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RECEIVED
24 July 2026

CITE THIS ARTICLE

Phanichnok, M., Juksu, K. and Intrchom, W., 2027. Carbon footprint of commercial vegetable production: A comparison of conventional and organic farming in Phitsanulok province. *Nature Environment and Pollution Technology*, 26(1), D1966.

<https://doi.org/10.46488/NEPT.2027.v26i01.D1966>

EARLY-ACCESS STATEMENT

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PUBLICATION STATUS

PEER REVIEW
Completed

ONLINE VERSION
Prepublished

FINAL ISSUE
March 2027

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Carbon footprint of commercial vegetable production: A comparison of conventional and organic farming in Phitsanulok province

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Abstract

The aim of this study was to assess and compare the life cycle greenhouse gas (GHG) emission of commercial vegetable production in conventional and organic production systems in Phitsanulok Province in Thailand. A cradle-to-farm-gate life cycle assessment approach was used to calculate the carbon footprint of lettuce, spring onion, and cabbage, in terms of one kg of fresh crop. Structured farm surveys were conducted on 36 farms, which were synchronized according to cultivation schedule. The results showed that the GHG emissions from conventional farming were always higher in all the crops investigated, with the GHG emission values of the crops lettuce, spring onion, and cabbage being 0.3493, 0.2009, and 0.2757 kg CO₂eq kg⁻¹ respectively. Organic practices lowered these values to 0.1123, 0.0753, and 0.1044 kg CO₂eq kg⁻¹ for the corresponding crops, resulting in the total carbon footprint reduction by approximately 62-68%. The crop management stage was found to be the most carbon intensive stage of both systems in inventory disaggregation. The rather distinct emission gap was mainly caused by differences in inputs in the course of crop management; conventional systems made heavy use of synthetic N-P-K fertilizers as well as grid electricity for irrigation, which resulted in high production burdens at the beginning of the value chain and high nitrous oxide (N₂O) emissions in the field. However, the organic alternative eliminated these hotspots by replacing chemical fertilizers with dried chicken manure and introducing solar-powered water pumping systems, thus reducing emissions associated with energy use. Furthermore, emission reduction from organic waste management was reduced by lower amounts of agricultural residues from the organic sector. The results enable the development of a science-based greenhouse gas emission inventory in the region and show that, by using organic amendments, low-carbon agricultural transitions can be achieved with a low carbon intensity in commercial vegetable production.

Keywords

Carbon footprint; Commercial vegetable; Life cycle assessment; Greenhouse gas; Organic farming

1. INTRODUCTION

The current state of the global food system is at a critical environmental situation, where agriculture is responsible for the estimated 23-30% of total greenhouse gas (GHG) emissions (Tubiello et al. 2013). The significant role of this substantial share of emissions in the atmosphere highlights the need for a shift in the agricultural sector towards more sustainable and climate-resilient production systems. This shift, however, is complicated by multiple global efforts, such as increasingly stringent regulations to meet international climate commitments, decreasing land and water resources, and the growing demand for food security (Godfray & Garnett 2014). These challenges have been addressed by implementing sustainable intensification in agriculture by increasing production efficiency while decreasing emissions and environmental impacts. To overcome these constraints, in this context, the agricultural sector is implementing sustainable intensification for efficient production and reduction in emissions and environmental impacts (Impallomeni et al. 2026). This method involves better nutrient management, conservation agriculture, effective mechanization, and efficient use of resources to boost yields, while also sequestering carbon, boosting soil health, and reducing the overall carbon footprint of the sector (Lal et al. 2015).

Global warming is an issue of great environmental interest to humanity and requires an integrated approach to policy, science, social action, and industry (Sending et al. 2019). This phenomenon is, in part, caused by three major anthropogenic greenhouse gases, which all make specific contributions to global warming. The most common is Carbon dioxide (CO_2), which is mainly produced by the burning of fossil fuels in power generation, transport, and heating. Methane (CH_4) is derived from anaerobic decomposition in landfills, rice paddies, wetlands, and enteric fermentation in farm animals. Nitrous oxide (N_2O), a byproduct of nitrogenous fertilizer application and denitrification, presents significantly higher global warming potentials (GWP) than CH_4 and CO_2 (IPCC 2021). Within this context, agricultural and land-use activities are disproportionately responsible for the global budget of CO_2 , CH_4 , and N_2O (Li et al. 2025; Han et al. 2019). Agriculture can play an important role in GHG emissions (Yang et al. 2024), and there is a serious feedback loop between agriculture and climate change, as well as scaling up agricultural production to meet the growing needs of a global population (Yang et al. 2024).

Carbon footprint (CF) has been recognized globally as a standardized tool to evaluate GHG emissions in agricultural production systems (Avasthe et al. 2023). In addition to its monitoring function, CF can also offer strategic information as regards sustainable food production, such as finding pathways to reduce agriculture's impact on climate change (Niemic et al. 2024). Extensive longitudinal studies, such as those conducted in China between 1990 and 2019, demonstrate high emission intensities in staple grain production, with rice ($4871 \pm 418 \text{ kg CO}_2\text{e ha}^{-1}$) significantly exceeding wheat and maize (Fan et al. 2022). Similarly, commercial perennial crops like cacao exhibit substantial variability, with carbon footprints ranging from $1.55\text{--}2.703 \text{ kg CO}_2\text{e kg}^{-1}$ of dry beans (Cornelius et al. 2025). For vegetable systems, the GHG emissions from the intercropping systems (collard greens and spinach, collard greens and chicory) resulted in CF values of 0.030 and $0.033 \text{ kg CO}_2\text{eq kg}^{-1}$ respectively, which are both lower than the monoculture systems, even by 31% less than monocultures (Pereira et al. 2022). In all of the various vegetable production scenarios, across different geographies, the main

sources of emissions are fertilizer, fuel (diesel), and irrigation, and they represent the highest contributing sources when considering the total GHG emissions.

Thailand is a major agricultural country in Southeast Asia, and the commercial crop sector is a significant contributor of GHGs in the country due to the intensive use of production inputs and farming practices, such as synthetic fertilizers, etc., on fields and farms (Pengthamkeerati 2024). As such, Thailand is highly climate-change sensitive and has always been among the top ten most climate change impacted countries in the past twenty years (2000-2019) (Eckstein et al. 2021). The agricultural sector was the second largest emitter of greenhouse gases, with estimated shares of 15-17% of total GHG emissions in the late 2010s (MNRE 2024). These emissions are primarily driven by crop cultivation practices, that are major sources of CO₂, CH₄, and N₂O (Kumar & Bordoloi 2024). In particular, Thai cassava farming experience shows that synthetic fertilizers produce almost 20 times as much GHGs, at 51.83 kg CO₂eq ton⁻¹ of cassava roots compared to only 2.74 kg CO₂eq ton⁻¹ from organic fertilizers (Janchai et al. 2025). In such systems, nitrogen application frequently turns out to be a major emitter, accounting for 60-80% of the total carbon footprint (Saeed et al. 2025), along with fuel use for machinery and energy use for irrigation (Li et al. 2018). The Province of Phitsanulok in Northern Thailand is a good example of this, with various types of crops grown there, as it is a strategic region for agriculture. In recent years, commercial vegetable production, especially that of leafy vegetables and brassica vegetables like lettuce, spring onion, and cabbage, has emerged as an important economic source for rural livelihoods (Nath et al. 1999). Despite the growth of organic agriculture in response to greater institutional support, intensive commercial farming is still common in the region and is still a significant source of greenhouse gas (GHG) emissions. The knowledge of the carbon footprint of these production systems in Phitsanulok Province will provide scientific inputs for developing targeted mitigation measures and for agricultural sustainable policy.

This study compares the carbon footprint of the organic and conventional farming models for vegetables. The analysis is conducted based on a methodology that combines the life cycle assessment (LCA) approach and Intergovernmental Panel on Climate Change (IPCC) and Thailand Greenhouse Gas Management Organization (TGO) guidelines by Janchai et al. (2025) and Traware et al. (2025), respectively. The system boundaries were identified with a cradle-to-farm-gate approach, accounting for all production related inputs and processes up to the harvest stage. The main purpose of this paper is to quantitatively analyze and compare GHG emissions of the conventional and organic cultivation of the three major commercial vegetables: lettuce, spring onion, and cabbage, along with the cultivation process in Phitsanulok Province. Emissions were broken down into input categories and cultivation stages to determine the contribution of individual cultivation activities to total carbon emissions. The results provide a science-based GHG emissions inventory representative of the region, which can be used in agricultural policy development and for farm level GHG emissions reduction and low carbon vegetable production strategies.

2. MATERIALS AND METHODS

2.1 The study area and vegetable production system

The study was done in the lower northern part of Thailand, in Phitsanulok Province. The tropical monsoon climate, with well-defined wet and dry seasons, is suitable for year-round commercial vegetable production in

this area. It has been more than 20 years since this area has been a major source of vegetables, which plays an important role in the regional and national vegetable market. The total agricultural area is approximately 552,218 ha; the area of 175,943 ha is dedicated to the field crops and vegetables sector (Phitsanulok Provincial Office of Agricultural Extension 2022). Conventional farming still prevails in this sector, and certified organic farming is still very small, less than 1% (Phitsanulok Provincial Office of Agricultural Extension 2022). The crops selected for this research were three economically important vegetable crops: lettuce (*Lactuca sativa* L.), spring onion (*Allium cepa* var. *aggregatum*), and cabbage (*Brassica oleracea* L. var. *capitata* L.)

In the conventional farming system used in this study, synthetic inputs, such as N-P-K fertilizers and chemical pesticides, are widely used, and there is a high use of fuel and electricity. On the other hand, organic farming in line with organic certification standards involves the use of natural amendments like animal manure compost and natural mineral supplements and avoids the use of synthetic chemical pesticides. Furthermore, part of the electricity consumption is covered by photovoltaic (PV) system in the organic system. Although there are some differences in management, both systems use tillage to prepare the soil, purchase seeds and seedlings, and perform other common farm activities.

2.2 Data collection methods and farm survey procedures

In this study, Phitsanulok Province was selected through purposive sampling to identify different clusters of conventional farms and organic farms in the province. In each farming system, six farms were sampled for each of the three target vegetable crops, namely lettuce, spring onions, and cabbage, giving a total of 36 farmers. Due to the purposive sample size of six commercial farms per crop system ($n=6$), the collected life cycle inventory data are presented as representative of the sampled commercial farming practices within the study area of Phitsanulok Province. The sampling design enabled a well-done comparative analysis of average performance of the farm under both systems, especially in terms of the efficiency of inputs and GHG emissions. Structured on farm surveys were employed to collect primary data by interviewing farm operators in 2025. The questionnaire used to collect the data was validated by three independent experts. The procedure that led to the validation of the questionnaire was appropriate and reliable. These interviews were conducted on input, management, and output of agriculture. In addition, secondary data were accessed from Thai national databases, namely Life Cycle Inventory (LCI) and CF repositories, peer reviewed literature, and local studies that reflect the setting and socioeconomic background of Thailand.

Life Cycle Inventory data for all agricultural inputs were compiled for each vegetable crop. The farming systems adopted were conventional and organic, and the farming schedules and duration were synchronized; for lettuce and spring onion (40-50 days), the first planting was in May (early rainy season), and the second was in July (mid-rainy season); for cabbage (50-60 days), the first planting was done in October (early winter), while the second one was in December (late winter). Systematic data collection was done from showing to carry out a detailed input-output analysis. The number of agricultural inputs used was measured for fertilizers, natural mineral use, pest control products, water, energy (i.e., fuel and electricity), seeds and seedlings, and machinery use. The total amount of crops (kg of fresh weight) and the volume of agricultural wastes were measured as the corresponding outputs. The inventory data, based on an area of 1,600 m², were broken down into four main

production stages: soil preparation (machine operation, initial amendments, pre-emergence herbicide); cultivation (seeding, initial fertilization); crop management (subsequent fertilization, pest control, irrigation); and harvest (machine operation, post-harvest irrigation). Data collection was carried out over an entire production cycle for each crop to reflect typical resource levels and farm activities (He et al. 2024).

2.3 Life cycle assessment methodology and system boundaries

A cradle-to-farm-gate life cycle assessment (LCA) methodology was used in this study, in line with the international standards of ISO 14040/14044. The entire system boundary included all upstream activities and the core activities, including the production of inputs and the final harvest. However, this study did not include post-harvest processing, transportation downstream to the market, retail distribution, and consumer use (Jensen et al. 2024). The four main stages of production systems logistics, soil preparation, cultivation, crop management, and harvesting are considered as a system boundary for both production systems, as well as the transport of all the material inputs and waste management during agricultural production. Conventional farming systems included chemical fertilizers, synthetic pesticides, and grid electricity for irrigation, as shown in Fig. 1. In contrast, the organic farming system relied on organic fertilizers, and electricity was generated by photovoltaic (PV) systems. Embodied carbon emissions associated with the manufacturing, installation, and infrastructure of the PV systems were excluded from the inventory. When allocated over an expected 20-year operational lifespan and total crop yield, these infrastructure emissions contribute negligibly per functional unit and do not impact the rounded carbon footprint results. All transport operations and mechanized farm operations, including fuel used for delivery of materials, soil preparation, and waste management, are fully included in the system boundary. A life cycle assessment of total GHG emissions was carried out for the full production process. To ensure a standardized comparison between the two farming systems and the three vegetable crops, the Functional Unit (FU) was defined as 1 kg of fresh crop yield, with the environmental impact expressed in kilograms of carbon dioxide equivalent per kilogram of product ($\text{kg CO}_2\text{eq kg}^{-1}$).

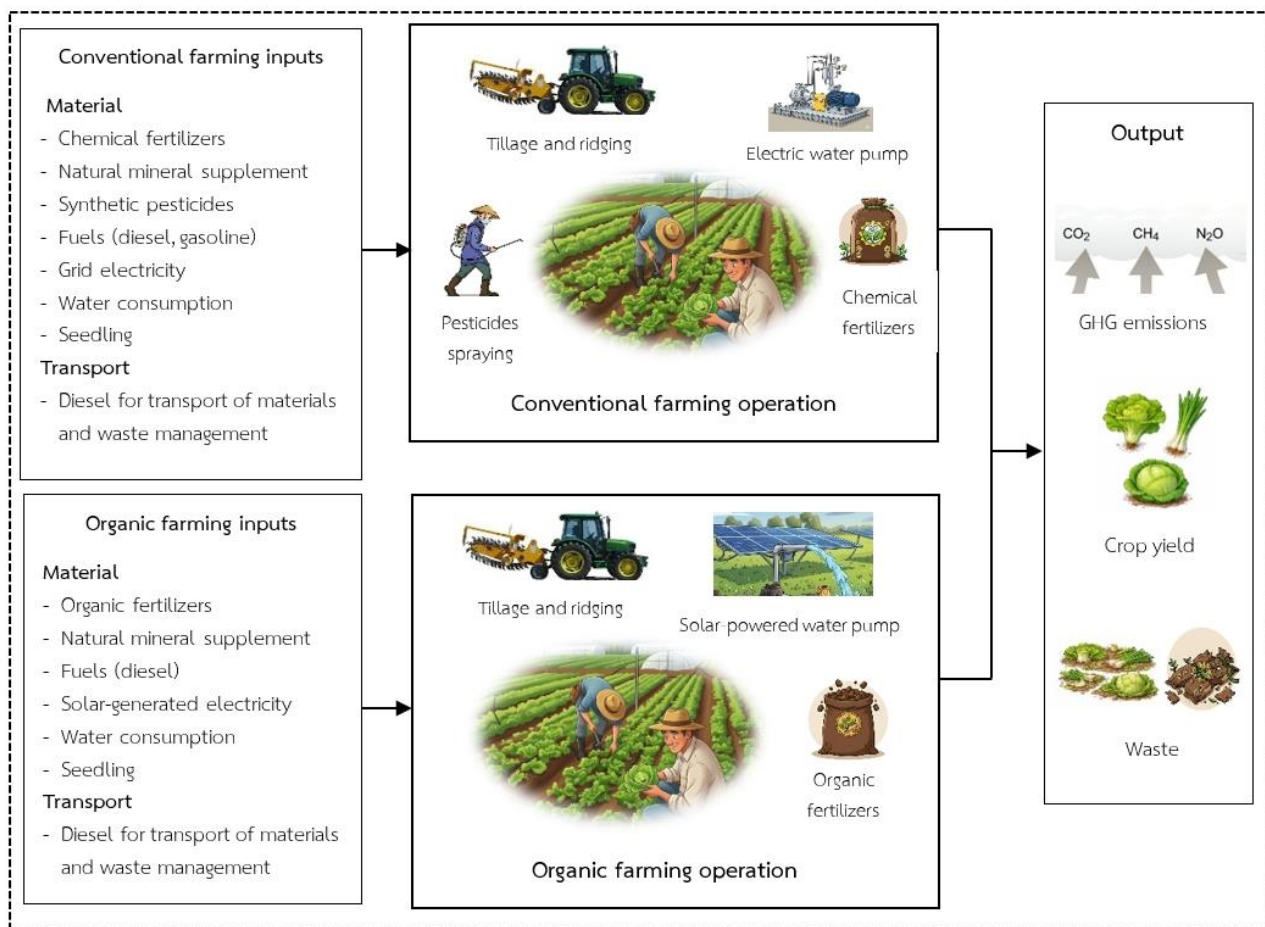


Fig. 1: System boundary of conventional and organic production of three commercial vegetable crops in Phitsanulok Province.

2.4 Carbon footprint calculation

Determination of the accurate carbon footprint (CF) of crops harvested is still a crucial process to assess the environmental efficiency and sustainability of contemporary agriculture (Marini 2020). Total GHG emissions were quantified in carbon dioxide equivalents (CO₂ eq) while using Global Warming Potential (GWP) with a 100-year time horizon. Following the strict rules of the IPCC Fifth Assessment Report (AR5), the mathematical model assigned GWP values of 1 for CO₂, 28 for CH₄, and 265 for N₂O (Mulya et al. 2025). Specific emission factors for all industrial and agricultural inputs were obtained from validated academic databases and national registries. The model recalibrated these and adjusted them to accurately reflect the actual transportation distances and actual production processes of Thailand's local agricultural supply chains.

The mathematical technique was in strict adherence to IPCC guidelines on monitoring agricultural pollution (Mulya et al. 2025). The total GHG emissions from each vegetable crop were calculated by applying the emission factors to the activity data, and the following simple equation was applied:

$$CF = \sum (Activity\ data_i \times EF_i \times GWP_i) \quad \dots(1)$$

Where: CF represents the carbon footprint ($\text{kg CO}_2\text{eq}$).

$Activity\ data_i$ denotes the exact quantity of material inputs, energy consumption, or waste management associated with vegetable production.

EF_i refers to the emission factor, representing the precise mass of pollution released per unit of farming activity.

GWP_i acts as the multiplier for the specific gas over a 100-year time horizon

The CFs for the individual farming systems were obtained by aggregating the environmental impacts of all relevant activities and input materials in the agricultural farming systems. Emission factors used for the assessment are listed in Table 1.

Table 1: Emission factors for vegetable production.

Agricultural activity data	Unit	Emission factor ($\text{kg CO}_2\text{eq/unit}$)	References
Material inputs			
Organic fertilizer	kg	0.1097	TGO (2022)
Chemical fertilizer as Nitrogen (N)	kg	3.3036	TGO (2016)
Chemical fertilizer as Phosphorus (P)	kg	1.5716	TGO (2016)
Chemical fertilizer as Potassium (K)	kg	0.4974	TGO (2016)
Dolomite	kg	0.0265	TGO (2022)
Alachlor	kg	8.0900	TGO (2022)
Chlorfenapyr	kg	13.4000	Agri-footprint database - SimaPro (2025)
Emamectin benzoate	kg	13.4000	Agri-footprint database - SimaPro (2025)
Diesel (upstream emission)	kg	0.3522	TGO (2022)
Diesel (field combustion emission)	L	2.9793	TGO (2022)
Gasoline (upstream emission)	kg	0.4024	TGO (2022)
Gasoline (field combustion emission)	L	2.3171	TGO (2022)
Electricity	kWh	0.5986	TGO (2022)
Waste management			
Vegetable waste - composting	kg	0.3326	TGO (2022)
Packaging waste - sanitary landfills	kg	0.7933	TGO (2022)
Transportation			
4-wheel pickup truck- 100% loading	tkm	0.1411	TGO (2022)
4-wheel pickup truck - 0% loading	km	0.3131	TGO (2022)
4-wheel van - 100% loading	tkm	0.2154	TGO (2022)
4-wheel van - 0% loading	km	0.2415	TGO (2022)
10-wheel van - 100% loading	tkm	0.0454	TGO (2022)
10-wheel van - 0% loading	km	0.5747	TGO (2022)
6-wheel garbage truck - 100% loading	tkm	0.0475	TGO (2022)
6-wheel garbage truck - 0% loading	km	0.4923	TGO (2022)

3. RESULTS

3.1. Life cycle inventory (LCI) of vegetable production systems

The vegetable production data used in the Life Cycle Inventory (LCI) also showed considerable differences between provinces, which are due to the differences in the farming systems and management practices in

Phitsanulok Province. These inventory metrics have been separated into four production stages and summarized in Table 2. The data revealed a difference in fresh yields, nutrient input, pest management, and energy management practices between conventional and organic farming systems.

Dolomite was used in both systems to address soil acidity and to improve the pH for soil nutrient availability as a nutrient amendment and/or to manage the soil's nutrient status, especially for Ca and Mg. The nutrient management in the conventional farming system was largely based on the application of synthetic nitrogen, phosphorus, and potassium (N-P-K) fertilizers (e.g., 15-15-15; 25-7-7; 16-16-16) and dried chicken manure. On the other hand, the concern with organic farming systems was the use of dried chicken manure to preserve soil fertility. Specifically, the manure needed for organic lettuce was 76.67 ± 8.16 kg, while that used to 56.67 ± 8.16 kg in the conventional system during the cultivation stage.

In terms of pest and weed control, weed control in conventional systems used the pre-emergence herbicide alachlor; in the organic systems, it did not use any of this herbicide. Conventional plots used synthetic insecticides, such as chlorfenapyr and emamectin benzoate, for insect management to reduce larval infestation. In the meantime, organic systems composed of certified organic materials were prevented from using any synthetic chemical inputs in order to meet the strict standard of certification.

There were differences between the two farming systems in energy use and in input use. The amount of diesel fuel consumed was similar, at approximately 12.00 to 14.00 L, for both systems for mechanized tillage and ridging. However, grid electricity and gasoline were required to operate irrigation and mechanical spraying in conventional plots, while solar energy was used in organic plots for pumping water. The high electricity consumption was observed in conventional production of cabbage, at the crop management stage, at 131.39 ± 6.73 kWh.

The collected data revealed that the conventional farming method generated a greater amount of waste, which consisted of vegetable waste. Conventional cabbage farming recorded the highest amount of agricultural waste at 493.33 ± 16.33 kg, whereas organic farming recorded a lower level of agricultural waste at 315.00 ± 25.88 kg.

Overall, there was no need for synthetic chemicals after conversion to the organic system, but more organic amendments were needed. The same change also resulted in reduced yields of crop residues per production cycle.

Table 2: Life Cycle Inventory (LCI) data on vegetable production between conventional and organic farming systems.

Activity data	Unit	Conventional farming (amount/1600 m ²)			Organic farming (amount/1600 m ²)		
		Lettuce (n=6)	Spring onion (n=6)	Cabbage (n=6)	Lettuce (n=6)	Spring onion (n=6)	Cabbage (n=6)
Fresh crop yield	kg	1,113.33 ±28.05	2,256.67 ±42.27	1,703.67 ±36.56	1,773.33 ±36.70	2,611.67 ±40.70 kg	2,085.00 ±36.19
Soil preparation							
Dolomite	kg	83.33±12.91	116.67±12.91	112.50±13.69	79.17±10.21	87.50±13.69	95.83±10.21
Alachlor	L	0.30±0.00	0.30±0.00	0.30±0.00	-	-	-
Diesel	L	14.00±1.10	13.67±1.51	13.50±1.22	13.00±1.10	13.33±0.52	12.00±0.63
Gasoline	L	0.50±0.00	0.50±0.00	0.50±0.00	-	-	-
Cultivation							
Dried Chicken Manure	kg	56.67±8.16	63.67±8.16	70.00±10.95	76.67±8.16	106.67±10.33	63.33±8.16
Crop management							
Fertilizer (15-15-15)	kg	44.17±4.92	56.67±5.16	41.67±9.83	-	-	-
Fertilizer (25-7-7)	kg	37.50±2.74	43.33±9.83	33.33±5.16	-	-	-
Fertilizer (16-16-16)	kg	-	23.33±19.66	-	-	-	-
Dried chicken manure	kg	-	-	-	136.67±15.06	133.33±0.52	113.33±10.33
Chlorfenapyr	L	0.09±0.00	0.09±0.00	0.09±0.00	-	-	-
Emamestin Benzoate	L	0.09±0.00	0.09±0.00	0.09±0.00	-	-	-
Gasoline	L	1.00±0.00	1.00±0.00	1.00±0.00	-	-	-
Electricity	kWh	94.07±1.54	87.09±2.52	131.39±6.73	-	-	-
Harvesting							
Diesel	L	5.67±1.03	5.83±0.98	5.50±0.48	5.33±0.52	5.17±0.41	5.25±0.42
Electricity	kWh	-	19.80±2.41	-	-	-	-
Waste management							
Vegetable waste	kg	286.67±15.06	243.33±10.33	493.33±16.33	226.67±22.51	188.33±13.29	315.00±25.88
Packaging waste	kg	1.08±0.20	1.20±0.17	0.87±0.08	1.10±0.11	1.10±0.11	1.07±0.10

3.2. Comparison of carbon footprint per functional unit of selected vegetables under different cultivation practices

The comparative assessment of GHG emissions for conventional and organic farming systems for lettuce, spring onion, and cabbage, as specified in Table 3, revealed substantial reductions in GHG emissions through the adoption of organic practices as compared to conventional practices. The total GHG emissions from conventional farming systems were higher for all three vegetable types, with values of 0.3493, 0.2009, and 0.2757 kg CO₂eq kg⁻¹ for lettuce, spring onion, and cabbage, respectively. In contrast, organic farming reduced these emissions to 0.1123, 0.0753, and 0.1044 kg CO₂eq kg⁻¹ for the same crops, respectively. Overall, the transition to organic farming can lead to a reduction of the CF of around 62-68%, showing a marked reduction compared to conventional farming. This emission gap was mainly due to the crop management stage. In conventional farming systems, synthetic fertilizers like 15-15-15, 25-7-7, and 16-16-16, were largely used, which created high emissions during both the production of synthetic fertilizers and N₂O emissions in the field during the farming process. In conventional cultivation, the highest percentage of CF contribution was from synthetic fertilizers and electricity use, while in the case of organic cultivation, these contributions were eliminated by using chicken manure instead of chemical fertilizers as an organic fertilizer. Furthermore, waste

management (composting of vegetable waste; sanitary landfills of packaging waste) were identified as an important emission source in the traditional farming system.

Organic farming's contribution to environmental benefits was mainly realized through the utilization of organic amendments rather than synthetic inputs, and by the use of renewable energy. However, the use of dried chicken manure led to reduced emissions in upstream areas compared with chemical alternatives. Incorporating solar pumping removed GHG emissions from electricity consumption during the crop management and harvesting phases. Across both systems, crop management remained the most carbon-intensive, followed by waste management and soil preparation, while transport, cultivation, and harvesting activities contributed the least to the total CF.

Table 3: Comparison of carbon footprint of conventional and organic farming system.

Activity data	GHG emissions (kg CO ₂ eq kg ⁻¹)					
	Conventional farming			Organic farming		
	Lettuce	Spring onion	Cabbage	Lettuce	Spring onion	Cabbage
Soil preparation						
Dolomite	0.0020	0.0014	0.0017	0.0012	0.0009	0.0012
Alachlor	0.0025	0.0012	0.0016	-	-	-
Diesel (upstream and field emission)	0.0413	0.0198	0.0260	0.0230	0.0167	0.0188
Gasoline (upstream and field emission)	0.0011	0.0006	0.0008	-	-	-
Cultivation						
Dried Chicken manure (upstream emission)	0.0056	0.0031	0.0044	0.0047	0.0045	0.0033
Dried chicken manure (field emissions as N ₂ O)	0.0085	0.0047	0.0067	0.0072	0.0068	0.0051
Crop management						
Fertilizer (15-15-15) (upstream emission)	0.0320	0.0202	0.0197	-	-	-
Fertilizer (15-15-15) (field emissions as N ₂ O)	0.0248	0.0157	0.0152	-	-	-
Fertilizer (25-7-7) (upstream emission)	0.0327	0.0186	0.0190	-	-	-
Fertilizer (25-7-7) (field emissions as N ₂ O)	0.0351	0.0200	0.0203	-	-	-
Fertilizer (16-16-16) (upstream emission)	-	0.0089	-	-	-	-
Fertilizer (16-16-16) (field emissions as N ₂ O)	-	0.0069	-	-	-	-
Dried chicken manure (upstream emission)	-	-	-	0.0085	0.0056	0.0060
Dried chicken manure (field emissions as N ₂ O)	-	-	-	0.0128	0.0085	0.0091
Chlorfenapyr	0.0011	0.0006	0.0007	-	-	-
Emametin Benzoate	0.0011	0.0006	0.0007	-	-	-
Gasoline	0.0031	0.0014	0.0016	-	-	-
Electricity	0.0506	0.0231	0.0461	-	-	-
Harvesting						
Diesel (upstream and field emission)	0.0167	0.0095	0.0106	0.0099	0.0065	0.0083
Electricity	-	0.0053	-	-	-	-
Waste management						
Vegetable waste	0.0856	0.0359	0.0961	0.0425	0.0240	0.0502
Packaging waste	0.0008	0.0004	0.0004	0.0005	0.0003	0.0004
Transportation						
Diesel for transport of materials	0.0037	0.0026	0.0028	0.0015	0.0012	0.0014
Diesel for transport of waste	0.0010	0.0004	0.0011	0.0005	0.0003	0.0006
Total	0.3493	0.2009	0.2757	0.1123	0.0753	0.1044

3.3. Contribution of farming activities to total carbon footprint.

Fig. 2 shows the distribution of CF across all four main phases (soil preparation, cultivation, crop management, and harvesting), and waste management and transportation for both systems. A detailed process-based analysis revealed differences between the GHG emissions associated with conventional and organic methods in all production steps. During soil preparation, conventional farming generated higher emissions than organic farming, with values of 0.0469 kg CO₂eq kg⁻¹, 0.0230 kg CO₂eq kg⁻¹, and 0.0301 kg CO₂eq kg⁻¹ for lettuce, spring onion, and cabbage, respectively. Organic practices lowered these emissions to 0.0242, 0.0176, and 0.0200 kg CO₂eq kg⁻¹, respectively.

During the cultivation stage, organic fertilizers were used in both systems. For lettuce and cabbage, conventional farming remained more carbon intensive approach, with emission reaching 0.0141, and 0.0111 kg CO₂eq kg⁻¹, respectively. Organic practices successfully lowered these values to 0.0119, and 0.0084 kg CO₂eq kg⁻¹ for lettuce and cabbage. The opposite trend was observed in spring onion cultivation, where the organic farming generated higher emission (0.0113 kg CO₂eq kg⁻¹) than the conventional farming (0.0078 kg CO₂eq kg⁻¹). For organic spring onion, this was found to be mainly due to the larger application of dried chicken manure during this stage, which was required to restore soil nutrients after the prior harvest.

Although this deviation is present, the crop management stage was still the main contributor to the carbon footprint gap between the two systems. In conventional farming, this stage accounted for the highest emission, reaching 0.1805, 0.1160, and 0.1233 kg CO₂eq kg⁻¹ for lettuce, spring onion, and cabbage, respectively. Organic farming, however, lower these values to 0.0213, 0.0141, and 0.0151 kg CO₂eq kg⁻¹. The major reason for this considerable decrease was the elimination of synthetic fertilizers and the adoption of solar-powered irrigation.

The organic systems' environmental benefits were verified in the post cultivation phases: harvesting, waste handling, and transport. Waste management represented a major emission hotspot, particularly for conventional cabbage, which generated 0.0965 kg CO₂eq kg⁻¹ nearly twice the 0.0506 kg CO₂eq kg⁻¹ emitted by the organic system. Similarly, for lettuce and spring onion, conventional waste management also led to higher emissions, at 0.0864, and 0.0363 kg CO₂eq kg⁻¹. The same trend was observed for transportation and harvesting, where the organic systems had lower carbon loads for all vegetable types. These outcomes showed that the adoption of organic farming can reduce carbon footprint during the resource intensive part of the management system and can ensure systematic emission reductions throughout the entire life cycle of vegetable production.

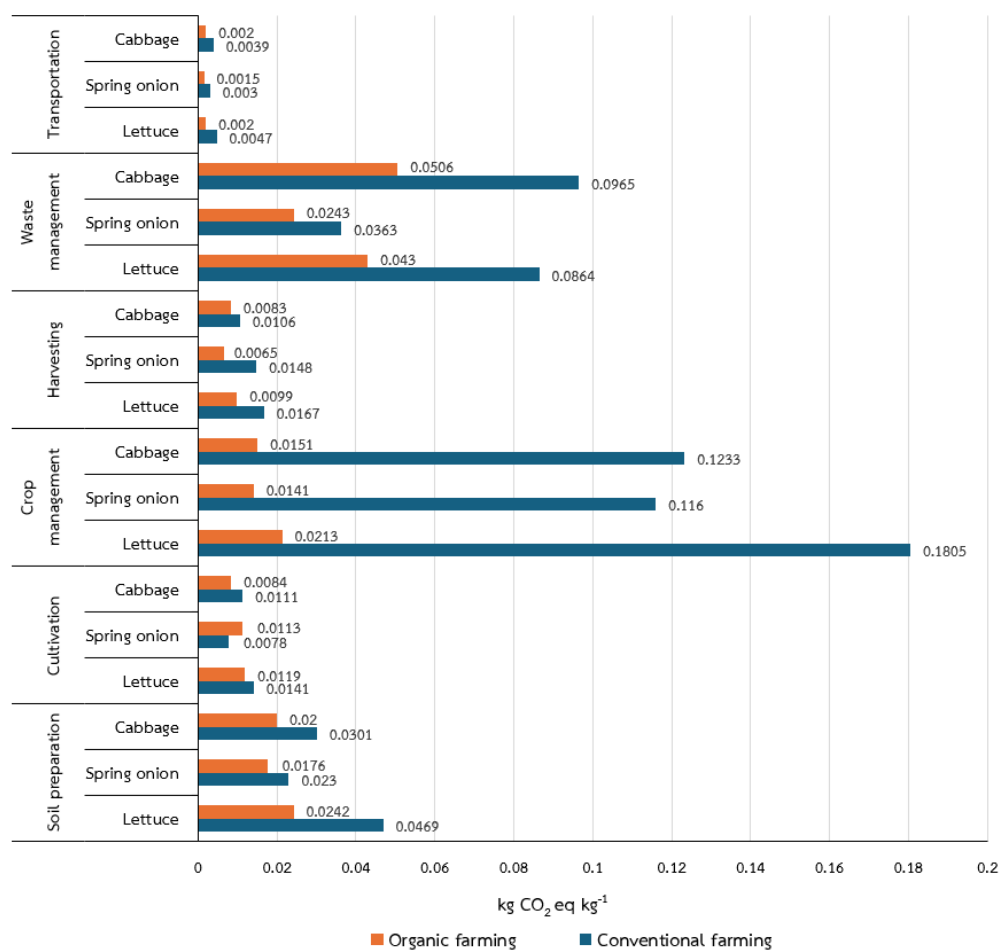


Fig. 2: Carbon footprint contributions by activity data for conventional and organic vegetables production.

3.4. Input emission sensitivity analysis of organic amendment variation for spring onion cultivation

An input emission sensitivity analysis was performed to evaluate how variations in dry chicken manure application affect greenhouse gas emissions during organic spring onion cultivation. The baseline application rate of 106.67 kg per 1,600 m² during the cultivation stage generated 0.0113 kg CO₂eq kg⁻¹ (under a constant baseline yield assumption). Three reduction scenarios were simulated: 10%, 20%, and 30%. Decreasing the application rate by 10% (96.00 kg) lowered the stage-specific emissions to 0.0102 kg CO₂eq kg⁻¹. Deeper reductions of 20% (85.34 kg) and 30% (74.67 kg) further minimized these emissions to 0.0090, and 0.0079 kg CO₂eq kg⁻¹, respectively. This sensitivity analysis demonstrates the direct input driven emission response to reduced organic amendments at the plot level; however, it reflects input variation rather than an optimized farm gate carbon footprint scenario. Reducing inputs lowers emission intensity per unit area, but in practical farming, it carries a crucial trade-off with crop productivity. Lower nitrogen application may cause soil nitrogen deficiencies, potentially reducing the fresh yield of spring onion and counteracting carbon footprint reductions per kilogram of harvested product (functional unit). Therefore, holding yield constant in this scenario serves exclusively to isolate input-emission sensitivity. Agronomic field trials are required to establish actual yield response curves before implementing input reduction strategies in commercial farming.

4. DISCUSSION

4.1. Carbon footprint analysis in conventional and organic vegetable production

This research found that the carbon footprints of organic vegetable production in Phitsanulok Province were substantially lower than those of conventional production, by 67.9%, 62.5%, and 62.1% for lettuce, spring onion, and cabbage, respectively. The observed 62-68% carbon footprint reduction is driven by an integrated cultivation practices rather than a single practice. Inventory disaggregation indicates that replacing synthetic N-P-K fertilizers with chicken manure accounted for the largest share of overall mitigation (45.2-54.8%), followed by the transition from grid electricity to solar-powered irrigation (31.8-37.1%), and reduced post-harvest residue generation (10.5-18.3%). These results were in line with the global trends reported in the life cycle assessment of agricultural systems. The reductions reported in this study were in line with the long term reductions reported by Graham et al. (2025), which reported reductions in emission of 52-74% for organic legume-based systems and 25-37% for manure-based methods compared to a conventional method. Eliminating energy-intensive synthetic sources was the biggest factor in reducing the carbon footprint in this study. This was also reported by Pandey & Pant (2026), who reported that total energy use in organic farming was reduced by 15-45%, primarily due to the lack of agrochemicals. This study also clearly revealed that the use of energy in organic farming is considerably less than conventional farming using both chemical inputs and electrical energy used for irrigation.

The difference in the carbon footprints of conventional and organic farming methods in Phitsanulok Province was mainly due to the intensive use of synthetic fertilizers in the conventional farming system. The crop management stage proved to be the highest emitter in conventional systems in this study. These emissions were primarily from the production of synthetic fertilizers (upstream) and release of N₂O from soils (downstream) after field application. This finding concurred with broader agricultural research conducted globally and across Asia. For instance, Ma et

al. (2021) indicated that synthetic nitrogen fertilizer accounted for 60-80% of total agricultural carbon footprints in certain cropping systems, placing the vegetable sector among the most emission-intensity categories.

Yet another difference between the two systems was emphasized by waste management, especially the composting of vegetable residues. The conventional cabbage production system generated 0.0965 kg CO₂eq kg⁻¹ from waste management operations, nearly doubling the 0.0506 kg CO₂eq kg⁻¹ recorded in the organic system. This differential was caused by the fact that, in the conventional system, a larger amount of vegetable scraps was generated per functional production unit. The higher number of residues in conventional plots was probably related to intensive chemical fertilization. This practice can encourage faster vegetative growth but can lead to increases in non-marketable biomass and outer-leaf trimming when compared to organic systems. Hence, the shift to organic farming reduced environmental impact by reducing the amount of waste generated, and thus the overall resource efficiency of the farming production cycle was enhanced, while at the same time input-related emissions were reduced.

4.2. Fertilizer application as the primary driver of greenhouse gas emissions

Fertilizer application was the highest source of GHG emissions in conventional systems. The nitrogen related emissions recorded in this study came from two sources: upstream emissions from the production of fertilizers, and N₂O emissions from the field related to soil nitrification and denitrification. Such a strong impact shows life-cycle system boundaries are essential to agricultural carbon accounting, where product footprint metrics evaluate combined emissions from both input manufacturing and on-field activities (Chaurasia et al. 2024). In conventional farming, the proportion of fertilizers (combining synthetic and organic) was 31-48% of all cultivation emissions. This proportion was much higher than in organic farming, where 22-33% of the sector could be attributed to organic fertilizers. The effects of synthetic pesticides, such as alachlor, chlorfenapyr, and emamectin benzoate, were limited and low (less than 2%) in the conventional plot and were not included in the organic plot, as it was not possible to certify pesticides in organic systems. These results were comparable to recent observations by Hou et al. (2024), who observed that nitrogen application in the Chengdu Plain, southwest China, accounted for about 70% of all emissions from the agricultural sector. For the same reason, longitudinal data spanning from 2011 to 2023 also reveals that although the carbon footprint of herbicides has continued to increase, fertilizer production was still the largest emission hotspot, especially in the production of vegetables as an intensive cultivation crop (Traware et al. 2025). Overall, the findings established that nitrogen management, instead of reducing the use of pesticides, is the most important lever to reduce GHG emissions from the vegetable subsector in Phitsanulok. Although organic farming provided a clear direction towards reducing the overall carbon footprint, the continued high levels of emissions from the use of fertilizers in both systems make clear the need for optimized nutrient management.

4.3. Diesel fuel and agricultural mechanization impacts

Diesel fuel consumption ranked among the top emission source across both farming systems, contributing 0.0167-0.0413 kg CO₂eq kg⁻¹ during soil preparation phase, to 0.0065-0.0167 kg CO₂eq kg⁻¹ throughout harvesting stage, and 0.0015-0.0047 kg CO₂eq kg⁻¹ of transportation for materials and waste management. These results are indicative of the general picture of mechanization in agriculture in the entire Southeast Asian region.

To illustrate, a comparative study of the two types of urban agriculture undertaken in Beijing by Hu et al. (2021) showed that, although the smallholder operations required fewer fixed factors of machinery production than the large-scale operations, the efficiency of the machines was not as high. The organic systems did not need to use gasoline-powered chemical sprayers for the application of pesticides, which were used in conventional systems in the Phitsanulok context. In addition, the usage pattern of energy in Phitsanulok Province was relatively clear, with a transition from diesel pumps to electric pumps for irrigation. This switch contributed to reducing the total carbon footprint, as the carbon footprint of grid electricity was less than the carbon footprint of direct diesel fuel combustion in this area. These infrastructural developments at the local level, coupled with the lower fuel consumption in organic farming for pest control, showed the potential of decarbonizing the vegetable production sector as a whole.

4.4. Electricity consumption and irrigation energy requirements

Energy sources for irrigation and post-harvest activities differed substantially between two farming systems. Conventional setup relied on grid-supplied electricity for irrigation pumping, which contributed 0.0506, 0.0231, and 0.0461 kg CO₂eq kg⁻¹ for lettuce, spring onion, and cabbage, respectively. In contrast, the organic systems used photovoltaic (PV) technology instead of grid electricity, thereby eliminating these operational emissions from the life cycle assessment. The change not only mitigated environmental issues but also long term energy expenses in the agricultural sector in the region. The findings of these were also consistent with the results obtained by Utami et al. (2025), who conducted a case study in Indonesia by implementing a smart solar-powered cold storage system for export vegetables that produced more than 12 kWh per day and reduced CO₂ emissions by about 212 kg per month. The environmental benefit of the use of solar energy in Phitsanulok was directly linked to the high amount of fossil fuel use of the national electricity grid, which, according to historical data from 2022, had an average emission factor of 0.5986 kg CO₂eq kWh⁻¹. PV technology has embodied carbon from manufacturing and installation but was demonstrated to reach carbon breakeven in 3 to 6 years of operation in tropical climates, and then provide emission-free electricity for a lifetime of 20 years (Samaarpap & Ruangrungrachai 2015).

4.5. Waste Management and Composting Emissions

Waste management was another major source of emissions, consistently the second largest after the crop management stage. Within conventional systems, vegetable residue composting accounted for 0.0359-0.0961 kg CO₂eq kg⁻¹. Specifically, conventional cabbage production generated 0.0961 kg CO₂eq kg⁻¹, a value roughly 1.9 times higher than that of the organic systems (0.0502 kg CO₂eq kg⁻¹). This difference is explained by the minimum post-harvest losses and the high quality of the crops in the organic plots, mostly due to lower absolute losses of the crop at harvest, but not to better methodologies of composting. To provide context on the organic fertilizer inputs, Chen et al. (2026) assessed the carbon footprint of poultry manure (PM) composting and determined that conventional methods generate around 684 kg CO₂eq per Mt, primarily from the release of methane in anaerobic conditions, whereas high-temperature microbial decomposition could raise the carbon footprint to 801 kg CO₂eq per Mt due to increased electricity consumption. To ensure sustainable management of residues,

it is essential that the process of vegetable residue decay is carried out by a controlled composting process with sufficient aeration, as stated by Nengsi (2025).

5. CONCLUSIONS

This life cycle assessment evaluated the environmental performance of prevailing observed integrated management systems for commercial vegetable production in Phitsanulok Province. The findings demonstrate that organic production systems achieve substantial GHG reductions compared to conventional practices, lowering the carbon footprints of lettuce, spring onion, and cabbage by 67.9%, 62.5%, and 62.1%, respectively. The observed 62-68% emission reduction reflects the synergistic performance of integrated cultivation practices rather than any single practice. Inventory disaggregation confirms that substituting synthetic N-P-K fertilizers with organic amendments delivered the single largest decarbonization benefit, while solar-powered irrigation and residue minimization provided secondary emission savings.

The data show that nutrient application is the main slice of the nutrient emission pie in both conventional and organic systems, ranging from 31-48% for conventional systems and 22-33% for organic systems. Thus, to maximize climate mitigation in the vegetable value chain in Phitsanulok, it is better to optimize nitrogen application than reduce the use of pesticides. Additionally, the integration of PV systems in organic operations eliminates irrigation-related emissions, which otherwise contribute up to 0.0506 kg CO₂eq kg⁻¹ in conventional lettuce production. Waste management operates as a secondary emission hotspot; for example, residue composting in conventional cabbage production generated 0.0961 kg CO₂eq kg⁻¹, nearly double the 0.0502 kg CO₂eq kg⁻¹ found in organic systems. Given that the agriculture sector contributes approximately 15-17% of the total GHG emissions in Thailand, growing more organics provides a feasible pathway towards achieving national climate targets. Though there are evident advantages of certified organic farming, it is only less than 1% of the agricultural land in Phitsanulok Province. Policy actions, therefore, need to focus on institutional measures to support the certification of organics, adaptation of renewable energy infrastructure, and nutrient management precision. Further studies are needed to assess the economic feasibility of transition to organic farming practices for small farmers and the potential for soil health to change over the long term in various agroecological regions of South-east Asia.

6. ACKNOWLEDGMENTS

The authors would like to acknowledge the Phitsanulok Provincial Office of Agricultural Extension for its valuable assistance in coordinating with relevant stakeholders and facilitating access to the agricultural data used in this research. This research was funded by Naresuan University through the University Revenue Budget for the fiscal year 2025, grant number R2568C026.

7. REFERENCES

1. Avasthe, R.K., Devi, S.H., Bhupenchandra, I., Kumar, A., Chongtham, S.K., Babu, S., Singh, R., Das, A., Gudade, B.A. and Bora, S.S., 2023. Agro-tactics for reducing carbon footprint in agricultural production systems: a review. *Indian Journal of Agronomy*, 68(2), pp.115–125. <https://doi.org/10.59797/ija.v68i2.332>.

2. Chaurasia, M., Srivastava, S. K. and Yadav, S. P., 2024. Evaluating sustainability: a comparison of carbon footprint metrics evaluation criteria. *Nature Environment and Pollution Technology*, 23(4), 2469-2476.
<https://doi.org/10.46488/NEPT.2024.v23i04.053>
3. Chen, Y.-N., Lin, Y.-C., Pan, S.-Y., Chang, C.-H. and Kuo, T.-C., 2026. Carbon footprint and environmental impact of poultry manure valorization as organic composts. *Poultry Science*, 105(3), 106457.
<https://doi.org/10.1016/j.psj.2026.106457>.
4. Cornelius, J.P., Hardy, F.W. and Harvey, C.A., 2025. Carbon footprint of primary production of cacao: a meta-analytical review. *Environmental Reviews*, 33, pp.1–18. <https://doi.org/10.1139/er-2024-0146>.
5. Eckstein, D., Künzel, V. and Schäfer, L., 2021. *Global Climate Risk Index 2021: Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2019 and 2000 to 2019*. Germanwatch: Bonn, Germany, 52 pp. Available online: <https://www.germanwatch.org/en/19777> (accessed on 23 April 2026).
6. Fan, J., Guo, D., Han, L., Liu, C., Zhang, C., Xie, J., Niu, J. and Yin, L., 2022. Spatiotemporal dynamics of carbon footprint of main crop production in China. *International Journal of Environmental Research and Public Health*, 19(21), 13896. <https://doi.org/10.3390/ijerph192113896>.
7. Godfray, H.C.J. and Garnett, T., 2014. Food security and sustainable intensification. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369(1639), 20120273. <https://doi.org/10.1098/rstb.2012.0273>.
8. Graham, M., Ghalegholabehbahani, A., Das, S., Carr, R. and Smith, A., 2025. Carbon footprint of organic and conventional arable crop production systems in a long-term trial. *Renewable Agriculture and Food Systems*, 40, e22.
<https://doi.org/10.1017/S1742170525100069>.
9. Han, M., Zhang, B., Zhang, Y. and Guan, C.H., 2019. Agricultural CH₄ and N₂O emissions of major economies: consumption- vs. production-based perspectives. *Journal of Cleaner Production*, 210, pp.276–286.
<https://doi.org/10.1016/j.jclepro.2018.11.018>.
10. He, Y., Su, R., Wang, Y., Li, S., Huang, Q., Chen, X., Zhang, W. and Yao, Z., 2024. Environmental impacts and nitrogen-carbon-energy nexus of vegetable production in subtropical plateau lake basins. *Frontiers in Plant Science*, 15, 1472978. <https://doi.org/10.3389/fpls.2024.1472978>.
11. Hou, L., Ma, C. and Liu, T., 2024. Revealing greenhouse gas emission and nitrogen fertilizer destination: a case study in Chengdu Plain cultivation industry. *Sustainability*, 16(14), 6073. <https://doi.org/10.3390/su16146073>.
12. Hu, Y., Sun, J. and Zheng, J., 2021. Comparative analysis of carbon footprint between conventional smallholder operation and innovative large-scale farming of urban agriculture in Beijing, China. *PeerJ*, 9, e11632.
<https://doi.org/10.7717/peerj.11632>.
13. Impallomeni, G., Kouka, D. and Barreca, F., 2026. Comparison of carbon footprints of lettuce cultivation systems in the Mediterranean area. *AgriEngineering*, 8(2), 46. <https://doi.org/10.3390/agriengineering8020046>.
14. Intergovernmental Panel on Climate Change (IPCC), 2021. *Climate Change 2021: The Physical Science Basis: Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (eds)]. Cambridge University Press: Cambridge, UK and New York, NY, USA, 2391 pp.
<https://doi.org/10.1017/9781009157896>.
15. Janchai, S., Nakkorn, N., Vorarat, S. and Thongprapa, S., 2025. Carbon footprint assessment using synthetic fertilizer and liquid organic biofertilizer in cassava cultivation to promote good cultivation practices and prevent greenhouse gas emissions from agricultural cultivation in Thailand. *ASEAN Journal of Scientific and Technological Reports*, 28(4), e257702. <https://doi.org/10.55164/ajstr.v28i4.257702>.

16. Jensen, A., Mogensen, L., van der Werf, H.M.G., Xie, Y., Kristensen, H.L. and Knudsen, M.T., 2024. Environmental impacts and potential mitigation options for organic open-field vegetable production in Denmark assessed through life cycle assessment. *Sustainable Production and Consumption*, 46, pp.132–145. <https://doi.org/10.1016/j.spc.2024.02.008>.
17. Kumar, R. and Bordoloi, N., 2024. Agriculture's contribution to the emission of greenhouse gas nitrous oxide (N₂O) and its feasible mitigation strategies. In: Abdelhafez, A.A. and Abbas, M.H.H. (eds) *Climate Smart Greenhouses—Innovations and Impacts*. IntechOpen: London, UK. <https://doi.org/10.5772/intechopen.113021>.
18. Lal, R., 2015. Restoring soil quality to mitigate soil degradation. *Sustainability*, 7(5), pp.5875–5895. <https://doi.org/10.3390/su7055875>.
19. Li, J., Yang, W., Wang, Y., Li, Q., Liu, L. and Zhang, Z., 2018. Carbon footprint and driving forces of saline agriculture in coastally reclaimed areas of eastern China: a survey of four staple crops. *Sustainability*, 10(4), 928. <https://doi.org/10.3390/su10040928>.
20. Li, L., Awada, T., Shi, Y., Jin, V.L. and Kaiser, M., 2025. Global greenhouse gas emissions from agriculture: pathways to sustainable reductions. *Global Change Biology*, 31(1), e70015. <https://doi.org/10.1111/gcb.70015>.
21. Ma, R., Yu, K., Xiao, S., Liu, S., Ciais, P. and Zou, J., 2022. Data-driven estimates of fertilizer-induced soil NH₃, NO and N₂O emissions from croplands in China and their climate change impacts. *Global Change Biology*, 28, pp.1008–1022. <https://doi.org/10.1111/gcb.15975>.
22. Marini, L., St-Martin, A., Vico, G., Baldoni, G., Berti, A., Blecharczyk, A., Malecka-Jankowiak, I., Morari, F., Sawińska, Z. and Bommarco, R., 2020. Crop rotations sustain cereal yields under a changing climate. *Environmental Research Letters*, 15(12), 124011. <https://doi.org/10.1088/1748-9326/abc651>.
23. Ministry of Natural Resources and Environment (MNRE), 2024. *Thailand's First Biennial Transparency Report (BTR1)*. Department of Climate Change and Environment: Bangkok, Thailand. Available online: <https://www.dcce.go.th/datacenter/2880/> (accessed on 23 April 2026).
24. Mulya, K.S., Tan, J.P., Yeat, S.P., Yeat, C.N.C., Farooque, A.A., Zhou, S. and Woon, K.S., 2025. Toward carbon mitigation resiliency in the agriculture sector: an integrated LCA-GHG protocol-IPCC guidelines framework for biofertilizer application in paddy field. *Journal of Environmental Management*, 389, 126005. <https://doi.org/10.1016/j.jenvman.2025.126005>.
25. Nath, P., Papademetriou, M., Piluek, K. and Herath, E.M., 1999. *The Vegetable Sector in Thailand: A Review*. RAP Publication 1999/38. Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific: Bangkok, Thailand. Available online: <https://www.fao.org/4/ac145e/ac145e00.htm> (accessed on 24 April 2026).
26. Nengsi, S.W., 2025. Integration of farming-livestock systems in sustainable agrocomplex development in Indonesia. *Journal of Agro Complex Development Society*, 2(1), pp.11–18. <https://doi.org/10.62012/agrocomplex.v2i1.12>.
27. Niemiec, M., Komorowska, M., Atilgan, A. and Abduvasikov, A., 2024. Labelling the carbon footprint as a strategic element of environmental assessment of agricultural systems. *Agricultural Engineering*, 28(1), pp.235–250. <https://doi.org/10.2478/agriceng-2024-0015>.
28. Pandey, S. and Pant, P., 2026. Organic agriculture as a climate mitigation strategy: evidence and prospects. *Advances in Agriculture*, 2026, 3551723. <https://doi.org/10.1155/aia/3551723>.
29. Pengthamkeerati, P., 2024. Pathways to net-zero: enhancing greenhouse gas mitigation in Thailand's agriculture sector. FFTC Agricultural Policy Platform. Available online: <https://ap.fttc.org.tw/article/3655> (accessed on 23 April 2026).
30. Pereira, B.J., Cecílio Filho, A.B., La Scala, N., Jr. and de Figueiredo, E.B., 2022. Greenhouse gas emissions and carbon footprint of collard greens, spinach and chicory production systems in Southeast of Brazil. *Frontiers in Plant Science*, 13, 1015307. <https://doi.org/10.3389/fpls.2022.1015307>.

31. Phitsanulok Provincial Office of Agricultural Extension, 2022. *General and Major Agricultural Information of Phitsanulok Province for the Year 2022*. Department of Agricultural Extension: Phitsanulok, Thailand. (in Thai).
32. Phitsanulok Provincial Office of Agricultural Extension, 2023. *Agricultural Information of Phitsanulok Province*. Department of Agricultural Extension: Phitsanulok, Thailand. (in Thai).
33. Saeed, Q., Niu, J., Xu, J., Mustafa, A., Zhang, S. and Yang, X., 2025. Carbon footprint of major wheat growing areas of Guanzhong Plain, Shaanxi Province of China based on farm survey data: a nitrogen dilemma. *Soil Use and Management*, 41(2), e70105. <https://doi.org/10.1111/sum.70105>.
34. Samaarpap, P. and Ruangrunghachikul, T., 2015. An economic assessment of solar water pumping systems for agriculture. *Thai Journal of Science and Technology*, 4(3), pp.217–226. <https://doi.org/10.14456/tjst.2015.6>. (in Thai).
35. Sending, O.J., Øverland, I. and Hornburg, T.B., 2019. Climate change and international relations: a five-pronged research agenda. *Journal of International Affairs*, 73(1), pp.183–194. Available online: <https://jia.sipa.columbia.edu/content/climate-disruption> (accessed on 24 July 2026).
36. Traware, O., Zhang, Y., Wang, L., Hopke, P.K. and Muluneh, M.G., 2025. Carbon footprint of agricultural pesticides on main crops in China from 2011 to 2023. *Journal of Environmental Management*, 394, 127605. <https://doi.org/10.1016/j.jenvman.2025.127605>.
37. Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N. and Smith, P., 2013. The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters*, 8(1), 015009. <https://doi.org/10.1088/1748-9326/8/1/015009>.
38. Utami, S., Mursid, S.P., Yusuf, E., Arasid, W., Nurdin, R. and Sabo, T., 2025. Smart solar energy systems for sustainable cold storage in export vegetable farming. *E3S Web of Conferences*, 664, 07003. <https://doi.org/10.1051/e3sconf/202566407003>.
39. Yang, Y., Tilman, D., Jin, Z., Smith, P., Barrett, C.B., Zhu, Y.-G., Burney, J., D'Odorico, P., Fantke, P., Fargione, J., Finlay, J.C., Rulli, M.C., Sloat, L., van Groenigen, K.J., West, P.C., Ziska, L.H., Michalak, A.M., The Clim-Ag Team and Lobell, D.B., 2024. Climate change exacerbates the environmental impacts of agriculture. *Science*, 385(6713), eadn3747. <https://doi.org/10.1126/science.adn3747>.

8. Description of Abbreviations

GHG	Greenhouse gas
CF	Carbon footprint
LCA	Life cycle assessment
IPCC	Intergovernmental Panel on Climate
TGO	Thailand Greenhouse Gas Management Organization
PV	photovoltaic

9. BACKGROUND INFORMATION FOR RECORD (NOT TO BE PRINTED)

Author Contributions: Conceptualization, M.P. and K.J.; methodology, M.P. and K.J.; software, M.P.; validation, M.P., K.J. and W.I.; formal analysis, M.P.; investigation, M.P. and K.J.; resources, M.P.; data curation, M.P.

and K.J.; writing—original draft preparation, M.P.; writing—review and editing, M.P., K.J. and W.I.; visualization, M.P. and K.J.; supervision, M.P., K.J. and W.I.; project administration, M.P.; funding acquisition, M.P. All authors have read and agreed to the published version of the manuscript. K.J. served as the corresponding author and managed the manuscript submission process.

Institutional Review Board Statement: “The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Naresuan University (protocol code P2: 0270/2568 and date of approval: 11 September 2025)

Informed Consent Statement: Informed consent was obtained from all participants involved in the study.

Conflicts of Interest: The authors declare no conflicts of interest.