공학박사학위논문

Environmental Assessment in Agriculture: A Utilisation of Life Cycle Assessment in Horticulture and Livestock Industry

농업 분야에서의 환경 평가 : 원예 및 축산 산업에서의 Life Cycle Assessment 활용 방안

2023년 2월

서울대학교 대학원

생태조경·지역시스템공학부

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ENVIRONMENTAL ASSESSMENT IN AGRICULTURE: A UTILISATION OF LIFE CYCLE ASSESSMENT IN HORTICULTURE AND LIVESTOCK INDUSTRY

A DISSERTATION

SUBMITTED TO THE DEPARTMENT OF LANDSCAPE
ARCHITECTURE AND RURAL SYSTEMS ENGINEERING AND
THE COMMITTEE ON GRADUATE STUDIES OF SEOUL
NATIONAL UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF

DOCTOR OF PHILOSOPHY

BY

CRISTINA SORIANO DECANO

FEBRUARY 2023

I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as dissertation for the degree of Doctor of Philosophy.

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Abstract

The ever-growing population emphasizes the serious need for food sufficiency and drives the attention of research works toward sustainable agriculture to guarantee the production of sufficient food. This is, especially true in today's challenging environment where resources are scarce, and the challengen is to develop solutions that maintain human and nature co-existence without compromising each other. With this, alternative and new technologies for sufficient food production have become an intriguing research focus. However, such production systems are associated with unknown environmental impacts which are needed to be elucidated to come up with more objective measures to mitigate and manage. This is especially relevant because agriculture has been reported as one of the major contributors to greenhouse gas (GHG) emissions.

In South Korea, greenhouse cultivation has increased significantly in the past few decades as indicated by domestic production reaching around 4.8 trillion won or 28% of the national horticulture production. Meanwhile, the livestock industry in South Korea has shown continuous growth reaching approximately 17 billion USD in 2020 or nearly 40.6% of the total agricultural production in the country (MAFR, 2021). Likewise, it shares 47.9% of the annual livestock production followed by the cattle industry (32.6%), and the chicken industry (13.1%). GHG emission is highest in livestock, especially those coming from enteric fermentation (48%) and manure application and management (22.4%). With the continuing growth of both horticulture and livestock industries, the resources for land, water, and energy has become scarce and contributed severe impacts on air, water, and soil quality, mainly because of the GHG emissions. From this alarming impact, it is important to conduct an environmental assessment of agriculture-related activities to assess and analyse emission and the influence it brings to the soil, water, and air.

Study 1 focused on the impact assessment of the heating and cooling systems of agricultural buildings particularly greenhouses producing mango with the use of Life Cycle Assessment (LCA) integrated with building energy simulation (BES). Specifically, the study aimed to identify the current integration approaches used to combine BES and LCA results to assess the environmental impact of different heating systems, such as absorption heat pump (AHP) using energy from thermal effluent, electricity powered heat pump, and kerosene-powered boilers used in a conventional multi-span Korean greenhouse. Results revealed that the environmental impact of the kerosene-powered boiler is largest in terms of the acidification potential (AP), global warming potential (GWP), and Eutrophication Potential (EP) of 1.15 x 100 kg SO_2-eq, 1.13 x 102 kg CO_2-eq, and 1.62 x 10-1 kg PO_4-eq, respectively. The main contributor for greenhouse gas emission was caused by the type, amount, and source of energy used to heat the greenhouse, which contributed to a maximum of 86.59% for energy from thermal effluent, 96.69% for electricity-powered heat pump, and a maximum of 96.47% for the kerosene powered heat pump, depending on the type of greenhouse gas being considered.

Study 2 aimed to review and conduct an impact analysis of various odour and GHG mitigation techniques used for the production of pigs. The review showed that three major phases have the highest impact on livestock emissions that include feed management, housing management, and manure storage and processing. The result analysis showed no pattern for each mitigation method, but it was identified that the frequency and method of manure removal contributed to the highest GWP, AP, and EP considered in the analysis. Similarly, in the case of manure management, solid manure was found to emit higher GHG compared to liquid slurry. These findings match with the result of scenario analysis that showed that utilizing the manure as feedstock for an anaerobic digester has an average of 28.01 % lower acidification potential for all the considered livestock animals.

Study 3 aimed to use field-measured olfactometric data in an LCA study. Traditionally, LCA usually excludes the analysis of livestock odour due to its complexity in terms of spatial and temporal scales. In this study, a pathway was developed to incorporate the odour concentration emitted from the pig facility.

Keyword: Greenhouse heating system, life cycle assessment, livestock, odour, pig

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Nomenclature

AD	Anaerobic digester
AHP	Absorption heat pump
ALO	Agricultural land occupation
AP	Acidification potential
BES	Building energy simulation
CED	Cumulative energy demand
CH_4	Methane
CML	Centrum voor milieukunde leiden
CO_2-eq	Carbon dioxide equivalent
COP	Energy efficiency
EP	Eutrophication potential
FAO	Food and agriculture organization
FD	Fossil depletion
FE	Freshwater ecotoxicity
FP	Farmers’ practice
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
Gt CO_2-eq	Billion tonnes carbon dioxide equivalent
HTm	Human toxicity
ISO	International organization for standardization

ISSM	Integrated soil-crop system management
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LO	Landuse
MD	Metal depletion
ME	Marine eutrophication
N_2O	Nitrous oxides
NO	Nitrous monoxide
NO_x	Nitrogen oxides
NPV	Net present value
PMF	Particulate matter formation
PO_4	Phosphate
POF	Photochemical oxidant formation
SO_2	Sulphur dioxide
SR	Soil remediation
TA	Terrestrial acidification
TE	Terrestrial ecotoxicity
TOE	Tonnes of oil equivalent
ULO	Urban land occupation

Abbreviations

Q_i	total heat gain of zone I (kJ)
Q_{surf}	convective heat gain or loss from surfaces (kJ hr^{-1})
Q_{inf}	heat gain or loss by infiltration (kJ hr^{-1})
Q_{vent}	heat gain or loss by ventilation (kJ hr^{-1})
Q_{ishcci}	absorbed solar radiation on all internal shading devices of zone and directly transferred as a convective gain to the internal air (kJ hr^{-1})
Q_{solar}	fraction of solar radiation entering a zone (kJ hr^{-1})
$Q_{(g,c)}$	internal convective gains (kJ hr^{-1})
Q_{cplg}	heat gain or loss due to connective air flow from adjacent zone (kJ hr^{-1})
NPV	Net present Value
R_t	net cash inflow during a single period
i	interest rate
t	Number of period

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Chapter 1. Introduction

1.1. Study Background

The interest to support sustainable agriculture has continuously increased in both developed and developing regions. The most notable challenge for sustainable agriculture at present is to produce a sufficient amount of food to meet the demand of the increasing population. Thus, to pursue sustainable agriculture, it is important to create and maintain a productive and favourable condition where both humans and nature can co-exist in harmony without compromising the ability to support the current and future generations.

The adoption of smarter and more efficient agriculture technologies to deliver sufficient high-quality products becomes a new trend. This progress corresponds to the introduction of new technologies to maximize production where environmental impact is unknown. According to the latest dataset from FAOSTAT (2020), agriculture is one of the main contributors to environmental pollution contributing to about 9.3 billion tonnes of carbon dioxide equivalent (Gt CO_2-eq) wherein 5.3 Gt CO_2-eq of which was released from agricultural activities of crops and livestock production (Figure 1-1). Consequently, the regional trend for emissions in agriculture is highly dominant in Asia which is known to have the highest average contribution (45%) followed by America (24.1%) and Africa (14.3%) from the year 2000 to 2020 (Figure 1-2).

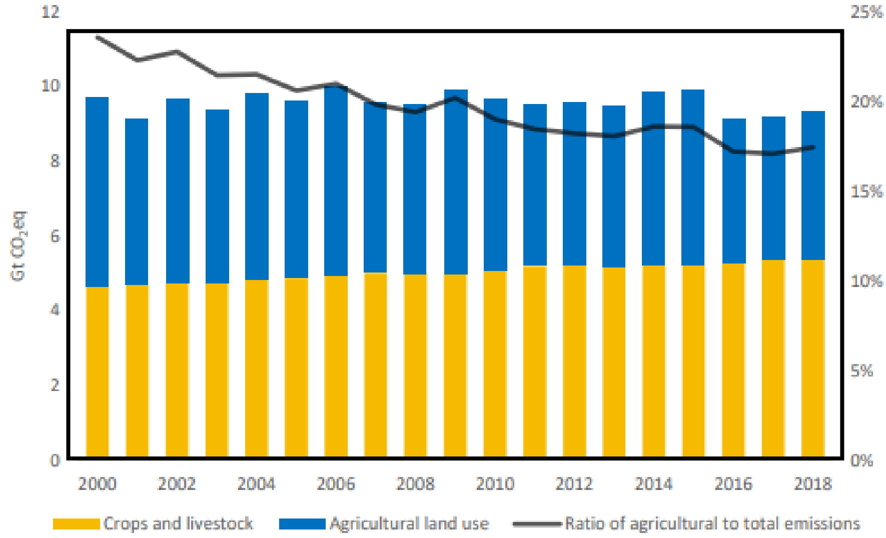


Figure 1-1 Annual GHG emission from agriculture (FAOSTAT, 2020)

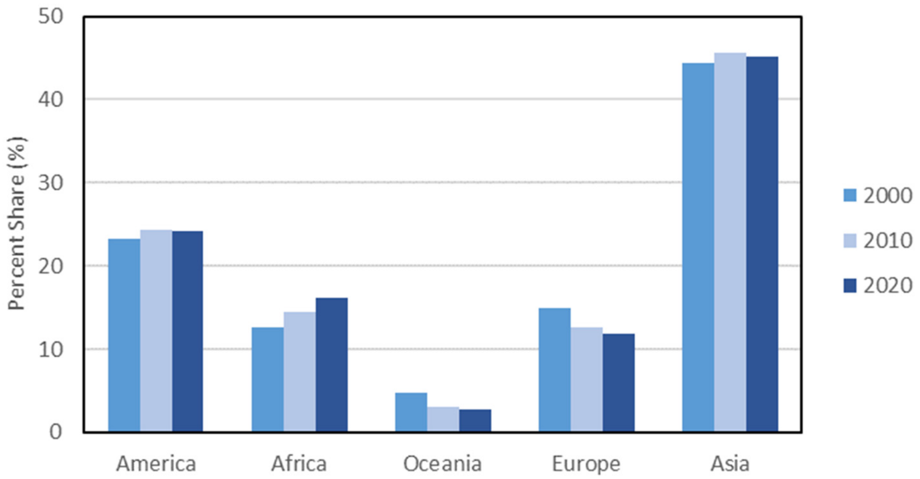


Figure 1-2 Regional GHG emission from agriculture for the past 20 years (FAOSTAT, 2020)

A large percentage of agriculture emissions is carbon dioxide (CO_2) which makes up most greenhouse gas emissions and is the primary driver of global climate change. It is widely recognised that to avoid the worst impacts of climate change, the world needs to urgently reduce emissions. Hence, environmental assessment of agriculture-related activities such as those in greenhouse and livestock production plays a vital role in assessing and analysing the total emission from agriculture that affects the soil, water, and air quality.

Greenhouse cultivation in South Korea has increased dramatically in recent years. The record from the Ministry of Agriculture Food and Rural Affairs (MFAR, 2021) states that the greenhouse industry in South Korea has a domestic production of 4.9 trillion won, which corresponds to 28.9% of the total national production in horticulture. Moreover, greenhouse horticulture in the country become sophisticated with the integration of complex information and communication technologies (ICT) convergence smart farms through the creation of environment-control devices and automation systems. The drawback of most greenhouses nowadays is being dependent on fossil-based energy. With this, the interest in new and alternative energy sources that can replace the use of fossil fuels has become a domestic trend. In addition, the country has also attempted to utilise renewable energy for heating and cooling systems in greenhouse facilities. To maintain optimum growing environments for the crop, around 30% of greenhouses utilise cooling and heating systems. Therefore, some attempts have been made to utilise waterpower, wind power, geothermal heat, and others. Furthermore, several published articles emphasized that the highest energy consumption and the largest source of environmental impact for greenhouse crop production are accounted from the heating and cooling systems (Arpa et al., 2016; Shen et al., 2018; Zhang et al., 2015). To date information related to the environmental impact assessment (carbon emissions, water pollution, soil pollution) of heating and cooling systems in greenhouses is very limited since most available published papers relate to heating and cooling systems to residential, commercial or industrial buildings and other applications (Beccali et al., 2012; Fatemeh et al., 2019; Koroneos & Tsarouhis, 2012).

The livestock industry has long been an important part of agriculture and its production has intensively increased to meet the exponentially growing demand of the population. For the past years, the livestock industry continuously competes for scarce resources such as land, water, and energy (De Vries and De Boer, 2010). This competition for resources, however, resulted in a severe impact on air, water, and soil quality because of the unwanted gas emissions (Thornton 2010). According to the Food and Agriculture Organization (FAO, 2017), for example, the world's livestock industry is responsible for 14.5% of the global emission of greenhouse gases. This contribution (4.5%) is mainly caused by the emission of carbon dioxide (CO_2) from manure and the emission of nitrous oxide from the application of fertilizer (De Vries and De Boer, 2010). Figure 1-3 illustrates that among all the agricultural activities, emissions from livestock contributed the highest in terms of GHG emissions, especially those coming from enteric fermentation (48%) and manure application and management (22.4%). Whereas, in South Korea, the total production of livestock has shown continuous growth reaching approximately 20.3 billion USD in 2021, which amounts to nearly 40.6% of the total agricultural production in the country (MAFR, 2021). The same reference also indicated that the pig industry has a percent share of 47.9% of the annual livestock production, followed by the cattle industry (32.6%), and the chicken industry (13.1%). As the country participates in the international community's effort for carbon emission reduction to respond to global warming, the country is estimated to accumulate up to 21.19 million tonnes of carbon emission where about 2.9% (9.41 million tonnes equivalent) were accounted for agricultural production. According to the latest report published by the Ministry of Environment (ME, 2021) ,about 44.3% of the emission from agricultural production originated from the livestock industry. This indicates that the livestock sector is the main source of greenhouse gas emissions in the agricultural industry.

The Life Cycle Assessment (LCA) is a standardized methodology used to estimate environmental impacts and qualitatively understand the distribution of resource demand within the "upstream" or upstream of a certain boundary system. It is a tool known to environmentally compare different kinds of commodities that are commercially available to support interventions or informed consumption choices.

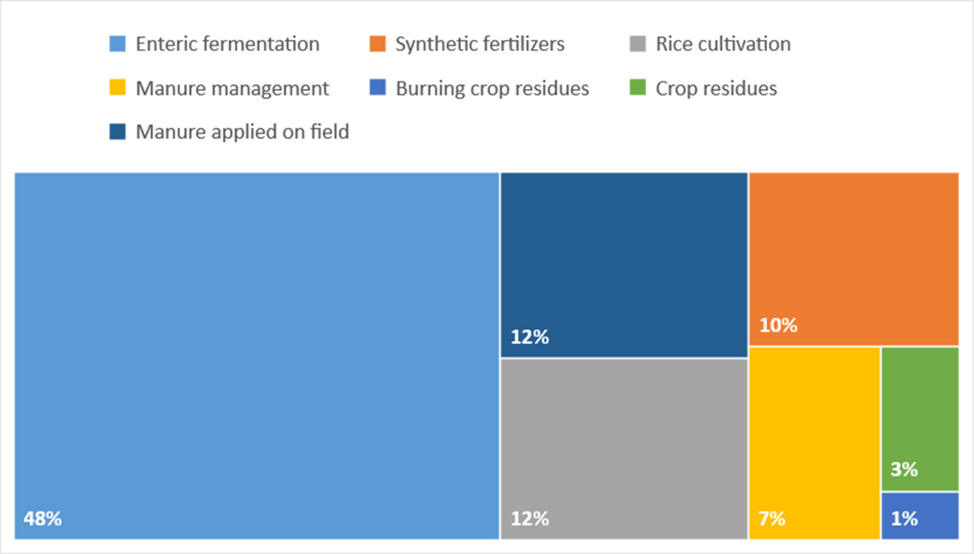


Figure 1-3 Distribution of emission from agriculture (FAOSTAT, 2022)

Bhatt and Abbassi (2021) emphasized that LCA in the agricultural industry is complicated as the emissions intensities from both greenhouse and livestock are not easy to quantify by the generic datasets that are currently available. In addition, a good assessment method requires a detailed quantification of the energy, and resource use during the entire life span. This process requires skills and a large amount of time to accurately estimate the amount of environmental burden manually. Fortunately, a commercial tool known for environmental modelling reduces all the struggles in doing LCA of various products and activities.

With increased consumption and production, understanding the livestock supply chains' impacts on the environment is very critical to ensure sustainability in agriculture (McAuliffe et al., 2016). However, the application of LCA has its limitation in terms of its application to both the horticulture and livestock industries.

Thus, the integration of other methods and tools to improve the assessment method of emission is very important.

1.2. Purpose of Research

LCA is a potent tool used to calculate the environmental impact caused by the different processes involved in the entire life of certain commodities. During the assessment, the materials and energy flow used during the different product phases (raw material extraction, construction, operation, disposal, and so on) are evaluated in detail. According to Hendricks (2012), LCA can identify the environmental hotspot for different environmental impacts allowing the conservation of energy, carbon, and water. The application of LCA has become widespread in the field of food and agriculture in recent years such as in the livestock industry, crop production, and many more. However, the most common type of reported agriculture-related LCA studies tends to be generic, i.e following the conventional methodology for environmental assessment. Thus, the purpose of this study was to supplement the limitation of LCA methodology in the agriculture industry through the introduction of new integration methods and LCA pathways. Therefore, in this manuscript, three different chapters were studied to formulate a new approach to accurately estimate the environmental impact of horticulture and livestock. Further, this paper identified the options for the use of LCA which could be used by industry or government regulators.

This study is divided into five chapters. The overall background and the purpose of this research work are explained in Chapter 1. Whereas, Chapter 2 presents a comprehensive review of literature related to life cycle assessment applied to horticulture and livestock industries to build the foundation of the content of the research. The reviewed articles were used to identify the limitations available in the current LCA methodologies applied in agriculture, specifically in the horticulture and livestock industries.

Chapter 3 focuses on the application of LCA to horticulture. Specifically, as most LCA-related research studies have focused on the overall environmental impact of the entire system without considering the energy load of the agricultural buildings, integrating the LCA tool with other design tools such as the building energy simulation (BES) to identify environmental hotspots and mitigation options becomes possible during the design process. In this chapter, an integrated approach is used to combine BES and LCA results to assess the environmental impact of different heating systems such as absorption heat pump (AHP) using energy from thermal effluent, electricity-powered heat pump, and kerosene-powered boilers used in a conventional multi-span Korean greenhouse.

Chapter 4 discusses the application of LCA to the livestock industry such as the impact analysis of various odour and GHG mitigation techniques used for the production of cattle, pigs, and poultry. Through this study, it was also identified that feed management, housing management, and manure storage were the main sources of GHG emissions in livestock facilities. Thus, the environmental impact of widely used GHG mitigation techniques under the above-mentioned categories was evaluated and analysed.

Chapter 5 offers an approach to incorporate livestock emission in the classical LCA framework. This chapter aims to examine whether the installation of odour reduction facilities at pig buildings will result in net environmental benefits or will only transfer additional environmental problems. Here, an actual application of odour pathways to identify odourous impact potential was employed through side-by-side comparison of “current” and “alternative” scenario modelling. Firstly, a target experimental pig farm was made where the measurement of internal odour concentration was selected. The collected odourous samples were evaluated using the standard olfactometry method (EN 13725).

Chapter 2. Literature review

2.1. Fundamentals of Life Cycle Assessment (LCA)

LCA is a generally accepted method to evaluate the environmental impact during the entire life cycle of a certain product (Guinée et al., 2002). An established LCA method enables the identification of environmental "hot spots" within the boundary system to prioritize areas where reductions can be made and is capable of comparing alternative products or processes (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010). According to the International Organization for Standardization (ISO), an LCA is known as a systematic process that involves various phases: goal and scope, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation (ISO 14040, 2006). The components of LCA are briefly illustrated in Figure 2-1.

The goal and scope definition involves defining system boundaries and functional unit (FU). Under this phase, the audience and how the study should be executed must be identified (McAuliffe et al., 2016). LCI on the other hand, is concerned with the formulation and construction inventory that has relevant inputs and outputs related to the defined system. Especially, the mass and energy flow throughout the systems were quantified and turned into consumption and emission flows which are referred to as "Inventory data". This phase of LCA was known to be the most laborious phase of the entire process. The third stage involves LCIA where the data from the LCI is applied to different impact categories (i.e. global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and so on). Finally, the last phase known as the interpretation phase tests model assumptions and uncertainty using sensitivity and uncertainty analyses. Under the final steps, researchers will be able to identify and recommend a solution to reduce the environmental impact.

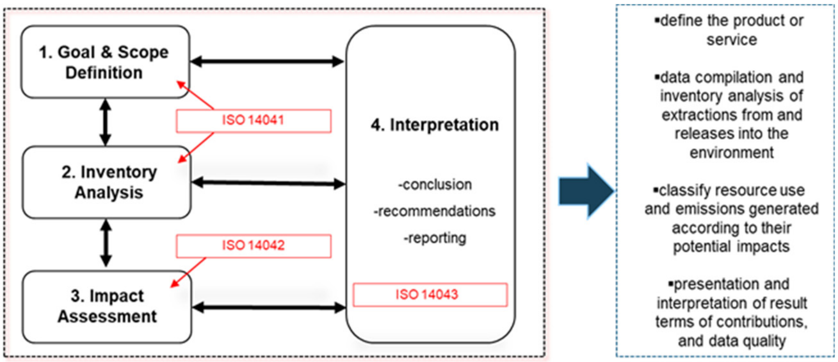


Figure 2-1 Fundamental component of LCA

2.1.1 Commonly used LCA boundary systems in agriculture

System boundaries in LCA define the processes to be analysed regarding material and energy flows and emissions (FAO, 2018). However, as emphasized by Li et al., (2014), it is very difficult to completely set accurate boundary systems in LCA because the acceptable standard is not yet available. At present, the LCA provide two categories for setting the system boundaries: consequential and attributional. The consequential LCA is known to provide boundaries that tackle all activities that contribute to environmental burdens. It refers to the activities that are within or outside the cradle-to-grave of the product that is being investigated. Allocation problems may be avoided by expanding the system boundaries to include affected processes outside the cradle-to-grave system. In contrast, for attributional LCA, allocation (partitioning) is often considered and describes how environmentally relevant flows will change in response to possible decisions (Finnveden et al., 2009). Listed in Table 2-1 are the corresponding boundary systems. The main boundary systems that are widely utilised in LCA research includes: cradle-to-grave, cradle-to-gate, or gate-to-gate.

Cradle-to-grave LCA is a methodology where all the effects are linked to all the phases of the production from obtaining raw materials to disposal or recycling of all the materials. This system analysed the full cycle of the product to determine the full carbon footprint of the system. In the case of LCA for livestock, this system was used for studies that constructed or created technologies for mitigating GHG and odour. For instance, Conti et al., (2021) evaluated the environmental effect of using wet scrubber for ammonia and odour reduction of the pig building facility. De Vries et al., (2012), Abdesalam et al., (2019), and Duan et al., (2020) used the cradle-to-grave approach to evaluate the impact of using solid/liquid manure separators and anaerobic digestion systems to manage the GHG and odour emission caused by manure storage and processing

Cradle-to-gate LCA, on the other hand, covers all the activities involved on the entire life cycle of the product being studied which include resource extraction to the gate of the conversion, storage, pre-processing, or distribution plant, involving the life cycle stages from biomass cultivation, harvesting, collection, pre-treatment, transportation, storage, and conversion.

Lastly, the gate-to-gate LCA focussed on a very small part of the product production chain. For example, the effect of ammonia reducing scrubber system. The gate-to-gate approach on this is the utilisation of various type of scrubber such as wet scrubber, air scrubber, etc.

Table 2-1. Widely used LCA boundary systems in Agriculture

Category	Boundary Systems	Reference
Horticulture		
Production system in general		
	Cradle-to-farm gate	Fan et al., (2022); Chen et al., (2022); Shrestha et al., (2022)
Energy footprint	Cradle-to-farm gate	Abdelkader et al (2022)
Growing medium	Cradle-to-grave	Legua et al., (2021); Hernández et al., (2022)
Scale of production	Cradle-to-grave	Stone et al., (2021)
Vicinity of production (local or imported)	Cradle-to-market	Payen et al., (2015)
Management practices	Cradle-to-market	Zhen et al., (2020)
Irrigation system	Cradle-to packing	Maham et al., (2020)
Production seasons	Cradle-to-farm gate	Naseer et al., (2022)
Energy consumption	Cradle-to-farm gate	Ntinas et al., (2017)
	Gate-to-gate	Jafrodi et al., (2022)
Livestock		
Feeding Management		
	cradle-to-grave	Abromaitis et al., (2011); Stasiulaitiene et al., (2013); Kadam (2002); Kaoula and Bouchair (2018)
	cradle-to-gate	Gonzales-Garcia et al., (2014); Noya et al., (2015); Dourmad et al., (2014)
	gate-to-gate	Alfonsin et al.,(2015); Gomez-Guervo et al., (2016)
Housing Management		
	cradle-to-grave	Abromaitis et al., (2011); Stasiulaitiene et al., (2013); Kadam (2002); Kaoula and Bouchair (2018)
	cradle-to-gate	
	gate-to-gate	De Vries et al., (2012a); De vries et al., (2012b); De Vries and Melse (2017)
Manure storage and processing		
	cradle-to-grave	Luo et al (2014); ten Hoeve et al., (2013)
	cradle-to- gate	Alfonsin et al., (2015); Gomez-Guervo et al., (2016)
	gate-to-gate	Gabriel et al., (2020); Cano et al., (2020)

2.1.2 Life cycle impact assessments (LCIA)

A comprehensive list of impact categories established by five international working groups including the Leiden List, Nordic List, SEDAC List, EDIP list, and ISO 14047 list was enumerated by Stranddorf et al., (2005). Generally, the impact categories that were included in LCIA are global warming, acidification, eutrophication, depletion of stratospheric ozone, photo-oxidant formation, and many more depending on the LCIA method being employed. However, the selection of impact categories depends mainly on the purpose of LCA research being conducted and based on the type of LCA application. GWP is a global effect that resulted in an increase in the earth's temperature or also known as the "greenhouse effect". In LCA, the global warming impact category expressed the effect of carbon dioxide in the atmosphere and is expressed in CO_2-eq at time horizons of 20, 100, or 500 years. The AP (SO_2-eq) on the other hand, is known to have a regional effect and is caused by the release of protons in terrestrial or aquatic ecosystems. The main known contributors of AP include an oxide of sulphur, nitrogen oxides, and ammonia. EP which is expressed in PO_4-eq is related to the enrichment of nitrogen and phosphorus which promotes excessive development of algae which later decreases oxygen rates leading to contamination of groundwater.

To quantitatively assess the environmental impacts, all the selected inventory data must be converted into a potential environmental impact using the characterisation factors, whereas, all the data inventory is multiplied by the specific factor to get the impact expressed in equivalent units.

Table 2-2. Overview LCA studies in agriculture

Author	Country	Environmental Impact (LCIA)	Categories
Horticulture			
Packaging			
Ríos-Fuentes et al., (2022)	Mexico	Recipe v1.1 midpoint, endpoint and single score categories	OD, TA, FE, ME, HT, POF, PMF, TE, FE, Et, IR, ALO, ULO, NLT, WD, MD, FD
Management practices in greenhouse (Conventional, organic, community-supported)			
Zhen et al., (2020)	China	Mid-point	ED, WD, AP, AEP, GWP, STP, ATP, HTP
Rufí-Salís et al., (2020) (Integrated rooftop garden structure)	Barcelona	Recipe midpoint	TA, FE, ME, FDP, ET
Irrigation			
Maham et al., (2020)	Canada	Recipe midpoint/damage	NP, AP, PP
Production Seasons			
Naseer et al., (2022)	Norway	Recipe 2016 Midpoint (H) V1.04	GW, OzHH, OzTE, TA, FwEu, Meu, TEco, FwEco, MEco, LU, MiRes, FRes
Rufí-Salís et al., (2020)	Barcelona	Recipe midpoint	CC, TA, FE, ME, FDP, ET
Payen et al., (2015) Off season production of tomato	France	Recipe at both midpoint and endpoint	CC, NREU (non-renewable enrgy use), TA, EP, Ecotoxicity
Crop Combinations			
Rufí-Salís et al., (2020)	Barcelona	Recipe midpoint	CC, TA, FE, ME, FDP, ET
Livestock			
Manure			
Prospasponga et al., (2010)	Denmark	Stepwise2006	
De Vries et al., (2012)	Netherlands	Recipe midpoint v.1.04	GWP, TA, ME, PMF, FFD
De Vries et al., (2012)	Netherlands	Recipe midpoint v.1.04	
Brockmann et al., (2014)	France	Recipe v1.07	
Luo et al., (2014)	China	CML 2	GWP, AP, EP

De Vries et al., (2015)	Netherlands	Recipe v1.04	
Corbala-Robles et al., (2018)	Belgium	Recipe V1.12	GWP, OMF, OOF, HTm TE, FE, ME, TA, ALO, ULO, FD
Makara et al., (2019)	Poland	ILCD 2011	GWP, OD, HT, *HT2, PMF, IR H, IR E, POF, AD, TE, DE, FE, ME, FET, LO, WRD, FD
Housing			
Dourmad et al., (2014)	Germany	CML2 Baseline	GWP, EP, AP, CED, LO
De Vries and Melse(2017)	Netherlands	Recipe v1.04	GWP, TA, ME, PMF, FFD
García-Gudiño et al., (2019)	Sweden	CML Baseline	GWP, *AC, EP, CED, LO
Feeds			
Garcia-Launay et al., (2014)	France	CML2 baseline	GWP, AP, EP, CED, TE, LO
Monteiro et al., (2016)	Brazil	CML 2001	GWP, AP, EP, CED, TE, LO
Esteves et al., (2021)	Brazil	CML 2001	GWP, AP, EP, CED, TE, LO

GWP: Global Warming Potential: TA: Terrestrial acidification; ME: Marine Eutrophication; CED: Cumulative Energy Demand; LO: Landuse; PMF: Particulate matter formation; HTm: Human toxicity; TE: Terrestrial ecotoxicity: FD: Fossil depletion; MD: Metal Depletion; FE: Freshwater ecotoxicity; ALO: Agricultural land occupation; ULO: Urban land occupation; POF: Photochemical oxidant formation; OD: Ozone depletion; MEt: Marine ecotoxicity; IR: Ionising radiation; NLT: Natural land transportation; WD: Water depletion,

2.2. Domestic and International Trends of LCA

2.2.1 Environmental impact affecting horticulture and livestock industry

It was known that the agriculture industry is one of the sectors responsible for CO_2 and other GHG emissions that were generated within the farm gate by crops, livestock, and other activities such as the conversion of natural ecosystems. These emissions often cause global warming and pollution of air, water, and soil.

Global warming can be simply explained when sun rays penetrate the atmosphere in which heat is absorbed and reflected off the earth's surface cannot escape back into space. Global warming can be further understood by considering the participation of greenhouse gases (GHGs). The UEPA (2022) on its recent update reported a total GHGs emissions of 5,981 million metric tonnes of CO_2-eq which are contributed by CO_2 (79%), CH_4 (11%), N_2O (7%) and Fluorinated gases (3%). These gases trap heat in the atmosphere by absorbing it and they seem to act as blanket or envelop insulation to the Earth. The phenomenon in which the energy is trapped or inhibited from escaping into space would result to global warming (GW). The sources of GHGs are mainly from human activities with burning fossil fuels for electricity, heat, and transportation being the highest contributors. UEPA (2022) reported that at least 27% of the GHGs was generated from transportation activities, followed by electric power (25%), industry (24%), commercial and residential (13%), and agriculture (11%). Previously, impact assessmentd have been conducted in various fields to assess possible global warming generated from certain processes. Results of assessments are useful to perform effective measures to reduce global warming potential (GWP). For instance, Li et al., (2022) recommended the reduction of fertilizer usage, having a high GWP, by farmers as a result of the impact assessment conducted in peach production. Likewise, Giusti et al., (2022) provided an objective recommendation to minimize fertilizer rate as it is one of the most impactful parts of the production process. Clark et al., (2022) found that growing strawberries under high tunnels with combined aluminium and plastic covering had high GWP.

The increase in the concentration of carbon dioxide does not only directly affect GW but can also have an adverse impact on the ocean chemistry as CO_2 readily dissolves into H_2O. The burning of fossil fuels releases acid-forming compounds, CO_2, and H_2O, that can promote acidification by directly mixing into coastal waters or by means of acid rain. The acidification potential (PW) assessments related to agricultural activities were well explored in the literature with notable recommendations to farmers. Temizyurek-Arslan et al., (2022) assessed the impacts of energy efficiency of organic and conventional vegetable production and found out that irrigation was the most influential as a result of the use of electricity by water pumps and useful recommendations to farmers such as the use of surface water, and mineral fertilizer were drawn to reduce AP by 25%.

Eutrophication is the excessive nutrient accumulation and enrichment in natural waters which leads to increased production of algae and macrophytes. Evidence of eutrophication is manifested in harmful algal blooms, dead zones, and fish kills. The eutrophication potential (EP) is also an important component of the environmental impact assessment presented in the literature. Yu et al., (2022) assessed, through LCA, the liquid digestate application against quantitative fertilizer on the agri-food chain with significant findings that 25% digestate replacement was favourable with 67% decrease in EP compared to the current practice.

2.2.2 International policies and goals

The CO_2 and GHG emissions have affected the environment severely causing an increase in global warming. Presently, various policies and goals have been implemented with an attempt to reduce the amount of GHG emission in the atmosphere. For instance, the United Nations of Climate Action emphasized the need to achieve a liveable climate which embodies a net-zero program that tackles the cutting of greenhouse gas emissions to as close to zero as possible. Whereas, the Paris Agreement of the world leaders' at the UN Climate Change Conference (COP21) have set long-term goals to guide all nations on climate change and its negative impacts. One of its goals is to substantially reduce global greenhouse gas emissions to limit the global temperature increase in this century to 2 °C while pursuing efforts to limit the increase even further to 1.5 degrees. To limit the rise in temperature to no more than 1.5 °C, emissions need to be reduced by 45% by 2030 and reach net zero by 2050. Specifically, according to the Intergovernmental Panel on Climate Change (IPCC), in order to reduce the atmospheric temperature by 2 °C, carbon dioxide (CO_2) emissions and other greenhouse gases (GHGs) must be decreased by 50% from the 1990 record. More importantly, an urgent call was made for developed countries to reduce more – between 80% and 95% by 2050 and advanced developing countries with large emissions such as China to slow down the emission growth.

In 2021, the global greenhouse gas emissions including land-use change and forestry (LUUCF) was estimated at 52.8 $GtCO_2e$. The top seven countries emitters were China, the United States of America, India, the European Union, Indonesia, the Russian Federation, and Brazil accounted for about half of global greenhouse gas emissions in 2020 (Figure 2-2).

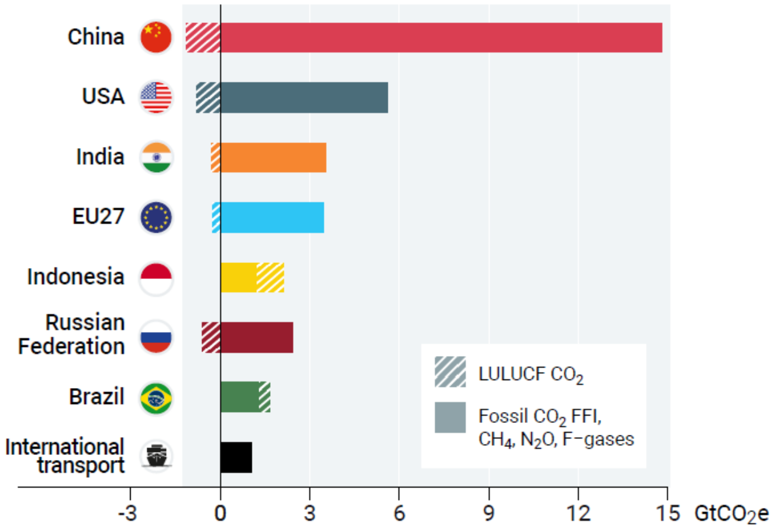


Figure 2-2 Total and per capita GHG emissions of major emitters in 2020, including inventory-based LULUCF (Adopted from: UNEP, 2022)

2.2.3 Domestic policies and goals

In South Korea, the total production of livestock has shown continuous growth reaching approximately 20.3 billion USD in 2021, which amounts to nearly 40.6% of the total agricultural production in the country (MAFR, 2021). The same reference also indicated that the pig industry has a percent share of 47.9% of the annual livestock production, followed by the cattle industry (32.6%), and the chicken industry (13.1%). This intensification in production has resulted in a negative impact through an escalation of GHG emissions in the atmosphere. As the government continuously exerts its effort to minimize the emission of GHG by enacting the Act on Low Carbon, Green Growth in 2012. The country also actively participates in the international effort to respond to climate change under the Paris agreement which was mentioned in the above section. Specifically, the country aimed to reduce its GHG emission by 37% by 2030 with its latest recorded emission shown in Table 2-3 (Greenhouse Gas Inventory and Research Center, 2021). Similarly, the Zero-Energy Building Certification that was introduced in 2017 is used to evaluate the energy consumption of building and rate the energy efficiency.

In the case of livestock farming, smart farms that were capable of increasing energy and reducing GHG have been constantly promoted to enhance productivity. Smart farms refers to a farms that are managed with the minimum use of unnecessary inputs such as fuel fertilizer and water by utilizing ICT and renewable energy. In the published report made by the Greenhouse Gas Inventory and Research Centre in 2021, the country have built a total of 1,425 stockbreeding farmhouses and is aimed to increase to 5,750 farms by 2022.

Table 2-3. Progress of GHG reduction Project by year in agriculture (Greenhouse Gas Inventory and Research Centre, 2021)

Category		Year				
	2015	2016	2017	2018	2019	2020
Voluntary GHG Reduction Projects for Agriculture industry (tCO_2-eq)	14,144	16,480	16,547	14,047	11,425	9,738
External Projects in Agricultural Industry(tCO_2-eq)	-	-	3,229	12,413	24,224	24,551
Low-carbon Agricultural and Livestock Goods Certification(tCO_2-eq)	9,154	11,901	25,963	68,455	74,947	77,769

2.3. Application of LCA in the Horticulture Industry

2.3.1 Status of the horticulture industry

The cultivation of horticultural crops under protected agriculture or greenhouse technology assures the production of abundant, cheap, and high-quality products with notable economic returns (Maham et al., 2020). It has been widely adapted especially to provide sufficient and high-quality produce that are safe for human consumption. Greenhouse-based production offers an alternative to open-field agriculture during the winter season to continuously meet the demand, and conducting an assessment on it is important to improve sustainability (Maham et al., 2020). Despite the advantages of cultivating crops under a greenhouse structure, there are still several bottlenecks and major environmental impacts developed that need serious attention for a proper solution to further improve production efficiency (Torrellas et al., 2012). Likewise, open field cultivation requires an urgent need to improve sustainable production by increasing yield at minimized environmental losses to avoid environmental deterioration (Zhen et al., 2020). Various measures have been proven effective at reducing environmental losses but crop yield is compromised (Wang et al., 2020). Vegetables, being an important component of human nutrition (Boeing et al., 2012), should be available in sufficient quantity. Previously, a systematic approach known as integrated soil-crop system management (ISSM) was developed to positively respond to these two aspects by increasing production while lowering environmental losses (Ladha et al., 2016). Specific to cereal production, ISSM improves fertilizer use efficiency, and reduces GHG emissions (Chen et al., 2014).

Fan et al. (2022) views that greenhouse production under a a polluting activity due to high energy consumption (EC), waste generation, and a large amount of materials input. In addition, commercial greenhouses are extensively applied with microclimate controllers such as temperature, chemical fertilizers, and pesticides (Maham et al., 2020). Likewise, the horticultural industry, especially in northern latitude contries like Norway (Naseer et al., 2022), consumes increasing amounts of energy and water that contributes to greenhouse gas emissions and global warming (Ntinas et al., 2017). Conducting environmental impacts for greenhouse production is necessary to accurately identify and quantify which among all the components has the greatest contribution to emission and how to mitigate or minimize the effect globally (Fan et al., 2022).

Types of horticultural management such as integrated soil-crop system management (ISSM), farmers' practice (FP), soil remediation (SR) (Wang et al., 2020), organic agriculture, conventional and community-supported, have also been assessed in various categories (Zhen et al., 2020). Zhen et al., (2020) found that community support had the highest profitability and eco-efficiency with lower environmental impacts. ISSM offered significantly lower N and C footprints by 39% and 30% respectively and a greater yield in pepper (48 t-hac-1) which was 10% higher than the FP and SR (Wang et al., 2020). Irrigation management and fertilization as assessed on organic production of tomato showed that increased irrigation that led to more water consumption had a direct impact on productivity with sharp reduction of environmental impacts.

2.3.2 Studies of greenhouse in LCA

Most greenhouses are constructed to produce high-value crops such as strawberries, tomatoes, and cucumbers. In other countries, greenhouses are also used to grow other products such as flowers and mushrooms. Additionally, common studies were focused on the comparison of conventional greenhouses for the production of tomatoes strawberries, lettuce, pepper, zucchini, melon, etc.

Despite the benefits derived from the efficient use of greenhouses, major environmental impacts still develop and need to be assessed for a proper solution to further improve production efficiency. According to Fan et al., (2022), LCA in horticulture has become vital due to its capabilities to identify environmental impacts and propose potential solutions to alleviate the environmental impact. The demand for the application of LCA in horticulture has increased significantly as indicated by a report generated from the Web of Science (Figure 2-2). It is noted that such a field has become an intriguing research focus starting from the year 2011 when the number of published works on LCA of horticulture numerously increased.

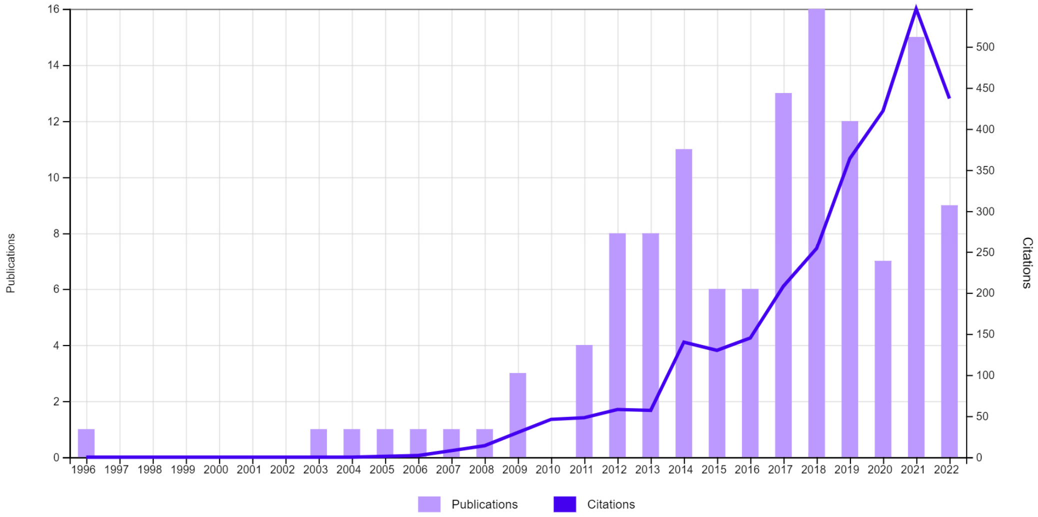


Figure 2-3. Analysed citation report from the Web of Science relating to the number of publications with the application of LCA on horticulture

Figure 2-3 shows the network map of studies concerning LCA as applied to different fields in agriculture assessing environmental impacts and burdens. The network map was created through the VOSviewer software with data from the Web of Science. The keywords, life cycle assessment, horticulture, and greenhouse were used in the Web of Science and data concerning keywords of each published work were exported as tab-delimited file and was used to create the network map in the VOS viewer. Some notable concerns were frequently subjected for LCA in general such as carbon footprint, GHG emissions, sustainability, including horticulture.

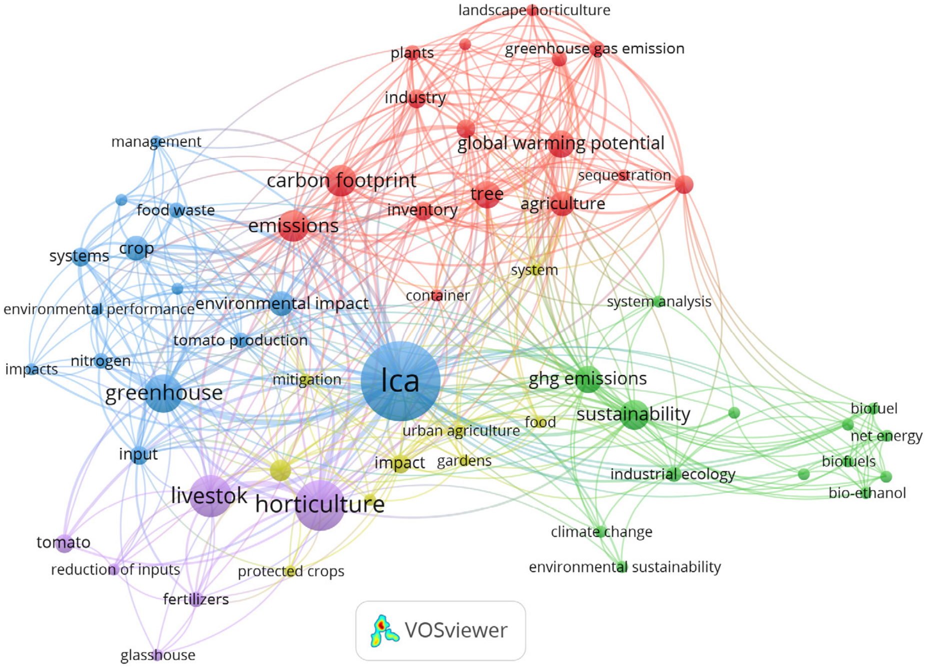


Figure 2-4. Network map of studies concerning various applications of LCA in agriculture with the common impact assessment indicators. The size of the circle indicates the frequency of occurrence of study in LCA.

2.3.3 Energy-related LCA studies for greenhouses

The energy used to produce high-value crops is very important as it has a direct impact on the quality and amount of GHG emissions generated during the entire production. The effective use of energy provides possibilities to increase profitability and agricultural competitiveness in rural communities. Accordingly, the increased use of energy for crop production has led to larger environmental issues including high energy resource (Fatameh et al., 2019; Knoshnevisan et al., 2014).

2.4. Application of LCA in the livestock industry

2.4.1 Livestock emission sources

Summarized in Table 2-3 are the different emission sources from the livestock industry. As can be seen, the largest GHG emitter is from the cattle and small ruminant industry with a combined total emission contribution of 79% followed by pigs (13%), and poultry (8%), respectively. Accordingly, it was identified that the main sources and types of GHG from livestock systems are methane production from animals, carbon dioxide from land use and its changes, and nitrous oxide from manure and slurry management (Moran and Wall, 2010). Especially, field measurements revealed that major sources of GHG such as carbon dioxide, CH_4, NO_2, and others were from cattle and small ruminants. These gases are usually converted to common metric units of CO_2 equivalent (CO_2-eq) that have varying global warming potential (Moran, 2011). In the livestock industry, the emission of carbon dioxide from the livestock has two major sources: exhalation and release from manure (Philippe and Nicks, 2014). Especially, the carbon dioxide exhalation can also be derived from the heat produced corresponding to the energy used by animals for growth, while carbon dioxide in manure is caused by the hydrolysis of urea into ammonia, aerobic fermentation, and aerobic degradation of organic matter. In terms of activities, feed production, and enteric fermentation from ruminants contribute to the highest GHG emission with 45% and 39% of the total GHG from livestock (Grossi et al., 2019), whereas manure management accounted for 10% of GHG emissions.

On the other hand, field experiment results highlighted that the type of housing systems was found to be affected by other gas (ammonia, methane, and hydrogen sulphide) and odour emissions in the livestock. This was confirmed by early studies conducted by Ongink et al., (2001) on different poultry and pig houses and Gallman et al., (2001) on different designs of pig houses. Especially, Ongink et al., (2001) emphasized that limiting the emitting surface of livestock emission below the designed floor systems can considerably reduce both the ammonia and odour emission by 29% and 70% respectively.

Table 2-4. Detailed livestock GHG emission contribution

Sources adopted from: Philippe and Nick, 2014

Industry	GHG emission/year			
	CO_2 emission	CH_4 emission	NO_2 emission	Total emission
Cattle and small ruminants	1236.1 (65%)	2317.3 (91%)	864.2 (78%)	4417.6 (79%)
Pigs	338.9 (18%)	237.3 (9%)	131.1 (12%)	707.3 (13%)
Poultry	332.2 (17%)	-	107.3 (10%)	439.5 (8%)
Total	1907.2		1102.6	5564.4

2.4.2 Carbon footprinting in odour and GHG mitigation for livestock production

As claimed by Lui et al., (2015), the GHG emitted from livestock production mainly include carbon dioxide methane (CH_4), and nitrous oxide (N_2O). Specifically, about 44% of the total GHG were accounted for methane, 29% for nitrous oxide, and 27% for carbon dioxide (IPCC, 2020). These greenhouse gases contribute to the trapping of heat in the Earth’s surface resulting in what others termed as the “greenhouse” effect. In the livestock industry, the total emission from livestock was

7.1 giga tonnes of CO_2-eq per year where about 65% of the emission from agriculture was caused by ruminants such as beef and dairy cattle producing large amounts of methane as part of a digestive process called “enteric fermentation” and is followed by pig and poultry production. In the case of livestock activity, literature found that feed production and management accounted for the largest GHG emission contributing to about 45%, while manure storage adds up to 10% from the total GHG, whereas, feed management dominates GHG emission from most livestock production, and manure storage and processing is the main source for pig production.

Attached in Annex A is the list of literature corresponding to the odour and GHG reduction potential of different mitigating techniques for livestock production with its corresponding abatement efficiency according to feed management, housing design, and manure storage and processing. Among each category, a total of 16 published articles were related to feeding management, 23 were for housing management, and 19 were for manure storage and processing. In the case of feed management, common mitigation technologies were focused on feed manipulation through reduction of crude protein content or addition of amino acids, whereas the studies found related to odour and GHG mitigation revolved mainly into the utilisation of scrubbing systems, biofilters, and biotrickling. Lastly, in the case of manure storage and processing, two common methodologies employed the integration of anaerobic manure systems and the separation of solid and liquid animal feces. Depending on the type of methodology used, the range of the reduction abilities varies depending on the type of gas being studied.

2.4.3 Livestock feed management

Considering the broad network of processes used to develop certain feed types for livestock, it was found that feed production has the highest environmental impact, especially for piggery and poultry (Nguyen et al., 2010). Moreover, additional environmental burdens are added to feed production as more resources and energy are utilised. In the case of environmental impact, it was confirmed that modifying the livestock diet such as low protein diets and addition of amino acids can reduce the amount of emission from the excreted manure. This then resulted to lower odour and gas emissions generated that cause high environmental burden. Moreover, several experimental studies also quantified the reduction of ammonia emissions with low protein diets (Portejoie et al., 2004; Osada et al., 2011). Other researches such as those published by Montes et al., (2013), and Liu et al (2014) proved that proper livestock management will result in reduced GHG (especially methane, carbon dioxide) emissions.

Similarly, mitigation techniques for odour reduction were tested and proven effective in terms of feed modification and management. Ogino et al., (2013) verified that a low protein and conventional feed diet will lessen the global warming potential and acidification by 5%, and eutrophication potential by 28%, while Garcia-Launay et al., (2014) evaluated the environmental implications of incorporating amino acid in pig production and found out that the incorporation of amino acid in diet contents can reduce to 17.8% acidification, 12.5% of eutrophication, and 1.3% for climate change. Liu et al., (2014) and Carter et al., (2012) both showed a significant decrease in odour emission through feed manipulation.

2.4.4 Housing management

Gerber et al., (2013) claimed that the type of structure used to house livestock animals affect the GHG emission as the housing design determines the method used to store and process manure from any kind of livestock. Accordingly, those designs that do not allow daily removal of livestock manure produces a higher amount of both ammonia and methane. For instance, Philippe et al., (2007) revealed that a straw-based litter has higher GHG compared with a concrete slatted floor. Moreover, the type of reduction systems such as biofilter, bio curtain, fogging systems, scrubbers and so on that are installed within the building affects the emission of various GHG and odourous gas. Though the above-mentioned techniques were commonly applicable for pig production, other techniques such as control and maintenance of proper ventilation systems were both applicable for cattle, pig, and poultry production (Chastain, 2004).

Among the collected literature, reduced methane production was dominant when using biofilters, scrubbing systems, and biotrickling (Montes et al., 2013; Ramirez et al., 2012; Veillette et al., 2012; Akdenizand Janni,2012). This implies that the utilisation of mitigation techniques under housing management has a significant effect on GHG emission mainly on methane emission. Based on the literature, it can also be concluded that the odour reduction mitigation potential of technologies can be very high, reaching to about 89% odour reduction depending on the method used.

2.4.5 Manure storage and processing

The current issue of manure management and processing has been a central topic in intensive livestock production due to its potential impact to the environment (Burton and Turner, 2003). As stated by Makara et al., (2019), livestock manure is not only a waste from livestock production but also an important nitrogen and phosphorus-enriched fertilizer that is beneficial for crop production. In fact, a large percentage of countries in Asia and other western continents utilise livestock manure as a natural nutrient additive to grow crops. However, the mishandling of manures creates negative environmental impacts due to the presence of different gas emissions, such as ammonia and GHG (Sommer et al., 2008; Prapaspongsa et al., 2010). Traditionally, livestock manure are used through direct application to agricultural soil to increase the micronutrients for better production. However, this alternative poses higher environmental threats as harmful gases are released. Several field experiments showed that during the livestock manure storage, nitrous oxide, and ammonia emission are highly correlated with nitrogen excretion. Presently, manure management is a central topic in the agronomic and environmental analyses of intensive livestock production systems. Figure 2-4 is an example of manure management setup aimed to reduce GHG emission.

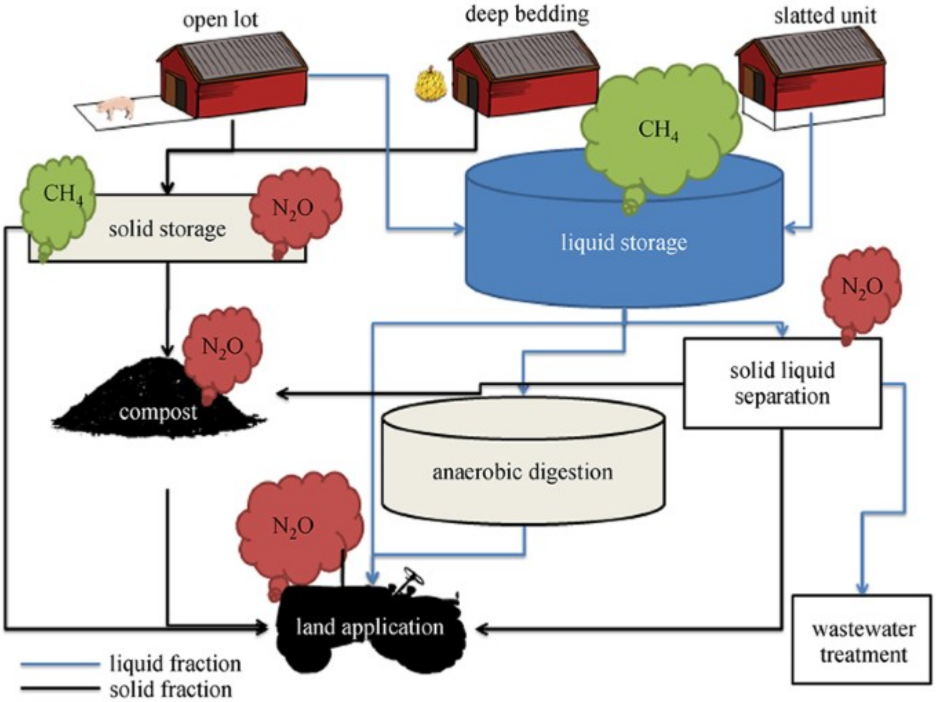


Figure 2-5. Illustration of collection and management options for piggery wastes (Dennehy et al., 2017)

Chapter 3. Integrated BES–LCA for Environmental Assessment of Agricultural Building

3.1. Introduction

Greenhouse production is now becoming the major crop production system in countries with four distinct seasons. Developed countries such as South Korea are becoming more dependent on protective agriculture to support the needs of the growing population. To increase the crop production rate, an optimum environmental condition must be maintained inside the greenhouse through the installation of high-efficiency heating and cooling systems. A heating and cooling system is used to control the stored heat inside the greenhouse buildings, which is very crucial in maintaining the desired air temperature during both extreme seasons. Approximately 85% of greenhouse owners in Korea use fossil fuel as an energy source for heating to maintain the optimum environment inside the greenhouse facilities (Lee & Lee, 2017). Thus, the South Korean government has been strongly promoting alternative ways to reduce the dependence on fossil fuel through the establishment of acts such as the Energy Act and Energy Use Rationalization that promotes the use of renewable energy sources for greenhouse crop production. Evidence of this can be seen in the increase of generated renewable energy from 21,751 thousand tonnes of oil equivalent (TOE) in 1995 to 51,427 thousand TOE in 2019, showing an increase of 57.77% (K.R.E., 2005).

The modern trend in greenhouse energy conservation practice utilised renewable energy to operate the greenhouse. In particular, the wasted heat energy from effluent generated by the thermal or nuclear power plants is being tapped to heat the greenhouse buildings. Thermal effluent refers to the heated seawater used to cool down the engine of the nuclear plant during its operation. During the cooling process, the seawater absorbs a large amount of thermal energy, resulting in a huge amount of energy loss from the power plant. Traditionally, the thermal effluent is 7 °C higher than the average temperature of normal seawater. The current practice of farm owners is to utilise the heat from thermal effluent for heating the greenhouse to maintain the optimum growing environment. As of 2020, a total of 30 units of thermal power plants that were generating a total power of 30,116 MW were strategically placed throughout South Korea, discharging a total of 47.3 billion tonnes of thermal effluent (KEPCO, 2017).

As mentioned in many studies, the highest energy consumption and the largest source of environmental impact for greenhouse crop production is accounted for by its heating and cooling systems (Arpa et al., 2016; Shen et al., 2018; Zhang et al., 2015). However, there have been very few studies related to the environmental impact assessment of heating and cooling systems in greenhouses since published papers usually relate heating and cooling systems to residential, commercial, or industrial buildings and other applications (Beccali et al., 2012, 2016; Fatemeh et al., 2019; Koroneos and Tsarouhis, 2012). The application of environmental impact tools to assess the burden in a conventional greenhouse was also limited in number. The common research studies concerning greenhouse building structures were usually focused on the environmental impact of crops produced in a controlled environment and were usually compared with the traditional crop production practice such as in open field production. Additionally, the understanding of the qualitative amount of gas emission to the atmosphere of different heating and cooling systems for crop production used in the greenhouse is also inadequate. Thus, a tool capable of qualitatively estimating the amount of gas emitted from the greenhouse structure is deemed important.

The Life Cycle Assessment (LCA) is a potent tool used to calculate the environmental impact caused by the different processes involved in the entire life cycle (Bird, 2011). During the assessment, the materials and energy flow used during the different product phases (raw material extraction, construction, operation, disposal, etc.) are evaluated in detail. According to Hendricks (2012), LCA is capable of identifying the environmental hotspot for different environmental impacts allowing the conservation of energy, carbon, and water. The application of LCA has become widespread in the field of food and agriculture in recent years, such as in building construction, (Röck et al., 2018; Rodrigues et al., 2018; Singh et al., 2011), livestock or crop production (Asemhiablie, 2019; Liao et al., 2015; Niero et al., 2015; Tuyet and Nguyen, 2013; H. Zhang et al., 2017). However, LCA also has main drawbacks, including the dependency on quality and availability of data used affecting the accuracy of the assessment result. Moreover, LCA-related studies only consider the actual energy used during a certain period of production only. Considering the life span of the building considered in LCA research studies, information related to energy load for the entire life span may not be available or not properly documented.

This limitation can be solved using the Building Energy Simulation (BES), which is a tool known to estimate the total energy gain and losses through building internal loads such as facility equipment and crops (Ha et al., 2015; Ha, 2018; P. Kumar et al., 2016; Rasheed et al., 2018, 2019). Very often, the BES tool is used to promote energy conservation building design and upgrade building energy code. Despite the increasing numbers of related studies regarding the use of LCA and buildingmodels, at present, current literature for the integrated BES–LCA is poor due to limited research. The integration of the BES and LCA approaches permits improved assessment of different alternatives that can be used in the system. However, the method, gap, and principles of combining these tools at different phases are still not well established. Thus, the final goal of this paper is to discuss the standard practice using LCA and identify the application limitation. Further, it aims to combine BES tools and LCA to facilitate integrated environmental assessment. Lastly, the integrated BES–LCA design approach was used to assess the environmental impact caused by different heating systems in a conventional multi-span Korean greenhouse facility.

3.2. Materials and Methods

3.2.1 Research flow

Figure 3-1 showed the research flow followed for integrating the BES tool with the LCA software. The first steps include the selection of the target experimental greenhouse and case scenarios. The next step is to determine the annual total energy load from the target experimental greenhouse building using BES software. Prior to simulation, the different energy exchange models such as greenhouse, heating and cooling, and crops to predict the annual energy load were modelled and combined. The detailed description of each model including the validation procedures were discussed in Lee et al., (2021). The computed annual energy was converted to annual primary energy use by applying annual average conversion factors. The subsequent step includes the LCA analysis to calculate the environmental impact.

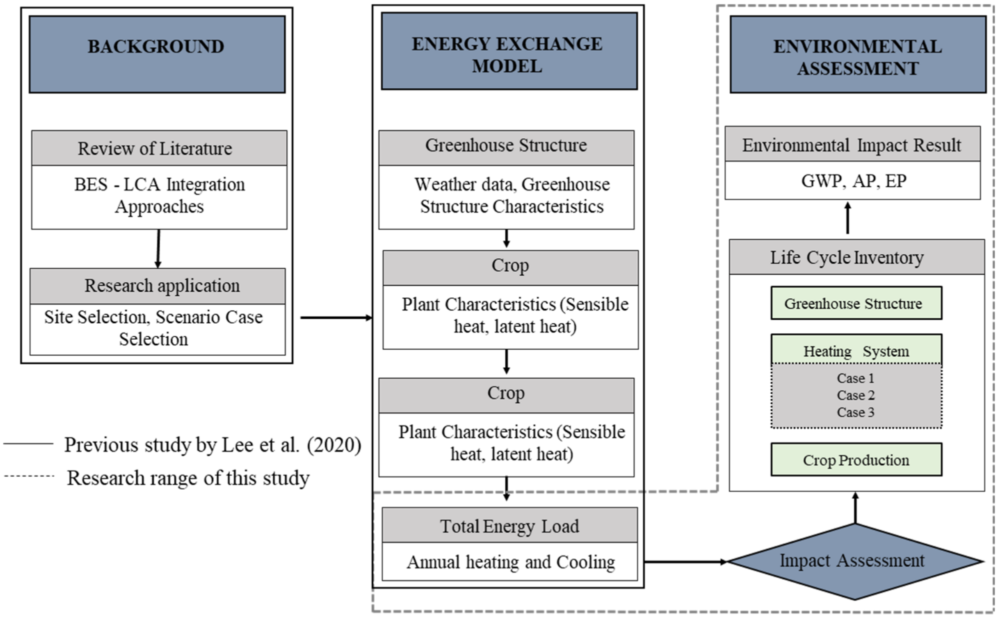


Figure 3-1 Research flow for integrated BES–LCA approach for environmental

assessment of greenhouse heating system

3.2.2 Target experimental greenhouse

The target experimental greenhouse is located in Chungcheongnam-do Province, South Korea. The facility is located in the western part of Boryeong Power Plant. The Boryeong power plant discharges thermal effluent at around 3 billion tonnes per year Lee (2017). The greenhouse grows a fixed number of Irwin mangoes and is intended for research purposes only. The greenhouse is divided into two partitions: plant growth room (762 m^2) and workroom (128 m^2), as shown in Figure 3-2. The plant growth room is occupied by 100 potted (7.68 m^2 spacing) Irwin mango trees pruned at the height of 1.5 m. To equalize the light interception, these mango trees were structured into a globular shape. The optimum growing environment for the mangoes inside the greenhouse was set at 20 °C. However, to bear fruit, the temperature must be lower than the optimum temperature. The experimental greenhouse has a total of 8 spans with a dimension of 34.2 m × 30.0 m (length × width) with a maximum ridge height of 5.7 m, and eave height of 4.5 m (Figure 3-3). The greenhouse was covered with 0.15 mm-thick single layer polyolefin film.

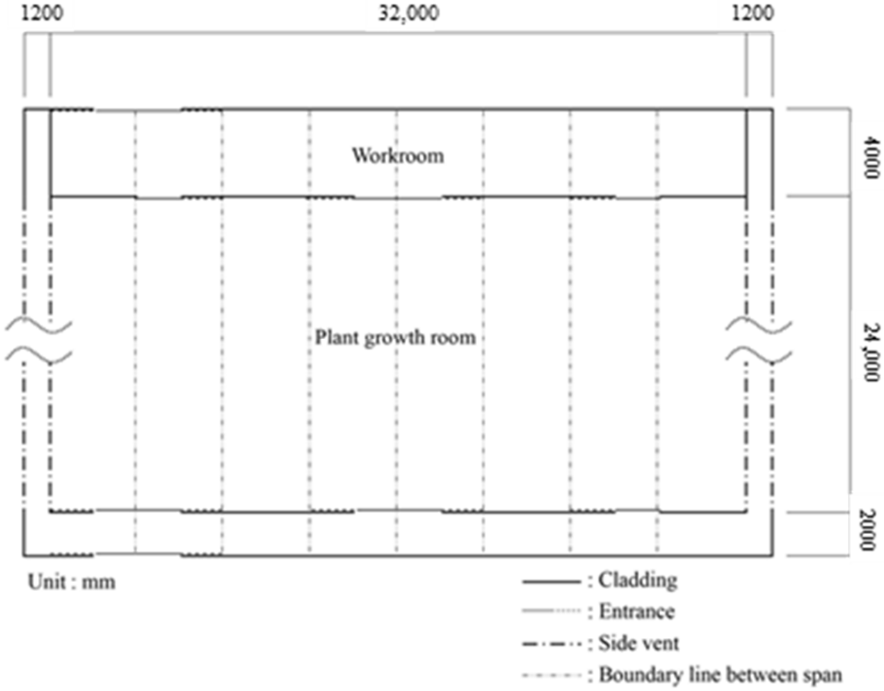


Figure 3-2 Description of the greenhouse floor plan

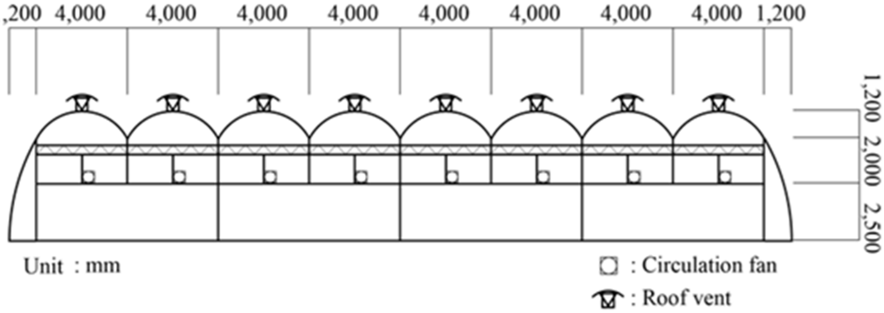


Figure 3-3 Front view of structural characteristics of the target greenhouse, (Reprinted with permission from Lee et al. (2017).

Shown in Figure 3-4 is the different equipment installed inside the greenhouse to facilitate an appropriate growing environmental condition. The structure was equipped with an absorption heat pump system where thermal effluent coming from the Boryeong power plant was used as an energy source for heating the greenhouse. Air ducts and 16 circulation fans with 35 m^3/min per unit capacity were strategically installed throughout the building to allow a uniform distribution of heat during the cold season. As can be seen from the figure, the main air duct (60 cm diameter) is directly attached to the heat pump, and the sub-air duct (40 cm diameter) is located near each tree pot.

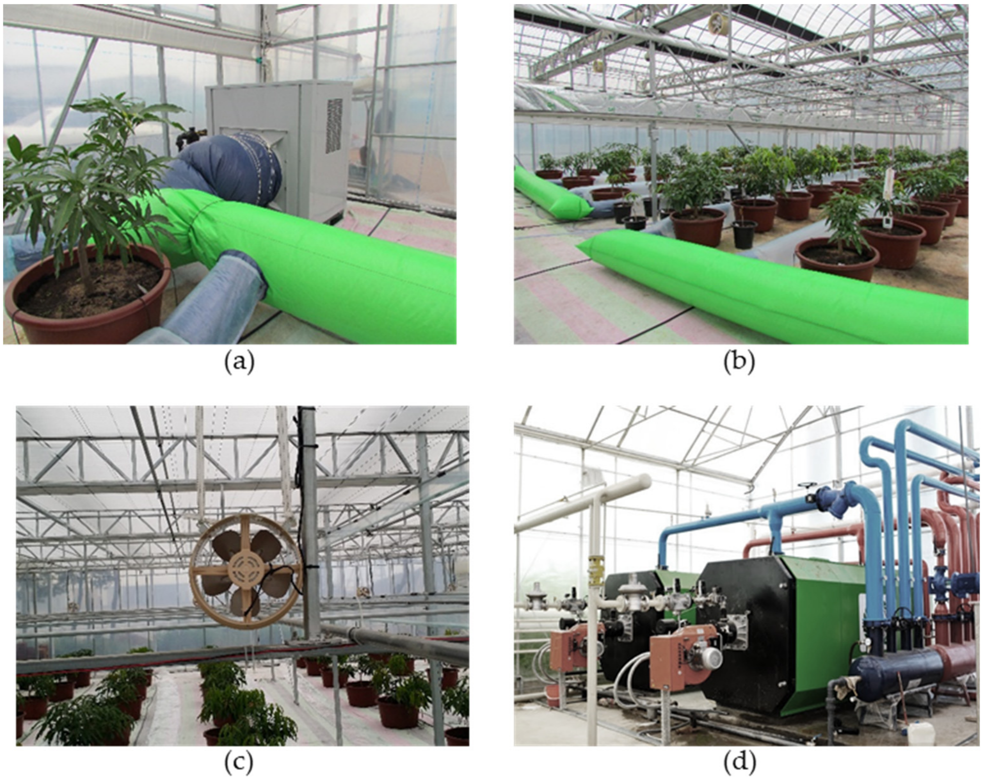


Figure 3-4 Equipment for heat distribution inside the greenhouse (a) main air duct, (b) sub air duct near crop surface, (c) circulation fan, and (d) heat pump unit

3.3. Softwares and Tools

3.3.1 Building total energy demand

In recent years, there was an increase in published researches for utilizing the different BES softwares for greenhouse buildings (Rasheed et al., 2018, 2019; H. Zhang et al., 2017). The TRNSYS software (Version 18, Solar Energy Laboratory, University of Wisconsin-Madison, USA) was used to calculate the energy exchange of the experimental greenhouse. TRNSYS refers to commercially available BES software used to predict the energy load of a building. It is a transient simulation software tool where the small component such as heat systems can be designed individually and then be combined with the multi-zone building complex. It also offers a wide range of source code and the availability of a large component library. Considering this, many energy simulations related studies utilised this software for convenience and accuracy.

Since the experimental greenhouse has thin cladding and plants, the target greenhouse was prone to change in environmental condition. Therefore, the energy loads were calculated using the a dynamic analysis method. As emphasized by Lee et al., (2021), a dynamic model refers to a method of calculating the energy load of the building considering the variable change due to the time factor. To calculate the thermal behaviour in the experimental greenhouse, the domain was divided into several zones using Eq. 3-1:

$$Q_i = Q_{surf} + Q_{inf} + Q_{vent} + Q_{ishcci} + Q_{solar} + Q_{(g,c)} + Q_{cplg} \quad \text{(Eq. 3-1)}$$

where Q_i is the total heat gain of zone I (kJ), Q_{surf} is the convective heat gain or loss from surfaces (kJ hr^{-1}), Q_{inf} is the heat gain or loss by infiltration (kJ hr^{-1}), Q_{vent} is the heat gain or loss by ventilation (kJ hr^{-1}), Q_{ishcci} is the absorbed solar radiation on all internal shading devices of zone and directly transferred as a convective gain to the internal air (kJ hr^{-1}), Q_{solar} is the fraction of solar radiation entering a zone (kJ hr^{-1}), $Q_{(g,c)}$ is the internal convective gains (kJ hr^{-1}), and Q_{cplg} is the heat gain or loss due to connective air flow from adjacent zone (kJ hr^{-1}).

However, unlike the expected energy requirement where a lower energy load is required during the early stage of crop production and a higher energy load is needed at the later stage of crops, in this study, the computed annual energy in the greenhouse was assumed to remain constant for the entire life span of the systems. Specifically, as previously mentioned, the temperature requirement for different growth stages of mango differs resulting in different energy requirements. A total of three dynamic energy exchange model was adopted to estimate the annual building energy load of the greenhouse facility including the greenhouse structure, the crop energy exchange, and heating systems. Shown in Figure 3-5 is the combined design of the BES model used for calculating the energy load of the greenhouse.

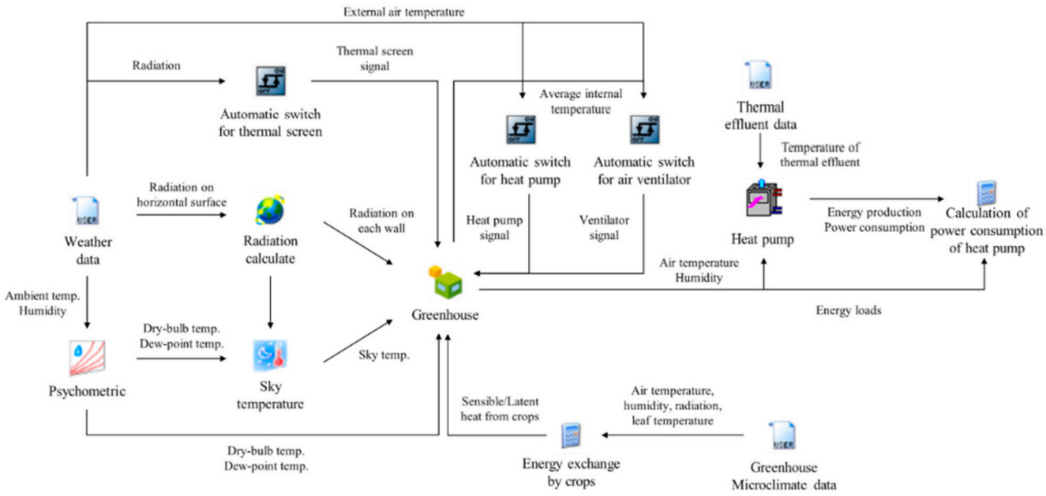


Figure 3-5 Design of BES model for calculating the energy loads of the greenhouse (adapted from Lee et al. (2021))

3.3.2 Greenhouse facility environmental impact assessment

In this study, the current versions of OpenLCA (Version 1.10.3, GreenDelta GmbH, Berlin, Germany) and Ecoinvent database (Version 3.6) were used to analyse the environmental impact of the greenhouse, the heating systems and the crop production materials. LCA follows the ISO standard 14040 up to 14044. As previously defined, LCA is a tool-known to quantify the economic burden of inputs and outputs over the entire life cycle. In particular, the LCA study comprised four general phases: the Goal and Scope Definition (ISO 14041), the Inventory Analysis (ISO 14041), the Impact Assessment (ISO 14042) and the Interpretation (ISO 14043). The goal definition determined the purpose of the study, while the scope definition process defined the boundaries of the systems being studied. The inventory analysis was considered to be the most laborious part of the LCA study. In this step, all the major components of the products were listed, and the equivalent unit used was determined either by field experiment data or through a series of literature data. A careful selection of the input inventory data was done to ensure that all the required input and processes were included in the system. The impact assessment involved the selection of an appropriate inventory assessment method. Under this step, the potential environmental effects of all the processes were considered. Finally, the last step in LCA where the systematic presentation of the key finding, including the critical sources of impact and the options to reduce these impacts.

The life cycle of a system is typically broken down into five stages: manufacturing, transportation, installation, operation, and end of life treatment. In terms of economic analysis, the net present value (NPV) was adopted. As described by Pombo et al., (2016), an energy-efficient building structure could increase energy and cost-saving throughout the entire life cycle. The author further emphasized that to make a certain product profitable, the energy cost saved over the lifespan must be the investment cost. Thus, in the calculation, all the cost related to investment were considered negative and all the energy savings were considered positive. Throughout the economic analysis of this research, the following values were used the annual inflation rate which was set at 4%, annual discount rate of 12%, electricity rate of 40.1 KRW/kWh based on agricultural electricity price and kerosene price which was set at an average of price of 1,291 KRW/liter. The NPV, which is the difference between the present value of cash inflows and the present value of cash outflows over a period of time expressed in Eq. 3-2 as:

$$NPV = \sum_{i=1}^{n} \frac{Rt}{(1+r)^{i}} - initial\ investment \qquad \text{(Eq. 3-2)}$$

where NPV is the net present value, R_t is the net cash inflows during single period, i is equal to the interest rate in present study, and t is the number of time periods.

3.4. Introduction to Scenario Cases

The initial step in the study is to calculate the total energy load that considers the energy exchange between the greenhouse facility, the heating systems, and the crops inside the target experimental greenhouse. Summarized in Table 3-1 is the computed total energy load using the BES model. A detailed description of the simulation procedure is discussed in Lee et al., (2021). The final stage of this study was to use the TRNSYS BES simulation result values through integration to OpenLCA software and apply the data to the selected scenario cases.

Case 1: Thermal effluent heat-powered absorption heat pump (AHP). When using an AHP as a heating system inside the experimental greenhouse, additional equipment must be installed. This includes but is not limited to the availability of water storage tanks, heat storage tanks, and fan coil units. The thermal effluent from the power plant flows into the heat pump inside the greenhouse. From the manufacturers' data, the heat pump had a 43,276 W in maximum cooling capacity and 36,786 W in maximum heating capacity. The energy efficiency (COP) for cooling and heating were 4.68 and 4.61, respectively. Storage tanks of 40 m^3 (cold) and 80 m^3 (hot) were also constructed to store the water flowing into the system. The fan coil had a power unit of 18,000 (Kcal h^{-1}) for cooling and 30,000 (Kcal h^{-1}) for heating. In the environmental assessment, the life span of the heat pump was assumed to be 20 years and was in continuous operation for 24 h a day during the entire winter season. As described in Figure 4, circulation fans and air ducts were installed to maintain the uniformity of heating distribution throughout the whole building.

Case 2: Electric-powered heat pump. The electric-powered heat pump included in the hypothetical case study had a maximum cooling capacity of 61.6 KW (−5 to 48 °C) and a maximum heating capacity of 69.3 KW (−20 to 24 °C). The unit had COP and power consumption of 3.55 and 17.35 KW for cooling and 4.15 and 16.70 KW for heating. Similar to the AHP (Case 1), the electric-powered heat pump (Case 2) used air ducts and fans to uniformly distribute heat throughout the building. Unlike Case 1, the Case 2 scenario does not require additional installation of facility such as storage tanks unlike those of Case 1 since the heat source was electricity. The principle of heating involved in this kind of heat pump allows the heat to move from lower temperature to high temperature. Under this case, the heat transferred in the fan coil provided a higher temperature to the surrounding. The electric-powered heat pump was set to have an expected life span of 15 years.

Case 3: Kerosene-powered boiler. The second hypothetical case includes the utilisation of a natural kerosene-powered boiler. Like the heat pump, the boiler heating system also comprised a various component which included the burner, chamber, heat exchanger, etc. The basic working principle of a boiler is to store water in a closed vessel and heated by burning fuel in a furnace to produce hot gases. The boiler used in the analysis was assumed to be manufactured abroad with a rated heating of 50 KW and fuel consumption of 5 L/hr. The boiler was also assumed to have 63% operational efficiency. The boiler had a stainless heat exchanger and brass gas burner. Given this material component, the boiler was assumed to be operational at the span of 30 years. Moreover, the kerosene used to power the power was set to have a heating value of 46.20 MJ/kg of kerosene fuel.

Table 3-1. Annual energy loads of the experimental greenhouse (Lee et al, 2021).

Year	Annual Heating(MJ)	Total Load (kWh)
2009 ~ 2010	838,243.37	315,960.47
2010~2011	825,247.94	312,197.47
2011~2012	802,653.62	297,472.02
2012~2013	901,318.95	332,306.58
2013~2014	786,186.39	306,118.99
2014~2015	813,409.80	297,472.27
2015~2016	782,307.87	290,323.42
2016~2017	793,454.47	300,480.89
2017~2018	813,209.88	300,179.06
2018~2019	755,980.29	322,996.59
AVERAGE	811,201.26	307,550.78

3.5. Environmental Assessment Process

The following subsections present different phases of an LCA on greenhouse facilities. In this section, the sequential flow of LCA analysis was presented following the four general phases of LCA.

3.5.1 Goal and scope

As previously mentioned, the goal of the research is to determine the optimum heating systems inside the greenhouse. To reach this goal, two hypothetical case studies (electric-powered system and kerosene-powered boiler) were added in the scenario case and were assumed to be used as a source of heating of the target greenhouse. The functional unit, which wass the basis for the comparative analysis, was defined as 1 m^2 of heated greenhouse floor area for the duration of 1 year. The scope of this work was restricted by omitting all processes that are not related to the function of the greenhouse and in particular those that could be separated from the operation of the greenhouse facilities such as the installation of greenhouse equipment including the microclimate sensors, vents, lightings and fixtures, etc. Moreover, the analysis was performed using a process-based approach wherein the life cycle of the systems was divided into distinct phases: extraction of raw materials, production and disposal.

3.5.2 Life Cycle Inventory (LCI)

As previously mentioned, the Ecoinvent 3.6 database was utilised to assess the environmental impact of greenhouse production, heating system, and crop production.

Accordingly, the dataset used for the greenhouse was set to a 25-year life span and represented the production up to the disposal of a 1 m^2 greenhouse with film covering. The building also included a fertigation system, CO_2 injection system, and storage facilities. For the different heating systems, the datasets for diffusion absorption heat pumps, brine-water heat pump, and oil boilers were used. In the case of the energy used, the reduced energy consumption of 59% was assumed considering the study result of Cecconet et al., (2020) for heat energy recovery of wastewater. Due to the absence of Irwing mango variety in the Ecoinvent 3.6 database for mango production, this study used a dataset that considered the Tommy Atkins, Palmer Keitt, and Kent and Palmar mango varieties instead. These databases were adjusted accordingly to suit the condition of the actual experimental greenhouse. The succeeding tables below showed the detailed data inventory for greenhouse building (Table 3-2), mango production (Table 3-3), thermal heat plant (Table 3-4), electric heat pump (Table 3-5), kerosene-powered boiler (Table 3-6) and energy source for heating greenhouse (Table 3-7) that were used in the study.

Table 3-2. Material inventory data for the Greenhouse.

Flow	Amount	Unit
Input		
acrylic varnish, without water, in 87.5% solution state	1.39×10^{-3}	kg
agricultural machinery, unspecified	9.50×10^{-3}	kg
aluminium scrap, post-consumer	-8.00×10^{-3}	kg
aluminium, cast alloy	8.00×10^{-3}	kg
bitumen seal	1.25×10^{-4}	kg
blow moulding	3.96×10^{-3}	kg
calendering, rigid sheets	1.25×10^{-3}	kg
concrete block	4.17×10^{-2}	kg
concrete block	9.20×10^{-2}	kg
copper	8.10×10^{-4}	kg
diesel, burned in building machine	4.67×10^{-1}	MJ
electricity, low voltage	2.35×10^{-3}	kWh
electronics, for control units	2.00×10^{-5}	kg
ethylene vinyl acetate copolymer	1.53×10^{-1}	kg
extrusion, plastic film	2.12×10^{-1}	kg
extrusion, plastic pipes	9.28×10^{-2}	kg
glass-fibre-reinforced plastic, polyamide, injection moulded	1.02×10^{-4}	kg
injection moulding	2.95×10^{-2}	kg
iron scrap, unsorted	-3.51×10^{-1}	kg
polycarbonate	1.25×10^{-3}	kg
polyester resin, unsaturated	1.71×10^{-3}	kg
polyethylene, high-density, granulate	5.99×10^{-2}	kg
polyethylene, linear low density, granulate	5.95×10^{-2}	kg
polymer foaming	6.13×10^{-3}	kg
polypropylene, granulate	3.77×10^{-2}	kg
polystyrene, expandable	6.13×10^{-3}	kg
polyvinylfluoride	2.99×10^{-2}	kg
section bar extrusion, aluminium	8.00×10^{-3}	kg
section bar rolling, steel	2.82×10^{-1}	kg

sheet rolling, steel	4.44×10^{-2}	kg
silicone product	1.50×10^{-4}	kg
steel, chromium steel 18/8	4.30×10^{-2}	kg
steel, low-alloyed	3.07×10^{-1}	kg
synthetic rubber	3.75×10^{-4}	kg
tractor, 4-wheel, agricultural	1.90×10^{-2}	kg
wire drawing, copper	2.25×10^{-3}	kg
zinc coat, coils	2.93×10^{-2}	m^2
Output		
waste concrete	1.19×10^{-0}	kg
waste electric and electronic equipment	8.30×10^{-4}	kg
waste plastic, mixture	1.41×10^{-3}	kg
waste polyvinylchloride	1.07×10^{-4}	kg
waste rubber, unspecified	3.60×10^{-4}	kg

Table 3-3. Material inventory data for mango production.

Flow	Amount	Unit
Input		
application of plant protection product, by field sprayer	4.51×10^{-3}	ha
carbon dioxide, in air	4.01×10^{0}	kg
chlorine dioxide	3.45×10^{-7}	kg
cobalt	1.09×10^{-4}	kg
dolomite	5.23×10^{-3}	kg
energy, gross calorific value, in biomass	3.26×10^{1}	MJ
ethoxylated alcohol (AE>20)	6.33×10^{-5}	kg
gypsum, mineral	1.66×10^{-1}	kg
harvesting, forestry harvester	1.25×10^{-4}	h
irrigation	1.07×10^{-2}	m^3
lime	2.62×10^{-4}	kg
magnesium oxide	2.96×10^{-2}	kg
mancozeb	1.73×10^{-4}	kg

manganese concentrate	1.39×10^{-3}	kg
mango seedling, for planting	4.71×10^{-3}	Item(s)
molybdenum trioxide	6.35×10^{-5}	kg
nitrogen fertiliser, as N	3.70×10^{-2}	kg
occupation, permanent crop, irrigated	3.76×10^{0}	m^2 * a
packaging, for fertilisers	7.91×10^{-1}	kg
packaging, for pesticides	5.49×10^{-2}	kg
pesticide, unspecified	2.71×10^{-3}	kg
phenol	1.98×10^{-5}	kg
phosphate fertiliser, as P2O5	2.64×10^{-2}	kg
planting with starter fertiliser, by no-till planter	1.25×10^{-5}	ha
polydimethylsiloxane	1.15×10^{-5}	kg
potassium fertiliser, as K2O	7.71×10^{-2}	kg
sulphur	1.93×10^{-2}	kg
tap water	4.26×10^{-5}	kg
tillage, harrowing, by offset leveling disc harrow	2.50×10^{-5}	ha
tillage, subsoiling, by subsoiler plough	1.25×10^{-5}	ha
transformation, from permanent crop, irrigated	1.88×10^{-1}	m^2
weed control, by brush cutter, pasture	2.25×10^{-3}	ha
zinc oxide	3.66×10^{-3}	kg
Output		
abamectin	1.58×10^{-6}	kg
ammonia	3.68×10^{-3}	kg
azoxystrobin	7.32×10^{-5}	kg
cadmium	1.13×10^{-6}	kg
cadmium, ion	1.58×10^{-8}	kg
cadmium, ion	3.53×10^{-9}	kg
carbon dioxide, fossil	2.55×10^{-2}	kg
chloride	3.45×10^{-7}	kg
chromium	9.36×10^{-6}	kg
chromium, ion	7.40×10^{-6}	kg
chromium, ion	3.92×10^{-7}	kg

copper	2.40×10^{-12}	kg
copper, ion	1.12×10^{-6}	kg
copper, ion	2.92×10^{-7}	kg
difenoconazole	6.61×10^{-5}	kg
dinitrogen monoxide	8.95×10^{-4}	kg
ethephon	9.65×10^{-5}	kg
indoxacarb	1.19×10^{-5}	kg
lead	4.48×10^{-7}	kg
mancozeb	1.73×10^{-4}	kg
nickel	1.98×10^{-6}	kg
nitrate	6.80×10^{-2}	kg
nitrogen oxides	1.46×10^{-3}	kg
pesticides, unspecified	1.94×10^{-3}	kg
phosphorus	1.67×10^{-5}	kg
pyraclostrobin (prop)	3.67×10^{-5}	kg
spinosad	5.48×10^{-8}	kg
tebuconazole	1.06×10^{-4}	kg
thiophanat-methyl	3.63×10^{-4}	kg
trifloxystrobin	1.05×10^{-5}	kg
waste wood, untreated	4.58×10^{-1}	kg
water	3.11×10^{0}	m^3
zinc	1.08×10^{-5}	kg
zinc, ion	5.76×10^{-6}	kg

Table 3-4. Material inventory data for thermal effluent heat source (Case 1).

Flow	Amount	Unit
Input		
aluminium, wrought alloy	4.30×10^{-3}	kg
ammonia, liquid	2.93×10^{-4}	kg
building, hall, steel construction	1.74×10^{-6}	m^2
building, multi-story	1.04×10^{-5}	m^3
copper	9.77×10^{-4}	kg
electricity, low voltage	7.81×10^{-3}	kWh
electricity, medium voltage	2.60×10^{-2}	kWh
electronics, for control units	1.95×10^{-5}	kg
helium	7.81×10^{-4}	kg
injection moulding	3.13×10^{-4}	kg
occupation, industrial area, built up	7.81×10^{-4}	$m^2 * a$
polyethylene, high density, granulate	3.22×10^{-2}	kg
reinforcing steel	6.25×10^{-3}	kg
sheet rolling, chromium steel	3.22×10^{-2}	kg
sheet rolling, steel	6.25×10^{-3}	kg
steel, chromium steel 18/8, hot rolled	1.56×10^{-3}	kg
stone wool, packed	6.25×10^{-6}	kg
transformation, from unknown	6.25×10^{-6}	m^2
transformation, to industrial area, built up	3.91×10^{-2}	m^2
tube insulation, elastomer	7.81×10^{-4}	kg
water, completely softened	4.18×10^{-4}	kg
water, completely softened	5.59×10^{-4}	kg
water, unspecified natural origin	5.96×10^{-5}	m^3
zinc coat, coils	2.93×10^{-3}	m^2
Output		
electronics scrap from control units	7.81×10^{-4}	kg
waste mineral wool	1.11×10^{-3}	kg
waste mineral wool	4.55×10^{-4}	kg
waste polyethylene/polypropylene product	4.41×10^{-4}	kg
waste polyethylene/polypropylene product	1.12×10^{-3}	kg
wastewater, from residence	1.99×10^{-5}	m^3

Table 3-5. Material inventory data for electric heat pump (Case 2).

Flow	Amount	Unit
Input		
copper	5.73×10^{-3}	kg
electricity, medium voltage	3.65×10^{-2}	kWh
lubricating oil	4.43×10^{-4}	kg
polyvinylchloride, bulk polymerized	2.60×10^{-4}	kg
refrigerant R134a	8.05×10^{-4}	kg
reinforcing steel	1.95×10^{-2}	kg
steel, low-alloyed, hot rolled	5.21×10^{-3}	kg
tube insulation, elastomer	2.60×10^{-3}	kg
Water, unspecified natural origin	1.84×10^{-4}	m^3
Output		
ethane, 1,1,1,2-tetrafluoro-, HFC-134a	9.20×10^{-1}	kWh
waste plastic, mixture	1.59×10^{1}	MJ
water	1.42×10^{-1}	m^3
water	8.02×10^{-1}	m^3

Table 3-6. Material inventory data for kerosene powered boiler (Case 3).

Flow	Amount	Unit
Input		
alkyd paint, white, without solvent, in 60% solution state	2.17×10^{-3}	kg
aluminium, cast alloy	1.30×10^{-2}	kg
brass	4.34×10^{-5}	kg
brazing solder, cadmium free	5.21×10^{-3}	kg
copper	$2.17 \times 10^{-2}2$	kg
corrugated board box	1.01×10^{-1}	kg
corrugated board box	8.58×10^{-3}	kg
polyethylene, high density, granulate	1.22×10^{-3}	kg
steel, chromium steel 18/8, hot rolled	2.17×10^{-2}	kg
steel, low-alloyed, hot rolled	4.21×10^{-1}	kg
stone wool, packed	1.65×10^{-2}	kg
tap water	6.43×10^{-1}	kg
waste paperboard, unsorted	-8.68×10^{-3}	kg
Output		
hazardous waste, for incineration	1.69×10^{-3}	kg
hazardous waste, for incineration	3.52×10^{-3}	kg
waste mineral wool, for final disposal	9.39×10^{-3}	kg
waste mineral wool, for final disposal	7.10×10^{-3}	kg
waste plastic, mixture	1.35×10^{-4}	kg
waste plastic, mixture	9.46×10^{-4}	kg
waste plastic, mixture	1.15×10^{-4}	kg
waste plastic, mixture	3.73×10^{-6}	kg
waste plastic, mixture	6.83×10^{-7}	kg
waste plastic, mixture	9.03×10^{-6}	kg
waste plastic, mixture	3.54×10^{-6}	kg
waste plastic, mixture	1.51×10^{-6}	kg
wastewater from pig iron production	6.22×10^{-5}	m^3
wastewater from pig iron production	4.72×10^{-4}	m^3
Water	9.65×10^{-5}	m^3
Water	1.29×10^{-5}	m^3

Table 3-7. Inventory for energy source used for heating the greenhouse.

Flow	Amount	Unit
Input		
heat, district or industrial, natural gas	4.34×10^2	MJ
heat, district or industrial, natural gas	1.06×10^3	MJ
kerosene	2.29×10^1	kg

3.5.3 Life cycle impact assessment (LCIA)

Technically, most greenhouse gases naturally occur within the Earth's surface; however, the emission was intensified by various human activities, which in turn caused climate change. Therefore, in this study, the CML 2001 method was used to evaluate and compare the impacts of the three heating systems. Specifically, acidification potential (kg SO_2-eq), global warming potential (kg CO_2-eq), and eutrophication potential (kg PO_4-eq) were used to compare the environmental impact of each case. The AP refers to the different acidifying contaminants, including sulphur dioxide (SO_2), nitrogen oxides (NO_x) and nitrogen monoxide (NO), that cause acid deposition on both soil and water (Cecconet et al., 2020). On the other hand, Bird et al.,(2011) and Kumar et al.,(2018) cited that the CO_2-eq, which causes climate change, not only represents CO_2 emissions but also represents the non-CO_2 greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) and has an equivalent factor that is dependent on average residence time in the atmosphere. The same definition and procedure as the GWP is employed when estimating the total PO_4-eq emission from the entire life cycle. According to Jan et al., (2012), the EP assesses the environmental burden caused by greenhouse gases such as nitrogen (N) and phosphorus (P) to the aquatic and terrestrial ecosystems.

3.6. Results and Discussion

3.6.1 Interpretation of case scenario environmental assessment results

The environmental impact caused by every process in the boundary system was studied by using the inventory dataset. Summarized in Figure 3-6 is the overall relative indicator results of the simulated scenario cases. As can be seen, the environmental impact caused by the kerosene-powered boiler had the largest contribution among all LCIA criteria. These may be caused by all the output gas emitted during the burning process of kerosene fuel to power the boiler system. The next highest environmental impact was attributed to Case 2, which used electricity to provide heat to the entire facility, while Case 1 showed the least environmental burden due to less dependency on energy used. Since the main goal of this paper is to analyse the emissions of the major greenhouse gas dispersed into the atmosphere, as previously mentioned, the AP, GWP, and EP were the only environmental burdens that are discussed in the following subsections.

Figure 3-7, on the other hand, shows the percent contribution of the different systems components used in the assessment. Specifically, it was found that the energy used for heating (source of heat) contributed to the highest environmental burdens with about 43.95% to 96.47, 86.59% to 95.73%, and 40.59% to 89.47% for AP, GWP, and EP, respectively. However, the construction and maintenance of greenhouse buildings were shown to contribute a maximum of 40.86% when a heat pump was used (Case 2) and only 4.94% when a kerosene-powered boiler was utilised. The low contribution of greenhouse building to environmental burdens in Case 3 was due to the very high impact of burning kerosene fuel during the operation of the heating systems. Subsequently, the materials used for the production of different heating systems have the least environmental burden at 0.88% to 6.01% contribution, 0.89% to 7.69% contribution, 0.36% to 1.94% contribution for Case 1, Case 2, and Case 3, respectively. This is because the heat pumps and boilers used in the analysis have a long life span. This means that a unit of heat pump or boiler can be used for several years.

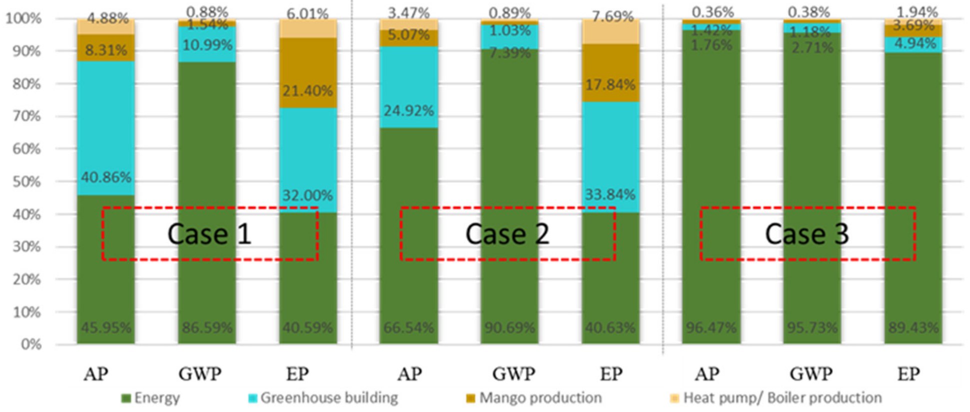


Figure 3-6 Detailed LCIA result

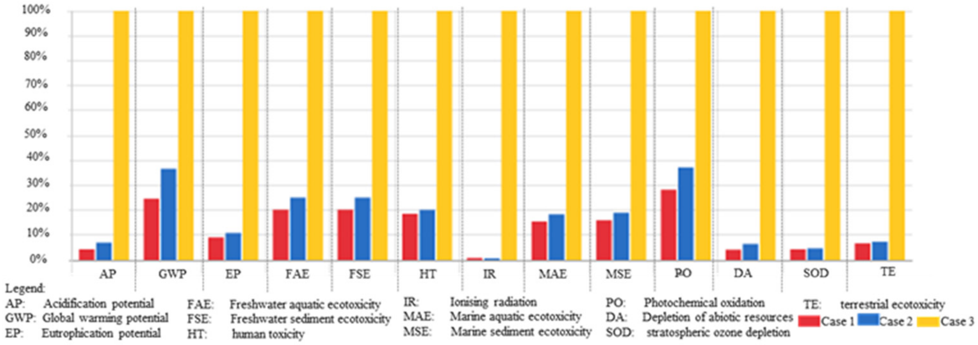


Figure 3-7 Environmental category based on system components

Table 3-8 shows the total quantitative impact categories of different heating systems used inside the greenhouse. The use of Case 1 reduces the AP to 4.954 × 10^{-2} (kg SO_2-eq), a very small emission compared to Case 3. However, in the case of the GWP in Case 1 and Case 2, it was greatly reduced from 1.13954 × 102 kg CO_2-eq when Case 3 was used. In addition to a higher CO_2 emission generated when operating the systems, based on the analysis of the results, the materials used to produce and operate one unit of electricity-powered heat pump also contributed to the high GWP, resulting in a difference in GWP with that of Case 1. Lastly, the EP of Case 3 was largest by an average of 1.47954 × 10-1 kg PO_4-eq when compared with Case 1 and Case 2.

Table 3-8. Total environmental impact of three scenario cases.

	AP (kg SO_2-eq)	GWP (kg CO_2-eq)	EP (kg PO_4-eq)
Case 1	4.96×10^{-2}	2.79×10^{1}	1.47×10^{-2}
Case 2	8.12×10^{-2}	4.15×10^{1}	1.77×10^{-2}
Case 3	1.16×10^{0}	1.14×10^{2}	1.63×10^{-1}

Summarized in Table 3-9 is the detailed quantitative LCIA result of the three case scenarios. From the environmental point of view, it can be observed that the energy used to operate the greenhouse had the highest influence on the assessment result. This was caused by the different processes involved to generate 1 MJ of energy. In the case of greenhouse building and mango production, constant input and output values were given to each case considering that the heating systems were assumed to be the only factor that changes in the boundary system.

Table 3-9. Total environmental impact of three scenario cases.

Impact	Description	Case 1	Case 2	Case 3
Acidification Potential (kg SO_2-eq)	Energy	2.28×10^{-2}	5.40×10^{-2}	1.11×10^{-0}
	Greenhouse building	2.03×10^{-2}	2.02×10^{-2}	2.02×10^{-2}
	Mango production	4.12×10^{-3}	4.11×10^{-3}	1.63×10^{-2}
	Heat pump/ Boiler production	2.43×10^{-3}	2.81×10^{-3}	4.11×10^{-3}
Global Warming Potential (kg CO_2-eq)	Energy	2.42×10^{1}	3.75×10^{1}	1.08×10^{2}
	Greenhouse building	3.07×10^{0}	3.06×10^{0}	3.06×10^{0}
	Mango production	4.29×10^{-1}	4.28×10^{-1}	1.33×10^{0}
	Heat pump/ Boiler production	2.46×10^{-1}	3.68×10^{-1}	4.28×10^{-1}
Eutrophication Potential (kg PO_4-eq)	Energy	5.97×10^{-3}	7.16×10^{-3}	1.45×10^{-1}
	Greenhouse building	4.71×10^{-3}	5.96×10^{-3}	7.99×10^{-3}
	Mango production	3.15×10^{-3}	3.14×10^{-3}	5.96×10^{-3}
	Heat pump/Boiler production	8.81×10^{-4}	1.35×10^{-3}	3.14×10^{-3}

The additional potential of LCA is its capability to execute environmental impact contribution analysis on the specific material or process. Presented from Figure 3-8 to Figure 3-10 are different illustrations showcasing the specific impact contribution of the input materials for the development and operation of the different heating systems considered in the study. It must be noted that the materials shown in each figure reflect only the dominant materials causing environmental impact and those with very little contribution were summed and coined as “others”. Moreover, those materials with less than 1% contribution were not labelled for better visualization. At analysis, the environment impact such as in AP, GWP, and EP was accounted to the energy used to operate the heating systems.

On the other hand, Figure 3-11 present different illustrations showcasing the specific impact contribution of the input materials for the construction and maintenance of the greenhouse building. From the analysis, the top five main contributors of environmental burdens include the use of zinc coating coils, the low alloyed steel used for constructing the greenhouse frame, polyvinyl fluoride and ethyl vinyl which were both used for greenhouse covering and lastly the chromium steel. This means that the volume of the materials used to construct the greenhouse building has the highest environmental impact.

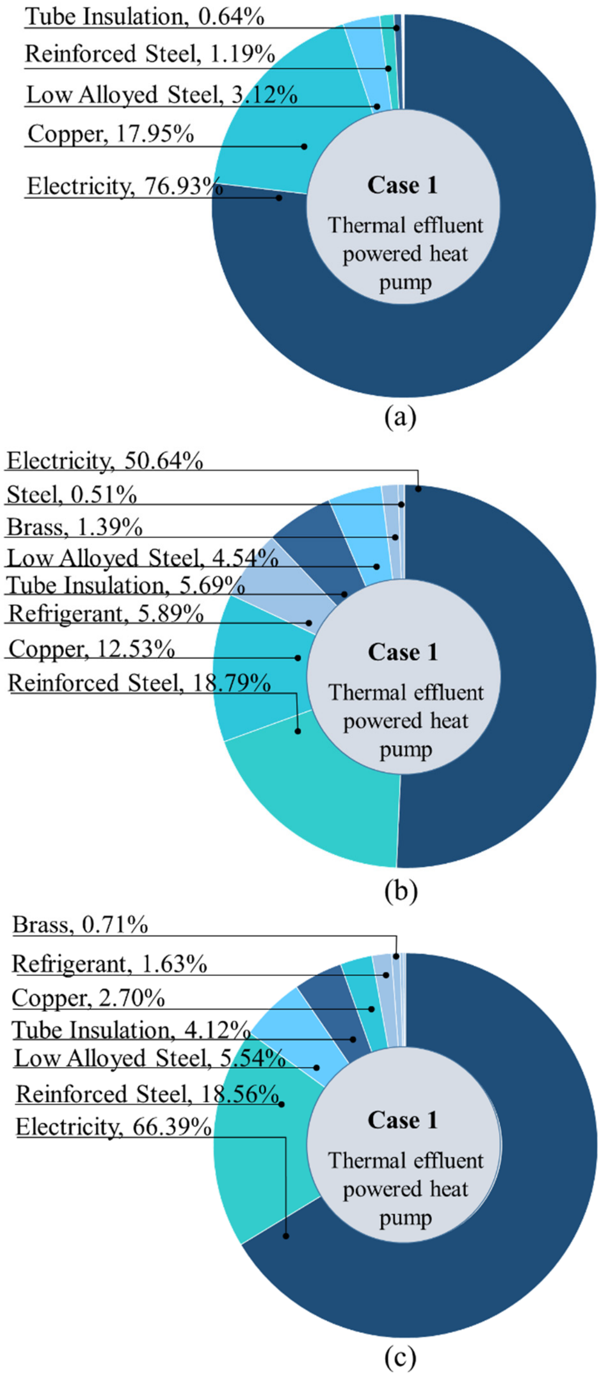


Figure 3-8 Detailed impact distribution for Case 1 (a) AP, (b) GWP, and (c) EP

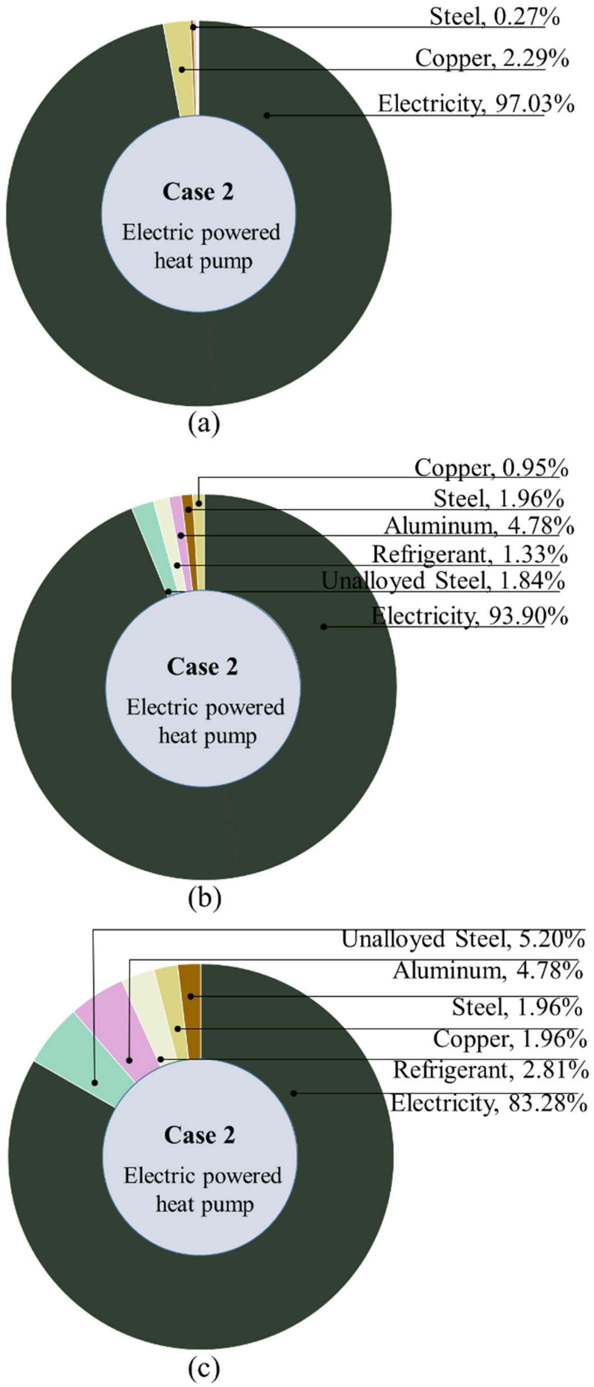


Figure 3-9 Detailed impact distribution for Case 2 (a) AP, (b) GWP, and (c) EP

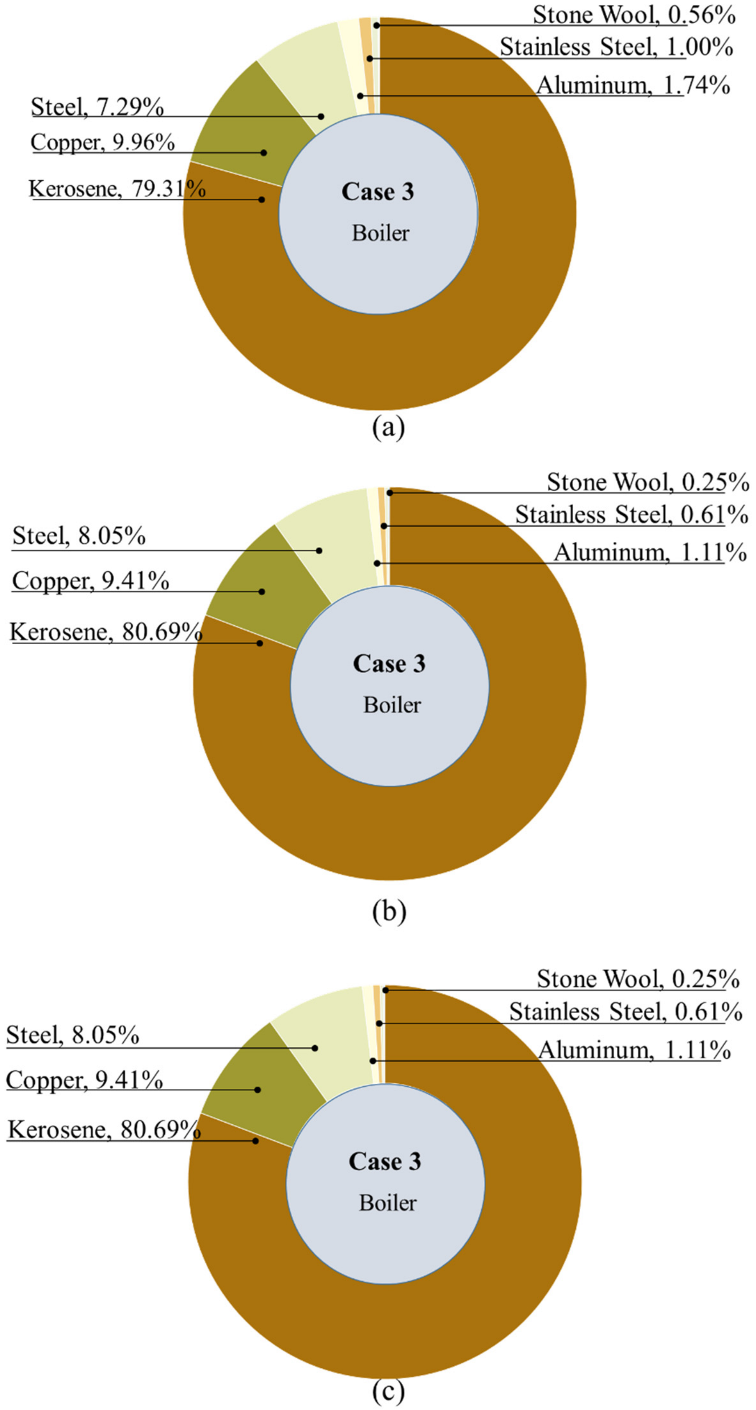


Figure 3-10 Detailed impact distribution for Case 3 (a) AP, (b) GWP, and (c) EP

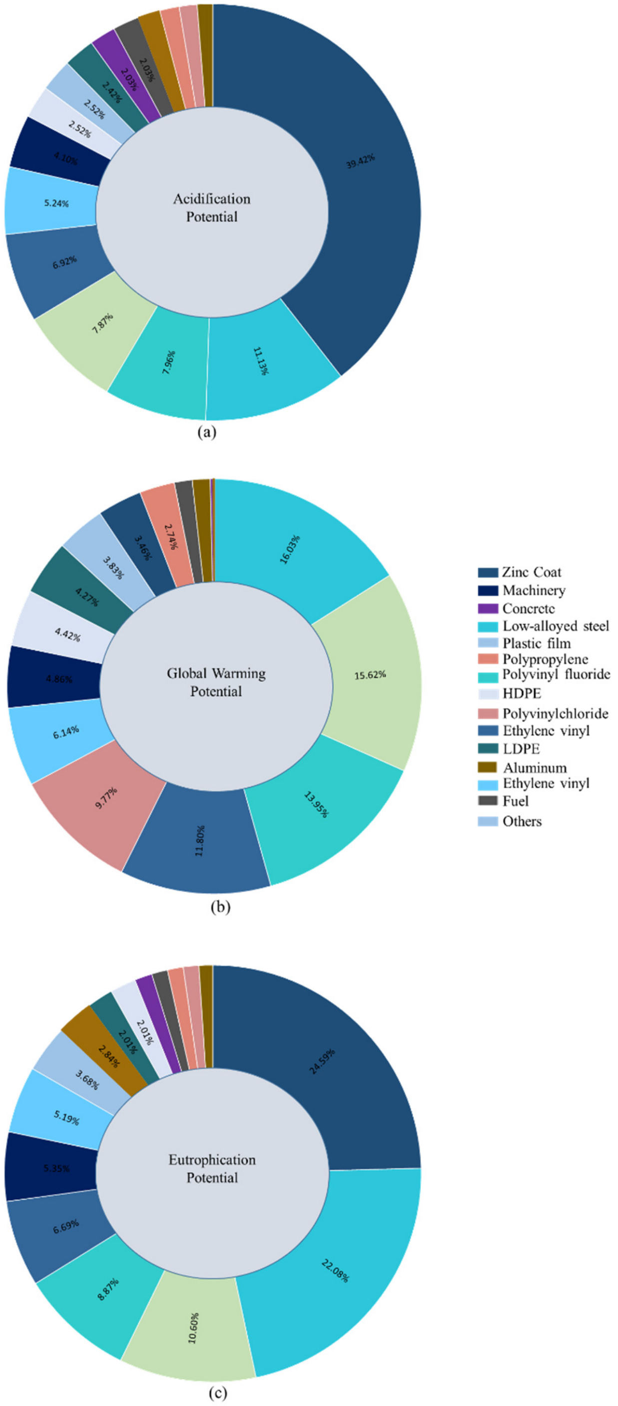


Figure 3-11 Impact distribution for greenhouse building (a) AP, (b) GWP, and (c) EP

3.6.2 Economic analysis

The target greenhouse was assumed to be used for research purposes, and therefore there was no economic gain during the entire life cycle of both greenhouse building and heating systems. This means that only the cash outflows were included in the NPV calculation. Ideally, if the NPV has a positive value, it means that the income generated was higher compared with all the accumulated cost. However, a negative NPV indicates that there is an economic loss in the investment. Considering the assumptions made in Section 3.3.2 and the initial cost of KRW 4.4 million for heat pumps and KRW 6.3 million for boiler, the NPV was calculated. The NPV calculation result of different heating systems showed that Case 1 has −120,685,762.44, Case 2 has an NPV of −131,489,523.75 and Vase 3 has −317,437,668.47. From this, it can be concluded that utilizing the heat pump system (Case 1 and Case 2) has a lower negative NPV compared with the use of a boiler. This calculation result accounted for the high maintenance cost of the boiler system, and a continuous hike in the price of kerosene to power the boiler resulted in the highest cash outflows.

3.6.3 Discussion on the comparison of different heating systems

The choice between a heat pump (Case 1 or Case 2) and boilers (Case 3) should be made based on what is most important to the farm owner, the budget, and the location of the greenhouse farm. When comparing the physical properties of different heating systems, Case 1 and Case 2 are effective and efficient heating systems due to high heating efficiency. As cited in many studies, many older boilers are only have low heating efficiency of 50–75%. This means that a large amount of energy used for the operation was not utilised and wasted. As claimed by several authors and manufacturing companies, the current boilers available on the market can achieve a high efficiency of 92% where only 8% of energy is wasted. Accordingly, to attain a high-efficiency boiler, it was suggested to replace the oil boilers used with a new modern model. However, the drawback of utilising Case 1 and Case 2 as a heating option is its lower lifespan which only last for about 15 to 20 years compared with boilers, which can last up to 30 years. Secondly, the installation of Case 1 and Case 2 required the utilisation of outside space. This is specifically true for Case 1, which needed to have a larger space for the construction of a hot-cold water storage tank, which added to the initial economic cost. For Case 2, a smaller outside space was needed, and in some cases, there will also be an indoor unit including the heat exchanger. In Case 3, a typical kerosene-powered boiler was considerably more compact compared with the previously mentioned heating systems.

One of the goals of this paper is to assess the environmental impact caused by different heating systems used in a greenhouse. The analysis revealed that the use of an electric-powered heat pump (Case 2) resulted in a higher environmental impact when compared with the use in Case 1 of thermal effluent heat-powered AHP. However, this result may be different if the source of electricity is obtained from renewable sources such as wind, solar, tidal, or hydropower energy source. The main factor that was found to give this assessment result is that a higher amount of heat energy from electric sources was being utilised to operate the system. Moreover, it was also found that Case 3 had the highest environmental burden. This is agreed by the conclusion stated by (Shah et al.,2008; Blum et al.,2010; Jan et al.,2012) which stated that a boiler has the highest carbon footprint compared to a different type of heat pump system. According to Greening and Azapagic (2012), in the case of GWP, heat pumps can save up to 36% of CO2-eq. Nevertheless, the Case 1 and Case 2 systems have higher efficiency, which makes them the far more environmentally friendly choice.

In the case of the economic aspect, although heat pumps use electricity which is around four times the price of gas to run,, the fact that the heat pump is so efficient means that it uses very little electricity. and the running costs are therefore comparable. An emphasis should also be given to the use of thermal effluent heat-powered AHP (Case 1) as a source of heat since the amount of heat extracted from the thermal effluent greatly reduces the amount of energy required to maintain the optimum environment of the target greenhouse. For Case 3, it was shown that a lower investment cost was possible using this heating system. However, due to overexploitation of fossil fuels like gas and oil continuously resulting in energy resource depletion, it is likely that these prices will continue to rise in the future, resulting in a higher economic burden to farm owners.

3.7. Conclusions

This study aims to assess and compare both the environmental and economic impact of different heating systems typically used in conventional Korean greenhouse facilities. In the first part of the research, the total energy load needed for crop production on the target experimental greenhouse was calculated using the Building Energy Simulation (BES) software. The average total annual heating load obtained from the calculation was used as the reference for the heating requirement for the life cycle analysis. Three scenario cases were analysed in the study, which included case 1 (thermal effluent heat powered absorption heat pump [AHP]), Case 2 (electric powered heat pump), and Case 3 (kerosene powered boiler). The OpenLCA free source software and Ecoinvent 3.6 database was used in the study. The result showed that the use of Case 3 as a heating source offers significant environmental disadvantages. Specifically, the environmental assessment revealed that the environmental impact caused by this system is largest in terms of the acidification potential (AP), global warming potential (GWP), and eutrophication potential (EP) of 1.15 × 100 kg SO_2-eq, 1.13 × 102 kg CO_2-eq, and 1.62 × 10-1 kg PO_4-eq, respectively. Among the three cases, the thermal effluent heat-powered AHP was found to have a lower environmental burden. Specifically, the AP of case 1 was 38.99 to 95.70%, GWP was 32 to 76% to 75.33%, and EP was 16.63% to 90.92% lower compared with Case 2 and Case 3. Detailed analysis of the results showed that the main contributor to greenhouse gas emission was caused by the type, amoun,t and source of energy used to heat the greenhouse, which contributed to a maximum of 86.59% for Case 1, 96.69% for Case 2 and a maximum of 96.47% for Case 3, depending on the type of gas being considered. The contribution of greenhouse gas emissions caused by building construction, operation, and maintenance can also contribute to up to 40.86% of the environmental burden. Finally, the economic analysis of three cases showed that Case 1 tends to give a lesser economic burden compared with the other two cases. The finding obtained from this study can be used to support decision making on the selection of the appropriate heating system to be used in the greenhouse. However, further evaluation is mandated considering other types of heating systems typically used in the greenhouse.

Chapter 4. Environmental Impact Assessment for Livestock

4.1. Introduction

During the past years, climate change has become one of the most discussed topics around the world. With this, gas emissions and environmental burdens generated by various industries are becoming serious public concerns (Peters et al., 2014). This is especially true since the population pressure urbanises rural areas that bring residential houses closer to existing agricultural structures where gas sources originate. This situation was further exacerbated by high-density animal husbandry operations that continued to proliferate. OECD-FAO (2021) projected that by the year 2031 there is a global increase in the number of heads for cattle (1.8 billion), pigs (1.0 billion), poultry (31.0 billion), and sheep (2.9 billion). Presently, the increasing production of livestock was observed in South Korea where cattle (3.7 million), pig (8.8 million), and chicken (303.2 million) were 10.8%, 17.7%, and 4.3% higher when compared with the production in 2015, respectively (Ministry of Agriculture, Forestry, Animal Husbandry, and Food Agriculture Management, 2021). If the GHG emissions intensities of these livestock are not reduced, the increase in production required to meet the population’s demand will lead to proportionate increases in GHG emissions. Thus, enhancing the knowledge of where and why emissions arise in livestock is a crucial step to identifying and improving the efficiency of GHG mitigation techniques (MacLeod et al., 2013) .

Consequently, the incidence of annoyance caused by livestock production also continuously grows as the production intensively increased to meet the exponential growth demand of the population. This competition for resources, however, resulted in a severe impact on air, water, and soil quality because of the unwanted gas emissions (Thornton 2010). According to the Food and Agriculture Organization (FAO, 2017), for example, the world's livestock industry is responsible for 14.5% of the global emission of greenhouse gases. This contribution (4.5%) is mainly caused by the emission of carbon dioxide (CO_2) from manure and the emission of nitrous oxide from the application of fertiliser (De Vries and De Boer, 2010).

Though there were hundreds of published articles related to LCA for agriculture, little attention has been paid so far to the environmental impact focussing on the livestock industry. Especially, choosing more environmentally friendly livestock growth products such as feed management, livestock housing, manure storage management and so on that could mitigate environmental impact has not been given enough attention. This strain may account for the difficulties in consistently assessing the environmental impact of each production stage due to a lack of inventory materials. Especially, Bhatt and Abbassi (2021) emphasized that LCA in the agricultural industry is complicated as the emissions intensities from the livestock are not easy to quantify by the generic datasets that are currently available.

In addition to this, the excessive production of unwanted odours and gases emitted from the facilities can be a real nuisance to the neighbouring residents who are located at the downwind part of any livestock production facility. This nuisance often leads to legal complaints that in turn may cause suspension of operation or total closure of facilities. Thus, farm owners and researchers have focussed on the development of various odour control techniques that can minimize operational difficulties related to livestock production. In addition, a good understanding of the different reduction techniques used in livestock production and their environmental effect is very crucial. However, to the extent of the researcher's knowledge, a detailed LCA for different odour and GHG mitigation techniques used in livestock production has not been published yet. Also, very limited information related to the potential environmental impact of adopting the GHG and odour mitigation measures on the health and welfare of both farm workers and animals are available at the present.

Thus, the main goal of the paper is to present an attempt to address the challenges of using the LCA tool for odour and GHG mitigation in the livestock industry through the identification of the environmental impact of different odour and GHG mitigation technologies for livestock production. In this context, it is reasonable to identify the different boundary systems and flows used for life cycle assessment for different livestock studies as it offers an opportunity to assess which livestock production stages contribute greater burden or harm to the environment. In this study, a detailed review of odour and GHG sources from livestock and the corresponding activities that cause the emission is presented first. Secondly, livestock LCA-related published research were screened according to different odour GHG and mitigation techniques. Lastly, based on the analysis of selected LCA articles, odour and GHG mitigation techniques used in different livestock production were analysed using an environmental approach.

4.2. Materials and Methods

The research flow of the study is shown in Figure 4-1. As previously mentioned, a careful selection of case studies included was made by considering different literature related to livestock odour and GHG mitigation techniques. This is followed by the conventional methodology of LCA following the ISO standard. Generally, the goal of the study is to analyse the impact of different GHG odour mitigation systems used for livestock production. In this study, odour mitigation techniques mainly focused on feeding, housing management, and manure processing. The mitigation techniques included in the study were limited to the addition of crude protein for feeding management, while housing management included the use of different scrubber systems, biofilters, and biotrickling techniques. Lastly, manure management and processing covered the use of an anaerobic biogas digester, urine, and feces separation.

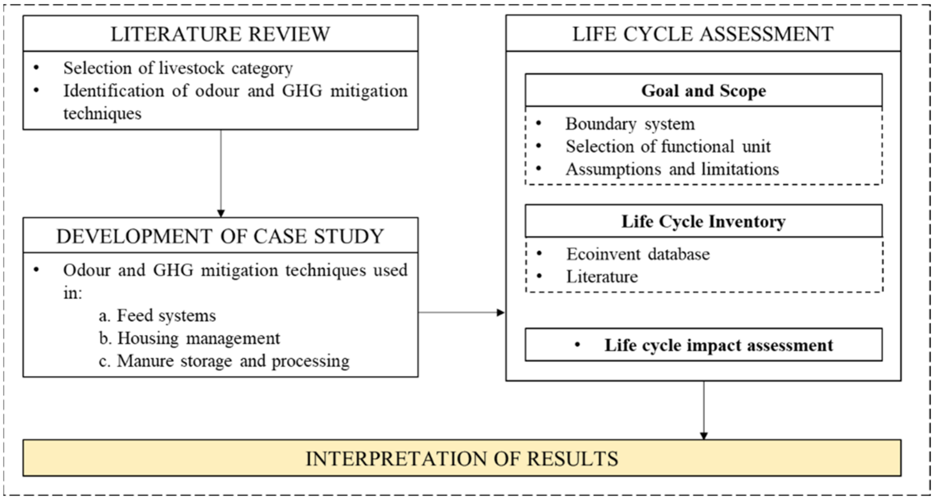


Figure 4-1 Research flow of the study

4.2.1 Selection of LCA related articles in the livestock industry

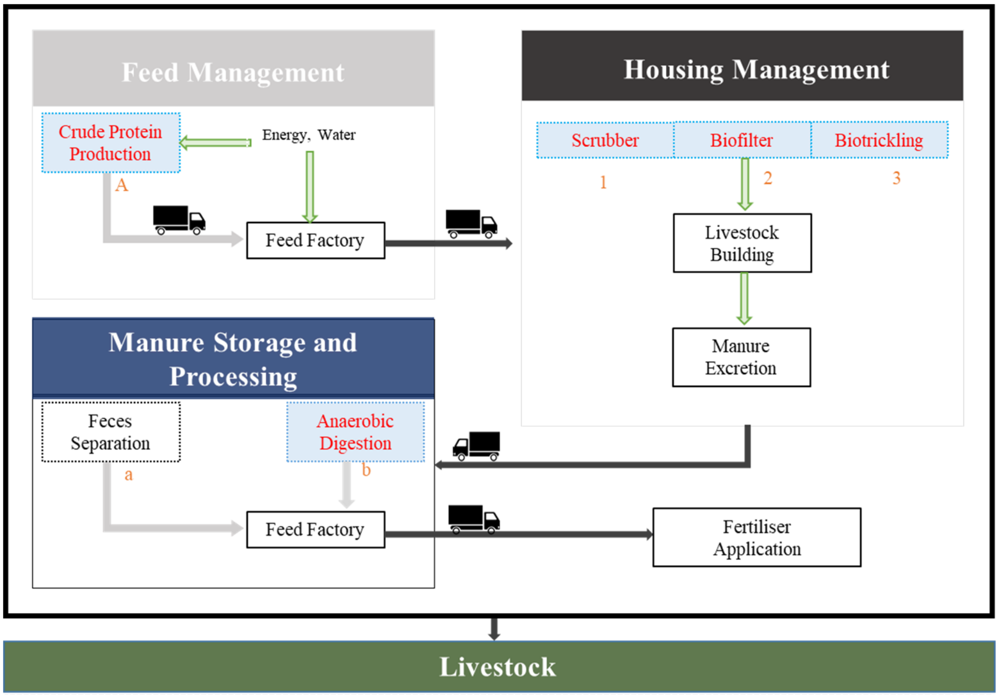
LCA studies for GHG and odour reduction in livestock production worldwide have been published in the past years. In this study, some of articles were downloaded and selected based on the latest publication years (2010 ~ 2021) to ensure that all the accumulated data were up to date. Selection criteria were set to ensure that the included research topics had the same research coverage that is related to environmental assessment for livestock. Firstly, all articles that are published in another language except English were excluded. Second, the articles must fall under the category of GHG and odour-reduction techniques through feeding, livestock housing, and livestock waste management which were the focus of the research. Third, each article must have a functional unit with any livestock unit (e.g. 1 kg of liveweight, 1 kg carcass, etc). Then, the research must be based on attributional LCA that does not consider the normative cut-off rules that isolate the investigated process from other factors. In addition, in the case of feeding systems, conventional feeding methods were only considered, and all other organic systems were excluded from the research. Furthermore, other articles that focused on livestock other than pig were not included despite having contained environmental assessment in their methodology and results. Lastly, all other publications that did not meet the selection criteria were excluded from the selection screening process. This includes those publications in the form of news, book chapters or those that were under the editor's notes.

4.2.2 Case scenarios

In South Korea, the largest portion of production which is about 40% of the total livestock industry in the country accounts for the pig industry (Ministry of Agriculture Food and Rural Affairs, 2018). Hence, the pig industry has been identified as one of the major contributors of GHG emission and known to be the major source of odour-related complaints in the livestock industry in the country. In recent years, technologies that solely aimed to reduce the odour and GHG emission from pig facilities has becomes the focus of research. In fact, pig farms have been continuously upgraded with ICT technologies and being slowly converted into smart farm facilities to minimize the emission. The benefits of installing structures capable of minimizing the emission such as scrubbing system, biofilter, etc have become known to farms. Thus, in this section, a sample case scenario using odour and GHG mitigation techniques from feeding, housing, and manure management of pig production was formulated to assess the environmental impact. This aimed to identify if the installation of such technologies will provide benefits or will just cause additional environmental burden.

Shown in the Figure 4-2 below is the detailed boundary system of each analysis. A total of 6 scenario cases A1a, A1b, A2a, A2b, A3a and A3b was analysed. The subcategories 1, 2, and 3 under the housing management represent the use of air scrubbing systems, biofilters, and biotrickling, respectively. While subcategories representing the small letters a and b under the housing storage and processing represent the use of feces separation and anaerobic digestion. Thus, the naming of each scenario was as follows: Scenario 1 utilised crude protein feed management, a air scrubber system, and feces separation while Scenario 2 used protein management, a wet scrubber, and an anaerobic digester. Scenario 3 included utilizing the crude protein, biofilters and feces separation. Scenario 4 used crude protein, biofilter, and anaerobic digestion, while Scenario 5 involved crude protein biotrickling and feces separation. Lastly, Scenario 6 used crude protein, biotrickling, and anaerobic digestion.

All the gas (CO_2, CH_4, NO_2, SO_2, etc) involved and emitted during the entire process of the livestock systems were taken into account by considering the gas emission from the different processes, whereas, the input materials such as water, energy, and transport cost used for the construction and operation of different odour and GHG mitigation techniques are also considered. The boundary systems used in the analysis focussed from cradle-to-gate with a functional unit of 1 kg of animal carcass. This means that the end processing for manure storage and processing where manure fertiliser was produced was not considered. In the analysis, the main emphasis on the assumptions made for the entire analysis is important. For instance, all the raw materials for producing low crude protein diets were transported to an identical location in the Asian region. A more detailed discussion of the assumptions used in the analysis is presented in Section 4.2.5.



A1a: Scenario 1 using crude protein, scrubber, and feces separation
A2a: Scenario 2 using crude protein, biofilter, and feces separation
A3a: Scenario 3 using crude protein, biotrickling, and feces separation
A1b: Scenario 4 using crude protein, scrubber, and anaerobic digestion
A2b: Scenario 5 using crude protein, biofilter, and anaerobic digestion
A3b: Scenario 6 using crude protein, biotrickling, and anaerobic digestion

Figure 4-2 Allocation of scenario cases for the environmental assessment of livestock animals

4.2.3 Goal, scope and functional unit

The definition of functional units (FU) in LCA research is crucial and essential especially when comparing different products. FU is a quantified description of the function of a product that acts as a baseline for all the necessary calculations regarding impact assessment (ISO 14040). As previously mentioned, it can be quantified be based on mass or volume. In some cases, it may also base on the quality, cost, and function, especially those that were concerned with the environmental impact of building constructions.

The comparison of different products used in LCA can only be possible when the FU used is identical. This is specifically true for any product that has been the interested of LCA studies. In the case of livestock production, typical FU used were based on the impact per kg of carcass. To express the LCA results of studies related to livestock production, the input, and output data in the inventory were recalculated according to the selected FU.

4.2.4 System definitions and assumptions

In this study, major GHG (CO_2, CH_4, NO_2, SO_2) were considered in the analysis. This means that the major GHG and odour emissions from each management source were taken into account. Shown in the Figure 4-2 below is the simplified system boundary of the study. Under each management source (feeding, housing and manure processing), different methodologies were subsequently inputted into the analysis. For instance, under feeding management, mitigation techniques such as the addition of crude protein were included. Under the housing management, mitigation techniques such as the utilisation of air scrubbing systems, biofilter or biotrickling is also added. In addition, due to the absence of actual emission data throughout the systems, all the required emission rates needed in the calculation were obtained based on the references and literature.

The raw materials used to formulate the feed intake of pig were assumed to be locally produced (within South Korea). In the case of energy used, it was assumed that the energy employed to operate the considered scenario cases was identical to the assumption made by De Vries et al. (2016). The energy referred to in this analysis was used for lighting, heating, and ventilation of the pig facility. Despite considering the whole production environmental assessment, it must be noted that the veterinary medicines and hygiene were not included due to the unavailability of reference data. In the case of the odour and GHG reduction systems, it was assumed that the case scenarios considered in the study had a treatment capacity of 45,000 m^3 per hour in reference to the study conducted by De Vries et al.,(2017).

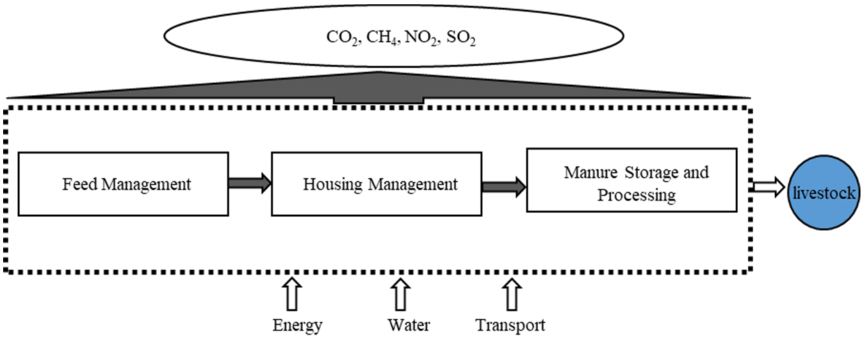


Figure 4-3 Simplified boundary systems of livestock production

4.2.5 Life cycle inventory (LCI)

In this study, the Ecoinvent 3.6 database was utilised to assess the environmental impact of different odour and GHG mitigation technologies from feed management, housing management, and manure storage and processing. Accordingly, the dataset used for air scrubber systems, biotrickler, anaerobic digesters, and solid-liquid separators was assumed to have a life span of 15 years, whereas, the biofilter material was assumed to have a life span of 10 years. In the case of feed management, inventory materials were adopted from the study of Esteves et al.,(2021) using a 15.15% crude protein. Summarized in Table 4-1 is the detailed components of feeds with low crude protein, whereas, the detailed description of material components of biotrickling was summarized in Table 4-2 (Housing Management). The remaining cases under housing management were obtained from the Ecoinvent 3.6 and adjusted according to the desired functional unit. Moreover, other relevant production materials used in the odour and GHG mitigation technologies such as high-density polyethylene (HDPE), were obtained also from Ecoinvent 3.6 database.

Lastly, the LCI of the pig house building (assumed to be a fully slatted floor) included an input of 0.063MJ FU^{-1} electric mix and drinking water 10.714 kg FU^{-1}. The output included emission of CH_4 (0.0178 kg FU^{-1}), N_2O (0.0005 kg FU^{-1}), and NH_3 (0.0204kg FU^{-1}).

Table 4-1. Ingredients and chemical composition of crude protein diet (Adopted from Esteves et al., 2021)

	Crude Protein Content		Crude Protein Content
Ingredients		Calculated Composition (%)	
Maize	75.06	Calcium	0.722
Soybean meal	18.01	Available phosphorus	0.357
Soybean oil	2.31	Sodium	0.19
Dicalcium phosphate	1.5	Potassium	0.57
Limestone	0.737	Chlorine	0.268
Sodium bicarbonate	0.475	SID lysine	1.069
Salt	0.127	SID methionine	0.399
L-Lysine HCl 78.0%	0.597	SID met + cys	0.631
DL-Methionine 99.0%	0.199	SID threonine	0.695
L-Threonine 98.5%	0.258	SID tryptophan	0.214
L-Tryptophan 98.0%	0.082	SID valine	0.738
L-Valine 98.0%	0.143	SID isoleucine	0.588
L-Isoleucine 100.0%	0.015	SID histidine	0.351
-		SID phenylalanine	0.629
		Metabolizable energy (kcal/kg)	3350

Table 4-2. Life Cycle Inventory of biofilter (adopted from Cano et al.,2018)

	Unit	Amount
Inputs		
Material Construction		
Steel	g	3.8
Steel Pipe	g	0.7
FRP	g	8.2
PVC	g	0.1
Polypropylene	g	1.2
Packing Material		
Polypropylene Pall Ring	m^3	1.2^{-4}
Daily operations		
Water	m^3	12.2
Electricity	kWh	20.4
Outputs		
Waste dumped		
Biomass	g	52.6
Steel	g	4.5
FRP	g	8.2
PVC	g	0.1
Polypropylene	g	1.2

Table 4-3. Environmental emission of cases scenarios under housing management

kg pollutant	Air Scrubber[a*]	Biofilter[a**]	BioTrickling[a*]
CO_2	8.1	8.4	7.7
N_2O	0.002	0.09	0.013
CH_4	0.025	0.5	0.025
NH_3	0.121	0.521	0.364
SO_2	0.06	0.03	0.019
NO_X	0.041	0.31	0.038
PO_4	0.008	-	0.008
PM10	0.015	-	0.014
Energy (MJ)	134	-	131

[a] *adjusted to desired FU*

[*] *adopted from the study published by De Vries et al., (2017)*

[**] *adopted from the study published by Shang et al., (2022)*

4.2.6 Life cycle impact assessment (LCIA)

The concern about the impact of different agricultural activities on the environment has been rising as manifested by the increasing number of studies concerning LCA which are usually linked to climate change and sustainability of resource use with carbon footprint receiving the highest research interest being aggregated to GHG emission per commodity. LCA is a known method to analyse the environmental impacts of a product throughout its entire life cycle. This life cycle can span from cradle-to-grave which refers to the extraction of raw materials, packaging, use, end-of-life treatment, and recycling until final disposal. Throughout each stage, the product is considered to interact with the environment by consuming the available natural resources and emitting pollutants to the air, water, and soil. In this study, a Cradle-to-farmgate approach was implemented for each livestock.

Further, the LCA framework provides several methodologies that can be used for environmental indicators such as Recipe 2008, CML 2001, EDIP′97, EDIP2003, EPS2000, EcoPoints, and so on. In this study, The CML 2 baseline was used as the LCIA method which analysed the global warming potential, eutrophication potential, acidification potential. Additional parameters such as energy and land use were also briefly analysed to evaluate the impact of different reduction systems in terms of energy consumption and land use utilisation. The LCIA method was chosen given the fact that it is widely used in most LCA studies for pig production (Monteiro et al., 2016).

Further, this section compares different systems by converting the functional units of each study into identical functional units, i.e. 1 kg of animal carcass weight. In this study, a one hundred live weight of pig was assumed to have an average of 80 kg carcass (Reckmann, 2016).Similarly, an open source software, OpenLCA (Version 1.10.3, GreenDelta GmbH, Berlin, Germany) was used to calculate the environmental impact of the different case scenarios included.

4.3. Results and Discussions

4.3.1 Overview of the literature

The list of collected research articles was identified in the search criteria but only a few relevant articles were included in the review analysis. In summary, LCA studies that are connected with the GHG and odour mitigation for livestock are usually homogenous due to the standard livestock production practiced worldwide. This means that the process and stages of livestock production for different countries around the world but slightly vary depending on the technology used for livestock rearing and management. In addition, those studies, which have the same functional units substantially vary due to the difference in animal characteristics and activities. These differences surely affect the environmental impact being considered. For instance, a direct comparison of feeding management between cattle and poultry cannot be directly compared as both animals have different digestion processes. Listed in Annex A is the list of research that was reviewed in this study. It included the influence of different mitigation techniques in the reduction of odour and GHG emissions from different livestock housing. From this, it can be concluded that various methodologies has been continuously installed and evaluated for the purpose of odour and mitigation.

According to the literature, in cattle production, methane production is the largest (271 lbs CH4/animal per year) due to the digestion process called enteric fermentation where microbes decompose and ferment feeding materials in cattle's digestive tracts

(FAO, 2001). Whereas, swine and poultry only produce 10.5 and 0.57 lbs CH4/animal per year Monteney et al., (2001)

Based on the collected literature, it was found that the largest contributors of GHG emissions were found in feeding, housing, and manure management. For instance, Montero et al., (2017) stated that reducing the crude protein of animal diet contributes to the improvement of environmental performance for growing pigs. The claim was emphasized in the study of Esteves et al., (2021) for changing the crude protein. Whereas, in poultry production, Ogino et al., (2021) found that manipulating the crude protein diet of poultry will result to lower acidification and eutrophication potentials Even though there were various odour and GHG mitigation techniques under the feed management, it was judged that among the practices in feed management manipulation for livestock, crude protein manipulation has the greatest environmental impact.

Similar, under the housing management categories, literature about the utilisation of scrubbing systems to reduce livestock odour are very common for pig production. Prapasponga et al., (2010) evaluated the environmental impact of 12 manure management and application methods in Denmark. De Vries et al., (2012) use the LCA to assess the reduction potential terms of the environmental effect of segregating liquid and solid manures compared with conventional manure management and storage. In addition, among all the livestock manure management techniques used, anaerobic digestion found to be widely used by farm owners due to its environmental benefits and capabilities to reduce global warming potential to zero. The process of anaerobic digestion (AD) as defined by Duan et al., (2020) refers to a method of decomposing livestock effluent through microorganisms through conversion into biogas (mainly carbon dioxide and methane).

4.3.2 Assessment of GHG emission livestock production

The amount of GHG emitted in the atmosphere has contributed to the increase of earth's atmosphere through absorption of energy and slowing the rate of energy that scapes to space. In this study, the analysis of the result for the three major livestock production showed that global warming potential has highest by 89.96% and 98.14% in cattle production compared to swine and poultry production, respectively. Specifically, results showed that the highest contribution for global warming potential was nitrous oxide while carbon dioxide showed the least environmental important greenhouse gases this is in agreement with the finding of De Vries et al., (2017).

In the case of pig production, a total of 13 LCA were summarized (7 under the feed management, 3 under housing management, and 3 for manure storage and processing) in Table 4-4. The Table summarized the different environmental impact (GWP, AP, EP, cumulative energy demand and land use) and functional unit used of odour, and GHG mitigation technologies. From these, the scenario cases described in section 4.2.2 was derived.

Table 4-4. Sample list of LCA studies for livestock (pig)

Author	Country	Strategy	FU	Type	GWP	AP	EP	Energy	LU
Feed management									
Ogino et al., (2013)	Japan	Amino acid	1 kg liveweight	conventional	3.16	9..1	21.7	-	-
				low CP	2.99	6.6	20.7	-	-
Garcia-Launay et al., (2014)	France	Amino acid	1 kg liveweight	Soy-noAA	2.68	21.2	53.2	-	-
				Soy-withAA	2.31	16.9	36.6	-	-
				Soy-LowCp	2.26	16.5	34.6	-	-
				Mix-noAA	2.41	21.6	48.3	-	-
				Soy-withAA	2.22	16.8	36.9	-	-
				Soy-LowCp	2.26	16.5	34.6	-	-
Cherubini et al., (2015)	Brazil		1 kg of body weight gain	CP18	2.35	-	-	-	-
				CP16	2.24	-	-	-	-
				CP15	2.29	-	-	-	-
				CP13	2.53	-	-	-	-
Monteiro et al., (2016)	Brazil	Amino acid	kg BWG	NoAA	2.37	62.4	18.6	-	-
				withAA	2.39	60.6	17.9	-	-
				lowCP	2.45	55.1	16.1	-	-
Mckenzie et al., (2016)	Canada		kg pig carcass	control	2.2	14.4	57.4	-	-
				meat meal	2.16	15.8	61.6	-	-
				DDGS	2.55	14.3	56.5	-	-
				Wheat shorts	1.95	16.6	56.9	-	-

				Bakery meal	2.13	14.1	55.8	-	-
Reyes et al., (2019)	Cuba	Feed formulation	50 kg PELU	Genetic Farm	6.87	-	0.07	-	-
				Multiplier Farm	9.34	-	0.12	-	-
				Reproduction Farm	9.65	-	0.13		
Esteves et al., (2021)	Brazil	Amino acids	1 kg of body weight gain	CP18.15	2.95	35.34	11.9	17.35	2.15
				CP17.15	2.87	34.25	11.36	17.44	2.03
				CP16.5	2.82	33.18	10.87	17.22	13.96
				CP15.5	2.8	31.58	10.31	18.36	1.89
Housing management									
Luo et al., (2014)	China	Alternative manure systems	500 kg live weight	Biogas	5714	79.4	91.7	-	-
				Biogas+land applicator	5632	58.9	56	-	-
				biogas alternative	5611	61.9	34.1	-	-
Corbala-Robles et al., (2018)	Belgium	Manure Treatment	1 m3 of raw manure		5.18			-	-
Makara et al., (2019)	Poland		1 kg of carcass weight	stored manure	6.83	0.218	0.964	-	99.1
				separated manure	7.12	0.183	0.465	-	75.7
				combined	6.92	0.181	0.63	-	72.4
Manure storage and processing									
Dourmad et al., (2014)	Germany			-	2.25	0.019	0.044	16.22	4.12

				-	2.56	0.006	0.044	16.5	4.7
				-	2.43	0.03	0.054	24.28	10.58
De Vries and Melse (2017)	Netherland	Scrubber			5.31	0.36		99.7	
					6.73	1		112	
					121	0.95		127	
De Vries et al., (2012)	Netherland	Urine and Feces Separation	1 tonne of mix manure	Reference	332	5.3		-	-
				Solid	109	3.72		-	-
				Liquid	56.3	2.77		-	-
*FU: Functional Unit; GWP: Global Warming Potential; AP: Acidification Potential; EP: Eutrophication Potential; LU: Land Use									

4.3.3 Interpretation of environmental assessment case scenarios results

a. Global Warming Potential

The amount of GHG emitted in the atmosphere has contributed to the increase of eath’s atmosphere through absorption of energy and slowing the rate of energy that scapes to space. The environmental assessment showed that the highest contributor for GWP in feed management was caused by the production of crops used to formulate the feeds for the pigs. Similarly, the influence of transport of materials such as maize, soybean, and so on describe in section 4.2.6 from farm site to factory added an impact on the GWP contributing to about 16.54% of the total GWP.

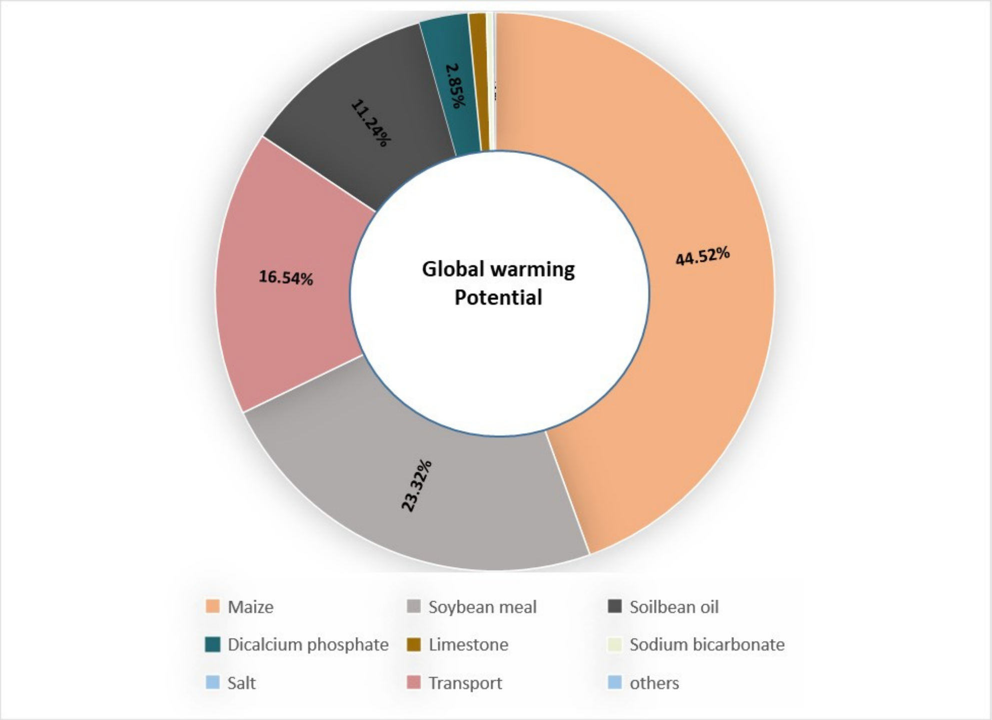


Figure 4-4 Global warming potential of feed management

The utilisation of reduction systems within the housing of livestock showed no significant difference between utilisation of scrubber and biotrickling in terms of the GWP. This is in contrast with the finding of De Vries et al., (2017) which states that biotrickling has a higher GWP impact compared with the utilisation of a scrubbing unit. The difference in the assessment result accounts to the exclusion of denitrification process in the designed cases scenario where higher N_2O production. However, the analysis showed that additional cost is added for the construction of each reduction system. Especially, about 12.20 kg CO_2-eq with the greatest contribution from the utilisation of electricity was found for the operation of the scrubber system and biotrickling. Similar findings were found when a biofilter method was used with a GWP of 6.10 kg CO_2-eq, this is 50% lower than the use of the air scrubber systems. Overall, the scenario cases in Figure 4-5 showed to have the highest GWP impact in terms of manure storage and processing with an average contribution of 43.10%, followed by raw feed management (32.47%), and the housing management (24.42%).

The assessment of scenario cases showed that the manure storage and management separating liquid, and solid feces showed an average emission of 2.65kg CO_2-eq. These results accounted for the prolonged exposure of the manure into various bacteria that breakdown organic manure matters into gases such as odour, ammonia, and other GHG causing gases. Whereas, the utilisation of anaerobic bacteria to breakdown organic manure matter showed a 30.18% reduced GWP potential or an average of 1.85 CO_2-eq. One factor that influences the assessment result is the conversion of methane to renewable energy that can be used within the farm such as heating systems during the cold season. In summary analysis of the results showed that the highest contribution for global warming potential was nitrous oxide while carbon dioxide showed the least environmental important greenhouse gases this is in agreement with the finding of De Vries (2017).

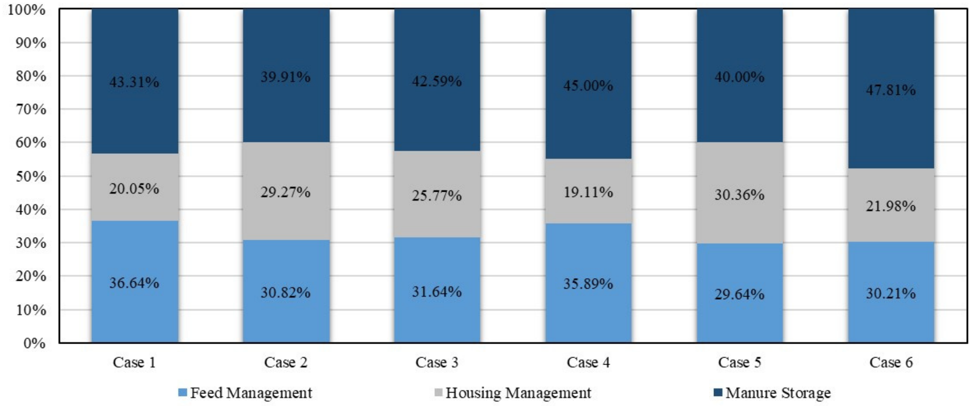


Figure 4-5 GWP environmental impact distribution according to scenario case

b. Acidification Potential

The fundamental gas that determines the acidification of both land and water are sulphur dioxide, nitrous oxide, and reduced nitrogen. In the livestock industry, the most important sources of acidifying emissions are storage and processing of manure slurries. Similar with the GWP, it was identified that the most important sources of acidifying emissions livestock production are manure storage and processing with an average contribution of 43.53%. This is followed by feed management and housing management with an average contribution of 30.12% and 26.35 respectively. The influence of feed production in terms of acidification potential is shown in Figure 4-6. Similar to that in GWP, the raw materials used for the production of low crude protein feeds plays a big part in the eutrophication potential. This is followed be the transportation of harvested produce from farm lot to the feed factory.

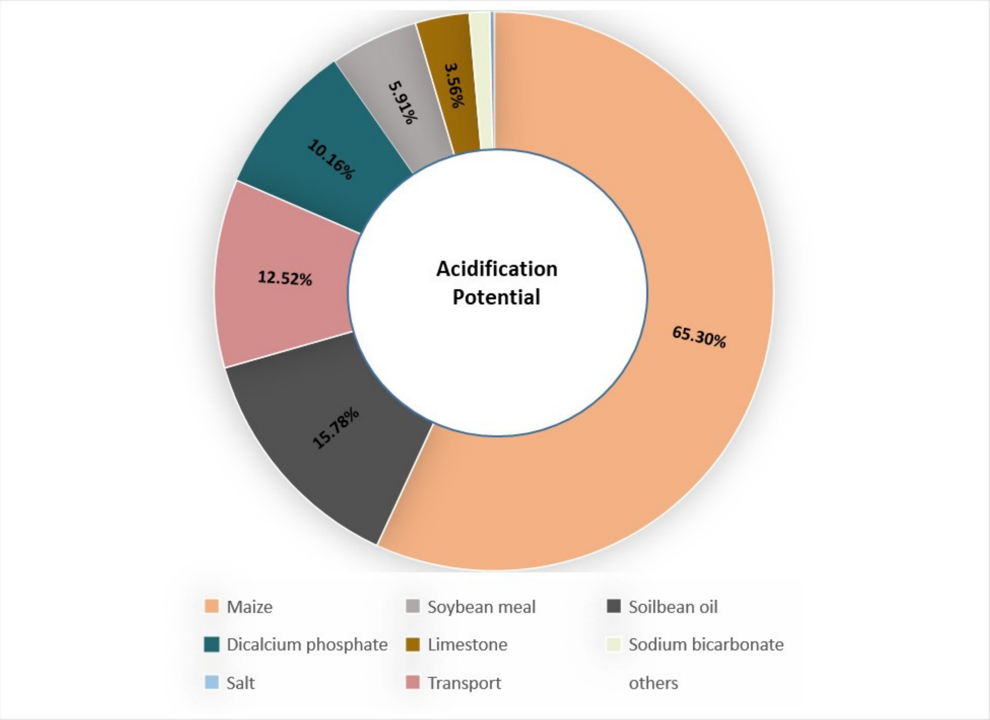


Figure 4-6 Acidification potential of feed management

Morover, emission was found to be lesser in case where liquid and solid feces were separated (Case 1, Case 2, and Case 3). This analysis was in contrast with the GWP findings which indicated that manure storage utilizing anaerobic digestion has lower environmental burden contribution. The root cause for this can be found in the manure management systems, indicating that manure in slurry form will cause greater ammonia emissions compared to manures where solid and liquid substances were separated. As agreed, the separation of solid and liquid feces has different acidification effects. For instance, solid manure was found to emit higher GHG compared to liquid slurry. These findings match with the result of scenario analysis that showed that utilizing the manure as feedstock for an anaerobic digester has an average of 28.01 % higher acidification potential. Presented in Figure 4-7 is detailed analysis results related to the acidification potential of various scenario cases. This result however, can be increased when the solid feces were applied as soil enhancer of farm lots which adds to environmental burden (Makara et al., 2019).

The Figure 4-7 illustrated the detailed environmental contribution of different scenario cases analysed in the study. Identical to that result found in GWP, the influence of manure storage, and processing has the greatest contribution of AP with 48.55%, 43.61%, 46.73%,40.56%, 39.21%, and 42.51% for Case 1, Case 2, Case 3, Case 4, Case 5, and Case 6, respectively.

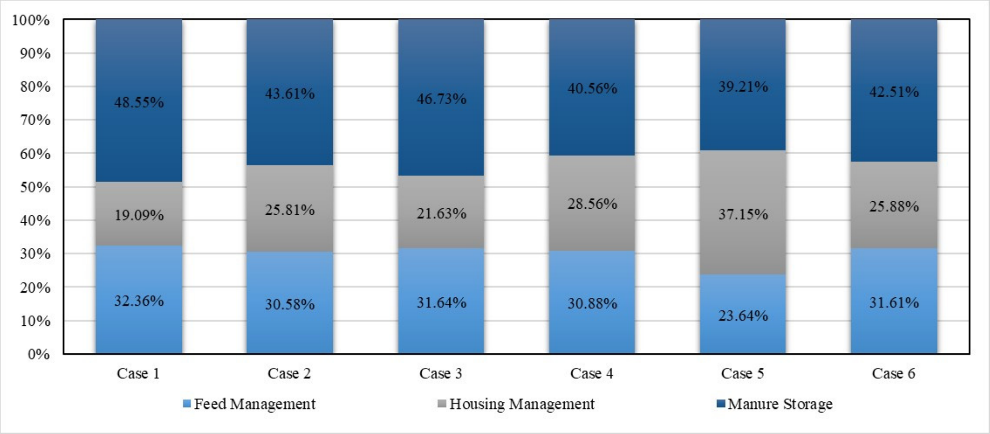


Figure 4-7 AP environmental impact distribution according to scenario case

c. Eutrophication Potential

The eutrophication potential by definition is a condition that leads to the environmental impact on the terrestrial and aquatic systems due to the excessive production of nitrogen and phosphorus (Guinee, 2001). Typically, the eutrophication potential results are given as phosphate equivalents (PO_4-eq) and characterization factors for different nutrients. Among the categories that were evaluated in this study, the highest source of nitrogen and phosphorus is through the manure generation. However, these nitrogen and phosphorus emissions can be reduced through manipulation of feeding operations and diet manipulation (EPA, 2018). Thus, modifying the type of diet the livestock is taking will result in a positive reduction of nitrogen and manure generation. In addition, analysis of the results showed that the ammonia emission into air and nitrate emission into water has a predominant effect on the eutrophication potential.

The result of scenario analysis in this study is summarized in Figure 4-8. Based on the result, the eutrophication potential showed highest in the manure storage and processing. Overall, the eutrophication potential per kg weight pig has a positive correlation with the GWP. This means that in every increase of GWP, there is also an increase in the eutrophication potential and vice versa. This statement accord with the statement of Heibela et al., (2021) which state that both the GWP and EP are statistically correlated.

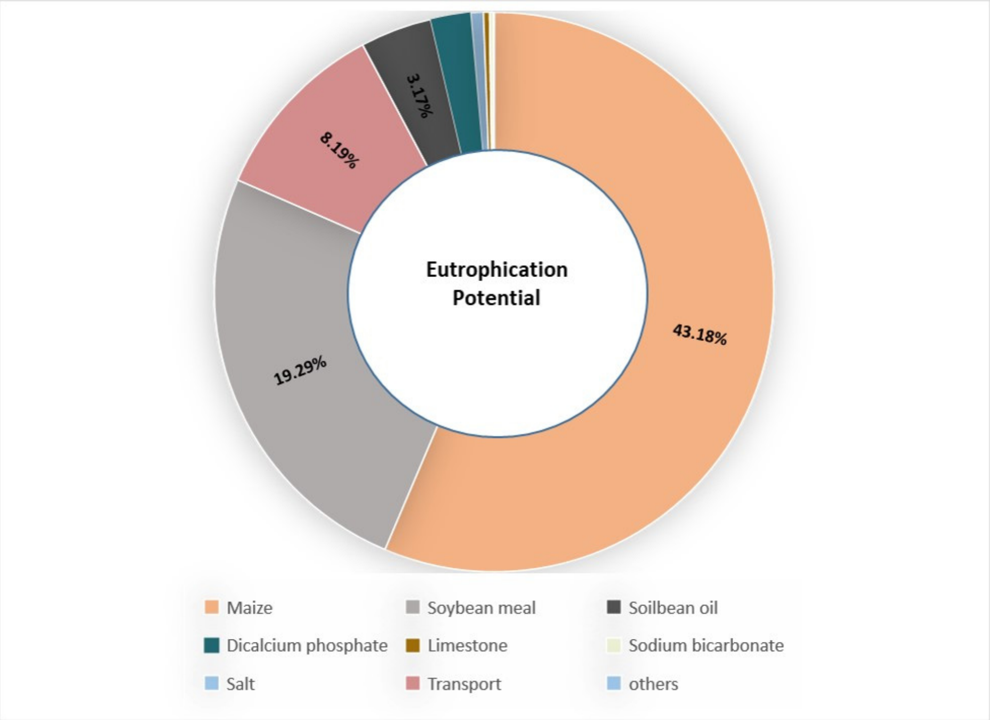


Figure 4-8 Eutrophication potential of feed management

For scenario cases, the feed management for was found to contribute to 20.46 to 38.99% of the total EP depending on the scenario cases being studied. As previously emphasized, the raw materials used to produce the feeds paid the highest environmental burden. In addition, reducing protein content in feed is the most important mitigation option to improve the sustainability of animal production (Esteves et al.,2021). In the case of housing and manure storage, De Vries et al., (2015) on the other hand suggested that mitigation actions such as segregation of urine and feces inside housing, the addition of zeolite to solid manure, and sealed storage in integrated manure management. In the case of housing management, an increased eutrophication found using biotrickling as shown in Figure 4-9. This in agreement with the findings of other studies which indicated that there is an increase in eutrophication of 0.061 kg-N-eq due to the increase of N_2O. This may be due to higher emission of ammonia within the livestock building. This result was in agreement with other researches which indicated that ammonia was one of the most important gases causing eutrophication in livestock.

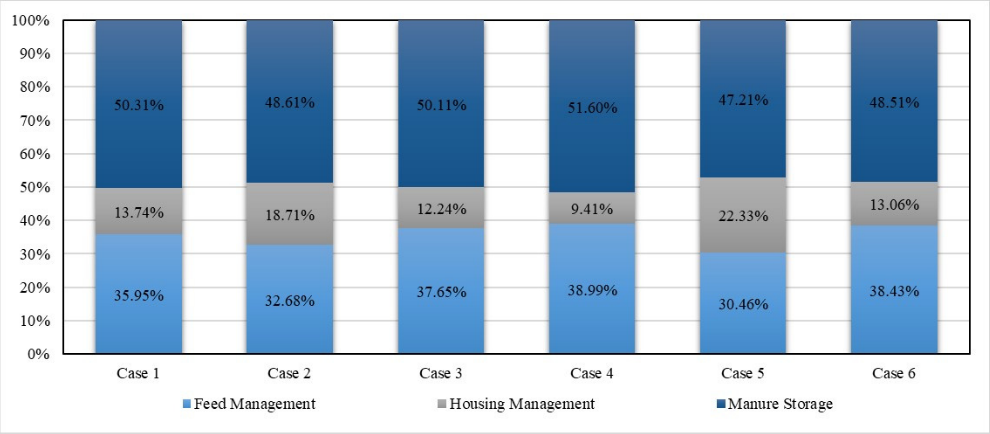


Figure 4-9 EP environmental impact distribution according to scenario case

d. Landuse and Cummulative Energy Demand

The land occupation used for the production of livestock animals plays a key role in determining how much land area needs to be used to grow 1 animal type. At present, land use is considered as the main driver for loss in diversity (de Baan et al., 2013). This statement is made especially true when forest areas are converted into the farm to produce raw material for animal feeds. Specifically, landuse for livestock production is unavoidably attached to the production of raw materials for feeds as it cannot be produced without utilizing the land. In addition, landuse has also an impact on the GHG emission from the land such as emission of methane and nitrous oxide. This GHG emission is somewhat related to the emission that resulted from the use of fertiliser on arable land.

Among the scenario categories included in the analysis of this study showed that feed management showed the highest landuse requirement for all scenario cases. In the scenario, since the percent crude protein content only considered 1 case, the literatures states that the impact of land use is reduced with the decrease in protein concentration of any feed type (Esteves et al., 2021).

On the other hand, additional criteria added in the evaluation is the cumulative energy demand which refers to the total energy that is directly or indirectly used throughout the life cycle of a product. This energy includes both renewable and non-renewable energy sources such as fossil, nuclear, biomass, wind solar, geothermal, and water) used in the whole system. This impact category is usually expressed in megajoules (MJ) units. Among the scenario categories, both the feed management and housing management utilised the highest cumulative energy (Table 4-5).

Table 4-5. Energy demand according to scenario case

Scenario Case	CED (MJ)	LU (m^2)
Case 1	8.44×10^0	9.20×10^{-2}
Case 2	4.30×10^0	8.10×10^{-1}
Case 3	3.42×10^1	1.00×10^{-2}
Case 4	1.24×10^1	8.90×10^{-2}
Case 5	5.20×10^0	6.35×10^{-1}
Case 6	4.89×10^1	2.89×10^{-1}

The assessment showed that the highest contributor of energy demand production were accounted to housing management (62%) and housing management (235), which were found to be the key drivers for eutrophication potential This is similar to the study of Leinonen et al.,(2012), which also found that feed production contributed greatly to primary energy use, along with processing and transport.

4.3.4 Comparison with other mitigation techniques

The summary of environmental burden analysed according to different odour and mitigation techniques is summarized in Table 4-6. The result of the analysis showed even though a positive ammonia and odour reduction was found in each technology, an additional burden can be added to the production system. This is especially true if the system will utilise more resources such as energy (for lighting, electricity, etc) and raw materials (HDPE, aluminium, crops, etc).

Based on the result, Case 5 which utilised a reduced crude protein diet, biofilter, and anaerobic digester possess less environmental burden to the environment. This was followed by Case 3 which utilised reduced crude protein diet, biofilter, and feces separation. This result may be accounted to the use of lesser energy input in the boundary system. Moreover, in Case 5, since AD can convert methane gas to renewable energy, the environmental burden caused by the electricity can be offset.

As high energy and water requirement is needed in the utilisation of air scrubber system and biotrickling, the GWP, AP, and EP also showed noticeable lower emission values

Table 4-6. Detailed summary of environmental burden according to scenario cases.

Scenario Cases	GWP ($kg\ CO_2$-eq)	AP ($kg\ SO_2$-eq)	EP ($kg\ PO_4$-eq)
Case 1	$1.62 \times 10\text{-}^{1}$	8.42×10^{-1}	7.30×10^{0}
Case 2	1.00×10^{-1}	3.22×10^{-1}	1.00×10^{-3}
Case 3	2.23×10^{-1}	1.25×10^{0}	7.82×10^{-2}
Case 4	1.44×10^{-1}	1.58×10^{0}	7.70×10^{-2}
Case 5	9.54×10^{-2}	6.50×10^{-1}	3.10×10^{-3}
Case 6	1.85×10^{0}	3.62×10^{0}	9.50×10^{-2}

4.5. Conclusion

This study is divided into three parts. First, a brief overview of common livestock odour and GHG sources was presented. This section aimed to identify which among the different livestock odour and GHG emission sources contributes to the highest emission. From this, it was found that three major phases had the highest impact on livestock emissions that included feed management, housing management, and manure storage and processing. The second stage involved the review of different odour and GHG technologies commonly used in livestock production that fall under the categories identified as the major contributors of livestock emission. The reduction efficiency and advantages of each system were also presented to identify the widely used systems in animal production. Analysis showed that the type of systems used for livestock odour and GHG emission reduction would greatly depend on how long the animals were bred and how the livestock manure was stored. The third and last stages of the study focussed on the evaluation of the environmental impact of different mitigation techniques. A total of 6 scenario cases involving mitigation method for feed management, housing management, and manure storage and processing was evaluated. Although the result analysis showed no pattern for each mitigation method, it was identified that the sequence of processes that contributed to environmental burden was through manure storage and processing (storage, transport) followed by feed management (feed ingredients production and transport) and housing management (energy and water use) which had less contribution to GWP, AP, and EP. In the same manner, the results showed that the method and location where the raw materials were developed also had high GWP which was mainly the effect of transportation and hauling cost. At this point, it is recommended that a more detailed scenario cases that separated each mitigation techniques should be done so that the mitigation hotspot for livestock production will be determined.

Chapter 5. Odour Potential Pathways for Pig Production using LCA

5.1. Introduction

With the continuous increase in livestock production to meet the demand for the population's consumption, the emission of livestock odour has increased significantly. As such, odour pollution is generally treated as a nuisance in countries where livestock production has greatly intensified. For instance, despite having a reduced number of livestock farms, the breeding size of livestock production in South Korea was increased by 26.2% in the recent 10 years. There were also about 33.65 million m^3 per year of odour-causing manure produced. Thus, livestock odour becomes a crucial topic in the livestock industry not only due to its social impacts but also its health impacts for both humans and animals. In fact, the recent record from Statistics Korea (2019) showed that 32.20% of the farm operated were subjected to legal complaints caused by the odour emitted from the farms. To cope with this problem, technologies and regulations were developed to regulate the effect of livestock odour on the public.

In South Korea, the largest portion of production which is about 40% of the total livestock industry in the country accounts for the pig industry (Ministry of Agriculture Food and Rural Affairs, 2018). Of the total manure generated from livestock facilities, about 53.0% accounted for the manure produced from the pig facilities (Ministry of Environment, 2019). The increased generation of manure has significantly affected the amount of odour emitted outside the pig facilities (Lorenzo et al., 2015). Odourous emissions are a key concern for intensive pig production. Odour, by definition, is caused by the continuous microbial degradation of organic substances such as animal feces, urine, and feeds that were usually wasted during the feeding process. It is comprised of hundreds of gas components released into the air, especially carboxylic acids, phenols, aldehydes, ammonia, and others with different concentrations. Technically, odours from manure storage (20%), buildings (30%), and manure field application (50%) were known to be the main sources of odour from pig houses (Mielcarek and Rzeznik, 2015). As stated by Decano-Valentin et al., (2022), the amount of odour emitted from pig facilities can be transported at varying rates depending on animal age, frequency of manure cleaning, feeding systems and so on. Moreover, these odourous substances can be dispersed at further distances downwind of the source due to poor odour mixing with external air. For the past years, many technologies have been developed by researchers with the sole purpose of reducing odour which can fall into either physical, chemical, or biological techniques. These techniques include manipulation of feed diet (Liu et al., 2014; Philippe and Nicks, 2014; Montes et al., 2013), housing management (Dumont et al., 2014; Montes et al., 2013; Lim et al., 2012; Akdeniz and Janni, 2012), and manure management (Blanes-Vidal et al., 2008; Melse et al.,2012; Aarnink et al., 2011; Parker et al., 2012).

In context, the amount of odour present in the atmosphere is often monitored and controlled at specific concentrations specified both by international and domestic standards. The European standard EN 13725 (CEN 2003) which defines odour as an organoleptic attribute perceptible by the olfactory organ. Sniffing certain volatile substances is one of the widely used methodologies to monitor the amount of odour in the atmosphere. However, compared with the greenhouse gas assessment, the attempts to incorporate the odour with life cycle assessment (LCA) have received little to no attention for the past years. Life cycle assessment which is widely known as an efficient method for evaluating the environmental impact of various processes and products usually excludes the analysis of livestock odour due to its complexity in terms of spatial and temporal scales (Zhao et al., 2015). Currently, very few researchers have discussed life cycle assessment and odour (Alfosin et al, 2015; Alfonsin et al., 2013; Bindra et al., 2015; Cadena et al., 2018; Marchand et al., 2013; Peters et al., 2014). In addition, most of these studies were applied for industrial and commercial purposes and almost no attempt was made to concentrate research on pig production.

Therefore, this study aims to analyze pathways and integrate the odourous impacts potential associated with pig production using life cycle assessment tools. The odour impact potential referred to in this study was used to evaluate the environmental impact of odourous emissions that were not widely discussed in the field of LCA. This method was first introduced by Heijung et al., (1992) using the "malodourous air" using the OTV in Guide and Background of LCA. The next attempt was when Cadena et al., (2018) utilised the odour impact potential solely to assess the waste management plants for plant management benchmarking. Thus, in this study, measured odour emissions exclusively from pig houses were evaluated and integrated into the LCA analysis. Through the evaluation of odour impact potential, the possibility of integrating field-measured data and LCA becames viable.

5.2. Materials and Methods

With the aim of integrating the odour impact potential and odour, this study followed the research flow shown in Figure 5-1. Firstly, the field measure odour concentration was obtained in a real pig farms following the standard procedure of capturing odour inside pig facilities. The collected odour was then evaluated using the standard dynamic olfactometry (EN13725). The measured odour concentration values were integrated with LCA methodology following the established odour impact potential pathway described in Figure 5-2.

Theoretically, the odour impact potential will indicate how much odourous samples must be diluted with clean air to obtain a detectable odour concentration. The definition just stated is similar to the definition for olfactometric measurement which corresponds to OU/m^3. However, in LCA studies, the amount of clean air (m^3) should be referred to as a functional unit.

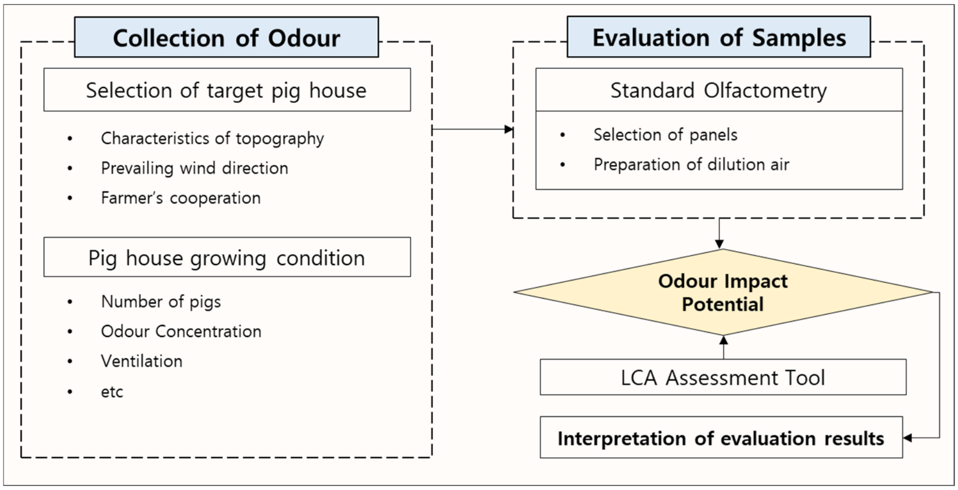


Figure 5-1 Conceptual framework of the assessment

5.2.1 Selection of experimental pig house for odour collection

The selected experimental pig house which was comprised of 15 pig buildings was located in Chungcheongbuk-do, Eumseong-gun, Samseong-myeon, Cheonpyeong-ri, South Korea (36o 58’ 51“ N 127o 29’ 49“ E, Elevation: 99 m). The satellite image of the pig farm as can be seen in Figure 5-2a shows that the target experimental farm is situated in an almost flat topography with no hills or mountains nearby. Figure 5-2b on the other hand, showcased both the external and internal conditions of the pig facilities. In this study, a total of three pig buildings were selected as experimental buildings where long-term field experiment was conducted. The Building #1 housedgrowing pigs, while Building #2 and Building #10 houses fattening pigs and weaners, respectively. The target pig farm used mechanical ventilation which was either side exhaust or roof-chimney exhaust fans with a minimum diameter of 300 mm. A detailed description of the ventilation of the selected facilities is shown in Table 5-1. The pig farm practised an “All-in-All-out” breeding production where pigs of a certain age were housed in a pig building and were moved at once after each rearing period.

(a)

(b)

Figure 5-2 a) Satellite Image of the experimental farm, b) external and internal conditions of the pig buildings

Table 5- 1.Detailed specification of the target experimental pig houses.

Specification	Building #1	Building#2	Building #10
Type of pig	Grower	Fatteners	Weaners
Building Specification			
Dimension (L x W)	31 m × 13 m	58 m ×13 m	29 m × 8 m
Ridge Height	4.73 m		4.40 m
Eave Height	2.86 m		2.78 m
Ventilation Specification			
Ventilation Type	Roof-chimney	Roof-chimney	Sidewall
Number of Fans	4 (300 mm Ø)	5 (300 mm Ø)	3 (300 mm Ø)

5.2.2 Field experiment to analyse the internal condition

To analyse the odour emitted from the pig house, it is important to observe both the internal and external conditions of the pig building. The internal environment mentioned refers to temperature, humidity, ventilation, number of growing pig, etc. Most importantly, the ventilation flow of each experimental building is a crucial factor that affects the internal environment of pig houses. A properly ventilated pig house will provide an appropriate growing environment for the pigs and a good working environment for both farmworkers and animals grown inside the pig building. In the case of most odour dispersion research, the actual ventilation flow inside each building facility determines the actual emission of odourous air in the atmosphere. For this reason, it is important to determine the actual flowrate of each ventilation fan installed in each pig building. In this study, a TESTO manufactured sensors were used. Throughout the conduct of the field experiment, two types of airflow meters were utilised as shown in Figure 5-3. In the case of higher wind airflow, the hot wire anemometer was used instead of using the flow hood meter that is only capable of measuring a lower air flow.

The compact temperature and humidity sensor used a Hobo data logger (UX100-003, Onset computer corporation, USA), which is 3.66×8.48×1.52 cm in size and weight suitable for attachment to a string with a weight of about 30 g. Small temperature and humidity sensors can freely adjust the measurement time interval from 1 second to 9 hours and store up to 84,650 data. In this study, three Hobo data loggers (UX100-003, Onset computer corporation, USA) were strategically placed at the centre aisle inside the target pig house to measure the real-time internal temperature and humidity of all the selected pig houses. In summary, the field experiment was conducted from June to September 2021 at the target experimental farm.

Figure 5-3 Device used to measure the ventilation rate

5.2.3 Analysis of odour concentration

The odourous air samples were collected using a commercially available gas collector that was strategically placed inside the target pig house. Following the field experiment, a sensory evaluation was conducted to determine the concentration of odour obtained from various sampling points. The test method followed the air dilution sensory guidelines of the odour process test. The collected air samples were transported to the laboratory for sensory evaluation within 24 hours and were kept at room temperature (15 to 25 °C) to maintain the quality of samples obtained from the field. After the samples have been collected and transported to the laboratory, the next step was to screen the panels that would evaluate the odourous air. When evaluating the odour samples, odour panel must have proper olfaction. Thus, an olfaction test kit was used to evaluate if the panel had the minimum requirements. A minimum of five panels were selected to evaluate the collected samples from the farm.

Accordingly, the sensory evaluation followed the following steps: first, a certain amount of air was extracted using a syringe from the odourous samples collected from the field. Second, the extracted odourous air was mixed with the odourless air, and diluted depending on the desired dilution. In addition, two odourless air bags were also made to provide three air bags to all panels. Lastly, the air samples were evaluated by panelists by sniffing all the three samples. Each of the panel member must select which among the three samples contain the diluted odour. When evaluating odour sensitivity, a multiple test with dilution multiples of 3, 10, 30, 100, 300, 1,000, and 3,000 times was conducted. Presented in Figure 5-4 are the equipment and materials used to collect and evaluate the odour emission from the pig houses. This includes the odour chamber and odourless air production device which was composed of an air filter and a large amount of activated carbon chamber. The polyester aluminium bags for air with 10L capacity with installation ring was used for the convenience of transportation and storage after collecting the samples. The air sample collectors were installed with 10L polyester aluminium bags (Top-Trading Corp, South Korea) where the air samples were stored and properly secured. Each of the collected air samples was carefully transported and evaluated within 24 hours after the collection

Figure 5-4. Evaluation of odour concentration using olfactometry method

5.2.4 LCA-established framework for odour

A classical odour framework for evaluating the odour impacts in LCA was adopted as shown in Figure 5-5. This framework recognizes the different challenges in incorporating the field-measured odour into the different phases of LCA. Under this framework, it was emphasized that environmental impacts usually occur in human health, ecosystem functions, and natural resources (Goedkoop et al., 2009). Moreover, it also identified two major impact points if the odour was integrated with LCA methodology. Firstly, midpoint indicators were based on some aggregating procedure for the burden placed on the environment by different emissions without describing the actual extent of the environmental damage, whereas, the endpoint impact indicates the effect of odour emission on parameters such as human health, animal health, landuse, and so on. In the case of odour impact potential for pig production, LCA under the midpoint impacts category was considered as no data are available for endpoint category were collected. Therefore, the qualitative impact potential of odour emitted from pig facility was only included in this study and the potential nuisance for both human and animals after inhalation was disregarded.

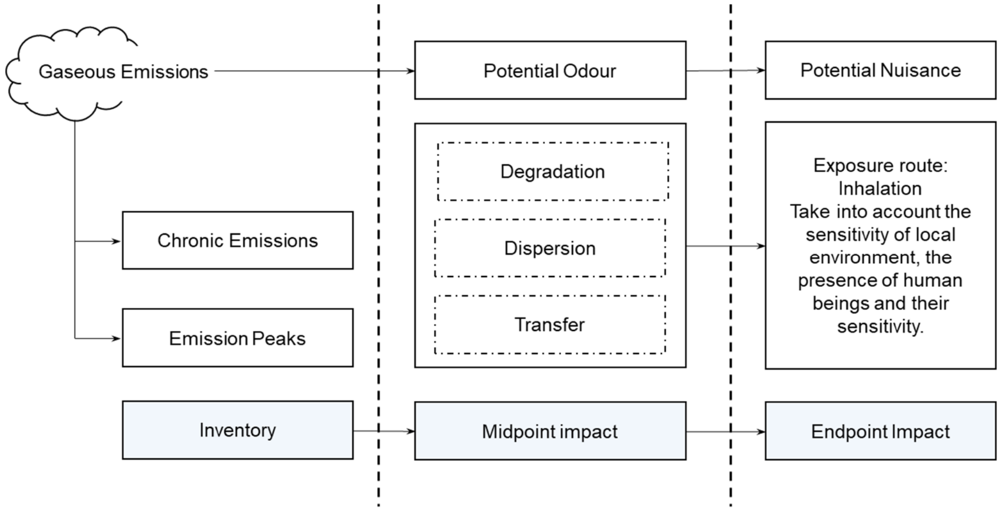


Figure 5-5 General framework of odour LCA (Improved from Peter et al., 2014)

a. Functional Unit

The first phase of any LCA-related study involves the goal and scope definition. Under this phase, the audience and how the study should be executed must be identified (McAuliffe et al., 2016). In this study, we aimed to integrate the field measured olfactometric data with LCA. Thus, the functional unit (FU) which was used in the study corresponded to OU pig^{-1}.

5.2.5 Odour impact potential determination

The focus of the LCA is to assess the environmental impacts of odour in the pig industry and help provide a framework for environmentally conscious decision-making. The environmental impact assessment of the selected models was implemented using the open-source LCA-based model called OpenLCA. This software can be used to perform LCA; provide data on life cycle inventory, characterisation, normalisation and weighting, and determine impacts on more than 10 environmental categories. The LCI step leading to the odour footprint is no different to the usual LCI step in LCA, with the exception that the analyst must have some knowledge of the typical odourants for the product or process under assessment.

As the odour emitted inside the pig facilities was comprised of different individual gases, it was impossible to utilise the readily available data sets for OTV for single gas. Thus, to determine the odour impact potential, the odour concentration was assumed to be represented by n-butanol gas equivalent to 123 micrograms as specified in EN 13725 (Standard dynamic olfactometry).

5.3. Results and Discussions

5.3.1 Field measured data inside pig buildings

Summarized in Table 5-2 and Table 5-3 are the breeding details during the conduct of the field experiment. The 1st to 5th experimental schedule represents the date when the field experiments were conducted.

Shown in Table 5-2 are the evaluation results on odour concentration conducted at the target experimental farm. As mentioned previously, the odour concentration evaluation inside each pig house followed standard procedures which were done within 24 hours after the samples had been collected. In general, the measured odour concentration inside each pig house varied depending on external temperature, ventilation rate, growing period and number of heads grown in the facility. However, a general trend was observed from the field measured data where the odour concentration inside each pig house tended to increase with the decrease in ventilation rate. For example, by comparing the odour concentration measured on August 11 and September 6, when the ventilation rate changed from 5,822 CHM to 1,908 CHM (67.2% ventilation reduction), the odour concentration for Building#10 was increased 10 times. This finding was in agreement with the result published by Shauberger et al., (2012) which stated that odour emission increases with the increase of ventilation rate. In addition, those pig houses with a higher number of pig head showed a higher odour concentration value. The average odour concentration inside the pig house was evaluated to have 298.0 OU m^{-3}, 620.7OU m^{-3}, and 953.4 OU m^{-3} for pigs in Building #1, Building #2, and Building #10, respectively.

In summary, the amount of odour concentration emitted from each experimental pig house varied through the experiment period which may account for the amount of ventilation, growing density, and age of the pig. The ventilation rate varied depending on the outside temperature. A reduced ventilation rate of exhaust fans resulted in an increased inside odour concentration. Secondly, the growing density of pigs inside each pig house influenced the total odour concentration accumulated within the pig house. Lastly, in the case of the age of the pig, a positive correlation between the age of the pig and the amount of odour emission generation was determined. This means that with the increase in the age of the pig, the odour emission also increased. Considering all of this, a direct comparison between the result of the field experiment evaluating the odour emission in pig houses was quite difficult as various parameters present within the experimental pig house were different in every experimental procedure. Nevertheless, the field-measured odour concentration obtained in this study can be used as an input value to test the accuracy of the developed dispersion models.

Table 5-2. Number of pig heads during the conduct of field experiment

Experimental schedule	Number of heads		
	Building #1	Building #2	Building #10
1st	340	424	168
2nd	332	160	164
3rd	335	835	161
4th	332	800	168
5th	332	800	168

Table 5-3. Number of growing days during the conduct of field experiment

Experimental schedule	Days		
	Building #1	Building #2	Building #10
1st	117	175	29
2nd	133	190	45
3rd	145	75	56
4th	170	100	44
5th	191	121	24

Table 5-4. Measured odour concentration inside the selected pig houses

Date		External Temperature (°C)	Odour Concentration ($OU\ m^{-3}$)		
			Building #1	Building #2	Building #10
30-Jun	1st	25.9	173.2	448.1	448.1
11-Aug	2nd	29.1	81.8	448.1	144.2
6-Sep	3rd	23.5	3107.0	1442.0	1442
22-Sep	4th	22.6	310.7	208.0	7.1
5-Oct	5th	26.2	2080.0	669.0	66.9
Average		25.46	1150.54	643.04	421.66

Building#1: Fatteners/ Grower; *Building#2: Fatteners/ Grower; *Building#10: Weaners

5.3.2 Odour impact potential determination from olfactometric data

The amount of odour present in the atmosphere is normally evaluated based on olfaction methods. This method usually employed at least five evaluators called "panels" who participate to test samples diluted at different ratios. The dilution ratio that half of the panellists cannot correctly identify was determined to be the odour concentration of the sample. This method, which can avoid the synergy and masking effects of compounds, plays an important role in evaluating the odour pollution levels for existing and real gas samples.

In this study, in the odour impact potential did not consider the amount of odourous air emitted outside the target experimental building. This means that the odour collected inside the pig buildings was the focus of the analysis.

Following the LCA framework illustrated in Figure 5-5, the odour impact potential for each experimental pig building was evaluated. Table 5-4 summarized the result of the assessment result using the average odour concentration measured inside the experimental pig farm.

Table 5-5. Average odour impact potential using the olfactometric data

	Odour Impact Potential (kg n-butanol-eq)	AP (kg SO_2-eq)	GWP (kg CO_2-eq)	EP (kg PO_4-eq)
Building #1	7.12×10^{-1}	5.68×10^{-1}	3.5×10^{1}	1.47×10^{-2}
Building #2	3.8×10^{-1}	8.12×10^{-2}	1.66×10^{1}	1.77×10^{-2}
Building #10	1.6×10^{-2}	$1.16 \times 10-^{3}$	$1.14 \times 10-^{2}$	1.63×10^{-1}

Since the odour emitted from pig building was complex, the odour impact potential was assumed to have a unit value of n-butanol. Accordingly, the odour impact potential from Building #1 had the highest value. This computed result may account for the difference in the growth stage and number of housed pigs inside the facility. On the other hand, the odour impact potential was observed to be significantly lower in the building housing weaning pigs which also corresponds to lower odour unit compared to Building #1 and Building #2. In terms of the acidification potential, global warming potential and eutrophication potential, an approximate 5 folds lower impact was observed to the building growing lower number of pigs

The additional potential of LCA is its capability to execute environmental impact contribution analysis on the specific material or process. Table 5-4 showcases the specific impact contribution of the input materials for the specified pig house building considered in the study. It must be noted that the result shown in each reflects only the dominant materials causing environmental impact and those with very little contribution were excluded. Moreover, those materials with less than 1% contribution were not labelled for better analysis. The top five main contributors of environmental burdens include the use of zinc coating coils, and the low alloyed steel used for the pig house facilities.

5.3.3 Impact assessment

This section of the study attempted to utilise the improved pathway of LCA methodology for odourous emission including the midpoint indicator to express both the detectability and the persistence of an odourous emission from pig facilities. While the result and methodology were not intended to complete assessment of an odourant removal technology, the article wanted to step- up the direction of a new impact category for odour which was not commonly included in the LCA research. More importantly, the methodology's purpose was to suggests that consideration of an odour indicator in LCA by odour control equipment is necessary. Odour reduction technologies are often installed with the sole purpose of reducing odour. An LCA ignoring the environmental impact of odour will always be unfavourablefor odour reduction technologies as extra energy and materials are required. However, the case also demonstrated some shortcomings of the method developed. One weakness study, and the established methods for assessment of odour in LCA, is that the synergistic effects and impacts of degradation products were not considered.

5.4. Conclusion

The pig industry, which occupies the highest share in the livestock industry, is being challenged to maximize its production. However, the number of pig farm households has been steadily decreasing since 2000, while the number of the pig head produced is steadily increasing every year. Because pigs are now intensively raised in the poor environments of pig houses, increased emission of odourous air dispersed in the atmosphere. Thus, the problem concerning odour has greatly intensified. Though the concentration of livestock odour can be evaluated using standard procedure such as those in EN 13725, the impact to environment is still unknown.

This study attempted to incorporate the odour measured in pig facilities in the LCA tool through evaluation of odour impact potential. The purpose of this was to be able to include the odour impact potential in LCA studies related to pig production. Through this, became possible to assess the potential impact of an installation by odourous emissions, an area not widely explored in LCA studies.

Chapter 6. Conclusion

The environmental impact of the utilisation of heating and cooling system agricultural greenhouses for livestock and horticultural production that apply new trends has been explored in this study with the use of life cycle assessment (LCA) and building energy simulation (BES). Modern greenhouses for livestock and horticulture have embraced the application of ICT, device control, and automation which made the whole structure dependent on energy for operation. A big chunk of the energy consumption of these greenhouse designs are contributed by the heating and cooling system. The environmental impact of such system is not yet fully assessed and detailed information of it is limited in the literature. The availability of such information would be helpful to establish mitigation control measures and possibly a lead to improve the existing designs of greenhouses. This study was conducted to assess the environmental impact of the heating and cooling system of agricultural greenhouses for livestock and horticulture.

The objectives of the study were: a) to identify the current integration approaches used to combine BES and LCA results to assess the environmental impact of different heating systems such as absorption heat pump (AHP) using energy from thermal effluent, electricity-powered heat pump, and kerosene-powered boilers used in a conventional multi-span Korean greenhouse; b) to review and conduct impact analysis of various odour and GHG mitigation techniques used for the production of livestock animals; c) to determine which among the different livestock activities contributes to the highest emission; d) to conduct a comprehensive review of different odour and GHG technologies commonly used in livestock production; and e) to evaluate the impact of different mitigation techniques previously identified.

Results of the study revealed that the environmental impact of the kerosene powered boiler is largest in terms of the acidification potential (1.15 x 10^0 kg SO_2-eq), global warming potential (1.13 x 10^2 kg CO_2-eq), and eutrophication potential (1.62 x 10^{-1} kg PO_4-eq). The main contributor for greenhouse gas emission was caused by the type, amount and source of energy used to heat the greenhouse. Furthermore, global warming potential was highest by 35.12% and 21.75% in cattle production compared to swine and poultry production, respectively. Similarly, in the case of manure management, solid manure was found to emit higher GHG compared to liquid slurry. Finally, it was revealed that the three major phases in livestock production have the highest impact on livestock emissions that includes feed management, housing management, and manure storage and processing. Systems used for livestock odour and GHG emission reduction was dependent on the duration of animals breeding and manure storage. Frequency and method of manure removal contributed to the highest GWP, AP, and EP for all types of livestock animals considered in the analysis.

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Annex

A. Literatures related to LCA in Agriculture

Reference	Technology	Ammonia	H_2S	Odour	GHG
A. Feeds Management					
Liu et al, 2014	Feed Manipulation	NS-79%	-	-11-59%	-
Philippe and Nicks, 2014	Feed Manipulation	-	-	-	-24-25% CO_2 -153% CH_4
Montes et al., 2013.	Feed Manipulation	reduced protein >30%	-	-	10-30% CH_4
Philippe et al., 2011	Feed Manipulation	40%	-	-	-
Eriksen et al., 2010	Feed Manipulation	BA 60-70%	M increased BA reduced	-	-reduced CH_4
Liu et al., 2014	Feed Manipulation	-	-	-	-18-NS CH_4
Montes et al.,2013	Feed Manipulation	>30%	-	-	-10-30% N_2O
Li et al.,2014	Feed Manipulation	0.14	-	-	-19% CH_4
Liu et al., 2014	Feed Manipulation	-	-	-	Not significant (N_2O, CH_4,CO_2)
Carter et al., 2012	Feed Manipulation	10-39%	-300-50%	0.3	17% CH_4
Carter et al., 2012.	Feed Manipulation	reduced	-	-	reduced CH_4
Petersen and Sommer, 2011	Feed Manipulation	reduced	-	-	reduced N_2O
Liu et al.,2014	Biofilters	18-96%	23-94%	51-95%	-
Dumont et al.,2014	Biofilters	30-100%	-	-	-
Montes et al., 2013	Biofilters	>30%	-	-	<10% CH_4
Ramirez et al.,2012.	Biofilters	-	-	-	35-48% CH_4
Chen, and Hoff, 2012	Biofilters	0.41	0.83	0.51	-
Veillette et al., 2012	Biofilters	-	-	-	50-85% CH_4
Hansen et al.,2012	Biofilters	-	0.75	-	-

Akdeniz and Janni, 2012	Biofilters	61-86%	49-85%	-	-29.2-12% N_2O -21.5-27.5% CH_4 NS CO_2
Kristiansen et al., 2011	Biofilters	70-97%	-	-	-
Kristiansen, et al, 2011.	Biofilters	0.9	-0.02	-	-
Akdeniz et al., 2011	Biofilters	0.56	0.88	<48%	-25% CH_4 -0.7% N_2O
Liu et al., 2014.	Scrubbers	70-90+%	-	0.27	-
Ubeda et al., 2013	Scrubbers	0.96	-	0.3	-
Melse et al., 2012	Scrubbers	-	-	-	-
Aarnink et al., 2011	Scrubbers	25-96%	-	-	-Not significant
Battini et al., 2014	Anaerobic Digestion	-	-	-	23.7-36.5%
Koirala et al., 2013	Anaerobic Digestion	-61--7%	-	-	-
Montes et al., 2013	Anaerobic Digestion	increased	-	-	reduced CH_4 reduced N_2O
Koger et al., 2014	Urine/Feces Segregation	0.73	-	0.6	71% CH_4
Liu et al., 2014	Urine/Feces Segregation	reduced	-	reduced	-
Philippe, and Nicks, 2014.	Urine/Feces Segregation	-	-	-	Not significant -47% CO_2 -20-90% CH_4 -250-50% N_2O
Koger et al., 2014.	Urine/Feces Segregation	reduced	-	reduced	-
De Vries et al., 2013	Urine/Feces Segregation	0.75	-	0.74	80% CH_4 increased N_2O
Philippe et al., 2011	Urine/Feces Segregation	0.5	-	-	-

국 문 초 록

인구의 끊임없는 증가로 인해 식량에 대한 수요가 증가하면서 식량 부족에 대한 심각성이 대두되고 있다. 뿐만 아니라, 현재 자원 부족의 문제를 동시에 당면하고 있기 때문에 인간과 자연이 공존하며 충분한 식량을 생산하기 위한 지속 가능한 농업을 목표로 한 연구가 수행되고 있다. 또한, 충분한 식량 생산을 위한 대안과 새로운 기술에 대한 연구도 새로운 연구 초점이 되었다. 하지만, 이러한 생산 시스템은 보다 객관적인 조치 및 관리 방안을 마련하기 위해 고려해야 하는 다양한 환경 영향과 관련되어있다. 특히 농업 분야가 온실가스(GHG, Greenhouse Gas)의 배출의 상당 부분을 차지하고 있기 때문에 더욱 불가피한 실정이다.

한국 온실의 생산량은 국내 원예 생산량의 28%인 약 4 조 8 천억 원에 달할 정도로 지난 수십 년 동안 크게 증가했다. 또한, 한국의 축산 생산액은 2020 년 기준 약 22 조원으로, 국내 전체 농업 생산량의 거의 40.6%에 달하는 지속적인 성장을 보여왔다 (MAFRA 2021). 그중 연간 돼지 생산량은 47.9%를 차지하여 소(32.6%)와 가금(13.1%) 보다 큰 비중을 차지하고 있다. GHG 배출량은 가축 생산 시 가장 많이 발생하는데, 특히 장내 발효(48%)와 분뇨 살포 및 관리(22.4%)에서 가장 높다. 원예 및 축산 산업의 지속적인 성장으로 토지, 물 및 에너지 자원은 고갈되고 있고, 온실가스 배출로 인해 대기, 수질 및 토양에 심각한 영향을 미쳤다. 따라서 온실가스의 배출량과 그것이 토양, 물 및 공기에

미치는 영향을 평가하고 분석하기 위해 농업에 대한 환경 평가를 수행하는 것이 중요하다.

연구 1 은 건물 에너지 시뮬레이션(BES, Building Energy Simulation)과 통합된 환경 영향 평가(LCA, Life Cycle Assessment)를 활용한 농업용 건물인 망고 온실의 난방 시스템 영향 평가에 중점을 두었다. 특히, 현재의 BES 와 LCA 의 통합적 접근 방식을 분석하기 위해 열 배출수 에너지를 사용하는 흡수 열 펌프(AHP, Absorption heat pump), 전기 구동 열 펌프 및 기존의 다연동 온실에서 사용되는 등유 보일러와 같은 다양한 난방 시스템의 환경적 영향을 평가하였다. 연구 결과, 등유 보일러의 환경 영향이 1.15 x 100 kg SO2-eq, 1.13 x 102 kg C O2-eq, 1.62 x 10-1 kg PO4-eq 의 산성화 지수(AP, Acidification Potential), 지구 온난화 지수(GWP, Greenhouse Warming Potential) 및 부영양화 지수(EP, Eutrophication Potential) 측면에서 모두 가장 큰 것으로 나타났다. 온실가스 배출의 주요 원인은 온실의 온도를 높이기 위해 사용되는 에너지의 종류, 양, 에너지원에 따라 발생했다. 고려된 온실 가스의 유형에 따라 흡수 열 펌프가 최대 86.59%, 전력 히트펌프가 96.69%, 등유로 작동하는 열 펌프 보일러의 경우 최대 96.47% 기여했다.

연구 2 는 3 대 축산업인 소, 돼지 및 가금류와 같은 가축 생산에 사용되는 다양한 악취 및 온실가스 저감 기술에 대한 영향 분석을 검토하고 수행하는 것을 목표로 했다. 검토 결과, 사료 관리, 축사 관리, 분뇨 저장 및 처리를 포함하는 세 가지 주요 단계가 축산 배출량에 가장 큰 영향을 미치는 것으로

나타났다. 저감 방법에 따른 뚜렷한 경향성은 나타나지 않았으나 분뇨 제거의 빈도 및 방법이 GWP, AP, EP 에 기여하는 것으로 확인되었다. 3 대 축산업 중 지구온난화 지수는 소가 돼지와 가금류에 비해 각각 35.12%, 21.75% 높았다. 또한, 분뇨 관리의 경우 고형 분뇨는 액비에 비해 더 많은 온실가스를 배출하는 것으로 나타났다. 이러한 결과는 분뇨를 혐기성 소화조의 공급 원료로 활용하는 것이 모든 가축에 대해 평균 28.01% 낮은 산성화 가능성이 있음을 보여주는 분석과 일치한다.

연구 3 은 LCA 연구에서 현장에서 측정한 악취 데이터를 사용하는 것을 목표로 했다. 전통적으로, LCA 는 복잡성으로 인해 시간, 공간적 규모 측면에서 가축 악취 분석을 제외한다. 이 연구에서는 돼지 시설에서 방출되는 악취 농도를 통합하기 위한 경로를 개발했다.

Keyword: 온실난방시스템, 환경영향평가(LCA), 축산, 악취, 돼지,

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감사의 글

Have I not commanded you? Be strong and courageous. Do not be afraid; do not be discouraged, for the Lord your God will be with you wherever you go (Joshua 1:9).

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