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Environmental impact assessment of vegetable production in West Java, Indonesia

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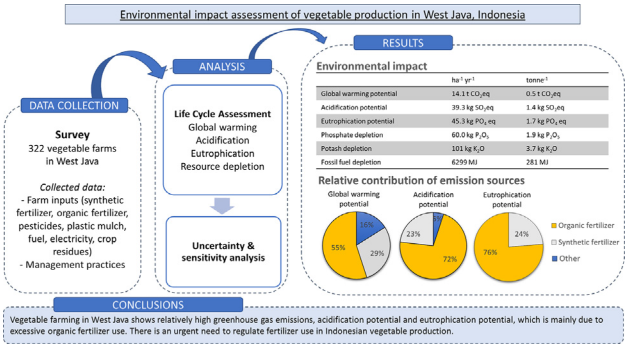
HIGHLIGHTS

- Environmental impacts of Indonesian vegetable production were quantified using LCA.
- Organic fertilizer use contributed the most to GHG, eutrophication, and acidification.
- Yield and organic fertilizer use explained most variation in GHG emission intensity.
- Organic fertilizer use should be included in the Indonesian fertilizer advisory system.

GRAPHICAL ABSTRACT



	$ha^{-1}\ yr^{-1}$	$tonne^{-1}$
Global warming potential	14.1 t CO_2eq	0.5 t CO_2eq
Acidification potential	39.3 kg SO_2eq	1.4 kg SO_2eq
Eutrophication potential	45.3 kg PO_4 eq	1.7 kg PO_4 eq
Phosphate depletion	60.0 kg P_2O_5	1.9 kg P_2O_5
Potash depletion	101 kg K_2O	3.7 kg K_2O
Fossil fuel depletion	6299 MJ	281 MJ

Vegetable farming in West Java shows relatively high greenhouse gas emissions, acidification potential and eutrophication potential, which is mainly due to excessive organic fertilizer use. There is an urgent need to regulate fertilizer use in Indonesian vegetable production.

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ABSTRACT

Indonesia is one of the world's economies contributing the most to greenhouse gas (GHG) emissions from the global food system. This study aimed to quantify the environmental impacts of Indonesian vegetable production and the relative contribution of different farm inputs. Data were collected from 322 vegetable farms in the Lembang sub-district in West Java. A Life Cycle Assessment (LCA) was carried out to estimate global warming potential (GWP), acidification potential (AP), freshwater eutrophication potential (EP), and abiotic resource depletion. Results of the LCA showed that GHG emissions were 14.1 t CO_2eq ha^{-1} yr^{-1} (0.5 t CO_2eq t^{-1}), AP was 39.3 kg SO_2eq ha^{-1} yr^{-1} (1.4 kg SO_2eq t^{-1}), EP was 45.3 kg PO_4eq ha^{-1} yr^{-1} (1.7 kg PO_4eq,), and depletion of phosphate, potash, and fossil fuel resources were 60.0 kg $P_2O_{5,}$ 101 kg K_2O, and 6299 MJ ha^{-1} yr^{-1}, respectively (1.9 kg P_2O_5, 3.7 kg K_2O, and 281 MJ t^{-1}). Organic fertilizer use contributed the most to impact categories of global warming, freshwater eutrophication, and acidification, followed by synthetic fertilizer. The sensitivity analysis showed that yield and organic fertilizer use explained most of the variation in GHG emission per ton product. Therefore, it is recommended to include organic fertilizer use in the fertilizer advisory system for vegetable production in Indonesia.

1. Introduction

Consumption of agri-food products is among the top three sectors contributing most to global environmental impacts (UNEP, 2012). The agriculture sector alone contributes 10–14 % of the global anthropogenic greenhouse gas emissions (GHGs) (Smith et al., 2014). Especially the nitrogen additions in agriculture are a dominant source of the emission of GHG nitrous oxide (N_2O), accounting for around 70 % of global anthropogenic N_2O emissions (Tian et al., 2020). Globally, the growth in N_2O emission has already surpassed the highest projected emission scenarios. In the future, emissions are expected to continue to rise due to the growing demand for food, feed, fibre, etc. (Tian et al., 2020). Besides global

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warming, reactive nitrogen and phosphorus introduced through the improper use of fertilizers can lead to other environmental issues, including terrestrial, marine, and freshwater eutrophication, acidification, soil degradation, reduced biodiversity; and depletion of the non-renewable resource phosphate (Sutton et al., 2013).

Indonesia is one of the top six economies that jointly contribute to more than half of the total GHG emissions from the global food system (Crippa et al., 2021). In 2015 Indonesia accounted for 8.8 % of the global food system GHG emissions. Indonesia's agriculture sector (including the Forest and Other Land use sector) accounted for 8 % of its national GHG emissions in 2016 (MoEF, 2018). Within this sector, direct N_2O emissions from managed soils accounted for 29 % of emissions (i.e., from the addition of urea, ammonium sulfate, and NPK fertilizers), with a 1.6 % rate of increase on average per annum since 2000. In its Intended Nationally Determined Contributions (INDC), Indonesia has pledged to reduce its total GHG emissions by 29 % - 41 % compared to a business-as-usual scenario by 2030, and utilization of organic fertilizer is one of the GHG mitigation strategies for the agriculture sector (MoEF, 2018).

Vegetable production systems are typically characterized by high nitrogen input and leaching (Tei et al., 2020). Globally, vegetable production accounted for 7.4 % of the total nitrogen (N) fertilizer consumption in 2014–2015 (Heffer et al., 2017). In recent years, environmental assessments of open field vegetable production have been carried out in several countries for different crops like tomato in Spain and Portugal (Clavreul et al., 2017) and Albania (Canaj et al., 2020); various types of vegetables in Spain (Martin-Gorriz et al., 2020); cabbage in China (Liang et al., 2021); and various types of vegetables in China (Zhang et al., 2021) and globally (Lam et al., 2021). These studies showed that fertilizer use was the major contributor to GHG emissions.

To the best of our knowledge, no previous study has estimated the GHG emissions of vegetable production in Indonesia using the Life Cycle Assessment (LCA) approach. At the same time, studies have shown that Indonesian vegetable farmers apply large amounts of organic and inorganic fertilizers (Pronk et al., 2020; Kurniawan et al., 2021). Therefore, this study aimed to quantify environmental impacts associated with Indonesian vegetable production and the relative contribution of different farm inputs, using LCA. Impact categories included global warming potential (GWP), acidification potential (AP), fresh water eutrophication potential (EP) and abiotic resource depletion (ARD; phosphate, potash, and fossil fuel resources). In addition, given the immense contribution of fertilizers to GHG emissions and Indonesia's interest in fertilizer use as a global warming mitigation strategy, specific attention was paid to GHG emissions from organic and synthetic fertilizer use.

2. Material and methods

2.1. Study area and data collection

The study was conducted in the Lembang sub-district of West Java, Indonesia. West Java is Indonesia's most important vegetable-producing province, accounting for about a quarter of the national vegetable production (BPS, 2020). Many types of vegetables are grown, with the main types being chili, cabbage, tomato, potato, shallot, and onion (BPS, 2020). The area is predominantly hilly with elevation varying between 1312 and 2084 m.

For the data collection process, first, 1738 vegetable farms were identified in the 16 villages of the Lembang sub-district using snow-ball sampling (Goodman, 1961). In the next step, 360 farms were randomly selected from the list of 1738 farms, of which 322 farmers were included in the final survey. A questionnaire was developed by Wageningen University and Research (WUR) and the Indonesian Vegetable Research Institute (IVEGRI), about farm characteristics, farming practices, yields, and use of fertilizer and other farms inputs. Questions targeted the farmer's recall of the four cropping seasons spanning one year. The questionnaire was implemented on the 322 farms by five employees of IVEGRI between September and November 2019. Further details of the survey and questionnaire are provided in Pronk et al. (2020).

2.2. Life cycle assessment methodology

An LCA was carried out to estimate GWP, AP, EP, and abiotic resource depletion (ARD) of vegetable farms in the Lembang sub-district.

2.2.1. System boundaries and functional unit

All processes up to the farm gate (i.e., 'cradle-to-gate') were included in the LCA, i.e., from the production of farm inputs up to harvesting stages of crop production, but excluding transport and processing of vegetables. The functional units chosen were one hectare (ha) of land and one tonne of fresh vegetable produce.

2.2.2. Data inventory

As per the survey results, large variations were found in the vegetable cropping system in Lembang, ranging from mono to multiple crops (1–3 crops) that were planted once per year (e.g., Casava) to every month (e.g., spinach). In general, farmers have four plantings per year when irrigation is accessible, and three plantings when they do not have irrigation access. In this study, all farmers had access to irrigation, with the exception of 25 farmers who had short fallow periods (max 2 months) due to labour or water shortage or both. In addition, the variety of crops produced by farmers was large (over 24 types) (Table 1) (details can be found in Pronk et al., 2020). Therefore, to allow comparable farm results, all farm inputs, outputs, yields, and crop residues of one year were aggregated and expressed in total inputs and total outputs per farm per year (Table 2). When crops failed, their inputs were included, and where crop harvest was ongoing at the time of the interview and thus incomplete, both inputs and outputs were dismissed. The total annual production was divided by the gross cropped area per farmer to derive yields.

2.2.2.1. Fertilizers and pesticides. For each farmer, the annual fertilizer application rate (in N, P, and K per hectare) was computed based on the rate of application (in kg ha^{-1}) and type (i.e., nutrient N, P, and K content) of each synthetic fertilizer (Table S1). The sum of fertilizer input (in kg ha^{-1}) for all cropping seasons was calculated as the annual amount. In the case of organic fertilizers, the amount of fertilizer used by a single farmer (in kg) was calculated by multiplying the number of sacks of each fertilizer used in the whole year and the weight of each sack, which was assumed to be 30 kgs for all organic fertilizers. The farm area remained same for a farmer in the entire year. Therefore, for each fertilizer type and each farmer, the application rate was derived in kg ha^{-1}. Then, depending upon the N, P, and K content of each fertilizer type (Table S1, S2) for a single farmer, the application rate in kg (N/P/K) ha^{-1} was calculated.

Composition of organic fertilizers was based on Indonesian literature sources, or, if not available, on international literature (Table S2). For the type of organic fertilizers most commonly used, i.e. chicken manure with rice husks (96 % of farmers) and cow manure products (15 % of farmers), nutrient composition was based on manure samples taken by other projects in the same region in West Java (20 samples of chicken manure and 33 samples of cow manure; Van den Brink et al., 2015, 2016; De Vries et al., 2020; Sefeedpari et al., 2020).

For emission calculation, synthetic fertilizers were classified into major types as per availability of emission factors. The emission associated with their production was calculated accordingly. For organic fertilizers, only the emission for application was considered since the emissions associated with the production (barn, storage, transport) of manure were not allocated to the crops but to the livestock sector.

For synthetic N fertilizer (F_{SN}), the total nitrogen (N) content of various types of synthetic fertilizers (used by farmers) was calculated based on the rate of application and N% of each major type of fertilizer. Similarly, for organic N fertilizer (F_{ON}), the N% of each type of organic fertilizer was based on literature, and the quantity of N was calculated based on application rates. For N in crop residues (F_{CR}), the amount of fresh weight crop residues

Table 1

List of vegetable crops included in this study.

Crops	Mono cropping system			Multiple cropping system		
	No. of plantings/ farm/yr	Average area per farm (ha)	Average marketable yield per planting [kg ha^{-1}]	No. of plantings/ farm/yr	Area (ha)	Average marketable yield per planting [kg ha^{-1}]
Asparagus	–	–	–	4	0.87	565
Beet root	2	0.02	12,619	7	0.10	7567
Broccoli	99	0.22	9510	136	0.25	8863
Cabbage	18	0.20	16,814	13	0.19	18,028
Cauliflower	40	0.21	17,527	57	0.25	15,876
Celery	3	0.12	10,606	8	0.19	4377
Chayote (Squash)	1	0.28	5357			
Chinese cabbage	22	0.37	21,760	24	0.25	20,072
Coriander	1	0.21	1905	1	0.13	1587
Cucumber				4	0.16	36,110
Eggplant	4	0.11	16,679	14	0.31	21,196
Horenzo (Japanese spinach)	18	0.12	3865	23	0.12	9172
Kaboca (Japanese pumpkin)	1	0.12	6706	4	0.27	4766
Kailan (Chinese kale)	1	0.07	4286			
Kyuri (Japanese cucumber)	2	0.18	21,707	2	0.18	14,921
Lettuce	90	0.25	12,611	198	0.21	9295
Long bean				1	0.28	2714
Mustard Green	14	0.10	7293	20	0.27	13,368
Potato	9	0.26	15,802			
Radish	2	0.08	7296	4	0.15	12,247
Spring onion	1	0.03	8929	4	0.14	1747
String bean	41	0.23	9155	29	0.27	7235
Sweet potato	1	0.07	1429			
Tomato	49	0.17	27,829	103	0.27	32,507

incorporated was taken from survey data. This was converted to dry weight` based on the average moisture content of multiple crops (Table S3).

For pesticides, the annual total number of doses for each farmer was multiplied by the emission factor of pesticides.

2.2.2.2. Diesel for irrigation and farm operations. Irrigation pumps ran on diesel. For each mm of irrigation water applied through flooding, the assumed energy use (in kilowatt-hour) was 1.7 MWh (Haverkort and Struik, 2015). The irrigation volume applied per irrigation event was set at 10 mm. The energy consumption per irrigation event becomes 61.2 MJ ha^{-1}, representing 1.7 l ha^{-1} diesel (energy content of diesel taken as 36.7 MJ l^{-1} (Dale, 2021)). Multiplied by the number of irrigation events per farmer, it becomes the total amount of diesel consumed. For diesel consumption for tillage, the annual gross cropped area was multiplied by the average diesel consumed per unit area (ha), i.e., 3.5 l ha^{-1} in the study region based on expert estimates. Similarly, the diesel consumed by power sprays was calculated based on the total area sprayed multiplied by the diesel consumption of power sprays per unit area i.e., 1.4 l ha^{-1} (Hillier et al., 2011).

Table 2

Data inventory sources.

Variable	Data type	Inventory (Mean value per year)	Data Source	Granularity
Yield	Quantity	50 t ha^{-1} Details in Table 2	Farmer survey	Tier 3 (Individual farmer)
Farm size	Area	–	Farmer survey	Tier 3
Synthetic fertilizer	Type and application rate	256 kg N ha^{-1} yr^{-1} 242 kg P_2O_5 ha^{-1} yr^{-1} 263 kg K_2O ha^{-1} yr^{-1}	Farmer survey	Tier 3
	N, P, K content (%)	Details in table S1	Secondary data (Indonesia specific)	Tier 2
Organic fertilizer/manure	Type and application rate	(in dry weight) 862 kg N ha^{-1} yr^{-1} 696 kg P_2O_5 ha^{-1} yr^{-1} 700 kg K_2O ha^{-1} yr^{-1}	Farmer survey	Tier 3
	N, P, K content (%)	Details in table S2	Secondary data (Indonesia and other countries)	Tier 2
Pesticide	Means of application (fuel-driven, manual)	–	Farmer survey	Tier 3
	Fuel use (per unit area)	0.2 l ha^{-1}	Secondary data	Tier 1
	No. of tillage operations	–	Farmer survey	Tier 3
Soil cultivation	Means of tillage (fuel-driven, manual)	Both (46 out of 322 farmers used fuel-based tillage)	Farmer survey	Tier 3
	Fuel use (per unit area)	1.3 l ha^{-1}	Expert estimate	Tier 2
	No. of applications	–	Farmer survey	Tier 3
Irrigation	Volume of application	10 mm/irrigation event	Expert estimate	Tier 2
	Fuel use per L irrigation applied	175 l ha^{-1}	Secondary data	Tier 1
	Use in the farm (yes/no)	–	Farmer survey	Tier 3
Plastic mulch	Application rate	40 kg ha^{-1}	Expert estimate	Tier 2
Crop residue burnt	Quantity estimates	151 kg ha^{-1} (dw)	Farmer survey	Tier 3
Crop residue incorporated		95 kg ha^{-1} (dw)		
Crop residue composted		276 kg ha^{-1} (dw)		

2.2.2.3. Plastic mulch. For plastic mulch consumption, an average of 11 rolls per ha (198 kg ha^{-1}) was taken as per expert opinion. It was assumed that plastic mulch is reused for successive cropping seasons, and therefore, was counted only once annually.

2.2.2.4. Seeds. We did not consider the GHGs associated with seeds as they have negligible contribution (< 1 %) to GHG emissions (Adewale et al., 2016).

2.2.3. Quantification of environmental impacts

2.2.3.1. Global warming potential. The GHG emission quantification for vegetable production was carried out using the LCA approach based on the PAS 2050:2011 protocol (BSI, 2011). As all farmers indicated that any land-use change occurred >20 years before the survey, changes in soil carbon content were excluded from the assessment as per PAS 2050 guidelines. Greenhouse gas emissions due to crop production included emissions from production and application of synthetic fertilizers, application of organic fertilizers, production of pesticides, crop residue handling (burning, composting, incorporation), and diesel use for irrigation, tillage, and power spray.

The GHG emissions associated with inputs were calculated using the following equation:

$$CF_A = \Sigma(A_i * EF_i) \quad (1)$$

Where, carbon footprint (CF) of activity, i.e., CF_A is the sum of GHG emissions (per hectare) due to ith activity or input in t CO_2-eq; A_i is the activity data or amount of ith activity or agricultural input (fertilizer (kg N ha^{-1}; kg P_2O_5 ha^{-1}), pesticide (kg ha^{-1}), or diesel (l ha^{-1}); and EF_i is the emission factor of the ith activity or input (in t CO_2-eq per unit volume or mass). The list of emission factors (and their sources) used for CF quantification are given in Supplementary Table S3. Data inventory and their sources are summarized in Table 1. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions were summed up to CO_2eq using the latest Intergovernmental Panel on Climate Change's (IPCC) 100-year GWP coefficients of 1, 28, and 265 respectively (IPCC, 2013).

Direct and indirect N_2O emissions were calculated using the following equations:

$$N_2O_{total} = N_2O_{direct} + N_2O_{indirect} \quad (2)$$

$$N_2O_{direct} = (F_{SN} + F_{ON} + F_{CR}) * EF_1 * \gamma_{N2O} \quad (3)$$

$$N_2O_{indirect} = N_2O_{(ATD)} + N_2O_{(L)} \quad (4)$$

$$N_2O_{(ATD)} = (F_{SN} * EF_4 * Frac_{GASF} + F_{ON} * EF_4 * Frac_{GASM}) * \gamma_{N2O} \quad (5)$$

$$N_2O_{(L)} = (F_{SN} + F_{ON} + F_{CR}) * EF_5 * Frac_{LEACH} * \gamma_{N2O} \quad (6)$$

Where F_{SN}, $F_{ON,}$ and F_{CR} are the amounts of N in synthetic fertilizer, manure, and crop residues (above-ground) respectively added to soils (in kg N /crop season). $N_2O_{(ATD)}$ and $N_2O_{(L)}$ are N_2O emissions from atmospheric deposition and leaching and run-off of nitrogen additions from managed soils, respectively. EF_1 is the emission factor for N_2O emissions from N inputs (kg N/ input); EF_4 and EF_5 are the emission factors for N_2O emissions due to volatilization (and redeposition) and leaching/run-off N respectively from fertilizer, manure and crop residues. $Frac_{GASF}$, $Frac_{GASM}$, and $Frac_{LEACH}$ are the fraction factors of atmospheric deposition of N volatilized from synthetic fertilizer, organic materials, and leaching from managed soil; γ_{N2O} (44/28) is the mass conversion factor for N_2 to N_2O (IPCC, 2019).

GHG emission due to crop residue burning was calculated using the following equation (IPCC, 2006):

$$CF_B = Crop\ residue\ weight^* \ DM^* \ Of^* \ EF \quad (7)$$

Where DM is the average dry matter content of multiple crops, O_f is the fraction oxidized, and EF is the emission factor for CH_4 and N_2O emitted while burning (Table S3). The fresh weight of crop residues burnt was derived from the farm survey. The CO_2 emission from residue burning was not included as per IPCC guidelines (IPCC, 2019).

The GHG emissions due to crop residue composting were calculated by multiplying the amount of composted residue (converted to dry matter in kg ha^{-1}) with EFs for CO_2, CH_4 and N_2O (Table S3). The emissions from CH_4 and N_2O were converted to CO_2eq and all three types of emissions were summed up. The GHG emissions of composted crop residues (in t CO_2eq/t) for each farmer was calculated as:

$$CF_{per\ unit\ weight} = \frac{CF_{per\ unit\ area}}{Yield} \quad (8)$$

2.2.3.2. Acidification potential, eutrophication potential, depletion of resources, and land use. Other life cycle impact categories, i.e., AP, EP, and ARD (phosphate, potash, fossil fuel resources), were evaluated based on the methodology by Brentrup et al. (2004). The characterization factors, fate factors, and emission factors used for each impact category are reported in Table S3.

Percentage of NH_3 and NO_x emitted from synthetic fertilizers, and manure (Table S3) were used to calculate the NH_3 and NO_X emissions for calculating acidification and eutrophication potential. The IPCC default value was used to calculate NO_3 emissions (due to nitrate leaching) used for calculating eutrophication potential. The phosphorus emission was estimated using the method by Nemecek and Kagi (2007).

2.3. Sensitivity and uncertainty analysis

A sensitivity analysis was carried out to address the variability in data and understand the effect of input parameters on GHG emissions. A sensitivity analysis was not carried out for eutrophication and acidification because only one or two factors were important for these impact categories (e.g. only N input was responsible for eutrophication). The sensitivity of the GHG emissions was analyzed in two steps to identify the most important explanatory parameters. In the first step the sensitivity of the GHG emissions to the primary data from the survey was assessed, i.e., farm inputs (Table S4), and in the second step the sensitivity of the GHG to the model input parameters used was assessed (Table S5). The analysis was done with GENSTAT 15 using the procedure EDCONTINUOS. For a selection of parameters, 11 in total (Table S4), the distribution was determined and used to generate 15,000 combined occurrences. Subsequently, a set of boundary conditions was forced on the sets of parameters (i.e., the percentage crop residue burned, composted, and incorporated should not exceed 100 %), resulting in 10,931 combinations of the 11 input parameters to estimate GHG emissions expressed per kg fresh vegetable produced.

The sensitivity analysis of the model input parameters was performed in the same way, but no boundary conditions were enforced on the generated 15,000 sets of parameters as all values were within the expected ranges.

3. Results

3.1. Farm yields and fertilizer use

3.1.1. Yield

In total, all the 322 farmers planted their fields 797 times in one year. Of this, 442 fields were planted with one crop i.e., monocropping, and 355 fields were planted with two or three crops (multiple cropping). In total, crops were planted 1221 times, of which broccoli, lettuce, tomato, string beans and cauliflower there the most popular crops planted (Table 1). Broccoli and lettuce also covered the largest area planted in both systems. The average (fresh weight) yield of the 322 vegetable farms was 50 t ha^{-1}, of which 95 % was sold, 4.4 % was dismissed as rot or stolen, almost 0.55 % was home consumption or paid to labour, and 0.05 % was saved for the next planting.

3.1.2. Fertilizers

All farmers used some kind of N-source, being synthetic fertilizers, organic fertilizers and/or incorporation of crop residues. Only three farmers did not apply synthetic fertilizers, and two farmers did not use organic

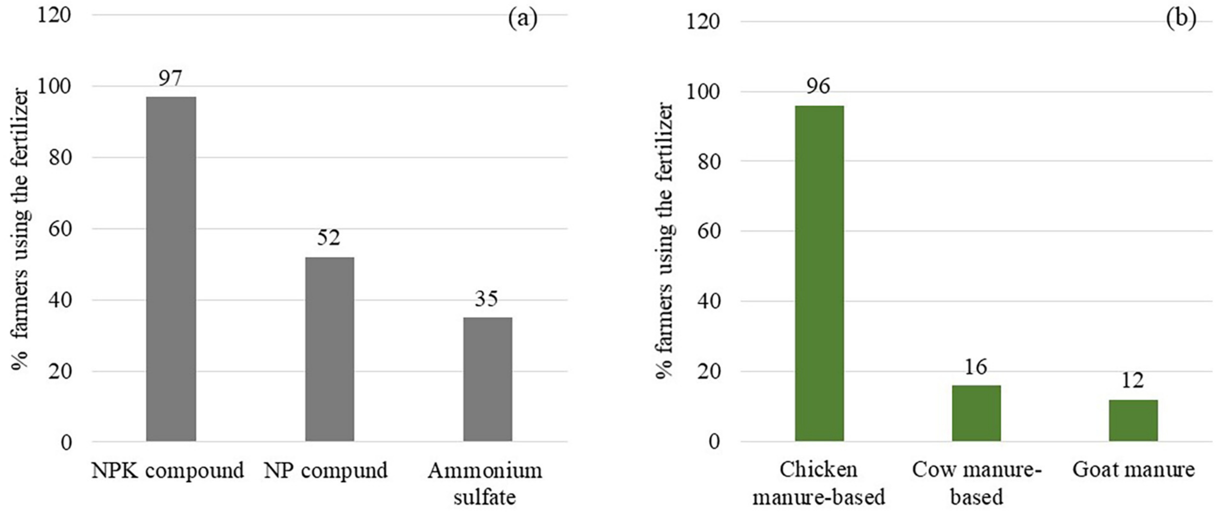

Fig. 1. Fertilizer use. Most commonly used a) synthetic fertilizers and b) organic fertilizers.

fertilizers. Mostly farmers used a mix of different types of synthetic and organic fertilizers. The most used synthetic fertilizers were compound NPK (97 %), followed by compound NP (52 %) and Ammonium sulfate (35 %) (Fig. 1; Details in Fig. S6). Most of synthetic N (average application rate: 256 kg ha^{-1} yr^{-1}) was applied with compound NPK (61 %), Ammonium sulfate (18 %), and urea (12 %).

In the case of organic fertilizer use, twenty-two different organic products were applied at a mean rate of 41 t ha^{-1} (average N application rate: 862 kg N ha^{-1} yr^{-1}). The most commonly used organic products were chicken manure-based (96 % of farmers), followed by cow manure products (15 % of farmers) and goat manure products (12 % of farmers) (Fig. 1; details in Fig. S7). Most farmers applied more than one type of organic product.

3.2. Global warming potential

The mean carbon footprint of vegetable production annually was found to be 14.1 ± 8.8 t CO_2eq ha^{-1} yr^{-1} and 0.5 ± 0.6 t CO_2eq t^{-1} fresh vegetable product (Table 3). The CF per unit of dry vegetable product was 55.1 t CO_2eq t^{-1}. On an average there were 3–4 cropping seasons annually. Among the 322 vegetable farmers, the carbon footprint ranged from 0.9 to 59.6 t CO_2eq ha^{-1} $yr^{-1}$and 0.1 to 7.4 t CO_2eq t^{-1} fresh vegetable product.

Organic fertilizer use (55 %) was the dominant source of GHG emissions, followed by synthetic fertilizer use (29 %; Fig. 2). In all, fertilizer use accounted for the major share of GHG emissions in vegetable crop production, contributing to 84 % of the emissions. This was followed by GHG emissions due to residues returned to field and pesticide use; each contributing 4 % to the overall emissions. Fuel use, crop residue burning, composting, and the use of plastic mulch contributed <4 % to GHG emissions.

Nitrous oxide emissions contributed to 74 % (10.5 t CO_2eq ha^{-1}) of the total GHG emissions in this study. Of this, direct and indirect N_2O emissions were 76 % and 24 % respectively (Fig. 3). Use of organic fertilizers accounted for 75 % (7.8 t CO_2eq ha^{-1}) of the N_2O emissions, while synthetic fertilizers accounted for 21 % (2.2 t CO_2eq ha^{-1}) of the N_2O emissions (Fig. 3). The rest (5 %; 0.5 t CO_2eq ha^{-1}) was accounted for by crop residue returned to the field. The production of synthetic fertilizers represented 16 % (1.8 t CO_2eq ha^{-1}) of the fertilizer-based emissions.

3.3. Other environmental impact categories

Characterization indices of acidification, freshwater eutrophication, depletion of phosphate, potash, and fossil fuel resources for one hectare of vegetable production were 39.3 kg SO_2eq, 45.3 kg PO_4eq, 60.0 kg P_2O_5, 101.3 kg K_2O, and 6299 MJ, respectively (Table 3). Per tonne of vegetable product, characterization indices of acidification, freshwater eutrophication, depletion of phosphate, potash, and fossil fuel resources were 1.4 kg SO_2eq, 1.7 kg PO_4eq, 1.9 kg P_2O_5, 3.7 kg K_2O, and 281 MJ, respectively.

Organic fertilizers accounted for 72 % and 76 % of acidification and freshwater eutrophication (Fig. 4a, Fig. 4b). Synthetic fertilizers contributed 23 % and 24 % to acidification and freshwater eutrophication. In addition, synthetic fertilizer use accounted for 100 % of phosphate and potassium depletion. Diesel use contributed 5 % to acidification and 0.1 % to freshwater eutrophication. The contribution of residue burning to environmental impacts was negligible.

3.4. Sensitivity analysis of GHG emissions

The sensitivity analysis among farm input parameters (i.e., variables from primary data) showed that the GHG emissions per ton vegetable was most sensitive for the yield produced. 19 % of the variability of the carbon footprint was explained by the variability in yield. This was followed

Table 3
Environmental impacts of vegetable production (per hectare and per tonne).

Impact category	Characterization index per hectare			Characterization index per tonne		
	Mean ± SD	Median	Min-Max	Mean ± SD	Median	Min-Max
Global warming (t CO_2eq)	14.5 ± 8.8	13.0	0.9–59.6	0.5 ± 0.6	0.3	0.1–7.4
Acidification potential (kg SO_2eq)	39.3 ± 28.6	35.1	1.8–212.5	1.4 ± 1.9	0.9	0.1–20.4
Freshwater eutrophication potential (kg PO_4eq)	45.3 ± 30.6	41.6	1.6–221.2	1.7 ± 2.4	1.0	0.02–25.6
Depletion of phosphate (kg P_2O_5)	60.0 ± 59.9	40.9	0–353.3	1.9 ± 2.4	1.2	0–17.3
Depletion of potash (kg K_2O)	101.3 ± 71.0	90.8	2.3–446.0	3.7 ± 5.2	2.2	0.2–54.8
Depletion of fossil fuel (MJ)	6299 ± 3898	5551	1074–27,360	280.9 ± 442.5	153.7	13.4–3801

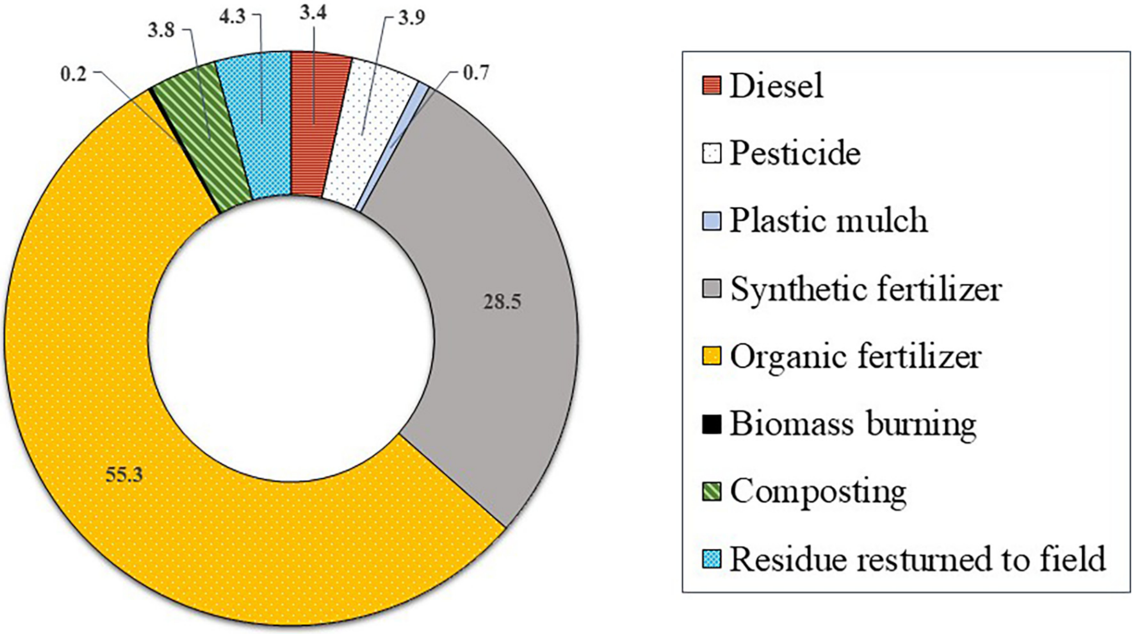

Fig. 2. Percentage contribution of various sources to total GHG emissions of vegetable production in this study.

by the use of 'organic fertilizers' and 'nitrogen in organic fertilizers', which explained 15 % and 4 % of the variation in carbon footprint respectively. Yield, organic fertilizer and N content in organic fertilizers jointly explained 40 % of the variation in CF. With regard to sensitivity to model input parameters, CF was most sensitive to the emission parameter EF_5, i.e., emission factor for N_2O emissions due to leaching/run-off N from fertilizer, manure and crop residues, explaining about 30 % of the variation. This was followed by $Frac_{LEACH}$ (i.e., fraction factor of leaching from managed soil) and EF_1 (emission factor for direct N_2O emission from N input) that explained 28 % and 22 % of the CF variations respectively. Jointly these three parameters explained 82 % of the variation.

Overall, when both farm inputs and model parameters (i.e., emission factors) were considered together, the CF of vegetables per tonne was most sensitive to yield, followed by organic fertilizer use and N content in organic fertilizers (20 %, 16 % and 5 % respectively). Since the functional unit in this case was 'per unit yield', it is not surprising that yield is the variable explaining most of the variation in CF. For CF per ha, the 'amount of organic fertilizer' contributed most (58 %) to the variability in CF, followed by 'N from organic fertilizers' and 'quantity of synthetic fertilizers' (contributing 17 % and 7 % respectively). Together, these three variables explained 81 % of the total variation in CF per ha.

4. Discussion and conclusions

4.1. GHG emissions

To our knowledge, this is the first study estimating GHG emissions from vegetable production systems in Indonesia. A comparison with other studies reporting annual emissions from open field vegetable production shows that estimated GHG emissions in this study (0.5 t $CO_2eq\ t^{-1}$) was higher than average GHG emissions from vegetable production globally (0.35 t $CO_2eq\ t^{-1}$, Nemecek et al., 2012; 0.37 t $CO_2eq\ t^{-1}$, Clune et al., 2017). The CF per ha found in our study (14.1 ± 6.7 t $CO_2eq\ ha^{-1}$) was also higher than in Australia (9.2 t $CO_2eq\ ha^{-1}$; Maraseni et al., 2010). The high rate of fertilization in the study area, combined with a relatively high N_2O emission factor for wet climate zones (Hergoualc'h et al., 2021) like in Indonesia, could be the principal reason behind the high GHG emissions from vegetable production in the present study.

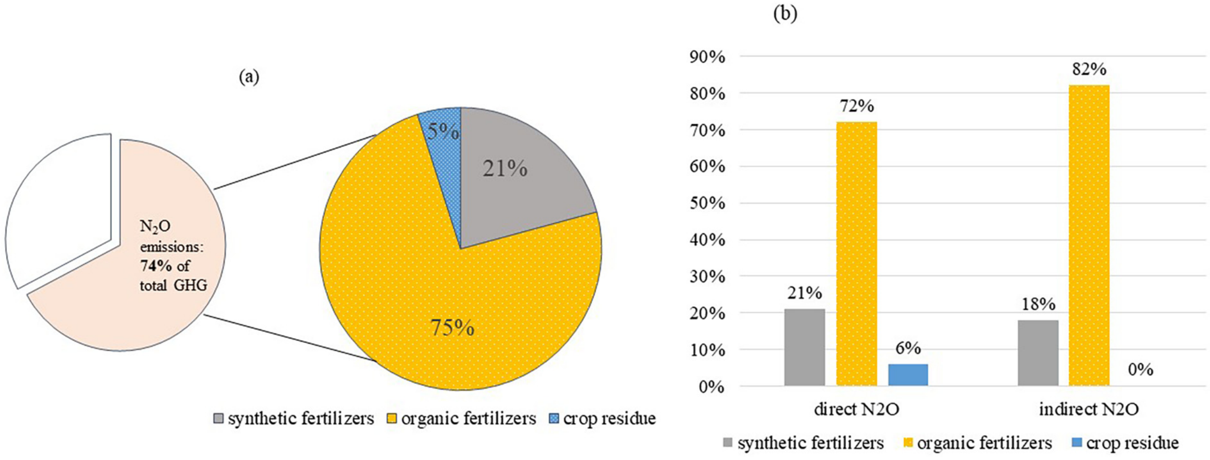

Fig. 3. Contribution of different nitrogen sources to a) total N_2O emissions and b) direct and indirect N_2O emissions.

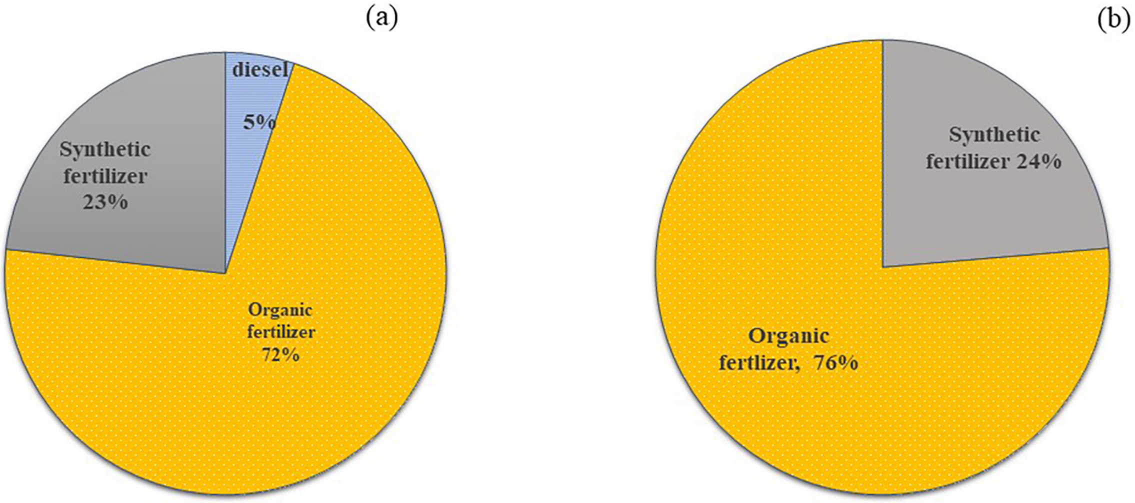

Fig. 4. Percentage contribution of different sources to a) Acidification potential, and b) Freshwater eutrophication.

Nitrous oxide emissions from vegetable production in this study (39.5 kg N_2O-N ha^{-1}) was also found to be higher than intensive open-field vegetable production (1.83 kg N_2O-N ha^{-1}) in China (Wang et al., 2018). Wang's study was a meta-analysis of field experiments with an average EF_1 of 0.69 %, while the EF_1 used in this study was 1.6 % as per the climate conditions. A high emission factor along with the high fertilization rates (265 kg N ha^{-1} vs 1118 kg N ha^{-1} in this study) could be the major reason behind the higher N_2O emissions in this study.

4.2. Other environmental impacts

Excess N and P application can lead to leaching and run-off of nutrients from the field, leading to eutrophication of soils, surface waters, and groundwater. Eutrophication of water bodies can lead to hypoxia, kill fish and other aquatic life, and contaminate drinking water sources (Biagini and Lazzaroni, 2018; Ward et al., 2018). The EP of vegetable production in our study (1.7 kg PO_4eq t^{-1}) was higher than that of vegetable production in semi-urban orchards (0.06 kg PO_4eq t^{-1}; Martinez et al., 2018) and farms (0.01 kg PO_4eq t^{-1}; Martin-Gorriz et al., 2020) in Spain, due to relatively high fertilizer use in our study (1118 vs. 439 kg N ha^{-1} yr^{-1}). However, depletion of fossil fuel resources in our study was much lower than values reported in other studies (Canaj et al., 2020; Martin-Gorriz et al., 2020). This could be explained by the lower use of diesel for field operations as only 14 % of the farmers used fuel for tillage and most of the farmers tilled their land manually. For the same reason, AP of vegetable production in our study (1.4 kg SO_2eq t^{-1}), was lower than the AP of vegetable production in Spain (2.4 kg SO_2eq t^{-1}, Martin-Gorriz et al., 2020).

4.3. Fertilizer use

Organic fertilizer use contributed the most to the impact categories of GWP, EP, and AP, followed by synthetic fertilizer. Fertilizer use has been reported as a dominant contributor to GHG emissions (Maraseni et al., 2010; Clavreul et al., 2017; Liang et al., 2021; Lam et al., 2021; Zhang et al., 2021) and AP (Martin-Gorriz et al., 2020) of open field vegetable cultivation. The high N fertilizer use in this study (1118 kg N ha^{-1} yr^{-1}) was comparable to the fertilizer use for open-field vegetable production in China (325 kg N ha^{-1} per season; Zhang et al., 2021), while other studies have reported a lower rate of overall N fertilization (e.g., Martin-Gorriz et al., 2020; Lam et al., 2021). The high application rates for organic manure found in the present study were in line with results of other studies in West Java (e.g. for potatoes 16 t ha^{-1} per planting (Adiyoga et al., 1999) or 232 kg N ha^{-1} per planting (Van den Brink et al., 2015)). However, the rate of use of organic fertilizers in our study (862 kg N ha^{-1}) was much higher than in other regions for vegetable production, ranging from 48 to 187 kg N ha^{-1} yr^{-1} (Bos et al., 2014; Aguilera et al., 2015; Lam et al., 2021). Moreover, the average organic fertilizer input in Indonesia (considering 3–4 plantings per year in Indonesia compared to 1–2 plantings in Europe), i.e., 239 kg N ha^{-1} for a single cropping season, is still higher than the annual EU permissible limit. The high organic N application arises from a combination of high volume of application and the N content of organic fertilizers. The majority of the farmers used chicken manure, which has the highest N content (Table S2) among the 22 types of organic fertilizers.

The reasons for the high rate of use of organic fertilizer in Lembang are largely unknown. One reason could be the sloping topography of the region with high soil erosion rates that could make it difficult for the soil to hold nutrients. Higher slope gradients not only lead to higher losses of N and P but might also lead to a reduction of fertilizer use efficiency due to runoff (Preltl et al., 2017; Zhong et al., 2018). It was found that slope gradients of 20° incurred 18 % and 11 % higher loss of N and P, respectively, than slope gradient of 5° (Yao et al., 2017a, 2017b). The slope gradient of Lembang varied from 9 to 14° in 5200 ha to >22° in 2970 ha of area (Ministry of Public Works and Housing, n.d). Therefore, the topography in the study area has a role in nutrient loss, which might have led to more nutrient input in crop production and higher environmental impacts due to N and P run-off and leaching. A second plausible reason for the high organic fertilizer use is the intensive cultivation along with the 'common knowledge' that the more intensively the land is cultivated, the higher organic fertilizer needed to maintain or improve the soil structure. Vegetables are capital-intensive crops and therefore are "treated well" by farmers to improve yield security. Moreover, organic fertilizers are relatively cheap in the study area, boosting their consumption. Finally, nutrient contents of organic fertilizers and the timing of the release of nutrients from organic matter are most often unknown to vegetable farmers. This makes it difficult for them to decide on suitable application rates for crops. The nitrogen in manure takes time to mineralize and become available to plants. At the same time, N in synthetic fertilizers is readily available and therefore preferred in initial growth stages to boost production. Many farmers in the study area used both synthetic and organic fertilizers. In the case of farms having multiple cropping cycles annually, adding fertilizers in the third/fourth cycle might be redundant since the N in the organic fertilizer would have started to mineralize and become available. This excess application could be reduced with calculated use and knowledge of the mineral content of fertilizers. Therefore, providing information about the nutrient composition of organic fertilizers (regular analysis) and educating farmers about organic fertilizer use (e.g. De Putter et al., 2021) would help to improve the situation as presently there are no complete fertilization guidelines for vegetable production in Indonesia.

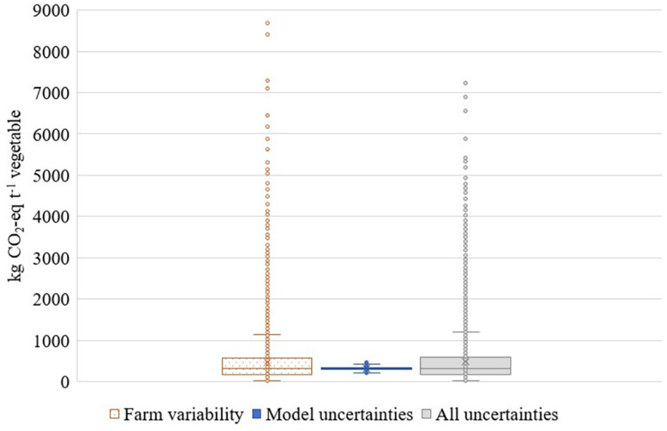

Fig. 5. Simulated distribution of CF of vegetable production with variation in input parameters (farm variability), model parameters, and all uncertainties.

4.4. GHG mitigation strategy

Whereas increased utilization of organic fertilizer to replace N fertilizers is one of Indonesia's long-term GHG mitigation strategies for its agriculture sector (Indonesia LTS-LCCR 2050, 2021), the present study demonstrated that absolute reduction of organic fertilizer is crucial to reduce both GHG emissions and other nutrient losses to the soil, water, and air from Indonesian vegetable farms. This could contribute to achieving Indonesia's NDC targets for reducing GHG in agriculture (NDC, 2016) and also to Indonesia's programs to reduce local nutrient pollution from agriculture, such as those for the Citarum River (Water and Sanitation Program, 2013).

More efficient fertilizer use, such as reducing excessive fertilizer use and improving application practices, is a well-known strategy to reduce GHG emissions and other environmental impacts related to fertilizer use (Tilman et al., 2002). In China, for example, improving nitrogen utilization efficiency (NUE) in rice, wheat, and maize reduced synthetic N use per year by 41 % and CO_2-eq by 39 % (Huang and Tang, 2010). On the other hand, partial substitution of synthetic fertilizers with organic fertilizers has been recommended to improve NUE, decrease GHG emissions and improve yields for intensive vegetable production (Xia et al., 2017; Zhou et al., 2019). Also, organic fertilizers tend to increase the C:N, which immobilizes N, while synthetic fertilizer mineralizes N and increases N_2O emissions (Xia et al., 2017; Zhou et al., 2019). Therefore, there is a trade-off requiring balance.

A potentially promising strategy for Lembang horticulture to lower excess N and P inputs from organic fertilizer is to replace the currently used chicken manure, which is imported into Lembang from other regions in Java. The imported chicken manure could be replaced with cattle manure that is already produced on dairy farms in Lembang, but mostly discharged into the environment by farmers (De Vries et al., 2019; Oosting et al., 2022). Replacing chicken manure by cattle manure would lower GHG emissions from Lembang horticulture because cattle manure has a much lower nutrient content than chicken manure (Table S2; De Vries et al., 2021). At the same time this can reduce current pollution due to overfertilization and discharging of cattle manure in the Lembang sub-district (Zahra, 2021). Replacement of synthetic fertilizer by organic fertilizer is expected to be less effective for reduction of GHG emissions in the situation of Lembang, and, from a practical view, considered unlikely as synthetic fertilizers are easily available at low cost (subsidized) and much easier to handle and transport than livestock manures (Pronk et al., 2020).

Guidelines for synthetic fertilizer use in vegetable crops are currently being developed in Indonesia (GAP1), which include some aspects of mineralization as it differentiates in nutritional status among fields. When these fertilizer guidelines are followed, synthetic fertilizer use is expected to increase compared to current practices, thus increasing environmental impacts (Pronk et al., 2020; De Vries et al., 2021). The present study illustrates the importance of including (mineralization of) organic amendments into fertilizer guidelines. It is to be noted that locally produced manure is recommended over synthetic fertilizers, provided the legal limit is not exceeded (Martin-Gorriz et al., 2020). For instance, the upper limit of nitrogen from livestock manure is 170 kg N ha^{-1} per year, according to the Nitrates Directive of the European Commission (https://ec.europa.eu/environment/water/water-nitrates/index_en.html). This could prove to be a significant step towards achieving Indonesia's INDC and also stands true for other Low-Middle Income Countries (LMICs) with similar production practices.

4.5. Sensitivity analysis

Results of the sensitivity analysis showed that, per ton of vegetable produced, most of the variation in GHG emissions could be explained by yield and organic fertilizer use. This means the CF will lower when yields are increased or organic fertilizer use is decreased, and, vice versa. The nitrogen content of synthetic fertilizer explained a relatively small part of the variability of CF of vegetable production (2 %), suggesting that changes in synthetic fertilizer use did not have a large impact on the CF. These results emphasize reducing organic fertilizer use in Indonesian vegetable farming while ensuring high yields. Further, our results indicate that the variability in CF due to input data obtained from the survey was much greater than variability due to model parameters (Fig. 5). This reiterates the fact that ample data collection is essential to get a good mean estimate amidst the variability (Clavreul et al., 2017).

4.6. Limitations

There are some methodological limitations to this study that should be considered when interpreting results. First, like in any survey, responses to the questionnaire were likely subject to self-reporting bias, such as farmers' estimates of amounts of farm inputs and outputs for multiple crops over one year. Second, as standard values for composition of organic fertilizers are not available in Indonesia, the nutrient composition was based on 53 manure samples in the region for the most commonly used organic fertilizers, and on literature for less frequently used organic fertilizers. Although this is a reasonable number of samples, nutrient contents of organic fertilizers are known to show considerable variation (depending on, e.g., animal feeding and methods of storing and processing the manure; Christensen and Sommer, 2013). To obtain more accurate estimates of average manure nutrient composition requires larger sampling campaigns. This will not only benefit future studies about environmental impacts of organic fertilizer use, but is also important for farmers to match fertilizer use with crop requirements and soil fertility, and reduce nutrient losses and environmental pollution (De Putter et al., 2021).

Third, diesel use for irrigation was estimated based on a standard energy consumption per irrigation event, but this estimate was highly sensitive to the assumed energy content of diesel. For example, changing the diesel energy content from 32.2 to 36.7 MJ l^{-1} led to a 12 % reduction in the mean diesel use and 61 % reduction in acidification potential. Therefore, in future studies direct estimates of diesel use for irrigation should be preferred over indirect estimates based on energy consumption.

CRediT authorship contribution statement

Durba Kashyap: analysis and writing – original draft preparation, Marion de Vries: funding acquisition, conceptualization, supervision, Annette Pronk: analysis, supervision, review & editing, Witono Adiyoga: data collection and curation, review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.160999.

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