LIFE CYCLE ASSESSMENT (LCA) OF 3D BONE TISSUE ENGINEERING(BTE) SCAFFOLDS BY USING GABI SOFTWARE

FARASYAFINAZ BINTI SENUSI

A thesis submitted
in fulfillment of the requirement for the award of the
Master in Engineering Technology

Faculty of Engineering Technology
Universiti Tun Hussein Onn Malaysia

SEPTEMBER 2023

To my beloved mother and father:

Pn Aminah binti Ahmad and Tn Hj. Senusi bin Tasek.

For the advices and encouragements from the very beginning of this Master Degree till the end of this journey

To my supportive supervisor:

Dr. Salwa binti Mahmood.

For keep pushing me to finish what I have started. Keep going on being a very supportive and cool supervisor to me and others

To my siblings and close friends:

For lending me ears to hear all the complaint and struggle all the way of this journey.

To organization:

Universiti Tun Hussein Onn Malaysia

For providing me the grants to fund this research.

ACKNOWLEDGEMENT

First and foremost, I bid to Allah The Almighty for blessing me strength to complete this Master Degree successfully. I would like to express my sincere appreciation to my supervisor, Dr. Salwa binti Mahmood for the consistent support given throughout the duration for this research. She provided the opportunity for me to continue my Master Degree under her supervision, helping me throughout this research and encouraging me to finish this thesis.

Next appreciation also goes to the important person in my life who always encourages and provides full supports for me to finish this journey. They are the one that encourage me to further this study and without them, I will not be able to think to continue studying in Master level and start this journey. This appreciation goes to my beloved parents, Senusi bin Tasek and Aminah binti Ahmad.I am also grateful for financial assistance provided from Universiti Tun Hussein Onn Malaysia (UTHM) under GPPS grants during my research years.And also to all of my friends that involved directly or indirectly towards the compilation of this thesis, who constantly hear me complaining and struggling to finish this thesis.

Last but not least, I want to thank myself for believing in me, doing all this hard work without giving up and never quit. As the result, able to finish this journey even though it is lonely and tough. Thank you.

ABSTRACT

Bone Tissue Engineering (BTE) scaffold is one of the methods used to repair bone defects caused by various factors. According to modern tissue engineering technology, three-dimensional (3D) printing technology for BTE provides a temporary basis for the creation of biological replacements. Based on the generated 3D BTE scaffolds from previous studies, environmental impact assessment has received less attention in research. Therefore, this research aimed to develop a Life Cycle Assessment (LCA) Model or cradle-to-grave technique for 3D BTE scaffold system boundary from raw material production, printing process, transportation to use and product disposal. Meanwhile, the digital light processing (DLP) 3D printing technology was used as the manufacturing process in the system boundary. The analysis of the LCA model was conducted using GaBi software. The parameters for the developed LCA model were determined by the system boundaries of DLP 3D printing technology. All emissions were identified such as emissions to air, freshwater, seawater, and industrial soil. From the output relative value emissions, it showed that the electricity grid mix contributed the highest emissions to deposited goods, air, fresh water and sea water. Meanwhile, the highest emissions to agricultural and industrial soil was from ethylene glycol and plastic waste on landfills. From the analysis, it showed that the Abiotic Depletion Potential (ADP) fossil has the highest value of 17.043 Mega Joules (MJ) with 96.35% for potential environmental impacts among others. Therefore, the results are expected to be used for improving the performance on the material and manufacturing process of the product life cycle. It is also to make the production process more environmentally friendly.

ABSTRAK

Perancah kejuruteraan tisu tulang adalah salah satu kaedah untuk memperbaiki kecacatan tulang yang disebabkan oleh pelbagai faktor. Menurut teknologi kejuruteraan tisu moden, teknologi pencetakan tiga dimensi (3D) untuk kejuruteraan tisu tulang menyediakan asas sementara untuk penciptaan penggantian biologi. Berdasarkan kajian terdahulu tentang perancah kejuruteraan tisu tulang 3D, penilaian untuk menilai kesan persekitaran mendapat perhatian yang kurang dalam penyelidikan. Oleh itu, penyelidikan ini bertujuan untuk mengembangkan model penilaian kitaran hidup (LCA) untuk perancah teknik tisu tulang teknologi percetakan 3D. Selain itu, projek ini menyajikan teknik analisis LCA dari *"cradle-to-grave"* untuk menilai kesan persekitaran yang berpunca dari pengeluaran bahan mentah, proses pencetakan, pengangkutan hingga penggunaan dan pelupusan produk. Seterusnya, teknologi pencetakan 3D pemprosesan cahaya digital (DLP) digunakan sebagai sistem sempdan bagi proses pembuatan ini. Analisis kajian ini dijalankan berdasarkan model LCA melalui aplikasi perisian GaBi. Parameter untuk model LCA ini juga ditentukan oleh batasan sistem teknologi percetakan 3D DLP. Semua pelepasan proses telah dikenal pasti iaitu pelepasan ke udara, air tawar, air laut, dan tanah industri. Pelepasan nilai relatif keluaran menunjukkan nilai campuran grid elektrik menghasilkan nilai pelepasan yang tertinggi kepada bahan tersimpan, udara, air tawar dan air laut. Selain itu, nilai pelepasan tertinggi kepada tanah pertanian dan tanah industri berpunca daripada etilena glikol dan sisa plastik di tapak pelupusan sampah. Analisis juga menunjukkan bahawaADP fosil menunjukkan nilai tertinggi untuk kesan nilai persekitaran dengan 17.043 MJ dan 96.35% dibandingkan dengan kesan persekitaran yang lain. Oleh itu, keputusan analisis data yang diperolehi diharapkan dapat digunakan untuk meningkatkan prestasi pada proses bahan dan pembuatan kitaran hidup produk. Ia juga membantu menjadikan proses pengeluaran lebih mesra alam.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

BTE	-	Bone Tissue Engineering
3D	-	Three Dimensional
LCA	-	Life Cycle Assessment
DLP	-	Digital Light Processing
ADP	-	Abiotic Depletion Potential
MJ	-	Megajoule
GWP	-	Global Warming Potential
AP	-	Acidification Potential
EP	-	Eutrophication Potential
HTP	-	Human Toxicity Potential
AM	-	Additive Manufacturing
RP	-	Rapid Prototyping
EOL	-	End Of Life
ISO	-	International Standard Organization
SDG	-	Sustainable Development Goals
ECM	-	Extracellular Matrix
CAD	-	Computer Aided Design
CAM	-	Computer Aided Manufacturing
SLS	-	Selective Laser Sintering
FDM	-	Fused Deposition Modeling
TE	-	Tissue Engineering
HA	-	Hydroxyapatite
PLGA	-	Poly(lactide-co-glycolide)
PCL	-	Polycaprolactone
SLA	-	Stereolitography

DMD	-	Digital Mirror Device
UV	-	Ultra Violet
2D	-	Two Dimensional
v	-	Eco-vector
EL	-	Environmental Load
M	-	Mass Flow
E	-	Energy Flow
P	-	Pollutants
IP_i	-	Mass Input
IE_i	-	Energy Input
P_i	-	Outputs
W_i	-	Wastes
$V_{m,e}$	-	Mass and Energy Eco Vectors
LCI	-	Life Cycle Inventory
EOL	-	End Of Life
CFCs	-	Cholorofluorocarbons
CO_2	-	Carbon Dioxide
H_2SO_4	-	Sulfur Dioxide
HNO_3	-	Nitrogen Oxide
H^+	-	Hydrogen
NO	-	Nitrogen Oxide
PO_4^{3-}	-	Phosphate
TPO	-	Diphenyl (2,4,6-trimethylbenzoyl) Phosphine Oxide
PEGDA	-	Polyethylene Glycol Dimethacrylate
USLCI	-	US Life Cycle Inventory
GUI	-	Graphical User Interfaces
kg	-	Kilogram
ODP	-	Ozone Layer Depletion

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Research

In the mid-1980s, additive manufacturing evolved and benefited from faster processing of products without the need for specialized tooling or dies. The use of additive manufacturing technology has become popular and proven ideal for Bone Tissue Engineering (BTE) (Bose *et al*., 2013). Tissue engineering continues to evolve to develop biological substitutes to restore, replace or regenerate defective tissues. Development of tissue isvital in directing biological functions. Cells, scaffolds and growth-stimulating signalsare the key components of tissue engineering. Scaffold is typically made of polymeric biomaterials that provide structural support for cell attachments and subsequent tissuedevelopment (Chan & Leong, 2008). Since scaffold provides structural support for cells, the design properties are the key factor in BTE, and represent more than just a passive component. It will control cell and tissue growth by balancing mechanical functions (Butscher *et al*., 2011). In a previous research, Cao *et al*., (2015) stated thatthe regeneration of bone is complex as it involves number of molecular, cellular, biochemical and mechanical cues. Appropriate macro and microstructures are key features, and it could influence cell penetration, transportation of gases and nutrients.Tissue engineering in additive manufacturing is the bioprinting process combining tissue engineering and additive manufacturing technology. The process of joining materials to create objects from layer-by-layer 3D model data is called three dimensional (3D) printing, or also known as additive manufacturing and rapid prototyping.

Additive manufacturing (AM) or Rapid Prototyping (RP) was developed in late 1980s and usually synonymous with AM in non-technical areas. It is a versatile technique to fabricate a wide variety of materials that can be used in many industrial applications such as BTE. 3D printing has attracted interest in biomedical field in terms of its versatility, ease of use and precise controls of the fabrication process. 3D printing is considered as the most advantageous techniques in fabricating tissue engineering scaffolds as it prints macro-micro structures that mimic the multi-scale structure of human body tissues (Cao *et al*., 2015). 3D technology has evolved throughout the years; hence, its manufacturingprocess has affected environmental ecosystem. Many researchers have begun to focuson environmental impact, and thus studies related to standard method to evaluate the inherent impacts have gained attention among researchers.

Life Cycle Assessment (LCA) is one of the standard methods for environmental impact assessment and has been applied to existing or established product systems. It is a technique to evaluate the potential environmental impact associated with all the stages of the product life from raw material extraction through materials processing, manufacture, distribution,usage, maintenance, and disposal or recycling (Loiseau *et al*., 2018). The purpose of LCA analysis is to understand the matter and energy flows which are assignable to products and services by quantifying all the inputs and outputs of materials flow, and also to find out what are the environmental critical points and prevent them from usingother materials or systems (Beltran *et al*., 2018). This research employed the ISO 14040:2006 to ensure that the standard LCA results were obtained. In addition, Gabi software was used for the development of LCA model as well as for obtaining the potential environmental impacts. It provides several benefits in conducting LCA analysis and provides a platform to conduct the analysis with wide range of features and capabilities even for model complex. Incorporates with Life Cycle Inventory (LCI) data, it give access to detailed information on materials, process and products. With its wide application, many organizations and industries start to assess this software in order to support sustainable decision of environmental impacts.

1.2 Problem Statement

LCA has been applied to various products or services to assess their potential environmental aspects. Numerous researches have emphasized the use of LCA for life cycle and environmental performance of product. Among those studies are Labuschagne & Brent, (2005) and Mannheim & Simenfalvi, (2020) who proposed improvement at various stages to encourage closed loops in industrial systems by reducing waste, raw materials and energy inputs. The LCA model displays theemission and environmental impacts during the entire life cycle of a product. Khasreen *et al*., (2009) reviewed LCA from a building perspective attenuating its importance as a decision making support tool. LCA is a tool to evaluate potential environments for the manufacturing and also construction industries. The Identification of potential improvements during the design phase allows the designersto clarify the activities involved in product development and detect the activies that govern the environmental impact of a product (Penciuc *et al*., 2016). Studies on LCAof 3D technology are still scarce, but there was research on LCA of 3D printed technology conducted by Cerdas *et al*., (2017) focusing on products manufactured in a distributed manufacturing system. However, no studies have been found specifically on the environmental assessment of 3D BTE scaffold. The development of the LCA model is able to evaluate the possible environmental impacts associated with all phasesof the life cycle of the product.

The 3D BTE scaffold is one of the latest technologies to recover bone defects generated from various causes. BTE has been constantly evolving since the tissue engineering idea was proposed. Bose *et al*., (2013) summarized a few selected material-binder system combinations for bone scaffolds using 3D printing technology. The development of 3D bone scaffolds LCA involves the stage of material selection and manufacturing process that contribute to environmental exposure from energy consumption and emission to land, water, and air. Saade *et al*., (2020) explained that careful measures in 3D printing are mostly focused on its energy performances; therefore, the environmental performance of the product needs to improve at various points in the life cycle of the proposed tissue engineering scaffold'. Ford and Despeisse (2016) justified that additive manufacturing provides opportunities to improve resource efficiency through technical approaches, and this statement is also approved by Smith *et al*., (2007). In other studies, Butscher *et al*., (2011) and Moncal *et al*.,

(2018) focused on a wide variety of materials used in 3D printing from synthetic and natural polymers to ceramics as well as composite ink solutions. Most of the previous research has discussed the fabrication of BTE through the 3D printing process, but they did not emphasize the environmental impacts of BTE scaffold process and product life cycle. Thus, this research proposed the development an LCA model to analyze the potential environmental impacts of 3D BTE scaffold using GaBi software.

1.3 Research Objectives

The objectives of this research are:

i. To develop an LCA model for 3D BTE scaffolds from cradle-to-grave ofsystem boundary.
ii. To identify the environmental impacts for the whole life cycle model of 3D BTE scaffolds by using GaBi software.
iii. To determine the factors that contribute the most to the environmental potential impact.

1.4 Research Scopes

The scopes of this research are as follows:

i. This research uses cradle-to-grave LCA analysis technique to assess the environmental impacts covering material selection until the End of Life (EOL) cycle of 3D BTE scaffolds.
ii. The analysis of LCA model is conducted using GaBi software.
iii. This research focuses on the environmental impacts in Abiotic Depletion Potential (ADP) Fossil, Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP) and Human Toxicity Potential (HTP).

1.5 Significance of Research

LCA is one of the tools that help a product manufacturing process flow. In this research, LCA was used to identify the potential environmental impacts related the 3D BTE scaffold. Factors affecting the environmental aspects included raw material, energy consumption, manufacturing process and waste in the entire life cycle to sustain environment factors. By controlling and identifying the entire life cycle of the product, it may lead to a sustainable manufacturing process.

GaBi software as one of the models uses in this research has benefit the user in providing extensive database while constantly updating life cycle inventory data. A complex life cycle models for product or process are easily can be create which enable users to assess environmental impacts from different regions. Moreover, application of GaBi software allowing to interpret the impacts of parameter assumptions and input data on LCA results while helps in identifying the uncertainties and variability within LCA model.

This research identified LCA impacts to society, environment and industry. Additive manufacturing has been applied in different sectors such as aerospace, manufacturing and healthcare industries. According to Ford & Despeisse, (2016), additive manufacturing in 3D BTE promises a future where the value chain is shorter, smaller, more localized, more collaborative, and offers significant sustainability benefits. It also has potential sustainability advantages such as less material wastage during the manufacturing process, ability to optimize geometry, and reduce energy consumptionand transportation costs. 3D printing helps medical industry especially in orthopedic implants and medical devices with biomaterials that are a purely sustainable process. There are several LCA studies on different types of biomaterials and manufacturing methods. It has been reported that 3D technology using biomaterials showed lower environmental impacts in the fabrication of orthopedic implants and medical devices (Yadav et al., 2020).

1.6 Summary

This chapter explained research background related to the 3D BTE scaffolds and methods to assess potential environmental impacts via the LCA model. To identify the environmental impact, the stage of 3D BTE scaffolding requires the involvement of raw material production, pre-manufacturing stage, printing process, transportation until the end of the product life cycle which included the use and disposal of the product. The implementation of LCA will help to identify the potential environmental impacts and the weak areas related to environmental aspects. Therefore, tissue engineering scaffold technology can be improved to reduce the environmental burden.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter describes relevant literature for each subtopic in this research. It includesdetailed concepts regarding LCA studies from previous research. In addition, this chapter explains in detail about 3D printing technology especially for the 3D BTE area.

2.2 Life Cycle Assessment (LCA)

LCA is one of the methods to evaluate the environmental impact. According to Sonnemann *et al*., (2004), LCA has been developed to analyzing the environmental performance of a product, determine its present status, and enable future improvements. According to the ISO 14040:2006, LCA is a tool for assessing the potential environmental aspects and potential aspects associated with a product or service. It is by compiling an inventory of inputs and outputs, evaluating the potential environmental impacts with those of inputs and outputs, and interpreting the results concerning the objectives of the study (ISO, 2006). LCA must be organized by dividing the manufacturing process into well-defined sections or phases, then identifying afterwards the part of the process responsible for each environmental effect. The early application of LCA helps to gain an insight of environmental performances and potential challenges at early stages (Yao *et al*., 2020).

The focus throughout the entire life cycle includes extraction resources, processing raw materials through manufacturing process, and final process in products disposal. Resource extraction in the product life cycle can be identified and quantified as energy released into air, water and soil. All of the resource extraction can cause environmental emissions. The emissions that have been quantified represent the sum of impacts from emissions then hit different ecosystems in different parts of the world and reflect the potential contributions to actual impacts to the environment (Finnveden *et al*., 2009).

There are two common types of uses in LCA, namely general uses and particular uses. For general use, it helps to compare alternative options and identify points for environmental enhancement. It also counts on a global perspective and is able to understand environmental consequences of human activities. Moreover, the general use of LCA establishes a picture of the interaction between products and the environment, and to support information for identifying environmental improvement opportunities. Meanwhile, particular use of LCA helps define the environmental performance of a product during its life cycle. Identifying the most relevant steps in the manufacturing processes related to a given environmental impact and comparing environmental performance with others are also particular use of LCA.

According to Sonnemann *et al*., (2004), an overview of the LCA history was not easy to describe precisely when studies related to the methodology later known as LCA started. One of the first studies was from the work of H. Smith as described by Consoli *et al*., (1994), where the calculation of energy requirements for the manufacturing of final and intermediate chemical products entered the public domain in 1963. LCA, as an environmental management tool, started in 1960s in different ways and with a variety of names, but the concept to explore the life cycle of products was initially developed in the United States in the fifties and sixties within the realm of public purchasing (Huppes & Curran, 2012). The origin of life cycle thinking has become a trademark for the US defense industry, and has been used to consider the operational and maintenance costs of systems (Khasreen *et al*., 2009). Novick (1959) stated that the first mention of the life cycle concept was in a report by the RAND Corporation that focused on Life Cycle Analysis of weapon system costs. It also has its early roots in packaging studies and focused mainly on energy uses and low emissions, spurring a largely un-coordinated method development in US and Northern

Europe (Bjørn *et al*., 2017). In 1969, Coca-Cola was one of the earliest companies that carried out a study to quantify and determine the type of container with the lowest environmental effects of packaging. The LCA study was carried out by Midwest Research Institute (MRI) (Consoli *et al*., 1994).

Over decades, numerous case studies have been carried out by companies and organizations to increase environmental awareness to the public. Numerous publications and conferences by organizations, such as Society for Environmental Toxicology and Chemistry (SETAC) and International Standard Organization (ISO), played a role in developing LCA methodology to be used in a practical manner by all product and service sectors (Khasreen *et al*., 2009). From the initiatives to standardize the LCA methodology, the most recognized standards were published by the International Standard Organization (ISO) (ISO, 2006). The ISO framework in LCA is explained in detail in Section 2.2.1, which is the LCA framework and ISO14000 patterns.

2.2.1 LCA Framework and International Standard

International Standard Organization, (ISO) standardized the LCA methodology and technical framework in the 1990s. Itis the most recognized standard and followed by the entire globe. To date, the development of ISO for LCA methodology continues to expand and be revised. The development of ISO for LCA as per below:

i. ISO14040: Environmental Management LCA, Principles and framework (1997).
ii. ISO14041: Environmental Management LCA, Goal definition and inventory analysis (1998).
iii. ISO14042: Environmental Management LCA, Life-cycle impact assessment (2000).
iv. ISO14043 Environmental Management LCA, Life-cycle interpretation (2000).
v. ISO14044 Environmental Management LCA, Requirements and guidelines (2006).

Finkbeiner *et al*., (2006) mentioned that the publication of new standards, namely ISO 14040 and ISO 14044, have technically revised and replaced the former fourstandards as written above. However, according to the scope of revision, the core partsof technical contents remain unchanged. The two new standards, ISO 14040 and ISO 14044, reconfirm the validity of the main technical content of previous standards.

The steps of LCA are distributed along with ISO patterns: ISO 14044 (2006) provides a general framework for LCA; ISO 14041 (1998) explains a guideline to determine goal and scope of LCA; ISO 14042 (2000) deals with the life-cycle impact assessment step; and ISO 14043 (2002) provides a statement to interpret results from LCA and the latest ISO 14044 (2006) mentioned specific requirements and guidelines for LCA that illustrate how to apply it proportional to the LCA framework and affect the other phases in some way.Figure 2.1 shows the general methodology of LCA framework.

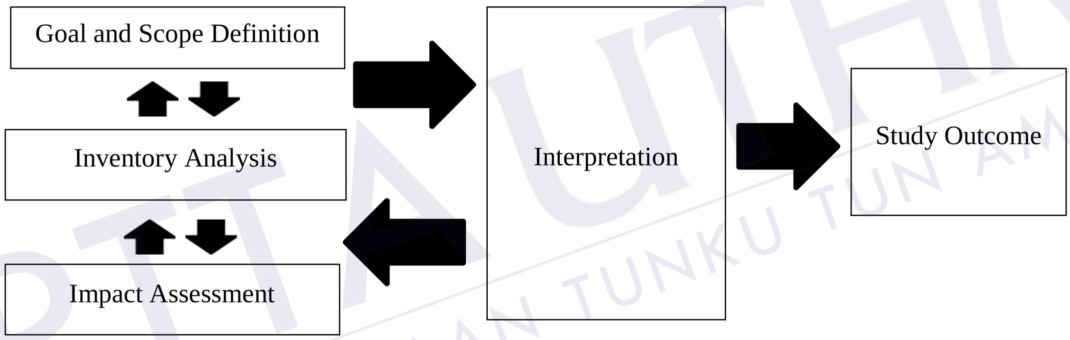

Figure 2.1: General Methodological Framework of LCA (Khasreen *et al*., 2009)

ISO 14041, in 1998, provided guidelines to determine goal and scope of LCA while conducting study. It was designed to obtain the required specifications and define the strategic aspects concerning LCA study. There were procedures that needed to be followed in the guideline. It is crucial to define the purpose of LCA study to have an efficient LCA process, which in turn recognizes the type and quality of the data easily. The purpose or goal of LCA will determine what information or what functional unit, which is the quantitative reference is needed for the study since it can affect the results of LCA (Khasreen *et al*., 2009). Then, the scope of study identified is able to establish spatial limit between product system and its neighborhood. Details of the product system will be simplified in drawing, or known as unit process flowchart.

REFERENCES

Backes, J. G., Traverso, M., & Horvath, A. (2023). Environmental assessment of a disruptive innovation: comparative cradle-to-gate life cycle assessments of carbon-reinforced concrete building component. *International Journal of Life Cycle Assessment*, *28*(1), 16–37. https://doi.org/10.1007/s11367-022-02115-z

Bagheri, A., & Jin, J. (2019). Photopolymerization in 3D Printing. *Applied Polymer Materials*, *1*(4), 593–611. https://doi.org/10.1021/acsapm.8b00165

Bjørn, A., Owsianiak, M., Molin, C., & Hauschild, M. Z. (2017). LCA history. In *Life Cycle Assessment: Theory and Practice*. https://doi.org/10.1007/978-3-319-56475-3_3

Bose, S., Vahabzadeh, S., & Bandyopadhyay, A. (2013). Bone tissue engineering using 3Dprinting.In *MaterialsToday*. https://doi.org/10.1016/j.mattod.2013.11.017

Butscher, A., Bohner, M., Hofmann, S., Gauckler, L., & Müller, R. (2011). Structural and material approaches to bone tissue engineering in powder-based three-dimensional printing. *Acta Biomaterialia*, *7*(3), 907–920. https://doi.org/10.1016/j.actbio.2010.09.039

Cao, C. (2017). Sustainability and life assessment of high strength natural fibre composites in construction. In *Advanced High Strength Natural Fibre Composites in Construction*. https://doi.org/10.1016/B978-0-08-100411-1.00021-2

Cao, X. F., Song, P. J., Qiao, Y. J., & Zhen, P. (2015). 3D printing of bone tissue engineering scaffolds. *Chinese Journal of Tissue Engineering Research*, *19*(25), 4076–4080. https://doi.org/10.3969/j.issn.2095-4344.2015.25.027

Cerdas, F., Juraschek, M., Thiede, S., & Herrmann, C. (2017). Life Cycle Assessment of 3D Printed Products in a Distributed Manufacturing System. *Journal of Industrial Ecology*, *21*, S80–S93. https://doi.org/10.1111/jiec.12618

Chaffee, C., & R. Yaros, B. (2008). *Life Cycle Assessment for Three Types of Grocery Bags*. https://plastics.americanchemistry.com/Life-Cycle-Assessment-for-

Three-Types-of-Grocery-Bags.pdf

Chan, B. P., & Leong, K. W. (2008). Scaffolding in tissue engineering: General approaches and tissue-specific considerations. *European Spine Journal*, *17*(SUPPL. 4). https://doi.org/10.1007/s00586-008-0745-3

Chong, S., Chiu, H. L., Liao, Y. C., Hung, S. T., & Pan, G. T. (2015). Cradle to Cradle® design for 3D printing. *Chemical Engineering Transactions*, *45*, 1669–1674. https://doi.org/10.3303/CET1545279

Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A., De Oude, N., Parrish, R., Perriman, R., Postelthwaite, D., Quay, B., Séguin, J., & Vigon, B. (1994). Guidelines for Life-Cycle Assessment: A "Code of Practice." *The Sesimbra Portugal 31 March 3 April 1993 Meeting of the Society of Environmental Toxicology and Chemistry SETAC*, *1*(1), 55–55. http://www.springerlink.com/content/g811hj24t46532u4/

Cubo-mateo, N. (2020). *Design of Thermoplastic 3D-Printed Sca ff olds for Bone Tissue Engineering : Influence of Parameters of "Hidden" Importance in the Physical Properties of Sca ff olds*.

El Haggar, S. M. (2005). Rural and developing country solutions. In *Environmental Solutions*. https://doi.org/10.1016/B978-012088441-4/50015-0

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91*(1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Fong, M. L., Lin, Z., Fong, K. F., Hanby, V., & Greenough, R. (2017). Life cycle assessment for three ventilation methods. In *Building and Environment*. https://doi.org/10.1016/j.buildenv.2017.02.006

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Gehin, A., Zwolinski, P., & Brissaud, D. (2008). A tool to implement sustainable end-of-life strategies in the product development phase. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2007.02.012

Ghinea, C., & Leahu, A. (2023). Life cycle assessment of sheep cheese production in a small dairy factory from Romanian rural area. *Environmental Science and Pollution Research*, *30*(3), 6986–7004. https://doi.org/10.1007/s11356-022-

22644-2

Gobio-Thomas, L. B., Darwish, M., & Stojceska, V. (2023, February 1). Environmental impacts of solar thermal power plants used in industrial supply chains. *Thermal Science and Engineering Progress*. Elsevier Ltd. https://doi.org/10.1016/j.tsep.2023.101670

Godina, R., Ribeiro, I., Matos, F., Ferreira, B. T., Carvalho, H., & Peças, P. (2020). Impact assessment of additive manufacturing on sustainable business models in industry 4.0 context. *Sustainability (Switzerland), 12*(17), 1–21. https://doi.org/10.3390/su12177066

Gómez-Monsalve, M., Domínguez, I. C., Yan, X., Ward, S., & Oviedo-Ocaña, E. R. (2022). Environmental performance of a hybrid rainwater harvesting and greywater reuse system: A case study on a high water consumption household in Colombia. *Journal of Cleaner Production*, *345*. https://doi.org/10.1016/j.jclepro.2022.131125

Gregor, A., Filová, E., Novák, M., Kronek, J., Chlup, H., Buzgo, M., Blahnová, V., Lukášová, V., Bartoš, M., Nečas, A., & Hošek, J. (2017). Designing of PLA scaffolds for bone tissue replacement fabricated by ordinary commercial 3D printer. *Journal of Biological Engineering*, *11*(1), 1–21. https://doi.org/10.1186/s13036-017-0074-3

Hembrick-Holloman, V., Samuel, T., Mohammed, Z., Jeelani, S., & Rangari, V. K. (2020). Ecofriendly production of bioactive tissue engineering scaffolds derived from egg- And sea-shells. In *Journal of Materials Research and Technology* (Vol. 9, Issue 6, pp. 13729–13739). https://doi.org/10.1016/j.jmrt.2020.09.093

Huppes, G., & Curran, M. A. (2012). Environmental Life Cycle Assessment: Background and Perspective. In *Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products* (pp. 1–14). https://doi.org/10.1002/9781118528372.ch1

International Reference Life Cycle Data System (ILCD) Handbook. (2010). General guide for Life Cycle Assessment - Detailed guidance. In *International Reference Life Cycle Data System (ILCD) Handbook.*

ISO. (2006). 14040: Environmental management–life cycle assessment—Principles and framework. *International Organization for Standardization*.

Iswara, A. P., Farahdiba, A. U., Nadhifatin, E. N., Pirade, F., Andhikaputra, G., Muflihah, I., & Boedisantoso, R. (2020). A Comparative Study of Life Cycle Impact Assessment using Different Software Programs. *IOP Conference Series: Earth and Environmental Science*, *506*(1). https://doi.org/10.1088/1755-1315/506/1/012002

Kafara, M., Süchting, M., Kemnitzer, J., Westermann, H. H., & Steinhilper, R. (2017). Comparative Life Cycle Assessment of Conventional and AdditiveManufacturing in Mold Core Making for CFRP Production. *14th Global Conference on Sustainable Manufacturing, GCSM 3-5 October 2016, Stellenbosch, South Africa*, *8*(October 2016), 223–230. https://doi.org/10.1016/j.promfg.2017.02.028

Kankala, R. K., Xu, X. M., Liu, C. G., Chen, A. Z., & Wang, S. Bin. (2018). 3D-printing of microfibrous porous scaffolds based on hybrid approaches for bone tissue engineering. *Polymers*, *10*(7), 1–17. https://doi.org/10.3390/polym10070807

Khasreen, M. M., Banfill, P. F. G., & Menzies, G. F. (2009). Life-cycle assessment and the environmental impact of buildings: A review. *Sustainability*, *1*(3), 674–701. https://doi.org/10.3390/su1030674

Khosravani, M. R., & Reinicke, T. (2020). On the environmental impacts of 3D printing technology. In *Applied Materials Today* (Vol. 20). https://doi.org/10.1016/j.apmt.2020.100689

Kim, T., & Tae, S. H. (2016). Proposal of Environmental Impact Assessment Method for Concrete in South Korea: An Application in LCA (Life Cycle Assessment). *International Journal of Environmental Research and Public Health*, *13*(11), 1074. https://doi.org/10.3390/ijerph13111074

Klüppel, H. J. (2005). The revision of ISO standards 14040-3: ISO 14040: Environmental management - Life cycle assessment - Principles and framework; ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines. *International Journal of Life Cycle Assessment*. https://doi.org/10.1065/lca2005.03.001

Labuschagne, C., & Brent, A. C. (2005). Sustainable Project Life Cycle Management: The need to integrate life cycles in the manufacturing sector. *International Journal of Project Management*, *23*(2), 159-168. https://doi.org/10.1016/j.ijproman.2004.06.003

Li, Y., Mao, Q., Yin, J., Wang, Y., Fu, J., & Huang, Y. (2021). Theoretical prediction and experimental validation of the digital light processing (DLP) working curve for photocurable materials. In *Additive Manufacturing* (Vol. 37). https://doi.org/10.1016/j.addma.2020.101716

Loiseau, E., Aissani, L., Le Féon, S., Laurent, F., Cerceau, J., Sala, S., & Roux, P. (2018). Territorial Life Cycle Assessment (LCA): What exactly is it about? A proposal towards using a common terminology and a research agenda. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2017.12.169

Maciel, V. G., Wales, D. J., Seferin, M., & Sans, V. (2019). Environmental performance of 3D-Printing polymerisable ionic liquids. *Journal of Cleaner Production*, *214*, 29–40. https://doi.org/10.1016/j.jclepro.2018.12.241

Mannheim, V., & Simenfalvi, Z. (2020). Total life cycle of polypropylene products: Reducing environmental impacts in the manufacturing phase. *Polymers*, *12*(9), 1–18. https://doi.org/10.3390/POLYM12091901

Martins, A. A., Mata, T. M., Costa, C. A. V., & Sikdar, S. K. (2007). Framework for sustainability metrics. *Industrial and Engineering Chemistry Research*. https://doi.org/10.1021/ie060692l

Melchels, F. P. W., Feijen, J., & Grijpma, D. W. (2010). A review on stereolithography and its applications in biomedical engineering. *Biomaterials*,*31*(24),6121–6130. https://doi.org/10.1016/j.biomaterials.2010.04.050

Mendoza Beltran, A., Prado, V., Font Vivanco, D., Henriksson, P. J. G., Guinée, J. B., & Heijungs, R. (2018). Quantified Uncertainties in Comparative Life Cycle Assessment: What Can Be Concluded? *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.7b06365

Morales-Méndez, J. D., & Silva-RodríGuez, R. (2018). Environmental assessment of ozone layer depletion due to the manufacture of plastic bags. *Heliyon*, *4*(12), https://doi.org/10.1016/j.heliyon.2018.e01020

Navajas, A., Uriarte, L., & Gandía, L. M. (2017). Application of eco-design and life cycle assessment standards for environmental impact reduction of an industrial product. *Sustainability*, *9*(1724), 1–16. https://doi.org/10.3390/su9101724

Ngadiman, N. H. A., Basri, M. A. B., Yusof, N. M., Idris, A., & Fallahiarezoudar, E. (2019). Digital Light Processing (DLP) 3D Printing Of Polyethylene Glycol (PEG) Biopolymer, Commercially Available Ultra-High And Tough (UHT)Resin And Maghemite (Γ-Fe2O3) Nanoparticles Mixture For Tissue Engineering

Scaffold Application. *Advanced Materials Letters*, *10*(11), 802–806. https://doi.org/10.5185/amlett.2019.0023

Nurulhuda, A., Izman, S., & Ngadiman, N. H. A. (2019). Fabrication PEGDA/ANFs biomaterial as 3D tissue engineering scaffold by DLP 3D printing tecshnology. *International Journal of Engineering and Advanced Technology*, *8*(6), 751–758. https://doi.org/10.35940/ijeat.F7989.088619

Nurulhuda, A., Sudin, I., & Ngadiman, N. H. A. (2020). Fabrication a novel 3D tissue engineering scaffold of Poly (ethylene glycol) diacrylate filled with Aramid Nanofibers via Digital Light Processing (DLP) technique. *Journal of Mechanical Engineering*, *Special Is*(1), 1–12.

Penciuc, D., Le Duigou, J., Daaboul, J., Vallet, F., & Eynard, B. (2016). Product life cycle management approach for integration of engineering design and life cycle engineering. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, *30*(4), 379–389.

Peng, T. (2016). Analysis of Energy Utilization in 3D Printing Processes. *Procedia CIRP*, *40*, 62–67. https://doi.org/10.1016/j.procir.2016.01.055

Qu, H. (2020). Additive manufacturing for bone tissue engineering scaffolds. *Materials Today Communications*, *24*. https://doi.org/10.1016/j.mtcomm.2020.101024

Saade, M. R. M., Yahia, A., & Amor, B. (2020). How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. *Journal of Cleaner Production*,*244*,118803. https://doi.org/10.1016/j.jclepro.2019.118803

Schmidleithner, C., Malferrari, S., Palgrave, R., Bomze, D., Schwentenwein, M., & Kalaskar, D. M. (2019). Application of high resolution DLP stereolithography for fabrication of tricalcium phosphate scaffolds for bone regeneration. *Biomedical Materials (Bristol)*, *14*(4). https://doi.org/10.1088/1748-605X/ab279d

Serafini, L. F., Feliciano, M., Rodrigues, M., & Gonçalves, A. (2023). Systematic Review and Meta-Analysis on the Use of LCA to Assess the Environmental Impacts of the Composting Process. *Sustainability*, *15*(2), 1394. https://doi.org/10.3390/su15021394

Seyednejad, H., Gawlitta, D., Dhert, W. J. A., Van Nostrum, C. F., Vermonden, T., & Hennink, W. E. (2011). Preparation and characterization of a three-dimensional printed scaffold based on a functionalized polyester for bone tissue engineering applications. *Acta Biomaterialia*. https://doi.org/10.1016/j.actbio.2011.01.018

Shao, H., He, J., Lin, T., Zhang, Z., Zhang, Y., & Liu, S. (2019). 3D gel-printing of hydroxyapatite scaffold for bone tissue engineering. *Ceramics International*, *45*(1), 1163–1170. https://doi.org/10.1016/j.ceramint.2018.09.300

Shen, Z., Cao, Y., Li, M., Yan, Y., Cheng, R., Zhao, Y., Shao, Q., Wang, J., & Sang, S. (2021). Construction of tissue-engineered skin with rete ridges using co-network hydrogels of gelatin methacrylated and poly(ethylene glycol) diacrylate. *Materials Science and Engineering C*, *129*. https://doi.org/10.1016/j.msec.2021.112360

Shi, Y., & Faludi, J. (2020). Using life cycle assessment to determine if high utilization is the dominant force for sustainable polymer additive manufacturing. *Additive Manufacturing*, *35*(June 2019), 101307. https://doi.org/10.1016/j.addma.2020.101307

Sonnemann, G., Castells, F., Schuhmacher, M., & Hauschild, M. (2004). Integrated life-cycle and risk assessment for industrial processes. In *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/bf02994195

Sonnemann, G. W., Schuhmacher, M., & Castells, F. (2000). Framework for the environmental damage assessment of an industrial process chain. *Journal ofHazardous Materials*, *77*, 91–106. https://doi.org/10.1016/S0304-3894 (00)00174-6

Speck, R. L. (2014). *A Comparative Analysis Of Commercially Available Life Cycle Assessment Software*.

Tumbleston, J. R., Shirvanyants, D., Ermoshkin, N., Janusziewicz, R., Johnson, A. R., Kelly, D., Chen, K., Pinschmidt, R., Rolland, J. P., Ermoshkin, A., Samulski, E. T., & Desimone, J. M. (2015). Continuous liquid interface production of 3D objects. *Science*, *347*(6228), 1349–1352.

Verma, S., Paul, A. R., & Haque, N. (2022). Selected Environmental Impact Indicators Assessment of Wind Energy in India Using a Life Cycle Assessment. *Energies*, *15*(11). https://doi.org/10.3390/en15113944

Wang, C., Huang, W., Zhou, Y., He, L., He, Z., Chen, Z., He, X., Tian, S., Liao, J., Lu, B., Wei, Y., & Wang, M. (2020). 3D printing of bone tissue engineering scaffolds. In *Bioactive Materials* (Vol. 5, Issue 1, pp. 82–91). KeAi

Communications Co. https://doi.org/10.1016/j.bioactmat.2020.01.004

Yadav, D., Garg, R. K., Ahlawat, A., & Chhabra, D. (2020). 3D printable biomaterials for orthopedic implants: Solution for sustainable and circular economy. *Resources Policy*, *68*. https://doi.org/10.1016/j.resourpol.2020.101767

Yao, Y., Hu, M., Di Maio, F., & Cucurachi, S. (2020). Life cycle assessment of 3D printing geo-polymer concrete: An ex-ante study. *Journal of Industrial Ecology*, *24*(1), 116–127. https://doi.org/10.1111/jiec.12930

Yu, J., Xia, H., & Ni, Q. Q. (2018). A three-dimensional porous hydroxyapatite nanocomposite scaffold with shape memory effect for bone tissue engineering. *Journal of Materials Science*. https://doi.org/10.1007/s10853-017-1807-x

Zhang, J., Hu, Q., Wang, S., Tao, J., & Gou, M. (2020). Digital light processing based three-dimensional printing for medical applications. *International Journal of Bioprinting*, *6*(1), 12–27. https://doi.org/10.18063/ijb.v6i1.242

VITA

The author was born in 3rd July 1996, in Johor Bahru, Malaysia. She went to Sekolah Menengah Sains Johor for his secondary school. She pursued her first degree at Universiti Tun Hussein Onn Malaysia (UTHM), and graduated with Bachelor in Mechanical Engineering Technology (Manufacturing) with Honors in 2019. Upon graduation, she experienced as an assistant engineer in a metal stamping company in Business and Product Development. Then, enrolled at Universiti Tun Hussein Onn Malaysia in 2020, to further her Master Degree by Research in Master in Engineering Technology. During her postgraduate time, she published one research paper in Biointerface Research in Applied Chemistry (BRIAC) Journal and one proceeding paper in The 7th International Conference andExhibition on Sustainable Energy and Advanced Materials (ICE-SEAM '21). Currently, she works as a Research and Development (R&D) engineer in a local company specialized in filtration of turbo machinery system for oil and gas also power plant industry.