Fakulta zemědělská a technologická
Faculty of Agriculture and Technology
Jihočeská univerzita v Českých Budějovicích
University of South Bohemia in České Budějovice

UNIVERSITY OF SOUTH BOHEMIA IN ČESKÉ BUDĚJOVICE
FACULTY OF AGRICULTURE AND TECHNOLOGY

Department of Agroecosystems

Dissertation autoreference

Environmental impact assessment of growing selected crops in conventional and organic farming systems

Author: **Ing. Chisenga Emmanuel Mukosha**

Supervisor: doc. Ing. Jan Moudrý, Ph. D.

České Budějovice
2024

Abstrakt

Zemědělský sektor čelí rostoucímu tlaku na zvýšení produktivity, snížení nákladů a snížení zátěže životního prostředí při zachování kvality produktů. Rostoucí globální poptávka po potravinách způsobená rozšiřující se lidskou populací a měnící se vzorce spotřeby budou mít za následek dopady na životní prostředí. Aby se udržela zvýšená poptávka, je potřeba najít udržitelné metody produkce plodin bez poškození životního prostředí. Volba systému hospodaření může mít významný vliv na zátěž životního prostředí vyplývající ze systémů zemědělské výroby. Hlavním cílem této disertační práce je zhodnocení vlivu vybraných plodin na životní prostředí v konvenčním a ekologickém zemědělství se zaměřením na emise skleníkových plynů. Pro provedení srovnávací studie byla použita metoda LCA (Life Cycle Assessment) pro posouzení vlivu pěstování vybraných plodin na životní prostředí v konvenčních a ekologických systémech zemědělství. V první fázi hodnotíme pěstování ozimé pšenice v obou systémech hospodaření. Ve druhé etapě posuzujeme pěstování bio směsí odrůd ozimé pšenice. Za třetí jsme hodnotili pěstování ozimé pšenice v suchých a zavlažovaných systémech při hnojení kompostem a nakonec ve čtvrté etapě jsme hodnotili pěstování cukrové řepy za různých minerálních hnojiv a dávek pesticidů. Primární vstupní data byla shromážděna z experimentálních polních pokusů a dotazníků a doplněna sekundárními daty pro databázi LCA Ecoinvent, WFLDB a Agri-footprint. K provedení výpočtu byl použit software SIMAPRO a OpenLCA. K transformaci výsledků inventarizačních dat do skóre indikátorů byla použita metoda hodnocení dopadu ReCiPe. Výsledky této práce se vztahují ke středním ukazatelům dopadu doporučeným pro zemědělství a ke třem ukazatelům koncových bodů. Celkově měl pěstební systém s nejmenším množstvím vnějších vstupů nejnižší zátěž pro životní prostředí napříč různými kategoriemi dopadů, ale byl spojen s nižšími výnosy. Nižší výnosy v organických systémech a nehnojené varianty v konvenčním zemědělství měly vyšší zátěž pro životní prostředí v kategorii dopadů změny klimatu a také vyžadovaly půdu pro generování stejného množství výnosu jako konvenční varianty.

Klíčová slova: Zemědělství, LCA; udržitelnost; dopad na životní prostředí; osevní systémy, emise skleníkových plynů

Abstract

The agriculture sector faces mounting pressure to increase productivity, reduce costs, and cause less burden on the environment while maintaining product quality. The increasing global food demand brought by an expanding human population and shifting consumption patterns will result in environmental impacts. Sustainable crop production methods are needed to sustain the increased demand without harming the environment. The choice of farming system can significantly affect the environmental burden arising from agricultural production systems. The main aim of this dissertation is to evaluate the environmental impact of selected crops in conventional and organic farming with a focus on greenhouse gas emissions. The LCA (Life Cycle Assessment) method was used to assess the environmental impact of growing selected crops in conventional and organic farming systems to perform a comparative study. In the first stage, we assess winter wheat growing in both farming systems. In the second stage, we assess the cultivation of organic winter wheat variety mixtures. Thirdly, we assessed the growing of winter wheat in dryland and irrigated systems under compost fertilization, and finally, in the fourth stage, we assessed the growing of sugar beet under different mineral ferlizer and pesticide doses. The primary input data was collected from experimental field trials and questionnaires and supplemented by secondary data for the LCA Ecoinvent, WFLDB, and Agri-footprint database. SIMAPRO software and OpenLCA software were used to perform the calculation. The ReCiPe impact assessment method transformed the inventory data results into indicator scores. The results of this work are related to midpoint impact indicators recommended for agriculture and three endpoint indicators. Overall the cropping systém with the least amount of external inputs had the lowest environmental burden across different impact categories but was associated with lower yields. The lower yields in organic systems and unfertilized variants in conventional farming had higher environmental loads in the climate change impact category. They required more land to generate the exact yield as the fertilized conventional variants.

Keywords: Agriculture, LCA, Sustainability, environmental impact, cropping systems, greenhouse gas emissions.

1 Introduction

The agriculture sector is a vital sector that provides food, fiber, and other products that keep humans and animals alive. Agricultural practices have significantly evolved, which has led to diverse farming systems. Nevertheless, agriculture also plays a major role in causing environmental change. Agriculture and the environment have a complicated relationship that involves both beneficial and harmful interactions that have an impact on human health, biodiversity, ecosystems, and climate. The demand for agricultural products rises in tandem with the growing global population, placing more strain on the planet's natural resources. This makes it necessary to critically assess agricultural methods to make sure they are environmentally friendly and sustainable. The growing number of extreme weather events, rising temperatures, and altered precipitation patterns all have a negative impact on agricultural productivity and even the profitability of farming.

Conventional and Organic farming systems stand out as the two prominent but contrasting methods of farming. Each farming system has its own set of principles and practices that have an impact on the environment, society, and economy. The predominant technique of producing food globally is conventional farming, sometimes known as industrial farming. This farming system mostly depends on synthetic inputs like pesticides, fertilizers, and herbicides for maximum agricultural yields and efficiency. A large amount of mechanization and monoculture techniques are frequently used, both of which have significantly increased agricultural productivity. However, concerns have been expressed about the environmental effects and long-term viability of these techniques. In contrast, ecological balance, biodiversity, and sustainability are prioritized in organic agriculture. Organic agriculture is believed to improve soil fertility, foster healthier ecosystems, and reduce agriculture's environmental impact. It is generally accepted that to preserve the sustainability of resource utilization, agriculture must maximize positive environmental effects while limiting negative ones (Salaheen and Biswas, 2019). Organic agriculture is believed to improve soil fertility, foster healthier ecosystems, and reduce agriculture's environmental impact instead of relying on organic inputs like manure and compost, as well as agricultural practices including polyculture, crop rotation, and biological pest control as the Use of synthetic chemicals and genetically modified organisms (GMOs) is not allowed in organic farming procedures.

As the world population continues to rise, the need for food is increasing, putting further pressure on agricultural systems. This poses serious concerns regarding the viability of present agricultural techniques and their capacity to supply food in the future without causing irreparable harm to the environment. It is difficult to identify the specific environmental effects of agriculture, nevertheless, due to the complex interactions that it has with the environment and natural resources. Despite its great productivity, conventional farming has been linked to detrimental effects on the environment, such as soil erosion, water pollution, and biodiversity loss. Although organic farming is better for the environment, it frequently has problems with lower yields and greater production costs. It is crucial to comprehend the trade-offs between these two systems to create sustainable farming methods that can guarantee both environmental health and food security.

2 Literature review

Agriculture is a key part of the primary sector of the economy. (Kuczuk and Widera, 2021). Crop production is fundamental in providing raw materials for human and animal consumption. The world's population is estimated to grow by about two billion by 2050 (Gerland et al., 2022). This rapid growth of the population will be accompanied by a significant increase in the demand for agricultural production (Guo et al., 2022).The increasing demand also presents a great challenge to achieving the Sustainable Development Goals (SDGs) and the Common Agriculture Policy (CAP) (EU, 2021). The CAP plays an important role in maintaining sustainable agriculture across the EU and in promoting environmentally and climate-friendly practices (Solazzo et al., 2016). To accomplish this, production agriculture will have to find ways to be even more efficient with inputs to maximize output per acre and limit the negative externalities created through production intensification (Mark and Griffin, 2016).

Climate change has the potential to irreversibly damage the natural resources agriculture relies on for food production and this poses a serious threat to agriculture and food security (Jantke et al., 2020). Agriculture and its activities are responsible for the impact on the environment (Poore and Nemecek, 2018), accounting for approximately 10–12 % of all anthropogenic GHG emissions, and it is still increasing (Tubiello et al., 2015), this contributes to climate change and global warming (Çakmakçı et al., 2023). Anthropogenic climate change is caused by multiple climate pollutants (Schmale et al., 2017). Emissions of greenhouse gases (GHGs) are the most important driver of human-induced climate change (Jantke et al., 2020), mainly emissions of carbon dioxide (CO_2), Methane (CH_4), and Nitrous oxide (N_2O) (Blandford and Hassapoyannes, 2018). The concentrations in the atmosphere and annual anthropogenic GHG emissions continue to grow and have reached a historic high (Global Carbon Project, 2020), causing an increase in the radiative forcing of the Earth's atmosphere (Gregorich et al., 2005). Since the start of the industrial era, the concentration of atmospheric CO_2, CH_4, and N_2O has risen by nearly 40 %, 150 %, and 20 %, respectively (Tian et al., 2016). Hence agricultural activities should be in a sustainable and environmentally friendly manner (Fallahpour et al., 2012).

Agricultural systems can use natural resources more efficiently and sustainably, reduce the environmental impact of using inputs more efficiently, and achieve a multitude of benefits (Çakmakçı et al., 2023). Cropping systems significantly affect the amount of emissions from agriculture (O'Neill et al., 2021). The use of synthetic chemicals and other environmental contaminants consumption has increased resulting in indifferent consequences such as soil acidification, emissions of gases with adverse effects, nitrogen leaching to groundwater, and eutrophication (Meisterling et al., 2009).

Transformation agriculture is necessary to ensure advantages for the ecosystem and to prevent the worst effects of global environmental change (Vanbergen et al., 2020). For instance, according to (Halpern et al., 2019), 59% of maritime regions are affected cumulatively by a variety of stressors, including pollution, overexploitation of resources, and climate change. Minimizing the inputs and increasing productivity remains key to improving farming systems (Shrestha et al., 2020). This can be achieved by increasing the adaptive capacity of farmers as well as increasing resilience and resource use efficiency in agricultural production systems (Lipper et al., 2014).

2.1 Organic agriculture

Organic agriculture is developing rapidly worldwide and agricultural lands and farms continue to grow across the world (Yussefi-Menzler, 2010), with over 74.9 million hectares of organic agricultural land, including in-conversion areas across 191 countries in the world in 2021 (Helga et al., 2021).

This growth is accompanied by a huge demand for organic products in the world (Tal, 2018). Organic agriculture is an alternative system of farming designed to confront the challenges of conventional (Loewen and Maxwell, 2024). The International Federation of Organic Agriculture Movements (IFOAM) defines Organic agriculture as a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity, and cycles adapted to local conditions, rather than using inputs with adverse effects (Helga et al., 2008). The four fundamental principles of health, ecology, fairness, and care were created by the IFOAM in the 1980s and serve as the foundation for the growth and development of organic agriculture. The primary goal is the enhancement of all forms of agriculture within a global framework, and these four guiding principles articulate that vision. In 2005 The IFOAM adopted the four principles of organic agriculture:

- ***The principle of health*** - Organic agriculture should sustain and enhance the health of soil, plant, animal, human, and planet as one and indivisible.

- ***Principle of Ecology*** - Organic agriculture should be based on living ecological systems and cycles, work with them, emulate them and help sustain them.

- ***Principle of Fairness*** - Organic agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities.

- ***Principle of care*** - Organic agriculture should be managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment.

Organic agriculture encompasses a series of management practices designed for environmentally sustainable production, which excludes synthetic fertilizers and pesticides. It emphasizes closed on-farm nutrient cycling, including biological nitrogen fixation and crop rotations, to enhance soil fertility through increased (Leifeld, 2012; Yussefi-Menzler, 2010). Maintaining and improving the health of ecosystems and creatures, from the smallest elements in the soil to humans, is the purpose of organic agriculture, regardless of farming, processing, distribution, or consumption (Attia et al., 2023; Bedoussac et al., 2015).

2.2 Conventional agriculture

Conventional farming, sometimes referred to as industrial or modern agriculture, is typified by methods that use intensive mechanization, high chemical inputs, and monocultures in an effort to maximize agricultural output and has continued to grow (Thakur et al., 2021). Global agricultural systems are developing as a result of technological breakthroughs and an expansion of human knowledge (Misra and Ghosh, 2024). The increasing demand for food around the world has been met in large part by these ideas. This method does, however, come with risks to one's health and the environment. As the human population grows and available resources (water, oil, and phosphorus) decline, conventional farming with high inputs will become less sustainable, so maintaining these systems is going to be challenging (Fess et al., 2011).

In conventional farming, the intended use of synthetic fertilizers is to supply plants with necessary minerals like potassium, phosphate, and nitrogen so they can develop more quickly and produce higher yields (Le Campion et al., 2020). Higher crop yield is the outcome of tailored nutrient delivery made possible by modern formulations (Zhang et al., 2015; Lassaletta et al., 2014). On the other hand, overapplication may result in greenhouse gas emissions, nutrient runoff, and eutrophication of waterways (Bouwman et al., 2013; Sutton et al., 2013). Pesticides, such as fungicides, herbicides, and insecticides, are used in conventional farming to control weeds and pests. By decreasing crop loss, these pesticides increase production (Aktar et al., 2021; Sutherland et al., 2020). Dependence on pesticides has sparked worries about resistance building, non-target species, and possible health hazards (Carvalho et al., 2017; Lázaro et al., 2016).

The practice of monoculture, which involves growing a single crop type across a wide region, reduces the need for machinery and streamlines farm management, which saves money (Gaba et al., 2018; Tamburini et al., 2020). Although this method encourages large yields, it may have detrimental effects on soil biodiversity and make the soil more vulnerable to illnesses and pests (Karp et al., 2018; Seufert et al., 2022).

Conventional farming relies heavily on mechanization, which is the use of equipment like tractors and combined harvesters to boost productivity (Basso et al., 2021; D'Emden et al., 2014). Although mechanization increases productivity and decreases the need for labor, it also increases the usage of fossil fuels and greenhouse gas emissions (Lal, 2020; Zhang et al., 2021). Conventional farming is characterized by the use of soil tillage as a way to incorporate organic matter into the soil, manage weeds, and prepare seedbeds. Persistent ploughing can weaken soil structure and lower organic carbon content, even when it provides temporary advantages for crop establishment (Alvarez et al., 2017; Zuber et al., 2015).

For crops to continue growing, conventional farming frequently uses irrigation systems, especially in areas with little rainfall. Water utilization is optimized by methods like precision agriculture and drip irrigation (Mancosu et al., 2015; Pereira et al., 2020). However, poor water management can worsen the salinization of the land and cause freshwater resources to run out (Van Loon et al., 2019; Hanjra & Qureshi, 2010).

High-yielding crop varieties that have undergone genetic improvement are a mainstay of conventional farming. To grow to their maximum potential, these crops frequently need large amounts of water, fertilizer, and pesticides (Foley et al., 2011; Pingali, 2012). High input needs raise questions regarding their sustainability even while they boost production (Hunter et al., 2017; Duvick, 2016).

2.3 Agriculture greenhouse gas emissions sources

Agriculture is a key driver and is also hugely affected by global climate change (Lipper et al., 2014; Tadesse et al., 2019; Yadav et al., 2022). It is imperative to highlight the key drivers of GHG emissions from the agricultural sector (Mukosha et al., 2023). The primary sources of GHGs produced in the agricultural sector are methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) (Balafoutis et al., 2017).

Greenhouse gas emissions from agriculture contribute to climate change, accumulate in the atmosphere, and vary significantly across categories, time, and regions. The agriculture and food production sectors are associated with all three greenhouse gases but are dominated by emissions of CH_4 and N_2O (Lynch et al., 2021). Methane and nitrous oxide are two of the most potent gases among these pollutants, which come from different processes and have varying global warming potentials (GWPs). Among the primary sources of agricultural emissions are crop residues, enteric fermentation, manure management, synthetic fertilizers, on-farm energy use, rice paddies, and soil fertilization (Goglio et al., 2018; Gong et al., 2022; Johnson et al., 2007).

2.3.1 Carbon dioxide (CO_2)

Carbon dioxide and water vapor tend to be the most important natural greenhouse gases because of their abundance (Steed and Hashimoto, 1994). Carbon dioxide is a vital greenhouse gas that as a significant role in the climatic system and the abundance of CO_2 in the atmosphere can result in climate change (Fung, 2003). Carbon dioxide is the most significant contributor to anthropogenic global warming (Etminan et al., 2016; Lynch et al., 2021). Human activities including agriculture have perturbed the carbon cycle in significant ways leading to climate change (Fung, 2003). According to the Intergovernmental Panel on Climate Change (IPCC, 2014), CO_2 emissions have risen since the industrial revolution leading to global warming. (Fingas, 2011) states that the average atmospheric levels are about 300 ppm, and levels near a burn can be around 500 ppm, which presents no threat to living organisms and agriculture. In comparison with other sectors the agriculture sector has fewer CO_2 emissions (Fais et al., 2016).

Different amounts of cropland and mechanization can result in varying emissions, affecting agricultural productivity and energy consumption. (Rehman et al., 2020). The atmospheric CO_2 emissions from the burning of fossil fuels(Tian et al., 2016), such as coal, oil, gasoline, natural gas, and diesel fuel produce significant amounts of CO_2 (Goel and Agarwal, 2014)A report from the CEMA European Agricultural Machinery Industry Association (CEMA, 2022) points out that the agricultural sector's greenhouse gas emissions in the EU27 correspond to 10% of the total emissions, and of this, approximately 1% is only the burning of fossil fuels by agricultural machinery.

Land use change, mainly deforestation and the conversion of natural ecosystems to agricultural land, is one of the leading causes of CO_2 emissions in the farming sector (Tian et al., 2016). Deforestation contributes 6–17% of global anthropogenic CO_2 emissions to the atmosphere (Van Der Werf et al., 2009). Carbon dioxide is the primary source of C for the cycle of life on Earth (Tedesco, 2022). The carbon held in plants and soil is released into the atmosphere when forests or grasslands are destroyed (Friedlingstein et al., 2023). Carbon dioxide is recycled in the ecosystem through respiration, photosynthesis, and combustion (Goel and Agarwal, 2014). Due to its ability to retain carbon (C) in soil and vegetation, agricultural soil can function as both a source and a sink of atmospheric CO_2 (Baah-Acheamfour et al., 2016; Yadav and Wang, 2017). As reported by Friedlingstein et al., (2023) the global CO_2 emissions from land use, land-use change, and forestry (LULUCF) averaged 1.3±0.7 Gt C yr−1 (4.7±2.6 Gt CO_2 yr−1) for 2013–2022.

The impacts of no-tillage on CO_2 and N_2O emission varied among studies with different management practices, soil types, climate, and cropping systems (Zhao et al., 2016). Conventional tillage disrupts soil structure and releases carbon stored in the soil, leading to increased atmospheric CO_2 levels (Lal, 2004). According to the findings of Kim and Dále (2005), under low tillage practice, GHG emissions associated with 1 kg of corn are

244 g CO_2 eq (−40 g CO_2 eq) under no-tillage. No-tillage practice reduces the fertilizer application rates and fuel use and increases the soil organic carbon, but it increases herbicide use compared to plow tillage practice. It is reported by Mangalassery et al. (2014) that no-tillage practices reduce GHG emissions by approximately 20.6–23.7 % compared to conventional tillage. This is also supported by the finding of Grosso et al. (2005), which reported a lower global warming potential of 33 % for no-tilled soil compared to tilled soil.

2.3.2 Methane (CH_4)

Methane (CH_4) is a significant greenhouse gas contributing to global climate change. Methane is generated as a result of the degradation of organic molecules in an atmosphere without oxygen (Karakurt et al., 2012). Along with many other greenhouse gases, methane (CH_4) accumulation in the atmosphere is one such gas that has increased from historical levels. Methane levels have risen by 115% from pre-industrial times (Steed and Hashimoto, 1994). Agriculture is the highest contributing sector of CH_4 climate watch (2023), as shown in Figure 3, accounting for approximately 40% of global methane emissions Food and Agriculture Organization (FAO, 2016). Despite being present in lower atmospheric concentrations than carbon dioxide, methane has a global warming potential of about 28 times larger than carbon dioxide, considering a 100-year timeline, respectively (IPCC, 2022). This makes it a powerful driver of global warming despite having a shorter atmospheric life span than CO_2. Methane can be emitted into the environment through both natural and anthropogenic activities. The release of methane occurs during the decomposition of organic matter in anaerobic environments such as wetlands (Kirschke et al., 2013) flooded rice fields (Karakurt et al., 2012), grasslands (Jones et al., 2005), manure and fertilizer management (Yusuf et al., 2012).

The release of methane by the process of enteric fermentation in ruminant animals (Gerber and Food and Agriculture Organization of the United Nations, 2013) occurs in the digestive system of ruminant animals, such as cattle, sheep, and goats (Rosa and Gabrielli, 2023) when microbes in the stomach of ruminants break down food and produce methane as a by-product. Tapio et al. (2017) state that enteric CH_4 is produced under anaerobic conditions by a vast community of methanogenic archaea, using predominantly hydrogen and CO_2 as substrates. The kind of ruminant, the physiology of the digestive tract, and the composition of the local microbial community can all affect the amount of CH_4 (Goopy et al., 2014; Smith et al., 2021). Methane production from ruminant cattle can range from 250 to 500 L daily (Johnson and Johnson, 1995). The increasing demand for meat and dairy products has been attributed to being one of the factors causing an increase in CH_4 emissions from enteric fermentation (FAO, 2016).

Methane production from animal wastes is also an anaerobic microbial process and occurs mainly when animal wastes are stored (Smith et al., 2021). Management such as fertilizer or manure application can have a substantial influence on the emissions of CO_2, N_2O, and CH_4 (Jones et al., 2005). Manure management accounts for approximately 10 % of methane emissions from agriculture (Gerber et al., 2013). Anaerobic conditions will arise when manure is processed or stored in liquid systems like lagoons, ponds, or pits, and the breakdown process will produce methane emissions (Steed and Hashimoto, 1994).

2.3.3 Nitrous oxide (N_2O)

Nitrous oxide is a small inorganic chemical molecule that is a colorless and nonflammable gas with a slightly sweet odor (Sethi et al., 2006) and is a significant type of nitrogen (N) pollution (Davidson and Kanter, 2014a). With a potential for 298 times more global warming than carbon dioxide (CO_2) during 100 years, nitrous oxide (N_2O) is a potent greenhouse gas (Crutzen et al., 2008) and contributes to Stratospheric ozone depletion (Del Grosso et al., 2008). Over the past few decades, emissions from this source have significantly increased due to increased N inputs into natural and agricultural soils (Kroeze et al., 1999). Since pre-industrial times, the concentration of N_2O in the atmosphere has increased by 19% (Ravishankara et al., 2009). (2011) state that about 56–70% of the world's N2O sources come from agriculture, primarily from using N fertilizer, managing manure, and emissions from natural soils. The secondary emissions occur from downwind or downstream soils and water bodies leached from the croplands. After nitrogen is released from croplands, ammonia or nitrogen oxide gases return to the atmosphere as atmospheric N deposition (Davidson and Kanter, 2014b).

Agricultural soils receive their N mainly from the application of manure and synthetic fertilizers, with extra N coming from crop residues, legume N fixing, and N deposition (Davidson and Kanter, 2014b). After the application of nitrogen fertilizers to agricultural soils, a large portion is transformed through microbial processes (Butterbach-Bahl et al., 2013). The two main microbial processes that turn ammonia into nitrate and subsequently into nitrogen gas, or nitrous oxide, are nitrification and denitrification. During the aerobic process of nitrification, ammonium (NH_4^+) is converted to nitrate (NO_3^-) and releases N_2O as a byproduct (Crutzen et al., 2008). While the denitrification is the anaerobic reduction of NO_3^- to N_2O and N_2 (Payne, 1981). Denitrification is associated with the most significant rates of N_2O, while the rates of N_2O by nitrification tend to be smaller (Skiba and Smith, 2000; Williams et al., 1992). Mineral Fertilizers are crucial in boosting food production to satisfy the demand. Nearly half the world's population is supplied with food produced from artificial fertilizers (Skowrońska and Filipek, 2014). Lack of synchronization between crop N demand and soil N supply is the primary cause of agricultural N_2O emissions, with crops often not using 50% of the N provided to the soil (Davidson and Kanter, 2014b). Effective tactics include using cover crops, conserving tillage techniques, and optimizing fertilizer applications to increase nitrogen use efficiency (Smith et al., 2014). Charles Munch and Velthof (2007) state that avoiding the application of manure and fertilizers during wet circumstances, particularly nitrate-containing fertilizers, can also reduce denitrification losses and N_2O emissions.

2.3.4 CO_2-Equivalent Emissions

The term "carbon dioxide equivalent," or "CO_2-eq," is used to describe many greenhouse gases in a single unit (Lynch et al., 2021). This is done by converting amounts of other greenhouse gases to the equivalent amount of carbon dioxide with the same global warming potential (GWP). This metric is scaled to CO_2 and is based on the overall disruption to the atmospheric energy balance (radiative forcing) caused by an idealized pulse emission of several gases throughout the 100 years that follow this pulse (Etminan et al., 2016; Intergovernmental Panel On Climate Change, 2014). Each greenhouse gas (GHG) has a varied global warming potential (GWP) and persists for a varying period of time in the atmosphere.

Greenhouse gas	*Formula*	*Individualist (20 years)*	*Hierarchist (100 years)*	*Egalitarian (1,000 years)*
Carbon dioxide	CO_2	1	1	1
Methane	CH_4	84	34	4.8
Nitrous oxide	N_2O	264	298	78.8

Table 1. Greenhouse gases three-time perspective global warming potentials Data source: (IPCC, 2014).

2.4 Estimating direct and indirect emissions for agricultural crop production systems

Agriculture contributes to the environment by emitting emissions directly and indirectly. The emissions that originate from agricultural practices are known as direct emissions. In contrast, indirect emissions occur due to agricultural practices but are not released directly at the farm gate. Farm management practices strongly influence direct emissions and depend on onsite characteristics (Nemecek et al., 2019). The emissions to air include ammonia (NH_3), nitrous oxide (N_2O), nitrogen oxides (NO_x), methane biogenic (CH_4), and carbon dioxide (CO_2), while emissions to water include Phosphorus (P), Phosphate, Nitrate (NO_3^-) Phosphate (PO_4^{3-}) (Nemecek et al., 2019).

2.4.1 Ammonia (NH_3)

Naturally occurring nitrogen (N_2) makes up 78% of the dry troposphere (Krupa, 2003) However, human activities such as agriculture are vital contributors to nitrogen compound emissions into the atmosphere, acting as a cause as well as a solution (Kurvits and Marta, 1998). N species in the atmosphere can exist as particles, vapors, or gases. These include ammonia (NH_3), nitrous oxide (N_2O), oxides of nitrogen (NOx, which is made up of nitric oxide, NO, and nitrogen dioxide, NO_2) (Krupa, 2003). The primary nitrogen compounds released from sources related to agriculture are nitrous oxide (N, O) from soils and animal waste, ammonia (NH_3), mostly from livestock manure and inorganic fertilizers, nitrogen oxides (NO) from fuel combustion in farm equipment, and fertilizer conversion in agricultural soils.(Kurvits and Marta, 1998).

There have been increasing concerns about the elevated atmospheric concentrations of NH_3 that are associated with environmental burdens (Robarge et al., 2002). Fertilizers containing ammonium are crucial for producing high-yield crops and play a significant role in atmospheric NH_3 (Warner et al., 2017). However, it is associated with an environmental burden (Mukosha et al., 2023; Robarge et al., 2002).Volatilisation is one of the primary ways that ammonia (NH_3) is lost in agricultural systems (Pan et al., 2016). Depending on the soil's texture and the type of N fertilizer used, ammonia losses from the soil might vary from 3 to 50%.(Nelson, 2015). There are several methods available for estimating the NH_3 emissions from agricultural systems, whereas the most widely used are the EMEP/EAA guidelines from the European Environment Agency (EEA, 2016; Nemecek et al., 2019).

2.4.2 Nitrous oxide (N_2O)

Nitrous oxide (N_2O) is a substantial anthropogenic greenhouse gas, and agriculture represents its largest source (Reay et al., 2012)Nitrous oxide is produced during nitrification and denitrification processes (Nemecek et al., 2019).

2.4.3 Methane (CH_4)

Measuring and estimating methane emissions from ruminants has been the focus of numerous technologies developed during the past century(Storm et al., 2012) such as the in vitro gas production technique (IVGPT) (Rymer et al., 2005), the SF_6 technique (Johnson et al., 1994), and respiration chambers (Storm et al., 2012) among many others. However, equations (3) and (4) are per IPCC (2006) Tier 2 default methodology is used to calculate methane emissions from animal husbandry.

2.4.4 Nitrate leaching to groundwater

Nitrogen (N), a vital component in agricultural fields for plant growth, is applied as a mineral or organic fertilizer to prevent yield-limiting deficiencies (Henryson et al., 2020). The nitrogen that is available to plants in the soil likely comprises either NO_3^- or NH_4^+, which soil microorganisms quickly convert to NO_3^- (Addiscott, 1996). Nitrate is entirely soluble in water and is prone to be leached because the negatively charged NO_3^- anion is repelled by negatively charged surfaces of clay minerals and soil organic matter (Padilla et al., 2018). Geographical location, soil properties, climate, and agricultural management all have an impact on the distribution of the various kinds of nitrogen emissions to air and water, as well as how they behave in the environment (Henryson et al., 2020; Rochette et al., 2018). The SQCB-NO3, a geographically unspecific and simple model, is used for the calculation of leached nitrates (Faist Emmenegger et al. 2009).

2.4.5 Phosphorous emissions to water

Phosphorus (P) is an essential, irreplaceable element in agriculture (Johnston et al., 2014). Large amounts of P are taken up by plants from the soil solution as phosphate ions, primarily $H_2PO_4^-$, but the concentration of P in the soil solution is very small, therefore P must be readily accessible in the soil to maintain this concentration as P is taken up by the roots (Roberts and Johnston, 2015). Soil amendments with P fertilizers are a common practice in agriculture to replace or have readily accessible P for plants, However, the large amounts of P-based fertilizers are associated with environmental impacts. Phosphorus losses from arable soils contribute to eutrophication of freshwater systems (Djodjic et al., 2004). Phosphorus (P) losses that can decrease surface water quality (Maguire and Sims, 2002). This results in the degradation of aquatic habitats for fish by causing oxygen fluctuation and inducing sedimentation as well as have an impact on human health (Dymond et al., 2013). According to Nemecek et al., (2019) there are three different pathways of phosphorus emissions to water are distinguished:(i) leaching of soluble phosphate (PO_4) to groundwater, (ii) run-off of soluble phosphate to surface water, and (iii) water erosion of soil particles containing phosphorus. P on the surface, the soil may intensify the risk of P losses and increase the movement of P below the plough layer (Jalali and Jalali, 2017). Long-term fertilizer and manure P applications in large amounts exceeding crop uptake needs can also be a source of downward movement of P through the soil (Koopmans et al., 2007). The leaching of P from soils can be influenced by a variety of parameters, including soil texture and P sorption saturation (Qin et al., 2010)the emission models are according to the SCALCA-P (Prasuhun 2006).

3 Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) is a methodological framework for estimating and evaluating the environmental impacts attributable to a product's life cycle (Rebitzer et al., 2004). The International Organization for Standardization (ISO) (14044 ISO, 2006) defines life cycle assessment (LCA) as a method to examine a product's, processes, or system's possible impact on the environment at every point of its life cycle. Products can be products or services; examples include waste management techniques, consumables, and electricity (14040 ISO, 2006).

LCA is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment, and to identify and evaluate opportunities to affect environmental improvements (Consoli, 1993; Fan et al., 2022). LCA looks at a product's whole life cycle, starting with the extraction of natural resources and going all the way through material manufacture, product assembly, product use, packaging, recycling, and eventual disposal. The evaluation of environmental impact can be made in different impact categories such as climate change, acidification, eutrophication, toxicity, resource use, etc (Rebitzer et al., 2004). The LCA methodology can be used to detect opportunities for improvement and to compare or monitor the environmental impact of a specific product or company (Consoli, 1993).The concept of the LCA emerged in the late 1960s and has evolved into a critical to evaluating the environmental profile of a product and policy making. The LCA method was used for the first time in 1969 by the Coca-Cola Company to study quantitatively and completely the environmental impacts and resource consumption associated with the whole life cycle of beverage bottles, from the extraction of raw materials to their final disposal (Fan et al., 2022).

Following a period of silence in the 1970s, the LCA methodological development increased in the 1980s, and worldwide collaboration and coordination in the scientific community increased (Bjørn et al., 2018). To properly comprehend energy use, the industrial sector investigated the Life Cycle Assessment (LCA) approach more in the 1980s (Fan et al., 2022). Over the past few decades, databases and techniques have been added to LCA analysis to allow for its detailed application in assessing impacts within the agricultural sector (Jensen et al., 2005). The research in agricultural LCA first began in the mid-1990s with the first agricultural LCA seminar held in 1993 and later in the year 1998 research on sustainable agriculture was conducted in Japan which later led to the rapid development of the agricultural LCA (Fan et al., 2022). Due to its capacity to pinpoint environmental hotspots, the Life Cycle Assessment (LCA) method has been extensively embraced in the agricultural industry for the assessment and comparison of production chains (Miller et al., 2006).

3.1 Life cycle assessment regulations

To facilitate the dependable and conscientious application of Life Cycle Assessment, the International Organization for Standardization (ISO) has created a range of guidelines encompassing the discipline. The LCA framework for conducting agricultural LCA studies is defined by the internally agreed standards ISO (14040

ISO, 2006; 14044 ISO, 2006). The LCA process is divided into four iterative phases: (1) goal and scope definitions, (2) inventory analysis (3) impact assessment, and (4) interpretation.

3.2 Goal and Scope Definition

According to the ISO 14040 and 14044 defining the goal and scope is the first step to be undertaken when conducting an agricultural LCA. This assures uniformity throughout the analysis and is a fundamental technique of the particular life cycle assessment to be carried out (14040 ISO, 2006). This part of the study is crucial because it lays out the framework for how the entire study will be conducted (Curran, 2017). Clearly stating the intended use of the LCA, the rationale for the study, the target audience, the functional units, system boundaries, allocation criteria, data sources, and the methodology to be employed is very crucial (Consoli, 1993).

3.2.1 Functional Unit

It is crucial to identify the functional units of the study as part of the Goal and Scope-defining step to maintain consistency throughout the study. The functional unit (FU) is a fundamental concept in LCA that serves as a reference basis for all inputs and outputs when comparing and contrasting products, services, and activities in life cycle assessments (Rebitzer et al., 2004). The functional unit should reflect the primary function of the product or the system must be pertinent to the study objectives and consistent with how the intended use of the results. The functional unit is a measurable value connected to the function of the system (Caffrey and Veal, 2013). For life cycle assessment (LCA) research, three primary functional unit types are typically employed: mass (e.g., kilogram, pound, ton), energy content (MJ, BT), and economic value (dollar, Euro) with the mass-based functional unit of kilogram (kg) being one of the most used FU in agriculture (Cellura et al., 2022).

3.2.2 System Boundaries

A vital part of a Life Cycle Assessment (LCA) is the system boundary, which indicates which processes, inputs, and outputs are included or excluded in the study. Defining the system boundaries ensures that the evaluation is thorough and pertinent to the study objectives, offering a full and true depiction of the environmental effects of the method, product, or service under evaluation. When defining the system boundary, several aspects of the scope must be taken into consideration, but above all, it must align with the study's main objective or objectives (Caffrey and Veal, 2013). A general input and output illustration is frequently used to illustrate the system boundary of LCA research (Jamekhorshid and Azin, 2023). A cradle-to-gate system boundary analysis illustrates the process upstream in the production chain of a product until a stage where the product is ready for use the cradle-to-grave covers the process from upstream production to the disposal phase at the end of the product life cycle (Singh et al., 2015).In agricultural LCA studies, the most common system boundary analysis is the cradle-to-farm gate as this is where much of the burden occurs on the farm (Sieverding et al., 2020).

3.3 Life Cycle Inventory

Life cycle inventory is a vital step in the Life cycle assessment process. Throughout a process, product, or service's life cycle, data about the inputs and outputs related to it are gathered and quantified. According to

(Curran, 2008) life-cycle inventory is a process of quantifying energy and raw material requirements, air emissions, waterborne emissions, solid wastes, and other releases for the complete life cycle of a product, process, or activity. This is one of the most time-consuming phases of the LCA study (Rebitzer et al., 2004). Kočí, (2009) states that this phase first involves the collection of data on unit processes, then it performs an inventory of the inputs and outputs of the entire system and its surroundings. As a result, the life-cycle inventory affects the results of an LCA and can be used to determine which elements have the biggest environmental impact (Davis et al., 2009).

A product's life cycle involves hundreds of human activities, all of which must be understood and recorded in terms of material and energy flows that are pertinent to the environment (Wernet et al., 2016). Bourgault et al., (2012) states that it is common practice when conducting LCA studies to use generic databases that represent the background web of exchanges while practitioners focus on foreground data collection processes. There are a lot of LCA databases on the market either for free or purchase such as Ecoinvent, WFLCD, GaBi, AGRIBALYSE, etc that are suitable for inventory data when performing an LCA study. Each LCA database is developed by an enterprise or organization located in a specific country or territory, and the modeled processes are based on its manufacturing characteristics (Martínez-Rocamora et al., 2016).The Ecoinvent database is one of the leading LCI databases in the world with more than 17,000 distinct datasets including waste management, food production, and resource extraction (Ecoinvent, 2023).

3.4 Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment transforms the inventory data into units of possible environmental impact score (Rosenbaum et al., 2018). Life cycle impact assessment aims to measurably compare the environmental impacts of product systems and compare their severity with each other using n quantifiable quantities designated as impact Categories (Kočí, 2009).Unlike the other three LCA phases, the LCIA is primarily automated by LCA software in practice; nonetheless, a thorough understanding of the underlying principles, models, and elements to ensure the insight required for a qualified interpretation of the results (Rosenbaum et al., 2018).

Performing an LCA usually requires manipulating a large number of data and assumptions and using specific software tools can facilitate this process (Pechenart and Roquesalane, 2014). The market offers a wide range of software either free or paid for to perform LCA studies. Amongst the leading software tools are SIMAPRO and OpenLCA which are commonly used worldwide. Each one of the software has unique features that can differ in terms of user interface, database accessibility, functionality, data quality control, and modeling concepts (Lopes Silva et al., 2019).

3.4.1 ReCiPe model of impact assessment

The ReCiPe impact assessment method is used in Life Cycle Assessment (LCA) to evaluate the environmental impacts associated with a product, process, or service throughout its life cycle by translating emissions and resource extractions into impact indicator scores employing characterization factors (Goedkoop et al., 2009). This method was first developed by (Goedkoop et al., 2009)and was initially called ReCiPe 2008 but was later updated to ReCiPe 2016. The ReCiPe has two mainstream ways of calculating characterization factors, namely, by expressing 18 mid-point indicators and 3 end-point indicator levels (Huijbregts et al., 2016).

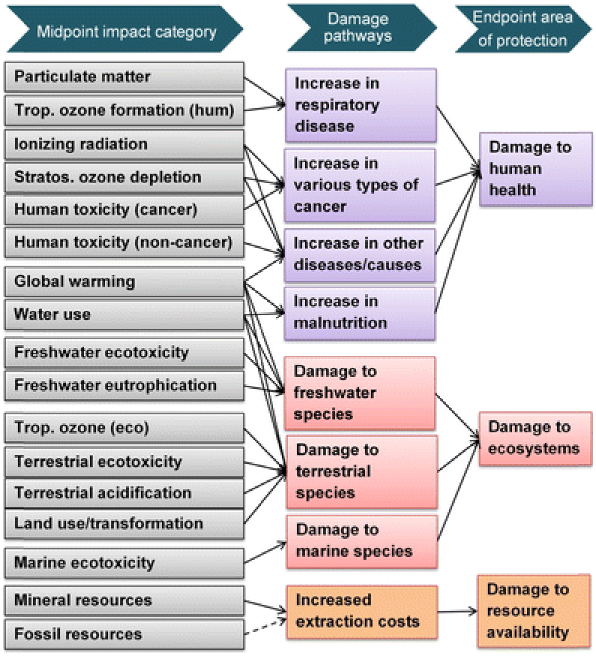

Figure 8: Overview of the impact categories that are covered in the ReCiPe2016 method and their relation to the areas of protection. The dotted line means there is no constant mid-to-endpoint factor for fossil resources. Data source: (Huijbregts et al., 2016).

The environmental assessment can be done based on midpoints and/or endpoints (Ismaeel, 2018). The selection of impact categories is considered dependent upon the application, goal, and scope of the study and is ultimately the responsibility of the study practitioner (Baumann and Tillman, 2004). The mid-point-level characterization factors are found anywhere along the impact pathway, usually at the point where all environmental flows allocated to that impact category have the same environmental mechanism while the endpoint characterization factors correspond to three areas of protection namely Human health, ecosystem quality, and resource depletion (Goedkoop et al., 2009). Typically these endpoints are located further along the environmental mechanism chain, such as skin cancers, plants, animals, cataracts, malaria, and manmade materials (Bare and Gloria, 2008). Midpoint modelling incorporates more intricate calculation procedures but also contains places when it is feasible to derive the characterization variables and describe the significance of emissions or extractions with a higher degree of accuracy and reliability (Ismaeel, 2018). Though impacts on the protected areas are modeled using the best available, but frequently more ambiguous, information about the links between resource extractions, emissions, and their endpoint impacts damages within the protected areas (Finnveden and Potting, 2014).

4 Aim of thesis

This thesis aimed to evaluate the environmental impacts associated with growing selected crops in conventional and organic farming systems. By conducting comparative life cycle assessment studies to identify major hotspots contributing to the environmental burden and subsequently identify mitigating strategies towards the key contributors. The research seeks to provide insights into the sustainability of different cropping systems and practices to promote environmentally friendly agricultural practices.

5 Results and Discussion

5.1 Environmental impact assessment of sugar beet under different fertilizer and pesticide doses in the Czech Republic

5.1.1 Emissions estimates and yield parameters

The results are related to a 2-year growing cycle of sugar beet under different mineral fertilizer and pesticide application rates SB1-SB5, respectively. The results of this study, within the assessed variants, show that the SB1 recorded the lowest yield, and this can be attributed to the non-input of mineral fertilizer and pesticides representing a 50.3 % yield reduction in comparison with the SB3 variant that had a full dose of 180 kg N ha^{-1}, phosphorus 50 kg N ha^{-1}, and potassium 200 kg N ha^{-1}. This is in line with the findings of (Azizpanah and Taki, 2024; Garcia Gonzalez and Björnsson, 2022). According to Tully and Ryals, (2017) the lack of mineral fertilizers can lead to a decline in crop productivity, with yields dropping by up to 60% in unfertilized fields. Hence, it poses a significant threat to food security as unfertilized plots consistently produce lower yields due to inadequate nutrient supply (Fan et al., 2005).

The results show a difference in yields of 1.4 t ha^{-1} between variants SB3 (180 kg N ha^{-1}, phosphorus 50 kg N ha^{-1}, and potassium 200 kg N ha$^{-1)}$ and SB4 (90 kg N ha^{-1}, phosphorus 25 kg N ha^{-1}, and potassium 100 kg N ha^{-1}), representing about 1.83 %. Bationo et al. (2006) observed a correlation between lower crop yields and reduced application of mineral fertilizers in long-term field trials. Low crop yields in the short term and soil nutrient depletion in the long term are linked to under-fertilizer use in crop cultivation, provided that nutrients are not replenished in the soil through alternative means (Michelson et al., 2023).

The results indicated a reduction of 15.8 % when the pesticide dose was reduced by half for the S2 variant compared with the S4 variant. The variants SB2 and SB5 received a half dose of pesticide and had a difference in yields of 1.7 t ha$^{-1,}$ with the SB5 that full dose of mineral ferlizer having a higher yield. This is similar to the findings of (Dědina et al., 2024; Hossard et al., 2014; Mukosha et al., 2023; Pathak et al., 2022), that report significant yield reductions due to reduced pesticide application.

Furthermore, persistent farming without the addition of fertilizer can hasten the processes of soil deterioration, such as erosion and the loss of organic matter, which can result in further productivity drops (Lal, 2004). The lack of fertilizers also makes it more difficult to reach the ideal canopy cover and plant density levels, which might worsen weed competition and decrease light interception (Bünemann et al., 2018; Seufert et al., 2012). Extensive research has demonstrated that, even in highly fertile soils, yields gradually decrease in the absence of fertilizer supplementation due to the gradual depletion of soil nutrient reserves (Smil, 2000). According to Foley et al., (2011), maintaining sustainable production levels requires replenishing nutrients in some way, which can be achieved either by synthetic fertilizers or organic amendments.

Table 6. The yield and emission estimations of Sugar beet production (1 ha).

	Unit	SB1	SB2	SB3	SB4	SB5
Outputs						
Yield	t ha^{-1}	38.6	63.4	76.7	75.3	65.1
Emissions						
Nitrogen dioxides	kg ha^{-1}	-	3.5	7.05	3.5	7.05
Nitrous oxide	kg ha^{-1}	-	4.49	6.47	4.95	6.49

Ammonia	kg ha^{-1}	-	1.42	2.84	1.42	2.84
Nitrate	kg ha^{-1}	-	119.9	143.8	111.1	152.3
Phosphate	kg ha^{-1}	-	0.2	0.22	0.2	0.22

SB1-control, SB2-half dose of fertilizer and treatment, SB3 – full dose of fertilizer and treatment, SB4 – half dose of fertilizer and full treatment, SB5 – full dose of fertilizer and half dose of treatment. N, nitrogen; P, phosphorous; K, potassium. Emissions are calculated following the IPCC (Intergovernmental Panel on Climate Change) methodology (determination of field emissions) and WFLCD (Nemecek et al., 2019).

According to the results regarding the variants SB3 and SB5, both had 180 kg N ha^{-1}, phosphorus 50 kg N ha^{-1}, and potassium 200 kg N $ha^{-1.}$ There was no difference in emission loads of nitrogen dioxide NO_2, Ammonia NH_3, and Phosphate PO_4^{3-}. However, the SB5 variant recorded higher nitrate (152.3 kg ha^{-1}) and nitrous oxide (6.49 kg ha^{-1}). The results indicate that variants SB2 and SB3 both had (90 kg N ha^{-1}, phosphorus 25 kg N ha^{-1}, and potassium 100 kg N ha^{-1} had no difference in emission loads of nitrogen dioxide NO_2, Ammonia NH_3, and Phosphate PO_4^{3-}. However, the SB2 variant recorded higher nitrate (119.9 kg ha^{-1}), while the SB4 reported nitrous oxide emissions of 4.95 kg ha^{-1}. According to the results, a reduction of mineral fertilizer input from SB3 (180 kg N ha^{-1}, phosphorus 50 kg N ha^{-1}, and potassium 200 kg N ha^{-1}) to SB2 (90 kg N ha^{-1}, phosphorus 25 kg N ha^{-1}, and potassium 100 kg N ha^{-1}) would show a reduction of about 17 % of leached nitrates. This is in line with many studies that found high nitrogen fertilizer application rates correlating with increased nitrate leaching, which posed risks to water quality (Addiscott, 1996; Sharma et al., 2019; Zareabyaneh and Bayatvarkeshi, 2015). It is imperative to decrease the amount of nutrients that leach into water bodies from agricultural areas in order to mitigate pollution and avoid eutrophication. It has been demonstrated that a variety of tactics work well to reduce nutrient losses. To better match crop nutrient demands, they include optimizing fertilizer application rates, timing, and location, lowering the chance of leaching surplus nutrients (Di and Cameron, 2002). Another commonly advised strategy is to incorporate cover crops. These can absorb leftover soil nitrogen following the main crop harvest, lowering the quantity that can leach during the off-season (Tonitto et al., 2006).

5.1.2 Environmental assessment of midpoint impact Categories

According to the characterization model, a contribution analysis was carried out for green silage maize under different fertilizer and pesticide doses. The results are related to a 2-year growing cycle of sugar beet under different mineral fertilizer and pesticide application rates SB1-SB5. The functional unit for this expression was 1 ton of the final product. From the data interpretation, it was also possible to determine different environmental impacts of sugar beet variants. The environmental impact levels were converted to percentage contribution scores in Figure 9 and Figure 10.

According to the results, the SB1 variant with no input doses of mineral fertilizer and pesticide was associated with higher environmental loads in 10 mid-point impact categories. The SB1 recorded higher environmental impacts in the impact Categories: global warming (0.049093 kg CO_2 eq), ozone formation human health (0.000597 kg NOx eq), ozone formation terrestrial ecosystem (0.000607 kg NOx eq), fine particular matter formation (0.000154 kg PM2.5 eq), marine eutrophication (0.000441 kg N eq), terrestrial ecotoxicity (0.872188 kg 1,4-DCB), human carcinogenicity toxicity (0.010396 kg 1,4-DCB), human non-carcinogenicity toxicity (0.054889 kg 1,4-DCB), land use (0.543973 m^2a crop eq), and fossil fuel resource scarcity (0.013681 kg oil eq). This environmental burden can be attributed to the low yield out for the SB1 variant. Low agricultural yields can have a wide range of complex impacts on the environment Figure 9 and Figure 10. Low agricultural output can affect the ecosystem in a variety of intricate ways. The adoption of more ecologically friendly farming practices, like organic farming or agroecology, which often require limited or non-chemical inputs and pollute less water and soil while promoting ecosystem health and biodiversity, may be encouraged by low yields (Tilman et al., 2002). On the other hand, low yields may be harmful to the environment, especially if they encourage the expansion of agricultural areas. This can lead to habitat loss, a decline in biodiversity, and an increase in carbon emissions (Gibbs et al., 2010). Comprehending the correlation between land use and yields is vital in formulating approaches that harmonize food production with ecological sustainability(Garnett et al., 2013).

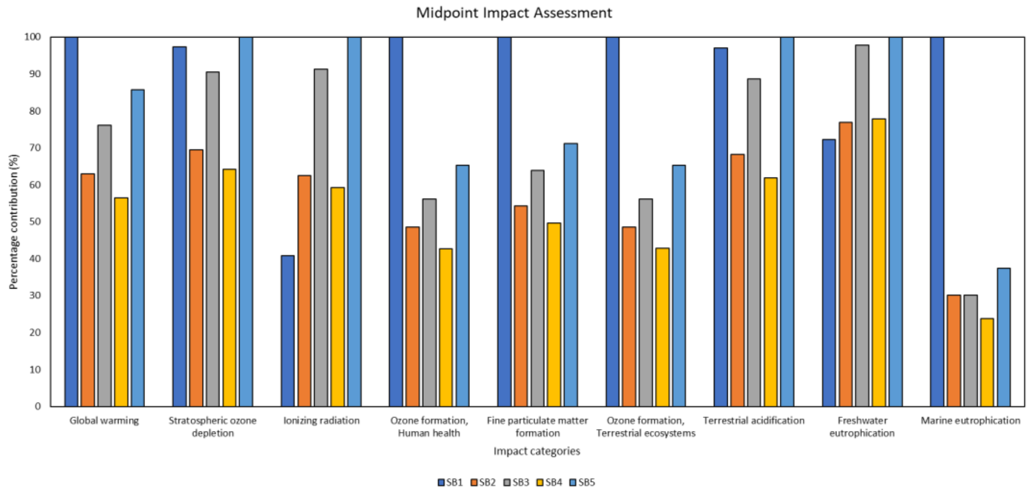

Figure 9. Environmental midpoint impact level for the unit of production from the cradle-to-farm gate. ReCiPe midpoint (H) method, characterization model, results were expressed kg ha^{-1}

However, according to the results in Table 4 the SB1 recorded the lowest environmental burden in impact categories freshwater eutrophication (7.51E-06 kg P eq), freshwater ecotoxicity (kg 1,4-DCB 0.001521), marine ecotoxicity (kg 1,4-DCB 0.002832), ionizing radiation (0.000598 kBq Co-60 eq) and resource scarcity (0.000235 kg Cu eq). Farms that maintain low yields without significantly relying on artificial fertilizers and pesticides also lessen their contribution to issues like eutrophication and groundwater pollution (Foley et al., 2011).

Table 7. Midpoint impact level for the unit of production from the cradle-to-farm gate.

Impact category	Unit	SB1	SB2	SB3	SB4	SB5
Global warming	kg CO_2 eq	0.049093	0.030894	0.037394	0.027682	0.042106
Stratospheric ozone depletion	kg CFC11 eq	6.96E-08	4.97E-08	6.47E-08	4.59E-08	7.15E-08
Ionizing radiation	kBq Co-60 eq	0.000598	0.000916	0.001339	0.000867	0.001466
Ozone formation, Human health	kg NOx eq	0.000597	0.00029	0.000335	0.000255	0.00039
Fine particulate matter formation	kg PM2.5 eq	0.000154	8.36E-05	9.84E-05	7.64E-05	0.00011
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000607	0.000295	0.000341	0.00026	0.000396
Terrestrial acidification	kg SO_2 eq	0.00036	0.000253	0.000329	0.00023	0.000371
Freshwater eutrophication	kg P eq	7.51E-06	7.98E-06	1.02E-05	8.09E-06	1.04E-05
Marine eutrophication	kg N eq	0.000441	0.000133	0.000133	0.000105	0.000165

For impact categories freshwater ecotoxicity (0.007677 kg 1,4-DCB) and mineral resource scarcity (0.000425 kg Cu eq), the SB3 variant with 180 kg N ha^{-1}, phosphorus 50 kg N ha^{-1}, and potassium 200 kg N ha^{-1} recorded the highest environmental load. High inputs of phosphorus and nitrogen frequently cause runoff that contributes to eutrophication in surrounding bodies of water, resulting in toxic algal blooms and subsequent hypoxic conditions that are damaging to aquatic life (Sharpley et al., 2013). Dead zones brought up by these blooms have the potential to reduce biodiversity and disturb food webs (Diaz and Rosenberg, 2008). Moreover, groundwater contamination from nutrient leakage can endanger human health and terrestrial ecosystems (Ryberg and Gilliom, 2015).

However, the SB3 recorded the lowest environmental burden in the land use impact category. Increased crop yields can greatly lessen the need to expand agricultural land, which will aid in preserving natural ecosystems and reducing deforestation. The urge to turn wetlands, grasslands, and forests into agricultural fields is lessened when productivity per unit of land rises since more food may be produced on the same or even less area (Balmford et al., 2005). High yields can be achieved while preserving or even decreasing the total area under cultivation by intensifying crop output through enhanced varieties, improved fertilizer management, and precision agriculture (Tilman et al., 2011).

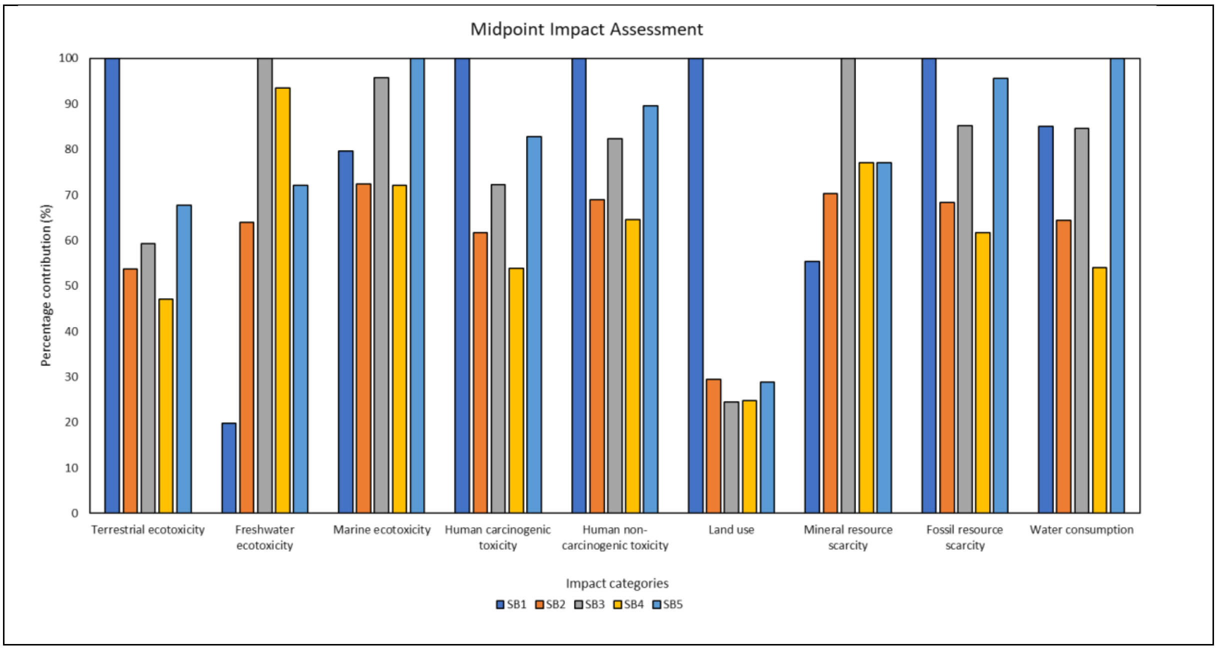

Figure 10. Environmental midpoint impact level for the unit of production from the cradle-to-farm gate. ReCiPe midpoint (H) method, characterization model, results were expressed kg ha^{-1}

According to the results, the SB4 variant recorded the least environmental burden in Terrestrial ecotoxicity (0.410068 kg 1,4-DCB), Human carcinogenic toxicity (0.005602 kg 1,4-DCB), Human non-carcinogenic toxicity (0.035419 kg 1,4-DCB), Fossil resource scarcity (0.008432 kg oil eq), Water consumption (0.000345 m^3), Global warming (0.027682 kg CO_2 eq), Stratospheric ozone depletion (4.59E-08 kg CFC11 eq), Marine eutrophication (0.000105 kg N eq), Terrestrial acidification (0.00023 kg SO_2 eq) and Ozone formation, Terrestrial ecosystems (0.00026 kg NOx eq). Crop nutrient utilization efficiency is essential for maintaining a balance between agricultural productivity and environmental effects, especially when it comes to nitrogen and phosphorus. The quantity of extra nutrients that can be lost to the environment through leaching, runoff, or gaseous emissions is decreased when crops use nutrients more efficiently for growth (Cassman et al., 2002). Effective nitrogen utilization by crops lowers the requirement for heavy fertilizer applications, which can otherwise result in nutrient losses and environmental problems such as greenhouse gas emissions and water pollution (Tilman et al., 2002). For example, gains in nitrogen use efficiency (NUE) in cereal crops have been associated with decreased emissions of nitrous oxide, a strong greenhouse gas, and nitrate leaching into groundwater (Snyder et al., 2009).

Conversely, low nutrient utilization efficiency can exacerbate environmental impacts by increasing the accumulation of unused fertilizers in the soil and water bodies, leading to eutrophication and hypoxia in aquatic ecosystems (Carpenter et al., 1998). Precision agriculture techniques, such as variable-rate nutrient application, have been shown to enhance nutrient use efficiency and reduce environmental impacts by tailoring fertilizer inputs to the specific needs of crops (Mulla, 2013). Additionally, integrating organic matter and cover crops into nutrient management can improve soil nutrient retention and reduce losses to the environment (Drinkwater and Snapp, 2007).

Table 8. Midpoint impact level for the unit of production from the cradle-to-farm gate

Impact category	Unit	SB1	SB2	SB3	SB4	SB5
Terrestrial ecotoxicity	kg 1,4-DCB	0.872188	0.468241	0.517283	0.410068	0.591017
Freshwater ecotoxicity	kg 1,4-DCB	0.001521	0.004915	0.007677	0.007178	0.005531
Marine ecotoxicity	kg 1,4-DCB	0.002832	0.002576	0.00341	0.002566	0.003558
Human carcinogenic toxicity	kg 1,4-DCB	0.010396	0.006419	0.007505	0.005602	0.008612
Human non-carcinogenic toxicity	kg 1,4-DCB	0.054889	0.037868	0.045205	0.035419	0.049168
Land use	m2a crop eq	0.543973	0.160556	0.133053	0.135084	0.156694
Mineral resource scarcity	kg Cu eq	0.000235	0.000299	0.000425	0.000327	0.000413
Fossil resource scarcity	kg oil eq	0.013681	0.009349	0.011652	0.008432	0.013073
Water consumption	m^3	0.000543	0.000412	0.000541	0.000345	0.000639

Overall, the SB4 variant, which had a half dose of mineral fertilizers (N 90 kg ha−1, P 25 g ha−1, and K 100 kg ha−1) and a full dose of pesticide, had the least environmental burden across multiple impact categories except overall and was deemed the most environmentally friendly variant.balanced fertilization practices, where nutrients are supplied in appropriate ratios, can further enhance nutrient utilization and mitigate environmental degradation (Fageria et al., 2011). Reducing the environmental footprint of agriculture requires an integrated approach that combines efficient nutrient management with sustainable farming practices (Robertson & Vitousek, 2009).

5.1.3 Endpoint Impact Categories

The results of the 18 midpoint impact categories relate to the three damage categories. According to the results, the SB1 variant recorded the highest impact in all three damage categories. According to the results, the S4 variant recorded the lowest environmental burden in all three protection areas and was deemed the most environmentally friendly. The SB5 variant recorded the second highest environmental burden, while the SB2 recorded the second lowest environmental burden across all three protection areas. To minimize environmental effects and maintain agricultural output, fertilizer application must be made efficiently. Farmers can apply fertilisers in a targeted way with precision agricultural techniques including soil testing and variable rate application, which greatly reduces misuse and runoff into water bodies (Zhang et al., 2016). According to Shcherbak et al. (2014), these methods increase crop yields and reduce problems, including soil degradation and nutrient contamination.

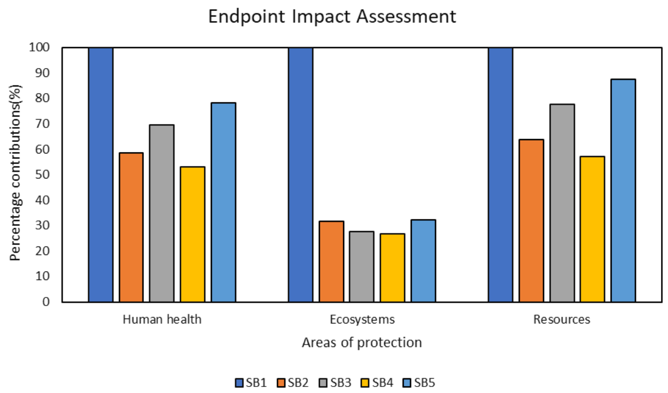

Figure 11. Environmental endpoint impact level for the unit of production from the cradle-to-farm gate

Moreover, integrated nutrient management strategies can decrease dependency on synthetic inputs and increase nutrient uptake efficiency, resulting in a smaller environmental footprint (Khan et al., 2015). These solutions combine organic and inorganic fertilizers. By optimizing fertilizer use, the agriculture industry may strike a balance between environmental sustainability and productivity.

5.2 The Effect of Cropping Systems on Environmental Impact Associated with Winter Wheat Production—An LCA "Cradle to Farm Gate" Approach

5.2.1 Interpretation Based on the Unit of Production

According to the characterization model, a contribution analysis was carried out for conventional and organic farming systems. The results are related to four winter wheat cropping systems and transferred to the environmental impact level in percentages. Figure 3 shows the results of the 3-year growing cycle of winter wheat in conventional and organic systems. From the data interpretation, it was also possible to determine different environmental impacts between individual cropping systems. The functional unit for this expression was 1 kg of the final product. Table 2 shows the results of a 3-year cycle of growing winter wheat in conventional and organic farming systems and monitoring the environmental load according to produc- tion unit (1 kg of the final product). According to the results of this study for the impact category global warming, ORG (0.1312 kg CO_2 eq) recorded the lowest environmental load, while OGR-F recorded the highest environmental demand for the impact categories climate change (0.2666 kg CO_2 eq), terrestrial acidification (0.0066 kg SO_2 eq), and marine eutrophication (0.000546 kg N eq), which is attributed mainly to the use and manage- ment of manure. CON-F recorded the highest environmental load for impact categories freshwater eutrophication (0.00012 kg P eq), terrestrial ecotoxicity (0.9794 kg 1,4-DCB), freshwater ecotoxicity (0.0170 kg 1,4-DCB), marine ecotoxicity (0.0114 kg 1,4-DCB), and water consumption (0.00179 m^3).

Table 2. Midpoint environmental load per production unit (1 kg of the final product).

Impact Category	Damage Category	Abbreviation	Unit	ORG-F	ORG	CON-F	CON
Global warming	Climate change	GWP	kg CO_2 eq	2.23×10^{-1}	1.31×10^{-1}	2.04×10^{-1}	1.40×10^{-1}
Terrestrial acidification	Ecosystem quality	TA	kg SO_2 eq	4.35×10^{-3}	2.92×10^{-4}	2.10×10^{-3}	3.14×10^{-4}
Freshwater eutrophication	Ecosystem quality	FE	kg P eq	1.18×10^{-4}	1.72×10^{-5}	1.29×10^{-4}	1.89×10^{-5}
Marine eutrophication	Ecosystem quality	ME	kg N eq	5.46×10^{-4}	4.90×10^{-4}	4.90×10^{-4}	5.00×10^{-4}
Terrestrial ecotoxicity	Ecosystem quality	TET	kg 1,4-DCB	2.71×10^{-1}	1.89×10^{-1}	9.79×10^{-1}	2.64×10^{-1}
Freshwater ecotoxicity	Ecosystem quality	FET	kg 1,4-DCB	3.14×10^{-3}	2.14×10^{-3}	1.70×10^{-2}	1.29×10^{-2}
Marine ecotoxicity	Ecosystem quality	MET	kg 1,4-DCB	3.79×10^{-3}	2.45×10^{-3}	1.14×10^{-2}	3.54×10^{-3}
Water consumption	Resources	WC	m^3	2.55×10^{-4}	1.40×10^{-4}	1.79×10^{-3}	1.82×10^{-4}

Figure 4 shows the results of the 3-year growing cycle of winter wheat in conventional and organic systems. From the data interpretation, it was also possible to determine differ- ent environmental impacts between individual cropping systems and convert them into percentages. The functional unit for this expression was 1 kg of the final product. The results of this study show that the unfertilized variants ORG and CON impose lower environmental load per production unit in seven impact categories compared to the fertilized variants ORG-F and CON-F, respectively. This is attributed to the overall low quantity of inputs in the production process, as shown in Table 1, and these variants are deemed to be more environmentally friendly compared to the fertilized variants. For the impact category terrestrial acidification, there was no significant difference in environmental load between ORG (4.5%) and CON (4.7%) systems. This can be attributed to the lack of N-fertilizer input in the ORG and CON systems. For impact categories freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and water consumption, CON-F recorded the highest environmental loads. For impact categories of global warming and terrestrial acidification, ORG-F recorded the highest environmental load, which is attributed to the use and application of manure.

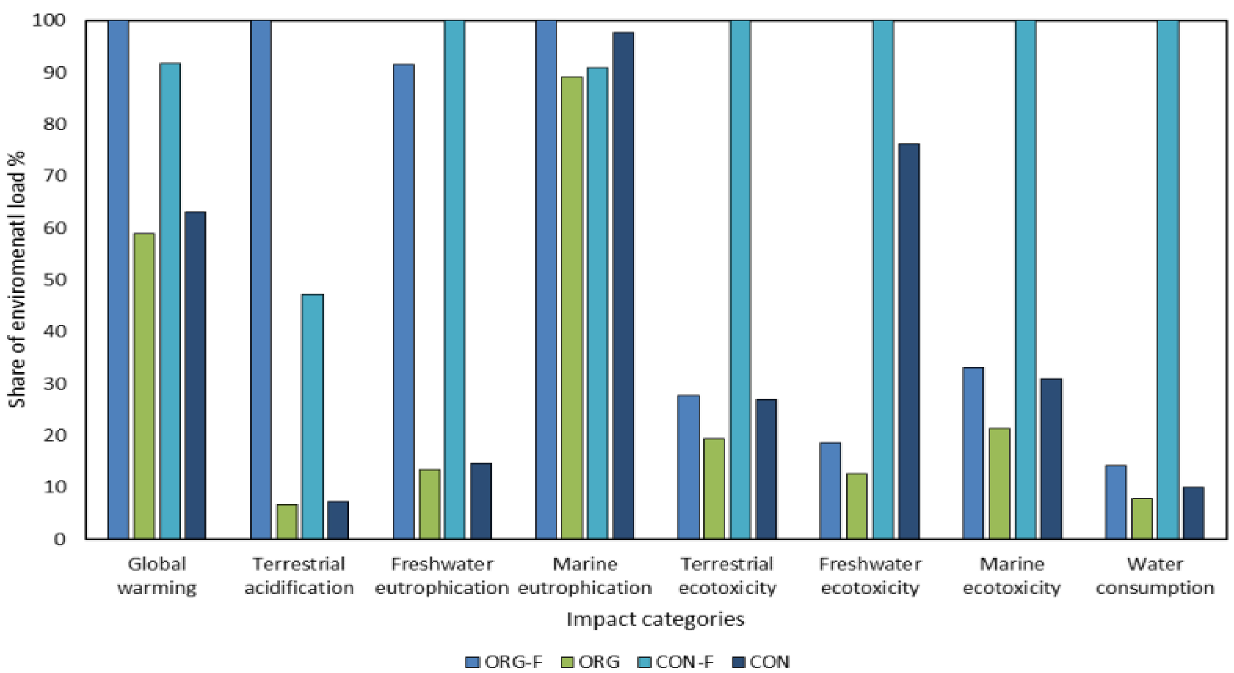

Figure 4. Midpoint environmental impact level for the unit of production (FU = kg ha^{-1}) from the cradle to farm gate approach for environmental impacts; ReCiPe midpoint (H) method, characterization model; results are expressed kg ha^{-1}.

5.2.2 Contribution Analysis from Cradle to Farm Gate for Midpoint Environmental Impact

Figure 5 shows the shares of inputs on the environmental load within selected impact categories. From the results based on the contribution analysis, the midpoint environmental impacts were mainly due to the input of fertilizers in the case of CON-F, and manure for ORG-F, and predominantly agrotechnological operations for all variants and impact categories. In the impact category of climate change, the highest contribution for ORG-F (0.0975 kg CO_2 eq) was associated with the use and management of organic fertilizer. For CON-F in the climate change impact category, the highest contribution was associated with the field emissions (0.0920 kg CO_2 eq) arising from the application of fertilizers and (0.0634 kg CO_2 eq) for the use of mineral fertilizers. CON recorded the highest contribution for agrotechnical operations (0.0465 kg CO_2 eq) and the use and application of herbicides (0.00052 kg CO_2 eq). Overall, for impact category climate change, ORG recorded the lowest environmental load.

For impact category terrestrial acidification, the highest contribution for CON-F (0.0014 kg SO_2 eq) was associated with the field emissions, and for ORG-F (0.0033 kg SO_2 eq) it was associated with the use and application of manure. There was no significant difference in all variants relating to agrotechnical operations, transport, and seeds in the im- pact category of terrestrial acidification. In the impact category freshwater eutrophication for the CON-F variant, the two highest contributions were field emissions (0.000076 kg P eq) and mineral fertilizers (0.000036 kg P eq). For impact category freshwater eutrophication, the highest contributions for the ORG-F variant were manure (0.000016 kg P eq) and field emissions (0.000084 kg P eq).

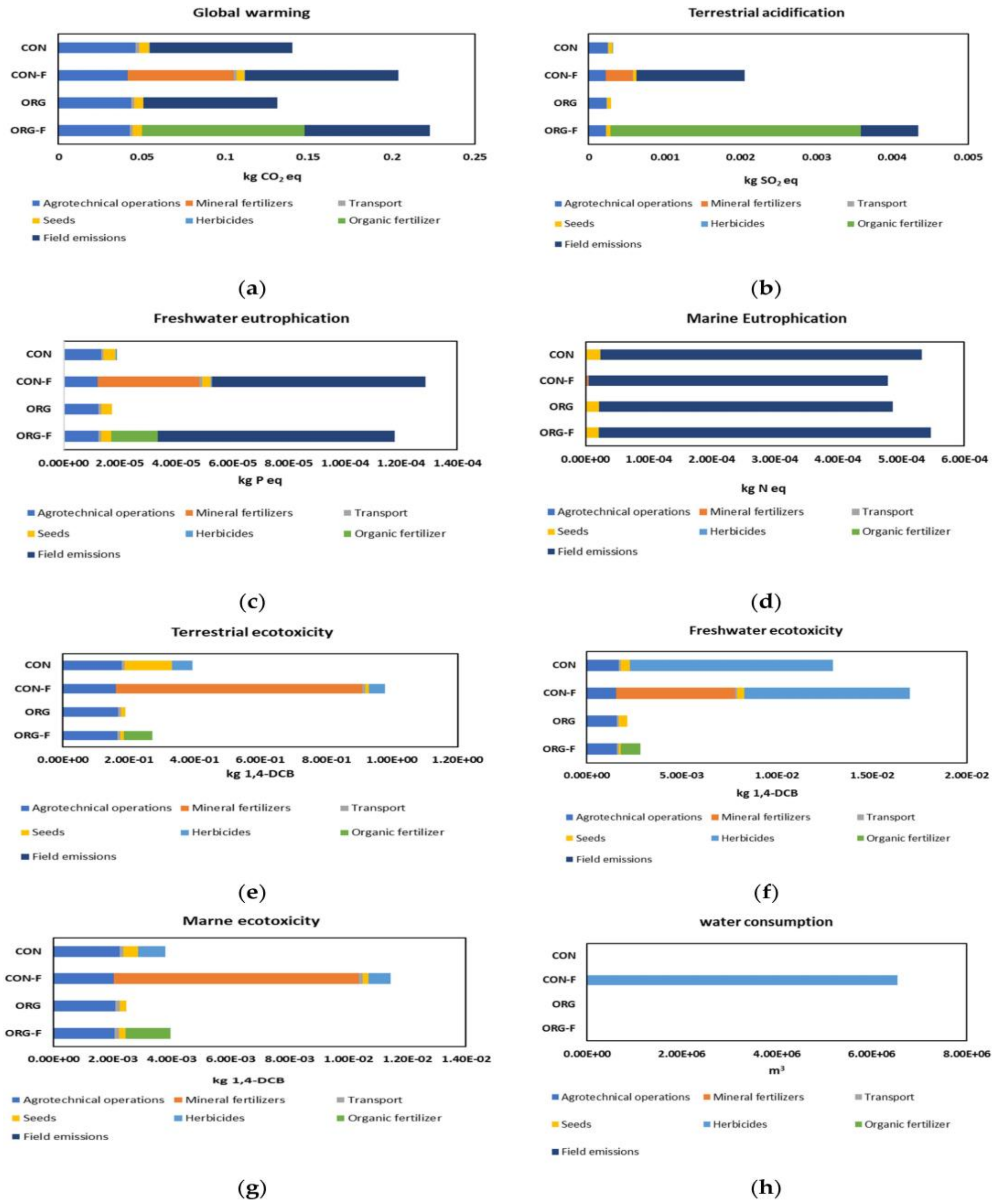
Global warming
CON
CON-F
ORG
ORG-F
0
0.05
0.1
0.15
0.2
0.25
kg CO_2 eq
Agrotechnical operations
Mineral fertilizers
Transport
Seeds
Herbicides
Organic fertilizer
Field emissions
(a)
Terrestrial acidification
0
0.001
0.002
0.003
0.004
0.005
kg SO_2 eq
(b)
Freshwater eutrophication
0.00E+00
2.00E-05
4.00E-05
6.00E-05
8.00E-05
1.00E-04
1.20E-04
1.40E-04
kg P eq
(c)
Marine Eutrophication
0.00E+00
1.00E-04
2.00E-04
3.00E-04
4.00E-04
5.00E-04
6.00E-04
kg N eq
(d)
Terrestrial ecotoxicity
0.00E+00
2.00E-01
4.00E-01
6.00E-01
8.00E-01
1.00E+00
1.20E+00
kg 1,4-DCB
(e)
Freshwater ecotoxicity
0.00E+00
5.00E-03
1.00E-02
1.50E-02
2.00E-02
kg 1,4-DCB
(f)
Marne ecotoxicity
0.00E+00
2.00E-03
4.00E-03
6.00E-03
8.00E-03
1.00E-02
1.20E-02
1.40E-02
kg 1,4-DCB
(g)
water consumption
0.00E+00
2.00E+06
4.00E+06
6.00E+06
8.00E+06
m^3
(h)

Figure 5. (**a–h**) Midpoint environmental impact level for the unit of production (FU = kg ha^{-1}). Contribution analysis from the cradle to farm gate approach for environmental impact categories; ReCiPe midpoint (H) method, characterization model.

From the results of the impact category marine eutrophication, the overall highest contribution was associated with the field emissions in all four variants. For impact category terrestrial ecotoxicity, the highest contribution for CON-F was mineral fertilizers (0.7487 kg 1,4-DCB). There was no significant difference in the contributions of agrotechnological operations in all four variants in the terrestrial ecotoxicity impact category. The CON variant recorded the highest contribution for herbicides (0.0621 kg 1,4-DCB) in the terrestrial ecotoxicity impact category. In the impact category freshwater ecotoxicity, the overall highest contributions were associated with herbicides for CON-F (0.0087 kg 1,4-DCB) and CON (0.0106 kg 1,4-DCB). The other main contribution for impact category freshwater ecotoxicity was mineral fertilizers, namely CON-F (0.0063 kg 1,4-DCB).

From the results for the impact category marine ecotoxicity, the main contributions were from agrotechnical operations and mineral fertilizers. There was no significant difference in the contributions for agrotechnical operations for all four variants, namely ORG-F (0.00208 kg 1,4-DCB), ORG (0.00208 kg 1,4-DCB), CON-F (0.00204 kg 1,4-DCB), and

CON (0.00223 kg 1,4-DCB). Overall, the ORG variant recorded the lowest impact in the marine ecotoxicity impact category. For impact category water consumption, the main contribution was from herbicides in the case of CON-F.

5.2.3 Interpretation Based on the Land Demand

Table 3 shows the results of a 3-year cycle of growing winter wheat in conventional and organic farming systems and monitoring the environmental load according to the land demand required to produce the same yield. There was an increase in the area unit, namely ORG-F (1.81 ha), ORG (1.31 ha), and CON (1.35 ha), to acquire the same yield as that of CON-F (1 ha), as shown in Table 1. This was a proportional increase in the environmental impact, reflecting the higher demand for land to produce the same yield [43]. The results for impact categories were as follows: freshwater eutrophication (1.98 kg P eq), terrestrial ecotoxicity (15092.11 kg 1,4 DCB) freshwater ecotoxicity (262.03 kg 1,4-DCB), marine ecotoxicity (176.39 kg 1,4 DCB), and water consumption (27.63 m^3). The CON-F system recorded the highest environmental loads. For impact categories global warming (3596.2 kg CO_2 eq) and terrestrial acidification (70.17 kg SO_2 eq), ORG-F recorded the highest environmental impact.

Table 3. Midpoint environmental load per land demand.

Impact Category	Damage Category	Abbreviation	Unit	ORG-F	ORG	CON-F	CON
Global warming	Climate change	GWP	kg CO_2 eq	3.60×10^3	2.21×10^3	3.15×10^3	2.29×10^3
Terrestrial acidification	Ecosystem quality	TA	kg SO_2 eq	7.02×10^1	4.92	3.16×10^1	5.14
Freshwater eutrophication	Ecosystem quality	FE	kg P eq	1.90	2.90×10^{-1}	1.98	3.09×10^{-2}
Marine eutrophication	Ecosystem quality	ME	kg N eq	8.82	8.21E+00	7.65	8.72
Terrestrial ecotoxicity	Ecosystem quality	TET	kg 1,4-DCB	4.38×10^3	3.19×10^3	1.51×10^4	4.31×10^3
Freshwater ecotoxicity	Ecosystem quality	FET	kg 1,4-DCB	5.07×10^1	3.62×10^1	2.62×10^2	2.12×10^2
Marine ecotoxicity	Ecosystem quality	MET	kg 1,4-DCB	6.13×10^1	4.14×10^1	1.76×10^2	5.79×10^1
Water consumption	Resources	WC	m^3	4.12	2.36	2.76E+01	2.97

5.2.4 Damage Categories

Figure 6 shows the endpoint damage categories of (1) climate change, (2) ecosystem quality, and (3) those relating to results of the eight midpoint impact categories: global warming, terrestrial acidification, freshwater eutrophication, marine eutrophication, terres- trial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and water consumption. From the data interpretation, it was also possible to determine different environmental impacts between individual cropping systems and convert them into percentages as shown in Figure 5. The functional unit for this expression was 1 kg of the final product.

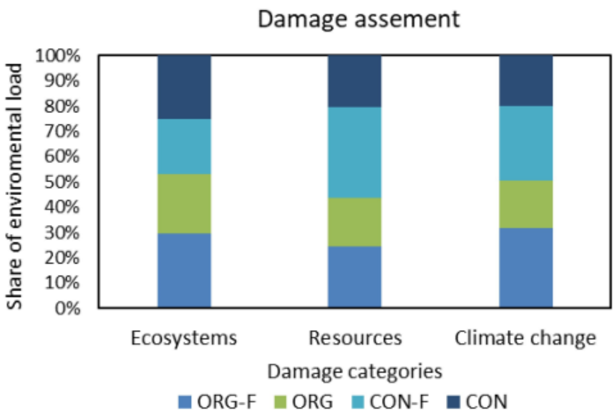

Figure 6. Environmental impact level for the unit of production (FU = kg ha^{-1}). Damage categories from the cradle to farm gate approach for environmental impacts; ReCiPe midpoint (H) method, characterization model; results are expressed kg ha^{-1}

The global attention paid to the environmental impacts caused by human activities continues to be a hot topic. Agriculture contributes to and is affected by environmental and mental impacts. Developments in intensive agriculture can lead to increased pollution of air, soil, and water bodies, as well as increase the consumption of resources. To address the potential mitigation of the environmental load within the framework of a standard farming process, we have to focus on all the sources of emissions arising from the production process [44]. The agricultural LCA has been seen as an effective way to assess resource consumption and environmental burdens in the whole process of agricultural production or agricultural activities [45]. The results of this study were related to impact categories corresponding to the agricultural LCA [31].

Global warming potential (GWP) is used to express the contribution that gaseous emissions from arable production systems make to the environmental problem of climate change [46] and is expressed based on the carbon dioxide equivalent (CO_2 eq) [47]. According to the result based on the unit of production for the impact category global warming, the fertilized variants in both organic and conventional systems recorded higher environ mental loads compared to the non-fertilized variants, namely ORG-F (0.223 kg CO_2 eq) and CON-F (0.204 kg CO_2 eq). There were similar trends from the results per land demand (land required to generate the same yield) for ORG-F (3596.17 kg CO_2 eq) and CON-F (3146.83 kg CO_2 eq). This can be mainly attributed to the use and application of mineral fertilizers for the CON-F system, and to the use and management of manure for the ORG-F system. This is supported by [48], who states that the greatest GHG emissions released into the atmosphere come mainly from N fertilizers. Significant greenhouse gas emissions in organic systems were linked to the usage of a large amount of organic manure [49]. Manure contains nitrogen, which when applied in excess or improperly handled, can lead to the deposition of nutrients in acidifying forms in the soil or release to air and water surfaces. Similar studies have linked the usage of organic manure to having an impact on the amount of GHG emitted [49,50]. As shown in Tables 2 and 3, for the climate change impact category, the ORG system recorded the lowest environmental load per unit of production and per land demand required to produce the same yield. For the climate change impact category, the ORG system was deemed to be more environmentally friendly, which can be attributed to the non-application or use of chemical fertilizers and plant protection products; however, this was associated with lower yields, as shown in Table 2. According to the IPCC (2006), farmers use N fertilizers to increase yields. However, these are a significant source of anthropogenic GHG emissions. The choice of fertilizer, its amount, and the method of its application in relation to N could significantly contribute to the mitigation of environmental impacts [51]. Minimizing inputs and increasing productivity is key to improving agricultural farming systems. The savings in the life cycle should be calculated not only per production unit, which is how most LCA outputs are determined, but also per area unit and time unit [43]. Crop rotation management can be used to reduce fertilizer and pesticide demand, which will also reduce the environmental impacts of crop production [52]. Utilizing nitrogen- fixing plants in a crop rotation can be a good way to avoid the overuse of nitrogen in the production system [53]. The other contributing factor to the higher environmental load is the burning and use of fossil fuels. Emission of CO_2 in the air at the farm level is generally caused by consumption of diesel fossil fuel in agricultural machinery [41,54]. This can have a direct or indirect effect on GHG emissions, e.g., during soil preparation, sowing, harvesting, plant protection, and chemical fertilizer application.

The interaction between natural processes and human impact must be carefully evalu- ated to understand ongoing soil processes concerning acidification [55]. Terrestrial acidi- fication describes how terrestrial ecosystems are negatively affected by a lowering of the soil pH caused by atmospheric deposition of acidifying substances [56]. According to the results for the impact category terrestrial acidification per production unit expressed as kg SO_2 equivalents, both fertilized variants, i.e., CON-F and ORG-F recorded higher environmental loads compared to the unfertilized variants, as shown in Table 2, which can be attributed to the loss of N during volatilization of ammonia NH_3. Conventional farming has been shown to have a higher impact on terrestrial acidification and eutrophication po- tential [57]. Nitrogen fertilizer is an essential fertilizer in winter wheat production [58], but when applied in excess quantities, the unused nitrogen results in enhanced volatilization of ammonia and nitrous oxide [59] through the process of nitrification and/or denitrifica- tion [60]. The volatilized ammonia is emitted into the air and runs off to the surface and groundwater as nitrate and ammonium [59]. There are several climatic factors, such as humidity, temperature, pH, and the amount of organic matter, that may influence the loss of nitrogen by volatilization [61,62]. Ammonia in the atmosphere may easily combine SO_2 and NOx to create particles [63]. The pollutants NH_3, SO_2, and NOx released from N fertilizer and diesel fuel lead to terrestrial acidification [64]. Extensive fuel combustion can increase SO_2 concentrations in the atmosphere [65], which can impact plant and animal species [66]. To mitigate the amount of ammonia volatilized in winter wheat production, the reduction in N fertilizer doses and incorporation of green cultivation methods to improve soil fertility, which results in the reduced need for N fertilizers, or the adoption of organic farming, can serve as mitigating strategies.

The eutrophication of surface water bodies has always been one of the main threats to global water security [67]. Eutrophication of water bodies refers to the over-enrichment of water bodies. According to the results for impact category freshwater eutrophication, CON-F (0.00013 kg P eq) recorded the highest environmental load per production unit. This is attributed mainly to the use of phosphorous fertilizers. For the impact category marine eutrophication per production unit, ORG-F (0.00055 kg N eq) recorded the highest environmental load. Manure is usually collected for use as organic fertilizer, which, if applied in excess, will lead to diffuse water pollution [68]. Extreme nutrient inputs containing nitrogen and phosphorus lead to the eutrophication of surface waters and increase toxicity [59]. This can lead to reduced water quality and habitat degradation. Nitrogen (N) and phosphorus (P) fertilizers cause 78% of the global marine and freshwater eutrophication [69]. Both N and P are emitted via surface runoff and erosion, but only N is considered to leach, while P is easily absorbed by soils [70]. From the results, ORG recorded the lowest environmental load on eutrophication per production unit. To mitigate the increase in water bodies' eutrophication it is necessary to reduce the excess amount of nutrients applied.

According to the results for impact categories freshwater and marine ecotoxicity per production unit and land demand, the ORG system recorded the lowest environmental load. Organic farming systems generate less damage to the environment, which is mainly attributed to the non-use of mineral fertilizers or chemical plant protection products. Nearly 70% of water resources worldwide are used for agriculture practices, which are responsible for an essential part of the pollution of water [59]. It is, therefore, necessary to protect the water resources from contamination, which can not only cause harm to the environment, but also to living organisms. From the results per production unit, the conventional variants recorded a higher environmental load, which is attributed to the use of herbicides. Similar to the impact category terrestrial ecotoxicity, CON-F had the highest environmental load. Ref. [71] stated that using chemical plant protection products is highly effective, but the dispersion of active substances in the environment causes the risk of contamination of waters and soils, as well as the bioaccumulation of these substances in living organisms. Agrochemical contamination has a long-term impact on humans, food chains, and the environment [47]. It is, therefore, important, as per Bessouet et al. (2013), that the chemical protection of crops and the fate of pesticides should be taken into account in agricultural LCAs [47]. The nutrient enrichment of waterbodies causes excessive growth of algae, deoxygenation, and biodiversity loss [72]. Our results showed that organic wheat farming reduces the environmental burden of ecotoxicity, which can be attributed to the non-use of plant protection products. To reduce the use of agrochemical protection in agriculture systems, crop rotation can be used to prevent the carryover of pathogens and the weed population [73], or organic farming can be adopted [74].

According to the results, CON-F recorded the highest environmental load both per unit production and land demand in the impact category of water consumption. This impact category refers only to the water used for the production processes relating to cultivation inputs [57]. For our results, this relates to the water required to dilute herbicide protection for the plants. Water is essential for every form of life, socio-economic development, and the maintenance of healthy ecosystems [68]. Water scarcity occurs when water supply is insufficient to meet water demand [75]. Therefore, it is important to protect water resources from scarcity. Overall, according to the results, ORG imposes the least amount of environmental load.

6 Conclusion

This study used the LCA method to quantify the environmental impacts associated with different cropping systems and strategies. The environmental loads of the sugar beet variants differ under different mineral fertilizers and pesticide doses. The result showed that applying mineral fertilizers and pesticides significantly impacted yields but was associated with a high environmental impact. The results also showed that lower-yielding crops are associated with high environmental impact. Thus, finding an appropriate balance between lowering agricultural input and obtaining sufficient yield outputs is imperative. Optimal fertilizer dosing in agriculture is crucial for balancing the need to enhance crop yields with the responsibility to mitigate environmental impacts. Recommending precise fertilizer applications based on crop requirements, soil nutrient levels, and local environmental conditions ensures that nutrients are used efficiently, minimizing environmental losses. Practices such as soil testing, precision agriculture techniques, and using slow-release fertilizers or inhibitors can significantly improve nutrient use efficiency, reducing the risks of leaching, runoff, and greenhouse gas emissions. Mitigation strategies should also include integrating organic amendments, adopting cover cropping, and implementing buffer strips to enhance nutrient retention and prevent pollution. By combining optimal fertilizer dosing with sustainable management practices, agriculture can achieve productivity gains while protecting natural resources, ensuring long-term food security and environmental health.