainability

Without a question, digital twins encourage businesses to innovate and perform better. The application of digital twin technologies for more efficient developing, visualising, monitoring, management, and upkeep of business assets is demonstrated in countless technical and nontechnical literature. Additionally, the use of digital twin technology has enabled a number of businesses to reuse their sustainability principles directly or indirectly. Digital twins are supposed to make it possible to think outside of the existing extract, create, consume, and discard industrial paradigm. In order to implement a "circular economy" system that considers nearly zero production of waste and pollution, maintains goods and materials longer in the recycling loop, and aids in the regeneration of natural systems, businesses and even entire cities have possibilities.

By 2030, worldwide carbon dioxide emissions might be reduced by 20% thanks to the use of digital twins. As a result of using or reusing lighter, more durable materials, businesses are able to change how goods and services are produced and provided, which results in energy savings.

Many manufacturers worldwide use digital twins to improve production efficiency. A recent white paper by the World Economic Forum's Global Lighthouse Network (GLN) highlights factories leading the way in digital transformations. Many of these factories emphasize process-focused digital twins as critical enablers for success.

One example is the LG Electronics factory in Changwon, Korea. The factory transformed its assembly line visual simulation tool into a digital twin by continuously integrating real-time production data into the system with updates occurring every 30 seconds. As a result, they improved productivity by 17%, product quality by 70%, and reduced energy consumption by 30%.

Another example is Procter & Gamble's factory in Guangzhou, China. The factory employed a digital twin to improve warehouse operations. Within a three-year period, the digital twin led to 99.9% of deliveries on time, a 30% reduction in inventory and a 15% reduction in logistic costs.

Virtual twins have many advantages, but the most significant one is how they can help society move towards a more circular economy, which is an economy where products and parts are made to be easily reused and repurposed and where waste is removed from the life cycle. Reduced product life cycle times, improved production quality and control, and more effective resource usage and recovery are all made possible by virtual twins.

Sustainability and production efficiency reinforce one another. Failing to incorporate all aspects into the digital twins model creates an incomplete digital picture and prevents

continuous improvement. If sustainability or efficiency is viewed as a byproduct rather than a result, the information is not fed into the model. As a result, it is impossible to build off these insights to facilitate further improvement. As digital twins mature, sustainability and production efficiency should be viewed as integrated components of a complex system or as core components of the industrial metaverse.

6.2. Limitations

There have been two issues that have prevented the widespread adoption of granular or particle rubber. The traditional way of material preparation has been the first. The second has been the creation of processing methods that take use of granular rubber's advantages.

Historically, the process of granulating rubber has been messy and noisy. It has been completely avoided in most factories for these health and safety grounds alone. The process requires a lot of labour and resources since, depending on the desired granule size, a guillotine must often feed one or more granulators. All of these pieces of machinery need to be maintained and operated. The standard granulator design technically puts limitations on the size of granules that may be generated as well as the effects of heat degradation on the rubber owing to friction in the cutting action.

Utilising a custom or trade processor's services is one option when granulating is necessary. This may be a pricey alternative, adding significantly to the cost of the materials, although often being convenient. A minimal batch size can correspond to many weeks' worth of manufacturing. This might be a drawback given the ongoing push to lower stock levels and the need for just-in-time (JIT) production techniques. Since material will seek to agglomerate despite the application of a partitioning agent, shelf life issues may arise. Additionally, there is a chance of cross-contamination since various materials go through the same machinery.

6.3. Recommendations

- Educate the public about the importance of recycling rubber rackets and sponges and provide clear information on where and how to recycle them.
- Work with sports clubs, schools, and other relevant organizations to set up collection points specifically for used sports equipment, including rubber rackets and sponges.
- Invest in research and development to find innovative recycling methods that are cost-effective and environmentally friendly.

- Engage with manufacturers to design products with easier recyclability in mind and explore ways to incentivize recycling programs.
- Support Recycling Facilities: Provide support and incentives to recycling facilities that process rubber rackets and sponges to help make recycling economically viable.
- Determining the structure from the perspective of material homogeneity. Following the discovery of the homogeneity of the materials used to construct the rackets, it was suggested to engrave some information about the different types of materials used in each component on the lateral surface of the rackets.
- Financial analysis to identify the best possible scenario for sustainability, circular economy, and pollution reduction.

Chapter 7: Conclusion

As global efforts to combat climate change and promote sustainability intensify, this dissertation's research on table tennis rubber racket and sponge recycling aims to contribute to the broader goal of waste reduction, resource conservation, and the creation of a more environmentally responsible sporting goods industry. By evaluating the current recycling processes and exploring potential improvements, this study seeks to provide valuable insights that can aid in devising effective strategies for recycling these essential components of the beloved game of table tennis.

Elastomeric materials have greatly accumulated and now pose a hazard to the environment as a result of the large production and consumption of rubbers, rubber blends, and rubber composites for a variety of uses. Rubber waste disposal and burning are prohibited for both ethical and practical reasons. Contrarily, initiatives that allow for the recycling and reuse of rubbers have received a lot of attention. Basically, traditional recycling practises have a number of problems, including the creation of airborne dust, fumes, and harmful gases as well as the contaminating of subsurface water supplies.

As a result, environmentally friendly and sustainable formulations and processing techniques are now prioritised and significant. Utilising the perspectives of sustainable development, this article reviews and discusses the scientific and technological aspects of managing waste rubber, including processing methods, product characteristics, industrial applications, and compatibility with other materials like thermoplastics, thermosets, and rubbers. Reactive extrusion is highlighted in particular as a highly adaptable in situ compounding technique that addresses sustainability issues and enables innovations. The current state of recycling green rubber and potential advancements in this technology are described in the last section.

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Appendix

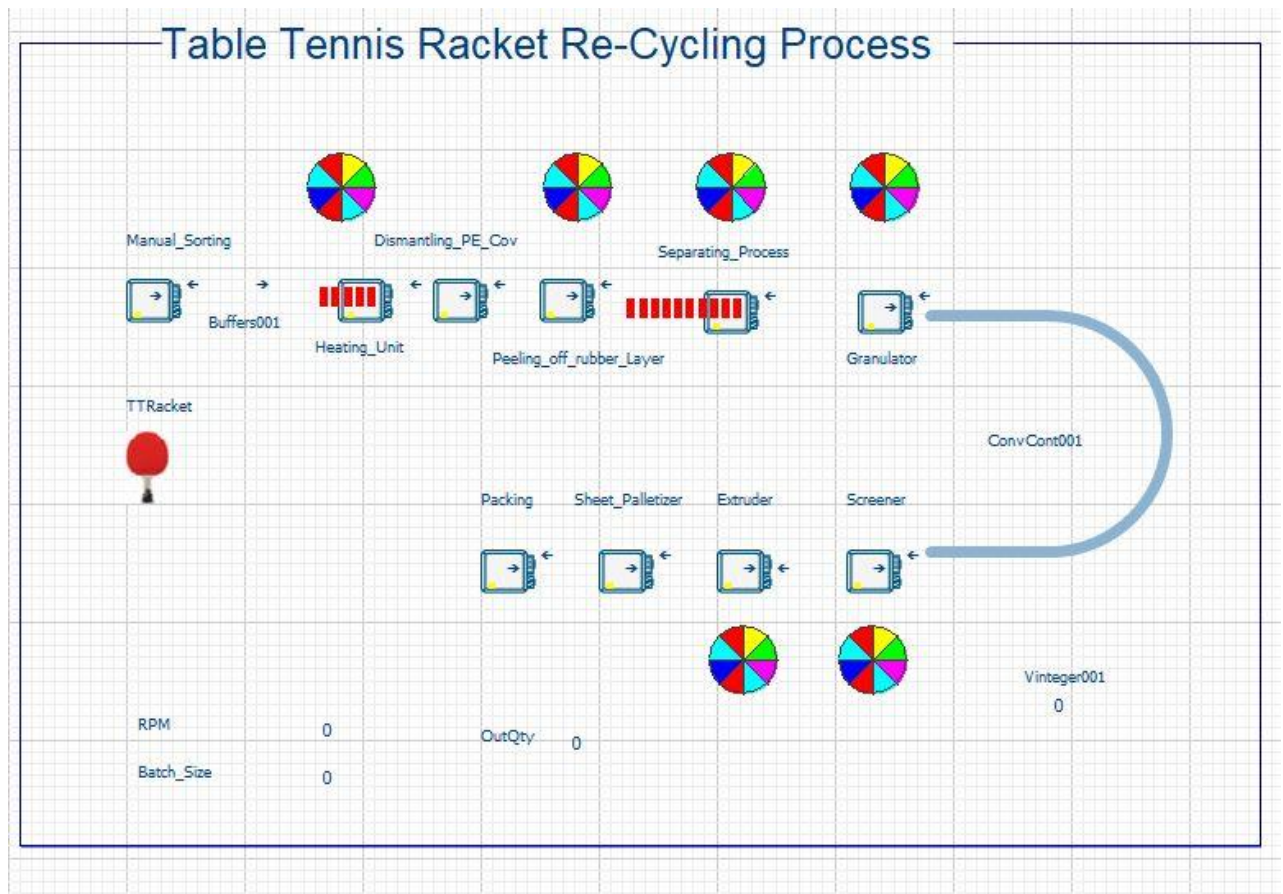
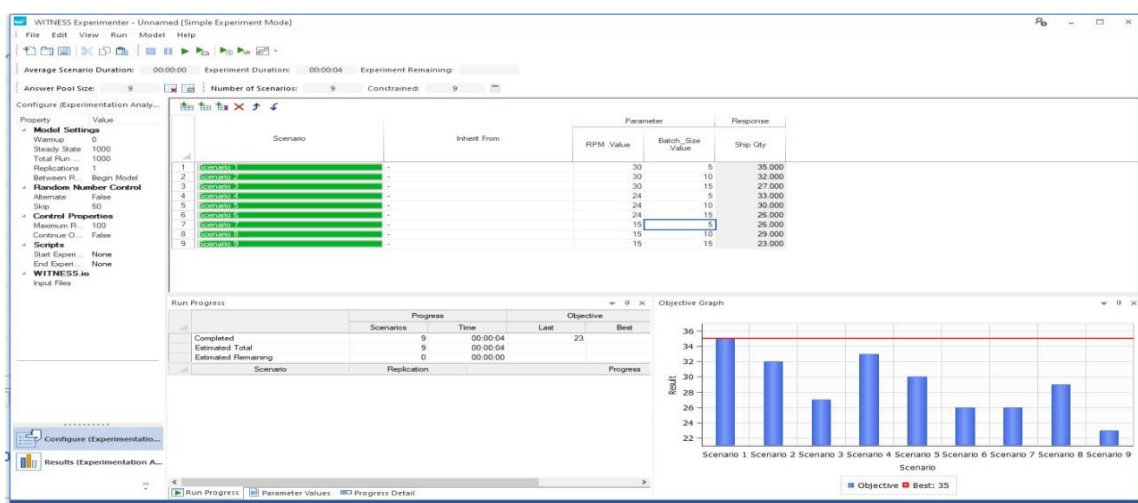


Table 1; Batch size vs Selection of RPM

No of products Batch	RPM
5	30
10	24
15	15



Types of rubbers used in table tennis rackets

Smooth	Most contemporary players employ smooth or "inverted" rubbers. With a layer of sponge below, the rubber has a flat, often shining surface. Over 85% of tournament players utilise the smooth, tacky surface because it offers the highest spin of any rubber type. Smooth inverted rubbers are preferred by players who hit, loop, are all-around, or play defence, which is why the Palio ETT series has them.
Short Pips	Rubbers with short pips are often called "pimpled" rubbers. They have a rough, unyielding top that frequently has a sponge layer below them. Short pip rubbers without sponge are referred to as "hard rubber" and are typically used for traditional "classic" or "hardbat" play. Short pips are typically employed by players who play with little spin and those who have trouble playing against spin. Some all-arounders, defensive players, and close-to-the-table hitters like short pips.
Long Pips	lengthy pips Rubbers are equipped with extra-long "pimples" that can turn an opponent's spin around. Long pips provide spin that is difficult to read, giving players an edge over opponents who are not accustomed to playing against this kind of rubber. Long pips, however, make it challenging to play aggressively, thus they are typically only used on one side of the bat.

Anti-Topspin	Although they have a flat surface, anti-topspin rubbers produce little spin. They aren't aggressive either since they move slowly. However, anti-topspin rubbers are great in counteracting opponents' spin, making it a good blocker. On the other side, some players pair the defensive rubber with an attacking rubber.
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