COMPARISON OF LIFE-CYCLE IMPACTS BETWEEN COMPRESSED BRICK AND FIRED BRICK: IMPACT 2002+ METHOD

CHING LIANG YI

UNIVERSITI TUNKU ABDUL RAHMAN

COMPARISON OF LIFE-CYCLE IMPACTS BETWEEN COMPRESSED BRICK AND FIRED BRICK: IMPACT 2002+ METHOD

CHING LIANG YI

A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

May 2022

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature :

Name : Ching Liang Yi

ID No. : 1704548

Date : 15 May 2022

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"COMPARISON OF LIFE-CYCLE IMPACTS BETWEEN COMPRESSED BRICK AND FIRED BRICK: IMPACT 2002+ METHOD"** was prepared by **CHING LIANG YI** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature :

Supervisor : Dr. Ong Chuan Fang

Date : 16/05/2022

Signature :

Co-Supervisor :

Date :

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. Ong Chuan Fang for his continuous supervision throughout this project. He has spent his precious time to check and monitor the project progress while consistently providing valuable insight and comments. He has shown immense patience and not hesitant in providing advice in any stage of the project. His guidance and support has allowed this project to be carried out and completed smoothly. It was a pleasure to complete a research project under his supervision.

Moreover, I appreciate the effort of the university trying to organise workshops and provide library services to enhance my research skills to expedite the completion of this report.

In addition, I am deeply grateful to my parents and my sister for offering me encouragement to strive for completing this project. I would like to extend my sincere thanks to my friends who are supportive and are willing to exchange idea in the writing of this project.

ABSTRACT

Fired bricks and compressed bricks are common construction material produced and applied worldwide since the early days. However, negative environmental impacts generated during brick manufacturing process are inevitable. In this setting, utilisation of life cycle assessment (LCA) to examine life cycle environmental implications of fired brick and compressed brick is preferable. Several studies have conducted LCA on various construction materials, including fired brick and compressed brick. However, limited research has been conducted to compare their environmental effects using Impact 2002+ methodology. The aim of this study was to evaluate and to make comparison on the environmental impacts of compressed brick and fired brick using Impact 2002+ method. Functional unit was set to 1 kg of bricks and the scope was limited to cradle-to-gate analysis. Ecoinvent database allocation at point of substitution (APOS) model was used to extract data for analysis. Fired brick and compressed brick mix proportions were obtained from existing literature. All Impact 2002+ endpoint categories and selected midpoint categories such as aquatic acidification, human toxicity and ozone layer depletion were analysed and discussed. The results have indicated that compressed brick is better for the environment compared to fired brick since it has lesser environmental implications in endpoint and midpoint categories. Furthermore, compressive strength and cost for both brick types are evaluated. It is found that both brick types can satisfy the minimum compressive strength requirement, but compressed brick comes at a lower cost. Compressed brick is recommended to be used since it is a more sustainable and cost-effective option, while fulfilling minimum strength requirement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

APOS	allocation at the point of substitution
ASTM	American Society for Testing and Materials
Bq	becquerel
CFC	chlorofluorocarbon
CML	Centrum voor Milieukunde Leiden
CO_2	carbon dioxide
CSEB	compressed stabilised earth brick
DALY	disability adjusted life years
EDIP	Environmental Development of Industrial Products
ELCD	European Reference Life Cycle Database
EN	European Standards
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
ISO	International Organisation for Standardisation
JEPIX	Japan Environmental Policy Index
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle inventory assessment
MJ	mega joule
MPa	mega pascal
MS	Malaysian Standard
PDF	potentially disappeared fraction of species
PM	particulate matter
PO_4^{3-}	phosphate
SO_2	sulphur dioxide
TIS	Thai Industrial Standard
TRACI	The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Bricks are common construction material worldwide since the early days, thanks to their durability and outstanding physical, mechanical and thermal properties. They are mainly used in pavements, refractory or structure building. The amount of bricks produced annually is estimated as 1391 billion units and this figure is expected to rise with increasing demand (Zhang, 2013). However, negative environmental impacts due to brick manufacturing process is inevitable, especially in carbon emissions and energy use (Koroneos and Dompros, 2007). Bricks made in kilns have a carbon footprint that varies from 162 to 338.19 g CO_2/kg brick (Kulkarni and Rao, 2016).

In Greater Dhaka region, Bangladesh, brick production industry is a rapidly growing sector. It is estimated that production of 3.5 million pieces of bricks annually will emit 1.8 million tons of CO_2 annually (Skinder et al., 2014). Due to increasing social concerns on general environmental issues, it is vital for the construction industry to consider construction materials that consume lower energy and sustainable. Thus, life cycle assessment (LCA) approach is suitable to be adopted in evaluating environmental sustainability of bricks and subsequently improve their environmental performances.

LCA is often used on a targeted product as a tool for analysing potential environmental effects generated during various stages of product life cycle. For instance, in phases such as acquisition and processing of raw materials, product manufacturing, product distribution and more. LCA is often conducted in accordance to international standards of ISO 14040 (Muralikrishna and Manickam, 2017). LCA can analyse a product’s life cycle stages’ contribution to environmental load, which will lead to improvements in products or processes to minimize the impact towards the environment.

1.2 Background Study

To date, various researchers have carried out LCA studies on various construction materials. LCA may provide an insight on environmental impacts of building materials although the results are dependent on system limitations. For instance, Marcelino-Sadaba et al. (2017) studied environmental footprints of products made of clay bricks in Spain and United Kingdom by gathering life cycle inventory (LCI) data using European Reference Life Cycle Database (ELCD), limiting research scope from cradle-to-gate. Christoforou et al. (2016) adopted LCA approach on sun-dried unfired clay bricks production with alternative production scenarios from cradle-to-site. Specific functional unit of 1kg of brick was chosen because it is commonly applied for comparison between multiple construction materials.

Traditionally, brick manufacturing involves the production process of kiln firing at high temperature. The bricks produced from this conventional manufacturing approach are known as fired bricks that are commonly used in construction of masonry structures. Large amount of conventional fired bricks has to be produced globally to meet the continuously increasing demand from the construction industry. Contrarily, compressed bricks are produced without burning process, thus no burning material such as coal is required in the manufacturing line. In compressed brick stabilisation process, instead of brick firing, additives are added into compressed bricks to improve their quality. Portland cement is the most commonly used binder or stabilising additive to enhance the performance of compressed bricks (Abid et al., 2021). Brick stabilisation can be done physically, mechanically or chemically.

Fired bricks and compressed bricks are undoubtedly common in the construction industry, however their environmental impacts should not be neglected. Thus, LCA can be utilised as an instrument to investigate the environmental consequences and performances of fired bricks and compressed bricks in the academia.

One of the research studies on compressed bricks was done by Muntohar (2011) investigating the impact of application of lime and rice husk into compressed stabilised earth brick (CSEB) design mix in terms of engineering characteristics. Marcelino-Sadaba et al. (2017) conducted LCA study onto seven clay-based products using CML01 method. In the study, environmental impacts comparison between non-fired bricks, Portland cement blocks and fired bricks was made. Elahi et al. (2021) also conducted a study on engineering characteristics and LCA on CSEB to assess potential damages inflicted to the environment as compared to traditional fired clay bricks. Asman et al. (2020) adopted LCA on interlocking compressed earth bricks to study their carbon footprint and it was found that compressed earth bricks are more sustainable compared to fired clay bricks. Dulal et al. (2021) also studied the carbon emission of interlocking compressed earth bricks usage in constructed brick houses and yielded results where emissions compressed bricks are lower compared to fired bricks. Bricks may undergo stabilisation process to replace the need of firing process. Strength and environmental analysis on stabilised bricks has been carried out by Nidzam et al. (2016) and it was found that unfired stabilised bricks are more energy efficient and reduces environmental damage.

Several studies on fired clay bricks were conducted to determine their environmental life cycle impacts. Kua and Kamath (2014) assessed the sustainability of fired clay bricks from cradle-to-grave and functional unit applied for the study is 1 kg of bricks. Similarly, Koroneos and Dompros (2007) analysed environmental footprint of fired brick production from cradle-to-grave but functional unit of a metric ton of bricks was chosen instead. Impact assessments were then carried out using Eco-Indicator 95 method. On the other hand, Kumbhar et al. (2014) conducted fired brick LCA in SimaPro software by adapting Eco-indicator 99 methodology, however the study scope was limited to cradle-to-gate approach.

Besides traditional fired clay bricks, environmental performances of modified clay bricks with incorporation of wastes has been studied as well. Bories et al. (2016) has studied the development and environmental impacts of porous fired bricks created using biological-based pore-foaming agents acquired from agriculture and chemical origins. The study focused on environmental impacts during development of clay bricks sample, hence cradle-to-gate analysis scope was adopted. Emphasis of LCA was put in steps like extraction of raw material and brick manufacturing. The inventory and impact evaluations were then performed using ReCiPe method offered in SimaPro 8.0 software.

LCA is also a viable method to compare environmental performances between different kinds of bricks. Dabaieh et al. (2020) investigated and compared embodied energy and carbon emissions of two brick products namely, fired and sun-dried bricks starting from material manufacturing stage until disposal. LCA comparison between one housing unit of waste-based bricks and burnt clay bricks can also be conducted using ‘GaBi’ LCA software, in which CML 2002 and ReCiPe are life cycle inventory analysis (LCIA) methods that are chosen to conduct the research (Joglekar et al., 2018).

LCA has to be conducted according to the framework. Often, LCA starts with definition of goal, scope and research objectives. Then, collection life cycle inventory data and lastly impact evaluation on the life cycle inventory constructed. Various researchers has chosen different LCIA methods to suit the need of their study. Impact 2002+ is one of the evaluation methods that can be chosen to carry out life cycle evaluation analysis. For instance, Owsianiak et al. (2014) conducted LCIA on four window design options and compared ILCD 2009 methodology with Impact 2002+ and ReCiPe 2008 by converting impact scores to common metrics. Common impact categories from these three methodologies are compared and studied.

Several studies had included Impact 2002+ method as one of the LCIA methodology in bricks LCA. Lozano-Miralles et al. (2018) investigated fired bricks environmental impacts using ReCiPe and Impact 2002+ methods. Conventional fired bricks are mixed with organic waste in the study. In order to establish environmental product declaration for conventional ceramic bricks, Almeida et al. (2015) carried out LCA on fired ceramic bricks that involves calculations of impact categories using CML and Impact 2002+ method. López-Aguilar et al. (2019) had evaluated the environmental impacts of traditional fired brick manufacturing process from cradle-to-gate utilizing EcoIndicator 99, Impact 2002+ and CML 2001 LCIA approaches.

Moreover, Impact 2002+ method can also be used to make environmental footprint comparison during manufacturing process of multiple types of building material. For example, it is adopted to compare environmental performances of walls made of three different materials namely, fired bricks, stabilised concrete brick and reinforced concrete from cradle-to-grave (de Souza et al., 2016). Besides comparing the sustainability of different building materials, environmental impacts of fly ash reuse in bricks can be evaluated using Impact 2002+ method as well (Huang et al., 2017). Poinot et al. (2018) had incorporated waste boiler ash into ceramic bricks with alkali-activation. The feasibility of boiler ash brick usage is not only evaluated in terms of strength and properties but also from its economical perspective and environmental impacts. In the matter of environmental impact evaluation, Impact 2002+ method was used and a comparison was made between alkali-activation made boiler ash brick and conventional fired clay brick.

1.3 Problem Statements

The construction sector has contributed significantly to consumption of natural resources and environmental damage. This trend has gathered interests from various researchers to develop sustainable construction technologies. LCA is a commonly used concept among researchers to study environmental performances of buildings, construction methodologies and construction materials. LCA can also be useful in evaluating sustainability of various construction materials, which is done by Joglekar et al. (2018), Dabaieh et al. (2020) and Marcelino-Sadaba et al. (2017).

Brick is a popular and abundantly used building materials worldwide and LCA on various types of bricks has been conducted to assess and examine sustainability of various types of bricks. Based on availability of data and scope of study, life cycle inventories are developed before analysis is carried out using several types of analysis methodology. Despite there are quite a number of studies investigating engineering properties and environmental impact of various types of fired brick and compressed brick, which are done by Lozano-Miralles et al. (2018), Almeida et al. (2015) and Muntohar (2011), the study that includes detailed LCA analysis to make comparison between the environmental performances of fired clay bricks and compressed bricks may still lacking, especially between conventional fired clay bricks and Cameron Highland residual sediment brick.

Moreover, there are abundant of LCIA methodologies available to conduct LCIA analysis. For example, CML, ReCiPe, Impact 2002+ and Eco Indicator 99. Some researches such as López-Aguilar et al. (2019) had adopted Impact 2002+ method to assess environmental impacts of different fired bricks production scenarios. Studies involving LCA comparison of fired bricks and compressed bricks using Impact 2002+ method may still be lacking. Hence, the study on LCA of fired bricks and compressed bricks using Impact 2002+ methodology will be conducted.

1.4 Aim and Objectives

The aim of the study is to assess and to make comparison on the environmental impacts between compressed brick and fired brick using Impact 2002+ method. A few objectives are developed based on the aim of the study:

(i) To identify the production process and life cycle inventory of compressed brick and fired brick.

(ii) To evaluate the environmental implications of compressed brick and fired brick based on Impact 2002+ method.

(iii) To compare the environmental impacts between compressed brick and fired brick based on Impact 2002+ method.

1.5 Scope and Limitation of the Study

LCA is capable to measure environmental impacts of compressed brick and fired brick from origin to end of product life. However, performing LCA on both compressed brick and fired brick requires a huge range of production data to fit into life cycle inventories. Furthermore, there are multiple analysis method available to perform LCA on these construction materials. Thus, due to availability of wide range of data and analysis methodology, it is vital to narrow down the scope of work to facilitate workflow.

The system boundary for LCA in this study is limited to cradle-to-gate approach. Ecoinvent database and APOS method is used to extract data for analysis. If input data is not available in the Ecoinvent database, then the information is extracted from existing literature. Impact 2002+ method will be used to perform LCA on compressed brick and fired brick. This method is chosen due to the ability to perform both midpoint and endpoint analysis on the product life cycle.

LCA on fired bricks to be carried out using the mix design similar to Kua and Kamath (2014) which is adopted from fired clay bricks manufacturing in Johor, Malaysia. The mix design of compressed brick used in this study is proposed by Ooi et al. (2015) created using Cameron Highland residual sediment.

1.6 Significance of Study

Due to increasing concerns on environmental impacts due to building construction, a suitable environmental performance analysis must be carried out onto various construction materials. Considering that brick masonry is one of the most abundant construction methods globally, the environmental impacts are significant. It is now vital for the construction industry to acknowledge the impacts of brick manufacturing in various product life stages to develop a solution for sustainable construction materials.

Besides traditional fired clay bricks, various alternative bricks such as compressed bricks that have been developed to tackle brick sustainability issue. The bricks are stabilised without firing in brick kiln and they are often deemed to be a more sustainable alternative in comparison to their conventional counterparts. To verify this hypothesis, LCA executed under the framework of ISO 14040 series can be utilised to evaluate environmental footprints and impacts of these two construction materials and effectively help the construction industry to make a comparison and opt for a more sustainable alternative in building materials selection.

Moreover, LCA as a powerful science-based tool that opens up the opportunity for building materials manufacturers to understand the environmental effects of their current manufacturing practices, which will help them to address the environmental issues responsibly. Eventually, this will lead to development of sustainable practices in a long run to reduce potential economic costs arising from undesired environmental effects (Buyle et al., 2013).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this section, topics related to fired brick, compressed brick and LCA are studied in depth and presented. The manufacturing process of the bricks as well as their properties and environmental impacts will be discussed here. Lastly, various aspects on LCA studies are mentioned as well.

2.2 Bricks

Clay bricks have been used as building materials since early days of mankind. Bricks for building purposes often can be easily produced and its raw materials are readily available. Bricks can offer moderate heat insulation properties, fire, chemical and corrosion resistance (Goel and Kalamdhad, 2017). Application of brick in construction can be seen in masonry structures, walls and pavements. Typically, mortar is used to serve as a bonding agent between bricks or the bricks will be produced with interlocking properties.

2.2.1 Fired Bricks

The most common way of manufacturing bricks involves firing of clay bricks in brick kiln in high temperature to obtain hardness. Bricks that are produced in this way are known as fired bricks. The main material to produce fired brick is clay, which is a common natural mineral material on earth. Clay used in brick manufacturing must possess plasticity property to allow them to be moulded into intended shapes and sizes (Brick Development Association, 2017). After moulding, clay bricks should also have sufficient strength and ability to maintain the moulded shape. Then, clay particles should fuse together and harden when they are exposed to high temperature during brick firing.

A typical clay fired bricks should constitute of silica, alumina, lime, iron oxide and magnesia. While materials such as pigments, dyes, refractory materials and glass powders can be added into clay bricks as well for colouring application and economic reasons. Silica and alumina are the vital ingredients that gives clay brick plasticity when mixed with water in appropriate proportions so that it can be moulded and dried easily.

2.2.1.1 Manufacturing Process

Manufacturing process of fired bricks can be categorised into four main processes namely material preparation, brick moulding, brick drying and brick burning process. Firstly, raw materials for brick manufacturing must be processed. Clay arrived to the brick production plant will first be weathered in piles for several days. Sandy clay loam, which is commonly available in Malaysia is the most suitable clay type to manufacture fired bricks (Kua and Kamath, 2014). Clay will be left exposed to atmosphere for softening. Raw clays can be mixed together and blended to designated sizes using crushers. Then, water is added into the clay mixture and tempering stage commences. Clay will be pressed and mixed to make the wet clay mass become stiff and permanently plastic.

Next, the bricks will go through forming stage where bricks will be moulded into designated shape and size. Traditionally, bricks can be moulded using hands, in which tempered clay is inserted into a mould until it fills up all the corners of the mould. Then, the mould is lifted, leaving raw bricks on the ground. Modern brick making technique will involve the use of machine to mould a great number of bricks simultaneously. It can be divided into two types of machine, namely plastic clay machine and dry clay machine. In a plastic clay machine, clay in plastic state is fed into the rectangular opening of the machine where the primary shape of the brick is formed before using wires in frames to cut them into strips according to the sizing of the brick.

After moulding bricks into designated sizing, the brick will be left to dry. Bricks can be air dried in a shed using free circulation of air, but they must be well-protected from weather elements. Natural drying of brick will usually take 7 to 14 days. Alternatively, bricks can be dried in a dryer that reuses the exhaust heat from brick kilns. The clay brick mix can be dried until it reaches 3% of moisture content to weight (de Souza et al., 2016). Drying process is vital since it will remove moisture content from the brick to accelerate the burning process and prevent damp bricks from cracking under direct burning.

Next, dried bricks are sent into brick kiln for burning, in which they will be burned at a temperature of approximately 950 ºC (de Souza et al., 2016). Tunnel kiln is commonly used in brick firing. This type of brick kiln consists of kiln cars that carries bricks through the hot tunnel on rails. The kiln cars are fire resistant and special channels are installed in kiln walls to facilitate air cooling. Fires in tunnel kilns are on fixing points and kiln cars containing dried bricks will travel across the kiln, firing the bricks in the process. Besides tunnel kiln, ring kilns are also available, but the position of brick cart is fixed while fire moves across the kiln. In the whole fired brick production process, firing in brick kiln is the most critical process where good heat absorption of bricks will contribute to quality fired brick product output (Stankovski et al., 2001). Clay properties are subjected to the temperature and time the bricks exposed to heat (Velasco et al., 2014). In tunnel kilns, bricks will undergo progressive stages of heating and cooling depending on the settings of tunnel kiln.

After firing, the bricks will be removed from the kiln and carried to dedicated storage area. Then, bricks will be packaged and transported out for delivery. The manufacturing process of fired brick can be summarised as in Figure 2.1.

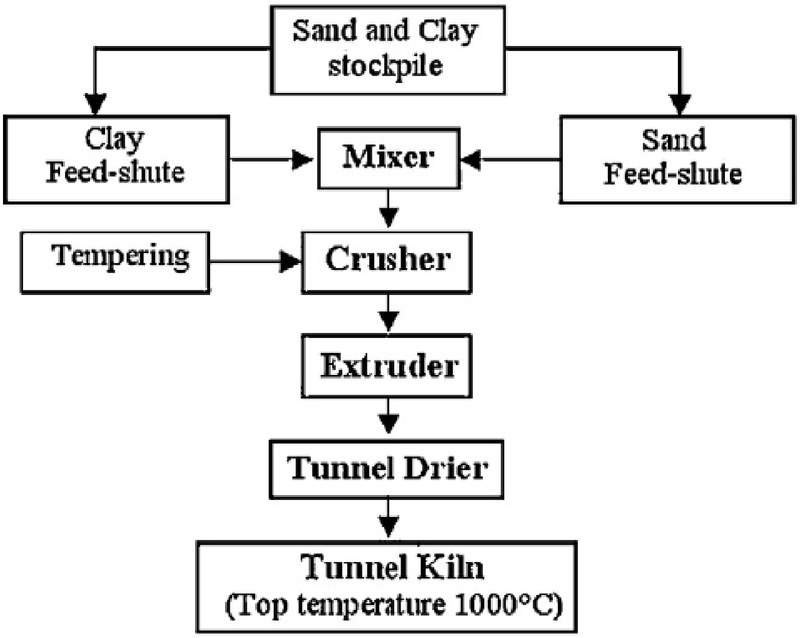


Figure 2.1: Manufacturing Process of Fired Bricks (Samara et al., 2009).

2.2.1.2 Sizing of Bricks

Typical materials required in production of fired bricks are clay, sand and cement. According to Malaysian Standard MS 76: Part 2: 1972, the length, width and height of a standard brick used in wall construction is 333.7 mm, 225 mm and 112.5 mm respectively (Manap et al., 2016). Good quality fired bricks should possess uniform shape and size to ease bricks binding works. Plus, the bricks must be burned evenly so that the bricks can be perfectly firm, ripe and durable at all faces. The quality and sizing of bricks should be consistent.

2.2.1.3 Compressive Strength

In specifications of clay bricks used in load bearing walls, a vital mechanical property that has to be determined is the compressive strength. High compressive strength will improve flexural strength and abrasion resistance. Besides that, compressive strength is also easy to determine via compressive strength test. Fired clay bricks' compressive strength will increase with temperature of brick firing as a result of bulk density increment and porosity reduction. Phonphuak et al. (2016) investigated properties of bricks fired at various temperature and it was found that compressive strength of fired brick burned at temperature of 1000 ºC is 20.18 MPa. Moreover, compressive strength of the brick can be linked to porosity of brick structure, where porous brick structure will lead to low compressive strength. Johari et al. (2010) investigated compressive strength of bricks at various firing temperature and it was found that the optimum firing temperature of brick is 1200 ºC which produces compressive strength of 89.5 MPa. Further increment in brick firing temperature will result in compressive strength reduction.

In short, compressive strength of fired brick can differ substantially according to material in brick production and the duration and temperature of brick firing. Due to this issue, compressive strength of fired brick is often classified according to its use in the construction industry (Ali, 2005). Ali (2005) conducted a study on fired brick properties from a manufacturer in Malaysia and found that values of fired facing brick and fired common brick mean compressive strength are 46 MPa and 35.7 MPa respectively. Facing bricks are bricks that are exposed to the outwards of the buildings, thus requiring smooth surface finish compared to common bricks which does not have this requirement.

Compressive strength of bricks has to meet a certain standards set by MS 76-1972. According to MS standard, the result of compressive strength of bricks with original quality obtained from compressive strength test should be at least 5.2 MPa (SIRIM, 1972) and is applicable for load-bearing use limited to double-storey dwelling units. However, the minimum average compressive strength to be achieved by bricks for load-bearing walls not limited to two-storey dwelling units should be classified according to Table 2.1.

Table 2.1: Average Minimum Compressive Strength of Bricks (SIRIM, 1972).

Type of Brick	**Class**	**Average Minimum Compressive Strength (MPa)**
Engineering brick	A	69.0
	B	48.5
Load-bearing brick	15	103.0
	10	69.0
	7	48.5
	5	34.5
	4	27.5
	3	20.5
	2	14.0
	1	7.0
Bricks for damp-proof courses	D P C	As per requested

2.2.1.4 Water Absorption

Mechanical properties including compressive strength, water absorption and permeability are impacted by fired bricks porosity. Water absorption property is a major factor that will affect the durability of fired bricks. Fired bricks prone to water penetration will be susceptible to degradation. Lingling et al. (2005) prepared specimens of standard fired clay bricks with proportion of fly ash : clay of 70 : 30 by volume and the water absorption of bricks are found to be 19% after immersion of bricks in water for 24 hours and 26% after 5 hours of bricks boiling in water. Supakata et al. (2017) conducted research on feasibility of producing bricks from dredged sediment and waste glasses in Thailand and it was asserted that as stated in TIS168-2546, satisfactory water absorption limit is less than 22%.

2.2.1.5 Environmental Impacts

Fired bricks are common construction material produced in large quantity to satisfy the demand. In countries with fast growing brick making industry, harmful gases emissions from brick kiln are inevitably related to health issues and air pollution. The examples of harmful gases emitted are carbon monoxide, nitrogen oxides, carbon dioxide, sulphur dioxide and particulates.

It was found that in the midst of all harmful gases, carbon dioxide has the most notable ecological consequences, which is followed by particulate matter (Khan et al., 2019). This is alarming since 1 kg of bricks manufactured in kilns can generate CO_2 at a range from 162 to 338.19 g (Kulkarni and Rao, 2016). The environmental impacts of fired bricks manufacturing process are the most significant during the brick firing phase since emissions are maximum in this phase (Kumbhar et al., 2014). Respirable inorganics which include pollutants such as particulate matter, nitrogen oxides, sulphur oxides and ammonia tend to be generated during incomplete combustion of coal, which are supplied as fuel in a brick kiln. Besides that, firing process tend to incorporate high amount of energy which will contribute to air emission and energy consumption. Harmful gas emissions from brick kilns will also cause negative environmental impact such as acid rain and ozone layer depletion.

Besides that, Supakata et al. (2017) also noted that in addition to environmental impacts generated by conventional fired bricks, leachate of heavy metals is also an environmental concern for fired bricks incorporating urban river sediments. Some examples of heavy metals generated are mercury, lead, cadmium, chromium and arsenic. It was mentioned that the concentration of heavy metals generated are well beneath the regulatory limits.

2.2.2 Compressed brick

Besides fired bricks, compressed bricks are another type of bricks that are produced without the need to go through the baking or firing process under high temperature. Instead, brick gained its strength by compressing the bricks in the mould under high pressure. The type of compressed brick used to conduct LCA study in this report is sediment brick produced using Cameron Highland reservoir sediment (Ooi et al., 2015). Properties of compressed bricks produced from dredged sediments are investigated by Manap et al. (2016) as well. The raw materials to produce compressed bricks from dredged sediments are cement, sand and water. Dredged sediments to partially replace the use of cement and water according to mix proportions. Compressed bricks can also exist in the form of stabilised earth brick where soil brick is stabilised using lime and rice husk ash (Muntohar, 2011).

2.2.2.1 Manufacturing process

There are four major stages in compressed brick production process namely, raw materials crushing, mixing, brick compacting and brick curing. The first procedure of compressed brick casting involves the preparation of sediment, which is the primary raw material of compressed brick. Sediment for brick casting must undergo drying, sieving and crushing process before mixing with other raw materials. Drying of sediment can be done under the sun before the sieving process where large debris will be removed from the sediment sample. Once debris has been removed, the sediment will be sent into a crusher to crush large sediment into smaller particles. Raw material must be precisely and carefully processed.

After preparation of sediment, the raw materials will proceed to the mixing stage. At this stage, sediment will be mixed with cement and iron oxide pigment in the blender. While mixing, water is added into the mixture and mixing action is carried out until a homogenous mix is formed. The sediment will bind together with other raw materials to form a mixture that will be sent to compaction stage for shaping later.

Next, the brick mix is sent to pressed brick machine using a conveyor belt. At the machine, the bricks will be pressed with a pressing load of 220 kN (Woen et al., 2018). High pressure compaction will force the mixture to be compacted into desired shape and size.

After formation of compressed brick, the bricks will be placed on a stacked rack and left to air dry in room temperature. After initial setting, bricks will be cured. The curing period for compressed brick sample is two days. Curing is done by pouring or spraying water onto the brick surface at an interval of 8 to 10 hours. Bricks should be placed in opened area and watered appropriately to assist brick hardening and strength gain in curing process (Manap et al., 2016). Desired brick strength will be achieved once the curing process ended. Bricks after the curing process is now ready to be used.

2.2.2.2 Sizing of Bricks

The dimension of compressed bricks depends on the amount raw materials inserted to the brick mix. Compressed bricks with different mix proportions are investigated and the length, width and height of compressed bricks are determined as 215 ± 3.2 mm, 100 ± 3.2 mm and 65 ± 3.2 mm respectively (Ooi et al., 2015). The dimensions of bricks have to be controlled properly by ensuring consistent amount of raw materials added during production of compressed bricks.

2.2.2.3 Compressive Strength

Compressed brick’s compressive strength is affected by two main factors: degree of compaction and the age of compressed brick samples (Abdullah et al., 2020). Ooi et al. (2015) conducted physical and mechanical properties study on compressed brick produced using sediments collected from Cameron Highlands reservoir and discovered that increment in sediment usage in compressed brick mix proportion will result in compressive strength decrement. This situation may be related to lower cement content that will contribute to compressive strength of compressed bricks in mixes with high sediment proportion. The optimum mix in the experiment requires 10% cement to reach the ASTM C129 requirements, while maximising the usage of sediments. Compressive strength recorded for compressed brick produced using optimum mix is 6.3 MPa. Besides that, Manap et al. (2016) found that the optimum mix of dredged sediments compressed bricks generated 7 and 28 days compressive strength of 9.2 MPa and 10.6 MPa respectively.

2.2.2.4 Water Absorption

Durability of compressed bricks is closely related to water absorption properties. Under weathering and burning conditions, the deterioration rate of the bricks depends on their durability. A study done by Ooi et al. (2015) has indicated that water absorption of compressed bricks will increase with increment in sediment content and decreasing of cement content in the mix. Mixes with lower cement mix tend to have weaker bonding ability, thus making the compressed brick more porous and able to absorb more water. The porosity of brick structure will result in reduction in compressive strength of compressed bricks. Thus, results of water absorption and compressive strength of bricks are closely linked together. The results of water absorption obtained from 7 sets of mixes ranges from 8.2% to 22.3%.

2.2.2.5 Environmental Impacts

Compressed bricks will only release 22 kg CO_2 / tonne, which makes its carbon footprint significantly lower in comparison with fired clay bricks with 200 kg CO_2 / tonne (Han et al., 2020). A study conducted by Zhang and Biswas (2021) has found that the global warming impacts of compressed interlocking bricks ranges from 46.5 $kgCO_2$ eq to 55.72 $kgCO_2$ eq using different construction methods and overall, the environmental impacts of compressed bricks are lower compared to fired bricks. Besides that, the results of carbon footprint obtained is close to the carbon footprint value of 56.79 $kgCO_2/m^3$ of wall found by (Asman et al., 2020).

2.3 Life Cycle Assessment

LCA methodology can be utilised in accessing a product’s environmental impact throughout its lifetime. LCA can examine environmental performances of studied product starting from initial stages such as from raw materials extraction to the processing and assembly stages until a final product is formed. Then, the packaging, distribution, maintenance and recycling of product before final disposal can be analysed using LCA as well. LCA can be a useful tool to conduct analysis on economic and environmental implications between various products or services that will lead to strategic decision making. The framework and principle of LCA study has been defined in ISO 14040. Basically, the framework of LCA can be divided into four main elements: definition of goal and scope, gathering LCI, conducting LCIA and lastly, life cycle interpretation. LCA framework, which includes the four main elements are shown in Figure 2.2. LCA framework itself possesses iterative and interactive nature, which means every component inside the framework can be amended any time to fulfil the requirements of LCA study.

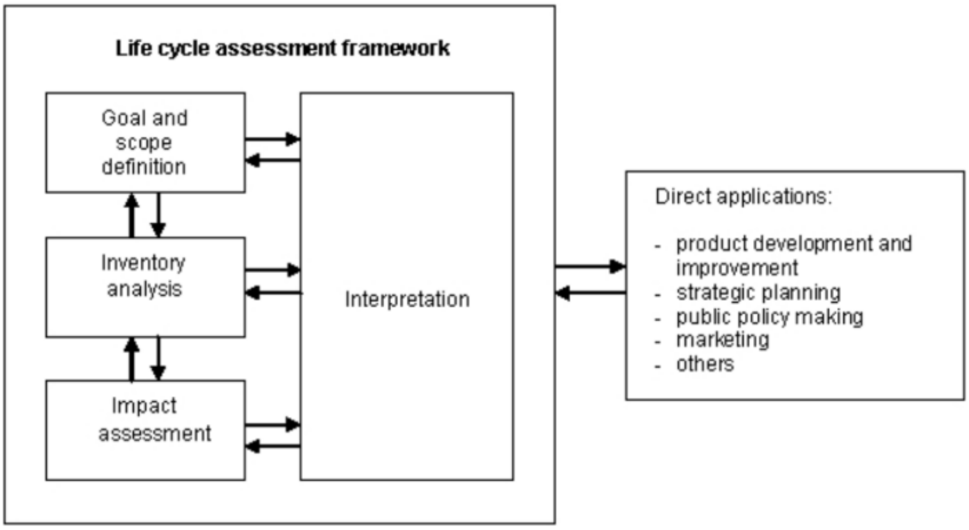


Figure 2.2: LCA Framework according to ISO 14040 (Menoufi, 2011).

2.3.1 Goal and Scope Definition

According to LCA framework, LCA study is kickstarted by identifying goal and scope. In this step, the product to be assessed by LCA must be defined properly. Next, the context of LCA has to be analysed as well. Goal and scope of study will define parameters such as time and resources required, system boundaries, assessment methodologies, assumptions and limitations. In other words, goal and scope definition will have significant impact on LCA assessment steps. Furthermore, goal and scope of LCA study will serve as a guide to LCA process until relevant results are achieved. LCA goal and scope can be revised and altered occasionally in LCA process due to iterative and interactive nature of LCA.

System boundaries and functional unit of product system must be provided in LCA goal and definition step. System boundary limits the LCA scope to the main focus of study. Functional unit is a quantified description and a basis that facilitates comparison between different goods and services (Rebitzer et al., 2004). Functional unit is not necessarily to be defined as quantity of material. It may be defined as volume, area or more depending on the service that the product provides.

2.3.1.1 System Boundaries

In LCA, system boundary will be used to indicate and determine the limit of product life cycle system to be evaluated. The number of phases from the life cycle of product to be evaluated in LCA study will be limited by the system boundary. Optimally, LCA study should include all phases from the product's life cycle (Dahmen et al., 2018). However, to put a limitation on study scope, the system boundary can cover only until certain part of product life cycle. To conduct LCA study, three main system boundary types are commonly used. A representation of scopes of various system boundaries is shown in Figure 2.3.

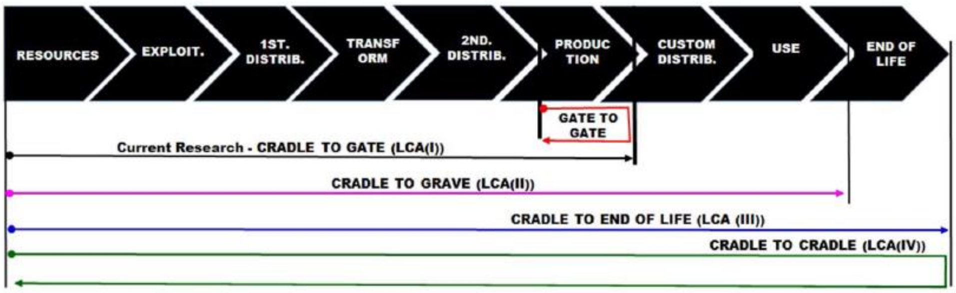


Figure 2.3: LCA Boundary Conditions according to ISO 14040 (Marcelino-Sadaba et al., 2017).

Cradle-to-grave LCA is a complete assessment that is conducted from manufacturing phase to disposal phase of a product. Thus, from the beginning until the end of the product's life cycle, every product system's inputs and outputs must be considered. For instance, LCA conducted with cradle-to-grave system boundary should evaluate the environmental impacts that involves all stages from the beginning until the end of life cycle, consisting phases like raw material acquisition, production, transportation and product disposal.

Cradle-to-gate is a LCA scope that is limited from manufacturing phase to the factory gate. The environmental impacts from end product delivery transportation, usage and product disposal phase are not evaluated. Cradle-to-gate LCA can serve as a basis for environmental product declaration for businesses. Evaluation of partial product life cycle can reduce the complexity of LCA.

Cradle-to-cradle assessment is a type of system boundary that replaces the disposal step during product's end of life with recycling process for manufacturing of new product. The new product manufactured can be identical or different compared to the original product assessed in the initial stage. However, evaluation of recycling of a multi-ingredient product may be a complex and complicated process (Marcelino-Sadaba et al., 2017).

2.3.2 Life Cycle Inventory

LCI is defined as the methodology that involves creating an inventory of resources input, wastes and emissions output attributable to the product system. In every manufacturing process, resources consumption and generation of emissions and wastes are inevitable. In the production process, they can be represented as inputs and outputs. Hence, inventory analysis results should present the total inputs from the environment and outputs to the environment (Menoufi, 2011). Materials and energy flows of the product analysed should be presented in order. Life cycle inventories obtained from various sites or regions of the world will be different from each other according to functional unit of product analysed. Besides that, time period of data collection will affect life cycle inventories and must be taken into consideration as well.

The processes within the product life cycle will be modelled together with the flows of materials, energy and waste input and output to generate a product system model. The inventory of environmental changes pertaining to functional unit is shown together with the product system model.

2.3.2.1 Ecoinvent LCA Database

The collection of input and output for LCA study is data-intensive (National Academy of Sciences, 2011). Instead of collecting primary data for LCA study, LCI databases will provide generic data to model the product system. This condition is known as background system where background LCI databases are utilised for LCA study. Datasets from different region will vary due to difference in geography and supply chains.

Ecoinvent v.3.5 database can be used to obtain the LCA database needed for a LCA research. In Ecoinvent, LCI data for use in LCA is harmonised and updated via a joint effort, covering different economic sectors and common LCA methodologies. Ecoinvent is the most commonly used database worldwide and its database contains LCI data collected globally, making their data transparent and consistent (OpenLCA Nexus, n.d.). LCI dataset is extensive in Ecoinvent database. For instance, it covers datasets from a plethora of industries. For instance, transportation, agriculture, energy generation and supply, materials extraction and waste management. Version 3 of Ecoinvent database divides the processes into three system models namely, APOS, cut-off and consequential models.

The cut-off model, as the name suggests, cuts off recyclable materials from the product system. Recyclable materials are considered as burden-free from the production line since there are no impacts or benefits allocated to them. In APOS, the model is expanded to include treatment process of all by-products, wastes and recyclables. Hence, there is no need to make distinction between wastes and recyclable materials since the environmental impacts of whole product system treatment process needs to be considered. In short, the difference between the two system models is present only in the allocation of recycling and waste treatment products. Lastly, consequential system model is a substitutional-based approach. Multi-product datasets can be converted into single-product dataset via substitution. Co-products can be linked to service or goods production that they are substituting (Wernet et al., 2016). Hence, impacts from other sources are avoided for by-products. Assumptions are required to assess the changes made to an existing system.

2.3.3 Life Cycle Impact Assessment

After identification of LCI, LCA shall proceed to LCIA stage. At this stage, LCI consisting of energy consumption and raw materials necessary for production of a product in question, is interpreted and converted into impact indicators that are understandable by LCA users. These interpretation of LCI provided in the form of indicators represent the severity of potential contribution to environmental load from various impact categories. A few examples of impact categories, which vary from one LCIA methodology to another are global warming, climate change, noise, land use, toxicological stress and resource depletion. LCIA results are generated after life cycle evaluation according to the functional unit set before conducting LCIA (Rebitzer et al., 2004). The impact categories in the impact pathway of a product's life cycle can be divided into midpoint and endpoint indicators according to approaches of characterisation.

2.3.3.1 Midpoint and Endpoint Method

Midpoint level characterisation models the impact earlier in the cause-effect chain. For instance, it is modelled using indicator situated at a location along the methodology mechanism, before reaching endpoint categories. In contrast, to perform characterisation of model at endpoint level, modelling of LCIA will be done until the end of cause-effect chain and the endpoint categories can be illustrated by various areas of protections. For instance, resources, human health, climate change and quality of ecosystem.

Midpoint approach can also be categorised as problem-oriented approach. In this approach, quantitative modelling will be limited to only the initial stages of the cause-effect chain. LCI flows are grouped into midpoint categories referring to environmental themes that they contribute. Common environmental themes covered in most LCIA studies are climate change, natural resources depletion, acidification, eutrophication, human toxicity, aquatic toxicity and more. The results from hundreds of complex flows are consolidated and simplified into a few environmental themes of interest. The environmental impacts are grouped according to environmental damage caused by input and output.

The term damage-oriented approach can also be used to replace endpoint approach. Similar to midpoint approach, endpoint approach also classifies the complexity of system flows into a few significant environmental themes. However, the cause-effect chain of the process must be modelled until the endpoint. Unlike midpoint approaches that are more specific on environmental themes, damage pertaining to various environmental areas of protection are considered. For instance, the damage of environmental themes according to human health, damage to resources and ecosystem health will be modelled. The environmental impacts are grouped according to the final damage.

Both midpoint and endpoint approaches have their own benefit and drawbacks. Midpoint methods results are more comprehensive and objective since they include all environmental impacts compared to endpoint methods that are not necessary to include all losses caused by environmental impacts (Park et al., 2020). However, results from endpoint methods are easier to understand compared to midpoint methods.

2.3.3.2 Impact 2002+ Methodology

Impact 2002+ is a LCIA methodology that will produce LCI results. The results with similar impact pathway can be consolidated into impact categories, while each impact category will have a category indicator. Placement of category indicator can happen at a position between results of LCI and damage category or located at category endpoint (Menoufi, 2011). The former is known as midpoint approach, while the latter is known as damage-oriented approach. Impact 2002+ is a LCIA methodology that is implemented by combining both midpoint and damage-oriented approach. LCI results are linked via several midpoint categories to 4 damage categories. The comparative assessment method of midpoint categories of human toxicity and ecotoxicity are newly established for Impact 2002+ method while the methods for other categories are adopted and taken from other methodologies like Eco-Indicator 99 and CML 2002 (Humbert et al., 2012).

The framework of Impact 2002+ method is shown in Figure 2.4, where LCI results are linked to the damage categories via midpoint categories. The arrows in the framework indicate that the impact pathway in the study is known and can be modelled quantitatively. However, some impact pathways located between the midpoint and damage categories can sometimes be assumed to exist but not modelled quantitatively. They are shown in dotted arrows.

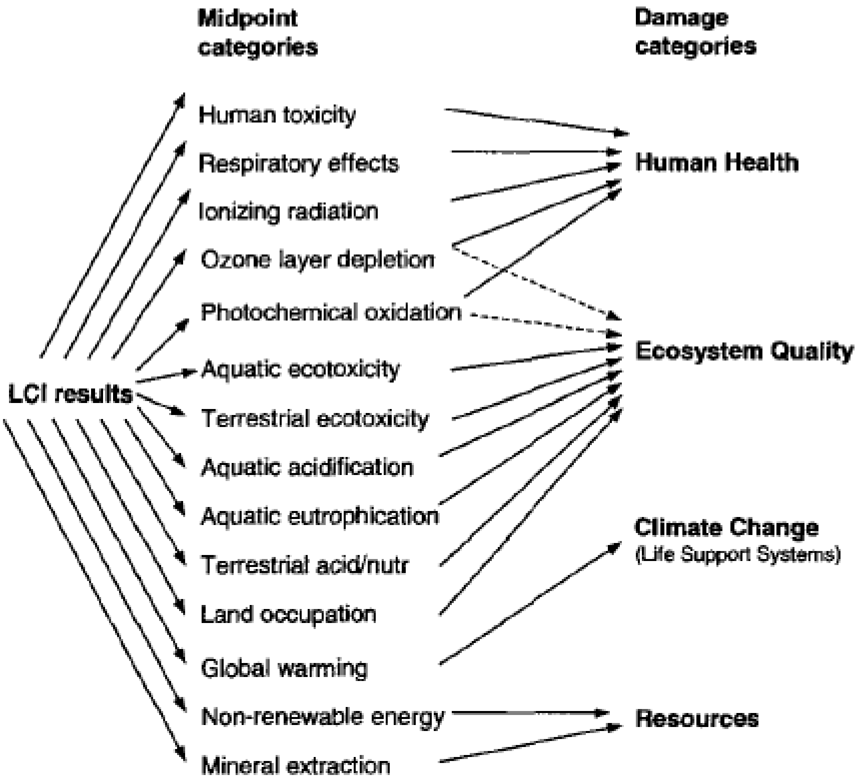


Figure 2.4: Impact 2002+ Framework (Jolliet et al., 2003).

At midpoint level, the characterisation scores are presented using equivalency principles. In other words, they will be stated in the unit of kg-equivalents of reference substance. At damage level, different damage units are assigned to each damage categories as well and a summary of units used in Impact 2002+ method will be shown in Table 2.2.

Table 2.2: Midpoint Categories Reference Substance and Damage Categories Damage Unit (Jolliet et al., 2003).

Midpoint Category	**Midpoint Reference Substance**	**Damage Category**	**Damage Unit**
Human toxicity (carcinogens + non-carcinogens)	kg_{eq} chloroethylene into air	Human health	DALY
Respiratory (Inorganics)	kg_{eq} PM2.5 into air		

Table 2.2 (Continued)

Ionizing radiations	Bq_{eq} carbon-14 into air	Human health	DALY
Ozone layer depletion	kg_{eq} CFC-11 into air		
Photochemical oxidation	kg_{eq} ethylene into air	Human health	DALY
		Ecosystem quality	-
Aquatic ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	PDF·m^2·yr
Terrestrial ecotoxicity			
Terrestrial acidification / nutrification	kg_{eq} SO_2 into air		
Aquatic acidification			
Aquatic eutrophication	kg_{eq} PO_4^{3-} into water		
Land occupation	m^2_{eq} organic arable land·year		
Global warming	kg_{eq} CO_2 into air	Climate change (life support system)	(kg_{eq} CO_2 into air)
Non-renewable energy	MJ Total primary non-renewable or else, kg_{eq} crude oil (860 kg/m^3)	Resources	MJ
Mineral extraction	MJ additional energy or kg_{eq} iron (in ore)		

Besides that, normalisation and weighting step can be applied into Impact 2002+ methodology to evaluate the proportion of contribution of each environmental footprint to the overall damage besides facilitating interpretation. Normalisation factor can be applied to midpoint or damage categories, and it is obtained by dividing impact per unit emission over total impact of substances in the category, where factors of characterisation exist. It is recommended to carry out normalisation after the step of damage characterisation. The normalisation factors for four damage categories of Impact 2002+ methodology are listed in Table 2.3.

Table 2.3: Normalisation Factors for Four Damage Categories of Impact 2002+ (Jolliet et al., 2003).

Damage Categories	**Normalisation Factors**	**Unit**
Human health	0.0077	DALY/pers/yr
Ecosystem quality	4650	PDF·m^2·yr/pers/yr
Climate change	9950	kg CO_2/pers/yr
Resources	152000	MJ/pers/yr

2.3.3.3 Other LCIA Methodologies

Besides Impact 2002+, different methodologies are also available to perform LCIA using different modelling approaches, be it midpoint or endpoint approaches. Some methodologies like Impact 2002+ will combine both midpoint and endpoint approaches. The difference between methodologies can be noticed in the amount of impact categories covered and characterisation steps which will vary based on the environmental and spatial background. The table of midpoint and endpoint oriented LCIA methodologies will be presented in Table 2.4 and Table 2.5 respectively.

Table 2.4: List of Midpoint Oriented LCIA Methodologies (Menoufi, 2011).

Methodology	**Midpoint Impact Categories**	**Areas of Protection**
CML	Obligatory impact categories: Land competition, abiotic resources depletion, climate change, ecotoxicity, stratospheric ozone depletion, marine aquatic ecotoxicity, freshwater aquatic human toxicity, eutrophication, photo-oxidant formation, terrestrial ecotoxicity and acidification. Optional impact categories: Biodiversity loss, waste heat, impacts of ionising radiation, malodorous air, loss of life support function, noise, lethal, non-lethal, casualties, malodorous water, desiccation, depletion of biotic resources, marine sediment ecotoxicity and freshwater sediment ecotoxicity.	Human health, natural environment, human resources, man-made environment.
EDIP 2003	Acidification, noise, aquatic eutrophication, ozone depletion, global warming, terrestrial eutrophication, human toxicity, ecotoxicity and photochemical ozone formation.	Ecosystem, human health and resources.
IMPACT 2002+	Respiratory effects, human toxicity, ionising radiation, depletion of ozone, mineral extraction, formation of photochemical oxidant, global warming, terrestrial eutrophication and acidification, non-renewable energy, aquatic ecotoxicity, land occupation, aquatic eutrophication and terrestrial ecotoxicity.	Climate change, depletion of resources, quality of ecosystem, human health

Table 2.4 (Continued)

RECIPE	Climate change, formation of particulate matter, urban land occupation, marine eutrophication, freshwater eutrophication, transformation of natural land, ozone depletion, formation of photochemical oxidant, freshwater ecotoxicity, terrestrial ecotoxicity, marine ecotoxicity, water depletion, terrestrial acidification, agricultural land occupation, depletion of fossil fuel, human toxicity, depletion of mineral resource, ionising radiation.	Ecosystem, human health and resources.
TRACI	Eutrophication, global warming, acidification, formation of smog, ozone layer depletion, human health cancer and non-cancer, ecotoxicity, depletion of fossil fuel and human health criteria pollutants.	Ecosystem, human health and resources.

Table 2.5: List of Endpoint Oriented LCIA Methodologies (Menoufi, 2011).

Methodology	**Damage Impact Categories**	**Areas of Protection**
EcoIndicator 99	Ozone layer depletion, climate change, eutrophication, acidification, ionising radiation, carcinogenic, ecotoxicity, respiratory effects, land-use, fossil resources and mineral resources.	Ecosystem, human health and resources.
IMPACT 2002+	Damage to climate change, damage to ecosystem quality, damage to resources and damage to human health.	Resources, quality of ecosystem, human health and climate change.

Table 2.5 (Continued)

EPS 2000	Life expectancy, morbidity, severe morbidity and suffering, element reserves depletion, severe nuisance, gas fossil reserves depletion, capacity of fish and meat production, capacity of wood production, nuisance crop production capacity, capacity of water production, base cation capacity, depletion of mineral reserves, share of species extinction, coal fossil reserves depletion and oil fossil reserves depletion.	Abiotic stock resources, ecosystem production capacity, human health, and biodiversity.
JEPIX	Respiratory effects, photochemical oxidant formation, ozone depletion, radioactive emissions, emissions to surface water bodies, emissions to groundwater, air emissions, emissions to soil, cancer due to radionuclides emitted into sea, reactive landfill municipal wastes, radioactive wastes, hazardous wastes (underground storage), primary energy resources, gravel consumption, water consumption, endocrine disruptors and biodiversity losses.	Ecosystem, human health and resources.
RECIPE	Damage to availability of resources, human health, diversity of ecosystem	Ecosystem, human health and resources.

2.3.4 Life Cycle Interpretation

Lastly, the impact assessment results are evaluated and interpreted before conclusions relating to decision making process are made. For instance, a comparison of results is made between two product alternatives and the product with lesser environmental impact is chosen oner the other one. The critical environmental impacts and the significance of environmental load contribution by product processes has to be identified and discussed.

Besides that, verification of results can be done based on the need of the study and data obtained from LCIA can be checked with respect to three categories namely, completeness of data, sensitivity analysis and consistency check (Menoufi, 2011). In completeness check, LCI and LCIA results must be structured properly to identify significant environmental issues. Results and information collected must be represented adequately, by referring to defined goal and scope. Besides that, uncertainties in data may arise in real world scenario. Thus, incorporation of sensitivity analysis into the study is recommended to evaluate the potential effects of uncertainties on LCA results (Wei et al., 2015). To ensure coherence with scope and objective of study, consistency check on methodologies, procedures and data treatment throughout the study should be carried out. To enhance reliability of study, consistency check can be conducted on geographical representation, system boundaries, assumptions, data accuracy and data source. Lastly, conclusions, limitations and recommendations are drawn according to LCA study conducted.

In short, interpretation of LCA results should include these main elements: identification, evaluation and conclusion, limitations and recommendations according to standards set by ISO 14040:2006 (Hernandez et al., 2019). According to LCA framework, the final step of LCA is life cycle interpretation.

2.3.5 LCA Software

OpenLCA is a type of open-source software for LCA developed by GreenDelta since 2007 (Di Noi et al., 2017). GreenDelta is a company that has been pioneering open-source solutions for LCA and providing LCA consultation to LCA community worldwide.

Data required for LCA can be obtained from an online repository known as OpenLCA Nexus. This repository houses LCA data from various providers including Ecoinvent, European Commission Joint Research Centre and PE International. LCA data can be imported into OpenLCA software. To overcome methodological differences in data collection, the databases has been harmonised in cooperation with data providers (Di Noi et al., 2017). In this study, datasets from Ecoinvent v.3.5 will be used to model the product system of fired bricks and compressed bricks.

2.3.6 Application of LCA

LCA can be applied in various situations such as during product improvement and development to minimise its environmental impacts, marketing, public policy making, strategic planning and more. Brick manufacturing industries contribute to economic development, but at the same time contributes to environmental pollution. Consequently, LCA can be established to evaluate and assess life cycle environmental footprint of bricks and the evaluation results can serve as key indicators in identifying feasible measures to move towards sustainable manufacturing. A summary of previous LCA studies conducted which are related to fired bricks and compressed bricks are shown in Table 2.6.

Table 2.6: LCA Studies Conducted on Fired Bricks and Compressed Bricks.

Reference	**Brick Type**	**Methodology**	**Application**	**Functional Unit**	**System Boundary**	**Impact Category**
Koroneos and Dompros (2007)	Fired bricks	EcoIndicator 95	To identify environmental issues associated with brick production in Greece.	1 ton of bricks	Cradle-to-grave	Greenhouse emissions, winter smog, solid waste, acidification, summer smog, eutrophication
Kua and Kamath (2014)	Fired bricks	Unknown	To study environmental impacts of concrete block replacement with bricks.	1 kg of bricks	Cradle-to-grave	Cumulative energy demand, human toxicity, acidification potential, global warming potential, eutrophication potential
Giama and Papadopoulos (2015)	Fired bricks	CML and EcoIndicator 95	To perform LCA and carbon footprint analysis on construction materials including bricks, cement, concrete, cement plaster and steel.	kg emission/ kg building material	Cradle-to-grave	Abiotic depletion, depletion of ozone layer, acidification, global warming, eutrophication, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, photochemical oxidation, human toxicity, marine aquatic toxicity

Table 2.6 (Continued)

López-Aguilar et al. (2019)	Fired bricks	CML 2001, EcoIndicator 99, ReCiPe, Impact 2002+	To evaluate environmental impacts of brick manufacturing.	1 clay fired brick	Cradle-to-gate	Carcinogens, ionising radiation, non-carcinogens, depletion of ozone layer, respiratory organics and inorganics, terrestrial acidification / nutrification, terrestrial ecotoxicity, aquatic ecotoxicity, aquatic eutrophication, land occupation, aquatic acidification, mineral extraction, non-renewable energy, global warming.
Manni et al. (2021)	Compressed bricks	ReCiPe 2016	To investigate the effectiveness of dredged sediment addition in reducing environmental impacts of bricks.	1 kg of bricks	Cradle-to-gate	Ionizing radiation, ozone formation, human health, global warming, terrestrial acidification, formation of fine particulate matter,

Table 2.6 (Continued)

						freshwater and marine eutrophication, terrestrial ecotoxicity, formation of ozone, terrestrial ecosystems, freshwater ecotoxicity, human carcinogenic toxicity, marine ecotoxicity, land use, human non-carcinogenic toxicity, stratospheric ozone depletion, scarcity of mineral and fossil resource, water consumption
Zhang and Biswas (2021)	Compressed bricks, Fired bricks	Australian Indicator Set v2.01, ReCiPe, CML, TRACI	To evaluate the environmental performances of interlocking compressed earth bricks and conventional fired bricks.	1 m^3 of brickwork	Cradle-to-gate	Land use and ecological diversity, eutrophication, water depletion, global warming, human toxicity, terrestrial, freshwater and marine ecotoxicity, abiotic depletion, acidification, ozone depletion, photochemical

Table 2.6 (Continued)

						smog, ionising radiation, respiratory inorganics.
Supakata et al. (2017)	Compressed bricks, fired bricks	Unknown	To investigate the environmental impacts of facing bricks production using dredged sediments with waste glasses and to make comparison with conventional fired bricks.	1 piece of brick	Cradle-to-gate	Acidification, human toxicity, depletion of ozone layer, global warming, eutrophication.

2.4 Summary

In short, this section has discussed the manufacturing process, environmental impacts and properties of compressed brick and fired bricks which are the two building materials chosen to conduct LCA in this study. Then, various aspects of LCA such as the LCA framework, LCA software and previous studies related to application of LCA on compressed bricks and fired bricks have been presented. After studying these topics in depth, the methodology to conduct LCA study is drafted and presented in subsequent chapter.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The approach for conducting LCA on fired and compressed bricks will be discussed in detail in this chapter. Fired bricks are bricks that undergo brick kiln firing process during their manufacturing stage while compressed bricks are bricks that are compressed to mould them into shape. According to the LCA framework, LCA can be divided into four main stages. The goal and scope are defined first, then the life cycle inventory is defined. Subsequently, LCIA methodology is selected and lastly, life cycle interpretation is conducted to wrap up the study. Stages in carrying out LCA will be discussed accordingly here.

3.2 Goal and Scope Definition

The environmental impacts of fired bricks and compressed bricks will be compared using cradle-to-gate approach. In other words, system boundary of LCA only covers stages from raw materials extraction to the production of final product. The scope is limited to cradle-to-gate to avoid the complexities that arise to model the life stages of bricks during usage and recycle stage. Bricks are building material that can be used in many applications.

For manufacturing process of fired bricks, these processes are considered: raw material extraction, brick moulding, brick drying and brick firing. For production process of compressed bricks, processes such as raw materials crushing, mixing, brick compacting, and brick curing are considered.

The source of input of the bricks has to be determined. The type of fired bricks used for analysis is conventional clay fired brick by Kua and Kamath (2014). For compressed bricks, the bricks are created from Cameron Highlands sediment in a study conducted by Ooi et al. (2015). 1 kg of bricks is selected as functional unit for analysis, which is similar to study conducted by Kua and Kamath (2014). The methodology selected for this LCA is Impact 2002+ midpoint and endpoint method. The system boundary of fired brick for the study is depicted in Figure 3.1, whereas illustration of compressed brick system boundary is available in Figure 3.2.

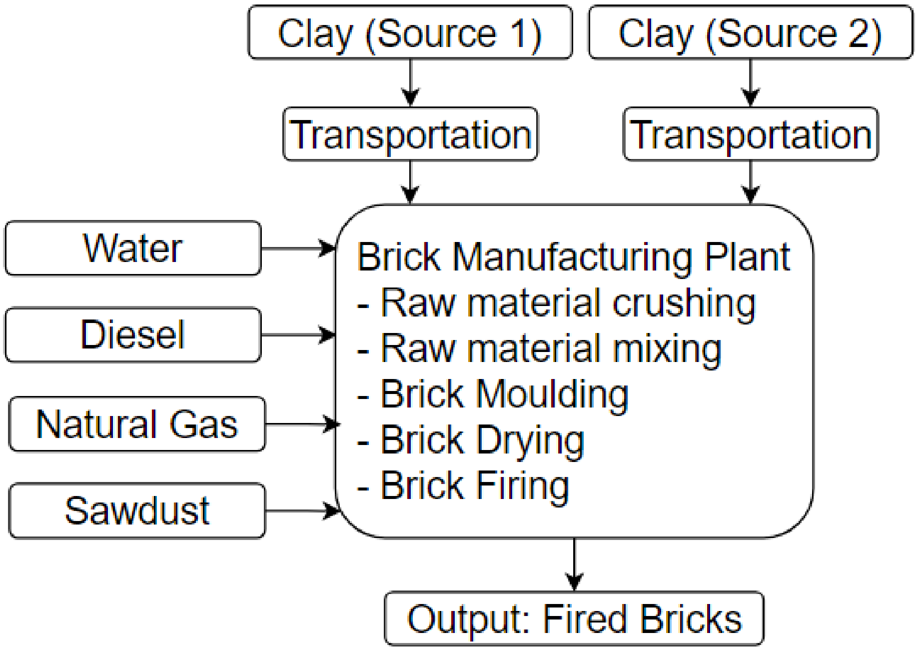


Figure 3.1: System Boundary of Fired Bricks.

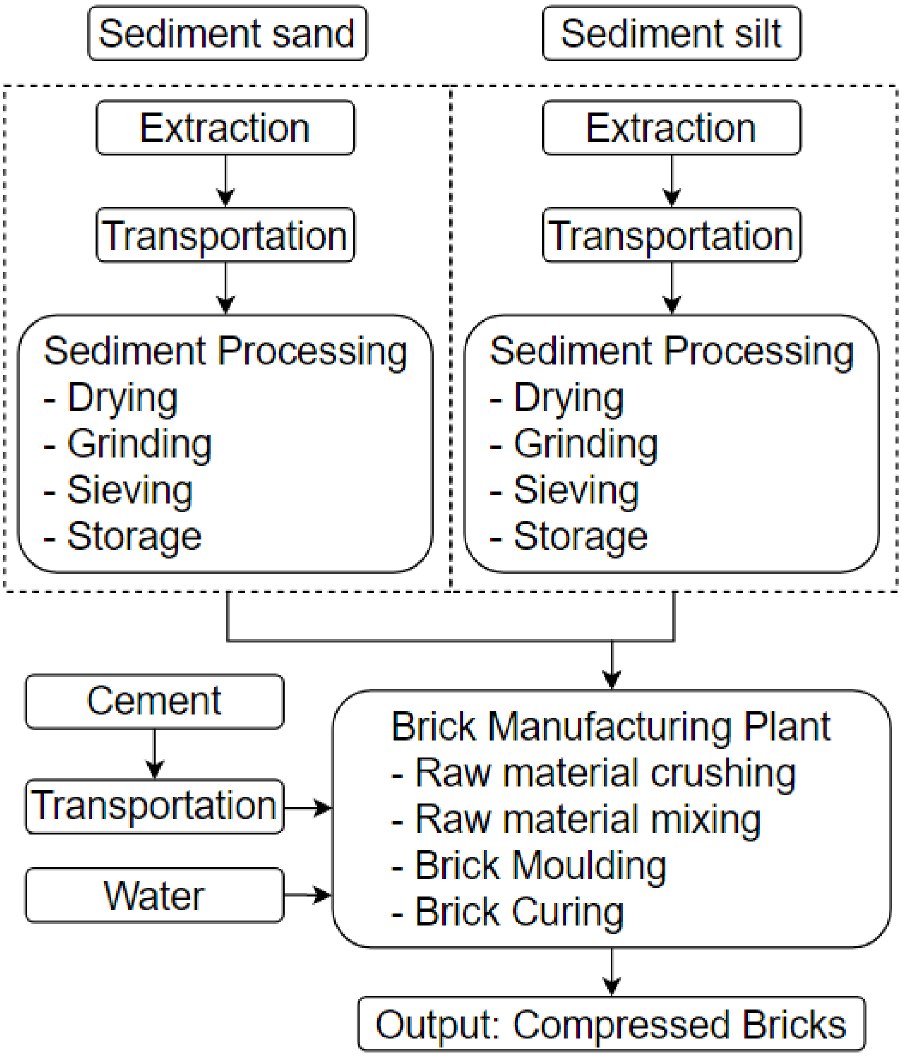


Figure 3.2: System Boundary of Compressed Bricks.

3.3 Life Cycle Inventory

Inputs and outputs data for fired brick and compressed brick manufacturing are identified in LCI stage. Ecoinvent 3.5 database is used as the data source of this study. The data originated from APOS modelling system. Raw materials of both fired bricks and compressed bricks, energy consumption in brick production plant, water and transportation are all included in the input data.

First and foremost, the mix design of both fired bricks and compressed bricks should be determined to identify the inputs for product life cycle modelling. Upon search in literature, the mix design used to conduct the modelling for this study is extracted from Kua and Kamath (2014) and Ooi et al. (2015) for fired bricks and compressed bricks respectively. The mix design are shown in the table below. The mix design of fired bricks requires clay material input from two different quarries or sources; hence the clay is separated into source 1 and 2. The clay from both sources will be mixed with a proportion of 60% and 40%. Since it is mentioned in the literature that 1.11 kg of clay is needed to make 1 kg of clay bricks, the amount of clay required from sources 1 and 2 are 0.666 kg and 0.444 kg respectively.

Water is added until the mixture achieves required consistency. According to Brick Industry Association (2006), mixing water in a range of 10% to 15% of dry weight of mixtures is required to produce plasticity. The mixing water proportion proposed by Sutcu et al. (2015) is 15% and it falls within the range. Hence, 15% of water of total dry weight of mixtures is used in the design mix. Table 3.1 and Table 3.2 summarises the design mix for fired bricks and compressed bricks respectively.

Table 3.1: Mix Design of Fired Bricks (Kua and Kamath, 2014).

Input Data	**Amount (% by weight)**
Clay (Source 1)	60
Clay (Source 2)	40
Water	10% to 15% water of the total dry weight of the mixtures

Table 3.2: Mix Design of Compressed Bricks (Ooi et al., 2015).

Input Data	**Amount (% by weight)**
Sediment silt	70
Sediment sand	20
Cement	10
Water	10% to 15% water of the total dry weight of the mixtures

The compressive strength of fired bricks and compressed bricks are evaluated. For compressed bricks, the compressive strength of bricks produced by the mix design specified above is 6.3 MPa. However, the compressive strength for fired bricks of the mix design used in not mentioned in the literature.

Hence, an assumption is made that the sizing of fired bricks of mix proportion proposed follows the Malaysian Standards since the mix proportion obtained originates from Johor, Malaysia. The compressive strength of common fired brick produced by a manufacturer in Malaysia is 35.7 MPa according to Ali (2005).

Besides that, raw materials transportation distance for fired brick is assumed based on the study done by Kua and Kamath (2014). It was mentioned in the study that the location of manufacturing plant is located within 5 to 10 km radius around the quarries and the transportation distance to manufacturing plant from both quarries is 15 km. Hence, transportation distance of 15 km is adopted in this study.

For compressed bricks, the sediment silt and sediment sand are sourced from Sungai Jasik and Sungai Habu respectively in the study done by Ooi et al. (2015). The location of Sungai Jasik and Sungai Habu is shown in Figure 3.3.

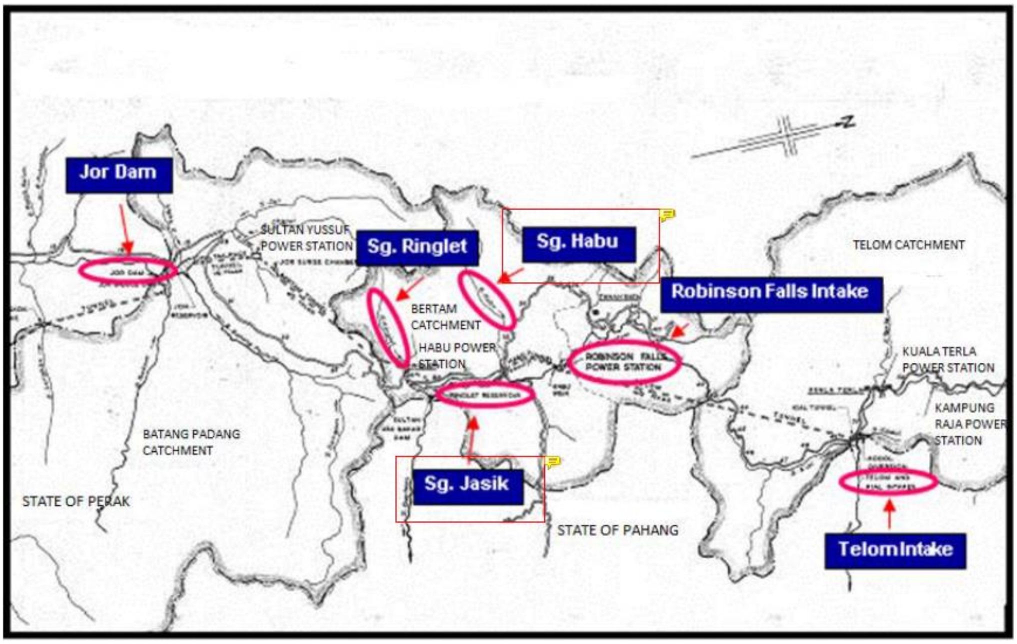


Figure 3.3: Location of Sungai Jasik and Sungai Habu (Ooi et al., 2015).

It was mentioned that the location of factory producing compressed brick is located within 1 km of silt excavation site. Therefore, the transportation distance is considered as 1 km for sediment silt. The distance between Sungai Jasik and Sungai Habu are approximately 4.1 km as shown in the map imageries in Figure 3.4, Figure 3.5 and Figure 3.6. Therefore, transportation distance for sediment sand is rounded up to 5 km. Moreover, cement is required to be transported to compressed brick manufacturing site as well. An assumption of 50 km transportation distance is made between the cement plant and compressed brick production site. The assumption is based on the average transportation distance of raw material used in the study done by Yuan et al. (2018).

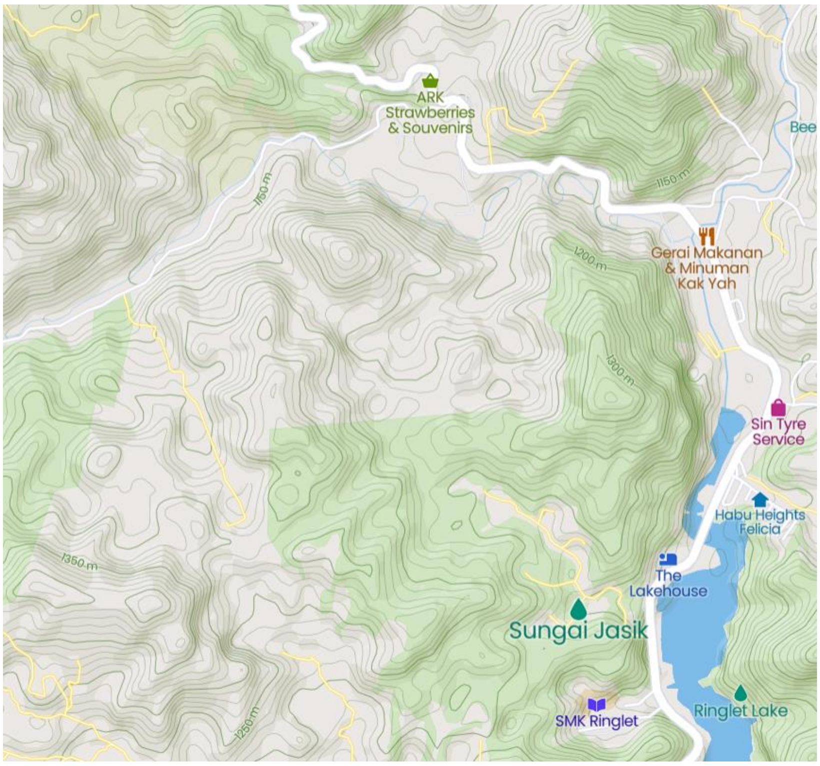


Figure 3.4: Location of Sungai Jasik.

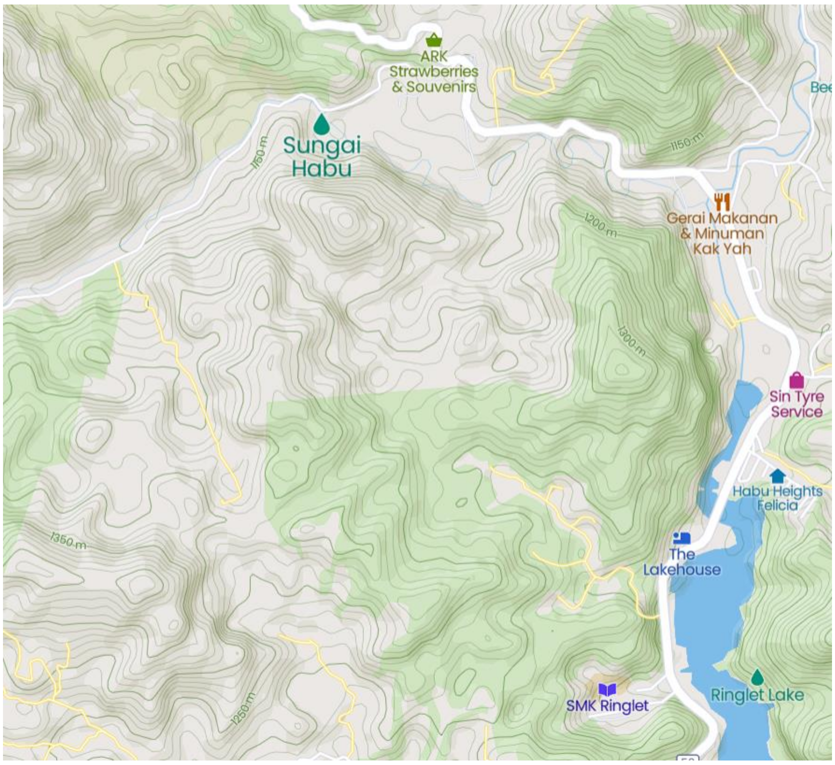


Figure 3.5: Location of Sungai Habu.

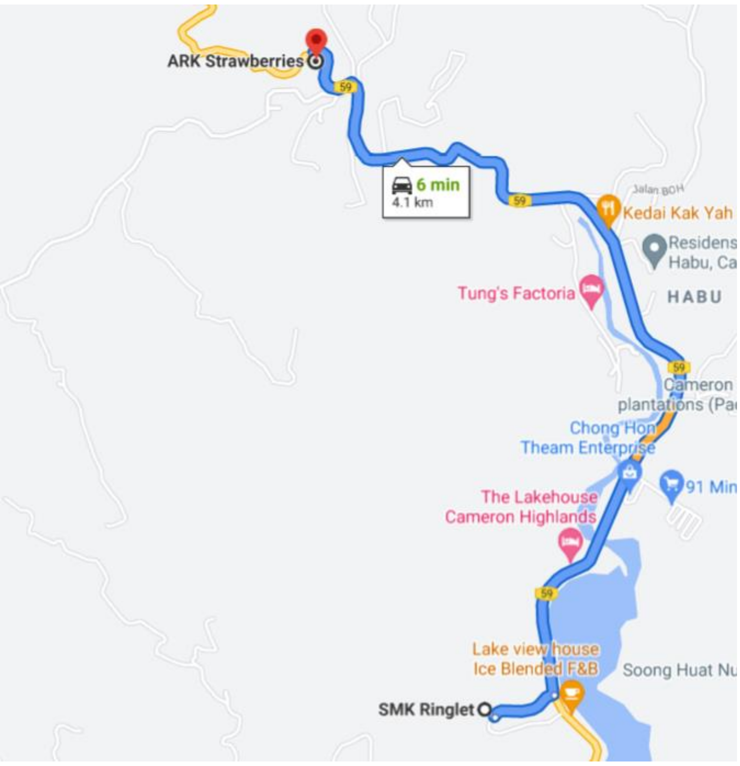


Figure 3.6: Distance between Sungai Habu and Sungai Jasik.

Next, inputs materials required to run the brick production plant for fired bricks and compressed bricks are determined. The raw materials required to produce fired brick are clay and water, which has been shown in the design mix proportion. Besides that, fuel mixture to fire up the brick kiln consists of sawdust, natural gas and diesel. Electricity input for fired brick production plant is considered as well. The inputs essential for manufacturing 1 kg of fired bricks are listed in Table 3.3.

Table 3.3: Inputs Required for Production of 1 kg of Fired Bricks (Kua and Kamath, 2014).

Input Materials	**Amount**	**Remarks**
Clay, source 1 (kg)	0.666	60% of 1.1 kg clay required.
Clay, source 2 (kg)	0.444	40% of 1.1 kg clay required.
Water (kg)	0.131	
Diesel (litre)	0.010	Equivalent to 0.085 kg
Electricity (kWh)	0.154	
Natural gas (kg)	0.009	Equivalent to 0.01324 m^3
Sawdust (kg)	0.100	

The inputs for production of compressed brick are determined. The raw materials required to produce compressed bricks are cement, sediment silt and sediment sand according to the mix proportion. However, processing of sediment silt and sediment sand collected from dredging site are required before compressed brick manufacturing. The processes involved in sediment processing is shown in the system boundary and the inputs required to process 1 ton of sediment are listed in Table 3.4. The sediments for compressed bricks manufacturing are sun-dried, so there is no energy consumption to run the dryer to dry the sediments. The remaining sediment processing steps that require input are sediment extraction, sediment crushing, grinding and sieving.

Table 3.4: Inputs for Processing of 1 ton of Sediment (Sadok et al., 2019).

Process	**Consumption**	**Amount**	**Remarks**
Extraction	Diesel (MJ/t)	76.9	Equivalent to 2 kg
Crushing	Electricity (KWh)	0.57	Total 16.92 kWh
Grinding	Electricity (KWh)	10.90	
Sieving	Electricity (KWh)	5.45	

Electricity requirement to produce 1 kg of compressed brick is calculated as well based on the information of power requirement for 1 hour, compressed brick amount produced in 1 hour, density and size measurements of 1 unit of compressed brick extracted from the study done by (Ooi et al., 2015). The calculations to determine the electricity requirement to manufacture 1 kg of compressed brick is shown in Table 3.5. A summary of inputs required for 1 kg of compressed brick production is shown in Table 3.6. Ecoinvent database contains LCA datasets from different regions of the world. In this study, most of the datasets are obtained from Switzerland and Rest of World. Dataset origins are summarised in Table 3.7. Furthermore, data source and quality assessment on raw material production inputs are presented in Table 3.8.

Table 3.5: Calculation for Electricity Input Required for Production of 1 kg of Compressed Bricks.

Information	**Calculation**
Power to run machine for 1 hour	16.9 kW
Brick can be produced in 1 hour	270 units
Density of 1 unit of compressed brick	1635.47 kg/m^3
Volume of 1 unit of compressed brick	210 mm x 100 mm x 65 mm = 1365000 mm^3 = 0.001365 m^3
Weight of 1 unit of compressed brick	1635.47 kg/m^3 x 0.001365 m^3 = 2.23 kg
Total weight of brick produced in 1 hour	270 x 2.23 kg = 602.1 kg
Power to run machine for 1 kg of compressed brick for 1 hour	16.9 kW / 602.1 kg = 0.028 kW / kg

Table 3.6: Inputs Required for Production of 1 kg of Compressed Bricks (Ooi et al., 2015).

Input Materials	**Amount**	**Remarks**
Sediment silt (kg)	0.7	70% by weight
Sediment sand (kg)	0.2	20% by weight
Cement (kg)	0.1	10% by weight
Water (kg)	0.15	15% of total weight of mixtures

Table 3.7: Origin of Dataset.

Dataset	**Origin**
Portland Cement	Switzerland
Tap water	
Clay	
Sawdust	
Diesel	
Transportation	Rest of World
Electricity	
Natural gas	

Table 3.8: Inputs for Raw Material Production (Ecoinvent, 2021).

Material	LCI Data Source	Data Quality Assessment
Cement production, Portland	cement production, Portland | cement, Portland | APOS, U	• This selected dataset expresses manufacturing of Portland Cement type CEM I in the country of Switzerland. CEM I 42.5 and CEM I 52.5 R are the two representative production mix covered in this dataset. Cement production mix shall conform to EN 197-1. • Activity of dataset commences with the cement clinker required for manufacturing of cement, which is located in the silo. Additional ingredients required for cement production are considered at cement production facility gate as well. • This activity considers also electrical energy requirement and electricity usage for cement clinker grinding process, tools to assist grinding, heat requirement for dehumidification of additional materials and terminates at the final product, which is cement manufactured from the cement mill. Elements such as administration and packaging are not included in this dataset.
Tap water	tap water production, conventional treatment | tap water | APOS, U	• The dataset expresses under pressure tap water production (1 kg) at the gate of water production facility. Water is ready for distribution into the piping network. The dataset considers the average and conventional water treatment operation for tap water production. Conventional water treatment process considered includes water coagulation and water decantation, water filtration and water disinfection. However, other treatment options such

Table 3.8 (Continued)

		as water oxidation (using ultraviolet radiation or ozone) and other adjustment on water quality in terms of pH and alkalinity can present in some water treatment plants.
Clay	clay pit operation | clay | APOS, U	• This dataset expresses 1 kg of clay production in a mine, assuming a thickness of the clay layer in nature of 30 m. • The activity starts from clay at ground, unexcavated. Activity starts from cradle stage, which includes every upstream activity. • The dataset ends with the transportation to first grinding machine. The dataset includes the land use and transformation and the recultivation of the area. The dataset doesn't include further treatments of the clay (i.e., water consumption).
Sawdust	Suction, sawdust | saw dust, loose, wet, measured as dry mass | APOS, U	• This data expresses sawdust collection service, which is expressed in the unit of per kg dry mass and transported to sawdust silo via the aspiration process. • The activity begins with sawdust generated at sawing machine. • This activity terminates at the sawmill site when the sawdust is collected at sawdust silo. The dataset excludes direct wood dust emissions and also specific infrastructure. This information is estimated roughly in the process of sawmilling.

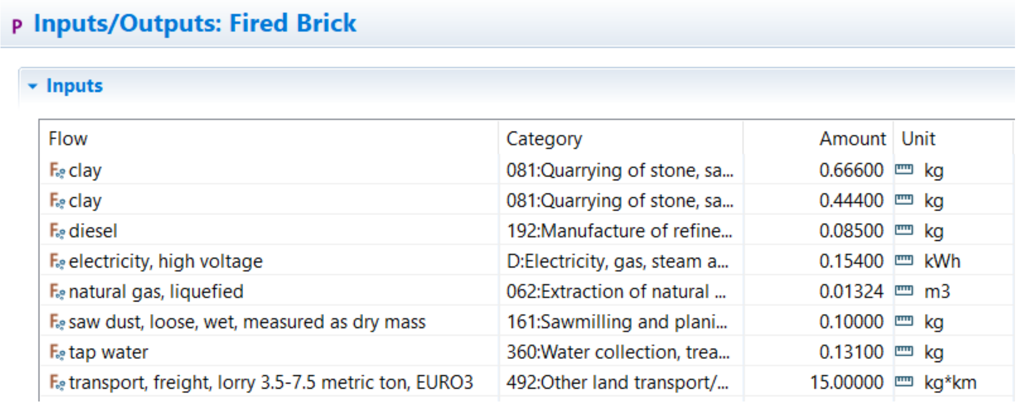
Table 3.8 (Continued)

Diesel	petroleum refinery operation | diesel [kg] | APOS, U	• A description of all energy and material flows due to output if 1kg crude oil in crude oil refinery. It is a multi-output process that delivers co-products such as diesel. Impacts of processing of diesel is allocated here. • The activity starts from the cradle, which encompasses all upstream activities. • The activity ends at all processes on the crude oil refinery facility. Emissions from burning facilities, process emissions, wastewater treatment and direct discharge into a river are excluded.
Transportation	transport, freight, lorry 3.5-7.5 metric ton, EURO3 | transport, freight, lorry 3.5-7.5 metric ton, EURO3 [metric ton·km] | APOS, U	• This dataset portrays 1 ton·km freight transport service operated with a gross vehicle weight 3.5-7.5 metric tons lorry. Emission class of the lorry used for transportation is Euro III. Transportation dataset is referred to whole life cycle of transport. For instance, the elements considered are: vehicle construction, vehicle maintenance, vehicle operation, vehicle’s end of useful life and roadway infrastructures. • Starting from engine’s fuel combustion, this dataset includes the lorry and road network infrastructure, as well as the materials and labour required to maintain them, not to forget fuel burned by the vehicle during the trip. Activity starts from cradle stage, which includes every upstream activity.

Table 3.8 (Continued)

		- The activity terminates at service of transportation of 1 ton·km and vehicular emissions from exhaust and other emissions into water, soil and air.
Electricity	electricity production, hard coal | electricity, high voltage [kWh] | APOS, U	- This dataset comprises of production of high voltage electricity inside an average hard coal power plant on the world in 2012. IEA electricity information 2014 has defined the term hard coal to cover coking coal, other bituminous coal and anthracite. - The activity starts from the constructed hard coal power plant ready to produce electricity. From reception of hard coal and operating materials at power plant gate. - The activity ends with 1kWh of high voltage electricity produced at the power plant and arrived at the busbar.
Natural gas	natural gas production, liquefied | natural gas, liquefied [m^3] | APOS, U	- This dataset have included liquefaction process of natural gas inside a natural gas liquefaction plant. Normalisation of process is performed on gaseous form of natural gas. - This activity commences with arrival of gaseous form natural gas in liquefaction plant. From cradle, which includes all upstream activities. - This activity terminates when natural gas is delivered to transport mode.

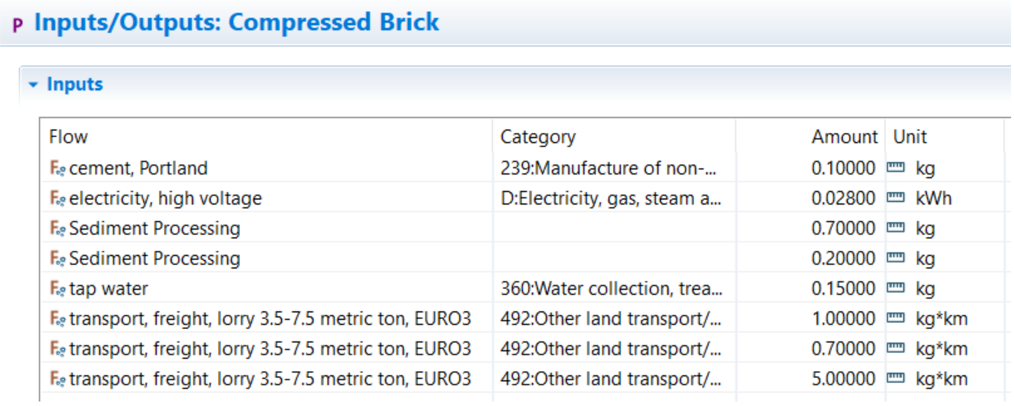
After listing out all the required inputs for 1 kg of fired brick and compressed brick production, the values are transferred into OpenLCA software. Since dataset of sediment silt and sediment sand processing are not available in the Ecoinvent database, they are created manually using the inputs for sediment processing found in literature. Input data of fired brick and compressed brick are displayed in Figure 3.7 and Figure 3.8 respectively. On the other hand, Figure 3.9 illustrates input data of sediment processing.


Inputs/Outputs: Fired Brick

Inputs

Flow	Category	Amount	Unit
clay	081:Quarrying of stone, sa...	0.66600	kg
clay	081:Quarrying of stone, sa...	0.44400	kg
diesel	192:Manufacture of refine...	0.08500	kg
electricity, high voltage	D:Electricity, gas, steam a...	0.15400	kWh
natural gas, liquefied	062:Extraction of natural ...	0.01324	m3
saw dust, loose, wet, measured as dry mass	161:Sawmilling and plani...	0.10000	kg
tap water	360:Water collection, trea...	0.13100	kg
transport, freight, lorry 3.5-7.5 metric ton, EURO3	492:Other land transport/...	15.00000	kg*km

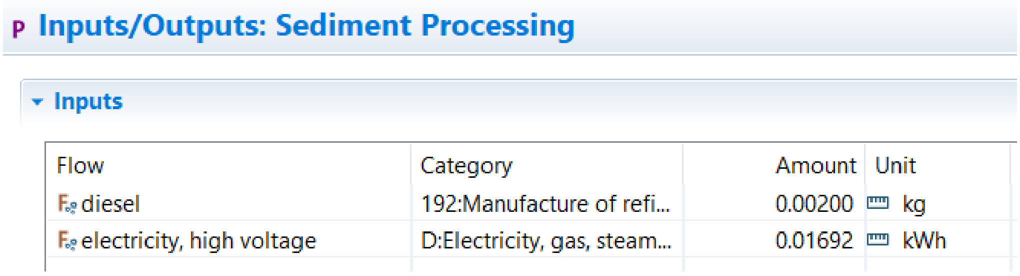
Figure 3.7: Input Data of Fired Brick.


Inputs/Outputs: Compressed Brick

Inputs

Flow	Category	Amount	Unit
cement, Portland	239:Manufacture of non-...	0.10000	kg
electricity, high voltage	D:Electricity, gas, steam a...	0.02800	kWh
Sediment Processing		0.70000	kg
Sediment Processing		0.20000	kg
tap water	360:Water collection, trea...	0.15000	kg
transport, freight, lorry 3.5-7.5 metric ton, EURO3	492:Other land transport/...	1.00000	kg*km
transport, freight, lorry 3.5-7.5 metric ton, EURO3	492:Other land transport/...	0.70000	kg*km
transport, freight, lorry 3.5-7.5 metric ton, EURO3	492:Other land transport/...	5.00000	kg*km

Figure 3.8: Input Data of Compressed Brick.


Inputs/Outputs: Sediment Processing

Inputs

Flow	Category	Amount	Unit
diesel	192:Manufacture of refi...	0.00200	kg
electricity, high voltage	D:Electricity, gas, steam...	0.01692	kWh

Figure 3.9: Input Data of Sediment Processing.

3.4 Life Cycle Impact Assessment

Inputs of LCI will undergo evaluation process to be translated into environmental impacts during the step of LCIA. The environmental impacts will be evaluated according to the earlier defined functional unit, which is 1 kg of bricks. The methodology used to carry out LCIA is Impact 2002+, since both midpoint and endpoint results can be modelled in using this method. Furthermore, as stated in problem statement, Impact 2002+ methodology is less commonly used in modelling of LCA of compressed bricks and fired bricks. Hence, in this study, both midpoint and endpoint results will be modelled to evaluate and study the environmental impacts of compressed brick and fired brick using Impact 2002+ methodology.

According to Impact 2002+ framework, the output data for midpoint categories consist of respiratory effects, global warming, aquatic acidification, depletion of ozone layer, terrestrial ecotoxicity, aquatic ecotoxicity, photochemical oxidation, mineral extraction, aquatic eutrophication, land occupation, terrestrial acidification, ionising radiation, non-renewable energy and human toxicity. The output data for damage or endpoint categories consist of only four items: resources, human health, ecosystem quality and climate change.

Some midpoint categories will be selected from the Impact 2002+ framework to be presented and discussed. The midpoint categories selected are human toxicity, aquatic acidification and depletion of ozone layer. These categories are selected since they are the commonly discussed midpoint categories in LCA studies as seen in Table 2.6 of literature review section. For instance, López-Aguilar et al. (2019) involves aquatic acidification in their study, while other studies in Table 2.6 consider acidification instead, which may still involve acidification towards water bodies. Kua and Kamath (2014), Giama and Papadopoulos (2015), Zhang and Biswas (2021) and Supakata et al. (2017) have involved human toxicity in their LCA study. Furthermore, studies consisting of depletion of ozone layer as impact category are done by Giama and Papadopoulos (2015), López-Aguilar et al. (2019), Manni et al. (2021), Zhang and Biswas (2021) and Supakata et al. (2017). For endpoint categories, all four damage categories will be discussed in the results and discussion section.

3.5 Life Cycle Interpretation

The final step in LCA is to interpret and to make comparison between the results of environmental impacts and footprints between the two brick products, namely fired bricks and compressed bricks. The outcome of life cycle interpretation is to make a set of conclusion and recommendations which will fulfil the research objective and benefit future studies. Scope of work during interpretation phase should include result identification, result evaluation and conclusion, recommendation and limitation identification (Hernandez et al., 2019).

The results of environmental impacts of fired bricks and compressed bricks are compared using midpoint and damage categories. The results must be structured and arranged in order to identify significant issues in the LCIA results. The results obtained should also be checked to fulfil the goal and scope of defined for the study. Then, the results should be evaluated based on the issues identified to enhance the reliability of study and to provide a clear view on the study outcome. The last step of life cycle interpretation involves drawing conclusion, stating limitations and making recommendations according to results of LCA. The brick type with lesser environmental impact or lesser environmental footprint is recommended to be used.

3.6 Summary

In short, the methodology to conduct LCA on fired bricks and compressed bricks are presented according to LCA framework which can be divided into four main stages. The details of each LCA stages have been divided into subtopics and discussed. Firstly, the scope of the study has been determined and system boundary for fired brick and compressed brick are shown to represent the study scope. Next, relevant LCI required to perform LCA are gathered and presented. Besides that, in LCIA, the Impact 2002+ methodology has been explained as well. Lastly, at final step of LCA, interpretation of LCA results has been discussed.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter shows and discusses the results of LCIA of fired bricks and compressed bricks using Impact 2002+ endpoint and midpoint methods. The functional unit of 1 kg of bricks is used to carry out LCIA, hence the results should be interpreted as the environmental impact of producing 1 kg of bricks as well. The endpoint impact categories of Impact 2002+ including resources, climate change, ecosystem quality and human health are investigated. The difference of results between fired bricks and compressed bricks are compared and discussed. Generally, LCA software will assign impact scores to each impact categories. The greater the impact score given onto a brick, the higher the environmental impact of the brick.

4.2 LCIA Results of Impact 2002+ Endpoint Method

According to Impact 2002+ framework, there are four endpoint categories to be discussed. The first endpoint category being discussed is climate change. Then, ecosystem quality, followed by human health categories will be analysed. Lastly, result of resources is explained. The contribution of individual processes are highlighted as well.

4.2.1 Climate Change

Figure 4.1 shows the impacts of climate change due to production of fired brick and compressed brick in the unit of kg_{eq} CO_2. Table 4.1 summarises the impacts from each raw materials of fired brick and compressed brick that is contributing towards climate change. It can be noticed that fired brick has higher environmental impact towards climate change compared to compressed brick. In total, the contribution of fired brick towards climate change is 2.39×10^{-1} kg_{eq} CO_2, while the environmental impact of compressed brick is 1.41×10^{-1} kg_{eq} CO_2.

It can be noticed from Figure 4.2 that electricity production is the major contribution towards climate change in the case of fired brick production. This is due to the fact that fired brick drying and burning process consumes more energy compared to compressed brick. The amount of embodied energy during manufacturing stage of fired brick is more significant compared to compressed brick (Bhairappanavar et al., 2021). Electricity production from coal fired power plant will involve coal burning process, causing gasses like carbon dioxide, sulphur dioxide and nitrogen oxides to be released, thus leading to climate change, global warming and impact to the air quality (Shindell and Faluvegi, 2010). Hence, fired brick production process involves high amount of energy usage which will lead to production of greenhouse gases that will eventually contribute to climate change impact.

Besides that, in the production of compressed brick, cement contributes significant amount of impact at 8.59×10^{-2} kg_{eq} CO_2. This is because cement is a main raw material required in production of compressed brick to help compressed brick to achieve desired strength. Cement production will cause notable environmental issues in terms of energy consumption and emissions to air, especially during fossil fuel combustion for cement clinker production and limestone calcination (Çankaya and Pekey, 2019). Greenhouse gases emission from cement production will eventually lead to climate change impact in brick production.

Table 4.1: Contribution of Various Processes to Climate Change Category in Impact 2002+ Endpoint Method.

	Climate Change (kg_{eq} CO_2)	
Process	**Fired Brick**	**Compressed Brick**
Electricity Production	1.82×10^{-1} (76.15%)	5.10×10^{-2} (35.96%)
Clay	9.51×10^{-3} (3.98%)	-
Cement	-	8.60×10^{-2} (60.65%)
Natural gas	6.29×10^{-3} (2.63%)	-
Transport	8.87×10^{-3} (3.71%)	3.97×10^{-3} (2.80%)
Diesel	3.31×10^{-2} (13.85%)	6.99×10^{-4} (0.49%)
Tap water	1.82×10^{-5} (0.01%)	1.39×10^{-4} (0.1%)
Sawdust	-3.21×10^{-4} (-0.13%)	-
Total	**2.39×10^{-1}**	**1.41×10^{-1}**

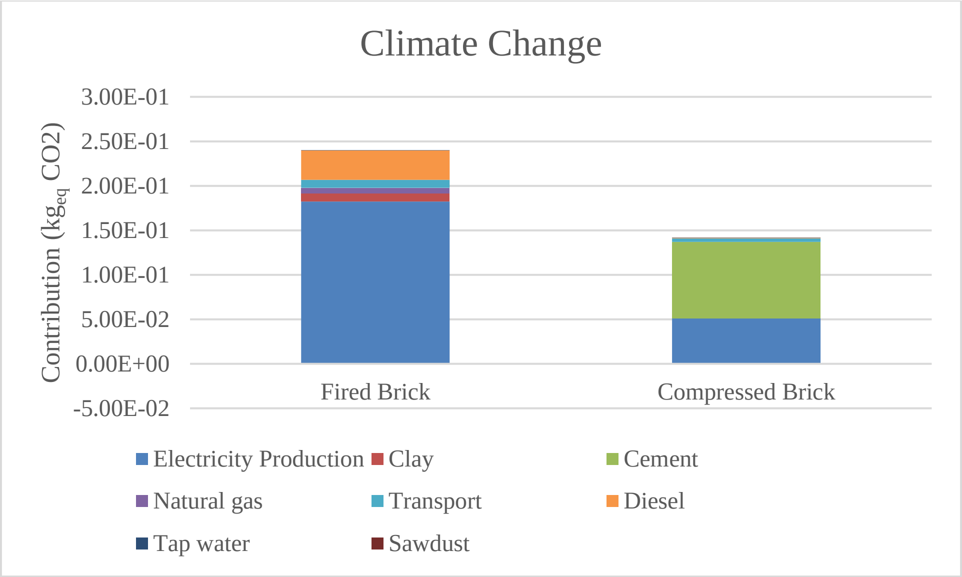


Figure 4.1: LCIA Results of Fired Brick and Compressed Brick for Climate Change Category.

4.2.2 Ecosystem Quality

Figure 4.2 illustrates the results of ecosystem quality impact due to fired brick and compressed brick manufacturing using Impact 2002+ endpoint method. From the figure, it can be noticed that environmental footprint of fired brick is greater as compared to compressed brick. Table 4.2 shows the breakdown of contribution of each raw material towards the ecosystem quality impact in terms of PDF·m^2·yr. Contribution of fired brick, in total, towards ecosystem quality impact is 3.05×10^{-2} PDF·m^2·yr, while contribution of compressed brick is found to be 1.21×10^{-2} PDF·m^2·yr, which is lesser compared to fired brick.

Electricity production and diesel are the two most impactful sources that contribute to the environmental impact in terms of ecosystem quality. Undoubtedly, manufacturing of fired brick requires high consumption of electricity and burning fuel which will lead to high environmental impact. According to Gomes and Hossain (2003), traditional fired brick production process is energy intensive and environmentally polluting. Modern energy-efficient brick kilns can be adopted to reduce the energy demand for brick production, thus reducing its environmental impact. The manufacturing process for compressed brick being studied is more energy efficient due to the absence of brick burning process, which consumes fuel and energy. Generation of electricity from coal fired power plant will produce ash wastes that may contaminate water bodies which will harm the ecosystem. Besides, coal mining also damages the flora and fauna habitat by deteriorating soil and water quality as a result of environmental contamination (Rocha and Silva, 2019). On the other hand, production of burning fuel such as diesel will increase the likelihood of groundwater pollution by toxins such as toluene, benzene, xylene and ethyl benzene, as well as the release of diesel combustion product such as sulphur dioxide and carbon monoxide into the atmosphere (Chauhan and Shukla, 2011).

The contribution of cement towards ecosystem quality impact is significant at 4.47×10^{-3} PDF·m^2·yr. Emissions from cement kiln system such as carbon dioxide, carbon monoxide, total organic carbon, volatile organic compounds and heavy metal will deteriorate ecosystem quality (Çankaya and Pekey, 2015). Besides that, cement plant will also generate particulate matter during raw material mining, crushing and grinding process. As a result, cement is a main contributor to damage in ecosystem quality, alongside with electricity generation and usage of burning fuel.

Table 4.2: Contribution of Various Processes to Ecosystem Quality Category in Impact 2002+ Endpoint Method.

	Ecosystem Quality (PDF·m^2·yr)	
Process	**Fired Brick**	**Compressed Brick**
Electricity Production	2.39×10^{-2} (46.68%)	6.71×10^{-3} (50.07%)
Clay	4.03×10^{-3} (7.87%)	-
Cement	-	4.47×10^{-3} (33.36%)
Natural gas	7.89×10^{-4} (1.54%)	-
Transport	3.88×10^{-3} (7.58%)	1.74×10^{-3} (12.99%)
Diesel	1.86×10^{-2} (36.33%)	3.95×10^{-4} (2.95%)
Tap water	5.52×10^{-6} (0.01%)	4.20×10^{-5} (0.31%)
Sawdust	-9.43×10^{-5} (-0.18%)	-
Total	$\mathbf{5.12\times10^{-2}}$	$\mathbf{1.34\times10^{-2}}$

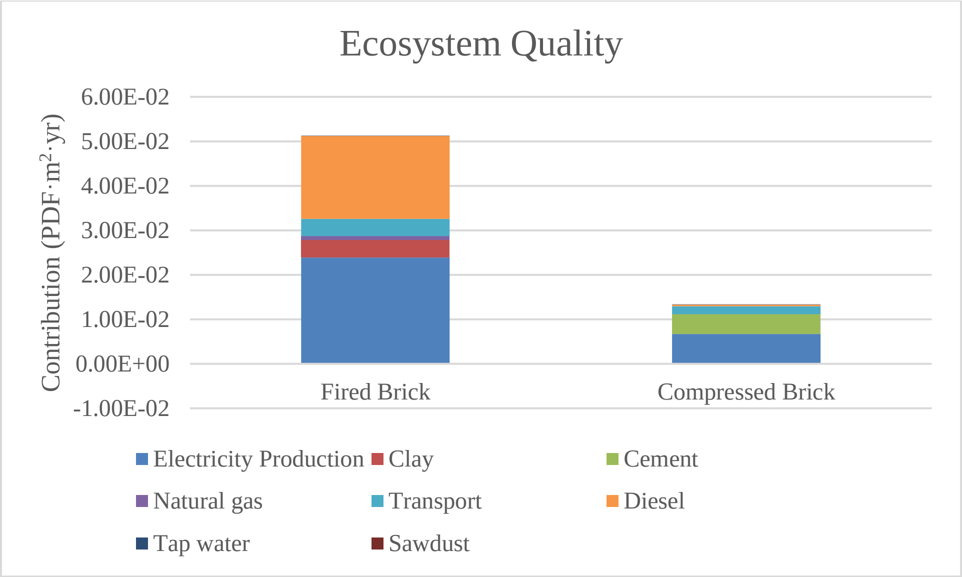


Figure 4.2: LCIA Results of Fired Brick and Compressed Brick for Ecosystem Quality.

4.2.3 Human Health

Figure 4.3 shows the impacts contribution of fired brick and compressed brick manufacturing towards human health. The results are summarised in Table 4.3 as well. It can be noticed that the total contribution of fired brick towards human health impact is higher at 1.77×10^{-7} DALY compared to compressed brick at 8.18×10^{-8} DALY. It can be said that manufacturing of fired brick will bring more harm to human health than manufacturing of compressed brick.

The results of fired brick and compressed brick shows that electricity generation from hard coal contributes the highest impact towards human health at 1.51×10^{-7} DALY and 4.23×10^{-8} DALY respectively. Impact of human health from compressed brick is lower compared to fired brick since lower electrical energy is consumed for production of compressed brick. Burning of coal will release aerosol particles into the atmosphere which is a hazard to human health. Besides that, inhalation of toxic secondary compounds formed by nitrogen, sulphur, minerals and organometallic compounds may trigger respiratory, cardiovascular and neurological diseases (Gasparotto and Martinello, 2021). Environmental protection measures should be implemented when coal is used as electricity generation source to minimise risks of human morbidity and mortality.

Both diesel and clay contributed 3.50×10^{-8} DALY towards human health damage category, making them the second most significant environmental impact in fired brick production process. Burning of fuel in brick kiln causes the emissions of toxic pollutants including carbon monoxide, nitrogen oxides and dioxins, resulting in adverse effect in human health (Skinder et al., 2014). Besides that, contribution of clay towards damage of human health can be associated with inhalation of kaolinite dust during clay mining process leading to respiratory disease like pneumoconiosis (Carretero et al., 2013).

Substantial environmental impact is generated from cement production process as it accounts for 1.81×10^{-8} DALY human health impact from the results of compressed brick. Manufacturing of cement is considered as a dusty process due to particulate matter emissions during raw material crushing and grinding process. Furthermore, burning of fuels such as coal, gas and oil, which are energy sources for cement kiln will further generate cement plant emissions. Cement plant emissions may include hydrocarbons, heavy metals, volatile organic compounds, nitrogen oxides, sulphur oxides and carbon monoxide (Raffetti et al., 2019). In short, exposure to emissions from cement manufacturing process increases the risk of developing respiratory disease and cancer among human population.

Table 4.3: Contribution of Various Processes to Human Health Category in Impact 2002+ Endpoint Method.

	Human Health (DALY)	
Process	**Fired Brick**	**Compressed Brick**
Electricity Production	1.51×10^{-7} (69.59%)	4.23×10^{-8} (63.51%)
Clay	3.50×10^{-8} (16.13%)	-
Cement	-	1.81×10^{-8} (27.18%)
Natural gas	4.20×10^{-9} (1.94%)	-
Transport	1.20×10^{-8} (5.53%)	5.35×10^{-9} (8.03%)
Diesel	3.50×10^{-8} (16.13%)	7.38×10^{-10} (1.11%)
Tap water	2.47×10^{-11} (0.01%)	1.89×10^{-10} (0.28%)
Sawdust	-4.39×10^{-10} (-0.20%)	-
Total	$\mathbf{2.17\times10^{-7}}$	$\mathbf{6.66\times10^{-8}}$

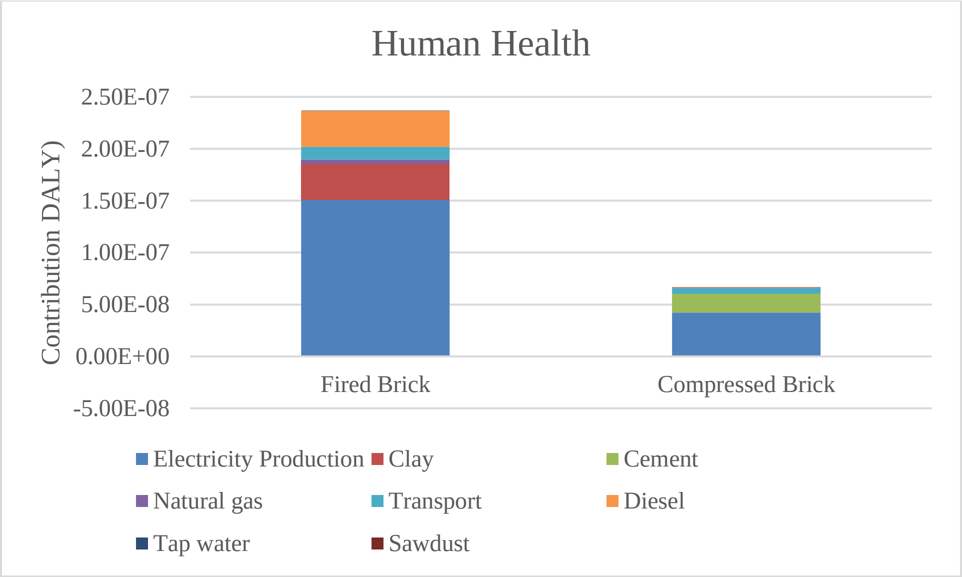


Figure 4.3: LCIA Results of Fired Brick and Compressed Brick for Human Health Category.

4.2.4 Resources

Figure 4.4 depicts the LCIA results of Impact 2002+ endpoint method on resources category. From the figure, it can be observed that the contribution from fired brick towards resources impact is higher compared to compressed brick. The results for this impact category are listed in Table 4.4. The total contribution of fired brick and compressed brick towards resources impact category are 2.54 MJ and 8.20×10^{-1} MJ respectively.

In terms of results on resources category, it can be noticed that the contribution of diesel is the highest at 4.26 MJ, while the second most substantial contribution originates from electricity production at 1.76 MJ. This can be attributed to the fact that diesel is produced from crude oil refining process. Crude oil is a thick, dark and viscous naturally occurring liquid that can be refined into various petroleum-based products, including fuel like diesel. Fossil fuels are considered as non-renewable source and deposits of fossil fuels are limited physically due to slow replenishment rate and high extraction rate. Deposition and accumulation of fossil fuel naturally requires millions of years, while the extraction is carried out rapidly, the rate of creation simply cannot keep up with the extraction rate (Höök and Tang, 2013). In short, fossil fuel is a finite resource and eventually will be depleted if extraction continues.

Generation of electricity via coal-fired power plant will also deplete crude oil resources as well. This is because generation of electricity using hard coal requires fuel, which is used to burn coal to generate steam that powers the turbine to generate electricity. Fired brick manufacturing require large amount of electricity and fuel such as diesel and natural gas to burn the bricks in brick kiln, hence it explains the substantial amount of resources impact in these categories. On the other hand, compressed brick manufacturing does not include the burning process.

Table 4.4: Contribution of Various Processes to Resources Category in Impact 2002+ Endpoint Method.

	Resources (MJ)	
Process	**Fired Brick**	**Compressed Brick**
Electricity Production	1.76 (25.62%)	4.97×10^{-1} (55.41%)
Clay	1.09×10^{-1} (1.59%)	-
Cement	-	2.52×10^{-1} (28.09%)
Natural gas	6.35×10^{-1} (9.24%)	-
Transport	1.23×10^{-1} (1.79%)	5.47×10^{-2} (6.10%)
Diesel	4.26 (62.08%)	9.01×10^{-2} (10.04%)
Tap water	5.58×10^{-4} (8.12%)	4.26×10^{-3} (0.47%)
Sawdust	-1.92×10^{-2} (-0.28%)	-
Total	**6.87**	**8.97×10^{-1}**

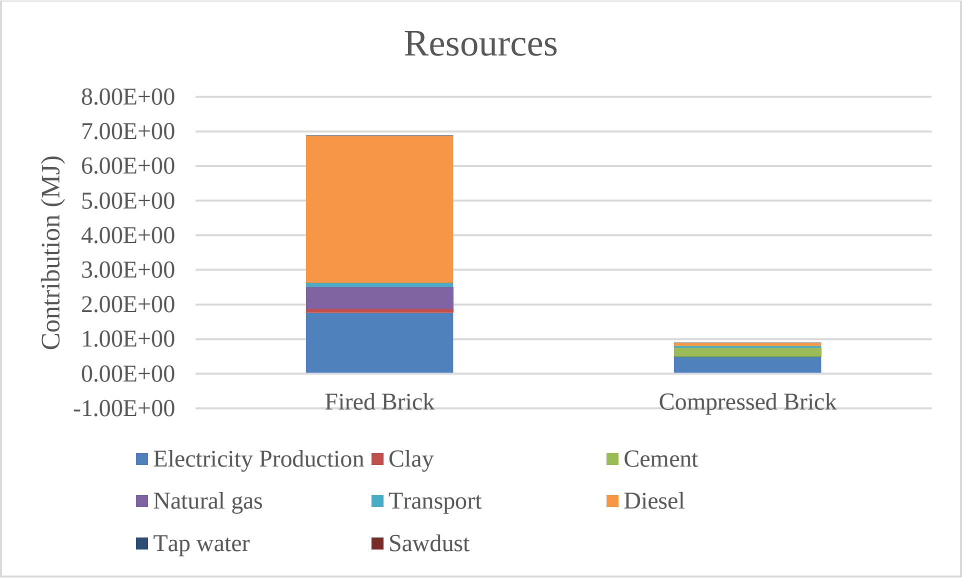


Figure 4.4: LCIA Results of Fired Brick and Compressed Brick for Resources Category.

4.3 LCIA Results of Impact 2002+ Midpoint Method

In total, there are fourteen midpoint categories in the Impact 2002+ framework. However, only three midpoint categories will be selected to be discussed in this section. The impact categories investigated in this section are aquatic acidification, human toxicity and ozone layer depletion. Similar to endpoint method, individual processes breakdown will be included as well.

4.3.1 Aquatic Acidification

Figure 4.5 shows the Impact 2002+ midpoint method results of compressed brick and fired brick in aquatic acidification category. The total contribution of fired brick towards this midpoint category is 2.23×10^{-3} kg SO_2 eq, which is higher compared to the total contribution of 5.46×10^{-4} kg SO_2 eq from compressed brick. The results are summarised in Table 4.5 as well.

Aquatic acidification refers to the process in which the pH value of aquatic ecosystem is dropping and becoming acidic. A drop in water pH below the optimal range may cause detrimental effects to the survivability of aquatic plants and animals. It can be observed that for both fired brick and compressed brick, electricity generation contributes the greatest impact to aquatic acidification category. However, electricity generation impact from fired brick is 1.81×10^{-3} kg SO_2 eq, which is more significant compared to 3.90×10^{-4} kg SO_2

eq from compressed brick. This is because production of fired brick requires more energy input than compressed brick to fire up the brick kiln. Coal-fired power plants are responsible for the emission of anthropogenic sulphur oxides and nitrogen oxides into the atmosphere, which can be transported and deposited in water basins, causing water acidification (Obolkin et al., 2016). To mitigate the potential of aquatic acidification from coal-fired power plants, measure such as flue gas desulphurisation can be adopted to reduce sulphur dioxide emissions.

Besides that, for fired brick, diesel is the second largest contributor to aquatic acidification. Diesel will generate acidic pollutants when burnt as source of fuel during fired brick burning process. As for compressed brick, cement is a major cause of aquatic acidification because cement production involves high energy input and fossil fuel requirements for cement kiln. Fossil fuel production and electricity consumption are significant acidification potential contributor, especially when fossil fuel is required in electricity generation (Stafford et al., 2016). Furthermore, the process of burning of cement clinker to produce cement is also responsible for emission of acidic pollutants such as sulphur dioxide into the atmosphere. For instance, in 2009, cement industry in China consumes 1.38 billion kWh of electricity and releases 0.89 million tons of sulphur dioxide into the air (Chen et al., 2015).

Table 4.5: Contribution of Various Processes to Aquatic Acidification Category in Impact 2002+ Midpoint Method.

	Aquatic Acidification (kg SO_2 eq)	
Process	**Fired Brick**	**Compressed Brick**
Electricity Production	1.81×10^{-3} (81.17%)	3.90×10^{-4} (71.43%)
Clay	6.95×10^{-5} (3.12%)	-
Cement	-	1.30×10^{-4} (23.81%)
Natural gas	2.56×10^{-5} (1.15%)	-
Transport	4.39×10^{-5} (1.97%)	1.96×10^{-5} (3.59%)
Diesel	2.80×10^{-4} (12.56%)	5.96×10^{-6} (1.09%)
Tap water	1.02×10^{-7} (4.57%)	7.79×10^{-7} (0.14%)
Sawdust	-1.34×10^{-6} (-0.06%)	-
Total	$\mathbf{2.23\times10^{-3}}$	$\mathbf{5.46\times10^{-4}}$

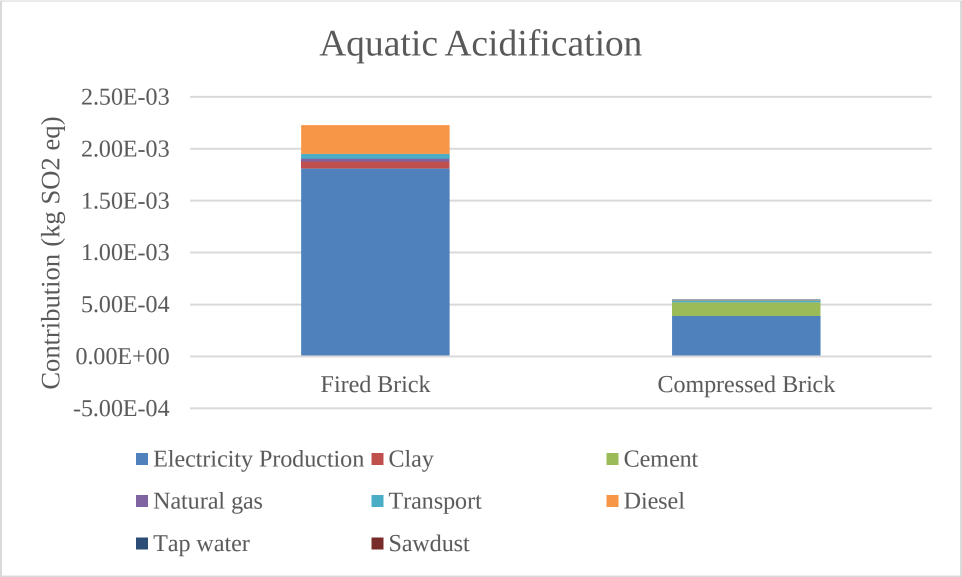


Figure 4.5: LCIA Results of Fired Brick and Compressed Brick for Aquatic Acidification Category.

4.3.2 Human Toxicity

Human toxicity midpoint category provides a relative comparison of amount of toxic chemicals that may cause cancer or other negative effects on human health. Figure 4.6 shows the human toxicity results of human toxicity category of Impact 2002+ midpoint category. Fired brick has greater impact in human toxicity category compared to compressed brick. Total impact of fired brick in human toxicity category is 9.30×10^{-3} DALY/kg chloroethylene, while total impact of compressed brick is 2.70×10^{-3} DALY/kg chloroethylene. The results are summarised in Table 4.6.

Transport is the main contributor to human toxicity category for fired brick and compressed brick. This is because motor vehicle emissions are the main contributor of particulate matter emission into the atmosphere. According to International Agency for Research on Cancer, toxicity in diesel-powered motor vehicles fumes can be carcinogenic and is related to deposition of ultra-fine particulate matters in respiratory tract, which can cause respiratory diseases and lung tumour (Turrio-Baldassarri et al., 2006). Besides that, exhaust emissions contain more than 40 toxic air contaminants. For example, benzene, arsenic and nickel, which are found in diesel exhausts are carcinogenic (Nelson et al., 2008). Diesel vehicle emissions are the main source of nitrogen oxides emissions as well. In a nutshell, toxicity of diesel fumes will cause substantial negative impact on human health.

Next, it can be observed that electricity and diesel input into fired brick production will also contribute significant impact to human toxicity. Electricity production and diesel contribution are recorded as 2.30×10^{-3} DALY/kg chloroethylene and 1.56×10^{-3} DALY/kg chloroethylene respectively. Electricity generation via coal and burning process of fired brick requires burning of fossil fuel. In the case of this study, diesel is the main source of fuel for brick firing process. The amount of input of electricity and diesel are significant in fired brick manufacturing compared to compressed brick, which explains the cause of high human toxicity potential in fired brick. Heavy metals like chromium, lead, mercury, cadmium and arsenic are products of combustion of fossil fuel released to the atmosphere that contain genotoxic properties (Jayasekher, 2009). Presence of heavy metals will cause adverse issues to human health.

Moreover, cement is a major contributor to human toxicity as well with a human toxicity potential value of 5.83×10^{-4} DALY/kg chloroethylene. Cement production is a dusty process, and its production plants are the main sources of particulate matters emissions. Besides that, cement plants are energy intensive, which requires large amount of fossil fuel burning to meet its production requirements, resulting in release of toxic pollutants into the air. For instance, carbon monoxide may reduce ability of oxygen transmission in human body. Sulphur dioxide and nitrogen oxides may trigger lung tissue damage and worsen prevailing lung conditions. Cement manufacturing process will also release a type of radioactive gas known as radon which can cause lung cancer if it is inhaled in large quantities (Etim et al., 2021).

Table 4.6: Contribution of Various Processes to Human Toxicity Category in Impact 2002+ Midpoint Method.

	Human Toxicity (DALY/kg chloroethylene)	
Process	**Fired Brick**	**Compressed Brick**
Electricity Production	2.30×10^{-3} (24.73%)	6.46×10^{-4} (23.93%)
Clay	1.20×10^{-3} (12.90%)	-
Cement	-	5.83×10^{-4} (21.59%)

Table 4.6 (Continued)

Natural gas	1.09×10^{-3} (11.72%)	-
Transport	3.17×10^{-3} (34.09%)	1.42×10^{-3} (52.59%)
Diesel	1.56×10^{-3} (16.77%)	3.31×10^{-5} (1.23%)
Tap water	2.60×10^{-6} (0.03%)	1.98×10^{-5} (0.73%)
Sawdust	-2.75×10^{-5} (-0.30%)	-
Total	**9.30×10^{-3}**	**2.70×10^{-3}**

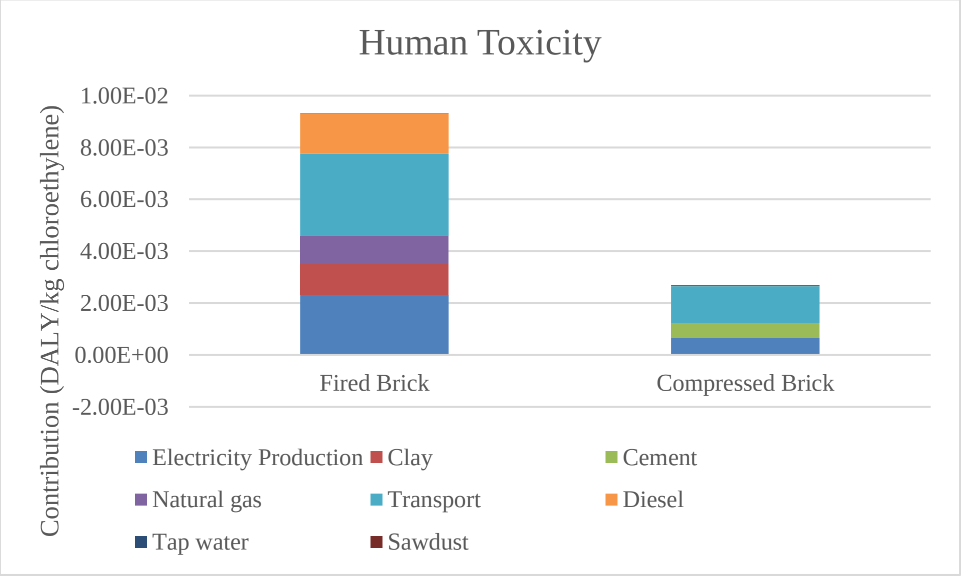


Figure 4.6: LCIA Results of Fired Brick and Compressed Brick for Human Toxicity Category.

4.3.3 Ozone Layer Depletion

Figure 4.7 shows the results of ozone layer depletion impact category of fired brick and compressed brick. According to Figure 4.8, ozone layer depletion impact of fired brick is 5.50×10^{-8} DALY/kg CFC-11, while impact of compressed brick in this impact category is 3.16×10^{-9} DALY/kg CFC-11. The results are recorded in Table 4.7 as well.

According to results of LCA, diesel is the greatest contributor towards ozone layer depletion in the case of fired brick. Ozone depletion category is a measurement of risk of stratospheric ozone destruction. The main function of ozone layer is to absorb ultraviolet radiation, which will negatively affect the human health. Chlorine and bromine atoms are common ozone-depleting substances. Crude oil refinery process for diesel production is the main contributor to ozone depletion potential, which can be attributed to Halon 1301 emissions (Morales et al., 2015). Furthermore, Halon 1301 emission from extraction of crude oil will damage the ozone layer as well (Requena et al., 2011). Besides that, combustion of fossil fuel will also lead to anthropogenic release of nitrous oxide into the atmosphere. Factors like technology of combustion, maintenance of kiln, fuel type and kiln operation will affect amount of nitrous oxide emitted (United States Environmental Protection Agency, 2022). Nitrous oxide is deemed as the largest ozone-destroying compound released by human activity among ozone depletion potential emissions (Portmann et al., 2012). In short, large amount of diesel is required for fired brick manufacturing process and it is the most significant contributor to ozone layer depletion potential. To reduce potential of ozone layer depletion, alternative fuel sources should be applied for brick manufacturing process.

Table 4.7: Contribution of Various Processes to Ozone Layer Depletion Category in Impact 2002+ Midpoint Method.

	Ozone Layer Depletion (DALY/kg CFC-11)	
Process	**Fired Brick**	**Compressed Brick**
Electricity Production	9.80×10^{-10} (1.78%)	2.75×10^{-10} (8.70%)
Clay	9.80×10^{-10} (1.78%)	-
Cement	-	1.16×10^{-9} (36.71%)
Natural gas	4.11×10^{-10} (0.75%)	-
Transport	1.34×10^{-9} (2.44%)	5.98×10^{-10} (18.92%)
Diesel	5.14×10^{-8} (93.45%)	1.09×10^{-9} (34.49%)
Tap water	4.09×10^{-12} (0.01%)	3.12×10^{-11} (0.99%)
Sawdust	-1.40×10^{-10} (-0.25%)	-
Total	$\mathbf{5.50\times10^{-8}}$	$\mathbf{3.16\times10^{-9}}$

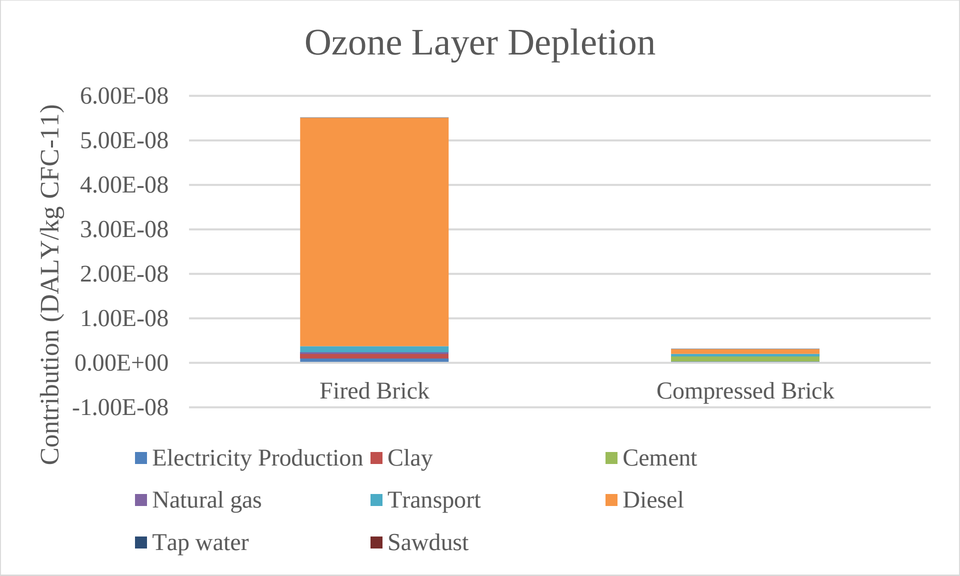


Figure 4.7: LCIA Results of Fired Brick and Compressed Brick for Ozone Layer Depletion Category.

4.4 Comparison on Environmental Impacts

In this study, LCIA results are presented in the form of relative indicator results to facilitate selection of bricks with lower environmental impact. LCIA results of Impact 2002+ endpoint method between fired brick and compressed brick is shown in Figure 4.8. The results of fired brick and compressed brick are compiled into a single bar chart to facilitate comparison between them. Overall, the environmental impact of fired brick is greater compared to compressed brick according to the results in terms of relative percentage. Compressed brick provides better environmental performance in every impact category specified in Impact 2002+ endpoint methodology. All values in the bar chart are positive, indicating there are negative impacts or damages on the environment.

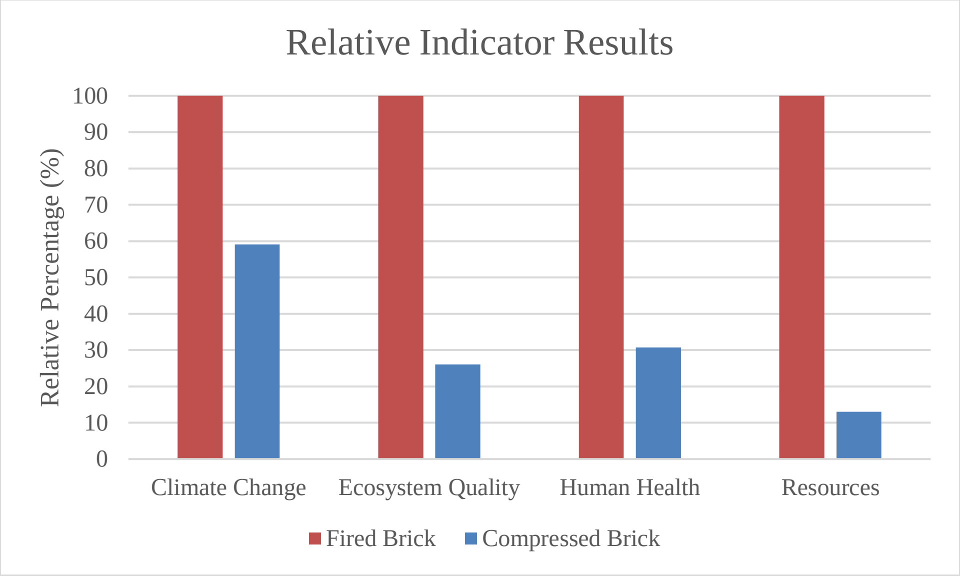


Figure 4.8: LCIA Results of Impact 2002+ Endpoint Method Expressed in Relative Percentage.

On the other hand, LCIA results of Impact 2002+ midpoint method is expressed in Figure 4.9. The midpoint impact categories featured in comparison are aquatic acidification, human toxicity and ozone layer depletion. Overall, the environmental burden of fired brick is greater compared to compressed brick. This trend is similar with that of the endpoint categories. Once again, all the bar chart values are positive, indicating production of fired brick and compressed brick will have negative impact to the environment. All in all, compressed brick is the more environmentally sustainable brick choice for construction compared to fired brick.

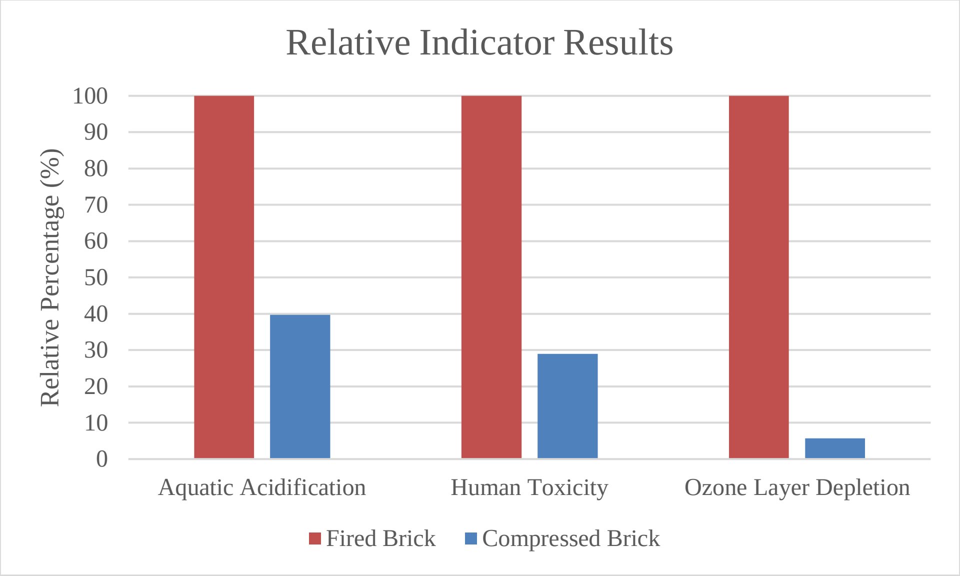


Figure 4.9: LCIA Results of Impact 2002+ Midpoint Method Expressed in Relative Percentage.

Several interesting findings can be obtained from the comparison of environmental implication of compressed brick and fired brick. Firstly, electricity generation will have significant impact on the results of LCIA on fired brick and compressed brick. For instance, electricity generation input for fired brick contributes the greatest environmental impact in climate change, ecosystem quality and human health endpoint categories, and aquatic acidification midpoint category. Whereas for compressed brick, contribution of electricity generation towards environmental implications is the most prominent in ecosystem quality, human health and resources endpoint categories, and aquatic acidification midpoint category. In this study, electricity is assumed to be generated via hard coal in coal-fired power plant, which will significantly affect the environment negatively. In fact, coal-fired power plant is the conventional power generation method with the most emissions to the environment (Bhat and Prakash, 2009). Thus, it is no surprise that electricity generation using hard coal will contribute a large margin of environmental impact to brick production. Considering fired brick manufacturing process is more energy intensive, fired brick is deemed to be less sustainable according to the results of LCIA. Moreover, considering the large portion of environmental impacts coming from electricity production, substituting electricity production with hard coal provider with other electricity production methods in OpenLCA software will also strongly affect the results of LCIA.

Next, it is found that diesel is the second most significant contributor to fired brick environmental consequences in climate change, ecosystem quality and human health category, and the largest contributor in resources category. Hence, it can be said that the burning fuel for fired brick is also another major environmental impact contributor after electricity generation. According to LCA study done by Tangprasert et al. (2015), direct energy use from fuel combustion and electricity usage during brick burning process will contribute the most emissions to the environment. To sum up, the brick firing process of fired brick is the major contributor to negative impacts to the environment, making fired brick an unsustainable option compared to compressed brick, which can be manufactured without the firing process.

Besides that, the raw material with the second most substantial environmental burden is cement in production of compressed brick. Compressed brick is manufactured without burning process; hence the amount of diesel input is not as great as compared to fired brick which uses diesel as burning fuel, resulting the cement becoming the second most significant environmental impact contributor to the endpoint categories. This is because cement production is a high emission and high embodied energy process. For instance, extraction of raw materials for cement production and cement processing steps in manufacturing stage contains high embodied carbon, which translates to significant potential of generating negative environmental impacts (Bhairappanavar et al., 2021). However, in comparison with conventional fired brick, compressed brick is still more sustainable.

4.5 Compressive Strength Comparison

Besides comparison of environmental impacts between compressed brick and fired brick, the compressive strength of both brick types can be considered as well to make a recommendation between them. Compressive strength is the capacity of a brick to withstand forces and loads that are applied onto it and it can be used to predict durability of the brick.

Compressive strength of fired brick is obtained from existing literature, and it can vary according to firing temperature, firing duration and materials used to produce fired brick. The literature source containing the mix proportion of fired brick used in this study is obtained from Kua and Kamath (2014), which is developed based on a manufacturer in Johor, Malaysia. However, this literature source does not cover compressive strength test on fired bricks. Hence, the compressive strength of fired brick is obtained from a study done by Ali (2005), which analyses the properties of fired brick from a manufacturer in the similar country. It was found that the mean strength of a common fired brick is 35.7 MPa, while mean strength for facing fired brick is 46 MPa. On the other hand, mix proportion of compressed brick used in this study is obtained from Ooi et al. (2015). It was discovered that the compressive strength of compressed brick is 6.3 MPa after 28 days of curing.

Compressive strength from both fired brick and compressed brick are satisfactory, since they exceed the minimum requirements of MS 76, which is 5.2 MPa. However, compressive strength of compressed brick is still significantly lower compared to fired brick, which may make its usage limited in terms of load-bearing wall applications. For instance, although bricks that exceed the minimum compressive strength of 5.2 MPa are allowed to be used on load-bearing wall of up to two-storey dwelling units, the minimum structural recommendation for load-bearing wall indicates that the minimum average compressive strength for load-bearing brick should be 7.0 MPa.

4.6 Cost Comparison

The costing between fired brick and compressed brick can be compared as pricing of bricks will influence the decision of buyers on choice of brick type. According to a study done by Ean (2014), in 2015, the sales price of one unit of compressed brick is RM 0.17 and the pricing is projected to increase by a rate of RM 0.02 per year. Hence, in 2022, the pricing of compressed brick is RM 0.31 per unit. In comparison, the price of fired brick is identified as RM 0.35 per unit of clay common bricks (Quantity Surveyor Online, 2022). Consumers tend to choose products that are cost-effective and reliable with necessary certification to fulfil their needs, while minimising construction cost.

4.7 Summary

To sum up, comparison has been made between compressed brick and fired brick in terms of environmental impacts, compressive strength and cost. LCIA results of Impact 2002+ endpoint and midpoint categories have indicated that compressed brick is the more environmentally friendly option since it possesses lesser environment burden. Breakdown of individual raw material contribution to each impact category has been provided and the major contributors to environmental damage are electricity generation, diesel and cement.

Despite compressed brick being a more sustainable option from the results of LCIA, compressive strength of compressed brick is lower compared to fired brick, which may affect its load-bearing capabilities. Fortunately, the compressive strength of compressed brick still fulfils the minimum requirement of MS 76, which makes it suitable to be used in non-load bearing wall construction. In terms of costing, compressed brick is deemed advantageous as the unit cost of compressed brick is lower compared to fired brick. Usage of compressed brick in a long run can be a cheaper option without compromising building quality. As a result, with all factors considered, usage of compressed brick is recommended since it is a greener construction material with satisfactory compressive strength at a lower cost.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study has evaluated and compared the environmental impacts between fired brick and compressed brick using Impact 2002+ method. The aims and objectives of this study has been satisfied. For instance, the production process and life cycle inventory of fired brick and compressed brick were identified using APOS model. Next, environmental impacts of fired brick and compressed brick were evaluated using Impact 2002+ method. Lastly, comparison of environmental impacts between compressed brick and fired brick was made according to the results obtained from Impact 2002+ midpoint and endpoint categories with the system boundary cradle-to-gate. Functional unit of this study is set as 1 kg of brick.

The results of LCIA of Impact 2002+ midpoint and endpoint are presented. All four endpoint categories of Impact 2002+ methodology are presented, namely, human health, ecosystem quality, resources and climate change. The three midpoint categories results presented are aquatic acidification, human toxicity and ozone layer depletion. Breakdown of individual raw materials contribution to each impact category is presented as well. For fired brick production, electricity generation using hard coal is the largest contributor to all endpoint categories except resources, and aquatic acidification midpoint category. Whereas for compressed brick, electricity production’s impact is dominant to endpoint categories except climate change, and aquatic acidification midpoint category as well. The second most significant contributor to environmental impact in fired brick and compressed brick are diesel and cement respectively. The results are in agreement with the findings that electricity generation via coal-fired power plant, manufacturing of cement and fuel production and combustion for brick firing are energy-intensive processes and generates significant negative impacts to the environment. Besides comparison on environmental impacts via LCIA results, fired brick and compressed brick are compared in terms of compressive strength and costing as well.

In general, compressed brick is deemed to has better environmental performance as compared to fired brick from the results of Impact 2002+ midpoint and endpoint categories. Compressed brick also fulfils the minimum compressive strength requirement according to MS 76 for application in the construction industry. Moreover, compressed brick is offered at a lower price as opposed to fired brick, which can be attractive in the prospect of cost reduction. Compressed brick is recommended to be used in the construction industry when sustainability is a main factor of concern.

The findings of this study are significant as they suggest that LCA is a vital tool that is useful in accessing environmental performances of construction materials. Considering fired and compressed bricks are common construction materials worldwide and are frequently mass produced, it is vital to acknowledge the environmental impacts of compressed brick and fired brick production to pave the way for development of green construction. LCA can help to raise the awareness in the construction industry on the need to adapt and to use sustainable construction materials for the betterment of the environment. In a long run, sustainable construction practices can reduce unwanted economic costs from environmental effects. To sum up, it is recommended to use compressed brick as an environmentally friendly option for sustainable construction.

5.2 Limitations of Study

It should be noted that the scope of study is limited to only cradle-to-gate. In other words, it is a partial life cycle assessment that commences from phase of materials extraction until production of bricks at the factory gate. Phases such as brick delivery to consumers, brick application in construction and brick disposal are not evaluated. Next, system expansion for recycled sediment silt and sediment sand is not considered in the system boundary. Moreover, the assumption of transportation distance of clay from nearby quarry is 15 km, which is obtained from existing literature. The transportation distance of dredged sediment silt, dredged sediment sand and cement are assumed to be 1 km, 5 km and 50 km respectively. These distance values are the results of estimation and assumption, which may differ from the actual transportation distance, causing difference in fuel consumption and vehicular emissions.

Furthermore, LCI for various electricity generation sources are available in the Ecoinvent database, however the only electricity generation source selected to be used in this study is electricity generation via hard coal. Usage of other electricity generation sources in analysis may yield different LCA results. Besides that, there is also lack of environmental information and localised input in life cycle inventory to carry out LCIA, resulting in datasets mostly originating from Switzerland and Rest of World. Besides that, the only LCIA method adopted in this study is Impact 2002+ methodology, when many other LCIA methodologies such as CML, ReCiPe and EcoIndicator 99 are available to facilitate comparison to improve reliability of results.

5.3 Recommendations for Future Work

To address the issues mentioned in the limitations of study section and to enhance the results in future work, some recommendations can be considered to be adopted:

(i) The scope of study can be expanded to cradle-to-grave analysis to include brick distribution, brick use and brick disposal life cycle phases.

(ii) System expansion can be included to identify the avoided environmental burden as a result of reusing sediment to obtain a more accurate result for compressed brick.

(iii) The study on transportation distances should be more specific in terms of identifying the exact origin and destination to compute the distance travelled based on actual roadway.

(iv) Sensitivity analysis on multiple electricity generation sources can be included to investigate environmental impacts of different sources.

(v) Data source to carry out LCIA related to brick industry in Malaysia is lacking. More research and data collection should be conducted to obtain more localised dataset.

(vi) More studies should be carried out to develop input data of sediment silt and sediment sand in the LCI database to improve the reliability of LCIA results related to recycled sediment.

(vii) More variety of LCIA methodologies can be incorporated into future research to make comparison between LCIA methodologies to validate and to enhance accuracy of environmental impact analysis.

REFERENCES

Abdullah, E.S.R., Mirasa, A.K., Asrah, H. and Lim, C.H., 2020. Review on interlocking compressed earth brick. *IOP Conference Series: Earth and Environmental Science,* 476(1), pp. 012029.

Abid, R., Kamoun, N., Jamoussi, F. and El Feki, H., 2021. Fabrication and properties of compressed earth brick from local Tunisian raw materials. *Boletín de la Sociedad Española de Cerámica y Vidrio*.

Ali, Z. A., 2005. *Properties of Malaysia Fired Clay Bricks and Their Evaluation with International Masonry Specification - a Case Study*. MSc. Universiti Teknologi Malaysia. Available at: <http://eprints.utm.my/id/eprint/4453/1/ZainabArmanAliKMKA2005.pdf> [Accessed 17 April 2022].

Almeida, M. I., Dias, A. C., Demertzi, M. and Arroja, L., 2015. Contribution to the development of product category rules for ceramic bricks. *Journal of Cleaner Production,* 92, pp. 206-215.

Asman, N.S.A., Bolong, N., Mirasa, A.K., Asrah, H. and Saad, I., 2020. Interlocking compressed earth bricks as low carbon footprint building material. *IOP Conference Series: Earth and Environmental Science,* 476(1), pp. 012086.

Bhairappanavar, S., Liu, R. and Shakoor, A., 2021. Eco-friendly dredged material-cement bricks. *Construction and Building Materials,* 271, pp. 121524.

Bhat, I. and Prakash, R., 2009. LCA of renewable energy for electricity generation systems—a review. *Renewable and sustainable energy reviews*, 13, pp. 1067-1073.

Bories, C., Vedrenne, E., Paulhe-Massol, A., Vilarem, G. and Sablayrolles, C., 2016. Development of porous fired clay bricks with bio-based additives: Study of the environmental impacts by Life Cycle Assessment (LCA). *Construction and Building Materials*, 125, pp. 1142-1151.

Brick Industry Association, 2006. *Manufacturing of Brick*. [online] Available at: <https://www.gobrick.com/docs/default-source/read-research-documents/technicalnotes/9-manufacturing-of-brick.pdf?sfvrsn=0> [Accessed 26 August 2021].

Buyle, M., Braet, J. and Audenaert, A., 2013. Life cycle assessment in the construction sector: A review. *Renewable and sustainable energy reviews*, 26, pp. 379-388.

Çankaya, S. and Pekey, B., 2015. Identifying environmental impacts of cement production with life cycle assessment: literature review. *J. Int. Sci. Publ*, 9, pp. 251-267.

Çankaya, S. and Pekey, B., 2019. A comparative life cycle assessment for sustainable cement production in Turkey. *Journal of environmental management*, 249, pp. 109362.

Carretero, M. I., Gomes, C. S. F. and Tateo, F., 2013. Clays, drugs, and human health. In *Developments in clay science*, 5, pp. 711-764.

Chauhan, S. K. and Shukla, A., 2011. Environmental impacts of production of biodiesel and its use in transportation sector. *Environmental Impact of Biofuels*, pp. 1-13.

Chen, W., Hong, J. and Xu, C., 2015. Pollutants generated by cement production in China, their impacts, and the potential for environmental improvement. *Journal of Cleaner Production*, 103, pp. 61-69.

Christoforou, E., Kylili, A., Fokaides, P. A. and Ioannou, I., 2016. Cradle to site Life Cycle Assessment (LCA) of adobe bricks. *Journal of cleaner production*, 112, pp. 443-452.

Dabaieh, M., Heinonen, J., El-Mahdy, D. and Hassan, D. M., 2020. A comparative study of life cycle carbon emissions and embodied energy between sun-dried bricks and fired clay bricks. *Journal of Cleaner Production*, 275, pp. 122998.

Dahmen, J., Kim, J. and Ouellet-Plamondon, C. M., 2018. Life cycle assessment of emergent masonry blocks. *Journal of cleaner production*, 171, pp. 1622-1637.

de Souza, D. M., Lafontaine, M., Charron-Doucet, F., Chappert, B., Kicak, K., Duarte, F. and Lima, L., 2016. Comparative life cycle assessment of ceramic brick, concrete brick and cast-in-place reinforced concrete exterior walls. *Journal of Cleaner Production*, 137, pp. 70-82.

Di Noi, C., Ciroth, A. and Srocka, M., 2017. *OpenLCA 1.7. Comprehensive User Manual*. [online] Available at: <https://www.openlca.org/wp-content/uploads/2017/11/openLCA1.7_User_Manual_v1.1.pdf> [Accessed 26 August 2021].

Dulal, P., Pradhan, P., Sthapit, L. and Giri, R. R., 2021. *Carbon emissions of interlocking cement-stabilized compressed earth brick houses in Dhungentar, Nepal*. In: Panyapiwat Institute of Management, Globalization revisited: Building organization resilience with digital transformation. Nonthaburi, Thailand, 3 March 2021. Thailand: Panyapiwat Institute of Management.

Ean, L. W., 2014. Study on the Utilization of Cameron Highlands Reservoir Sediments to Form Prototype of "Green" Bricks - Phase 2. Final Report, pp. 1-73.

Ecoinvent, 2021. *Ecoinvent Database Search.* Available at: <https://v35.ecoquery.ecoinvent.org/Search/Index> [Accessed 30 August 2021].

Elahi, T. E., Shahriar, A. R. and Islam, M. S., 2021. Engineering characteristics of compressed earth blocks stabilized with cement and fly ash. *Construction and Building Materials*, 277, pp. 122367.

Etim, M.-A., Babaremu, K., Lazarus, J. and Omole, D., 2021. Health risk and environmental assessment of cement production in Nigeria. *Atmosphere*, 12, pp. 1111.

Gasparotto, J. and Martinello, K. D. B., 2021. Coal as an energy source and its impacts on human health. *Energy Geoscience*, 2, pp. 113-120.

Giama, E. and Papadopoulos, A., 2015. Assessment tools for the environmental evaluation of concrete, plaster and brick elements production. *Journal of Cleaner Production*, 99, pp. 75-85.

Goel, G. and Kalamdhad, A. S., 2017. Degraded municipal solid waste as partial substitute for manufacturing fired bricks. *Construction and building materials*, 155, pp. 259-266.

Gomes, E. and Hossain, I., 2003. Transition from traditional brick manufacturing to more sustainable practices. *Energy for Sustainable Development*, 7, pp. 66-76.

Han, L. C., Bin Mirasa, A. K., Saad, I., Bte Asrah, H. and Bin Abdullah, E. S. R., 2020. Use of Compressed Earth Bricks/Blocks in Load-Bearing Masonry Structural Systems: A Review. *Materials Science Forum*, 997, pp. 9-19.

Hernandez, P., Oregi, X., Longo, S. and Cellura, M., 2019. Life-Cycle Assessment of Buildings. *Handbook of Energy Efficiency in Buildings*. pp. 207-261.

Höök, M. and Tang, X., 2013. Depletion of fossil fuels and anthropogenic climate change - A review. *Energy policy*, 52, pp. 797-809.

Huang, T., Chiueh, P. and Lo, S., 2017. Life-cycle environmental and cost impacts of reusing fly ash. Resources, *Conservation and Recycling*, 123, pp. 255-260.

Humbert, S., De Schryver, A., Bengoa, X., Margni, M. and Jolliet, O., 2012. *IMPACT 2002+: user guide*. [online] Available at: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.454.741&rep=rep1&type=pdf> [Accessed 30 August 2021].

Jayasekher, T., 2009. Aerosols near by a coal fired thermal power plant: Chemical composition and toxic evaluation. *Chemosphere*, 75, pp. 1525-1530.

Joglekar, S. N., Kharkar, R. A., Mandavgane, S. A. and Kulkarni, B. D., 2018. Sustainability assessment of brick work for low-cost housing: A comparison between waste based bricks and burnt clay bricks. *Sustainable cities and society*, 37, pp. 396-406.

Johari, I., Said, S., Hisham, B., Bakar, A. and Ahmad, Z., 2010. Effect of the change of firing temperature on microstructure and physical properties of clay bricks from Beruas (Malaysia). *Science of Sintering*, 42, pp. 245-254.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G. and Rosenbaum, R., 2003. IMPACT 2002+: a new life cycle impact assessment methodology. *The international journal of life cycle assessment*, 8, pp. 324-330.

Khan, M. W., Ali, Y., De Felice, F., Salman, A. and Petrillo, A., 2019. Impact of brick kilns industry on environment and human health in Pakistan. *Science of the Total Environment*, 678, pp. 383-389.

Koroneos, C. and Dompros, A., 2007. Environmental assessment of brick production in Greece. *Building and Environment*, 42, pp. 2114-2123.

Kua, H. W. and Kamath, S., 2014. An attributional and consequential life cycle assessment of substituting concrete with bricks. *Journal of cleaner production*, 81, pp. 190-200.

Kulkarni, N. G. and Rao, A. B., 2016. Carbon footprint of solid clay bricks fired in clamps of India. *Journal of cleaner production*, 135, pp. 1396-1406.

Kumbhar, S., Kulkarni, N., Rao, A. B. and Rao, B., 2014. Environmental life cycle assessment of traditional bricks in western Maharashtra, India. *Energy Procedia*, 54, pp. 260-269.

Lingling, X., Wei, G., Tao, W. and Nanru, Y., 2005. Study on fired bricks with replacing clay by fly ash in high volume ratio. *Construction and building materials*, 19, pp. 243-247.

López-Aguilar, H. A., Huerta-Reynoso, E. A., Gómez, J. A., Duarte-Moller, J. A. and Pérez-Hernández, A., 2019. Life cycle assessment of a traditional brick manufacture improvement. *Revista internacional de contaminación ambiental*, 35, pp. 195-206.

Lozano-Miralles, J. A., Hermoso-Orzáez, M. J., Martínez-García, C. and Rojas-Sola, J. I., 2018. Comparative study on the environmental impact of traditional clay bricks mixed with organic waste using life cycle analysis. *Sustainability*, 10, pp. 2917.

Manap, N., Bedali, R. A. A. R., Sandirasegaran, K., Masrom, M. A. N. and Yahya, M. Y., 2016. Strength of brick made from dredged sediments. *Jurnal Teknologi*, 78(7-3), pp. 87-92.

Manni, M., Frota de Albuquerque Landi, F., Giannoni, T., Petrozzi, A., Nicolini, A. and Cotana, F., 2021. A Comparative Study on Opto-Thermal Properties of Natural Clay Bricks Incorporating Dredged Sediments. *Energies*, 14, pp. 4575.

Marcelino-Sadaba, S., Kinuthia, J., Oti, J. and Meneses, A. S., 2017. Challenges in Life Cycle Assessment (LCA) of stabilised clay-based construction materials. *Applied Clay Science*, 144, pp. 121-130.

Menoufi, K. A. I., 2011. *Life cycle analysis and life cyle impact assessment methodologies: a state of the art*. MSc. Universitat de Lleida. Available at: <https://repositori.udl.cat/bitstream/handle/10459.1/45831/Ali.pdf?sequence=2&isAllowed=y> [Accessed 26 August 2021].

Morales, M., Gonzalez-García, S., Aroca, G. and Moreira, M. T., 2015. Life cycle assessment of gasoline production and use in Chile. *Science of The Total Environment*, 505, pp. 833-843.

Muntohar, A. S., 2011. Engineering characteristics of the compressed-stabilized earth brick. *Construction and Building Materials*, 25, pp. 4215-4220.

Muralikrishna, I. V. and Manickam, V., 2017. Chapter Five - Life Cycle Assessment. *Environmental Management*, pp. 57-75.

National Academy of Sciences, 2011. *Data needs for life-cycle assessment.* [online] Available at: <https://sites.nationalacademies.org/cs/groups/pgasite/documents/webpage/pga_068711.pdf> [Accessed 20 August 2021]

Nelson, P. F., Tibbett, A. R. and Day, S. J., 2008. Effects of vehicle type and fuel quality on real world toxic emissions from diesel vehicles. *Atmospheric Environment*, 42, pp. 5291-5303.

Nidzam, R. M., Norsalisma, I. and Kinuthia, J. M., 2016. Strength and environmental evaluation of stabilised Clay-PFA eco-friendly bricks. *Construction and Building Materials*, 125, pp. 964-973.

Obolkin, V., Khodzher, T., Sorokovikova, L., Tomberg, I., Netsvetaeva, O. and Golobokova, L., 2016. Effect of long-range transport of sulphur and nitrogen oxides from large coal power plants on acidification of river waters in the Baikal region, East Siberia. *International Journal of Environmental Studies*, 73, pp. 452-461.

Ooi, J. L., Ean, L. W., Mohammed, B. S., Malek, M., Wong, L. S., Tang, C. W. and Chua, H. Q., 2015. Study on the Properties of Compressed Bricks Using Cameron Highlands Reservoir Sediment as Primary Material. *Applied Mechanics and Materials*, 710, pp. 25-29.

OpenLCA Nexus, n.d. *Ecoinvent*. [online] Available at: <https://nexus.openlca.org/database/ecoinvent> [Accessed 20 August 2021]

Owsianiak, M., Laurent, A., Bjørn, A. and Hauschild, M. Z., 2014. IMPACT 2002+, ReCiPe 2008 and ILCD's recommended practice for characterization modelling in life cycle impact assessment: a case study-based comparison. *The International Journal of Life Cycle Assessment*, 19, pp. 1007-1021.

Park, W.-J., Kim, R., Roh, S. and Ban, H., 2020. Analysis of major environmental impact categories of road construction materials. *Sustainability*, 12, pp. 6951.

Phonphuak, N., Kanyakam, S. and Chindaprasirt, P., 2016. Utilization of waste glass to enhance physical–mechanical properties of fired clay brick. *Journal of Cleaner production*, 112, pp. 3057-3062.

Poinot, T., Laracy, M. E., Aponte, C., Jennings, H. M., Ochsendorf, J. A. and Olivetti, E. A., 2018. Beneficial use of boiler ash in alkali-activated bricks. Resources, *Conservation and Recycling*, 128, pp. 1-10.

Portmann, R., Daniel, J. and Ravishankara, A., 2012. Stratospheric ozone depletion due to nitrous oxide: influences of other gases. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 367, pp. 1256-1264.

Quantity Surveyor Online, 2022. *Prices of Building Materials.* [online] Available at: <http://quantitysurveyoronline.com.my/materials-prices> [Accessed 17 April 2022]

Raffetti, E., Treccani, M. and Donato, F., 2019. Cement plant emissions and health effects in the general population: a systematic review. *Chemosphere*, 218, pp. 211-222.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B. P. and Pennington, D. W., 2004. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment international*, 30, pp. 701-720.

Requena, J. S., Guimaraes, A., Alpera, S. Q., Gangas, E. R., Hernandez-Navarro, S., Gracia, L. N., Martin-Gil, J. and Cuesta, H. F., 2011. Life Cycle Assessment (LCA) of the biofuel production process from sunflower oil, rapeseed oil and soybean oil. *Fuel Processing Technology*, 92, pp. 190-199.

Rocha, D. H. and Silva, R. J., 2019. Exergoenvironmental analysis of a ultra-supercritical coal-fired power plant. *Journal of cleaner production*, 231, pp. 671-682.

Sadok, R. H., Tahlaiti, M., Belas, N. and Mazouzi, R., 2019. Environmental life cycle assessment of industrialization process of calcined dredged sediments, *Journal of Materials and Engineering Structures*, 6, pp. 25-37.

Samara, M., Lafhaj, Z. and Chapiseau, C., 2009. Valorization of stabilized river sediments in fired clay bricks: Factory scale experiment. *Journal of hazardous materials*, 163, pp. 701-710.

Shindell, D. and Faluvegi, G., 2010. The net climate impact of coal-fired power plant emissions. *Atmospheric Chemistry and Physics*, 10, pp. 3247-3260.

SIRIM, 1972. *MS 76:1972 Malaysian Standard. Specification for bricks and blocks of fired brickearth, clay or shale. Part 2: Metric units*. [online] Available through: United States Documents website <https://documents.pub/document/ms-76-1972.html> [Accessed 20 August 2021]

Skinder, B. M., Sheikh, A. Q., Pandit, A. K. and Ganai, B. A., 2014. Brick kiln emissions and its environmental impact: A Review. *Journal of Ecology and the Natural Environment,* 6, pp. 1-11.

Stafford, F. N., Dias, A. C., Arroja, L., Labrincha, J. A. and Hotza, D., 2016. Life cycle assessment of the production of Portland cement: a Southern Europe case study. *Journal of cleaner production*, 126, pp. 159-165.

Stankovski, M., Kolemisevska-Gugulovska, T., Spasovski, M. G., Milkovski, Z. and Kuzmanovska, P., 2001. Intelligent Control of a Tunnel Kiln for Clay-Brick Production. *IFAC Proceedings Volumes,* 34(3), pp. 125-130.

Supakata, N., Prachapadoong, P., Chaisupharut, P. and Papong, S., Characteristics and environmental assessment of facing bricks produced from dredged sediments and waste glasses. *Materials Science Forum,* 883, pp. 37-45.

Sutcu, M., Alptekin, H., Erdogmus, E., Er, Y. and Gencel, O., 2015. Characteristics of fired clay bricks with waste marble powder addition as building materials. *Construction and Building Materials,* 82, pp. 1-8.

Tangprasert, W., Jaikaew, S. and Supakata, N., 2015. Utilization of dredged sediments from Lumsai Canal with rice husks to produce bricks. *International Journal of Environmental Science and Development*, 6, pp. 217.

Turrio-Baldassarri, L., Battistelli, C. L., Conti, L., Crebelli, R., De Berardis, B., Iamiceli, A. L., Gambino, M. and Iannaccone, S., 2006. Evaluation of emission toxicity of urban bus engines: Compressed natural gas and comparison with liquid fuels. *Science of the Total Environment*, 355, pp. 64-77.

United States Environmental Protection Agency, 2022. *Overview of Greenhouse Gases.* [online] Available at: <https://www.epa.gov/ghgemissions/overview-greenhouse-gases> [Accessed 17 April 2022]

Velasco, P. M., Ortíz, M. M., Giró, M. M. and Velasco, L. M., 2014. Fired clay bricks manufactured by adding wastes as sustainable construction material–A review. *Construction and Building materials*, 63, pp. 97-107.

Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P. and Mathias, J. D., 2015. How to conduct a proper sensitivity analysis in life cycle assessment: taking into account correlations within LCI data and interactions within the LCA calculation model. *Environmental science & technology*, 49, pp. 377-385.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E. and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, 21, pp. 1218-1230.

Woen, E. L., Malek, M. A., Mohammed, B. S., Chao-Wei, T. and Tamunif, M. T., Experimental study on compressive strength of sediment brick masonry. *AIP Conference Proceedings*, 1930, pp. 020017.

Yuan, X., Tang, Y., Li, Y., Wang, Q., Zuo, J. and Song, Z., 2018. Environmental and economic impacts assessment of concrete pavement brick and permeable brick production process-A case study in China. *Journal of Cleaner Production*, 171, pp. 198-208.

Zhang, L., 2013. Production of bricks from waste materials–A review. *Construction and building materials*, 47, pp. 643-655.

Zhang, X. and Biswas, W. K., 2021. Development of eco-efficient bricks–A life cycle assessment approach. *Journal of Building Engineering*, 42, pp. 102429.