Potential of reducing greenhouse gas emissions through improved nutrient circularity in agriculture in West Java

Working Paper No. 390

CGIAR Research Program on Climate Change,
Agriculture and Food Security (CCAFS)

Marion de Vries
Annette Pronk
Witono Adiyoga

CGIAR

RESEARCH PROGRAM ON
Climate Change,
Agriculture and
Food Security

CCAFS

Working Paper

Potential of reducing greenhouse gas emissions through improved nutrient circularity in agriculture in West Java

Working Paper No. 390

CGIAR Research Program on Climate Change,
Agriculture and Food Security (CCAFS)

Marion de Vries
Annette Pronk
Witono Adiyoga

To cite this working paper
De Vries M, Pronk AA, Adiyoga W. 2021. Potential of reducing GHG emissions through improved nutrient circularity in agriculture in West Java. CCAFS Working Paper no. 390. Wageningen, the Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

About CCAFS working papers
Titles in this series aim to disseminate interim climate change, agriculture and food security research and practices and stimulate feedback from the scientific community.

About CCAFS
The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is led by the International Center for Tropical Agriculture (CIAT), part of the Alliance of Bioveristy International and CIAT, and carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. For more information, please visit https://ccafs.cgiar.org/donors.

Contact us
CCAFS Program Management Unit, Wageningen University & Research, Lumen building, Droevendaalsesteeg 3a, 6708 PB Wageningen, the Netherlands. Email: ccafs@cgiar.org

Abstract

The discharging of cattle manure into the environment by dairy farmers in West Java, Indonesia, is causing environmental pollution and social issues. The objective of this study was to explore effects of increased utilization of cattle manure and good agricultural practices (GAP) on GHG emissions from the dairy and horticultural sector in Lembang Sub-District in West Java. Environmental consequences of various scenarios to avoid discharging of cattle manure were explored, including different manure processing methods, utilization of manure in either the dairy sector or the horticultural sector, and different levels of GAP in horticulture. Results showed that, compared to discharging, utilizing cattle manure on land for forage production and in horticulture lead to reduced GHG emissions, but only when cattle manure replaced currently used fertilizers. In a similar vein, results showed that implementing good agricultural practices (GAP) in horticultural production led to significant reduction of GHG emissions from the dairy and horticultural sectors in Lembang Sub-District.

Keywords

Horticulture; vegetable production; dairy cattle; manure; GHG; Good Agricultural Practices.

About the authors

Marion de Vries (coordinating author) is a Researcher at the Livestock and Environment Department of Wageningen Livestock Research, part of Wageningen University and Research (WUR). Email: marion.devries@wur.nl

Annette Pronk is a Researcher at the Agrosystems Research Department of Wageningen Plant Research, part of Wageningen University and Research (WUR). Email: annette.pronk@wur.nl

Witono Adiyoga is a researcher at the Indonesian Vegetable Research Institute (IVEGRI).

Acknowledgements

This work was implemented as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), with funding support from the government of The Netherlands. CCAFS is carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. For details please visit https://ccafs.cgiar.org/donors. The views expressed in this document cannot be taken to reflect the official opinions of these organizations.

Contents

1. Introduction

Manure from livestock production systems accounts for 20% of the total methane emissions and 30-50% of the total nitrous oxide emissions from agriculture (Oenema et al., 2005; FAO, 2006). Besides greenhouse gas (GHG) emissions, animal manures are a source of ammonia and malodorous gases, and pollution of surface waters and groundwater with nitrogen (N) and phosphorus (P) due to leaching and run-off. The loss of nutrients to surface waters leads to eutrophication and algal bloom, while high nutrient concentrations in groundwater can lead to contamination of drinking water sources due to nitrate leaching (Biagini and Lazzaroni, 2018; Ward et al., 2018). Also, valuable resources are lost from the nutrient cycle, such as organic substance, macronutrients (N, P, K, Ca, Mg, etc.), and trace elements (Mn, Cu, etc.). Especially phosphate, a finite resource, is becoming a major challenge due to global imbalances (MacDonald et al., 2011). Recycling livestock manures as a fertilizer, therefore, is one of the four cornerstones of circular food systems, as it contributes to minimizing the input of finite resources and prevents leakage of nutrients from the food system (Oosting et al., 2021).

In West Java, Indonesia, dairy farmers are discharging cattle manure into the environment, due to a lack of possibilities or incentives to apply or sell the manure (De Vries and Wouters, 2017; Zahra et al., 2021). The discharged manure leads to above mentioned environmental pollution and loss of nutrients, and is also considered a social problem locally due to nuisance (i.e., annoyance of inhabitants about manure being deposited in their living environment; Zahra, 2021). At the same time, organic and synthetic fertilizers are imported to the region and often applied at excessive rates on land for both forage and food crop production (Widowati et al., 2011; Van den Brink et al., 2015; Pronk et al., 2017; De Vries et al., 2020). The overfertilization leads to N and P pollution of soils, water and air, including GHG (N_2O) (Kashyap et al., in prep.).

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). Indonesia's agriculture sector accounted for 8% of the National GHG emissions in 2016 (Republic of Indonesia, 2018), and Indonesia has settled targets for 4 to 9 Million ton (Mton) reduction of GHG in agriculture towards 2030 compared to the business as usual scenario (NDC, 2016). Besides ambitions to mitigate GHG, the Indonesian Government has initiated programs to reduce nutrient pollution from agriculture, such as the Citarum Harum task force preventing manure disposal from farms near the Citarum River (Water and Sanitation Program, 2013).

Although recycling of cattle manure as a fertilizer shows potential for reduced pollution of local ecosystems in West Java (Zahra, 2021), implications for GHG emissions are still unknown. As GHG emissions related to manure discharging are thought to be relatively low compared to manure storage and processing emissions (de Vries et al., 2019; Apdini et al., 2021), recycling cattle manure could lead to net higher GHG emissions from cattle manure storage, transport and application (methane (CH4), nitrous oxide (N2O), and carbon dioxide (CO2) (Opio et al., 2013)). Recycled cattle manure, however, may also replace other organic fertilizers or inorganic fertilizers, which affect net emissions along the whole manure value chain. For example, replacement of chemical fertilizer by livestock manures is a well-known strategy to reduce GHG emissions (Tilman et al., 2002).

Besides utilization of organic manures, more efficient fertilizer use, such as reducing excessive use of synthetic fertilizer and improving application practices, can reduce GHG emissions and other environmental impacts related to fertilizer use (Tilman et al., 2002). In China, for example, improving nutrient use efficiency (NUE) in rice, wheat, and maize reduced synthetic N use per year by 41%, and CO2-eq by 39% (Huang and Tang, 2010). Improvements in NUE can also have positive effects on farmers' income. For example, a 22% reduction in fertilizer costs was observed in shallot in West-Java (WUR/IVEGRI, 2011).

The objective of this study was to explore effects of increased use of cattle manure and good agricultural practices (GAP) on GHG emissions from agriculture in West Java. The dairy and horticultural sector in Lembang Sub-District in West Java were used as a case study, being the two main agricultural sectors in Lembang. Replacement of chemical fertilizer by organic fertilizer in the horticultural sector in Lembang was considered unlikely under current practical conditions, as nutrients in chemical fertilizers are easily available at low cost (subsidized), and are easier to handle and transport than livestock manures according to farmers' perceptions (Pronk et al., 2020). Therefore, scenarios for increased utilization of cattle manure in horticulture were based on dose-based replacement of chicken manure, which is the main organic amendment used by horticultural farmers in Lembang (Pronk et al., 2020).

Sub-objectives were:

- To evaluate environmental consequences of different manure processing and utilization strategies to avoid the discharging of 1 ton of cattle feces;
- To evaluate environmental consequences of replacing presently used chicken manure in horticulture by cattle manure;
- To evaluate environmental consequences of applying good agricultural practices (GAP) in horticultural production.

2. Brief description of horticultural and dairy sector in Lembang Sub-District

2.1 Dairy sector

Cattle in dairy farms in Lembang are housed in tie-stalls with no access to grazing (zero-grazing systems). On average, the herd size is four adult cows and two young stock (De Vries and Wouters, 2017). Most farms are specialized dairy farms, and there are some mixed crop-livestock farms in Lembang as well (16%). In most farms the main purpose of keeping cattle is to produce milk for sale. The feed ration of mature cows consisted mainly of home-grown grass (king grass or elephant grass), roadside grass, rice straw, industrial by-products (mainly tofu waste and cassava waste), and compound feed. In the dry season, home-grown grass is often replaced by rice straw and other crop residues, and in case of the lactating cows, supplemented with an increased amount of compound concentrate feed. In 84% of the dairy farms in Lembang at least part of the manure (feces, urine, or both) is discharged to the environment (De Vries and Wouters, 2017). When manure is not discharged, it is used as a soil amendment for forage production (32%) or food crops (10%) or sold or given away to other farms (less than 10% of farms).

Common types of manure management for utilization as a fertilizer on forage or food crops in Lembang include (De Vries et al., 2020):

- Daily spread: Daily application of manure on forage, i.e. flushing of feces and urine from the cow barn 2 or more times per day, and application on land close to the cow barn, e.g. via pipes or ditches.
- Fresh feces in sacks: Fresh cow feces are collected in sacks and stored for a period of several weeks or months;
- Compost: Composting is the thermophilic process (>45 °C) of microbial degradation, stabilization, and sanitization of organic wastes under aerobic and/or anaerobic conditions (Swati and Hait, 2018). In Indonesia composting of cattle feces is performed

by mixing with the drier broiler manure and beddings (postal), which are composted for several weeks, often with infrequent turning;

- Vermi-compost (or ‘worm-compost’): Similar to composting, the vermicomposting process involves mesophilic (<30 °C) bio-oxidation and sanitization of organic wastes. This exclusively takes place in aerobic conditions by earthworms and microbial actions, converting the waste into earthworm castings (vermicast; Singh et al., 2011);
- Farm yard manure (FYM): Cow feces stored for a period of several months in piles or stacks together with feed leftovers (e.g. padi straw).

2.2 Horticultural sector

Lembang is one of the three main highland vegetable production areas in West Java. The district center, Lembang, is situated north of Bandung. In the central part of the valley vegetables are grown at 1000 meters upwards. The climate is characterized as a tropical highland with average monthly temperatures ranging from 17 to 21 degree Celsius and average monthly rainfall ranging from less than 100 mm during June to September to about 200 mm in October, April and May to over 300 mm in November to March. Approximately 2500 ha are under vegetable cultivation. Part of this area is under irrigation, depending on the position of the fields.

The horticultural sector is characterized by a large diversity in crops cultivated in an intensive production system of three to four distinct planting seasons per year (Pronk et al. 2020). The vegetable farmers in Lembang are small-scale farmers where most cultivation practices are done manually and generally employ family labors, except during the peak season. They usually have several plots at different locations that are intensively cultivated throughout the year by frequently applying multiple cropping systems. The average farm size is 0.3 ha which is about 50% owned land. Inputs such as seeds, fertilizers and pesticides are bought from agro-shops close by.

Vegetable farmers in Lembang use an abundant variety of organic amendments which are mainly based on chicken manure. More than 90% of the farmers use broiler manure (Pronk et al., 2020), locally called ‘postal’. Postal is a mixture of chicken manure and beddings of rice husk, and mostly obtained from outside Lembang, i.e. from Tasikmalaya, Subang and Ciamis. The products are bought in plastic bags, applied manually and incorporated by hand in the top 5 to 10 cm. Chicken manure is frequently mixed with manure from other animals such as cows, goats or rabbits. Only 13% of farmers in Lembang used cattle manure (Pronk et al., 2020). Organic amendments are applied to a specific crop in the rotation, usually the crop with the higher economic value for the purpose of soil improvement rather than for the nutritional value of the product.

3. Materials and Methods

3.1 Scope

This study focused on GHG emissions from cattle manure value chains in small-scale agriculture in Lembang Sub-District. System boundaries included (Figure 1):

- Dairy sector in Lembang: collection, storage, treatment, discharging, and application of cattle manure on land for forage production, including methane (CH_4) and nitrous oxide (N_2O) emissions;
- Transport of organic manures to horticultural farms, i.e., fossil carbon dioxide (CO_2) emissions;
- Horticultural sector in Lembang: utilization of cattle manure, chicken manure, and chemical fertilizer in horticulture, including N_2O and CO_2 emissions from production of imported chicken manure and manufacturing of chemical fertilizer, and N_2O emissions from fertilizers' application.

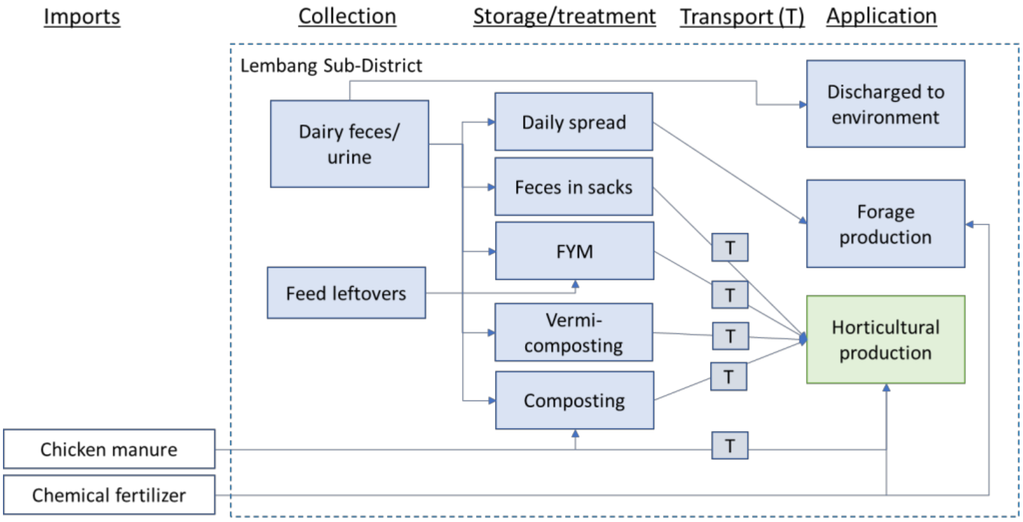

Figure 1. System boundaries of the manure value chain in this study, including manure management by dairy farms in Lembang, application of cattle manure in dairy and horticultural farms in Lembang, and organic and chemical fertilizers imported from outside Lembang.

3.2 Data collection

3.2.1 Dairy sector

Primary data was collected from the dairy sector in Lembang:

- Data about manure management, herd composition, feed ration, and crop nutrient management practices on dairy farms were based on a survey implemented at 300 dairy farms in Lembang between November and December 2016. The surveyed dairy farms were randomly selected from a list of 4,361 farms delivering milk to the dairy cooperative Koperasi Peternak Sapi Bandung Utara (KPSBU) Jabar in Lembang. More details about the survey can be found in (De Vries and Wouters, 2017).
- Compositions of cattle manure products were based on samples collected in February 2019 from 18 small-scale dairy farms involved in a pilot study about improved manure management in Lembang District (De Vries et al., 2020). Samples included 18 samples of fresh feces, 2 samples from FYM, 8 samples of compost, and 5 samples of vermi-compost. Samples were analyzed by IPB University.
- Composition of postal (mixture of broiler manure and rice husk, hereafter called “chicken manure”) was based on 16 samples of chicken manure collected in a trial about the composting dairy cattle feces and chicken manure at Indonesian dairy farms (Sefeedpari et al., 2020). Samples were analyzed by IPB University. Besides manure composition, assumptions on composting methods (e.g. ratio of postal to cattle feces) were based on this study (Sefeedpari et al., 2020).

With regard to secondary data, data about the size of the dairy population in Lembang sub-district were obtained from databases kept by the dairy cooperative KPSBU Lembang (census 2018); estimates of N excretion were based on Zahra et al. (2020); final estimates of the composition of chicken manure were based on Van den Brink et al. (2015; 2016), besides Sefeedpari et al. (2020); chicken manure production methods and transport distances of chicken and cattle manure were based on expert opinion (pers. comm. D. Suharyono, August 2021). For broilers, animal mass (TAM) and volatile solid (VS) excretion rates were based on IPCC default values for mean productivity broiler systems in Asia (IPCC, 2019). Both for dairy cattle and broilers, maximum methane producing capacity of manure (BO) were based on IPCC default values for low productivity systems, and methane conversion factors (MCF) of manure management systems were based on IPCC default values for warm tropical montane climate zones (IPCC, 2019).

3.2.2 Horticultural sector

A farmer survey was conducted in Lembang sub-district of West Java, Indonesia (Pronk et al. 2020). In total 322 vegetable farms in the 16 villages of Lembang sub-district were selected out of 1738 initially identified farmers using snow-ball sampling method (Goodman, 1961). A questionnaire was developed by Wageningen University and Research (WUR) and the Indonesian Vegetable Research Institute (IVEGRI) about farm characteristics, farming practices, and use of fertilizer and other farms inputs. Questions were targeting the farmer’s recall of the four cropping seasons spanning one year. The questionnaire survey was conducted by 5 employees of IVEGRI between September and November in the fall of 2019. For more details, see Pronk et al. (2020).

3.3 Scenario descriptions

Greenhouse gas emissions from manure value chains were evaluated based on two functional units (FU): 1 ton of excreted cattle feces and 1 hectare of horticultural land. The scenarios using 1 ton of feces as FU were aimed at evaluating effects of different strategies for processing and utilization of cattle feces to avoid the discharging of 1 ton of cattle feces. The scenarios using 1 ha of horticultural land as FU aimed at evaluating effects of replacing currently used chicken manure in horticulture by cattle manure, as well as applying good agricultural practices (GAP) in horticulture.

3.3.1 Alternatives for utilization of 1 ton of faeces

Three scenarios were evaluated as strategies to utilize 1 ton of cattle feces, instead of discharging the feces:

- Applying 1 ton of previously discharged cattle feces on land for forage production within the dairy sector via daily spread;
- Processing and/or storing 1 ton of previously discharged cattle feces into cattle manure products and application in horticulture, thereby replacing part of the chicken manure used in horticulture;

- Processing 1 ton of previously discharged cattle feces into vermi-compost and application in horticulture, on top of current fertilizers used.

Scenario 1: Daily spread

In this scenario we evaluated effects of utilizing 1 ton of feces and associated urine on land for forage production close to the cow barn, thereby avoiding discharging of feces and urine and urea application. System boundaries included manure management by dairy farms, application of cattle manure, and reduction of chemical fertilizer use (urea) by the dairy sector in Lembang (Figure 2).

The following assumptions were made:

- Application of 1 ton feces on forage with 0.3% N (wet basis) and associated N in urine via daily spread (corrected for 20% N loss: 2.8 and 2.9 kg N, resp.);
- For forage production, 1 ton of feces was assumed to be N-equivalent to 4.9 kg of urea (46% N), based on a plant-available N coefficient of 1.0 and 0.4 for urea and cattle feces, respectively;
- Avoiding the discharging of 1 ton of feces with 3.5 kg N in feces and 3.6 kg N in associated urine (Zahra et al., 2020).

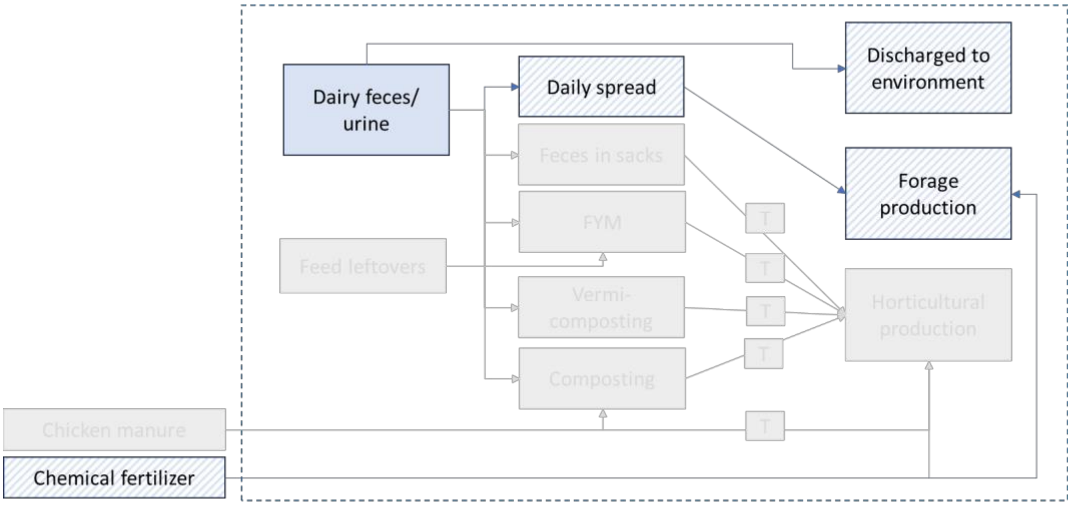

Figure 2. Process included in scenario 1: applying cattle manure on land for forage production via daily spread (functional unit: 1 ton fresh feces). Processes with marginal changes are indicated with diagonal strips.

Scenario 2: Applying cattle manure in horticulture

In these scenarios we evaluated the storage and/or processing of 1 ton of feces and application in horticulture, compared to discharging the feces. Four types of cattle manure products were evaluated: compost, vermi-compost, fresh feces in sacks, and farm yard manure (FYM; see description in section 2).

System boundaries included manure management by dairy farms in Lembang, application of chicken manure and cattle manure by horticultural farms in Lembang, transport of chicken manure and cattle manure, and production of chicken manure and urea imported from outside Lembang (Figure 3), and excluded manufacturing and application of chemical fertilizers in horticulture.

The following assumptions were made:

- 1 ton of excreted feces processed on the dairy farm into cattle manure products that are transported and applied in the horticulture sector, thereby avoiding the discharging of 1 ton of feces but associated urine is still discharged;
- Weight loss during storage of cattle feces, with weight equivalents of final products (compared to 1 ton of excreted feces; Table 1) as follows:
- FYM: 0.43 ton (amendment of padi straw in ratio 1:15 (based on 2 kg of amendment per cow/d; Amon et al., 2001), 60% weight loss)
- Composting (thermophilic): 0.34 ton of compost (amendment of postal in ratio postal : cattle feces 1:7, 70% weight loss, Sefeedpari et al., 2020)
- Vermi-compost (mesophilic): 0.40 ton (60% weight loss)
- Feces in sacks: 1 ton of feces (assuming no weight loss)
- Weight-based[1] replacement of chicken manure (Table 1) in horticulture multiple cropping system 4 (see next section) by cattle manure products (hence, in the same

---

[1] A weight-based replacement was assumed because horticultural farmers in Lembang generally appreciate organic amendments for benefits for soil structure, and are not familiar with the nutrient composition of organic amendments. Therefore, it was expected that in practice a weight-based replacement would be more likely than a nutrient-based (e.g., N) replacement.

dose), thereby avoiding production and application emissions of chicken manure, and avoiding 115 km transportation distance of chicken manure (average of distance between Lembang and Tasikmalaya, Subang and Ciamis);

- Because of different weight equivalents of cattle products, reference values for the amount of chicken manure applied in horticultural differed per scenario (i.e. different baselines; see explanation in scenarios below);
- Transportation distance of cattle manure products: 10 km, by lorry.

Table 1. Weight equivalents of 1 ton cattle feces in different stages of the manure chain.

Scenario	Excreted (ton fresh feces)	Applied on forage (ton product)	Stored (ton product)	Transported (ton product)	Applied in horticulture (ton product)	Replaced chicken manure (ton product)
Discharging	1	1	-	-	-	-
Daily spread	1	1	-	-	-	-
FYM	1	-	1+0.06*	0.43	0.43	0.43
Compost	1	-	1+0.13**	0.34	0.34	0.34
Vermi-compost	1	-	1	0.40	0.40	0.40
Feces in sacks	1	-	1	1	1	1

* amendment padi straw in ratio 1:15 (straw:cattle feces)

** amendment chicken manure in ratio 1:7 (chicken manure:cattle feces)

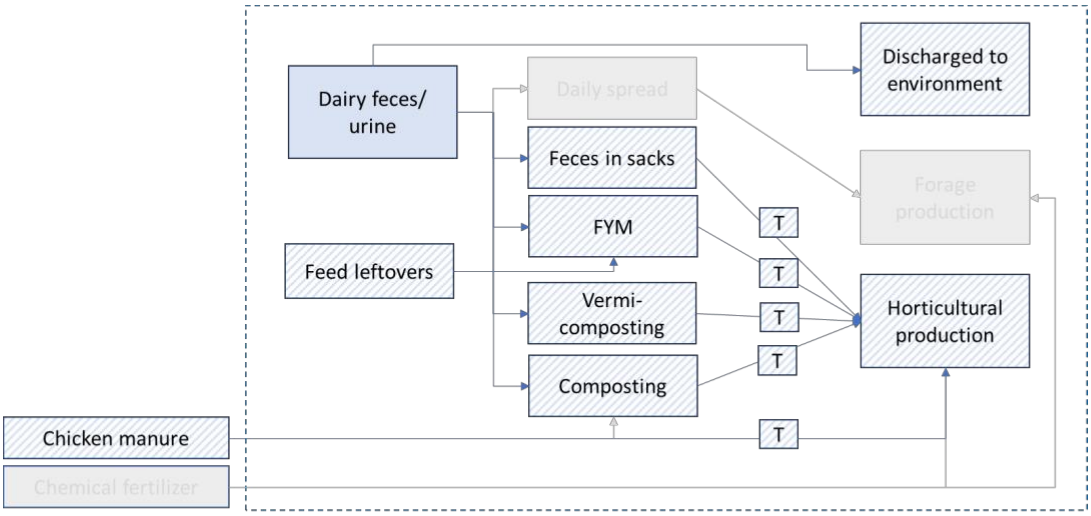

Figure 3. Processes included in scenario 2: processing cattle manure, transport (T) and application in horticulture (FU=1 ton fresh feces). Processes with marginal changes are indicated with diagonal strips.

Scenario 3: Adding cattle manure to current fertilizer use in horticulture

In this scenario we evaluated adding vermi-compost to current fertilizer use in horticulture, avoiding the discharging of 1 ton of feces, but not replacing chicken manure in horticulture. Other assumptions are the same as those in Scenario 2.

3.3.2 Replacement of fertilizers in horticulture by cattle manure

Crops and rotation

According to the survey results (Pronk et al. 2020), many different crops were planted. To reduce the number of crops, they were combined at species level meaning that all tomato types, (cherry, beef) were merged into Tomato and that all Lettuce types (leavy, baby, head, Lollo Rossa, Romaine) were merged into Lettuce.

Furthermore, survey results showed that the total area of the most recent planting was 71 ha of which 40% (28 ha) was mono cropped, e.g. 1 crop planted at one planting, and 60% (43 ha) was multiple cropped, e.g. more than 1 maximal 3 crops planted at one planting. The total area planted for the past year (all plantings) of all surveyed farmers was 179 ha. The previous planting had 57 ha which was lower than the most recent planting, the planting therefore 37 ha, again a substantial decrease compared to the most recent planting, and the oldest planting only 15 ha. Occasionally, a farmer indicated to plant a crop 6 to 12 times, in the case of a mono cropping system with Broccoli (6 plantings) or Lettuce (12 plantings). Additionally, farmers could indicate to have a mono cropping system for the latest planting and a multiple cropping system for earlier plantings.

In the present study, two types of cropping systems were defined, based on common cropping systems present in Lembang as described above. To this end, in the first step the data from the survey were split according to the farming system: mono or multiple cropping system. Most planted crops in the mono cropping system were Broccoli, followed by Lettuce and Tomato (planted 99, 88 and 49 times, respectively; (Table 2) at an area representing 22.8, 23.3 and 8.5% of the total area planted with mono crops annually; hence jointly covering 55% of the area used for monocropping. The corresponding yields as marketable products were 9.3, 12.4 and 28.7 ton/ha for respectively Broccoli, Lettuce and Tomato. In the multiple cropping system Lettuce, Broccoli and Tomato were planted 200, 136 and 103 times respectively. However, this was not always a combination of these three crops. The combination of Lettuce-Broccoli, Lettuce-Tomato and Broccoli-Tomato were planted less frequently, 60, 7 and 10 times respectively. In the multiple cropping system, Lettuce combined with any other crop was planted on 22% of the area, Broccoli with any other crop 18% and Tomato with any other crop on 15% of the area; hence jointly covering 55% of the area used for multiple cropping. The corresponding yields as marketable products were 2.5, 5.2 and 10.4 tons/ha for respectively Lettuce with Broccoli or Tomato, Broccoli with Lettuce or Tomato and Tomato with Lettuce or Broccoli.

All farmers indicated that they had access to irrigation on owned as well as rented land.

Table 2. The most common crops planted, and the percentage of area planted in the mono cropping and multiple cropping systems

Cropping system	Crop	Times planted	% of Total area (includes all crops)
Mono	Broccoli	99	22.8
	Lettuce	88	23.3
	Tomato	49	8.8
Multiple	Lettuce	200	22.0
	Broccoli	136	17.8
	Tomato	103	14.9

From these data, 2 crop rotations for each cropping system were selected (Table 3).

Table 3. The selected crop rotations for the mono and multiple cropping systems

No.	Cropping system	First planting		Second planting		Third planting		Fourth planting	
		crop 1	crop 2	crop 1	crop 2	crop 1	crop 2	crop 1	crop 2
1	Mono	Lettuce		Broccoli		Lettuce		Broccoli	
2		Lettuce		Broccoli		Lettuce		Tomato	
3	Multiple	Lettuce	Broccoli	Lettuce	Broccoli	Lettuce	Broccoli	Lettuce	Broccoli
4		Lettuce	Broccoli	Broccoli	Tomato	Lettuce	Broccoli	Lettuce	Tomato

Fertilization with mineral fertilizers and organic amendments

The application of mineral fertilizers for the baseline scenarios were based on application rates and products as reported by farmers in the survey. These applications are presented in Table 4. The dominant products were compound NPK (90% of the total N applied), compound NK (10% of the total N applied), Triple Superphosphate (100%) and Potassium Chloride (100%). The application rates of the latter two did not change with changing scenarios.

Table 4. Chemical fertilizers applied in the 4 selected crop rotations in the reference situation, baseline scenario

Crop Rotation	N [kg/ha]	P_2O_5 [kg/ha]	K_2O [kg/ha]
1	289	287	316
2	273	247	323
3	357	286	393
4	485	500	544

The amount of organic amendments for the baseline scenarios were also based on the applied amounts reported by farmers in the survey. However, here application rates of farmers that planted the above-mentioned crops and combinations of crops were selected, and the application rates were not based on the application rates of the specific plantings. This was done because organic fertilizers are applied to improve soils and less to a specific crop. The amount of organic amendments was 43 and 48 tons/ha in the mono and multiple cropping systems respectively, with 860, 591 and 727 kg N, P_2O_5 and K_2O per ha in the mono cropping system and 960, 660 and 727 kg N, P_2O_5 and K_2O per ha in the multiple cropping system (assuming organic fertilizer compositions shown in Table 4).

Mineralization of nitrogen from organic amendments

Most farmers in Indonesia apply some kind of organic product. Depending on the composition of the organic product and climatic conditions nitrogen is released from these organic applications. This nitrogen is a valuable nutrient for crops to grow. Most fertilizer recommendations adjust chemical fertilizer applications to mineralized N from organic applications. The mineralization of the organic applications is estimated with the simple mono component mineralization model Yang (Yang and Janssen, 2000). Inputs for this model are the average soil temperature, the composition of the organic product applied (N and C content), the mineralization parameters for the type of product (R and S) and the composition of the microbial biomass in the soil. The mineralization is estimated for a period of 1 year. Based on this simple approach the estimated mineralization of N from the applied products is 74%.

Scenarios and step wise approach

System boundaries included application of cattle manure, chicken manure and chemical fertilizers in horticultural farms in Lembang and the production and transport of cattle manure products by dairy farms in Lembang (Figure 4), but excluded application of cattle manure on forage by dairy farms in Lembang.

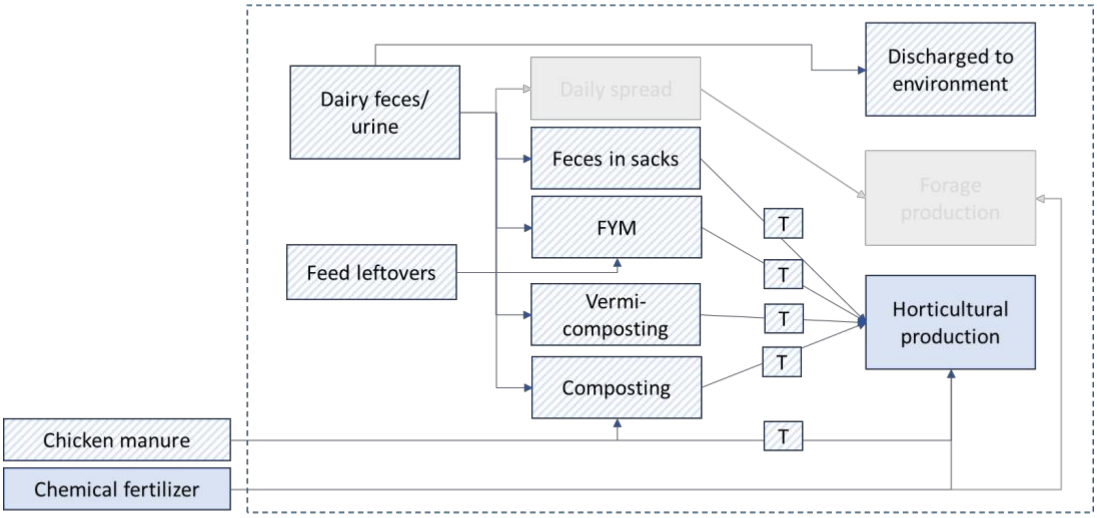

Figure 4. Processes included in scenario X: production of organic and chemical amendments and their application in horticulture (FU=1 ha), and discharging of cattle manure. Processes with marginal changes are indicated with diagonal strips.

The scenarios include 4 cropping systems in the baseline scenario (Baseline 1 to 4, see Appendix II), 4 scenarios' assuming replacement of chicken manure-based products by cow manure-based products.

In the scenarios assuming replacement of chicken manure-based product by cow manure-based products, the chicken manure-based product was replaced with a cow manure-based product in the same dose (weight-based). Four types of cow manure-based products were evaluated (compost, vermi-compost, FYM, and feces in sacks).

3.3.3 Good Agricultural Practice (GAP)

Fertilizer recommendations for horticultural crops in Indonesia are being developed by IVEGRI (pers. comm. Nikardi Gunadi, IVEGRI, Oct. 2021) and used in this study to implement GAP. For the first step the doses of the organic amendments were kept the same as in the Baseline but the chemical fertilizer guidelines were included. Therefore, the nutritional status of the soil was considered high for phosphate and potassium and an average guideline for vegetables were generated of 125, 75 and 100 kg N, P_2O_5 and K_2O per ha respectively per planting, yielding in total 500 kg N, 300 kg P_2O_5 and 400 kg K_2O/ha for the four plantings. These values were applied in all GAP scenarios.

In Indonesia it is not common to include the mineralization of nutrients from organic amendments into the fertilizer schedule. However, GAP does include the release of nutrients from organic amendments, as those nutrients may otherwise be lost to the environment. Three scenarios were evaluated assuming good agricultural practices (GAP). The first scenario (GAP 1) assumes an application rate for organic amendments of the baseline scenario and the chemical fertilizer application rates indicated above. The second GAP scenario (GAP 2) takes into account mineralization of organic amendments and reduces the chemical N fertilizer application rates accordingly. In the third GAP scenario (GAP 3) the organic amendments are balanced in dose to meet the crop requirement where 25 kg N/ha of chemical fertilizer is left for side dressing per planting. This means that a farmer applies organic amendments of which N is mineralized to the crop demands minus 100 kg N/ha for 4 plantings.

The GAP scenarios were applied for two situations: the use of chicken manure, and the use of the above-mentioned dairy manure products as organic amendment. The use of fresh feces is not included, because the attitude of farmers towards the use of fresh feces is not very positive as they strongly believe that fresh feces may burn their crops (Pronk et al., 2020).

3.4 Calculation of GHG emissions

3.4.1 Storage and transport of livestock manures

Storage

GHG emissions related to the storage of cattle and broiler manures were calculated based on IPCC guidelines on emissions from livestock and manure management (IPCC, 2019). For both production systems manure management was assumed to take place in the climate zone ‘warm tropical montane’.

Default IPCC manure management systems (MMS) were used as proxy for the local systems considered in this study, as follows: IPCC MMS ‘Poultry manure with litter’ as proxy for chicken manure (postal), ‘liquid/slurry/pit storage (with cover)’ for fresh cattle feces in sacks, ‘solid storage’ for cattle farm yard manure (FYM), ‘composting passive windrow (infrequent mixing and turning)’ for cattle compost, and ‘daily spread’ for daily spread of cattle manure.

IPCC does not provide proxy's for the practice of discharging manure and for vermicomposting. Therefore, for manure discharged from barns, CH_4 and N_2O emission factors of 'pasture/range/paddock' (PRP) were used (IPCC, 2019) with an N leaching factor of 65%. For vermicomposting, a methane conversion factor (MCF) of 76%, a direct N_2O emission factor of 70%, and indirect N_2O emission factors of 85% of those of thermophilic composting (intensive windrow) were assumed, based on comparisons of emissions from thermophilic composting and vermicomposting by (Nigussie et al., 2016). Vermi-composting is a multi-output process yielding compost and worms, economic allocation was applied for GHG emissions from vermi-composting (90% compost, 10% worms). In all cases N_2O emissions related to urine were included in the emission factor for each type of manure management, based on N excretion in urine. In case of daily spread, urine was assumed to be used as fertilizer on land for forage production (using N_2O emissions factors of daily spread). In all other cases, urine was assumed to be discharged (using N_2O emission factors of PRP).

Methane (CH_4) emissions during storage of manures were calculated for each livestock category and MMS according to Equation 10.23 in IPCC guidelines (2019):

$$CH4_{(T,S)} = VS_{(T)} \times B_{O(T)} \times 0.67 \times MCF_{(T,S)} \qquad \text{Eq. 1}$$

Where, $CH4_{(T,S)}$ is the annual CH_4 emission for livestock category T (adult dairy cow, replacement heifer, or broiler) and manure management system S in kg CH_4 animal^{-1} year^{-1}, $VS_{(T)}$ is the annual volatile solid excretion for livestock category T in kg dry matter animal^{-1} year^{-1}, $B_{O(T)}$ is the maximum CH_4 producing capacity for manure produced by livestock category T in m^3 CH_4 per kg of VS excreted, 0.67 is the conversion factor of m3 CH_4 to kg CH_4, and MCF is the methane conversion factor for livestock category T and manure management system S. In the final $CH_{4(T,S)}$ for dairy, a weighted average of the $CH4_{(T,S)}$ of adult dairy cows and replacement heifers was calculated, based on the ratio of cows to heifers in the population in Lembang according to the KPSBU database (12.6:1).

For broilers, volatile solid (VS) excretion was calculated using a Tier 1 approach, according to IPCC Equation 10.22A:

$$VS_{(broiler)} = VS_{rate(broiler)} \times \frac{TAM_{broiler}}{1000} \times 365 \qquad \text{Eq. 2}$$

Where, $VS_{(broiler)}$ is the annual VS excretion for broilers in kg VS animal^{-1} year^{-1}, $VS_{rate(T)}$ is the default VS excretion rate for mean productivity broiler systems in Asia in kg VS (1000 kg animal mass)$^{-1}$ day^{-1}, and TAM is the typical mass for broilers in mean productivity broiler systems in Asia in kg animal^{-1}.

For dairy cattle, VS excretion was calculated for adult cows and replacement heifers on an average dairy farm in Lembang using a Tier 2 approach, according to IPCC Equation 10.24:

$$VS_{(T)} = \left[GE_T \times \left(1 - \frac{DE_T}{100}\right) + 0.04 \times GE_T\right] \times \left[\frac{1-0.08}{18.45}\right] \qquad \text{Eq. 3}$$

Where, $VS_{(T)}$ is the annual VS excretion for livestock category T (adult dairy cow or heifer) in kg VS animal^{-1} year^{-1}, $GE_{(T)}$ is the gross energy intake in MJ animal^{-1} year^{-1}, $DE_{(T)}$ is the digestibility of the feed in %, 0.04 is the urinary energy as fraction of GE, 0.08 is the ash content of manure as a fraction of the DM intake, and 18.45 is the default conversion factor for dietary GE per kg DM. Likewise CH_4 (see previous paragraph), the final $VS_{(T)}$ for dairy was based on a weighted average of the $VS_{(T)}$ of adult dairy cows and replacement heifers.

Direct nitrous oxide (N_2O) emissions during storage of manures were calculated, modified after IPCC Equation 10.25:

$$N2O_{direct(T,S,EX)} = \left[\left[N_{ex\ (T,EX)}\right] \times EF_{3\ (T,S)}\right] \times \frac{44}{28} \qquad \text{Eq. 4}$$

Where $N2O_{direct(T,S,EX)}$ is the annual N_2O emission for livestock category T (adult cow, heifer, or broiler), manure management system S, and type of excretion EX (feces or urine) in kg N_2O animal^{-1} year^{-1}; $Nex_{(T,S,EX)}$ is the annual N excretion in kg N per animal^{-1} year^{-1}; EF_3 is the emission factor for direct N_2O emissions from manure management system S in kg N_2O-N per kg N in manure management system S; and 44/28 is the conversion factor of N_2O-N emissions to N_2O emissions. N excretion of adult cows was based on a weighted average of estimates for N excretion of dry cows and lactating cows (Zahra et al., 2020), based on the ratio of lactating cows to dry cows (6.8:1) in De Vries and Wouters (2017). Furthermore, likewise CH_4 (see above), the final N_2O_{direct} for dairy was based on a weighted average of the $N2O_{direct}$ of adult dairy cows and replacement heifers, and N_2O_{direct} from feces and urine were aggregated. Emissions of chicken manure during storage on the poultry farm were included in the analysis, but not its emissions as amendment during composting of cattle feces.

Indirect N_2O emissions due to volatilization of NH_3 and NO_x from manure management were calculated according to IPCC Equation 10.28:

$$N2O_{vol(T,S,EX)} = \left[N_{vol(T,S)} \times EF_{4\,(T,S)}\right] \times \frac{44}{28} \qquad \text{Eq. 5}$$

Where $N_2O_{vol(T,S,EX)}$ is the indirect N_2O emission due to volatilization of N for livestock category T (adult cow, heifer, or broiler), manure management system S, and type of excretion EX (feces or urine) in kg N_2O animal^{-1} year^{-1}; $N_{vol(T,S)}$ is the amount of nitrogen in manure that is lost due to volatilization in kg N animal^{-1} year^{-1}; and $EF_{4(T,S)}$ is the emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces in kg N_2O-N (kg NH_3-N + NO_x-N volatilized)$^{-1}$.

The amount of nitrogen in manure that is lost due to volatilization of NH_3 and NO_x was calculated according to IPCC Equation 10.26:

$$N_{vol(T,S,EX)} = \left[N_{ex(T,EX)}\right] \times Frac_{GasMS\,(T,S)} \qquad \text{Eq. 6}$$

Where $N_{vol(T,S,EX)}$ is the annual amount of manure nitrogen that is lost due to volatization for livestock category T (adult cow, heifer, or broiler), manure management system S, and type of excretion EX (feces or urine) in kg N animal^{-1} year^{-1}; $Nex_{(T,EX)}$ is the annual N excretion in kg N per animal^{-1} year^{-1}; and $Frac_{gasMS(T,S)}$ is the fraction of managed nitrogen that volatilizes as NH_3 and NO_x in manure management system S. Emissions of chicken manure during storage on the poultry farm were included in the analysis, but not its emissions as amendment during composting of cattle feces.

Indirect N_2O emissions due to leaching and runoff of N from manure management systems were calculated according to IPCC Equation 10.29:

$$N2O_{leach(T,S,EX)} = \left[N_{leach(T,S)} \times EF_{5\,(T,S)}\right] \times \frac{44}{28} \qquad \text{Eq. 7}$$

Where $N_2O_{leach(T,S,EX)}$ is the indirect N_2O emission due to leaching and runoff for livestock category T (adult cow, heifer, or broiler), manure management system S, and type of excretion EX (feces or urine) in kg N_2O animal^{-1} year^{-1}; $N_{leach(T,S)}$ is the amount of nitrogen in manure that is lost due to leaching and runoff in kg N animal^{-1} year^{-1}; and $EF_{5(T,S)}$ is the emission factor for N_2O emissions from N leaching and runoff in kg N_2O-N (kg N leached and runoff)$^{-1}$.

The amount of N lost due to leaching and runoff from manure management systems was calculated according to IPCC Equation 10.27:

$$N_{leach(T,S,EX)} = \left[N_{ex(T,EX)}\right] \times Frac_{LeachMS\,(T,S)} \qquad \text{Eq. 8}$$

Where $N_{leach(T,S,EX)}$ is the annual amount of manure nitrogen that is lost due to leaching and runoff for livestock category T (adult cow, heifer, or broiler), manure management system S, and type of excretion EX (feces or urine) in kg N animal^{-1} year^{-1}; $Nex_{(T,EX)}$ is the annual N excretion in kg N per animal^{-1} year^{-1}; and $Frac_{LeachMS(T,S)}$ is the fraction of managed nitrogen that is leached from the manure management system S. N loss of chicken manure during storage on the poultry farm were included in the analysis, but not its N loss as amendment during composting of cattle feces.

Total GHG emissions per animal^{-1} year^{-1} were converted to emissions per ton of excreted feces by dividing the emissions by the total amount of feces excreted per animal^{-1} year^{-1}. Total GHG emissions per ton of excreted feces were converted to emissions per ton of processed feces by multiplying emissions with a fraction [1-$Frac_{weightloss(S)}$], where $Frac_{weightloss(S)}$ is the fraction of weight lost during processing of cattle feces in manure management system S.

Transport

GHG emissions related to the transport of processed manures were calculated according to the following equation:

$$CO2_{transport(T,S)} = Dist_T \times \left[1 - Frac_{weightloss\,(T,S)}\right] \times EF_{truck} \qquad \text{Eq. 9}$$

Where, $CO_{2transport(T,S)}$ is the annual CO_2 emission due to transport of manure for livestock category T (dairy or broiler) and manure management system S in kg CO_2 ton^{-1} processed manure; $Dist_{(T)}$ is the hauling distance by truck in km; $Frac_{weightloss(S)}$ is the fraction of weight lost during processing of cattle feces in manure management system S; and EF_{truck} is the emission factor related to transportation by truck in CO_2 km^{-1} ton^{-1}.

Fossil carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions were converted into CO_2-eq using the IPCC 100-year global warming potential (GWP) coefficients of 1, 28 and 265 respectively (IPCC, 2014).

3.4.2 Application of organic and chemical fertilizer

For each scenario the carbon footprint was calculated with respect to chemical fertilizer use and organic amendments when products have arrived at the field. All products are applied manually so no costs for fossil fuels are included, not for transport or incorporation.

The GHG emission quantification for use of organic amendments described in the scenarios above was carried out using a LCA approach based on the PAS 2050:2011 protocol (BSI 2011). Due to system boundaries in the present study (manure value chain), we focused on GHG emissions from chemical fertilizers and organic amendments only, while other sources of GHG emissions from horticultural production were not included.

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

$$CF_A = \sum(A_i * EF_i) \qquad \text{Eq. 10}$$

Where the carbon footprint (CF) of an activity i.e., CF_A is the sum of GHG emissions (per hectare) due to ith activity/i 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; kg P_2O_5/ha); and EF_i is the emission factor of the ith activity or input process (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 Appendix 1.

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

$$N_2O_{total} = N_2O_{direct} + N_2O_{indirect} \qquad \text{Eq. 11}$$

$$N_2O_{direct} = (F_{SN} + F_{ON}) * EF_1 * \gamma_{N2O} \qquad \text{Eq. 12}$$

$$N_2O_{indirect} = N_2O_{(ATD)} + N_2O_{(L)} \qquad \text{Eq. 13}$$

$$N_2O_{(ATD)} = (F_{SN} * EF_4 * Frac_{GASF} + F_{ON} * EF_4 * Frac_{GASM}) * \gamma_{N2O} \quad \text{Eq. 14}$$

$$N_2O_{(L)} = (F_{SN} + F_{ON}) * EF_5 * Frac_{LEACHING} * \gamma_{N2O} \quad \text{Eq. 15}$$

Where F_{SN} and F_{ON} are the amount of N in chemical fertilizers and organic amendment respectively added to soils (in kg N/year).

$N_2O_{(ATD)}$ and $N_2O_{(L)}$ are N_2O emissions from atmospheric deposition and leaching and runoff of N additions from managed soils respectively. EF_1 is the emission factor for N_2O emissions from N inputs (kg N/kg input); EF_4 and EF_5 are the emission factors for N_2O emissions due to volatilization, and leaching and run-off N respectively from fertilizer and organic amendments applications. $Frac_{GASF}$, $Frac_{GASM}$, and $Frac_{LEACHING}$ are the fraction factors of atmospheric deposition of N volatilized from mineral fertilizer, organic amendments, and leaching from managed soil; γ_{N2O} (44/28) is the mass conversion factor for N_2 to N_2O (IPCC, 2006).

$$CF_{N_2O} = N_2O_{total} * 265 \quad \text{Eq. 16}$$

Where the CF is the GHG emission due to N_2O emissions and 265 is the GWP of N_2O (IPCC, 2014).

Chemical fertilizers

GHG emissions associated with the production of chemical fertilizers were calculated based on the amount of the classified product used and corresponding emission factor of Appendix 1.

4. Results and discussion

4.1 GHG emissions in the manure value chain

Table 5 shows estimates of GHG emissions related to collection, storage, transport and application of different types of cattle manure products and chicken manure. For cattle manure products, emissions are expressed both per ton excreted (fresh) feces and per ton processed manure product, because of weight loss. Per ton excreted feces, feces in sacks showed the highest storage and transport emissions, and vermi-compost the lowest. Per ton product, compost showed the highest storage and transport emissions, and vermi-compost the lowest. Storage and transport emissions of chicken manure were intermediate, compared to cattle manure products. For application emissions, chicken manure showed highest emissions per ton product, and feces in sacks showed the lowest emissions per ton product, as related to the N content of manure products. Transport emissions were higher for chicken manure than for cattle manure, due to the long transport distance to Lembang Sub-District. Overall, transport emissions were relatively low compared to storage and application emissions.

Table 5. Greenhouse gas emissions (in kg CO_2-eq) of livestock manures in different processes the manure value chain (functional units: 1 ton fresh feces and 1 ton final product).

	Application dairy sector*	**Collection/ Storage***	**Transport**	**Total storage and transport**		**Application horticulture**
Manure management	**(kg CO_2-eq/ton fresh feces)**	**(kg CO_2-eq/ton fresh feces)**	**(kg CO_2-eq/ton fresh feces)**	**(kg CO_2-eq/ton fresh feces)**	**(kg CO_2-eq/ton product)**	**(kg CO_2-eq/ton product)**
Cattle manure:						
-Discharging	49.2	-	-	-	-	-
-Daily spread	27.3	6.7	-	6.7	-	-
-FYM	-	64.0	0.8	64.8	151.8	43.7
-Compost	-	63.6	3.4	67.1	195.7	49.9
-Vermi-compost	-	38.7	0.8	39.5	98.8	43.7
-Feces in sacks	-	128.0	1.9	130.0	130.0	21.5
Chicken manure	-	103.8	22.2	-	126.0	124.8

* Including emissions from urine associated with 1 ton feces (either discharged or applied via daily spread).

4.2 Alternative processing methods for cattle manure

Figure 5 shows changes in GHG emissions in the dairy sector and horticultural sector for alternative pathways to utilize 1 ton of previously discharged feces. In all scenarios GHG emissions from manure discharging were reduced and (except for the scenario in which cattle manure was added to current fertilizer use in horticulture) GHG emissions from production and transport of chicken manure, and emissions from organic fertilizer application in horticulture were reduced. Emission reductions per scenario are described below.

4.2.1 Daily spread on forage

Shifting from discharging to daily spread of 1 ton of feces (and associated urine) reduced GHG emissions per ton fresh feces by 67%. This was mainly due to avoided emissions from discharging cattle manure and avoided emissions from urea manufacturing and application on forage (N-based replacement). Daily spread has a very low emission factor (IPCC, 2019) due to the short retention time in the barn. Application emissions of daily spread of manure were slightly lower than for urea application.

4.2.2 Manure processing and application in horticulture

Shifting from discharging to application of processed cattle feces in horticulture reduced GHG emissions per ton fresh feces by 38-62%. This was mainly due to (weight-based) replacement of chicken manure in horticulture, thereby avoiding N_2O emissions from storage and application of chicken manure. More N is lost from chicken manure due to a relatively high N content compared to cattle manure products (2% vs 0.3-0.8% on a wet basis). It should be noted, therefore, that a nutrient-based replacement would yield different results; this is further discussed in the Discussion section. Emissions from cattle manure storage increased in this scenario, but this did not compensate the reduction in emissions due to avoiding chicken manure and discharging of feces (urine still discharged). Emission reduction was largest in vermi-compost (62%), due to relatively low storage emissions (Table 5), followed by feces in sacks (50%) and FYM (47%). Emission reduction was smallest in compost (38%) because a higher weight loss was assumed for compost, and hence less chicken manure was replaced. On the contrary, for feces in sacks no weight loss was assumed, leading to more replacement of chicken manure and associated emissions.

Additional calculations showed that replacing chicken manure by vermi-compost based on N content also reduced GHG emissions, but to a lesser extend (31%; result not shown in Figure 5). This implies about half of the reduction in GHG was due to the lower N content of the organic amendment used.

4.2.3 Adding cattle manure to current fertilizer use

When vermi-compost was added on top of current fertilizer use in horticulture, rather than replacing fertilizers, GHG emissions increased by 5%. In this situation, avoided emissions from discharged manure did not compensate for increases in emissions from storage and application of cattle manure.

Avoiding chicken manure does not mean chicken manure is not produced. When emissions related to storage of chicken manure were taken into account, however, total GHG emissions still reduced (by 34% in case of vermi-compost; results not shown).

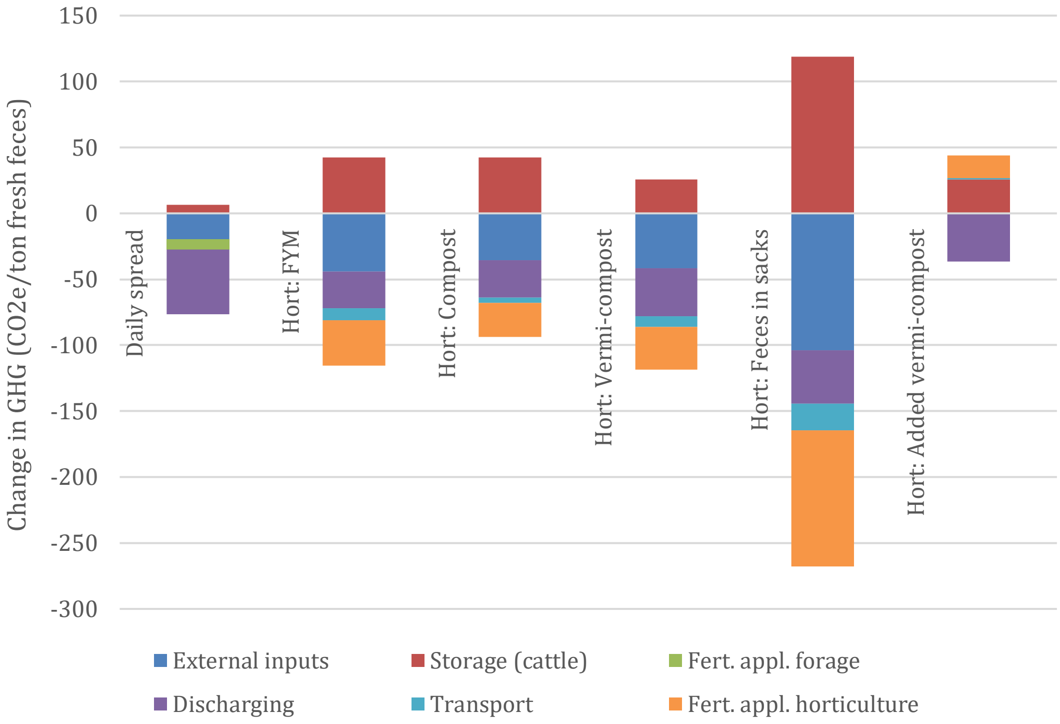

Figure 5. Changes in GHG emissions (in CO_2e per ton fresh cattle feces) in three scenarios to avoid the discharging of 1 ton cattle feces: i) daily spread on land for forage production, ii) replacing chicken manure by different types of cattle manure products in horticulture, and iii) adding vermi-compost to current fertilizer use in horticulture.

4.3 Replacing fertilizers in horticulture by cattle manure

GHG emissions related to the production and use of chicken manure with rice husk (baseline) and the use of chemical fertilizers ranged from 15,000 to almost 20,000 kg CO_2-eq/ha in the different crop rotations (Figure 6; ‘postal’). The mono cropping system with only Lettuce and Broccoli (crop rotation 2) that used chicken manure had the lowest emission per hectare compared to the other cropping systems with chicken manure as total N inputs were the lowest (Table 4), where the multiple cropping system with crop rotation 4 had the highest emissions per hectare as total N inputs in this crop rotation were the highest (Table 4).

Replacement of chicken manure with dairy manure products reduced emissions by 1 to 31% (Figure 6, prevented discharge of cattle feces not included). The reduced emissions, except for compost, were closely related to the reduction of the emissions of the use of dairy products (open bars) caused by the lower N content of these amendments. This result indicates that the reduction in emissions related to the application of dairy based products are greater than the increase in emissions from the production of those products, causing that net GHG emissions decreased in all dairy-based scenarios compared to the baseline scenario (chicken manure).

Additionally, changing from chicken manure to cow manure products prevents the discharge of fresh cow feces. For the use of 1 ton FYM instead of chicken manure, 2.3 tons fresh manure were not discharged, thus 113.2 kg CO_2-eq of emissions were prevented which equals 4866 kg CO_2-eq for the application of 43 tons FYM/ha. When compost or vermi is applied at 43 tons/ha, the savings are 6135 or 5289 kg CO_2 eq respectively. The avoided emissions increase when 48 tons of cow manure products is applied. Replacement of chicken manure with dairy manure products when emissions related to the prevented discharge are taken into account, reduced emissions by 37 to 67% (see percentages in Figure 6 above bars of Total).

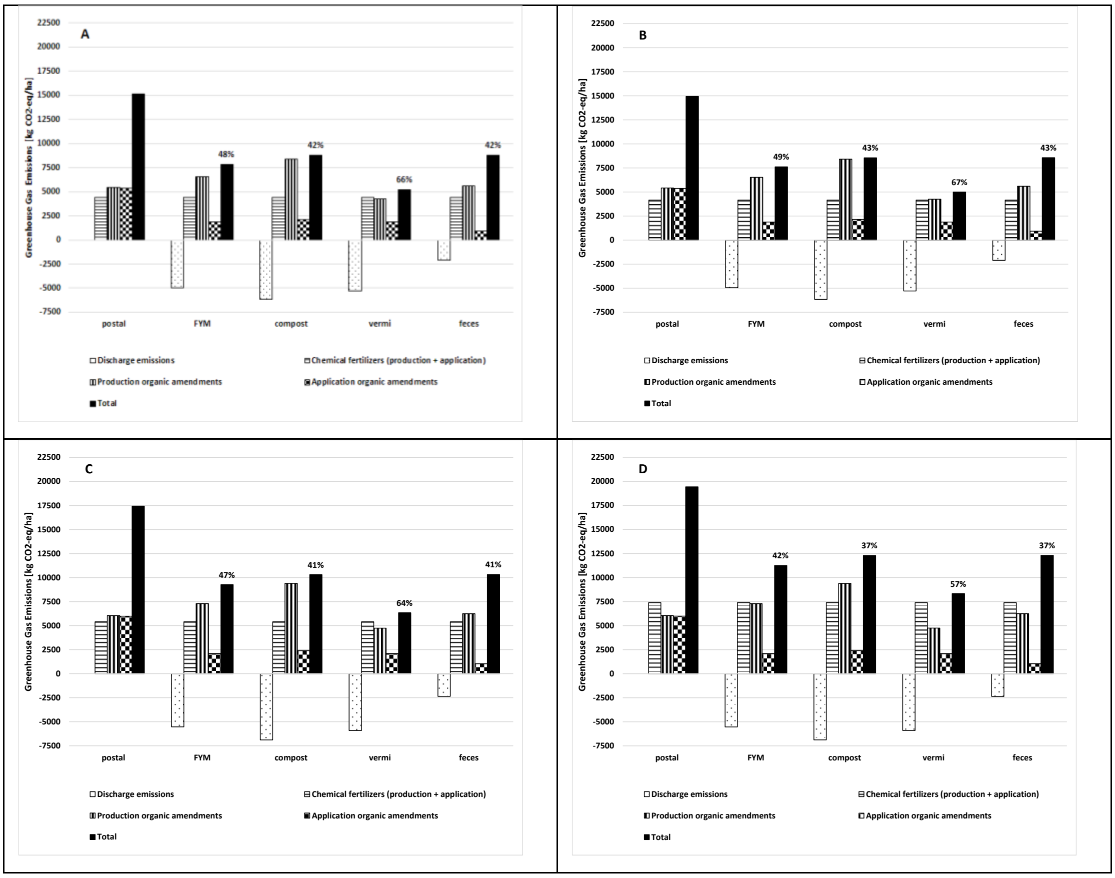

Figure 6. Greenhouse gas emissions related to the discharging of cattle manure (░), production and application (▤) of chemical fertilizers and the production (▥), application (▦) and total ■) for the application of postal (chicken manure with rice husk; baseline) and 4 different types of cattle manure products in cropping system 1 (A), 2 (B), 3 (C) and 4 (D): farm yard manure (FYM), compost, vermi-compost (vermi) and fresh feces in sacks (feces). The percentages above each bar indicate the reduction compared to the baseline (postal) in each crop rotation.

Emissions related to the application of organic amendments depend on the total applied N and are most sensitive to the emission factor EF1 (Kashyap et al., in prep.). EF1 is based on the agricultural system of which horticulture is known to have high emissions compared to other agricultural systems. Evaluated crop rotations showed high expected losses as N-removal with harvested products for crop rotation 1 to 4 were estimated at 221, 196, 137 and 157 kg N/ha per year using a N content of 0.45% on a fresh weight basis for Lettuce and Broccoli (Fink and Feller, 2001) and of 0.25% on a fresh weight basis for Tomato (Vázquez et al., 2006). Although a considerable amount of N in crop residues remains at the field, compared to the total N applied of 1133 to 1445 kg N/ha and available N for crop uptake of 910 to almost 1200 kg/ha (Appendix 1), this explains why EF1 is high.

4.4 Good Agricultural Practice (GAP)

In Table 6 effects of implementing GAP on GHG are presented. The table shows the emissions when an organic amendment is applied according to the current practiced dose ('baseline dose') and the emissions when GAP 1 to 4 are applied. For each GAP (1-4), the relative change in emissions compared to the baseline dose are shown as percentage change, both compared to the use of chicken manure as baseline dose ('Δ baseline postal' (%)) and compared to the use of the dairy manure product as baseline dose ('Δ baseline dairy' (%)).

4.4.1 Applying GAP to chicken manure

The advised application doses for GAP of chemical fertilizers for N, P_2O_5 and K_2O for 4 plantings exceeds the currently applied chemical fertilizer applications as reported in Pronk et al. (2020). Consequently, emissions increased in GAP1, as shown by a positive relative change in Table 6 for GAP 1, for the first 3 crop rotations. Only for crop rotation 4 the chemical fertilizer application rate was comparable with GAP, 485 kg N/ha (see Table 6) so no differences were found. For GAP 2 however, where consideration of mineralization of organic amendments in the GAP led to lower chemical N application, emissions reduced significantly up to 29% (Table 6). GAP 3 showed the largest reduction of emissions, up to 56%, compared to all other scenarios. In this GAP 3 scenario, the organic amendments dose was increased up to 400 kg N/ha mineralization, thus using the optimal amount of organic amendments to contribute to the N demand of the crops and reducing chemical fertilizer use.

4.4.2 Applying GAP and replacing postal with dairy manure products

The greenhouse gas emissions of the baseline were compared to emissions when GAP was applied, and when dairy manure products replaced chicken manure in combination with GAP (Table 6). Emissions related to transport and production of chemical fertilizers were included and discharged manure was additionally included for organic amendments. Two relative differences are presented in Table 6. First, the relative difference of the use of GAP was compared to the baseline (chicken manure with practiced chemical fertilizer applications in the 4 crop rotations), columns Δ baseline postal in Table 6. Second, the relative difference of the use of GAP was compared to the baseline dairy manure product, columns Δ baseline dairy.

The application of the baseline dose of chicken manure in combination with GAP 1 increased emissions in all crop rotations except for crop rotation 4 (Table 6). An increase in emissions for crop rotations 1, 2 and 3 was found because the total N applications increased (see Appendix II), where no increase was found for crop rotation 4. However, when GAP 2 and 3 were applied, emissions reduced by 16% to 49% for GAP 2 crop rotation 2 and GAP 3 crop rotation 4 (Table 6).

Using dairy manure products instead of chicken manure products reduced emissions for all GAP scenarios, from 21% in the scenario with crop rotation 2, compost and GAP 2, to 83% in the scenario with crop rotation 4, vermicompost and GAP 3.

Furthermore, emissions increased when the baseline scenario with a specific cattle manure product changed to GAP, for all crop rotations. This increase ranged from 0% in the scenario with crop rotation 4 and compost, to 66% in the scenario with crop rotation 2 and vermicompost. Changing to GAP 2 and 3 showed increase as well as decrease of emissions, where crop rotation 3 and 4 reduced emission and crop rotation 1 and 2 sometimes increased and sometimes decreased emissions, although the increases were small (maximum 4%).

In general, shifting from chicken manure to dairy manure products reduced emissions where the use of GAP 1 increased emissions in crop rotations 1, 2 and 3 and no differences were found for crop rotation 4. However, shifting to GAP 2 and 3 irrespectively of manure type, did reduce emissions in crop rotations 3 and 4 where little improvements were found in crop rotations 1 and 2 for the change of FYM and compost. Changing to vermicompost did also not reduce emissions for GAP 2 in crop rotations 1 and 2.

Table 6. Greenhouse gas emissions (in kg CO_2-eq/ha) of production, transport and application of chemical fertilizer and organic amendments (includes discharge emissions) at baseline doses and in 3 different scenarios for GAP (1-3) in the 4 crop rotations.

Organic amendment	Crop rotation	Baseline dose	GAP 1	Δbaseline postal (%)	Δ baseline dairy (%)	GAP 2	Δ baseline postal (%)	GAP 2 (%)	GAP 3	Δ baseline postal (%)	GAP 3 (%)
Postal (chicken manure)	1	15178	18231	20		12538	-17		9860	-35	
	2	14944	18231	22		12538	-16		9860	-34	
	3	17440	19485	12		13792	-21		9860	-43	
	4	19427	19485	0		13792	-29		9860	-49	

FYM (manure (dairy)	1	7845	10898	-28	39	7727	-49	-1	7948	-48	1
	2	7610	10898	-27	43	7727	-48	2	7948	-47	4
	3	9253	11299	-35	22	7760	-56	-16	7948	-54	-14
	4	11240	11299	-42	1	7760	-60	-31	7948	-59	-29
Compost (dairy manure)	1	8786	11839	-22	35	8216	-46	-6	8662	-43	-1
	2	8552	11839	-21	38	8216	-45	-4	8662	-42	1
	3	10305	12350	-29	20	8305	-52	-19	8662	-50	-16
	4	12291	12350	-36	0	8305	-57	-32	8662	-55	-30
Vermi-compost (dairy manure)	1	5230	8283	-45	58	5113	-66	-2	3266	-78	-38
	2	4995	8283	-45	66	5113	-66	2	3266	-78	-35
	3	6335	8380	-52	32	4841	-72	-24	3266	-81	-48
	4	8321	8380	-57	1	4841	-75	-42	3266	-83	-61

5. General discussion and conclusions

The objective of this study was to explore effects of increased use of cattle manure and good agricultural practices in horticulture on GHG emissions from agriculture in Lembang sub-district, West Java. Effects of increased use of cattle manure were explored in two ways: based on a FU of 1 ton of excreted feces and based on a FU of 1 ha of horticultural land. The first method was aimed at evaluating GHG impacts of alternative manure processing and utilization strategies to avoid the discharging of 1 ton of cattle feces. The second method was aimed at evaluating GHG impacts of replacing currently used chicken manure in horticulture using various cattle products. Results showed that:

- utilizing cattle feces as fertilizer on land for forage production will decrease GHG emissions compared to discharging feces;
- utilizing cattle feces in horticulture will decrease GHG emissions from the dairy and horticultural sector in Lembang, but only when the cattle feces replace (part of the) fertilizers currently used;
- processing and application as vermi-compost was the lowest-emission strategy to utilize currently discharged cattle feces;
- in a similar vein, implementing good agricultural practices (GAP) in horticultural production was shown to substantially reduce GHG emissions.

Therefore, this study showed that avoiding discharging manure does not only reduce local environmental impacts, such as pollution of aquatic and terrestrial ecosystems, and drinking water sources, but also shows synergies with reduction of GHG emissions in Indonesian agriculture.

5.1 Methodological limitations

There are a number of methodological limitations of this study. First, to our knowledge, GHG emissions of discharged cattle manure has not been investigated and documented and are not included in IPCC guidelines (2019). For this reason an expert best guess was made for CH4 and N2O emissions from discharged manure, using the EF of “pasture/range/paddock” in IPCC guidelines as a proxy and with an N leaching fraction of 0.65. Knowing that there is some extent of uncertainty, results should be interpreted with care. Second, availability and quality of data are common issues in developing countries and were also a limitation of the present study. Like in any survey, responses to the questionnaires by horticultural and dairy farmers were likely subject to self-reporting bias, particularly farmers' estimates of amounts of farm inputs and outputs. Third, as organic fertilizers generally show large variation in nutrient contents, nutrient composition of manures may deviate from the compositions assumed in this study. Also, as nutrient contents are often unknown and the timing of release of nutrients from the organic matter is uncertain (both cow and chicken manure), this makes it difficult for farmers to decide on suitable application rates for crops.

The last limitations are related to several assumptions on replacement of chicken manure in this study:

- Chicken manure was replaced by cattle manure in the same dose in this study (weight-based replacement). This was expected to be more likely in practice than a nutrient-based (e.g. N) replacement, as horticultural farmers in Lembang apply organic amendments as soil enhancer rather than accounting for the nutritional value (Pronk et al., 2017) and are generally not familiar with the nutrient composition of organic amendments. In case we would have assumed N-based replacement, emission reductions could be less or absent, which is further discussed in the paragraphs below.
- Emissions from chicken manure were assumed to be absent in scenarios in which chicken manure was replaced by cattle manure, but this does not mean chicken manure is not produced. When we included storage emissions from chicken manure in scenarios omitting chicken manure, however, total emissions were still reduced, however this did not include emissions from application of the omitted chicken manure elsewhere.
- In the present study we evaluated replacement of chicken manure by cattle feces because this scenario was considered more likely than replacement of chemical fertilizer in practice, due to additional benefits of organic fertilizers besides nutrients for soil quality and structure, and the cheap availability and ease of use of chemical fertilizers. Replacing chemical fertilizer, however, could be more effective in reducing overall GHG emissions from agriculture than replacing chicken manure, as we showed in GAP

scenarios. Reduction of chemical fertilizer by horticulture in Lembang would imply less chemical fertilizer is produced, where reduction of use of chicken manure by horticulture in Lembang does not mean less chicken manure is produced (see previous paragraph).

5.2 Low-emission strategies for avoiding discharging of cattle feces

Results showed that, compared to the discharging of feces and urine, reductions in GHG emissions were largest when feces were used as daily spread in the dairy sector, followed by vermi-compost, feces in sacks, FYM and compost in horticulture. The emission reduction of daily spread could not be directly compared to use of cattle manure in the horticultural sector, however, because replacement was based on different assumptions: in case of daily spread, N-based replacement of chemical fertilizer by cattle manure was assumed, whereas in case of utilization in horticulture, weight-based replacement of chicken manure was assumed. When N-based replacement was assumed for horticulture as well, daily spread still showed the largest reduction in GHG emissions of all evaluated strategies (results not shown), due to much lower storage emissions (IPCC, 2019).

5.2.1 Daily spread

According to De Vries and Wouters (2017) daily spread is already performed by one third of dairy farmers in Lembang and is the least costly manure management option for dairy farms, together with discharging into the environment (applying N via daily spread was even less costly than applying N via urea; De Vries et al. 2020). Implementation is hampered by the distance from cow barns to land due to land fragmentation on Java, however, as well as practical and social barriers, such as land of neighbors that needs to be passed. Therefore, land consolidation is an important strategy to enhance daily spread (e.g. Jiang et al., 2022).

5.2.2 Vermi-composting

Vermi-composting was shown to be the lowest-emission strategy to utilize currently discharged cattle feces in horticulture. Estimates of vermicompost in our study were in line with Wang et al. (2014), who found cumulative CH4 and N2O emissions from vermicomposting of duck manure ranged from 15 to 58 kg CO2e/ton DM (i.e. about 25-100 kg/ton fresh). Similar to results of our study, Swati and Hait (2018) concluded from a literature review that GHG emissions of vermicomposting are lower than composting.

Various studies have shown that the presence of earth worms reduces both N2O and CH4 emissions from vermi-compost (e.g. Chan et al., 2011; Wang et al., 2014). About 5% of dairy farmers in Lembang perform vermi-composting (De Vries and Wouters, 2017), and the number is increasing because it is a profitable business, particularly as a result of worm sales. Vermicomposting may not be feasible for many farms, however, because of required space and large investment (De Vries et al., 2020), and a limited worm market.

5.2.3 Composting

According to De Vries and Wouters (2017) composting is performed by 8% of dairy farmers in Lembang, and likely feasible to a larger number of farmers than vermi-composting because of less required space and investment. Compost is appreciated by horticultural farmers due to its potential to improve the physical properties of soil, enhance soil nutrients, and microbial diversity. However, GHG emissions from composting were relatively high compared to other cattle manure products, due to high N loss (both N2O and NH3). GHG estimates of compost in our study were higher than results of composted cattle feces in the study of Bai et al. (2020), who found cumulative CH4 and N2O emissions of 392 kg CO2e/ton DM (i.e. about 150 kg/ton fresh when based on 35-40% DM content). This difference is likely due to the inclusion of emissions from production of broiler manure as amendment for composting in our study, which increased emissions by 25%. GHG emissions from composting can be variable because they are influenced by many factors such as amendment characteristics, process parameters like aeration, moisture content, temperature regime, etc. Contrary to vermi-composting, the production and sales of compost may not always be cost-effective for Indonesian dairy farmers (De Vries et al., 2020).

5.2.4 Farmyard manure

FYM was assumed to cause higher GHG emissions than compost when expressed per ton excreted feces, but lower emissions than compost when expressed per ton final product. Similar to our results, Amon et al. (2001) showed that, expressed per livestock unit, N2O and CH_4 emissions were higher from the anaerobically stacked FYM than from composted manure (282.1 kg vs. 210.7 kg CO_2eq/LU/mo, incl. housing emissions). Bai et al. (2020) showed GHG emissions per kg DM were much lower for FYM (stockpiled) than compost, but their estimates of GHG emissions of FYM were lower than ours. About 12% of dairy farmers in Lembang store manure as FYM (De Vries and Wouters, 2017).

5.2.5 Risk of overfertilization

There are risks in promoting cattle manure as a fertilizer, as this can lead to overfertilization, causing pollution of soils, ground- and surface waters due leaching and run-off, and increased GHG emissions (N2O). Application rates up to 5751 kg N/ha/y have been observed in dairy farms in Lembang using daily spread (De Vries et al., 2020). The present study showed that adding vermi-compost to current fertilizer regimes in horticulture increased total emissions. In a similar vein, reducing overfertilization of land for forage or crop production results in an even larger reduction in GHG emissions than avoiding discharged manure, as GHG emissions related to overfertilization are higher than those of discharged manure (De Vries et al., 2020). Hence, adding cattle manures on top of current fertilizer regimes without omitting other fertilizers is not a sustainable solution to the problem of discharging cattle manure in West Java.

5.3 Low-emission strategies for horticulture

Replacing chicken manure by cattle manure products in horticulture reduced GHG emissions per hectare by 42 to 66% (Figure 6A) when applied at the same dose as postal. The reduction was closely related to the reduced N applied with cattle manure products compared to chicken manure. As farmers in Lembang currently apply organic amendments as soil enhancer and do not account for the nutritional value of the amendments (Pronk et al. 2017), a reduced N input is not likely to affect farm performance, such as production levels. In all scenarios application rates cover the demand of available N of the fertilizer guidelines of 500 kg N/ha (Appendix II).

The application of fresh cattle manure reduced the GHG emissions per ha the most. However, farmers in horticulture hardly use fresh manure as they strongly believe that it will burn their crops. With current practice this is likely to happen, but fresh manure can well be used with small modifications, changes in application techniques and for a number of horticultural crops (e.g., Tomato, Broccoli, Cabbage, Potato). It is therefore recommended to develop application guidelines for the use of fresh cow manure with demonstrations and training of farmers.

The approach of expressing GHG per ha in horticulture differed from the approach described above, in which GHG were expressed per ton feces. In the horticultural scenarios, the amount of previously discharged manure differed depending on the final cattle manure product used in horticulture. For example, per ton of cattle manure compost used in horticulture, 2.9 ton of discharged feces was avoided, whereas 2.3 ton of feces was avoided per ton of FYM (Table 5). Based on the total area used for horticulture in Lembang Sub-District of approximately 2500 ha and an application dose of 43 tons/ha, the estimated total amount of chicken manure applied is 106,597 tons per year. Assuming an annual production of 0.15 Mton fresh feces from cows and heifers in the dairy cooperative KPSBU Lembang, of which about 0.09 Mton is discharged, about 0.05 Mton of FYM could be produced. This amount of FYM would cover about 43% of the horticultural area in Lembang when chicken manure is replaced (weight-based) by FYM. In a similar vein, when fresh feces are processed into about 0.04 Mton of compost or vermi-compost, 34-40% of the area used for horticulture could be supplied with compost or vermi compost instead of chicken manure. Hence, the horticultural area in Lembang has enough room to apply feces from the local dairy sector when processed into a product that is used at the same dose as postal, thereby avoiding GHG emissions related to discharged feces, i.e. 4,434 ton CO_2-eq per year, as well as pollution of local ecosystems.

However, vegetable farmers have several barriers towards the use of cattle manure products that need to be overcome. Their main concern is about the maturity of the product as they strongly believe that immature products burn their crops (Pronk et al, 2020).
Secondly, farmers favor chicken manure as it is easy to handle so acceptance of a cattle manure processed product is most likely increased when handling resembles that of chicken manure.

5.4 Good Agricultural Practice

Currently, Indonesia has not established complete fertilizer guidelines for vegetable crops, whereas these are an important first step towards GAP. This may also indicate that there is still a long way to go before GAP 2 and GAP 3 of this study are developed and implemented in Indonesia. The guidelines under development include some aspects of mineralization as they differentiate nutritional status among the fields. Rich fields need less nutrients than poor fields. The present study illustrates the importance of including organic amendments into these guidelines and that mineralization is an important factor to include in the chemical fertilizer guidelines, both from a financial and environmental point of view. A farmer may save money and reduce GHG at the same time when doing so. This study also suggests that the fertilizer guidelines under development may not sufficiently include mineralization of organic amendments at the current application rates. For example, N fertilizer trials showed that the optimal N application rate for potatoes ranged from 107 to 170 kg N/ha for the optimization by a broken stick or quadratic plateau method respectively (Brink et al., 2016).

When the fertilizer guidelines are followed chemical fertilizer applications will increase compared to current practices, and thus emissions increase. Therefore, only implementing chemical fertilizer guidelines as part of GAP 1 did not reduce emissions.

GAP 3 is the most advanced technique for Good Agricultural Practices, in which chemical N fertilization is reduced as much as possible and replaced by N mineralized from organic amendments. Here, an organic amendment with a high N-mineralization allows high chemical N fertilizer replacement and thus reduce GHG emissions of chemical fertilizer production and application, as shows from Table 6, for vermi-compost all crop rotations and FYM and compost crop rotations 3 and 4 reductions in GHG emissions ranged from 14 to 61% compared to GAP 1. However, GAP 3 is not likely to happen since fertilizer costs are around 20% of the production costs including 10% for manure products at 22 tons/ha (Pronk & Gunadi 2017). Increasing manure use up to 68 or 77 tons/ha increases application costs for manure that is most likely not profitable.

6. Recommendations

Based on this study, the following recommendations were drawn.

For the dairy sector:

- Discharging of cattle manure should be avoided in order to reduce pollution of local ecosystems and drinking water sources, and GHG emissions from Indonesian agriculture;
- To reduce GHG emissions from manure management in the dairy sector:
  - instead of discharging, cattle manure should be applied on land for forage production via daily spread while replacing urea, but overfertilization should be avoided;
  - instead of discharging, cattle manure should be processed into products that can replace chicken manure in horticulture, preferably vermicompost as this is the cattle manure product with the lowest GHG emissions;
- Adding cattle manure to current fertilizer regimes without replacement of current fertilizers in the dairy sector and horticultural sector should be avoided, as this increases GHG emissions;

For the horticultural sector:

- Replacement of chicken manure by processed cattle manure at the same dose reduces GHG emissions and should therefore be promoted;
- Current GAP fertilizer guidelines should not be used in combination with currently used doses of organic amendments in horticulture in Lembang (representative sample). For current GAP guidelines, lower amounts of organic amendments are advised to reduce nutrient losses to the environment;
- To stimulate adoption of horticultural farmers to change from chicken manure to cattle manure products, cattle manure products should be comparable to chicken manure with respect to product composition, as related to ease of handling and maturity;
- There is enough horticultural land available to apply all processed cattle manure products in Lembang sub-district, even at lower doses.

7. References

Amon, B., T. Amon, J. Boxberger, and C. Alt. 2001. Emissions of NH3, N2O and CH4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutrient Cycling in Agroecosystems 60: 103-113.

Apdini, T., W. Al Zahra, S. J. Oosting, I. J. M. de Boer, M. de Vries, B. Engel, and C. E. van Middelaar. 2021. Understanding variability in greenhouse gas emission estimates of smallholder dairy farms in Indonesia. The International Journal of Life Cycle Assessment 26: 1160-1176.

Bai, M., T. Flesch, R. Trouvé, T. Coates, C. Butterly, B. Bhatta, J. Hill, and D. Chen. 2020. Gas emissions during cattle manure composting and stockpiling. Journal of environmental quality 49: 228-235.

Biagini, D. and C. Lazzaroni. 2018. Eutrophication risk arising from intensive dairy cattle rearing systems and assessment of the potential effect of mitigation strategies. Agriculture, Ecosystems & Environment 266: 76-83.

Chan, Y. C., R. K. Sinha, and W. Weijin. 2011. Emission of greenhouse gases from home aerobic composting, anaerobic digestion and vermicomposting of household wastes in Brisbane (Australia). Waste Manag Res 29: 540-548.

De Vries, M. and A. P. Wouters. 2017. Characteristics of small-scale dairy farms in Lembang, West-Java. Wageningen Livestock Research, The Netherlands.

De Vries, M., W. A. Zahra, A. P. Wouters, C. E. van Middelaar, S. J. Oosting, B. Tiesnamurti, and T. V. Vellinga. 2019. Entry Points for Reduction of Greenhouse Gas Emissions in Small-Scale Dairy Farms: Looking Beyond Milk Yield Increase. Frontiers in Sustainable Food Systems 3.

De Vries, M., B. Wouters, D. Suharyono, A. Sutiarto, and S. E. Berasa. 2020. Effects of feeding and manure management interventions on technical and environmental performance of Indonesian dairy farms: Results of a pilot study in Lembang Sub-District, West Java. Wageningen Livestock Research, Wageningen, the Netherlands.

FAO. 2006. Livestock's Long Shadow–Environmental Issues and Options. Food and Agriculture Organization of the United Nations (FAO), Rome.

Fink, M. and C. Feller. 2001. Düngung im Freilandgemüsebau. IGZ.

Goodman, L. A. 1961. Snowball Sampling. The Annals of Mathematical Statistics 32: 148-170.

Hergoualc’h, K., H. Akiyama, M. Bernoux, N. Chirinda, A. del Prado, Å. Kasimir, J. D. MacDonald, S. M. Ogle, K. Regina, and T. J. v. d. Weerden. 2019. N2O emissions from managed soils, and CO2 emissions from lime and urea application.

Huang, Y. and Y. Tang. 2010. An estimate of greenhouse gas (N2O and CO2) mitigation potential under various scenarios of nitrogen use efficiency in Chinese croplands. Global Change Biology 16: 2958-2970.

Indonesia LTS-LCCR 2050. 2021. INDONESIA Long-Term Strategy for Low Carbon and Climate Resilience 2050 (Indonesia LTS-LCCR 2050). https://unfccc.int/sites/default/files/resource/Indonesia_LTS-LCCR_2021.pdf.

IPCC. 2019. IPCC 2006 Guidelines for National Greenhouse Gas Inventories prepared by the National Greenhouse Gas Inventories Programme, updated 2019. Eggleston, H.S., Buenida, L., Miwa, K., Nagara, T. and Tanabe, K. (eds). IGES, Japan.

Jiang, Y., Y.-T. Tang, H. Long, and W. Deng. 2022. Land consolidation: A comparative research between Europe and China. Land Use Policy 112: 105790.

Kool, A., M. Marinussen, and H. Blonk. 2012. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization. GHG Emissions of N, P and K fertiliser production.

MacDonald, G. K., E. M. Bennett, P. A. Potter, and N. Ramankutty. 2011. Agronomic phosphorus imbalances across the world's croplands. Proceedings of the National Academy of Sciences 108: 3086-3091.

Nigussie, A., T. W. Kuyper, S. Bruun, and A. de Neergaard. 2016. Vermicomposting as a technology for reducing nitrogen losses and greenhouse gas emissions from small-scale composting. Journal of Cleaner Production 139: 429-439.

Oenema, O., N. Wrage, G. L. Velthof, J. W. van Groenigen, J. Dolfing, and P. J. Kuikman. 2005. Trends in Global Nitrous Oxide Emissions from Animal Production Systems. Nutrient Cycling in Agroecosystems 72: 51-65.

Oosting, S., J. van der Lee, M. Verdegem, M. de Vries, A. Vernooij, C. Bonilla-Cedrez, and K. Kabir. 2021. Farmed animal production in tropical circular food systems. Food Security.

Opio, C., P. Gerber, A. Mottet, A. Falcucci, G. Tempio, M. MacLeod, T. Vellinga, B. Henderson, and H. Steinfeld. 2013. Greenhouse gas emissions from ruminant supply chains – A global life cycle assessment. Food and Agriculture Organization of the United Nations (FAO), Rome.

Pronk, A., M. de Vries, W. Adiyoga, N. Gunadi, M. Prathama, A. E. Merdek, and J. Sugiharto. 2020. Fertilisation practices on small-scale vegetable farms in Lembang, West Java: Understanding drives and barriers of farmers on the use of chicken and cattle manure. Wageningen Plant Research, Wageningen.

Pronk, A. A., L. van den Brink, N. Gunadi, and U. Komara. 2017. Economics and agronomics of Atlantic and Granola potato production in the dry season 2014 in West Java. Page 47 in vegIMPACT External Report 36. Wageningen-UR, Wageningen.

Ramachandra, T. 2009. Emissions from India's transport sector: statewise synthesis. Atmos Environ 43: 5510-5517.

Rashti, M. R., W. Wang, P. Moody, C. Chen, and H. Ghadiri. 2015. Fertiliser-induced nitrous oxide emissions from vegetable production in the world and the regulating factors: A review. Atmos Environ 112: 225-233.

Republic of Indonesia. 2018. Indonesia Second Biennial Update Report (BUR). M. o. E. a. F. Directorate General of Climate Change, ed, Indonesia.

Sefeedpari, P., M. De Vries, F. de Buisonjé, D. Suharyono, B. Wouters, and W. A. Zahra. 2020. Composting dairy cattle feces at Indonesian small-scale dairy farms: Results of a composting trial in Lembang Sub-District, West Java. Wageningen Livestock Research, Wageningen.

Singh, R. P., P. Singh, A. S. F. Araujo, M. Hakimi Ibrahim, and O. Sulaiman. 2011. Management of urban solid waste: Vermicomposting a sustainable option. Resources, Conservation and Recycling 55: 719-729.

Swati, A. and S. Hait. 2018. Greenhouse Gas Emission During Composting and Vermicomposting of Organic Wastes – A Review. CLEAN – Soil, Air, Water 46: 1700042.

Tilman, D., K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. Nature 418: 671-677.

Van den Brink, L., N. Gunadi, R. Wustman, T. K. Moekasan, L. Prabaningrum, A. K. Karjadi, and H. Hengsdijk. 2015. Results of fertilizer demonstration trials in Pangalengan and Garut, Indonesia, May – August 2014. in vegIMPACT Report 16.

Van den Brink, L., N. Gunadi, R. Wustman, T. K. Moekasan, L. Prabaningrum, A. K. Karjadi, H. Hengsdijk, and A. Pronk. 2016. Results of potato fertilizer demonstrations in Pangalengan and Garut, Indonesia : Wet season 2014/2015 and dry season 2015. Wageningen UR, Wageningen.

Vázquez, N., A. Pardo, M. L. Suso, and M. Quemada. 2006. Drainage and nitrate leaching under processing tomato growth with drip irrigation and plastic mulching. Agriculture, Ecosystems & Environment 112: 313-323.

Wang, J., Z. Hu, X. Xu, X. Jiang, B. Zheng, X. Liu, X. Pan, and P. Kardol. 2014. Emissions of ammonia and greenhouse gases during combined pre-composting and vermicomposting of duck manure. Waste Management 34: 1546-1552.

Ward, M. H., R. R. Jones, J. D. Brender, T. M. de Kok, P. J. Weyer, B. T. Nolan, C. M. Villanueva, and S. G. van Breda. 2018. Drinking Water Nitrate and Human Health: An Updated Review. Int J Environ Res Public Health 15: 1557.

Widowati, L. R., S. De Neve, Sukristiyonubowo, D. Setyorini, A. Kasno, I. A. Sipahutar, and Sukristiyohastomo. 2011. Nitrogen balances and nitrogen use efficiency of intensive vegetable rotations in South East Asian tropical Andisols. Nutrient Cycling in Agroecosystems 91: 131.

Yang, H. S. and B. H. Janssen. 2000. A mono-component model of carbon mineralization with a dynamic rate constant. European Journal of Soil Science 51: 517-529.

Zahra, W. A., C. E. V. Middelaar, I. J. M. de Boer, and S. J. Oosting. 2020. Predicting nutrient excretion from dairy cows on smallholder farms in Indonesia using readily available farm data. Asian-Australas J Anim Sci 33: 2039-2049.

Zahra, W. A. 2021. Improving manure management at smallholder dairy farms in Indonesia: a multi-level analysis. in Animal Production Systems group. Vol. Doctor. Wageningen University and Research, Wageningen, The Netherlands.

Zahra, W. A., M. de Vries, and H. de Putter. 2021. Exploring barriers and opportunities for utilization of dairy cattle manure in agriculture in West Java, Indonesia. in Public Report 1315. Wageningen Livestock Research, Wageningen.

8. Appendix I. Emission factors, characterization factors and fate factors for environmental impact categories

Inputs	**Emission factor**	**Unit**	**Reference**
Diesel	2.75	kg CO_2 eq/l	(Ramachandra, 2009)
Compound NPK	7.62	kg CO_2 eq/kg N	(Kool et al., 2012)
Compound NK	17.2	kg CO_2 eq/kg N	(Kool et al., 2012)
Triple Super Phosphate (TSP)	0.36	kg CO_2 eq/kg P_2O_5	(Kool et al., 2012)
Di-Ammonium Phosphate (DAP)	3.24	kg CO_2 eq/kg N	(Kool et al., 2012)
Potassium chloride (KCl)	0.56	kg CO_2 eq/kg K_2O	(Kool et al., 2012)
N_2O Emissions			
EF1 (Global average vegetable fertilization)	0.94	%	(Rashti et al., 2015)
EF_4 (Wet climate)	0.014	kg N2O–N (kg NH3–N + NOX–N volatilised)-1	(Hergoualc'h et al., 2019)
EF_5	0.011	kg N2O–N (kg N leaching/runoff)-1	(Hergoualc'h et al., 2019)
$Frac_{GASF}$	0.11	(kg NH3–N + NOx–N) (kg N applied)–1	(Hergoualc'h et al., 2019)
$Frac_{GASM}$	0.21	(kg NH3–N + NOx–N) (kg N applied or deposited)–1	(Hergoualc'h et al., 2019)
$Frac_{Leach}$	0.24	kg N (kg N additions or deposition by grazing animals)-1	(Hergoualc'h et al., 2019)

9. Appendix II Overview of scenario's and their inputs

Name scenario	Type amendment	Crop rotation	Organic amendment	Chemical fertilizers [kg/ha]			Organic amendments [kg/ha]			Total N applied	Plant available N
			[t/ha]	N	P2O5	K2O	N	P2O5	K2O	[kg/ha]	[kg/ha]
Baseline	Chicken manure with rice husks (postal)	1	43	289	287	316	860	591	727	1149	926
		2	43	273	247	323	860	591	727	1133	910
		3	48	357	286	393	960	660	727	1317	1067
		4	48	485	500	544	960	660	727	1445	1196
Dairy manure 1	Dairy manure: FYM (solid manure)	1	43	289	287	316	301	197	172	590	512
		2	43	273	247	323	301	197	172	574	496
		3	48	357	286	393	336	220	192	693	606
		4	48	485	500	544	336	220	192	821	734
Dairy manure 2	Diary manure: compost	1	43	289	287	316	344	296	215	633	544
		2	43	273	247	323	344	296	215	617	528
		3	48	357	286	393	384	330	240	741	641
		4	48	485	500	544	384	330	240	869	769
Dairy manure 3	Dairy manure: vermi-compost	1	43	289	287	316	301	394	172	590	512
		2	43	273	247	323	301	394	172	574	496
		3	48	357	286	393	336	440	192	693	606
		4	48	485	500	544	336	440	192	821	734
Dairy manure 4	Dairy manure: feces in sacks	1	43	289	287	316	148	96	791	437	399
		2	43	273	247	323	148	96	791	422	383
		3	48	357	286	393	166	107	883	523	479
		4	48	485	500	544	166	107	883	651	608
Baseline + GAP 1	Chicken manure with rice husks postal	1	43	500	300	400	860	591	727	1360	1136
		2	43	500	300	400	860	591	727	1360	1136
		3	48	500	300	400	960	660	811	1460	1210
		4	48	500	300	400	960	660	811	1460	1210
Baseline + GAP 2		1	43	100	300	400	860	591	727	960	736
		2	43	100	300	400	860	591	727	960	736
		3	48	100	300	400	960	660	811	1060	810
		4	48	100	300	400	960	660	811	1060	810
Baseline + GAP 3		1	27	100	300	400	540	371	456	640	500
		2	27	100	300	400	540	371	456	640	500
		3	27	100	300	400	540	371	456	640	500
		4	27	100	300	400	540	371	456	640	500
Dairy manure 1 + GAP 1	Dairy manure: FYM	1	43	500	300	400	301	197	172	801	723
		2	43	500	300	400	301	197	172	801	723
		3	48	500	300	400	336	220	192	836	749
		4	48	500	300	400	336	220	192	836	749
		1	43	277	300	400	301	197	172	578	500

Dairy manure 1 + GAP 2		2	43	277	300	400	301	197	172	578	500
		3	48	251	300	400	336	220	192	587	500
		4	48	251	300	400	336	220	192	587	500
Dairy manure 1 + GAP 3		1	77	101	300	400	539	353	308	640	500
		2	77	101	300	400	539	353	308	640	500
		3	77	101	300	400	539	353	308	640	500
		4	77	101	300	400	539	353	308	640	500
Dairy manure 2 + GAP 1	Diary manure: compost	1	43	500	300	400	344	296	215	844	755
		2	43	500	300	400	344	296	215	844	755
		3	48	500	300	400	384	330	240	884	784
		4	48	500	300	400	384	330	240	884	784
Dairy manure 2 + GAP 2		1	43	245	300	400	344	296	215	589	500
		2	43	245	300	400	344	296	215	589	500
		3	48	245	300	400	344	296	215	589	500
		4	48	245	300	400	344	296	215	589	500
Dairy manure 2 + GAP 3		1	68	97	300	400	544	467	340	641	500
		2	68	97	300	400	544	467	340	641	500
		3	68	97	300	400	544	467	340	641	500
		4	68	97	300	400	544	467	340	641	500
Dairy manure 3 + GAP 1	Dairy manure: vermi-compost	1	43	500	300	400	301	394	172	801	723
		2	43	500	300	400	301	394	172	801	723
		3	48	500	300	400	336	440	192	836	749
		4	48	500	300	400	336	440	192	836	749
Dairy manure 3 + GAP 2		1	43	277	300	400	301	394	172	578	500
		2	43	277	300	400	301	394	172	578	500
		3	48	251	300	400	336	440	192	587	500
		4	48	251	300	400	336	440	192	587	500
Dairy manure 3 + GAP 3		1	77	101	300	400	539	706	308	640	500
		2	77	101	300	400	539	706	308	640	500
		3	77	101	300	400	539	706	308	640	500
		4	77	101	300	400	539	706	308	640	500

CGIAR

RESEARCH PROGRAM ON
Climate Change, Agriculture and Food Security

CCAFS

The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) brings together some of the world's best researchers in agricultural science, development research, climate science and Earth system science, to identify and address the most important interactions, synergies and tradeoffs between climate change, agriculture and food security. For more information, visit us at **https://ccafs.cgiar.org/.**

Titles in this series aim to disseminate interim climate change, agriculture and food security research and practices and stimulate feedback from the scientific community.

CCAFS is led by:

Alliance

Bioversity International

CIAT
International Center for Tropical Agriculture
Since 1967 Science to cultivate change

CCAFS research is supported by:

CGIAR
Science for a food-secure future

Australian Government
Australian Centre for International Agricultural Research

Irish Aid
An Roinn Gnóthaí Eachtracha agus Trádála
Department of Foreign Affairs and Trade

Ministry of Foreign Affairs of the Netherlands

NEW ZEALAND
FOREIGN AFFAIRS & TRADE
Aid Programme

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development and Cooperation SDC

UKaid
from the British people

USAID
FROM THE AMERICAN PEOPLE

IFAD
Investing in rural people