Bachelor’s Thesis

Life Cycle Assessment of Glass Fiber or Basalt Fiber Composite Baseball Bats; A Comparative Environmental Analysis

A Case Study of Baseball Bats, L-Tec Sports Oy

Ajay Ghimire

2023

Degree Thesis

Ajay Ghimire

Life Cycle Assessment of Glass Fiber or Basalt Fiber Composite Baseball Bats; A Comparative Environmental Analysis

Arcada University of Applied Sciences: Mechanical and Sustainability Engineering, 2020.

Identification number:

Student Code: 26018

Thesis Number: 9039

Commissioned by:

Arcada University of Applied Sciences

L-Tec Sports Oy

Abstract

Composite materials have gained popularity during the past few decades. Because of their mechanical properties and lightweight materials, composite materials have been utilized in various sectors. This research deals with the life cycle assessment of a sports product "baseball sports bat" made from glass fiber composite or basalt fiber composite. These baseball bats are particularly made by L-tec Sports Oy, based in Porvoo, Finland. The research investigates the cradle-to-gate environmental impacts of baseball bats during their manufacturing process till they leave the factory gate.

This research deals with the impact assessment of glass and basalt fiber composite baseball bats in various categories such as global warming potential, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, and human carcinogenic toxicity. This Life cycle assessment also deals with the comparison of the environmental impacts of glass fiber composite and basalt fiber composite. The research finds glass fiber composite has a higher impact on global warming potential than basalt fiber. Glass fiber composite baseball bat has 8.63 kg CO_2 eq whereas basalt fiber has only 1.91 kg CO_2 eq, showing basalt fiber has 351% less environmental impact than glass fiber. Similarly, a glass fiber composite baseball bat has 0.0198 kg SO_2 eq terrestrial acidification and a basalt fiber composite baseball bat has 0.00153 kg SO_2 eq, showing basalt fiber has 1194% less impact than glass fiber composite baseball bats. In addition, freshwater eutrophication made by glass and basalt fiber composite bats are 0.000958 kg P eq and 0.000123 kg P eq respectively making basalt fiber have 678% less impact. The Life cycle assessment of glass fiber and basalt fiber shows that using basalt fiber for producing baseball bats has far less impact than glass fiber.

Keywords: Life cycle assessment, Composite material, Glass Fiber, Basalt fiber, epoxy resin, Functional unit, Life cycle inventory

Acknowledgements

I would like to express my deepest gratitude to Arcada University of Applied Sciences for providing me with the opportunity to pursue my academic goals. The university's resources support and conductive learning environment have played an integral role in shaping the research outcome.

I am sincerely thankful to my thesis supervisor, Stewart Makkonen Craig for his constant direction, mentorship, and insightful advice throughout the entire research process. His knowledge, support, and feedback have all been very helpful in enhancing the scope and methodology of this study.

I also want to express my gratitude to Alexander Clark for his collaboration and support in providing valuable resources and access to crucial information. The collaboration with him not only enriched the research but also provided the theoretical aspect of the study with a useful context.

Finally, I extend my heartfelt appreciation to everyone who helped me directly or indirectly to complete this thesis. I sincerely appreciate your assistance with the teamwork which has been essential.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ASTM	American Society for Testing and Materials
BF	Basalt Fiber
CO_2	Carbon dioxide
CFC	Chlorofluorocarbon
DCB	Dichlorobenzene
GF	Glass Fiber
GFRC	Glass Fiber Reinforced Composite
IEA	Integral Environmental Analysis
ISO	International Organization for Standardization
KG	Kilogram
LCA	Life cycle Assessment
LCI	Life cycle Inventory
LCIA	Life cycle Impact Assessment
MJ	Megajoule
N	Nitrogen
P	Phosphorus
REPA	Resource and Environmental Profile Analysis
SO_2	Sulphur Dioxide

1. Introduction

This thesis deals with the environmental impact analysis of baseball bats made from composite materials. This chapter includes the introduction of composite materials, glass fibers, basalt fiber, and resin systems. It also contains the physical and mechanical properties of glass fiber, basalt fiber, and resin. In addition, it contains the research objectives, and thesis structure.

1.1 Glass Fiber

The growing advancement in composite materials brought material science into the new world. Glass Fiber Composite is the first modern composite, and it has widely been used as composite material ever since. Glass fibers are used to reinforced thermoset plastic resins which are also known as glass fiber reinforced composites (GFRC) (Foruzanmehr, Elkoun, Fam, & Robert, 2016). The fiber provides weight, dimensional stability, and heat resistance. Additives determine the surface finish, give colour, and have numerous qualities, like durability and flame resistance. The final properties of GFRP are determined by several factors including orientation of reinforcement and kind, quantity, and composition of resin (JyotiKalita & Singh, 2018).

Presently, glass fibers are among the most versatile industrial and household materials. They may easily find them in sufficient quantity to satisfy their needs (Martynova & Cebulla, 2018). Almost, all glass fibers are mostly composed of silica (Yasufuku, 1994). They demonstrate the desired qualities such as hardness, clarity, chemical resistance, consistency, and inertness, in addition to fiber qualities like strength, flexibility, and stiffness. Glass fibers are utilized in the production of printed circuit boards, structural composites, and several other special-purpose products. Fiberglass, often known as glass fiber, is one of the most widely used fibers in the reinforced polymer sector. Fiberglass may be made into sheets and is incredibly flexible.

There are various glass fibers can be used in composite manufacturing which have specific physical, chemical, and mechanical properties, for example, E-glass has higher strength and electrical resistivity, S-glass fiber has higher tensile strength, C-glass fiber has higher corrosion resistance (Srivastava & Kumar, 2022). There are various types of glass fiber are used as per the properties required. The following Table 1 contains the physical and mechanical properties of fiberglass.

Fiber	Density ($g\,cm^{-3}$)	Tensile strength (GPa)	Young's modulus (GPa)	Elongation (%)	Coefficient of thermal expansion (10^{-7}/°C)	Poisson's ratio	Refractive index
E-glass	2.58	3.445	72.3	4.8	54	0.2	1.558
C-glass	2.52	3.310	68.9	4.8	63		1.533
S2-glass	2.46	4.890	86.9	5.7	16	0.22	1.521
A-glass	2.44	3.310	68.9	4.8	73		1.538
D-glass	2.11–2.14	2.415	51.7	4.6	25		1.465
R-glass	2.54	4.135	85.5	4.8	33		1.546
ECR-glass	2.72	3.445	80.3	4.8	59		1.579
AR glass	2.70	3.241	73.1	4.4	65		1.562

Table 1: Various glass fiber properties (Sathishkumar, Satheeshkumar, & Naveen, 2014)

The different glass fiber has densities ranging from 2.58 gcm^{-3} to 2.70 gcm^{-3}. The tensile strength ranges from 2.41 Gpa to 4.89 Gpa. Similarly, Young's modulus ranges from 51 Gpa to 86 Gpa.

Glass Fiber-reinforced polymer composites are produced by various manufacturing techniques and are widely used for various applications. Glass fiber-reinforced composites are used in the marine and pipeline industries for their superior environmental and damage resistance from the impact of load, high specific strength and stiffness (Faizal, Beng, & Dalimin, 2006). Since GFRC is better suited in various applications, it has been widely used in avionics and aviation components (Krishna, Nagaraju, Roy, & Kumar, 2016). GFRC can also be used in structural elements, baggage bins and storage racks, flooring, closets, cargo liners, and chairs. It is also often used in gear that deals with the ground. It is frequently used to create flooring, flight deck shields, couches, and protective coverings for automobiles. S-glass is nonconductive and has more noticeable mechanical qualities. It provides improved stealth technology, giving these materials sharp edges for aviation equipment, by providing lower radar warm profiles. GFRC is widely utilized in several consumer goods. These are used in the construction of furniture pieces, ornamental objects, sports, and gym equipment, etc. Because of its increased flexibility, reduced mass with improved strength, durability, easy formability, excellent surface, and resistance to corrosion and wear, it is utilized as a necessary component in consumer goods. It also finds extensive use in the production of furniture and home appliances, including coffee tables, racks, rooftop sheets, and bathroom accessories (Srivastava & Kumar, 2022).

1.2 Basalt Fiber

Basalt fibers are produced from the natural volcanic basalt rock as raw material. Melting basalt rock at temperatures between 1450 and 1500 degrees Celsius using a platinum-rhodium alloy bushing results in continuous fiber and known as basalt fiber. It is also known as the "volcano rock silk" of the twenty-first century, this new fabric protects the environment and is also known as golden fiber due to its golden-brown colour (Li, Ma, Ma, & Xu, 2018). The process of manufacturing basalt fiber is similar to glass fiber, but it has several advantages over glass fiber or carbon fiber as it consumes less energy and no additives are needed while manufacturing which makes it cheaper than other fibre (Fiore, Scalici, Di Bella, & Valenza, 2015). Basalt fibers can be a good alternative to glass fibers as they are non-combustible, have high chemical stability, and have good resistance to weather, alkaline, and acidic exposure (Czigány, 2006).

The thermal properties of basalt fiber (BF) have a broader temperature range from -200 to around 650/800°C (Novitskii, 2004). The tensile strength of basalt fiber is in the range of 3000 to 4840 MPa. They are more robust and rigid than fibers made of E-glass. The specific gravity of basalt fiber (BF) varies between 2.6 and 2.8g/cc. Basalt fiber exhibits superior resistance to fungus and corrosion. They don’t react with gasses, water, or air. Less than 1% of BF's moisture content is present. Hard filaments in basalt range in hardness from 5 to 9 Mohr's scales. A basalt filament have superior and more robust abrasion resistance (Tavadi, Naik, Kumaresan, Jamadar, & Rajaravi, 2021).

The research conducted by Wei, Cao, and Song (2011) shows that glass fiber is found to be less resistant to salt and water solutions than basalt fibers and their composites whereas in an acidic environment, glass outperforms basalt fibers. Additionally, it is concluded that coupling agents and matrices can be used to change the characteristics of basalt. Epoxy-based basalt fiber and glass fiber, for instance, showed comparable deterioration when tested with a seawater solution using epoxy-reinforced BFs and glass fibers.

Basalt fibers also have a wide range of applications because of their properties. Basalt fibers have excellent fire resistance and, thus, are used in the building industry, particularly in civil projects. Additionally, railway sleepers, tunnels, and bridges employ these fibers. Reinforced concrete has mechanical strength because of 80% basalt fibers and epoxy glue that make up basalt rebar, which is less expensive. Basalt fibers are novel materials that can be utilized for building interiors, doors, and sound absorption in buildings. Their sound resistance characteristics are outstanding. Up to 1800 Hz is the frequency range in which it can function as fencing. These fibers work effectively as slabs for building home features like ceilings (Tavadi et al., 2021).

1.3 Epoxy resin

Epoxy resin is classified as a major polymer under the umbrella term "thermosetting resins," which includes unsaturated polyester resins, phenol-formaldehyde resins, and amino resins, among other cross-linking polymers. When heated, thermosetting polymers produce a covalently cross-linked, thermally stable network structure that results in an infusible and insoluble mass. They are often amorphous and have several advantageous characteristics, including superior chemical and heat resistance, easy processing, high tensile strength, and dimensional stability. Prepolymers and cured resins are also referred to as epoxy resins; the former is distinguished by a tripartite ring called the epoxy, epoxide, oxirane, or ethoxy-line group (Thomas).

Epichlorohydrin and at least two active hydrogen atoms combine to form the most common epoxy resin used commercially, produced by a dehydrohalogenation process. The compounds can be obtained from aliphatic diols, polyols, dimetric fatty acids, amino phenols, mono and diamines, heterocyclic imides and amides, and polyphenolic compounds. Glycidyl-based epoxy resins are those made from epichlorohydrin. Alternatively, cycloolifin compounds are directly epoxidized by parasetic acids to yield epoxy resins derived from cycloaliphatic dienes or aliphatic epoxidized chemicals (Rudawska, 2017).

Through a curing process, epoxy resin polymers build a solid, insoluble, and infusible three-dimensional cross-linked network. For epoxy resins to form cross links during the curing process, additional materials are required and known as hardeners or curing agents. The curing agent controls the degree of cross-linking, the kind of chemical connection that forms, and the viscosity and reactivity of epoxy resins. The curing process generally has an impact on the epoxy crystal structure, and the parameter is categorized as having an amorphous, non-homogeneous structure with a high cross-links density (Pascault, Sautereau, Verdu, & Williams, 2002). A mixture of amine, thiol, and alcohol molecules are mostly used to cure epoxy resins (Bauer, 1985).

The following Table. 2 explains the different properties of epoxy and hardener.

Properties	Test Method	Values For (LY-556)/ EPOXY RESIN	For Hardener (HY-951)/TETA	For Hardener (DDA)
Epoxy Group Content	SMS 2062	5150-5490 M Mol/Kg	-	-
Molecular Weight	-	182-194 gram	146.24 gm.	198 gm.
Viscosity	ASTM D445	9-14 Pa	450 Mpa	455 Mpa
Color	Appearance	White	Clear Light White/Yellow	Clear Light Brown
Density (At 25^0 C)	SMS1374	1.16 Kg/M^3	0.90 Kg/M^3	0.92 Kg/M^3
Flash Point	ASTM D93	>150 ^{0}C	129 ^{0}C	230 ^{0}C

Table. 2 Properties of Epoxy and Hardner (Agarwal & Agarwal, 2019)

The above table explains the basic properties of epoxy resin (LY556) and two hardeners (HY-951/TETA and DDA) used in manufacturing composite materials. The epoxy group indicates the number of reactive sites crucial for bonding, while molecular weight exhibits the mass of individual molecules influencing material characteristics. Viscosity measures the fluid resistance and impacts processability. Colour appearance indicates visual attributes. Density influences overall properties and handling. Flash point, representing the lowest ignition temperature which is crucial for safety during processing.

Typically, composite materials are made from polymer matrix reinforced with various fibres. The fibre provides strength and stiffness whereas the matrix provides shape and protects the fiber. Fibres such as glass fiber, carbon fiber, basalt fiber, or natural fiber are reinforced with thermosetting plastics/resins. The use of plastic in the matrix explains the name Fiber Reinforced Plastic. Fiber-reinforced plastic (FRP) may also contain fillers, additives, core materials, or surface finishes intended to improve the manufacturing process, appearance, and performance of the product.

The development of composite materials such as carbon fiber composites, boron fiber composites, ceramic fibers composites, metal fiber composites, basalt fiber composites, and natural fiber composites are widely used in several industries such as the aerospace industry, automotive industry, construction industry, sports industry, marine industry, medical industry, energy industry and so on. This is because composites have lightweight properties with higher strength and stiffness (Sathishkumar et al., 2014). By selecting the right combination of reinforcement and matrix materials, manufacturers can create properties that exactly match the requirements of a particular structure for a specific purpose by choosing the right combination of reinforcement and matrix materials (JyotiKalita & Singh, 2018).

1.4 Thesis Objectives

L-Tec Sports Oy, based in Porvoo, Helsinki, is one of the companies that has continuously manufactured industrial components, sports, and health products, and customized products from composites since 2009. L-Tec Sports Oy manufactures tubes, baseball bats, golf club shafts, high-performance ski poles, kinesiology tapes, personal care products, training protectors, and more. This research is being conducted in partnership with L-Tec Sports Oy. The main objective of this research is to conduct a life cycle analysis (LCA) of L-Tec Sports Oy baseball bats.

These bats are made from composite materials, Glass Fiber composites, and Basalt fiber composites Epoxy Resin. This research aims to find out how much environmental impact it does when baseball bats are made from fiber composites. This would help to obtain the carbon footprint produced by these bats during their manufacturing. This thesis also deals with the comparative life cycle study of baseball bats made of glass fiber and basalt.

1.5 Thesis Structure

In Chapter 1, the study presented information about glass fiber, basalt fiber, epoxy resin, and the application of composite material in various sectors. Chapter 2 explains the ISO, methodological framework of Life cycle assessment. Chapter 3 presents the specific methodology and data used to model the glass fiber and basalt fiber composite baseball bat assessment. Chapter 4 presents the results of the impact assessment and compares the results of glass fiber composite baseball bat and basalt fiber composite baseball bat. Chapter 5 examines the study results, provides a conclusion, and provides recommendations and potential for future research opportunities.

2. Literature of Life Cycle Assessment

LCA deals with the impact assessment of products or processes. To be consistent with the objective of the research LCA methodology is adopted. In this chapter, firstly the concept of LCA, LCA tools, process, and application are discussed.

2.1 Life Cycle Assessment

The best approach to understanding life cycle assessment (LCA) and its significance is to understand how the concept emerged and the condition that contributed to its continuous conceptual development. Formerly, before the term LCA, it is known for environmental profile analysis, integral environmental analysis (IEA), eco-balance, and analysis of the resource and environmental profiles (REPA) (Moussa, 2014). The evolution of LCA methodology was progressively developed over time. The first Life Cycle Assessment (LCA) standard released by the International Organization for Standardization (ISO) was ISO 14040, Environmental Management (Life Cycle Assessment -Principles and Framework), in 1997 which was revised in 2009. ISO 14041 (Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis) is another LCA standard that was released in 1998 and revised in 2003. Two more LCA standards, ISO 14042 (Life Cycle Assessment—Life Cycle Impact Assessment) and ISO 14043 (Life Cycle Assessment—Life Cycle Interpretation), were released by ISO in 2000. To replace ISO 14041, 14042, and 14043, ISO 14044 Life Cycle Assessment - Requirements and Guidelines was published in 2006. All the ISO series are taken as the foundation for the present-day LCA methodology as a whole (Moussa, 2014).

LCA is defined more in detail by the Society of Environmental Toxicology and Chemistry (SETAC) as follows: “A process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements”. The life cycle assessment involves the entire life cycle of the product, process or activity, including extracting and processing raw materials; production, transportation and distribution as well as use, re-use, maintenance; recycling, and final disposal (Fava et al., 1994).

Life Cycle Assessment is tool that determines the primary energy uses during manufacturing of any products or materials and its impact on the environment from its projected life spans. Standardization (1996) defines the Life Cycle Assessment as holistic tool to identify, quantify, and qualify significant environmental aspects during product's life cycle. LCA is important as it helps to improve and compare the solution at different manufacturing stages. In an addition, it helps to identify which phases are the main contributors to the overall impact and to make an environmental trade-off.

The European Commission considers LCA tools as the most efficient tool to carry out environmental performance analysis and reduce the risk of greenwashing (Del Borghi, 2013). The Life cycle assessment tool has been standardized by the International Organization for Standardization (ISO) in ISO 14040 series. There are four certified ISO standards covering different areas of life cycle assessment (Standardization, 1996).

ISO 14040: 1997 (Principles and framework)

ISO 14041: 1998 (Goal and Scope definition and inventory analysis)

ISO 14042: 2003 (Life Cycle Impact assessment)

ISO 14043: 2003 (Interpretation)

The framework of the LCA process as standardized by the ISO 14040 series is shown in the figure below.

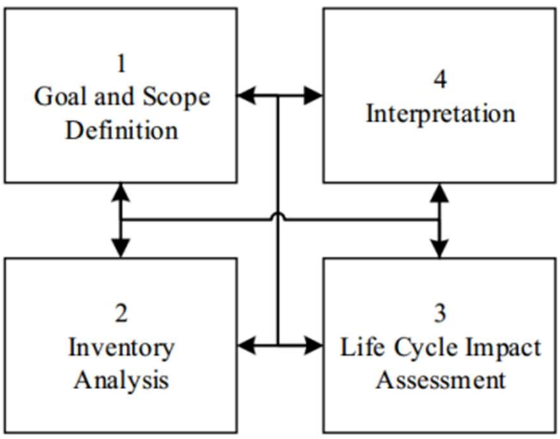

Figure 1: Framework for LCA, ISO 14040 (Petroche et al., 2015)

The two most used systems selected for LCA studies are cradle-to-gate and cradle-to-grave. A cradle-to-factory-gate LCA study includes all stages from raw material and fuel extraction, through all subsequent manufacturing steps to product delivery at the factory gate. Cradle-to-gate analyses are mostly published by material manufacturers. The Cradle-to-Grave system includes all steps of the Cradle-to-Factory Gate system plus the use and disposal stages. A cradle-to-grave analysis has the advantage of covering all stages of the life cycle. When comparisons between different disposal options are not available, a cradle-to-factory-gate analysis can provide initial insights into environmental impacts (Shen & Patel, 2008).

To evaluate the environmental profiles of polymers and composites for their ability to provide an initial image of the environmental impacts of the materials, cradle-to-gate, life cycle assessments (LCA) are commonly used (Yu & Chen, 2008). The method of LCA, cradle-to-gate is also known for partial life cycle assessment, or LCA, starts the same as the cradle-to-grave procedure but ends when the finished product is manufactured and exits the factory gate (Hammond, Jones, Lowrie, & Tse, 2008).

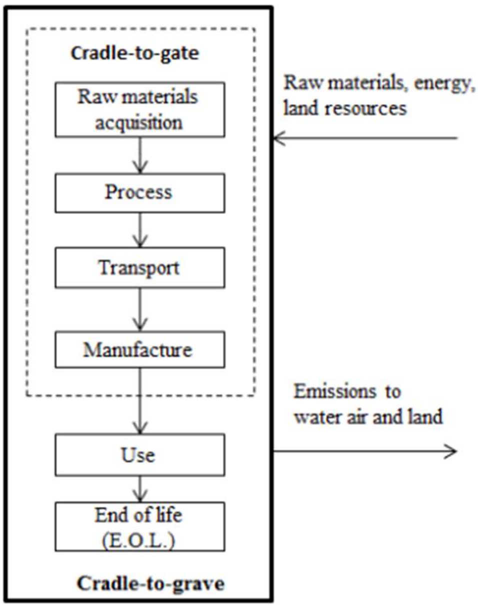

Figure 2: Life Cycle system boundaries (Baumann & Tillman, 2004)

2.2 Life Cycle Inventory Data

Life cycle inventory data is defined as the primary inputs and outputs of products and processes for conducting LCA. The researchers and practitioners of LCA find the biggest challenges when collecting data for inputs and outputs of materials and processes. The robustness, defensibility, and significance of LCA study results depend upon the input the information is reliable, accurate, and significant (Deru, 2009). It is important to understand the difference between foreground data and background data. To develop the model, the product system empirical data is considered. On the other hand, background data are generic for materials, energy, etc. (Herrmann & Moltesen, 2015).

2.3 Life Cycle Impact Assessment (LCIA)

Life cycle impact assessment determines the inventory results into different impact categories. The impact categories are separated into three groups: environmental impacts, human impacts, and resource depletion. The environmental impact assessment categories and criteria were established by the assessment aim and purpose since the environmental performance of a product may vary based on these factors (Abdullahi, 2021). Global Midpoint H 1.08, impact assessment method has various impact categories such as global warming, ozone depletion, ionizing radiation, ozone formation and fine particulate matter, ecosystem impact, human toxicity, resource use, and water consumption can be analysed.

3. Methodology and Data

This study follows the structural and methodological guidelines for life cycle assessment specified by ISO 14040 and 14044 international standards. Stakeholders generally accepted these criteria, which are meant to produce consistent, reliable, transparent, and comparable results of impact assessment (Finkbeiner, Inaba, Tan, Christiansen, & Klüppel, 2006). As introduced in Chapter 2, the required methodology is addressed and discussed in this chapter.

3.1 Goal Definition

The explanation of the purpose of the study is an important aspect of the goal definition. The purpose of LCA should identify the intended application, including an explanation for conducting research and intended audience i.e., to whom the findings are to be shared. The intended application of the result and the user of the result must be specified in the goal definition (Finkbeiner et al., 2006).

The goal of this study is to evaluate the environmental impacts of single baseball bats until they leave the factory gate. The baseball bats are made from composite materials. The baseball bats are made either from glass fiber or basalt fiber. The environmental impact made by the amount of composite material, in kg, needed to produce one baseball bat that meets all the relevant baseball sports requirements is the main goal of this research.

The result is intended for company use at L-Tec Sports Oy. This LCA will provide insight into the environmental impact of their products, baseball bats, compared with glass fiber baseball bats with basalt fiber bats.

3.2 Scope Definition

LCA's scope determines the evaluation technique that is applied and what is incorporated into the system. The scope must be specified such that the study's depth, breadth and specifics are adequate to meet the necessary objective.

The cradle-to-gate system boundary ends when the composite baseball bat is produced, which is suitable for sports. The product system does not include transportation of finished baseball bats, use phase and end of life.

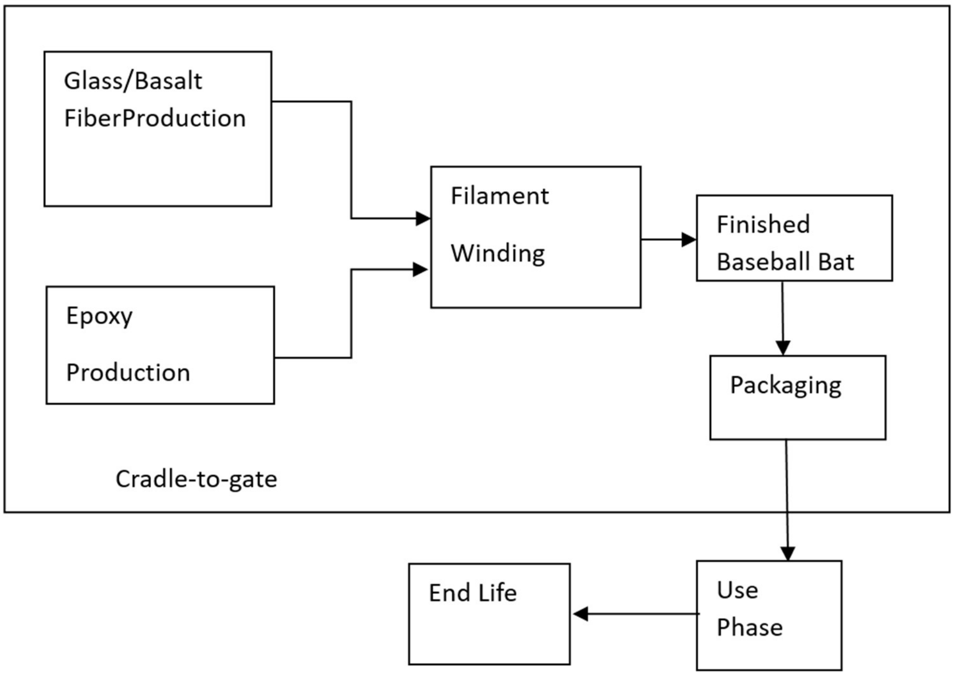

Figure 3: System boundary for the production of composite baseball bat.

According to accepted practice, the limit of this study for foreground data comprises capital equipment operation but excludes its production (Consultants, 2008). This assumption is supported by the fact that capital equipment utilized in bulk production systems has very little environmental impact.

3.3 The Function and Functional Unit

This study assumes that both glass fiber and basalt fiber composite bat have similar functions. The functional unit for this research is defined as one baseball bat made from composite material. The amount of composite material, in kg, needed to produce one baseball bat that meets all the relevant baseball sport requirements.

The choice of functional unit in LCA is important step and can significantly impact the results. In this case, choosing mass as the functional unit rather than number of baseball bats can be explained based on following factors.

The quantity of material required is directly related to the production of baseball bats. By considering mass as a functional unit, it helps to consider for extraction, processing, and transportation of raw materials which are significant contributor to environmental impacts. By utilizing the mass as functional unit, the change in design, size, or material consumption can be overlook. When analysing the effects of transportation, mass is important factor to consider.

The following figure: 4 represent the system boundary for analysing the impact assessment. This includes all the process releated to the manufacturing of base material, their transportation and manufacturing of baseball bats.

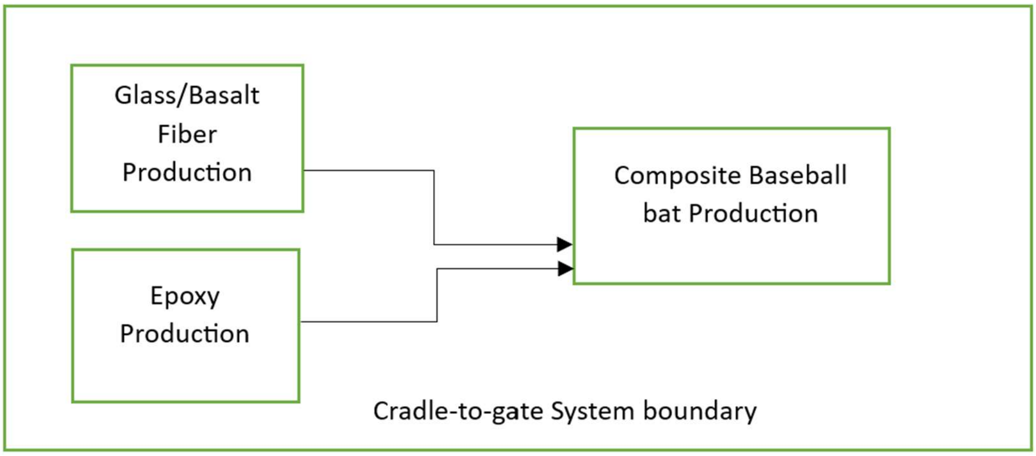

Figure 4: System boundary.

3.4 Reference Flows

The outputs from processes in a given product system required to fulfil the function expressed by the functional unit" are measured by a reference flow (Klöpffer, 2012). In this life cycle assessment, the baseball bat can be produced by glass fiber or basalt fiber. The baseball bats are equivalent in function and same volume and dimensions. The input and output are converted in terms of functional units. These data are computed in SimaPro for life cycle assessment.

3.5 Limitations

Like the majority of LCA studies, certain model assumptions and data quality have weakness. The research is restricted to a study of baseball bats. They are made from the composite materials, glass fiber and basalt fiber and epoxy resin. The research is also designed to focus on LCA of case study baseball bats which were manufactured in L-Tec Sports Oy.

The use of existing datasets, which are mostly based on European production technology, practices, conditions, and assumptions, places limitations on the study. When it is utilized in a different geographic location, these data have restrictions related to technology and resources.

Except for the empirical L-tec data, most of the data included in this analysis are from secondary or tertiary sources and may be subject to significant levels of uncertainty. An assessment of uncertainty was made, and SimaPro pedigree uncertainty calculations assign uncertainty values to reduce the high uncertainty.

3.6 Life Cycle Inventory (LCI)

The collection of input and output data for the product system under investigation is covered in this section. The analysis of the manufacturing composite bat system made use of both freshly created and preexisting unit process data. The U.S. Life Cycle Inventory (LCI) database or the EcoInvent database provided the secondary and tertiary data that were utilized to model each unit process.

The Swiss Centre for Life Cycle Inventories (the EcoInvent Centre) is the source of the life cycle inventory (LCI) database EcoInvent. The EcoInvent database is meant to be used as background information and covers environmental activities at the system and unit process levels. The EcoInvent Center ensure and validate the review system and supports the quality of EcoInvent data.

3.7 Data and Data Validity

Obtaining primary data for LCA involves collecting data directly from the source through surveys, tests, measurement, or direct observation. On the other hand, collecting primary data for each phase of product's lifecycle can be resource-intensive, time consuming and in some cases, it becomes impractical. Therefore, researcher frequently turn into secondary data.

The secondary data collected for this LCA study taken from published journal and research articles. The Granta Edu Pack is most growing software for sustainable product design and data can be rely on. The researchers Patel (2003), Shen and Patel (2008) and Kemna and van Elburg (2006) have already done the detail study in glass fiber, basalt fiber and epoxy resin. Those data can be considered valid for this LCA study.

3.8 LCA Tool

The unit process was modelled using the software SimaPro version 9.5.0. SimaPro software was firstly adopted in 1990. It was developed by PRé Consultants in the Netherlands and widely adopted by more than 80 countries. SimaPro is develop on the framework of the ISO 14040 and 14044 standards and is used to evaluate and analyse environmental performance of a product or service's (Kim et al., 2013).

SimaPro is an LCA software that models the gathered inventory data, characterization, and the LCA approach. The program includes a big dataset, several calculating algorithms, and impact assessment approaches that make it simple to model and detail the life cycle assessment (LCA). This report makes use of the software's educational license, suggesting that access to some parts of the database is restricted.

SimaPro utilizes plans, procedures, and flows to operate its Life Cycle Assessment (LCA) models. These components work together to create a connected and related web of data that is used to perform an internal computation on the selected categories. A plan is a visual representation of the product cycle that includes flows and processes in the form of a flowchart.

With its user-friendly interface, flexibility in conducting life cycle assessment (LCA), and sufficient useful databases and datasets (EcoInvent), SimaPro is widely utilized by both industry and academics. SimaPro allows users to evaluate and alter pre-existing LCIA methods, develop new methods, adjust analysis choices, and compare two or more distinct products and processes.

3.8 Unit Processes

The modelling of production of glass fiber and basalt fiber was based on the research done by Shen and Patel (2008), Kemna and van Elburg (2006), and Ecoinvent v2.2. These data represent all the input materials used in the production of glass fiber and basalt fiber including energy and water usage. Other secondary data were obtained from the Granta Edu pack. The data contains the production of glass fiber yarn virgin grade used energy, CO_2 and water usage. The following table 3 contains the input and out to produce 1 kg glass fiber with functional unit conversion.

Unit Process	Flow Type	Input/Output	Unit	Value	Value in Terms of Functional Unit	Data Source
Glass Fiber production (1 kg)	Input Material	Energy	MJ/kg	54.3	29.87	(Shen & Patel, 2008), (Kemna & van Elburg, 2006), Granta Edupack
		Water	l/kg	99.2	54.56	
	Emission	CO_2	kg/kg	3.14	1.727	

Table 3: Process input and output to produce 1 Kg Glass Fiber with Functional unit Conversion.

The following table 4 contain the input and output to produce 1 kg of basalt fiber and values in terms of functional unit.

Unit Process	Flow Type	Input/Output	Unit	Value	Value in Terms of Functional Unit	Data Source
Basalt Fiber production (1 kg)	Input Material	Energy	MJ/kg	0.955	0.5252	(Shen & Patel, 2008), (Kemna & van Elburg, 2006), Granta Edupack
		Water	l/kg	14.4	7.92	
	Emission	CO_2	kg/kg	0.06	0.033	

Table 4: Process input and output to produce 1 Kg Basalt Fiber with Functional unit Conversion.

The following table 5 contains the input and out to produced 1 kg of Epoxy resin and values in terms of functional unit.

Unit Process	Flow Type	Input/Output	Unit	Value	Value in Terms of Functional Unit	Data Source
Epoxy production (1 kg)	Input Material	Energy	MJ/kg	127	25.4	(Patel, 2003), (Kemna & van Elburg, 2006), Granta Edupack
		Water	l/kg	29.4	5.88	
	Emission	CO_2	kg/kg	6.23	1.246	

Table 5: Process input and output to produce 1 Kg Epoxy resin with functional unit value.

The table 6 contains the input and output to produce 1 baseball bat. The R&D head Alexander Clark, L-Tec Oy explains the 1:1 ratio to produce glass fiber and basalt fiber composite baseball bats for which the input and output for the production of glass fiber baseball bats and basalt fiber baseball bat are equivalent. He further explains that because of the similar properties and density of both fiber the production process would be similar.

Unit Process	Flow Type	Input/Output	Unit	Functional Unit Value	Data Source
Composite single baseball bat (Glass fiber and Basalt	Input Material	Glass fiber	kg	0.55	L-Tec OY
		Basalt Fiber	kg	0.55	
		Epoxy resin	kg	0.2	
		Energy	MJ	3600	
		ABS	kg	0.025	

Fiber)		Packaging (Plastic)	kg	0.05	
		Acetone	L	0.029	
	Waste Material	Composite	kg	0.15	

Table 6: Process input and output to produce 1baseball bat with Functional unit Conversion.

4 Results

This chapter includes the LCA cradle-to-gate for the refrence flow of 1 unit of base ball bat of glass fiber and basalt fiber which is 0.6 kg and provides the results of the comparasion between glass fiber baseball bats and basalt fiber baseball bats. The results are intrepretaed as Global-Midpoint H 1.08 version in SimaPro 9.5.0.

4.8 Impact Assessment Result of Glass Fiber Composite Baseball Bat

In this section, the environmental impacts associated with the production of baseball bat is presented. The result of impact catagories for the production of glass fiber composite baseball bats are summarized in Table 7.

Impact category	Unit	Total
Global warming	kg C02 eq	8.63
Stratospheric ozone depletion	kg CFCII eq	1.42E-06
Ionizing radiation	kBq Co-60 eq	4.53
Ozone formation, Human health	kg NOX eq	0.0148
Fine particulate matter formation	kg PM2.5 eq	0.00847
Ozone formation	kg NOX eq	0.0149
Terrestrial acidification	kg S02 eq	0.0198
Freshwater eutrophication	kg P eq	0.000958
Marine eutrophication	kg N eq	0.00015
Terrestrial ecotoxicity	kg 1,4-DC8	5.26
Freshwater ecotoxicity	kg 1,4-DC8	0.0616
Marine ecotoxicity	kg 1,4-DC8	0.0852
Human carcinogenic toxicity	kg 1,4-DC8	0.19
Human non-carcinogenic toxicity	kg 1,4-DC8	2.76
Land use	m27 crop eq	0.077
Mineral resource scarcity	kg Cu eq	0.0074
Fossil resource scarcity	kg oil eq	1.24
Water consumption	m3	0.097

Table 7: Glass fiber composites impacts results in various categories.

The Life Cycle Assessment (LCA) of the glass fiber composite baseball bat reveals that it has a moderate environmental footprint across various impact categories. The primary contributor is global warming potential, with the bat contributing for 8.63 kg of CO_2 equivalent emissions. It has minimal impact on ozone depletion but sits a slight risk in terms of ionizing radiation. The baseball bat has modest contributions to air and water pollutants, including ozone formation, particulate matter, acidification, and eutrophication. Particularly, it exhibits significant ecotoxicity effects on terrestrial and freshwater ecosystems, along with contributions to both carcinogenic and non-carcinogenic human toxicity. In terms of resource use, the bat has moderate land use, low mineral resource scarcity, and moderate fossil resource scarcity. Water consumption is relatively low at 0.097 m^3.

4.9 LCA Characterization and Normalization Result of Glass Fiber Bat

The characterization results explain, evaluate, and quantify the potential environmental impacts identified in the inventory analysis. The results are typically express in terms of environmental indicator such as kg CO_2 equivalent for global warming potential, kg of nitrogen equivalent for eutrophication and so on.

Each bar in a graph for characterization and normalization refers to the impact category; the first bar in the figure explain the global warming potential, secondly, ozone depletion, similarly, ionizing radiation, ozone formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and lastly water consumption are expressed in the figure respectively.

The following Figure 5 explains the impact of various process in manufacturing of glass fiber baseball bats. The first bar on figure 5 explains the most global warming potential cause by the base material of the baseball bats and small impact cause by the transportation of base materials. Similarly, 8^{th} and 9^{th} bar in the graph shows cause of freshwater and marine eutrophication is from raw material acquisition and the packaging of the products. Thus, various process has impacts on various categories.

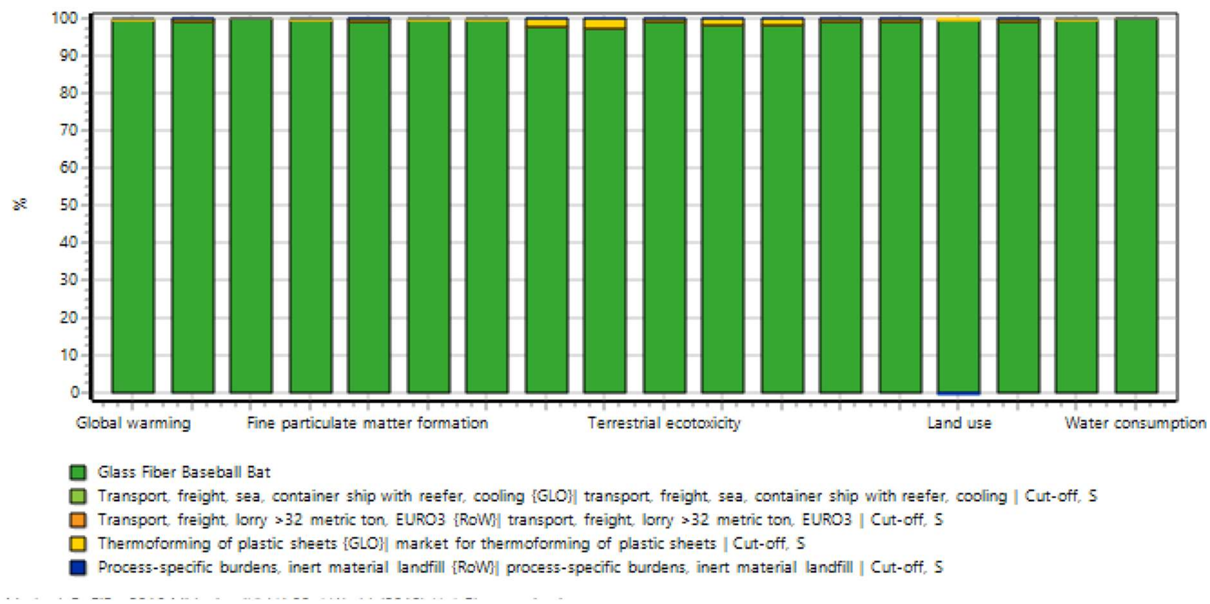

Figure 5: Characterization result of glass fiber composite baseball bat

The above figure explains the impact of various processes during the manufacturing of glass fiber composite baseball bats. The manufacturing of raw materials such as glass fiber and resin for baseball bats has higher impact on environment. Similarly, the transportation of raw material, packaging and waste has moderate impact on environment.

Normalization means the comparing the environmental effects among various impact categories. Comparing the characterisation results to benchmarks or reference values is intended to put them into context. This optional step is frequently used to determine which effect categories have the most overall environmental burden contributions.

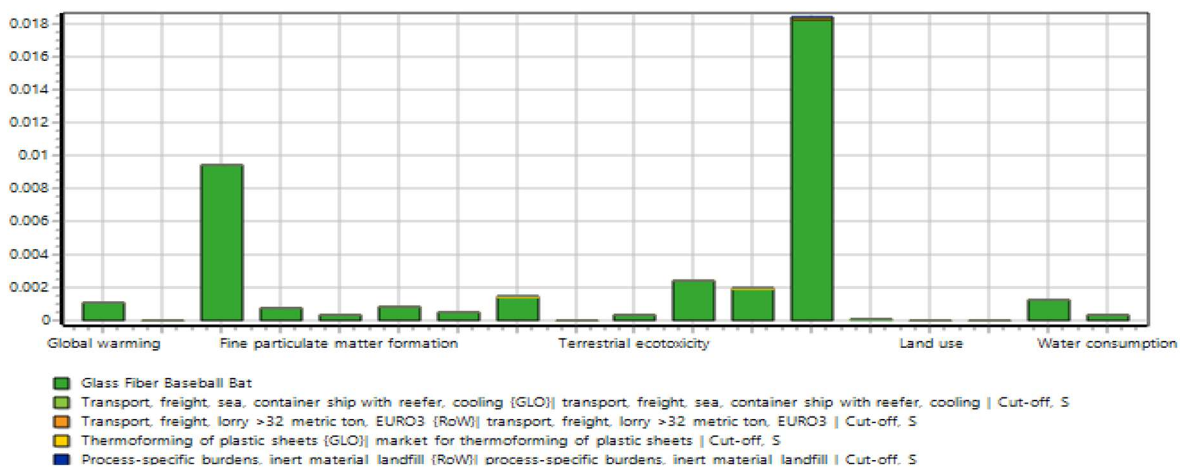

Figure 6: Normalization result of glass fiber composite baseball bat

When the impacts are normalized in the same units, in this case same scale, the figure 6 explains that ionizing radiation and human carcinogenic toxicity has higher impacts among other categories. The normalization LCA results exhibits significant ecotoxicity effects on terrestrial and freshwater ecosystems, along with contributions to both carcinogenic and non-carcinogenic human toxicity.

4.10 Impact Assessment Result of Basalt Fiber Composite Baseball Bat

In this section, the environmental impact associated with the production of basalt fibre composite baseball bat is presented. The following Table 7 summarises the impact catagories for the production of basalt fiber composite baseball bat.

Impact category	Unit	Total
Global warming	kg C02 eq	1,91
Stratospheric ozone depletion	kg CFCII eq	6,15E-7
Ionizing radiation	kBq co-60 eq	4,57
Ozone formation	kg NOX eq	0,00127
Fine particulate matter formation	kg PM2.5 eq	0,000654
Ozone formation, Terrestrial	kg NOX eq	0,00134
Terrestrial acidification	kg S02 eq	0,00153
Freshwater eutrophication	kg Peq	0,000123
Marine eutrophication	kg N eq	9,4E-5
Terrestrial ecotoxicity	1,4-DCB	3,63
Freshwater ecotoxicity	kg 1,4-DCB	0,044
Marine ecotoxicityty	kg 1,4-DCB	0,0556
Human carcinogenic toxicity	kg 1,4-DCB	0,0422
Human non-carcinogenic t	kg 1,4-DCB	0,996
Land use	m2a crop eq	0,0282
Mineral resource scarcity	kg Cu eq	0,00619
Fossil resource scarcity	kg oil eq	0,199
Water consumption	m3	0,0353

Table 7: Basalt fiber composites impacts results in various categories.

The basalt bat has lower contributions to global warming (1.91 kg CO2 eq), ozone depletion, ionizing radiation, and various air and water pollutants. Eutrophication impacts are minimal, and ecotoxicity is lower, indicating a more environmentally friendly option. The bat contributes to both carcinogenic and non-carcinogenic human toxicity, but the values are relatively low. Additionally, it exhibits reduced land use and lower impacts on mineral and fossil resource scarcity. Water consumption is relatively low at 0.0353 m^3.

4.11 Characterization and Normalization result of Basalt Fiber Baseball Bat

Similarly, each bar in a graph for characterization and normalization results refers to the impact category; global warming potential, ozone depletion, similarly, ionizing radiation, ozone formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and lastly water consumption are expressed in the figure respectively.

The following Figure 7 shows the impact of various processes during the manufacturing of basalt fiber baseball bats. Most of the impact is made during the production of base material and relatively contributed by the transportation of base material. The packaging of finished baseball bats also has significant impact on environment.

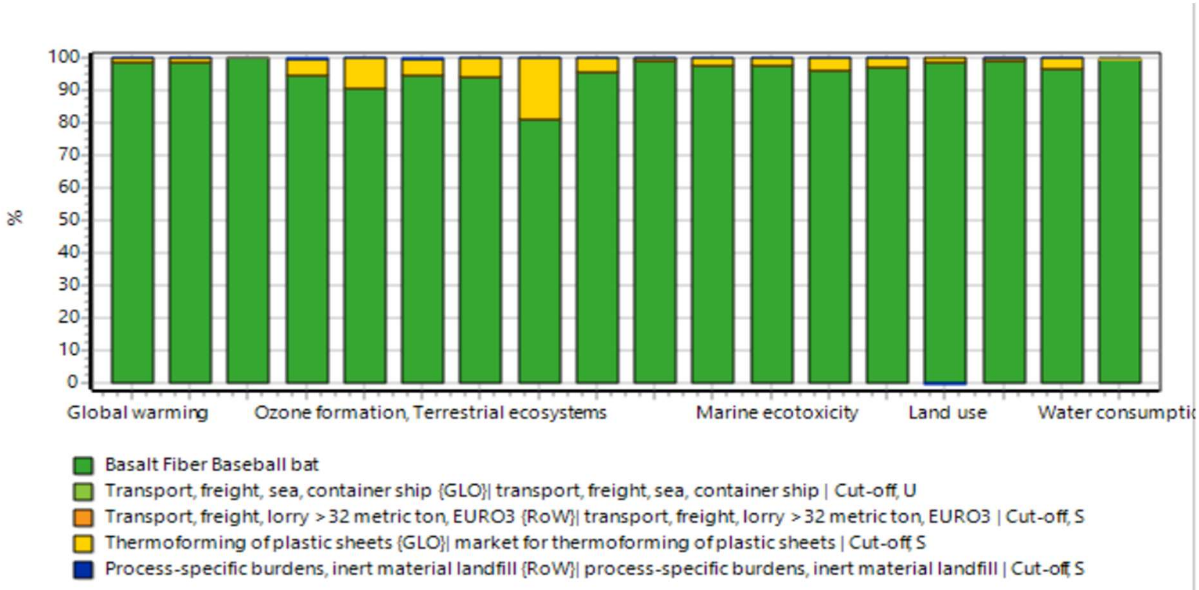

Figure 7: Normalization result of Basalt fiber composite baseball bat

The figure 8 explain the normalization result of impact analysis which helps to compare all impact categories with same unit.

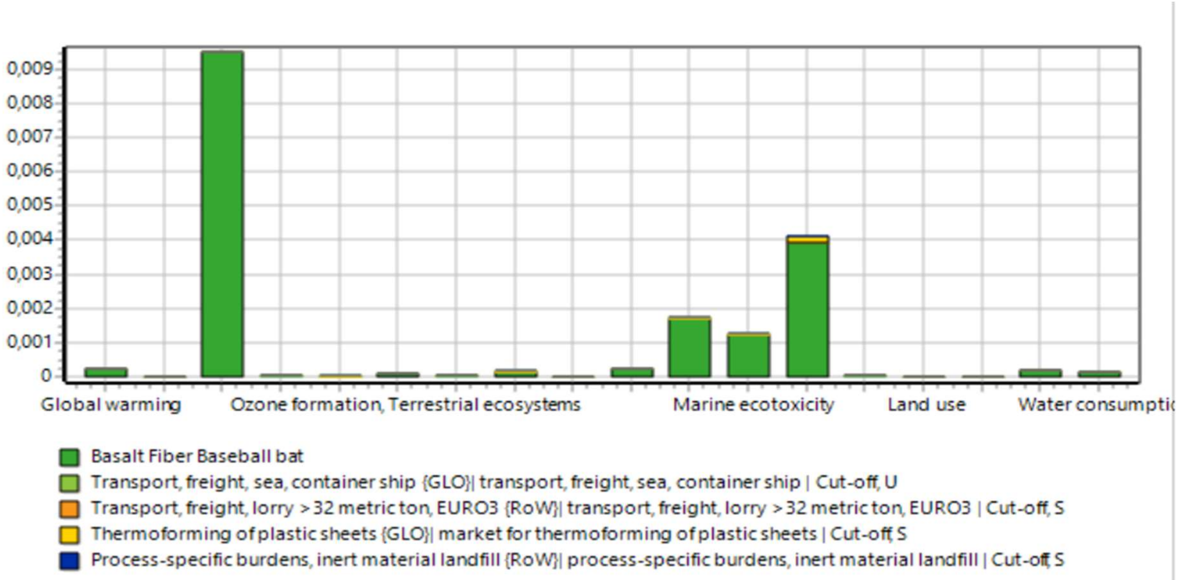

Figure 8: Normalization result of basalt fiber composite baseball bat

The above figure explains the impact results of different impact categories with same unit reference. Basalt fiber has ozone depletion impact has higher than other impact categories. The normalize results also shows that glass fiber has less ionizing impact whereas basalt has higher ionizing impact and in impact category human carcinogenic toxicity glass fiber have higher impacts than basalt. The result helps to analyse the impact categories with same reference.

4.12 Comparison between Glass and Basalt Fiber Composite Baseball Bat

In this section, the environmental associated with glass and basalt fiber composite baseball bats are compared and analysed.

Comparasion		GF BB	BB BB	% Difference
Impact category	Unit	Total	Total	Total
Global warming	kg C02 eq	8.63	1.91	-351.83
Stratospheric ozone depletion	kg CFCII eq	1.42E-06	6.15E-07	-130.89
Ionizing radiation	kBq Co-60 eq	4.53	4.57	0.87
Ozone formation, Human health	kg NOX eq	0.0148	0.00127	-1065.35
Fine particulate matter formation	kg PM2.5 eq	0.00847	0.000654	-1195.10
Ozone Formation, Terrestrial	kg NOX eq	0.0149	0.00134	-1011.94
Terrestrial acidification	kg S02 eq	0.0198	0.00153	-1194.11
Freshwater eutrophication	kg P eq	0.000958	0.000123	-678.86
Marine eutrophication	kg N eq	0.00015	9.40E-05	-59.57

Terrestrial ecotoxiciby	kg 1,4-DC8	5.26	3.63	-44.90
Freshwater ecotoxiciby	kg 1,4-DC8	0.0616	0.044	-40
Marine ecotoxicity	kg 1,4-DC8	0.0852	0.0556	-53.23
Human carcinogenic toxicity	kg 1,4-DC8	0.19	0.0422	-350.23
Human non-carcinogenic toxicity	kg 1,4-DC8	2.76	0.996	-177.10
Land use	m27 crop eq	0.077	0.0282	-173.04
Mineral resource scarcity	kg Cu eq	0.0074	0.00619	-19.54
Fossil resource scarcity	kg oil eq	1.24	0.199	-523.11
Water consumption	m3	0.097	0.0353	-174.78

Table 9: Comparison of environmental impact of glass and basalt fiber composite baseball bat.

The Life Cycle Assessment (LCA) results for basalt fiber baseball bats show a reduced environmental impact compared to glass fiber bats. The basalt fiber composite baseball bat has lower impact on global warming potential. It is 351% lower impact than glass fiber baseball bat. The comparison between glass fiber and basalt fiber composite baseball bats shows that the basalt fiber bat normally has lower environmental impact across various categories. Similarly, manufacturing of basalt fibre composite baseball bat can reduce 1194.11% terrestrial acidification in compared to glass fiber composite baseball bat manufacturing.

The following figure 9 shows impacts in different categories and illustrate the difference in impact between glass. It can be seen that most of the impact categories the glass fiber composite baseball bat has higher impact than basalt fiber composite baseball bat.

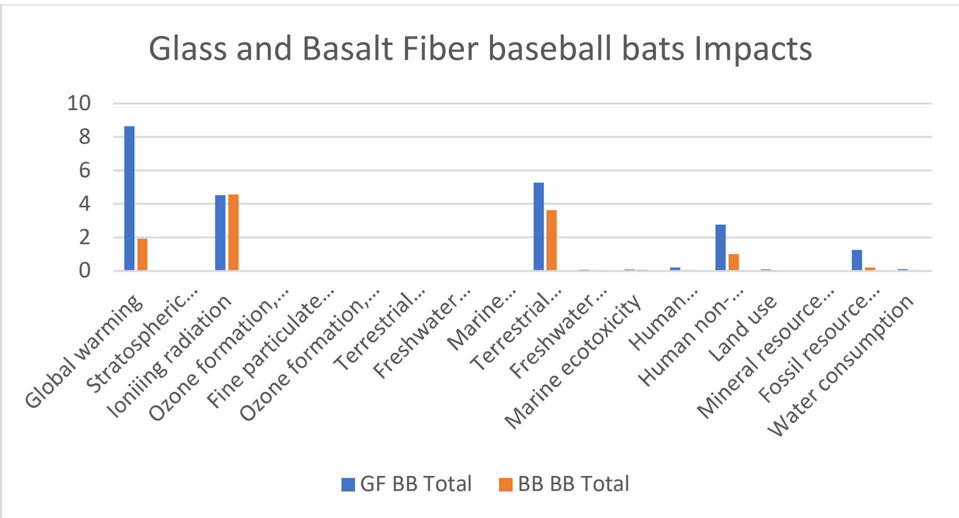

Figure 9: Impact difference of glass and basalt fiber composite baseball bat

The following figure 10 explains glass fiber composite baseball bats has higher impacts than basalt fiber composite baseball bats. It can be seen in the figure that the difference in impact of glass fiber composite baseball bat has relatively higher than basalt fiber baseball bat.

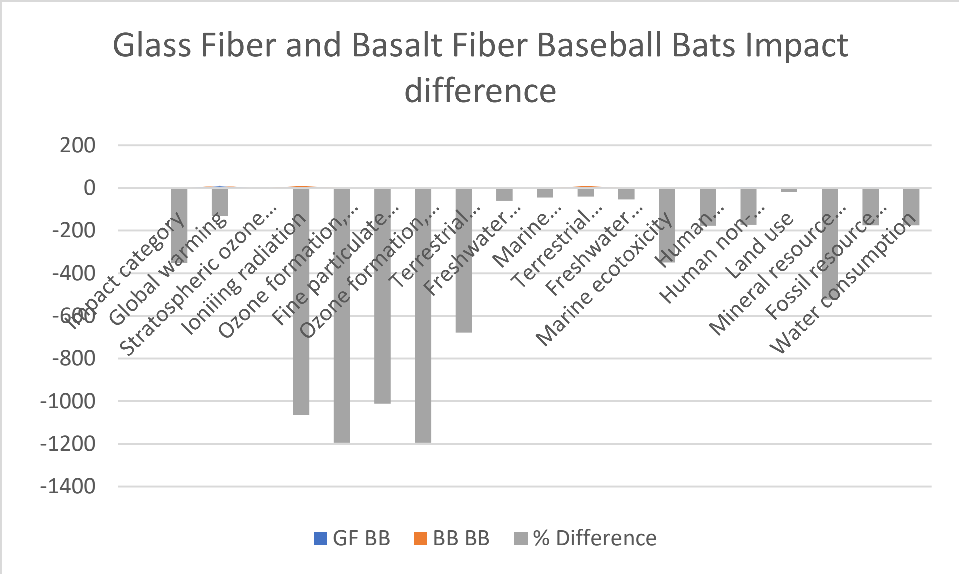

Figure 10: Glass fiber and basalt fiber impact difference

Thus, it can be concluded that the basalt fiber has many advantages over glass fibre in terms of environmental impact. The huge impact difference between glass fiber and basalt fiber, manufacturers choice of material can be basalt fiber in terms of environmental awareness and low carbon footprint.

5 Discussion and Conclusion

This section discusses whether the glass fibre or basalt fiber is most promising material for manufacturing baseball bats with more sustainable way.

5.8 Comparative Discussion

The LCA results for the glass fiber composite baseball bat revealed a substantial impact on global warming, contributing 8.63 kg of CO2 equivalent. Additionally, it showed contributions to various environmental categories, including stratospheric ozone depletion, ionizing radiation, air and water pollution, eutrophication, ecotoxicity, and resource use. The LCA results for the basalt fiber composite baseball bat presented a further advancement in sustainability compared to glass fiber composite baseball bats. The basalt fiber bat shows significant reductions in most of the impact categories. Furthermore, it exhibits lower resource use and water consumption, portraying an eco-friendlier alternative. The LCA result suggested that basalt fiber holds promising material with improved environmental performance, marking a positive step towards sustainable sports equipment.

5.9 Implication and Consideration

The findings from these LCAs have implications for L-Tec OY, consumers, and the sports industry. Manufacturers could consider adopting more sustainable materials and processes, such as basalt fiber, to reduce environmental footprints. Based on the environmental impacts of products consumer purchase, they, in turn, could be encouraged to make informed choices based on the environmental impacts of the products they purchase. The sports industry has an opportunity to contribute to broader sustainability goals by adopting eco-friendly materials and practices.

Future Research

Several future research opportunities are identified which are listed below:

- It is recommended that future researcher consider assessing environmental impact throughout its whole life (Cradle-to-grave)
- It is also recommended to the future researcher for performing scenario analysis.

5.10 Conclusion

The research highlights the growing landscape of sustainable practice in the production of composite material baseball bats. The traditional material has growing concern on environmental impacts. Even glass fiber composite has higher impact level than basalt fiber. Thus, adoption of basalt fiber shows positive trend towards more sustainable and responsible manufacturing. The results focus the importance of continuous effort to develop, innovate and optimize materials and processes in sport industry for more environmentally aware future.

It is important to make decision regarding disposal and recycling method for glass fiber and basalt fiber composite baseball bats. Traditional composite materials have difficulty in recycling because of complex combination of fiber and resin. Because of the less opportunity for recycling, option for disposal such as landfilling, or incineration may have associated environmental impacts. To solve these issues, advancement in material science aims to address these challenges. Other option might be the waste composite materials can be use in cement factory. Additionally, encouraging sustainability practice throughout the life cycle of these composite baseball bats depends heavily on consumers and making them aware about appropriate disposal techniques and the environmental effects of various end-of-life scenarios.

6 References

Abdullahi, S. S. (2021). *Comparison of the environmental impacts of a glass-reinforced plastic composite and steel slideway.* University of Twente,

Agarwal, K. K., & Agarwal, G. (2019). A study of mechanical properties of epoxy resin in presence of different hardeners. *Technol. Innov. Mech. Eng*, 1-9.

Bauer, R. (1985). Epoxy resins. In: ACS Publications.

Baumann, H., & Tillman, A.-M. (2004). The hitch hiker's guide to LCA.

Consultants, P. (2008). Introduction to LCA with SimaPro 7. *PRé Consultants, 284*.

Czigány, T. (2006). Special manufacturing and characteristics of basalt fiber reinforced hybrid polypropylene composites: mechanical properties and acoustic emission study. *Composites science and technology, 66*(16), 3210-3220.

Del Borghi, A. (2013). LCA and communication: environmental product declaration. In (Vol. 18, pp. 293-295): Springer.

Deru, M. P. (2009). *US Life cycle inventory database roadmap*: National Renewable Energy Laboratory.

Faizal, M. A., Beng, Y. K., & Dalimin, M. N. (2006). Tensile property of hand lay-up plain-weave woven e-glass/polyester composite: Curing pressure and Ply arrangement effect. *Borneo Sci, 19*, 27-34.

Fava, J., Denison, R., Jones, B., Curran, M., Vigon, B., Selke, S., & Barnum, J. (1994). A Technical Framework for Life-cycle Assessments (Vol. Second printing). *Pensacola, USA: SETAC Foundation for Environmental Education*.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H.-J. (2006). The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The international journal of life cycle assessment, 11*, 80-85.

Fiore, V., Scalici, T., Di Bella, G., & Valenza, A. (2015). A review on basalt fibre and its composites. *Composites Part B: Engineering, 74*, 74-94.

Foruzanmehr, M., Elkoun, S., Fam, A., & Robert, M. (2016). Degradation characteristics of new bio-resin based-fiber-reinforced polymers for external rehabilitation of structures. *Journal of Composite Materials, 50*(9), 1227-1239.

Hammond, G., Jones, C., Lowrie, F., & Tse, P. (2008). Inventory of Carbon & Energy: ICE: Sustainable Energy Research Team. *Department of Mechanical Engineering, University of Bath*.

Herrmann, I. T., & Moltesen, A. (2015). Does it matter which Life Cycle Assessment (LCA) tool you choose?–a comparative assessment of SimaPro and GaBi. *Journal of Cleaner Production, 86*, 163-169.

JyotiKalita, J., & Singh, K. K. (2018). *Tribological properties of different synthetic fiber reinforced polymer matrix composites-A review.* Paper presented at the IOP Conference Series: Materials Science and Engineering.

Kemna, R. B., & van Elburg, M. (2006). Methodology for Ecodesign of Energy-using Products (EuP). *ENERGY EFFICIENCY IN DOMESTIC APPLIANCES AND LIGHTING*, 257.

Kim, D., Thoma, G., Nutter, D., Milani, F., Ulrich, R., & Norris, G. (2013). Life cycle assessment of cheese and whey production in the USA. *The international journal of life cycle assessment, 18*, 1019-1035.

Klöpffer, W. (2012). The critical review of life cycle assessment studies according to ISO 14040 and 14044: origin, purpose and practical performance. *The international journal of life cycle assessment, 17*, 1087-1093.

Krishna, K. R., Nagaraju, D. B., Roy, M. R., & Kumar, B. A. (2016). Studies on tribological properties of SiC and fly ash reinforced glass fiber epoxy composites by Taguchi method. *International Journal of Mechanical Engineering and Technology, 7*(6), 199-208.

Li, Z., Ma, J., Ma, H., & Xu, X. (2018). *Properties and applications of basalt fiber and its composites.* Paper presented at the IOP Conference Series: Earth and Environmental Science.

Martynova, E., & Cebulla, H. (2018). Glass fibers. *Inorganic and composite fibers*, 131-163.

Moussa, H. (2014). *Life cycle assessment of a hybrid poly butylene succinate composite.* University of Waterloo,

Novitskii, A. (2004). High-temperature heat-insulating materials based on fibers from basalt-type rock materials. *Refractories and Industrial Ceramics, 45*(2), 144-146.

Pascault, J., Sautereau, H., Verdu, J., & Williams, R. (2002). Are Cured Thermosets Inhomogeneous. ______*. Thermosetting Polymers. New York: Marcel Dekker*.

Patel, M. (2003). Cumulative energy demand (CED) and cumulative CO2 emissions for products of the organic chemical industry. *Energy, 28*(7), 721-740.

Petroche, D., Ramírez, A., Rodríguez, C., Salas, D., Boero, A., & Duque-Rivera, J. (2015). Life cycle assessment of residential buildings: A review of methodologies. *WIT Transactions on Ecology and the Environment, 194*, 217-225.

Rudawska, A. (2017). 17 Epoxy Adhesives. *Handbook of Adhesive Technology, 10*(11), 415.

Sathishkumar, T., Satheeshkumar, S., & Naveen, J. (2014). Glass fiber-reinforced polymer composites–a review. *Journal of Reinforced Plastics and Composites, 33*(13), 1258-1275.

Shen, L., & Patel, M. K. (2008). Life cycle assessment of polysaccharide materials: a review. *Journal of Polymers and the Environment, 16*, 154-167.

Srivastava, J. P., & Kumar, P. (2022). Introduction to Glass Fiber-Based Composites and Structures. *Natural and Synthetic Fiber Reinforced Composites: Synthesis, Properties and Applications*, 1-16.

Standardization, I. O. f. (1996). *ISO 14001: 1996: Environmental Management Systems-Specfication with Guidance for Use*: ISO.

Tavadi, A. R., Naik, Y., Kumaresan, K., Jamadar, N., & Rajaravi, C. (2021). Basalt fiber and its composite manufacturing and applications: An overview. *International Journal of Engineering, Science and Technology, 13*(4), 50-56.

Thomas, R. Micro-and Nanostructured Epoxy/Rubber Blends.

Wei, B., Cao, H., & Song, S. (2011). Degradation of basalt fibre and glass fibre/epoxy resin composites in seawater. *Corrosion Science, 53*(1), 426-431.

Yasufuku, S. (1994). Application of glass fiber-reinforced plastics to electrical and electronic apparatus in Japan. *IEEE Electrical Insulation Magazine, 10*(1), 8-15.

Yu, J., & Chen, L. X. (2008). The greenhouse gas emissions and fossil energy requirement of bioplastics from cradle to gate of a biomass refinery. *Environmental science & technology, 42*(18), 6961-6966.