Improving manure management at smallholder dairy farms in Indonesia: a multi-level analysis

Windi Al Zahra

Invitation

You are kindly invited to
attend the public defence of
my PhD thesis, entitled

Improving manure management at smallholder dairy farms in Indonesia: a multi-level analysis

Windi Al Zahra

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On Tuesday 23rd of November 2021 at 11.00 am

in the Aula of
Wageningen University,
Generaal Foulkesweg 1A,
Wageningen

Paranymphs

Margret Wenker
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Propositions

1. Managing faeces has a higher priority than managing urine on smallholder dairy farms.
   (this thesis)

2. Policies promoting the use of biogas technology at dairy farms are pointless if the integration of such technology into the farms and the creation of an enabling institutional environment are not part of the policies.
   (this thesis)

3. Social media campaigns are more effective than science in improving the sustainability of the palm oil industry.

4. Online teaching hampers Sustainable Development Goal 4.

5. Investing in your own knowledge is more profitable than investing in stocks.

6. Tempeh is a polished gift from Indonesia to the world.

Propositions belonging to the thesis, entitled

Improving manure management at smallholder dairy farms in Indonesia: a multi-level analysis

Windi Al Zahra

Wageningen, 23 November 2021

Improving manure management at smallholder dairy farms in Indonesia: a multi-level analysis

Windi Al Zahra

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This research was conducted under the auspices of the Graduate School of Wageningen Institute of Animal Sciences (WIAS)

Improving manure management at smallholder dairy farms in Indonesia: a multi-level analysis

Windi Al Zahra

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
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To my Dad (Ayah), this PhD is for You

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Chapter 1

General introduction

1. Background

The Indonesian population, which equalled 270 million people in 2020, is projected to increase by 13% to 312 million in 2045 (BPS, 2020a; BPS, 2018a). This growing population increases the demand for food, including animal-source food (e.g., meat, eggs, and milk). Furthermore, like other countries in Asia, Indonesia is shifting towards diets with increased animal-source food (FAO, 2011); the consumption of protein from animal-source food in Indonesia, for example, increased by 80% between 2013 and 2018, from 4.1 to 7.3 g capita^{-1} day^{-1} (BPS, 2019b). This increase in animal-source food consumption has two main causes. First, the growth of the middle-class in the Indonesian population and second, an increased awareness among the Indonesian population that animal-source food is healthy.

The demand for milk increased annually by 9.7% over the period from 2015-2019, and this trend is expected to continue. The demand for milk, however, is not followed by the national milk supply, which grew by 4.8% annually over the last five years. In 2019, the national fresh milk production was only 1.0 million tons, while the demand for milk was 5.9 million tons (liquid milk equivalents). Consequently, national milk production only supports 17% of total milk demand, and the gap in milk demand is filled with milk import (Figure 1). The costs of these milk imports were about one billion USD per year, and were higher than those of other imported animal source-food (e.g., costs of egg imports were about 10 million USD per year; costs of meat imports were about 749 million USD per year) (Kementrian pertanian, 2019).

In Indonesia, national milk production relies on the milk produced by smallholder dairy farms. About 90% of the domestic milk is produced by smallholder dairy farms (Hermawan et al., 2013), whereas

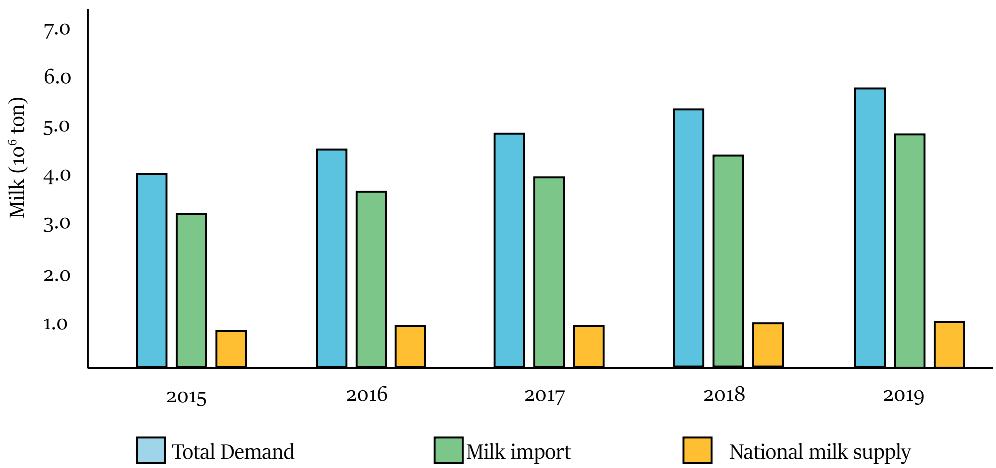

Figure 1. Demand and supply of milk in Indonesia (2015-2019) (Kementrian pertanian, 2019).

the other 10% is produced by industrial large-scale farms. Smallholder dairy farms have, on average, 2-4 dairy cattle that produce 10-14 litres milk per cow per day. Moreover, about 90% of smallholder dairy farms are located in Java island, especially in the highlands (Kementrian pertanian, 2019). The existence of dairy farms in the highlands of Java island is due to a combination of climate, economic growth of the island, and its history.

Java island is the centre of dairy farming in Indonesia. The climate in the highlands of Java island is favourable for raising dairy cattle as temperatures range from 15-24 ^{0}C and humidity ranges from 56-90% (Mariana et al., 2018; Jaenudin et al., 2018; Heraini et al., 2016). The Frisian Holstein is the main breed at Indonesian smallholder dairy farms. The economy of Java island contributes for 60% to the total national gross domestic product (GDP) (BPS, 2020b). In addition, 78% of milk processing industries can be found on Java island (BPS, 2018b). The population on Java island in 2020 was 152 million people, which equals 56% of the total Indonesian population (BPS, 2020a), being a potential market for dairy products. In the following section, I first describe the historical development of dairy farms in Java island.

1.1 The history of dairy farming in Java island

Historically, Indonesia is a non-dairying country. The presence of dairy farming occurred as a response to the milk demand during the Dutch colonial age. At that time, milk was an important part of the diet for the Dutch and hardly found in the tropical environment. The Dutch imported flour to make bread, butter, and cheese from the Netherlands, but not milk, as this is a perishable product. Therefore, they tried to raise dairy cattle and gradually set up dairy farms to produce milk (Booth, 1998; Hartog et al., 1986).

Dairy farming developed mainly on Java island because it was the economic and government centre (Batavia), and most Europeans lived on this island. Figure 2 shows the location of dairy farms in Java island between 1920 to 1940.

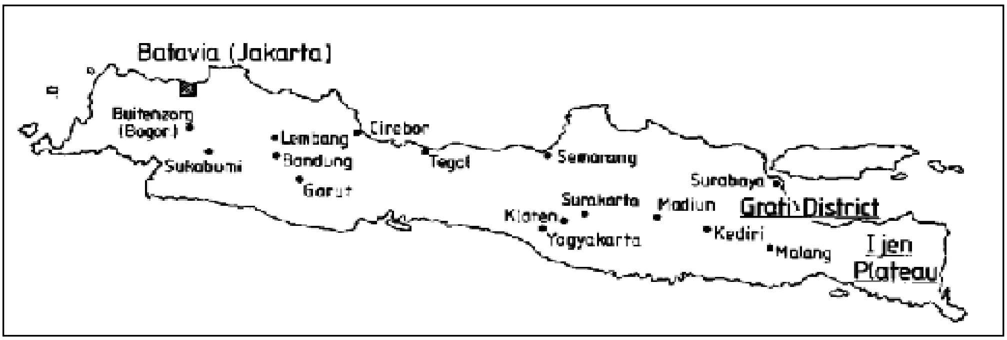

Figure 2. The dots show the distribution of dairy farms regions in Java island (1920-1940). The largest dairy farms in Java island were found in Bandung and Surabaya (Hartog et al., 1986).

Java island has fertile soils and a favourable climate for farming, and most of the agricultural production was for subsistence, with little or no cultivation of cash crops (Figure 3). Java island is big (128,297 km^2; 3 times as big as the Netherlands), and population numbers were low, i.e. 28 million people in the early 1900s (Ricklefs et al., 1981).

Until 1920, most dairy farms were in poor conditions. Cow sheds were dirty, and many farms were located in towns, with only little space for sheds. Fresh milk, furthermore, was not clean, tuberculosis contamination occurred, and manure was discharged directly into the surrounding environment. In those days, farm sizes were medium (about 8 to 10 dairy cows) (Figure 4) to large scale (i.e., in Surabaya there were 40 dairy farms with a total of 1,000 cows in 1923), and the average milk production in Java island was 1,755 litres per cow per year. In 1930, some modern dairy farms were established in Java Island. These modern farms were in the hills and good farming practices were introduced on these farms. At these modern farms, the cow sheds were built on concrete floors, standards of hygiene were met, and a breeding program with Dutch and Australian cross bred cows was introduced (Hartog et al., 1986).

The development of dairy farming activities in Java island was hampered by the economic crisis of the Netherlands in 1930. Many dairy farms were severely impacted by the crisis and disappeared. The sweetened condensed milk invented in 1856 was consumed as an alternative for fresh milk. The price of imported sweetened condensed milk was much lower than for fresh milk and contributed to the decline of fresh milk consumption, gradually diminishing the dairy farms business. The dairy cattle population in Indonesia further declined when the Japanese occupied Indonesia (1942-1945), and the European-owned dairies disappeared. The dairy farms were taken over from the Dutch by Indonesians and the dairy farms were restructured from medium and large-scale farms into smallholder farms (Hartog et al., 1986). Nowadays, smallholder dairy farms are the most dominant dairy farming system in Indonesia.

Figure 3. Agriculture activities in Lembang, Bandung, West Java in 1900 (Source: Southeast Asian & Caribbean Images/ KITLV; 2020).

Figure 4. A dairy farm in Pengalengan, Bandung, West Java in 1930 (Source: Southeast Asian & Caribbean Images/ KITLV; 2020).

1.2 Consequences of increasing dairy cattle population on manure production

As a response to a high demand for milk and low national milk supply, the Indonesian government aims to increase national milk production by increasing milk yield per cow via improving animal health care, improving farm management practices, and by increasing numbers of milk processing industries and the dairy cattle population. Following this policy, the dairy farms will be restructured (i.e., from small to medium dairy farms), shifting from 2-4 dairy cattle per farm to 7 dairy cattle per farm (National Blueprint for milk 2013-2025; Kementrian Pertanian, 2017). Because of this policy, there will be more dairy cattle on Java island, which will have consequences especially on feeding and manure management.

Providing enough feed is important when more cows are to be added to Java island. A higher number of dairy cattle will require more feed. In addition, increasing dairy cattle productivity increases the demand for feed because high productive dairy cattle need more feed per animal. The feed of dairy cattle consists of grass, and purchased feed, such as concentrate and agro-industrial by-products (i.e., tofu waste, cassava waste, and rice straw). As the land for growing home-grown feed (HGF) in Java island is limited, the dairy farmers use relatively high amounts of purchased feed.

Most purchased feeds are not produced on Java island. For example, wheat pollard, being a by-product of the flour industry and one of the ingredients in concentrate feed, is imported from Western Australia. Palm kernel meal, being a by-product from the palm oil industry and one of the ingredients in concentrate feed, is produced in Sumatra island (Indonesia). Soybeans are imported from the USA.

Soybeans are the major input for the tofu production industry which produces as co-product the tofu waste that is used as an ingredient for concentrate feed.

An issue to be mentioned here is food-feed competition. Feeding high amounts of concentrates can increase food-feed competition. Food-feed competition implies that the products being consumed by the dairy cows may compete for resources with the supply of human food (van Hal et al., 2020; van Zanten et al., 2019; Mihailescu et al., 2014). In this case, food-feed competition occurs when the feed that is fed to dairy cows is also suitable for human consumption (e.g., concentrate ingredients) or uses land that could also be used for direct cultivation of human food crops (for example if grass is cultivated on food crop land). Food-feed competition should be avoided because it impedes food security and reduces the amount of nutrients being available for human consumption (van Zanten et al., 2019).

An increase in the number of dairy cows followed by an increase in imported feed products results in various environmental impacts. One of the main impacts relates to the large amount of nutrients being imported into the region. Importing large amounts of nutrients through feed can easily result in excess of nutrients in a region, i.e., when means to recycle nutrients to crop fields are limited, and in nutrients being lost to air, water or soil. Performing proper manure management can help to improve nutrient cycling and to reduce nutrient losses. Manure management is the core of this thesis and will be elaborated further in the next sections.

1.3 The importance of manure management

The increase of the dairy cattle population has a significant impact on manure production at a farm. Manure is an inevitable by-product of dairy production. The nutrients from the feed, consumed and digested by the animals, are converted into energy, and being used to maintain body temperature and perform other metabolic functions (i.e., maintenance, milk and meat production, and reproduction). The nutrients that are not used for those functions, end in manure, consisting of a solid part (faeces or dung which consists for a major part of undigested feed) and a liquid part (urine). As the nutrient composition in faeces and urine differs (Bonten et al., 2014; Horn et al., 2007; Valk et al., 2002; NRC 2001), and management practices may vary between the solid and liquid part, it is important to consider faeces and urine separately.

Manure has number of benefits if it is appropriately managed. The nutrient content of manure is primarily composed of nitrogen (N), phosphorus (P), and potassium (K), which are essential elements for plant growth. N is a significant nutrient for plants and plays a role in various critical physiological processes (i.e., growth and development) (Hao et al., 2020; Leghari et al., 2018; Torres-Olivar et al., 2014) and is the most important factor for biomass production (Li et al., 2016; Brennan et al., 2007). Next to N, P is a vital element for plant growth, and stimulates seed germination, root development, and seed formation (Malhotra et.al., 2018; Schroder et al.,2010). K is also essential for plant development, as it is required during growth, and contributes to crop yields (Sardans et al., 2021; Kumar et al., 2020). In addition, adding manure to the soil is very relevant for maintaining the soil organic matter content, and for minimizing the risk of soil depletion. Long-term application of manure improves the quality and fertility of the soil and contributes to sustainable soil productivity (Shiwakoti et al., 2020; Hua et al., 2020; Wang et al., 2018).

However, high manure production followed by improper manure management impacts the environment. The losses of nutrients from manure, mainly N and P, are harmful to water bodies (rivers, lakes, and ground water) as they contribute to eutrophication. Eutrophication of waterbodies is an excessive richness of nutrients in the water which causes a dense growth of plants and algae. Eutrophication occurs either naturally or as an impact of anthropogenic activities, such as applying excess fertiliser to crops, and discharging urban waste and animal manure into the water. Eutrophication harms water-use for fisheries and impacts terrestrial and aquatic biodiversity (Biagni et al., 2018; Adenuga et al., 2016; WHO 2016; Chislock et al., 2013; Anzai et al., 2006; NRC 2001). Apart from eutrophication, improper manure management may cause that groundwater becomes unsuitable for drinking due to nitrate (NO_3^-) pollution. The excess of NO_3^- in drinking water can cause harmful biological effects such as methemoglobinemia, hypertension, infant mortality, stomach cancer, thyroid disorder, cytogenetic defects, and congenital disabilities (Sahoo et al., 2006; Höring et al., 2004).

In addition, during the storage, treatment, application and deposition of manure, gases can emit into the environment. The emissions of methane (CH_4), direct and indirect emissions of nitrous oxide (N_2O), ammonia (NH_3) and nitrogen oxides (NO_x) are released during the storage, treatment, and application of manure (IPCC, 2019; Vanderzaag et al., 2013). Direct N_2O emission occurs via combined nitrification and denitrification activities of N from manure during storage, treatment, and application. Indirect N_2O emission results from volatile N losses that occur primarily in the forms of NH_3 and NO_x, and runoff and leaching into the soil in the form NO_3^- (Wang et al., 2019; IPCC, 2019; Velthof et al., 2010). Globally, manure management on dairy farms contributes to 26.5 % of total greenhouse gas emissions (GHGE) along the dairy value chain (Gerber et al., 2013).

Since manure is produced at dairy farms, it must be managed appropriately to avoid these adverse environmental impacts. High manure production on smallholder dairy farms is often not followed by proper manure management practices. A study of de Vries et al. (2017) showed that an alarming 80% of manure from smallholder dairy farms in Indonesia is being discharged, indicating only a small proportion of manure is being managed. The above-mentioned environmental problems related to the production and use of manure at dairy farms and the fact that manure management at smallholder dairy farms is lacking are reasons for which improvements in manure management are needed.

2. Knowledge gaps

Improving manure management is important especially when the dairy cattle population is expected to increase further. To improve manure management at smallholder dairy farms, information about the N-P excretion of dairy cattle is first needed. Quantification of N-P is crucial because both managed and unmanaged N-P lead to environmental emissions. Mathematical models are often used to predict N-P excretion of dairy cows. Most N-P excretion models, however, are developed for dairy farming systems in developed countries, and not for smallholder systems in Indonesia. A generic model to predict N-P excretion of dairy cows on smallholder dairy farms is not available.

Information on N-P excretion can subsequently be used to estimate the flows and losses of nutrients on smallholder dairy farms. Flows and losses in dairy farming systems, however, may also depend on manure management system (MMS). Different MMSs exist in smallholder dairy farms in Indonesia (de Vries et al., 2017). So far, it is unknown how nutrient flows and losses differ across systems. Furthermore, it is unknown to what extent the dairy sector contributes to the pollution of the Citarum river, being the longest river in the province of West Java (Garg et al., 2018; Yoshida et al., 2017; Kerstens et al., 2013). Though the dairy sector is presumed to contribute to the pollution of this river, its exact contribution is so far unknown.

Whereas estimating N-P losses is relevant with regard to local environmental impacts such as eutrophication and contamination of drinking water, climate change happens at a global scale, and quantification of GHGE therefore requires a value chain level approach. So far, most studies that assessed GHGE on smallholder farms in tropical regions used data collected at one particular moment in time (i.e., cross-sectional observation) or used data based on farmers' recall. The climate of Indonesia, however, is characterized by a dry and a rainy season, and dairy farmers adapt their practices to these seasons, mainly with regard to feeding and manure management. Such seasonal differences can be an important source of variability in estimates of the GHGE-intensity (GHGEI) i.e. the GHGE per kg milk. Longitudinal studies could provide insight into the impact of seasonal differences on GHGEI estimates, and into the implications of the number of farm visits on the accuracy of the estimate but are currently not available.

In order to reduce GHGE from dairy farms, insight into the impact of mitigation strategies is needed. An important mitigation strategy proposed is increasing milk yield per cow. This strategy is promising because there is a non-linear negative association between milk yield and GHGE per unit of milk output (Gerber et al., 2011). However, this strategy often appears difficult to adopt at smallholder dairy farms because it requires a combination of improving feed supply and quality, improving animal health and cow fertility, and improving genetic potential. Therefore, alternative strategies for mitigating GHGE are required. So far, however, strategies to reduce GHGE from smallholder dairy farms in Indonesia beyond milk yield increases are unexplored.

Proper manure management is presently not well adopted at Indonesian smallholder farms and the adoption is probably having diverse constraints. The nature of these constraints for proper manure management in Java is unknown. Understanding these constraints and what prevents them from being resolved may contribute to policy making for improving manure management at the farm level and subsequently decreasing environmental impacts at the regional level.

3. Multi-level analysis to improve manure management

Improving manure management at smallholder dairy farms involves many aspects (e.g., feeding type and composition, the physiological stage of the animals, land for storing manure and applying manure, costs for manure management etc). The knowledge about many of these aspects is lacking. Hence, in this thesis, I analyse such aspects related to manure management and I will do this at different aggregation levels (i.e., the animal, farm, regional, and value chain level).

Many studies investigated the relevance of manure management specific at only one level. Studies of Qu et al. (2017), Alvarez-Fuentes et al. (2016), and Reed et al. (2015) provided models to estimate nutrient excretion from dairy cows in order to evaluate nutrient use efficiency at animal level. Studies of Mihailescu et al. (2015) estimated nutrient balances from dairy farms in order to improve nutrient use efficiency at farm level. Studies of Wilkes et al. (2020) and Chadwick et al. (2011) analysed the relevance of manure management to GHGE at value chain level. The study of Ndambi et al. (2019) analysed manure management practices in Sub-Saharan Africa and the relevant policies in order to improve manure management at regional level.

When the analysis is done as a multi-level analysis, it gives a broad and rich insight into potential solutions in improving manure management at smallholder dairy farms. An example of a multi-level study is the one by Šebek et al. (2014), that analysed factors effecting nutrient excretion from livestock at animal level and at different EU countries (regional level). The study, furthermore, assessed the implications of nutrient excretion from livestock to estimate N balances (at farm level) and GHGE (at value chain level). The study of Šebek et al. (2014) illustrates the fact that a multi-level study gives broad and rich insights. They for example stated that improvement options at animal level may affect environmental impacts at other levels (i.e., farm, value chain, and regional level) and there could be trade-offs but also synergies among improvement options at different levels. For this reason, I did a multi-level analysis in my studies. In a multi-level analysis, the multi-level hierarchy is considered (van Passel et al., 2012). For example, the animal is part of the farm, and improvement at this level will affect the whole farm. A farm belongs to a value chain, and improvement at the farm level affects the whole value chain. Therefore, performing a multi-level analysis of a system provides insight into improvement options at different aggregation levels which can be used to support decision making for all aggregation levels combined. Figure 5 shows a schematic overview of the multiple levels of analysis of manure management at smallholder dairy farms addressed in this thesis.

In the following paragraphs, I describe the evaluation of the emissions to the environment related to manure management at aggregation level. At animal level, the evaluation is focused on the quantity of nutrients excreted by a dairy cow, in faeces and/or in urine, together referred to as manure. At the animal level, the aspects related to manure management include feed (i.e., purchased feed and forage), production of milk and calves and production of manure. Nutrients (N-P) flow into the animal via feed and nutrients flow out from the animal via milk, calves and manure. The nutrients in the feed that are not taken up either for maintenance or to produce milk, body weight gain or calves end up in manure.

At farm level, the evaluation is focused on nutrients flows in-out from a group of dairy cows in a farm. At farm level, nutrients flow from the soil via nutrients in inorganic fertilizer and manure to the crop. The crop is fed to the dairy cows and manure is returned to the soil. Manure management has an important role in determining the flow of nutrients at a farm. Four different MMSs are recognized at smallholder dairy farms in Lembang: 1) applying manure directly on forage land, without treatment, 2) selling or exporting manure, 3) using manure as substrate for anaerobic digestion, and 4) discharging manure. At farm level, the nutrient balances are determined by the inflow of the farm via inorganic fertilizer and purchased feed and the nutrient outflow of the farm via milk, livestock, and manure. Improper manure management affects the nutrient balances of a farm. Furthermore, at farm level there are constraints hampering proper manure management.

The purchased feed and inorganic fertilisers being used at farm level are produced at dairy value chain level. The production of purchased feed and inorganic fertilisers at value chain level emit environmental impacts at a global scale (i.e., GHGE). Hence, at value chain level, the evaluation from cradle up to farm gate is focussed on the assessment of GHGE from dairy activities in the farm in total. These are subdivided into up-stream and on-farm activities. The GHGE from up-stream activities consists of those from the production, processing, and transportation of purchased feeds and inorganic fertilizer to the farm. The GHGE from on-farm activities consists of those from management of the dairy herd, manure management, and forage cultivation.

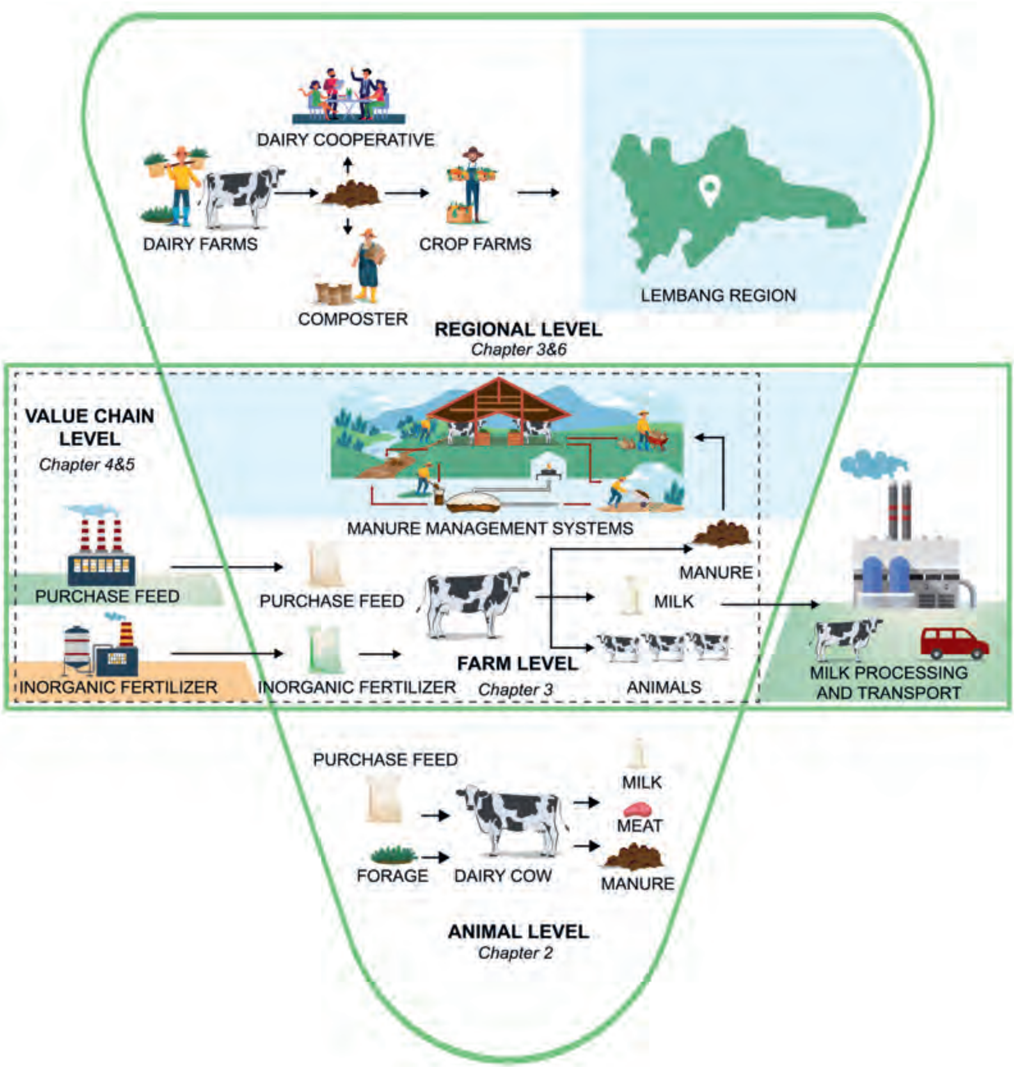

Figure 5. A schematic overview of the multiple levels of analysis of manure management at smallholder dairy farms; the dashed line at the value chain level indicates that the study at the value chain level is performed from the cradle up to the farm gate.

At regional level, the evaluation is focused on the potential risk related to nutrient imbalances associated with manure produced from all dairy farms in the region. The nutrient imbalances at farm level times the number of farms in the region, determine the nutrient imbalance at regional level. In addition, solutions to overcome constraints on manure management can be done at the regional level, for example if farmers and other stakeholders have to collaborate. Hence, at regional level, the aspects of importance are nutrient balances from dairy farms, the number of farms in the region, the constraints and their solutions for proper manure management, and stakeholders related to manure management.

4. Aim

This thesis aims to evaluate emissions to the environment associated with manure management and to identify improvement options on smallholder dairy farms in Indonesia.

5. Outline of the thesis

5.1 Thesis structure

The structure of this thesis is shown in Figure 6. A generic model to accurately predict N-P excretion from a dairy cow on smallholder farms in Indonesia based on readily available farm data was developed at animal level **(Chapter 2)**. At farm level, nutrient flows, and balances of dairy farms with different MMSs were quantified and the results were scaled to the regional level to determine the sector's contribution to the pollution of the Citarum river. The Citarum river is heavily polluted by the untreated waste disposal from industries, households, and livestock, including dairy farms **(Chapter 3)**. An approach to better estimate GHGEI that considers variation in farm management practices and seasonal changes was developed at farm and value chain level. A longitudinal observation approach followed by a linear mixed model were used to address variability of GHGEI **(Chapter 4).** Moreover, at value chain level, mitigation strategies to reduce GHGE, beyond the strategy of milk increases, were explored **(Chapter 5)**. At farm and regional level, constraints on manure management were investigated **(Chapter 6).** Finally, in **Chapter 7**, the main findings of all chapters are presented, methodological issues and potential improvements are discussed, and, suggestions to create an enabling environment for better manure management are proposed **(Chapter 7).**

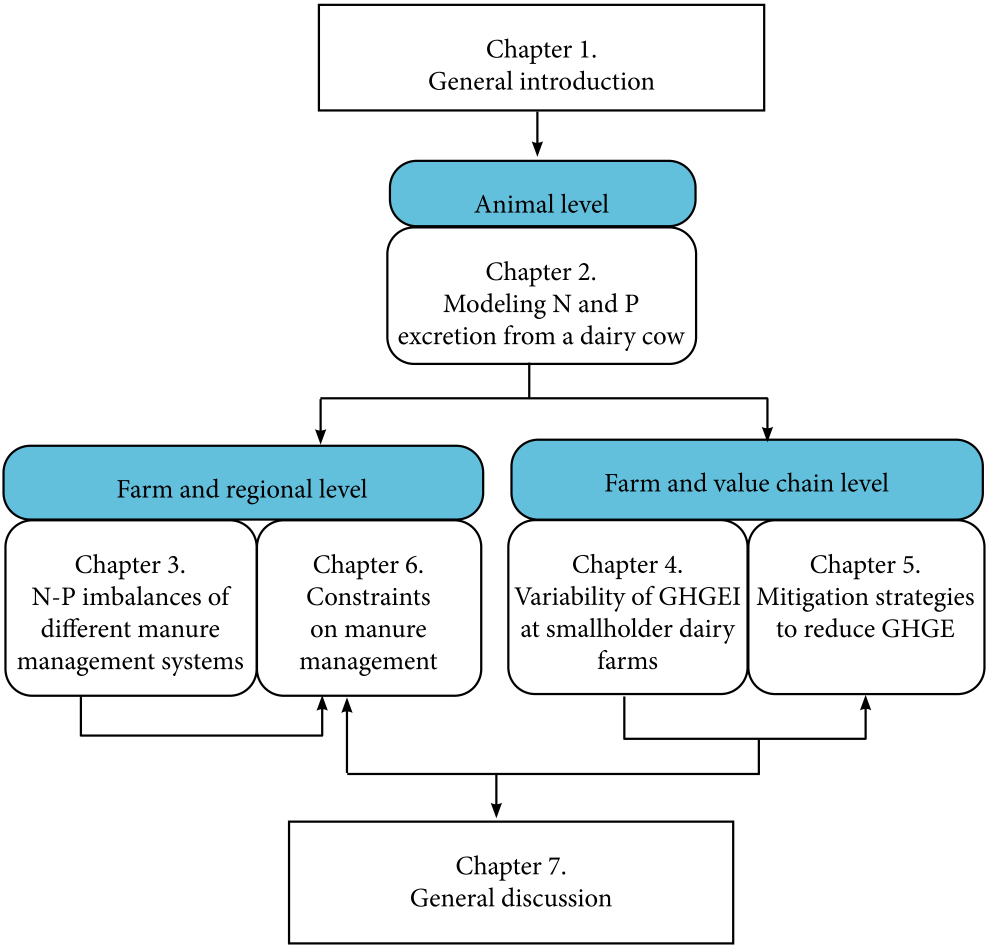

Figure 6. The structure of the thesis.

5.2 Study site

The study was conducted in the Lembang sub-district, West Java Province, Indonesia. This district is one of the largest clusters of smallholder dairy farms in West Java and represents 43% of milk production in West Java. At national level, this district supplies 14% of the national milk production. There are about 29,000 dairy cattle in this area, producing about 150 tons of milk per day (Kementrian Pertanian, 2019). The district is located in the highlands (1,250 m above sea level). The average daily temperature of this area ranges from 19.6 to 29.3°C, humidity ranged from 64 to 81%, and rainfall ranged from 867 to 1,742 mm per year. The district covers 9,560 ha and has 196,690 inhabitants. Agriculture is an important sector in this area, because 20% of the inhabitants work in the agriculture sector (crops, livestock, plantation, and forestry). The cropland occupies 35% of the total area (BPS,

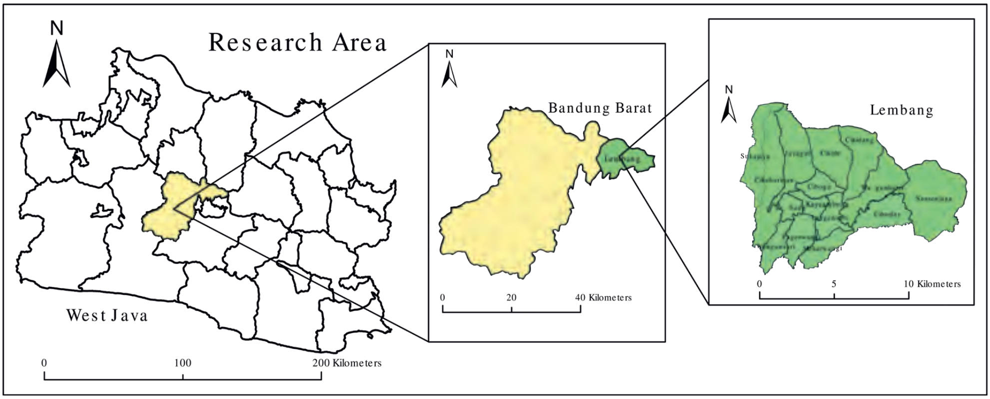

Figure 7. Study site, the Lembang sub-district, West Java, Indonesia.

Chapter 2

Predicting nutrient excretion from dairy cows on smallholder farms in Indonesia using readily available farm data

Manure application at the Lembang region

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Abstract

This study was conducted to provide models to accurately predict nitrogen (N) and phosphorus (P) excretion of dairy cows on smallholder farms in Indonesia based on readily available farm data. The generic model in this study is based on the principles of the Lucas equation, describing the relation between dry matter intake (DMI) and faecal N excretion to predict the quantity of faecal N (Q_{FN}). Excretion of urinary N and faecal P were calculated based on National Research Council recommendations for dairy cows. A farm survey was conducted to collect input parameters for the models. The data set was used to calibrate the model to predict Q_{FN} for the specific case. The model was validated by comparing the predicted quantity of faecal N with the actual quantity of faecal N (Q_{FNACT}) based on measurements, and the calibrated model was compared to the Lucas equation. The models were used to predict N and P excretion of all 144 dairy cows in the data set. Our estimate of true N digestibility equalled the standard value of 92% in the original Lucas equation, whereas our estimate of metabolic faecal N was −0.60 g 100 g^{-1} DMI, with the standard value being −0.61 g 100 g^{-1} DMI. Results of the model validation showed that the R^2 was 0.63, the MAE was 15 g $animal^{-1}$ d^{-1} (17% from Q_{FNACT}), and the RMSE was 20 g $animal^{-1}$ d^{-1} (22% from Q_{FNACT}). We predicted that the total N excretion of dairy cows in Indonesia was on average 197 g $animal^{-1}$ d^{-1}, whereas P excretion was on average 56 g $animal^{-1}$ d^{-1}. The proposed models can be used with reasonable accuracy to predict N and P excretion of dairy cattle on smallholder farms in Indonesia, which can contribute to improving manure management and reduce environmental issues related to nutrient losses.

1. Introduction

The number of dairy cattle in Indonesia has increased from 503,000 in 2014 to 550,000 in 2018 due to an increase in the demand for milk and a governmental decision to support the growth of the national dairy sector (Kementrian Pertanian, 2018). This increase in dairy cattle, mainly kept on smallholder dairy farms, has enhanced the negative consequences associated with the lack of manure management on those farms, resulting in large amounts of discharged manure. Because dairy production in Indonesia is concentrated in regional clusters, this discharge of manure leads to high concentrations of nitrogen (N) and phosphorus (P) in local rivers and groundwater of densely populated areas, impacting human health and natural ecosystems (Biagni et al., 2018). Manure management on smallholder dairy farms must be improved to reduce those negative consequences. Approximately 84% of the smallholder dairy farms in Indonesia discharge at least part of their manure into the environment (de Vries et al., 2017). While the urinary or liquid fraction is totally discharged, part of the solid fraction may be collected and sold to manure traders, crop or flower farmers, or used on the farm itself, i.e., as organic fertiliser or to produce biogas for cooking. In some cases, the solid manure fraction is composted before being sold or applied as fertiliser.

To improve manure management, information about N and P excretion of dairy cattle is needed. This information can be used to estimate nutrient losses from different manure treatment options and to quantify differences in nutrient use efficiency among farms and manure management systems. To accurately predict related environmental problems and losses of N and P, the N and P excretion in faeces and urine should be calculated separately. This separation between faecal and urinary fraction is important, because these fractions are differently managed at the Indonesian dairy farms. Moreover, the nature of losses differs between both manure fractions: ammonia volatilization is much higher for the urinary than for the faecal fraction (Laubach et al., 2013).

Quantifying N and P excretion from dairy cattle can be done by different methods, including actual measurements (e.g., in feeding trials) or by means of mathematical modelling. Both methods have advantages and drawbacks. Feeding trials are generally used to analyse the digestibility of individual feed ingredients and complete diets, providing an accurate estimate of N and P excretion (Knowlton KF et al., 2010). This approach, however, is laborious, expensive, and difficult to scale to the level of a dairy farm. Mathematical modelling offers a method to predict N and P excretion using on-farm data, including animal and dietary characteristics (Qu et al., 2017; Ge´rard-Marchant et al., 2015; Nennich et al., 2005). A linear regression equation with dry matter intake (DMI) and crude protein (CP) intake was used to predict the N excretion of Chinese Holstein dairy cows (Qu et al., 2017). Similarly, a linear function of DMI and P intake (PI) was used to estimate P excretion in high productivity lactating Holstein dairy cows (Nennich et al., 2005). Mathematical models may be useful to predict N and P excretion on dairy farms, but many of these models are developed based on input-output relationships that are applicable only to the specific condition under which the input-output model was assessed. Hence, such models may not be suitable for the Indonesian situation, because of differences not just regarding dietary composition and animal productivity, but also regarding, among others, environmental factors, breed, and production level which can have a substantial effect on the relation between feed intake and N and P excretion (Weiss et al., 2007). So far, a generic model to predict N and P excretion of dairy cows on smallholder farms in Indonesia is not available. Therefore, this study aims to provide models to accurately predict N and P excretion of dairy cows on smallholder farms in Indonesia based on readily available farm data. In this study, we calibrated and evaluated a generic model to predict faecal N excretion and we subsequently applied this model in combination with existing guidelines to predict N and P excretion in faeces and urine for 144 cows on 30 smallholder dairy farms in Indonesia.

2. Methods

The generic model in this study is based on the principles of the Lucas equation, describing the relation between DMI and faecal N excretion (Krizsan et al., 2014; Weisbjerg et al., 2004; Van Soest et al., 1994; Lucas et al., 1964). In addition, we used the guidelines of the National Research Council (NRC) to calculate the daily N and P requirements of dairy cows (NRC, 2001), which were then used to calculate the excretion of urinary N and faecal P. The following section describes the model and guidelines. Subsequently, a description of the collection of farm data is provided, followed by a description of the calibration and evaluation of the faecal N model. Finally, we illustrate the reliability of the models by presenting the effective sample sizes required to identify a difference between treatments.

2.1 Modelling N excretion

The Lucas equation describes the apparent digestibility of nutrients, independent of the feed, based on true digestibility, and the endogenous loss of that nutrient in the faeces, (equation 1a) and is widely used in nutrient digestibility studies for ruminants, but most for protein and N (Krizsan et al., 2014; Weisbjerg et al., 2004; Van Soest et al., 1994; Lucas et al., 1964). The general Lucas equation for N is:

$$DN = m\ TN + b \qquad \text{(eq.1a)}$$

where DN is the concentration of digestible nitrogen in ingested dry matter (g 100 g^{-1}), TN is the concentration of total nitrogen in ingested dry matter (g 100 g^{-1}), the slope (m) is the true digestibility of the protein in the feed (fraction) and the intercept (b) is the concentration of endogenous N in ingested dry matter (g 100 g^{-1}). If we multiply the left and right-hand-side of equation (1a) with DMI (g $animal^{-1}$ d^{-1}), we get equation 1b.

$$DNI = (m \times TNI) + (b \times DMI) \quad \text{(eq.1b)}$$

where DNI is the digestible N intake (g animal^{-1} d^{-1}), and TNI is the total N intake (g animal^{-1} d^{-1}).

This reformulated Lucas equation enables prediction of the quantity of N in faeces (Q_{FN}) (g animal^{-1} d^{-1}) since Q_{FN} is the difference between total N intake (TNI) and digestible N intake (DNI), equation 2a:

$$Q_{FN} = TNI - DNI \quad \text{(eq.2a)}$$

Subsequently, we substitute DNI in equation (2a) by the reformulated Lucas equation (1b), yielding our equation to predict the quantity of faecal N given in equation (2b or 2c):

$$Q_{FN} = TNI - [(m \times TNI) + (b \times DMI)] \quad \text{(eq.2b)}$$
$$Q_{FN} = [(1-m) \times TNI] - (b \times DMI) \quad \text{(eq.2c)}$$

The quantity of urinary N (Q_{UN}) (g animal^{-1} d^{-1}) can subsequently be calculated by subtracting total N retained (N_{Ret}) (g animal^{-1} d^{-1}) for producing milk, pregnancy, growth and scruf protein, and Q_{FN} (g animal^{-1} d^{-1}) from the total N intake (TNI) (g animal^{-1} d^{-1}), given in equation 3.

$$Q_{UN} = TNI - N_{Ret} - Q_{FN} \quad \text{(eq.3)}$$

Subsequently, the quantity of total N in manure (Q_{TN}) (g animal^{-1} d^{-1}) is calculated as the sum of Q_{FN} (g animal^{-1} d^{-1}) and Q_{UN} (g animal^{-1} d^{-1}), given in equation 4.

$$Q_{TN} = Q_{FN} + Q_{UN} \quad \text{(eq.4)}$$

The N_{Ret} (g animal^{-1} d^{-1}) can be calculated for lactating, dry cows and young cows based on the NRC guidelines (NRC 2001). The scurf protein consists of protein loss from skin, skin secretions, and hair, and is calculated as $0.3 \times BW^{0.60}$ (Live weight). The retained N for milk production equals N in milk (N_{Milk}) (g animal^{-1} d^{-1}) and is calculated by multiplying the daily milk production (g animal^{-1} d^{-1}) with the protein concentration of milk, divided by 6.38 which is the conversion factor from milk protein to N. The retained N for foetal growth in a pregnant animal (N_{Preg}; g animal^{-1} d^{-1}) is calculated by dividing the metabolizable protein requirement for pregnancy (MP_{Preg}) by 6.25. For cows between 190 to 279 days of pregnancy, MP_{Preg} is computed as:

$$MP_{Preg} = [(0.69 \times \text{days in pregnancy}) - 69.2 \times (CBW/45)]/Eff_{MPPreg} \quad \text{(eq.5)}$$

where, CBW is calf birth weight (kg), and Eff_{MPPreg} is the efficiency of use of metabolised protein (MP) for pregnancy, which is assumed to be 0.33.

For our model we assume that N retained for growth (N_{Growth}) of lactating and dry cows is zero. In young cows, N_{Growth} (g animal^{-1} d^{-1}) is estimated by dividing the metabolizable protein for growth (MP_{Growth}) by 6.25. The MP_{Growth} is computed based on equation 6:

$$MP_{Growth} = NP_g/(0.834-(EQSBW\times0.00114) \qquad \text{(eq.6)}$$

where NP_g is net protein for gain and is calculated from SWG×(268−[29.4×(RE/SWG)]). SWG is the shrunk weight gain and is assumed to equal $13.9\times NE_{Growthdiet}{}^{0.9116}\times EQSBW^{-0.6837}$. $NE_{Growthdiet}$ is the net energy requirement for growth available (Mcal/d) and calculated as $(0.84\ BW^{0.355}\times WG^{1.2})\times0.69$. BW is the current live weight of an animal (kg) and WG is the weight gain per animal (g d^{-1}). EQSBW is the equivalent shrunk body weight and is calculated as SBW×(478/MSBW). SBW is shrunk body weight (animal weight after an overnight fast without feed or water) and being set at 96% of the current live weight. MSBW is the mature shrunk body weight and being set at 96% of the expected mature live weight (MW). The retained NE (RE) (Mcal d^{-1}) is assumed to equal $0.0635\times EQEBW^{0.75}\times EQEBG^{1.097}$. EQEBW is equivalent empty body weight (weight without ingesta), and assumed to equal 0.891×EQSBW. EQEBG is the equivalent empty body weight gain, being calculated as 0.956×SWG.

2.2 Modelling P excretion

Unlike N that is in faeces and urine, P is mainly in faeces. The P that is contained in urine of dairy cows is minimal and, therefore, can be neglected (Alvarez-Fuentes et al., 2016; Valk et al., 2002; NRC, 2001). The daily quantity of P excreted via faeces (Q_{FP}; g animal^{-1} d^{-1}) is calculated as the differences between daily PI (g animal^{-1} d^{-1}) and P retained (P_{Ret}; g animal^{-1} d^{-1}) for milk production, pregnancy, and growth per day (equation 7). To calculate PI (g animal^{-1} d^{-1}), information about DMI (g animal^{-1} d^{-1}) and P concentration of the ingested DM (g kg^{-1}) is required (equation 8).

$$Q_{FP} = PI-P_{Ret} \qquad \text{(eq.7)}$$

$$PI = DMI\times P\ \text{concentration of ingested DM} \qquad \text{(eq. 8)}$$

The retained P for milk production equals P in milk (P_{Milk}; g animal^{-1} d^{-1}) and is calculated by multiplying the daily milk production (kg animal^{-1} d^{-1}) with the P concentration of milk (g kg^{-1}). P retention for pregnancy (P_{Preg}; g animal^{-1} d^{-1}) is calculated for cows in 190 to 279 days pregnancy based on equation 9:

$$PPreg = 0.02743e^{(0.05527-0.000075t)\ t} - 0.02743e^{(0.05527-0.000075(t-1))\ (t-1)} \qquad \text{(eq. 9)}$$

where t is day of gestation.

The retained P for growth (P_{Growth}) of lactating and dry dairy cows is assumed to be zero. In young cows, P retention for growth (P_{Growth}; g animal^{-1} d^{-1}) is estimated based on equation 10:

$P_{Growth} = [1.2+(4.635\times MW^{0.22})\times(BW^{-0.22})]\times(WG/0.96)$ (eq. 10)

where the MW is the estimated expected mature live weight per animal (kg), BW is current live weight per animal (kg), and WG is the weight gain per animal (g d^{-1}).

2.3 Data collection

A farm survey was conducted to collect data for model calibration to predict N and P excretion of dairy cows in Indonesian smallholder farms. The survey was conducted in December 2017 in the Lembang district, West Java, Indonesia. This district is known as one of the largest clusters of smallholder dairy farms in Indonesia. We selected 30 out of the 300 dairy farms which participated in a baseline survey conducted within the project Sustainable Intensification Dairy Production in Indonesia (de Vries et al., 2017). The district has approximately 5,000 dairy farms. The selection of the 30 farms was purposively done to include four distinct manure management systems. However, the difference in manure management systems is not relevant for this paper, and, therefore, will not be discussed here. All farmers were members of a dairy cooperative in Lembang, West Java.

The input parameters to calibrate and evaluate the models to predict N and P excretion were the animal's diet and production stage including herd composition (lactating, dry, and young cows), daily milk yield, manure composition and the live weight of the animals (Table 1). The number of days in pregnancy for dry cows was provided by the farmers during the interview (range from 210 to 240 days). The live weight (BW) of each cow was estimated based on the hearth girth using the Schoorl equation (Kusuma et al., 2017). Information about calf birth weight (CBW), expected mature live weight (MW) and weight gain (WG) was not available from the survey and, therefore, was estimated based on literature representing the Indonesian situation. CBW per animal was assumed to be 40 kg [Aprily et al., 2016], MW per animal was assumed as 500 kg, and WG per animal was assumed to equal 450 g d^{-1} (Salman et al., 2014).

The feed for the animals was offered three times daily (i.e., in the morning, at noon and in the afternoon) and the quantity of offered feed (g $animal^{-1}$ d^{-1}) was measured at each feeding time using a weighing scale. The net individual diet on fresh weight basis (g $animal^{-1}$ d^{-1}) was determined based on the difference between feed offered and feed left-over with the latter being collected the day after before the first feeding time. The feed leftover comprised the roughages only. At each farm we collected feed samples of all feeds offered such as roughages, compound feed, and agro-industrial by-products. Dry matter (DM), ash, CP, and P concentration of each feed product of each farm were measured in the laboratory.

During the farm survey, from each lactating cow we measured daily milk production (g $animal^{-1}$ d^{-1}) using a weighing scale and we collected a milk sample twice a day during milking time (morning

Table 1. Input parameters to calibrate and evaluate the models to predict nitrogen (N) and phosphorus (P) excretion on smallholder dairy farms.

Input parameters	Data required	Method
Feed intake	Type of feed	Interview with the farmers
	Daily feed intake in fresh weight basis per animal class	On-farm measurement
	Concentration of: • Dry matter • Ash • Crude protein	Laboratory analysis[1)]
	Daily feed intake on dry matter basis per animal class	Daily feed intake in fresh weight basis × DM concentration of diet
	Concentration of digestible dry matter	Literature (Feedipedia, 2019; Tatra et al., 2005)
Feed requirement	Nitrogen for producing milk (NMilk) Nitrogen for pregnancy (NPreg) Nitrogen for growth (NGrowth) Phosphorus for producing milk (PMilk) Phosphorus for pregnancy (PPreg) Phosphorus for growth (PGrowth)	(NRC, 2001)
Milk	Daily milk yield	On-farm measurement
	• N concentration of milk • P concentration of milk	Laboratory analysis[1)]
Manure	Concentration of • Dry matter • N • P	Laboratory analysis[1)]
BW[2)]	Heart girth of the animal	On-farm measurement

[1)] Laboratory analysis was conducted at Faculty of Animal Science IPB University, Indonesia.
[2)] Live weight.

and afternoon). Each milk sample was analysed for N and P concentration (g kg^{-1}). Furthermore, a sample of fresh faeces was collected from each farm for analysis of DM, N, and P concentration (g kg^{-1}).

The laboratory analysis of DM concentration of the feed samples was determined by drying at 105 °C until constant weight and ash was determined by ashing at 600 °C. We assumed that the nutritional composition of feeds was similar for offered feed and feed left-overs. The DM concentration of the fresh faeces was determined in a 105°C drying process. The N analysis was done by using the standard Kjeldahl method. The N value was multiplied by 6.25 for feed and faeces, and by 6.38 for milk to determine the protein concentration. The P concentration was analysed using a titrimetric method for the feed sample and a microcolorimetric method for the milk and faeces sample. The laboratory analysis of feed, milk, and faeces was conducted in the Faculty of Animal Science, IPB University, Indonesia.

2

2.4 Model calibration and evaluation

The farm data were used to calibrate and evaluate the Q_{FN} model. To calibrate the Q_{FN} model for the Indonesian context, the data set was divided into a training data set (3/5 of the total data set) and a testing data set (the remaining 2/5). The training data set was used to estimate the intercept and the slope of equation (1a) (Table 2). The testing data set was used for model evaluation. The training and testing data were randomly selected.

As the first step of model evaluation, we predicted the quantity of N in the faeces (Q_{FNPRED}; g animal^{-1} d^{-1}) using equation (2c). Following this, we compared the values of Q_{FNPRED} with the actual measurement of faecal N from the independent data set (Q_{FNACT}; g animal^{-1} d^{-1}). The Q_{FNACT} values were calculated by multiplying the values of indigestible DMI (IDMI; g animal^{-1} d^{-1}) (Table 2) with the N concentration in faeces (g kg^{-1}) that was obtained from the laboratory analysis (Table 1). Finally, the proposed Q_{FNPRED} model was statistically evaluated against the Q_{FNACT} by using the mean average error (MAE) in equation 11 and the root mean square error (RMSE) in equation 12. Both RMSE and MAE were presented as absolute and as relative value. The mean square error (MSE) consists of the bias error, the slope error, and the random error (Bibby J and Toutenburg H, 1977). A low score of MAE and RMSE indicates a better model performance.

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}(X_{observation} - X_{prediction}) \qquad \text{(eq. 11)}$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_{observation} - X_{prediction})^2} \qquad \text{(eq. 12)}$$

Table 2. Parameters and equations to calibrate and evaluate the Q_{FN} model.

Parameters	Equations
DMI (g animal^{-1} d^{-1})	The net daily feed intake in fresh weight basis (g animal^{-1} d^{-1}) × DM concentration (g kg^{-1})
DDMI (g animal^{-1} d^{-1})	DMI (g animal^{-1} d^{-1}) × DDM concentration (g kg^{-1})
IDMI (g animal^{-1} d^{-1})	DMI (g animal^{-1} d^{-1}) – DDMI (g animal^{-1} d^{-1})
TNI (g animal^{-1} d^{-1})	DMI (g animal^{-1} d^{-1}) × CP concentration in feed/6.25 (g kg^{-1})
IDNI or QFNACT (g animal^{-1} d^{-1})	IDMI (g animal^{-1} d^{-1}) × N concentration in the faeces (g kg^{-1})
DNI (g animal^{-1} d^{-1})	NI (g animal^{-1} d^{-1}) × IDN (g animal^{-1} d^{-1})

In addition, the predicted intercept and slope of Q_{FN} model for smallholder dairy farms (Q_{FNPRED}) were compared to the intercept and slope reported for the Lucas equation for N in literature (Van Soest, 1994). The literature values for intercept and slope of the Lucas equation for N are 92% and −0.61 g N /100 g DMI, respectively.

2.5 Effective sample size

The accuracy of a model determines the effective sample size (i.e., the number of dairy cows required) in a study to detect a specific difference between two treatments (e.g., before and after an intervention) (Cohen J. et al., 1998). A larger sample size is needed when a less accurate model is used. The accuracy of a model is expressed by the reliability score which is equal to the coefficient of determination (R^2) of the model. In this study, the R^2 was the R^2 from the regression of Q_{FNPRED} on Q_{FNACT}. The R^2 from the actual measurement of faecal N (Q_{FNACT}) was assumed as without error ($R^2 = 1$).

The Cohen method (Cohen J. et al., 1998) was used to determine the effective sample size for Q_{FNPRED} and Q_{FNACT} (equation 13):

$$n = \frac{2\delta^2}{(d)^2} \qquad \text{(eq.13)}$$

where, n is the effective sample size and δ is the critical value of t, and the t is the critical t-value in the t-test distribution given as $t_{1-\alpha}$ and $t_{1-\beta}$. The δ is calculated as $\delta = (t_{1-\alpha} - t_{1-\beta})$. The indicates the probability of a type I error and the probability of a type II error. The d is the standardized effect size and calculated as $(m_A - m_B/\sigma)$ where m_A and m_B are the means of populations A and B, respectively (e.g. with and without an intervention), and σ is the population standard deviation. The two populations (A and B) were assumed to have equal variances and an equal reliability coefficient, was set at *p = 0.05* (one-tailed), and at *p = 0.20*. In this study, we calculated the effective sample sizes in order to detect a specific difference of Q_{FN} ranging from 1 to 30 g animal^{-1} d^{-1}. All statistical analyses in the present study were performed in R (R Core Team, 2018).

3. Results

3.1 Farm survey findings

The 30 smallholder dairy farmers in this study kept a total of 144 dairy cows, i.e., 106 lactating cows, 12 dry cows, and 26 young cows. The young cows counted 12 replacement females with an average age between 6 to 24 months, and 14 calves (males and females) with an average age between 4 and 5 months. Lactating cows had an average live weight of 433 kg, and an average milk yield of 13 kg per day. Dry cows had an average live weight of 419 kg and were 210 to 240 days in pregnancy.

Young cows had an average live weight of 278 kg. Table 3 provides an overview of the feed types and the average feed intake per animal class. There was no difference between the type of feed fed to lactating cows, dry cows, and young cows. Overall, on a DM basis, the diet of lactating cows, dry cows and young calves, but at different intake levels, consisted of roughages such as elephant grass, road side grass, and rice straw (48%), agro-industrial by-products, such as tofu waste and cassava waste (22%), and concentrates (28%). Relatively low amounts of other feed products such as legumes (0.3%), premix (0.01%), banana stalks (0.09%), and crop leftovers (0.6%) were fed. These products were excluded from the model since the amount was insignificant, and the usage was inconsistent across farms.

Table 4 shows the average nutrient composition of feed, milk and faeces. The average CP concentration of 140 g kg^{-1} DM in concentrate feed was at the lower range of CP levels in concentrates for dairy cattle generally used in Indonesia (140 to 210 g kg^{-1} DM) (Badan Standarisasi Nasional, 2009). The average protein concentration of 34 g kg^{-1} for milk met the minimum Indonesian requirement of 27 g kg^{-1} milk (Badan Standarisasi Nasional, 1998). The average N concentration of 24 g kg^{-1} DM for the faeces was within the range of 22 to 26 g kg^{-1} DM as found in literature (Van Vliet et al., 2007; Wattiaux MA et al., 1998) and the P concentration of 7 g kg^{-1} DM for the faeces was in the range of 5.2 to 7.4 g kg^{-1} DM as found in literature (Wang et al., 2014).

Table 5 presents the feed intake per animal class. Results show that the quantity of feed differed among animal classes. Intake of DM, N, and P were higher in lactating cows than in dry cows, which in turn had higher intake of these nutrients than young stock. On average, lactating cows consumed 22% more than dry cows, and 46% more than young cows. Similarly, on average, the NI was 25% higher in lactating cows compared to dry cows and 48% higher compared to young cows. The average PI was 27% higher in lactating dairy cows compared to dry cows and 48% higher compared to young cows.

Table 3. An overview of the feed types and the average of feed intake (mean±standard error) by lactating, dry and young cows on a dry matter basis (g $animal^{-1}$ d^{-1}) on 30 smallholder dairy farms in the Lembang, West Java, Indonesia.

Feed type	Lactating cows	Dry cows	Young cows
Elephant grass	3,620±284	4,319±1,130	3,310±744
Road side grass	1,342±293	752±656	571±396
Rice straw	949±137	515±276	485±251
Cassava waste	1,230±151	713±253	295±159
Tofu waste	1,944±211	1,881±496	1,049±258
Concentrate	4,796±351	2,590±940	1,763±453
Total	13,881±632	10,769±603	7,472±466

Table 4. Average nutrient composition of feed, milk, and faeces samples collected (mean±standard error).

Nutrients composition of feed (g kg^{-1} DM)						
Feed type	n[1]	DM	CP	P	Ash	DDM
Elephant grass	27	178±11	101±6	4±0.1	112±6	529[2]
Road side	9	188±15	103±7	5±0.4	101±9	489[3]
Rice straw	11	319±32	90±3	3±0.3	198±13	408[2]
Tofu waste	15	155±7	201±2	3±0.2	33±2	865[3]
Cassava waste	17	181±13	61±5	4±0.5	28±10	768[2]
Concentrate	30	876±3	140±1	7±0.4	73±3	861[2]
Nutrient composition of milk (g kg^{-1})	n[1]		Protein		P	
	106		34±0.4		0.6±0.005	
Nutrient composition of faeces (g kg^{-1} DM)	n[1]		DM		N total	P
	30		138±10		24±0.5	7.0±0.2

DM, dry matter; CP, crude protein; P, phosphorus; DDM, dry matter digestibility; N, nitrogen.
[1] Number of sample. [2] Feedipedia (2018), [3] Tatra et al. (2015)

3.2 Model calibration and evaluation

The training data set (n = 86) was used to estimate the intercept and the slope for equation (1a). The intercept was found to be −0.60 g 100 g^{-1} DMI and the slope was found to be 0.92. This implies that the amount of metabolic faecal N increases by 0.6 g per 100 g DMI with a predicted true digestibility of the protein in the feed of 92%. The proposed Q_{FN} model for Indonesian smallholder dairy farms is therefore:

$$Q_{FN}\ (\text{g animal}^{-1}\ \text{d}^{-1}) = [0.08 \times \text{TNI}\ (\text{g animal}^{-1}\ \text{d}^{-1}) + 0.60 \times \text{DMI}\ (100\ \text{g animal}^{-1}\ \text{d}^{-1})] \qquad \text{(eq.14)}$$

The testing data set (n = 58) was subsequently used to evaluate the Q_{FN} model in equation 14, by comparing Q_{FNPRED} with Q_{FNACT} (Figure 1). The coefficient of determination (R^2) of Q_{FNPRED} and Q_{FNACT} was 0.63 (Residual standard error = 17.6, $p<0.05$). In this regression line, the intercept was significantly different from zero ($p = 0.0003$), however, the slope did not significantly differ from one ($p = 0.16$). The MAE was 15 g animal^{-1} d^{-1} which translates to 17% deviation of Q_{FNPRED} from the Q_{FNACT}. The RMSE was 20 g animal^{-1} d^{-1} which translates to 22% deviation of Q_{FNPRED} from the Q_{FNACT}. The bias error of the MSE was 9%, the slope error was 12% and the random error was 79%. The slope and intercept which we estimated for equation 2c were similar to those reported in literature (Van Soest et al., 1994).

Table 5. Feed intake on a dry matter basis per animal class (g animal^{-1} d^{-1}) used to calibrate and evaluate N and P excretion model.

Parameters	Minimum	Maximum	Mean ± SE
Lactating dairy cows (n = 106)			
DMI	6,548	22,048	13,881±632
DDMI	4,706	16,159	9,738±232
IDMI	1,815	7,370	4,142±114
CPI	859	3,214	1,756±49
NI	138	514	281±8
IDN	42	273	101±4
DN	67	319	180±5
PI	26	141	71±3
Dry dairy cows (n = 12)			
DMI	5,615	19,476	10,769±603
DDMI	4,611	13,215	7,300±700
IDMI	833	6,261	3,500±500
CPI	798	2,166	1,320±111
NI	128	346	211±18
IDN	24	130	84±8
DN	43	228	127±16
PI	26	125	52±8
Young dairy cows (n = 26)			
DMI	3,403	15,548	7,472±466
DDMI	2,624	10,400	4,853±398
IDMI	589	5,147	2,578±198
CPI	654	1,886	918±69
NI	51	302	147±11
IDN	38	144	63±6
DN	32	190	84±8
PI	15	102	37±4

SE, standard error; DMI, dry matter intake; DDMI, digestible dry matter intake; IDMI, indigestible dry matter intake; CPI, crude protein intake; NI, nitrogen intake; IDN, indigestible nitrogen intake; DN, digestible nitrogen intake; PI, phosphorous intake.

3.3 Effective sample size

The effective sample size i.e., the number of dairy cows required in an experimental treatment to detect a specific difference between Q_{FN} of different treatments was compared between Q_{FNPRED} (i.e., derived from equation (14)) and Q_{FNACT} (i.e., derived from measurements). The relationship

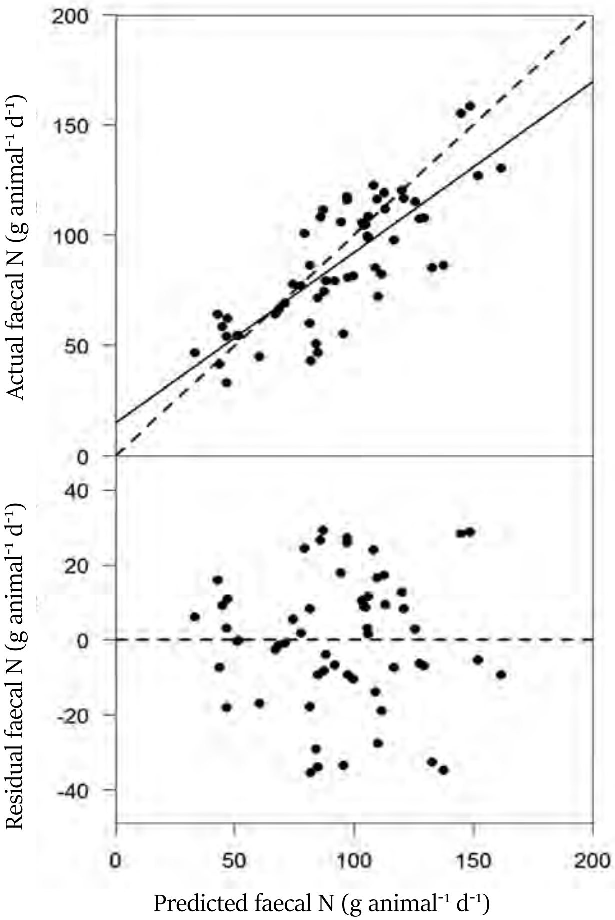

Figure 1. Plot of model evaluation of QFN for the data set. The solid line indicates the regression line of prediction faecal N (Q_{FNPRED}) and actual faecal N (Q_{FNACT}). The dashed line is the line of unity. QFN, quantity of faecal N; Q_{FNPRED}, predicted quantity of faecal N; QF_{NACT}, actual quantity of faecal N.

between effective sample size of dairy cows (n) and a specific difference of Q_{FN} (g animal^{-1} d^{-1}) in two alternative models (Q_{FNPRED}; R^2 = 0.63 and Q_{FNACT}; R^2 = 1) is illustrated in Figure 2. To detect a specific difference in Q_{FN} of 10 g animal^{-1} d^{-1}, for example, requires 68 animals when using Q_{FNACT}, while 107 animals are needed when using Q_{FNPRED}. For specific differences higher than 20 g animal^{-1} d^{-1} the effective sample size did not differ much between the two models.

3.4 Model application

Equation (14) and the NRC guidelines (NRC, 2001) were used to predict N and P excretion and retention for all dairy cows in the data set (n = 144). Table 6 shows the average prediction of N and P excreted and retained (g animal^{-1} d^{-1}) per animal class. The average Q_{FN} was higher for lactating

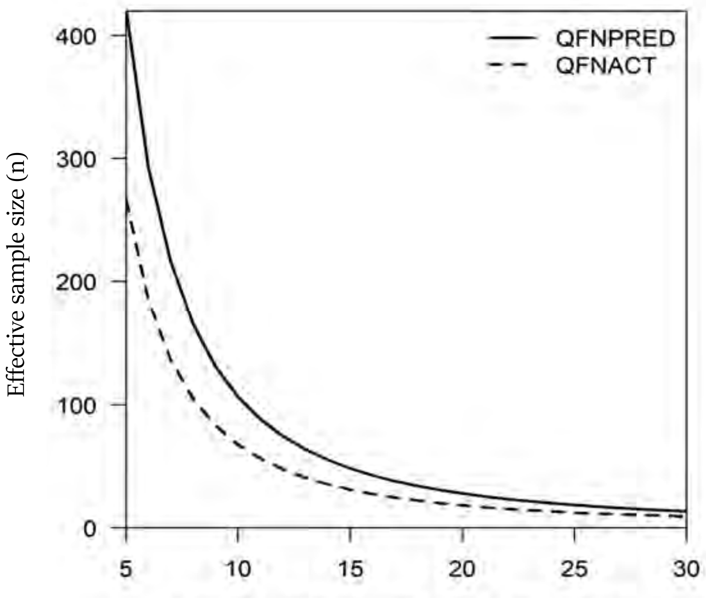

Figure 2. The relationship between effective sample size of dairy cows (n) and a specific difference of Q_{FN} (g animal^{-1} d^{-1}) in two alternative models (Q_{FNPRED}; R^2 = 0.63 and Q_{FNACT}; R^2=1). The solid line indicates the Q_{FNPRED} and the dashed line indicates the Q_{FNACT}.

cows (107 g animal^{-1} d^{-1}, 38% of TNI) than for dry cows (83 g animal^{-1} d^{-1}, 39% of TNI) and young cows (57 g animal^{-1} d^{-1}, 39% of TNI). Similarly, the average Q_{UN} was higher for lactating cows (111 g animal^{-1} d^{-1}, 40% of TNI), than for dry cows (99 g animal^{-1} d^{-1}, 47% of TNI) and young cows (60 g animal^{-1} d^{-1}, 41% of TNI). Overall, the average Q_{FN} was 96 g animal^{-1} d^{-1} and Q_{UN} was 101 g animal^{-1} d^{-1}. The average N_{Ret} was 63 g animal^{-1} d^{-1} for lactating cows (22% of TNI), 29 g animal^{-1} d^{-1} for dry cows (14% of TNI), and 30 g animal^{-1} d^{-1} for young cows (20% of TNI). In the case of Indonesian smallholder dairy farms, on average 22% of TNI was retained and the remaining 78% of TNI was found in manure, with 38% in the faeces and 40% in the urine.

Table 6. Predicted N and P excreted and retained (mean±SE) in lactating cows, dry cows and young cows on 30 smallholder dairy farmers in Lembang, West Java, Indonesia (g animal^{-1} d^{-1}).

Parameters estimate	Lactating cows	Dry cows	Young cows	Average
Q_{FN}	107±2.5	83±8.2	57±4.3	96±2.6
Q_{UN}	111±5.3	99±11.9	60±6.0	101±4.5
Q_{TN}	218±7.8	182±20.1	117±10.3	197±7.1
N_{Ret}	63±1.9	29±0.02	30±2.3	54±1.80
Q_{FP}	63±5.6	47±8.4	32±4.2	56±2.5
P_{Ret}	8±0.1	5±0.1	5±0.05	7±0.2

SE, standard error; Q_{FN}, quantity of faecal N; Q_{UN}, quantity of urinary N; Q_{TN}, quantity of total N; N_{Ret}, retained N; Q_{FP}, quantity of faecal P; P_{Ret}, retained P.

The average Q_{FP} was 63 g animal^{-1} d^{-1} (89% of PI) for lactating cows, 47 g animal^{-1} d^{-1} (90% of PI) for dry cows, and 32 g animal^{-1} d^{-1} (86% of PI) for young cows. The average P_{Ret} was 8 g animal^{-1} d^{-1} (11% of PI) for lactating cows, 5 g animal^{-1} d^{-1} (10% of PI) for dry cows, and 5 g animal^{-1} d^{-1} (14% of PI) for young cows. In the case of Indonesian smallholder dairy farms, on average 12% of PI was retained and 88% of PI was found in the manure. Average daily N and P excretion per farm (three lactating, one dry and one young cow) is approximately 947 g N and 268 g P.

4. Discussion

Since it is very difficult to sample manure and assess manure quantity at dairy farms we calibrated and evaluated the Q_{FN} model, and subsequently predicted $Q_{FN,}$ Q_{UN}, and Q_{FP} in our case region based on feed intake and composition, milk production and its composition, and manure composition. The Lucas equation is an important element of the Q_{FN} model, and the model calibration for dairy cattle at the farms in the study area was essentially an evaluation of the Lucas equation for the Indonesian situation. Our estimate of true N digestibility equalled the standard value of 92% in the original Lucas equation, whereas our estimate of metabolic faecal N was −0.60 g 100 g^{-1} DMI, with the standard value being −0.61 g 100 g^{-1} DMI. Our estimates of true N digestibility and metabolic faecal N, furthermore, were similar to those reported in literature (Van Soest et al., 1994). Hence, the standard Lucas equation for N seems to apply under a wide array of conditions, including Indonesian smallholder dairy farms (Oosting et al., 1994). Consequently, the Q_{FN} model presented in this study can be applied under very different circumstances, and the standard values from the Lucas equation can likely be used.

To test the robustness of model, we applied a calibration/evaluation approach instead of using a sensitivity analysis. Results of the model evaluation showed that the Q_{FNPRED} model had a relatively high relative MAE (17%) and relative RMSE (22%). In literature (Van der Linden et al., 2019) errors of 20% were found during the quantification of potential and feed-limited growth of three beef cattle breeds by a generic model which was followed by a model evaluation on independent experimental data. This error is comparable to our findings. The systematic errors (bias error and slope error) were limited and the major source of error was the random error (79%). The relatively high error could in part be attributed to the fact that some model parameters such as DDM had to be derived from literature (Tatra et al., 2015; Feedipedia, 2009). The specified information of DDM for many feed types, for example the roughage, is limited for the Indonesian situation, whereas the variation in DDM quality of roughage among farmers is expected to be high. In addition, the Q_{FNACT} that was used as actual value for model evaluation and for the estimation of the effective sample size was considered without error. In reality, the Q_{FNACT} also has an estimation error because of errors related to sampling, to laboratory analysis and to the DDM values used to estimate Q_{FNACT}. Hence, the MAE and RMSE of Q_{FNPRED} when evaluated against a real direct assessment (full collection of faecal and urinary excretion separately and compositional analysis of each fraction) will likely be higher than when compared to the Q_{FNACT} in the present study.

We used the NRC guideline to estimate the nutrient requirements. In Indonesia, it is widely used because of the absence of a national system to estimate dairy cattle feed requirements. Nevertheless, since the cattle were high grade Holstein Friesian cows, we believe that most NRC predictions are applicable to the breed in Indonesia, and because the weather conditions in the research area are relatively mild, they also apply to the climatic conditions.

We selected the farms randomly and we collected feed samples from each farm, so we assume the farm and feed samples represented the actual situation. The variation in composition of agro-industrial by-products and concentrate was low with limited difference between dry and rainy season because they were produced by agro-industries which use standardized processes, hence delivering standard quality, even of the by-products they sell. In addition, the concentrate was produced by the dairy cooperative with the aim to deliver standardized quality to the members of the cooperative. The roughage differed only slightly between seasons (Haegele MT et al., 2017). Since the Lembang area is small, conditions for all farmers are similar. Hence, variation in composition between diets and within feeds was small in the Lembang area.

The average predicted Q_{FN} was lower (96 g animal^{-1} d^{-1}) than some values reported in literature (147 to 242 g animal^{-1} d^{-1}) (Qu et al., 2017; Knowlton et al., 2010; Nennich et al., 2005). The difference between our estimate and these reported values could be due to the lower DMI and NI in our study. To verify this conclusion, we inserted the DMI and NI values from study Qu et al. (2017), Knowlton KF et al. (2010), Nennich TD et al. (2005) into our Q_{FN} model, and the result showed that the relative deviation of predicted Q_{FN} values from the values reported in previous studies varied from –15% to 19%.

We calculated nutrient use inefficiency for nitrogen (NUI_N) by expressing excreted N as percentage of NI. In our study, this NUI_N was 78% meaning that 78% of N intake ended up in manure, and only 22% in milk and meat. The NUI_N in literature (Jiao et al., 2014; Knowlton et al., 2010; Nennich et al., 2005) was lower than the one found by us i.e. 70% to 72%. This could mean two things: either N losses via manure were higher from the cattle in our study caused by a low efficiency of N utilization in the animal which could be caused by limitation by other nutrients, by the genetic potential of the animals or by health-related factors (Van der Linden et al., 2019) or it could just be that too much N was offered through the diets. These reasons imply that improving feeding management for example through nutritionally balanced rations (Garg et al., 2018), adjustment of the dairy genetics to the production potential at the present feed base and animal health care may potentially reduce nutrient excretion.

Some mathematic models to predict N and P excretion of dairy cows are developed based on input-output relations from dairy farms in a specific context. Although such models are compelling because they only require limited data to predict the N and P excretion, they may fail when applied in systems different from the one for which they were created (Duarte et al., 2003). Applying such existing models to the case of smallholder dairy farms in Indonesia, therefore, may lead to over or under estimation of N and P excretion because of differences in feed input (lower feed intake) and animal characteristics (lower milk production and body weight). Therefore, a generic model is proposed. The generic model in this study described the process of N digestion and N utilisation for maintenance, growth and production based on well-established methods generally applied in animal nutrition (Lucas equation and NRC). Additionally, this generic model is calibrated and evaluated, and the model evaluation showed that the model can be used to estimate faecal N at smallholder dairy farms in Indonesia.

5. Conclusion

We developed, calibrated and evaluated a generic model to predict Q_{FN} from dairy cattle on smallholder farms in Indonesia using readily available farm data, and applied this model, in combination with existing guidelines of the National Research Council, to predict N and P excretion in faeces and urine for 144 dairy cows on 30 farms. In conclusion, the proposed models can be used with reasonable accuracy to predict N and P excretion of dairy cattle on smallholder farms in Indonesia using readily available farm data. The model can be used as a basic tool to improve manure management and to reduce nutrient losses in Indonesian smallholder dairy farms.

Chapter 3

Nutrient imbalances from smallholder dairy farming systems in Indonesia: the relevance of manure management

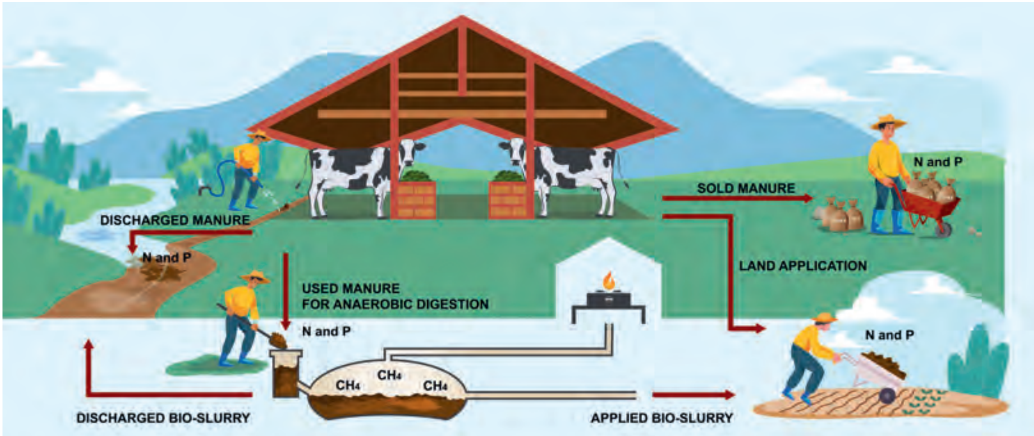

Illustration of different manure management systems at smallholder dairy farms

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Submitted

Abstract

Nitrogen (N) and phosphorus (P) imbalances from dairy farming systems (DFSs) in West Java lead to environmental problems, such as eutrophication of the Citarum river. Insight into N-P imbalances from DFSs is lacking. This study aims to analyse N-P balances of DFSs at farm and regional level. As the type of manure management system (MMS) may influence nutrient balances, we compared N-P balances of 30 farms with four different MMSs: applying manure directly on forage land, without treatment (ADL), selling or exporting manure (SEL), using manure for anaerobic digestion (ADI), and discharging manure (DIS). We derived N-P balances from differences between N-P in- and outflows at farm and sub-system level. Our study showed that N balances at DFS averaged 222 kg N farm^{-1} yr^{-1}, 1,007 kg N ha^{-1} yr^{-1} or 12 kg N ton FPCM^{-1} yr^{-1}, and did not differ between MMSs. Average P balances at DFS did differ between MMSs; balances were highest for DIS (83 kg P farm^{-1} yr^{-1}; 440 kg P ha^{-1} yr^{-1}; 4 kg P ton FPCM^{1} yr^{-1}), and lowest, for SEL (-25 kg P farm^{-1} yr^{-1}; -176 kg P ha^{-1} yr^{-1}; -2 kg P ton FPCM^{-1} yr^{-1}). Soil P balances did not differ between MMSs and were mostly negative, except for four ADL farms. Annually, all dairy farms in Lembang region caused a loss of 1,061 tons of N and 290 tons of P into the environment, and extracted 8 tons of P from soils. Overall, N-P imbalances from dairy farms in this region are high, especially due to discharging manure into the environment. To reduce imbalances, dairy farms must improve the collection and on-farm use of manure, and sell excess manure to crop farms. The carrying capacity for high-input high-output dairy farming is determined by the capacity of arable farms to apply their manure surplus.

1. Introduction

The current dairy sector in Indonesia is responsible for about 15-20% of the national milk consumption (Livestock Statistic, 2020). The demand for milk is projected to increase by 9% each year. This increase is not only due to a rise in the number of middle-class consumers, but also due to an increase in perceived health of dairy products by consumers. To meet this increasing milk demand, the Indonesian government aims to increase the domestic production of dairy milk by increasing the dairy cattle population and improving their productivity (Kemenko Ekon, 2016). Increasing the dairy cattle population, via importing dairy cattle, is seen as a short-term solution because improving productivity (e.g., milk yield per cow) is often more difficult (de Vries et al., 2019). Consequently, the dairy cattle population grows rapidly, among others in the Lembang region, a province in West Java (Indonesia). This increase in cattle numbers can cause environmental pollution, such as eutrophication of rivers or contamination of drinking water (Adenuga et al., 2020; Clay et al., 2020; Hoekstra et al., 2020; de Vries et al., 2015).

The contribution of dairy farming to eutrophication of rivers and drinking water is mainly caused by leaching of nitrogen (N) and phosphorus (P). Leaching of N-P into rivers can cause, for example, excessive growth of algae and higher plants, whereas leaching of nitrate (NO_3^-) can make water unsuitable for drinking (Biagini et al., 2018; Anzai et al., 2016; Chislock et al., 2013; WHO, 2016). The Citarum river in West Java, being the longest river in the province (350 km length and basin area of 6,600 km^2), has been dubbed as one of the most polluted rivers in the world. The river is a crucial water source for agriculture, households, and electricity production. Studies have shown that about two-thirds of water pollutions originate from domestic and municipal activities and about one-third from agriculture activities, including dairy farming (Garg et al., 2018; Yoshida et al., 2017; Kerstens et al., 2013). The Indonesian Government has set a seven-year (2018-2025) clean-up program of the Citarum river, called Citarum Bestari (Bappenas, 2020; Fridayani et al., 2020; Erianti et al., 2019). Though the dairy sector is presumed to contribute to this water pollution, its exact contribution to pollution of the Citarum river is so far unknown.

All dairy cattle in the Lembang region are owned by smallholder farmers, keeping on average two to four milking cows per farm. Nutrient balances (surplus/deficit) from these smallholder dairy farming systems (DFSs) are partly associated with their manure management. The relation between manure management and especially nutrient surplus has been shown in studies (Varma et al., 2021; Sefeedpari et al., 2019; Wei et al., 2018; Oenema et al., 2007). Different manure management systems (MMSs) exist in this region (de Vries et al., 2017), such as: direct land application of manure to the homegrown feed (HGF) area, storage of manure in sacks and selling it to manure traders, and using manure as substrate for bio-energy production in biodigesters. The type of MMSs might have an important influence on nutrient balances, but so far, insight into nutrient flows and balances of DFSs with different MMSs in Indonesia is lacking.

To quantify N-P imbalances from the dairy sector in the Lembang region and identify improvement options, this study aims to analyse nutrient balances from DFSs with different MMSs at farm level. Furthermore, nutrient balances from farm level are upscaled to regional level to determine the sector's contribution to the pollution of the Citarum river and the potential options for improvement.

2.Materials and methods

2.1 Characteristics of the farms

The assessment of nutrient balances from smallholder dairy farms was conducted in the Lembang sub-district, West Java province, Indonesia (Figure 1). To quantify nutrient balances, we selected 32 farms from a previous study of de Vries et al. (2017). De Vries et al. (2017) visited 300 randomly selected dairy farms in the Lembang region. Discharge of manure was the common practice on these smallholder dairy farms. If dairy farms collected manure, it was only the solid part (faeces), whereas the liquid part (urine) was discharged into the environment. In addition, most of the DFSs applied more than one MMSs. We therefore first assigned each of the 300 farms from the study of de Vries et al. (2017) to an MMS. If more than 40% of the faeces was managed according to one of the MMSs, the farm was assigned to that MMS.

We assigned the farms to one of the following MMSs:

- Applying manure directly on forage land, without treatment (ADL): faeces is collected and used as organic fertiliser for cultivation of HGF.
- Selling or exporting manure (SEL): faeces is collected in sacks and sold to manure traders or used at crop farms outside the DFS.
- Using manure as substrate for anaerobic digestion (ADI): faeces is collected to produce bioenergy (methane) in a biodigester. Most of the digestate (i.e., by-product of biodigester) is discharged; only a small part is used as organic fertiliser for HGF or crops.
- Discharging manure (DIS): faeces is not collected and, in most farms, flushed from the barns into the environment.

We randomly selected 8 farms per MMS out of the 300 available farms. After the start of the assessment, one farm changed its MMS from SEL to DIS, whereas two farms changed their MMS from ADL to ADI. We excluded these last two farms because they were breeding farms with more than 30 cows, and specific information related to nutrient inflows and outflows was not available. Hence, we ended up with 30 dairy farms and an unequal number of farms per MMS. Table 1 presents

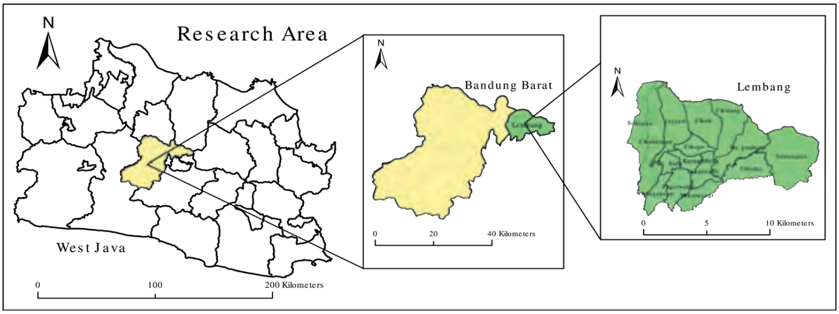

Figure 1. The Lembang sub-district, sampled area for data collection.

the characteristics of the DFSs for the different MMSs. Most DFS characteristics did not differ among MMSs, only the proportion of faeces collected differed among MMSs.

2.2 System description

Figure 2 provides a schematic overview of the DFS as well as their N-P flows. A DFS has maximally two sub-systems: the dairy herd, and the soil sub-system. Manure can either be used as fertiliser to produce HGF, it can be digested (and the digestate can be used as fertilizer), it can be sold, or it can be discharged. Farms without land only have the dairy herd sub-system.

Nutrients flow into the DFS via purchased feed, inorganic fertiliser, and flow out of the DFS via milk, livestock, sold crops, and sold manure. Sold manure is exported to other systems, such as to crop farming systems or other users outside the system boundary of our study. Discharged manure is assumed to be lost to the environment.

Table 1. Average characteristics of dairy farms for each manure management system (standard error between brackets).

Parameters	ADL[1]	SEL[2]	ADI[3]	DIS[4]
Number of farms	6	7	8	9
Number of lactating cows	3.6 (0.55)	3.4 (0.85)	3.5 (0.60)	3.6 (0.57)
Number of dry cows	0.4 (0.08)	0.4 (0.08)	0.6 (0.19)	0.4 (0.08)
Number of young stocks	2.3 (0.73)	2.3 (0.40)	1.8 (0.53)	1.5 (0.34)
FPCM[5](kg cow^{-1} yr^{-1})	4,964 (221)	4,863 (221)	4,985 (342)	5,798 (273)
FPCM[5](ton $farm^{-1}$ yr^{-1})	17 (2.5)	17 (4.4)	17 (2.7)	21 (3.8)
Land size (ha $farm^{-1}$)	0.43 (0.07)	0.37 (0.16)	0.41 (0.11)	0.29 (0.06)
DMI[6](ton $farm^{-1}$ yr^{-1})	22 (2.4)	22 (5.2)	21 (3.7)	23 (3.9)
DMI purchased (% of total DMI)	58 (2.4)	67 (6.7)	72 (4.7)	71 (2.7)
Faeces collected (% of total faeces)	76^{c} (5.6)	93^{d} (2.4)	46^{b} (4.9)	5^{a} (2.2)

[1]Applying manure directly on forage land, without treatment, [2]Selling or exporting manure, [3]Using manure as substrate for anaerobic digestion, [4]Discharging manure [5]Fat-and-protein-corrected milk, [6]Dry matter intake, Different superscripts letter show significant difference (P-value < 0.05)

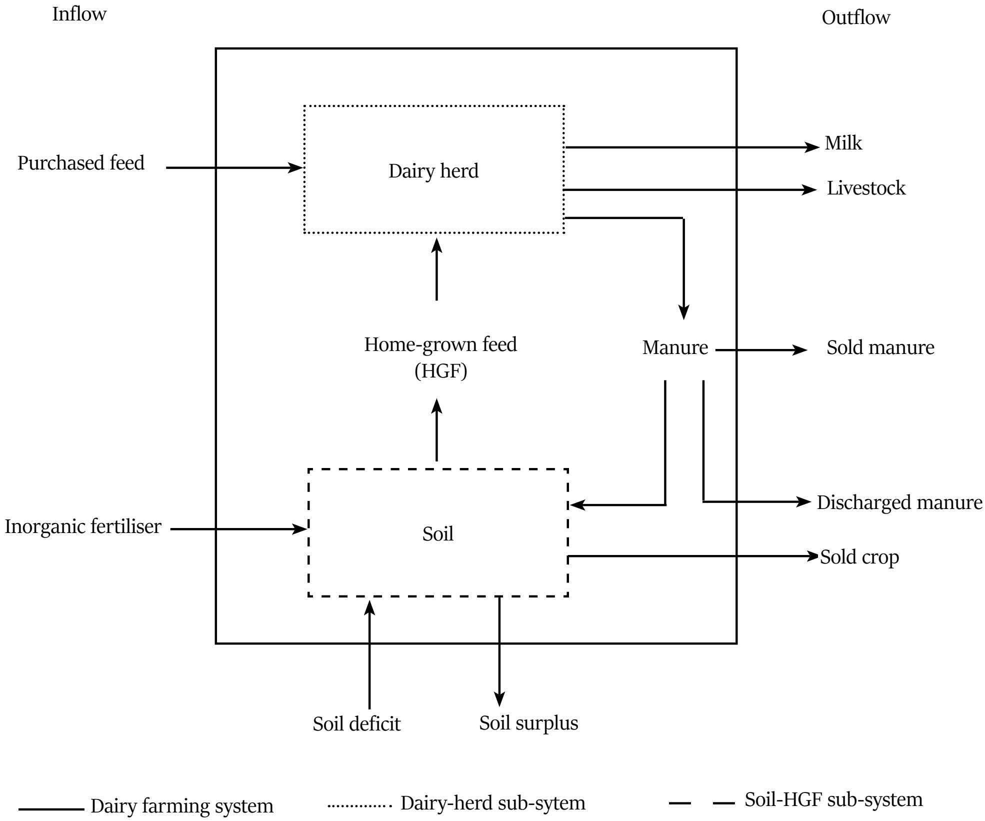

Figure 2. Nutrient in- and outflows of the dairy farming system, and its sub-systems dairy herd and soil-home-grown-feed cultivation.

Nutrient balances of DFS were determined as the difference between nutrient inflows and outflows. We not only computed nutrient balances of the entire DFS, but also of its sub-systems. Nutrient balances of the dairy sub-system were determined as the difference between nutrients in purchased and home-grown feed, and nutrients in milk and livestock. Nutrient balances from the soil-HGF sub-system were determined as the difference between nutrients in inorganic fertilizer and manure, and nutrients in harvested feed. If the total nutrient input into the soil exceeded the total output, the difference was assumed to be lost to the environment, which implies we assumed no change in soil organic stocks (i.e., mineralisation equals immobilization). If the total nutrient input into the soil is lower than the total output, we assumed it was extracted from inorganic nutrient reserves in the soil (i.e., no change in soil organic stock).

2.3 Data collection and quantification of nutrient balances

To quantify above-described nutrient balances, we collected data through a farm survey. This survey was conducted by six bimonthly farm visits from December 2017 to October 2018. Data gathered through the farm survey were feed intake of the cows, daily milk yield, and cattle body weight. At each farm visit, we asked the dairy farmers about the herd composition (number of lactating cows, dry cows, and young stock of <2 years old), sold animals, HGF area and production, and the quantity of inorganic fertiliser (i.e., urea) applied on HGF area. We asked the farmers to estimate the proportion of manure being collected, used for land application, used for bio-energy production, and the proportion being sold, and discharged.

3

The nutrient inflow via purchased feed (QN_{PUR}) equals the nutrients in the net ingested purchased feed (presented in dry matter basis). To quantify QN_{PUR}, we first weighed the fresh matter quantity of each purchased feed for each animal (lactating and dry cows, and young stock) at the first day of each farm visit. We then subtracted the leftovers of each purchased feed, which we collected and weighed on the morning of the second day of the farm visit. To compute the dry matter intake (DMI) of each purchased feed type, we multiplied the net ingested fresh matter quantity of each purchased feed with its DM content. The main types of purchased feed were concentrate, rice straw and agro-industrial by-products, such as tofu and cassava waste. To determine the DM and N-P content of each purchased feed, we collected samples of each purchased feed from each farm (for details regarding method see Table 2). These feed samples were collected at the first farm visit only, as we assumed that the

Table 2. Average nutrient content of feed and milk samples (standard error between brackets).

Parameters	DM[1,2] (g kg^{-1})	N[3,4] (g kg^{-1} DM)	P[5,6,7] (g kg^{-1} DM)	Fat (g kg^{-1} DM)
Feed sample				
Purchased feed				
Tofu waste	156 (7)	32 (0.5)	3 (0.3)	N/A[8]
Cassava waste	181 (13)	10 (0.8)	4 (0.6)	N/A[8]
Rice straw	288 (15)	14 (0.7)	3 (0.2)	N/A[8]
Concentrate	876 (3)	22 (0.2)	8 (0.5)	N/A[8]
Homegrown feed				
Elephant grass	157 (8)	17 (0.7)	6 (0.4)	N/A[8]
Road side grass	199 (11)	17 (1.1)	5 (0.4)	N/A[8]
Milk sample				
Milk	N/A[8]	4.6 (0.1)	0.6 (0.01)	40 (0.7)

[1]Dry matter, [2]Drying process at 60 °C and 105 °C, [3]Nitrogen, [4]Kjeldahl method for N analysis, [5]Phosphorous, [6]ash was determined by ashing at 600 °C, [7]titrimetric method for the feed sample and a microcolorimetric method for the milk sample, [8]Not available

variation in nutritional composition of purchased feeds was minimal due to standardized processing and little variation in ingredients. To quantify QN_{PUR} (kg yr^{-1}), we first multiplied the DMI of each purchased feed (kg yr^{-1}) with its N-P content (kg kg^{-1} DM), and subsequently summed across all ingested purchased feeds.

The nutrient inflow via home-grown feed (QN_{HGF}) equals the nutrients in the net ingested HGF (presented in dry matter basis). To quantify nutrients in the net ingested HGF, we followed the same procedure as described in case of purchased feed. The two types of HGF were elephant grass and roadside grass. Most of the farmers used elephant grass, whereas only a few farmers used roadside grass. We collected samples of HGF from each farm to determine the DM, and N-P content. The HGF samples were collected once in the rainy season (first farm visit) and once in dry season (fifth farm visit), as we assumed the content of HGF was affected by season (Haegele et al., 2017; Warly et al., 2004).

The nitrogen inflow via inorganic fertiliser N (QN_{IOF}; kg yr^{-1}) was calculated by multiplying the quantity of purchased urea (kg yr^{-1}) with its N content (kg kg^{-1}). The N content of urea was based on the standardized N content of subsided urea (i.e., 0.46 kg kg^{-1}) (Pupuk Indonesia, 2011). The P inflow via inorganic fertiliser was zero for all MMSs.

To calculate the nutrient outflow via milk (QN_{MY}), we measured the daily milk yield from lactating cows at each farm visit during the morning and afternoon milking. To analyse N-P and fat content of this milk, milk samples were collected from each lactating cow on the first and the fifth farm visit. Laboratory analyses were performed at the Faculty of Animal Science, IPB University, Indonesia (for details regarding method see Table 2). We quantified QN_{MY} (kg yr^{1}) by multiplying the milk yield from each lactating cow (kg yr^{-1}) with its N-P content (kg kg^{-1}) and subsequently summed across all milk yield from lactating cows.

To calculate the estimated amount of nutrients in livestock leaving the farm (QN_{LV}), we first measured body weight of the young stock during each farm visit using the Schoorl method (Kusuma et al., 2017). We subsequently multiplied measured body weights of sold young stock with the estimated amount of nutrients in livestock (i.e., 0.04 kg N kg body $weight^{-1}$ and 0.01 kg P kg body $weight^{-1}$). The estimated amounts of nutrients in livestock leaving the farm were assumed to equal the retained nutrients for growth which are sold for meat production (NRC, 2001).

To determine the impact of different uses of manure (e.g., applying to the field, selling, discharging), we first quantified the amount of nutrients excreted in manure (Equation 1), which actually equals the nutrient balance of the sub-system dairy herd:

$$QN_{MAN} = QN_{PUR} + QN_{HGF} - QN_{MY} - QN_{LV} \tag{1}$$

where, QN_{MAN} is the amount of nutrients excreted in manure (kg yr^{-1}), QN_{PUR} is the amount of nutrients in purchased feed (kg yr^{-1}), QN_{HGF} is the amount of nutrients in homegrown feed (kg yr^{-1}), QN_{MY} is the amount of nutrients in milk (kg yr^{-1}) and QN_{LV} is the amount of nutrients in livestock leaving the farm (kg yr^{-1}).

3

Subsequently, nutrient outflows via manure consisted of nutrient flows in faeces and urine, and these flows need to be separated. The separation of nutrient flows in faeces and urine fractions is important because in smallholder dairy farms faeces and urine are managed separately (i.e., faeces is partly collected, and urine is completely discharged). To quantify the outflow of faecal N, we multiplied the N excretion in manure at the DFS with the proportion of faecal N in manure-N (i.e., 48%), which was based on the study of Zahra et al. (2020). The study of Zahra et al. (2020) used a mathematical model to describe the relation between DMI and faecal N excretion to predict the quantity of faecal N excreted. To quantify urinary N, we subtracted the quantity of faecal N from manure-N. Most of P ends up in the faecal fraction, and we therefore assumed that the amount of urinary P was negligible (Valk et al., 2002).

To quantify the amount of faecal N-P being collected in each MMS, we multiplied the proportion of faeces being collected with the quantity of faecal N-P. To quantify the amount of faecal N-P being discharged in each MMS, we subtracted the quantity of faecal N-P being collected from the total quantity of faecal N-P. All urinary N was assumed to be discharged into the environment. To quantify the total N from discharged manure, we summed the quantity of discharged faecal N and all urinary N.

Nutrient inflows and outflows on bimonthly basis were summed up and expressed on a yearly basis. We expressed nutrient inflows, outflows, and balances per farm, per unit of land, and per unit of product (i.e., milk). We present balances per farm because farms were comparable in terms of herd size, milk production, land size, and feed quantity. Nutrient balances per hectare of land (kg ha^{-1} yr^{-1}) give insight into the local environmental pressure from dairy farms of the area, whereas nutrient balances per unit of product reflect efficiency of production, e.g. how much nutrients are lost per unit of milk produced (Mu et al., 2016; Ryan et al., 2012; Halberg et al., 2005). Nutrient balances per unit of product were expressed per ton of fat-and-protein-corrected milk (FPCM) (IDF, 2015), which was computed according to Equation 2:

$$\text{FPCM (ton yr}^{-1}) = \text{milk yield (ton yr}^{-1}) \times [0.1226 \times \text{milk fat (\%)} + 0.076 \times \text{milk protein (\%)} + 0.2534] \quad (2)$$

where the milk fat and protein percentages were based on collected milk samples. To compute milk protein percentage, the measured N content of milk was multiplied with the factor of 6.38 times 100 (Table 2).

2.4 Statistical analysis

To determine the impact of MMSs on nutrient balances, means of nutrient inflows, outflows, and balances per unit of farm, as well as nutrient balances per unit of product and land, were compared across farms differing in MMSs using ANOVA, followed by the Tukey's post hoc test with a critical significance level of 5%. We also compared means of total nutrient inflows, outflows, and balances of the dairy herd sub-system and the soil-HGF sub-system. We first used the Fisher's exact test to examine if the proportion of farms with positive (surplus) and negative (deficit) N-P balances at the soil-HGF sub-system and DFS differed across MMSs. All DFS farms had a positive N balance, so there was no need to perform a Fisher's exact test. At soil level, we found no difference in the proportion of farms with a negative and positive N balance ($P = 0.143$) and therefore, did not distinguish surplus and deficit farms in our comparison of MMSs. Hence, we summed the surplus and deficit farms and calculated the average in order to compare the soil N balance at soil-HGF sub-system and N balance at DFS across MMSs. The proportion of farms with a negative and positive P balance, however, differed across MMSs at both soil ($P = 0.0005$) and DFS level ($P = 0.000005$). We, therefore, compared positive P balances (surplus) and negative P balances (deficit) of the soil-HGF subsystems and DFS across MMSs also separately. We presented the average of N-P balances across farms, the average of positive N-P balances (surplus), and the average of negative N-P balances (deficit). The statistical analysis was performed in R software (R Core Team 2019).

2.5 Upscaling nutrient balances of the dairy farms to regional level

Nutrient balances at farm level (section 2.3) were scaled-up to regional level to estimate the total nutrient balances from the dairy sector in the Lembang region and to explore the potential to improve nutrient balances at regional level. To do so, the proportion of each MMS from the 300 dairy farms in the study of de Vries et al. (2017) was multiplied with the number of dairy farms within the region (3.985 dairy farms) to get the number of dairy farms at regional level in each MMS. We assumed that the distribution of MMSs among the 300 dairy farms reflected the distribution of MMSs at regional level because the farm selection was performed at random.

The number of dairy farms at regional level in each MMS was multiplied with the average nutrient balances per farm of that particular MMS as found in the current study and aggregated into one value as the estimated total nutrient balances from dairy farms at regional level. We considered the total positive nutrient balance (i.e., total surplus) as an indication for environmental pollution of the Citarum river (Figure 3).

A potential way to reduce nutrient surpluses from dairy farms is to use excess manure to fertilize cropland in the region. To gain insight into the reduction potential of linking dairy and arable production, we estimated the potential amount of manure-N to be applied to cropland in the Lembang region. The crop farms occupy about one-third of the land in this region (i.e., 3,419 ha from the total of 9,560 ha). We made a scenario in which manure-N was applied to tomato, chili, long bean and green been cultivation areas, as these are the major crops in this region. To calculate the application potential of manure-N at these crop farms, we collected information about the N application rate from inorganic fertiliser of each crop, for which we refer to the Indonesian Vegetable Research Institute (IVEGRI) (Setiawati et al., 2007). Following this, we divided the N application rate from inorganic fertiliser for each crop with the N efficiency rate of organic fertiliser for each crop. The N efficiency rate of organic fertiliser for such crops ranges from 50 to 60% in Indonesia (Sari

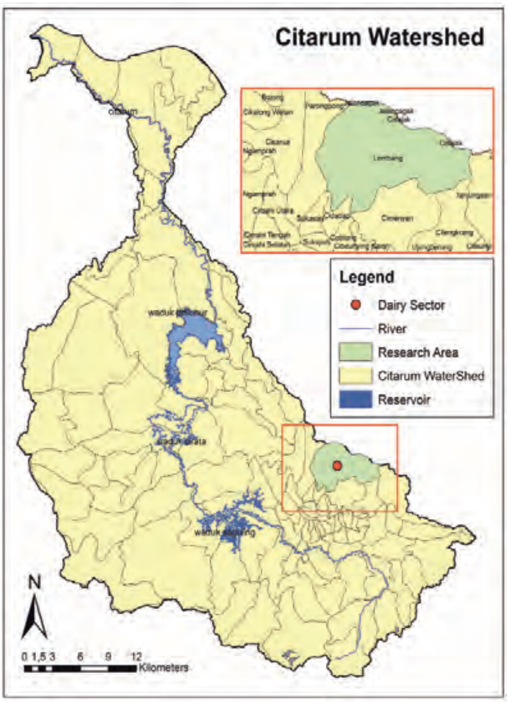

Figure 3. The Citarum river basin area. The red dot indicates the dairy sector of the Lembang region (Kementan, 2017).

et al., 2019; Anggara et al., 2016; Sumarni et al., 2005). Subsequently, we multiplied the land size of each crop in the region, with the quantity of applied manure-N at each crop to estimate the potential amount of applied manure-N in each crop at regional level.

3. Results

3.1 Nitrogen balances

Table 3 shows the average N inflows, outflows, and balances of the DFS, as well of the dairy herd and of the soil-HGF sub-systems, per MMS. At DFS level, N inflows did not differ among MMSs. On average, purchased feed caused the largest N inflow in all MMSs (343 kg N farm^{-1} yr^{-1}), followed by inorganic fertiliser (35 kg N farm^{-1} yr^{-1}).

At DFS level, total N outflows also did not differ among the four MMSs. Milk caused the highest N outflow in ADL (82 kg N farm^{-1} yr^{-1}), ADI (80 kg N farm^{-1} yr^{-1}) and DIS (99 kg N farm^{-1} yr^{-1}), while this was sold manure in SEL (166 kg N farm^{-1} yr^{-1}). N outflow via sold manure in SEL was significantly higher than in other MMSs, but, as said, this did not result in a difference in total N outflow, nor in a difference in total N balances between MMSs. The average N balance of all farms at DFS level was positive (surplus), equalled 222 kg N farm^{-1} yr^{-1}, 1,007 kg N ha^{-1} yr^{-1} or 12 kg N ton FPCM^{-1} yr^{-1} and did not differ between MMSs. All farms had an N surplus at DFS level.

In the dairy herd sub-system, total N inflows and N outflows did not differ between MMSs. However, in the soil-HGF sub-system, total N inflows differed between MMSs. The highest N inflows were found in ADL (134 kg N farm^{-1} yr^{-1}), followed by ADI (52 kg N farm^{-1} yr^{-1}), DIS (40 kg N farm^{-1} yr^{-1}) and SEL (31 kg N farm^{-1} yr^{-1}). Differences among MMSs were due to differences in applying manure to the HGF area. Manure was applied in ADL (97 kg N farm^{1} yr^{1}) and ADI (20 kg N farm^{-1} yr^{-1}), but not in SEL and DIS. For three out of six farms in ADL, N outflows of the HGF-soil sub-system exceeded N inflows (soil deficit) (-41 to -110 kg N farm^{-1} yr^{-1}); this was six out of eight farms in ADI (-7 to -161 kg N farm^{-1} yr^{-1}), and eight out of nine farms in DIS (-21 to -162 kg N farm^{-1} yr^{-1}). All farms in SEL had soil deficit (-7 to -243 kg N farm^{-1} yr^{-1}). For all other farms, N inflows of the HGF-soil sub-system exceeded N outflows (soil surplus); ADL (24 to 122 kg N farm^{-1} yr^{-1}), ADI (8 to 14 kg N farm^{-1} yr^{-1}), and DIS (11 kg N farm^{-1} yr^{-1}). The average N balance in the soil-HGF sub-system was negative (deficit) for all MMSs and did not differ among MMS classes. Six farms had a soil N surplus, which averaged 40 kg N farm^{-1} yr^{-1}, whereas 24 farms had a soil N deficit, which averaged -78 kg N farm^{-1} yr^{-1}.

Table 3. Average N inflows, outflows, and balances of the dairy farming systems, as well of the dairy herd and of the soil-HGF sub-systems, per manure management system, (standard error between brackets).

	DFS			
	ADL[1]	SEL[2]	ADI[3]	DIS[4]
N Inflows (kg farm^{-1} yr^{-1})				
Purchased feed	304 (50.5)	347 (100.7)	345 (69.8)	364 (70.5)
Inorganic fertiliser	37 (8.3)	31 (5.2)	32 (8.7)	40 (5.9)
Total inflow	341 (47.5)	378 (101.6)	377 (66.4)	403 (74)
N Outflows (kg farm^{-1} yr^{-1})				
Milk	82 (12.7)	81 (20.9)	80 (14.2)	99 (16.9)
Livestock	19 (6.5)	21 (3.6)	16 (5.2)	15 (3.1)
Sold manure	28^{a} (14.7)	166^{b} (43.4)	24^{a} (7.5)	6^{a} (3.6)
Total outflow	129 (14.3)	268 (66.2)	120 (19.9)	120 (18.4)
N Balances (kg farm^{-1} yr^{-1})	212 (42.1)	111 (40)	257 (52.4)	284 (582)
	Dairy herd sub-system			
N Inflows (kg farm^{-1} yr^{-1})				
Purchased feed	304 (50.5)	347 (100.7)	345 (69.8)	364 (70.5)
HGF	134 (14.5)	114 (31.1)	105 (28.8)	110 (22.1)
Total inflow	438 (55.7)	461 (110.5)	450 (78.8)	474 (90.7)
N Outflows (kg farm^{-1} yr^{-1})				
Milk	82 (12.7)	81 (20.9)	80 (14.2)	99 (16.9)
Livestock	19 (6.5)	21 (3.6)	16 (5.2)	15 (3.2)
Total outflow	101 (16.2)	102 (23.1)	96 (18.4)	114 (18.4)
N Balances[5] (kg farm^{-1} yr^{-1})	333 (39.5)	355 (87.1)	348 (62.6)	354 (73.5)
	Soil-home-grown feed sub-system			
N Inflows (kg farm^{-1} yr^{-1})				
Inorganic fertiliser	37 (8.3)	31 (5.2)	32 (8.7)	40 (5.9)
Applied manure	97^{b} (38.1)	0^{a}	20^{b} (10.1)	0^{a}
Total inflow	134^{b} (36.3)	31^{a} (5.2)	52^{ab} (10.2)	40^{a} (5.9)
N Outflows (kg farm^{-1} yr^{-1})				
HGF yield	134 (14.5)	114 (31.1)	105 (28.8)	110 (22.1)
N Balances[6] (kg farm^{-1} yr^{-1})				
N Balances[7]	-0.4 (34.6)	-82 (33.2)	-53 (25.1)	-70 (20.9)
N Surplus[8]	68 (18)	N.A.[10]	11 (3)	11 (N.A.[10])
N Deficit[9]	-69 (21)	-82 (33.2)	-74 (29)	-80 (21)

[1]Applying manure directly on forage land, without treatment, [2]Selling or exporting manure, [3]Using manure as substrate for anaerobic digestion, [4]Discharging manure, [5]N balances are calculated based on the difference between N inflows and N outflows of the dairy herd sub-system, [6]N balances are calculated based on the difference between N inflows and N outflows of the soil HGF sub-system, [7]based on N balances across farms in each MMS, [8]N surplus are calculated when the total nutrient input into the soil exceeded the total output (HGF yield), [9]N deficit are calculated when the total nutrient input into the soil is lower than the total output (HGF yeild), [10]N.A. is not applicable, Different superscripts letter show significant difference (P-value < 0.05)

3.2 Phosphorous balances

Table 4 shows the average P inflows, outflows, and balances of the DFS, as well of the dairy herd and of the soil-HGF sub-systems, per MMS. At DFS level, P inflows did not differ among MMSs. On average, purchased feed caused the largest P inflow in all MMSs (80 kg P farm^{-1} yr^{1}). None of the farms used inorganic fertiliser (P), hence the inflow of inorganic P was zero for all MMSs.

At DFS level, total P outflows differed among the four MMSs. Total P outflow in SEL (94 kg P farm^{-1} yr^{-1}) was highest, followed by ADL (36 kg P farm^{-1} yr^{-1}), ADI (26 kg P farm^{-1} yr^{-1}), and DIS (21 kg P farm^{-1} yr^{-1}). Differences are explained by differences in the P outflow of sold manure, being significantly higher in SEL than in other MMSs. As a result, P balances at DFS level also differed between MMSs. At DFS level, P balances differed among MMSs. P balances (surplus) were highest for DIS (83 kg P farm^{-1} yr^{-1}; 440 P ha^{-1} yr^{-1}; 4 kg P ton FPCM^{-1} yr^{-1}). All DIS farms had a positive P balance (surplus), and the P surplus was higher for DIS than for ADI farms. One out of six ADL farms had a negative P balance (deficit) (-16 kg P farm^{-1} yr^{-1}); the same holds for one out of eight ADI farms (-6 kg P farm^{-1} yr^{-1}), and all SEL farms (-6 to 48 kg P farm^{-1} yr^{-1}). At DFS level, 21 farms had a P surplus, which averaged 63 kg P farm^{-1} yr^{-1}, whereas nine farms had a P deficit, which averaged -22 kg P farm^{-1} yr^{-1}.

In the dairy herd sub-system, total P inflows and P outflows did not differ between MMSs. However, in the soil-HGF sub-system, total P inflows differed between MMSs. The highest P inflow was found in ADL (68 kg P farm^{-1} yr^{-1}), followed by ADI (7 kg P farm^{-1} yr^{-1}). Total P inflows in SEL and DIS were zero. The difference was explained by a difference in the quantity of P from applied manure, which was higher in ADL (68 kg P farm^{-1} yr^{-1}) than in other MMSs. For two out of six farms, P outflows of HGF-soil sub-system exceeded P inflows (soil deficit) in ADL (-18 to -36 kg P farm^{-1} yr^{-1}) and four out of six farms, P inflows of HGF-soil sub-system exceeded P outflows (soil surplus) (9 to 96 kg P farm^{-1} yr^{-1}). For all other farms, P outflows of HGF-soil sub-system exceeded P inflows (soil deficit) in SEL, ADI and DIS (-2 to -78 kg P farm^{-1} yr^{-1}). The negative P balances in the soil-HGF sub-system (soil deficit) differed between MMSs and were lower in ADL (-27 kg P farm^{-1} yr^{-1}) than DIS and SEL. The positive P balances (soil surplus) were only found for ADL (48 kg P farm^{-1} yr^{-1}) and absent for other MMSs.

Table 4. Average P inflows, outflows, and balances of the dairy farming systems, as well of the dairy herd and of the soil-HGF sub-systems, per manure management system, (standard error between brackets).

	DFS			
	ADL[1]	SEL[2]	ADI[3]	DIS[4]
P Inflows (kg farm^{-1} yr^{-1})				
Purchased feed	80 (10.6)	69 (19.0)	62 (12.8)	104 (13.9)
Inorganic fertiliser	0	0	0	0
Total inflow	80 (10.6)	69 (19.0)	62 (12.8)	104 (13.9)
P Outflows (kg farm^{-1} yr^{-1})				
Milk	11 (1.6)	11 (2.8)	11 (2.3)	13 (2.3)
Livestock	5 (1.6)	5 (0.8)	4 (1.0)	3 (0.7)
Sold manure	20^{a} (10.9)	78^{b} (17.6)	11^{a} (3.8)	5^{a} (3.3)
Total outflow	36^{ab} (9.5)	94^{b} (20.5)	26^{a} (5.5)	21^{a} (4.1)
P Balances (kg farm^{-1} yr^{-1})				
P Balances[7]	44^{bc} (15.2)	-25^{a} (5.7)	36^{b} (9.6)	83^{c} (11.8)
P Surplus	56^{ab} (13.2)	N.A.[10]	42^{a} (9.1)	83^{b} (11.8)
P Deficit	-16 (N.A.)	-25 (5.7)	-6 (N.A.[10])	0
	Dairy herd sub-system			
P Inflows (kg farm^{-1} yr^{-1})				
Purchased feed	80 (10.6)	69 (19.0)	62 (12.8)	104 (13.9)
HGF	51 (11.6)	30 (6.3)	31 (7.9)	35 (6.4)
Total inflow	131 (20.7)	99 (19.7)	93 (19.2)	139 (18.7)
P Outflows (kg farm^{-1} yr^{-1})				
Milk	11 (1.6)	11 (2.8)	11 (2.3)	13 (2.3)
Livestock	5 (1.6)	5 (0.8)	4 (1.0)	3 (0.7)
Total outflow	16 (2.5)	16 (3.0)	15 (3.0)	16 (2.7)
P Balances[5] (kg farm^{-1} yr^{-1})	115 (19.1)	83 (16.9)	78 (17.3)	123 (16.1)
	Soil-home-grown feed sub-system			
P Inflows (kg farm^{-1} yr^{-1})				
Inorganic fertiliser	0	0	0	0
Applied manure	68^{b} (30.2)	0	7^{a} (2.60)	0
Total inflow	68^{b} (30.2)	0	7^{a} (2.60)	0
P Outflows (kg farm^{-1} yr^{-1})				
HGF	51 (11.6)	30 (6.3)	31 (7.9)	35 (6.4)
P Balances[6] (kg farm^{-1} yr^{-1})				
P Balances[7]	17 (19.1)	-30 (6.3)	-24 (7.2)	-35 (6.4)
P Surplus[8]	48 (25.5)	N.A.[10]	N.A.[10]	N.A.[10]
P Deficit[9]	-27^{a} (8.7)	-30^{b} (6.3)	-24^{ab} (7.2)	-35^{b} (6.4)

[1]Applying manure directly on forage land, without treatment, [2]Selling or exporting manure, [3]Using manure as substrate for anaerobic digestion, [4]Discharging manure, [5]P balances are calculated based on the difference between P inflows and P outflows of the dairy herd sub-system, [6]P balances are calculated based on the difference between P inflows and P outflows of the soil HGF sub-system, [7]based on P balances across farms in each MMS, [8]P surplus are calculated when the total nutrient input into the soil exceeded the total output (HGF yield), [8]P deficit are calculated when the total nutrient input into the soil is lower than the total output (HGF yeild),[10]N.A. is not applicable, Different superscripts letter show significant difference (P value <0.05)

Table 5. The estimated N-P balances from dairy farms at the Lembang region.

MMS	Number of dairy farms in baseline study (n)	Proportion of MMSs in dairy farming system[1] (%)	Number of dairy farms at the Lembang region (n)	N balances at regional level (ton yr^{-1})	P balances (surplus) at regional level (ton yr^{-1})	P balances (deficit) at regional level (ton yr^{-1})
ADL[2]	30	10	396	84	22	-2.2
SEL[3]	12	4	141	16	0	-3.5
ADI[4]	27	9	360	93	15	-2.3
DIS[5]	231	77	3,061	868	253	0
Total	300	100	3,958	1,061	290	-8

[1] Based on study of de Vries et al. (2017), [2]Applying manure directly on forage land, without treatment, [3]Selling or exporting manure, [4]Using manure as substrate for anaerobic digestion, [5]Discharging manure

3.3 Nutrient balances at regional level

Table 5 presents estimated N-P balances from the dairy farms of the Lembang region. The dominant MMS in dairy farming in this region was DIS, followed by ADL, ADI, and SEL. By upscaling the results in section 3.1 and 3.2, we estimated that about 1,061 tons of N and 290 tons of P are lost annually from dairy farms in the Lembang region and potentially pollute the Citarum river. We also estimated that about 8 tons of P yr^{-1} are extracted from nutrient reserves in soils. Total N loading in the Citarum river was estimated at 51,555 ton yr^{-1}, of which 2,182 ton yr^{-1} was estimated to originate from all cattle sectors (Yoshida et al., 2017). Total N imbalances from dairy in the Lembang region potentially constitute about 2% of the total N loading or 48% of the total N loading from the cattle sector.

Table 6. Land size, nitrogen (N) application from inorganic fertiliser, and manure application room of the four major crops in the Lembang region.

Crops	Land size (ha)[1]	N from inorganic fertiliser (kg ha^{-1} yr^{-1})[2,3]	Total N from inorganic fertiliser (ton yr^{-1})	N from manure (kg ha^{-1} yr^{-1})	Total N from manure (ton yr^{-1})
Long bean	349	162	57	324	113
Chili	336	1,125	361	1,875	403
Tomato	321	600	202	1,200	601
Green bean	287	405	116	810	232
Total	1,293	2,292	736	4,209	1,350

[1]According to BPS (2018), [2]calculated for one-year calendar (4-6 six times harvest a year), [3]According to Indonesian Vegetable Research Institute (IVEGRI)

Table 6 shows the estimated amount of manure-N that could potentially be applied to the major crops being produced in the Lembang region. Based on the land size per crop type and N efficiency rate of the organic fertiliser per crop, the potential amount of manure application to cropland in this region is 1,350 tons of N yr^{-1}. This value exceeds the estimated total N balances (surplus) from the dairy sector (Table 5), which shows that fertilization of cropland in the region offers enough application room for the total amount of N being currently lost from the dairy sector.

4. Discussion

This study quantified N-P balances from smallholder dairy farms at farm and regional level, and analysed differences between farms with different MMSs. We not only analysed nutrient flows and balances at the level of the farming systems, but also at the level of the dairy herd and the soil-HGF sub-system. Identifying nutrient balances at each sub-system enables us to identify improvement options for nutrient management of the entire farming system.

If the difference between nutrient inputs and outputs was positive, these nutrients were assumed to be lost into the environment, and to potentially pollute the environment. A positive N balance (surplus) includes emissions of acidifying gases (e.g., ammonia, nitrogen oxide), greenhouse gases (nitrous oxide), and run-off and leaching of nitrate into ground and surface water, whereas a positive P balance (surplus) refers to run-off or leaching of phosphate. In reality, however, a N-P surplus will not be entirely lost to the environment, as nutrients may be partly stored in the soil. P, for example, is rather immobile and can be stored in the soil for long periods and significant P surplus occur only if the P status in the soil is high (Nobile et al., 2020; van Leeuwen et al., 2019; Takeda et al., 2009). The soil types in our case study had a high P content but not all P is available for the plant (i.e., the Lembang region has andosol or volcanic soil with high phosphate retention) (Sukarman, A, 2014).

In contrast, a negative nutrient balance indicates a deficit of nutrients or potentially a decline in soil fertility (Quemada et al., 2020; Godinot et al., 2014). At DFS level, SEL has a P deficit, implying more nutrients flow out than in the farm. Negative balances N-P (deficit) in the soil-HGF sub-system can imply a depletion of the soil N or P stock. Godinot et al. (2014) demonstrated that we should include a change in soil organic matter into our nutrient balance. We, however, could not exactly quantify the change in soil organic matter, and therefore, excluded changes in soil organic matter from our nutrient balances.

Our study showed that, at DFS, P balances differed among MMSs, whereas N balances did not. N balances did not differ between MMSs, because all urine was discharged in all MMSs. The classification of MMSs was based only on the methods of faeces being collected. The fact that urine was discharged in all MMSs made N balances among MMSs largely comparable, because the N excretion via urine is higher than via faeces (Zahra et al., 2020; Jiao et al., 2014; Knowlton et al., 2010). At DFS, P balances did differ between MMSs because faeces was the most important fraction for P (i.e., P in urine is minimal and can be neglected) (Valk et al., 2002), and faeces collection differed across MMS.

It is important to realize that whether or not manure is seen as a valuable output largely affects the calculation of nutrient balances at DFS. Our study and the study of Spears et al. (2003) considered sold manure a valuable output, because of its value as organic fertiliser. The emissions related to the use of sold manure on, for example arable farms, however, is not included in a nutrient balance as it falls outside the system boundary we applied in the present study. In smallholder dairy farms, using manure as a substrate for anaerobic digestion is promoted as a potential solution to avoid discharging of manure. The effectiveness of this solution, however, depends on the final use of the digestate (i.e., an output when it is sold or exported to other farms, and a loss when it is disposed). We argue that it is important to consider the final use of digestate, because most smallholder dairy farms discharge the digestate instead of utilizing it as fertilizer, implying a loss of valuable nutrients (Bonten et al., 2014).

We expressed nutrient flows and balances per farm because farm characteristics did not differ among MMSs. In addition, we also expressed nutrient balances per unit of land and per unit of product, to enable comparing our results with other studies. Average N balance (surplus) per unit of land (i.e., 1,007 kg N ha^{-1} yr^{-1}), and P balance per unit of land (111 to 440 kg P ha^{1} yr^{1}) were found to be higher compared to Irish and Dutch dairy farms (ranging from 175 to 227 kg N ha^{-1} yr^{-1} and 3.5 to 5.6 kg P ha^{-1} yr^{-1}) (Mu et al., 2016; Mihailescu et al., 2015), which was mainly due to the fact that most of Indonesian dairy farms are land-less (i.e., on average of 0.37 ha). In our study, area-based imbalances varied from 2,513 kg N per ha yr^{-1} for land-less farms (0.1 ha of farmland) to 256 kg N ha yr^{-1} for farms with 1 ha of land. Results indicate that the decoupling of animal and crop production is likely to be one of the main reasons for high nutrient pollution of Indonesian dairy production.

The average N surplus per unit of product of our farms (12 kg ton $FPCM^{-1}$ yr^{-1}) was lower than those at Irish dairy farms (17 to 30 kg ton $FPCM^{-1}$ yr^{-1}), but higher than those at Dutch dairy farms (6 to 8 kg ton $FPCM^{-1}$ yr^{-1}) (Mu et al., 2016; Mihailescu et al., 2014). These lower N surpluses could be explained by lower N inflows on Indonesian smallholder dairy farms than on Irish dairy farms. Furthermore, the type of inflows differed between Indonesian and Irish farms. On Irish dairy farms, inorganic fertiliser for grassland was the major N inflow, while in our study purchased feed caused the majority of N inflow. In contrast, average P balance (surplus) per unit of product (ranging from 2 to 4 kg ton $FPCM^{-1}$ yr^{-1}) was higher than those at Irish dairy farms and Dutch dairy farms (0.1 to 1.2

kg ton $FPCM^{-1}$ yr^{-1}) (Mu et al., 2016; Mihailescu et al., 2015). This higher average P surplus per unit of product at Indonesian smallholder dairy farms resulted from a higher P inflow via purchased feed, lower P outflow via milk (Zahra et al., 2020), and discharging of P via manure.

To gain insight into soil nutrient balances, we examined nutrient balances of surplus and deficit farms separately. To avoid a N-P surplus in the soil-HGF sub-system, some ADL farms need to sell the excess of faeces, whereas to avoid N-P deficits in the soil-HGF sub-system, SEL, DIS, ADI and some ADL farms need to increase faeces use and begin to use urine. Overall, we found that, on the one hand, large amounts of nutrients (N-P) are subtracted from the soil (soil deficit), while on the other hand nutrients are lost because of poor manure management (e.g., DIS). A soil deficit, particularly for P, most likely may not be a problem in the short-term. Monitoring N-P status in the soil, and applying manure at the soil-HGF sub-system at the right rate and time could improve fertilizer use efficiency, mitigate soil depletion and improve soil productivity (Wu et al., 2020; Cai et al., 2019).

Our results show that nutrient losses from dairy farms in the Lembang region (about 1,061 tons of N and 290 tons of P per year) potentially pollute the Citarum river. As mentioned earlier, however, we know that not all N surplus is leaching into the Citarum river. Part of N surplus is released to the air, via volatilisation of NH_3 or emissions of N_2O and NOx, or stored in the soil. The N surpluses of dairy farming at regional level can be reduced if manure management is improved. Farmers can improve manure management at their farm by collecting all animal excreta, including urine, and improving the application of collected urine and manure at the expense of artificial fertiliser. Only excess manure, i.e., manure that cannot be applied on on-farm land, should be sold to other farms. Selling all manure, as is currently the case in SEL, causes soil nutrient deficient at farm level.

The excess manure from dairy farms can be applied to fertilize cropland in the region. Crop farmers are currently relying mainly on inorganic fertilisers, being subsidised by the Indonesian government. Those subsidies reduce the price of inorganic fertilisers up to 60% (FAO 2017; Warr et al., 2014), and are therefore an important constraint for farmers to replace inorganic fertiliser with manure from neighbouring farmers. Furthermore, crop farmers can partly substitute inorganic fertiliser by manure, but if they use it additionally, it will not solve the problem. In addition, N balances (surplus) in the form of NH_3, Nox, and N_2O and NO_{3-} are released when manure is applied at the crop cultivation area, generating other imbalances from manure of dairy farms. High density of dairy farms in this region has consequently contributed to high N imbalances and implying heavy environmental pressure on the Lembang region and the Citarum river. The nutrient imbalances from the dairy sector in the region will not be solved if both dairy and crop farms are reluctant to collaborate.

We furthermore need to realize that by importing purchased feed (e.g., concentrates) into the Lembang region, you basically import "nutrients" into the region. In the past, dairy farming used to be a low-input, low-output practice, utilizing crop residues or pasture as the major feed to avoid negative environmental issues (Bijttebier et al., 2017; Zhang et al., 2017). By importing large amounts of feeds (high input) current dairy farms may be able to increase their milk productivity (high output), but the capacity to sustain such high-input high output systems is limited by the capacity of arable farms to apply excess manure. Finally, to close the loop of nutrients, we furthermore may need to recycle nutrients from human excreta back to the region of feed production (Harder et al., 2019; Andriani et al., 2015).

5. Conclusions

We quantified nutrient flows and balances from smallholder dairy farms at farm and regional level, and analysed differences in balances between MMSs. All farms had a positive N balance, and we found no differences between MMSs. Some farms had a positive, whereas other farms had a negative P balance. P balances differed between MMSs, and where highest for DIS and lowest for SEL. To reduce nutrient imbalances at farm level, dairy farms can improve the collection and on-farm use of manure and sell excess manure to crop farms. To reduce nutrient imbalances at regional level, crop farms can replace their use of inorganic fertilisers with manure from dairy farms.

Chapter 4

Understanding variability in greenhouse gas emission estimates of smallholder dairy farms in Indonesia

Typical smallholder dairy farms in Indonesia

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Abstract

Life cycle assessment studies on smallholder farms in tropical regions generally use data that is collected at one moment in time, which could hamper assessment of the exact situation. We assessed seasonal differences in greenhouse gas emissions (GHGE) from Indonesian dairy farms by means of longitudinal observations and evaluated the implications of number of farm visits on the variance of the estimated GHGE per kg milk (GHGEI) for a single farm, and the population mean. An LCA study was done on 32 smallholder dairy farms in the Lembang district area, West Java, Indonesia. Farm visits (FVs) were performed every two months throughout one year: FV1-FV3 (rainy season) and FV4-FV6 (dry season). GHGE were assessed for all processes up to the farm-gate, including upstream processes (production and transportation of feed, fertiliser, fuel and electricity) and on-farm processes (keeping animals, manure management, and forage cultivation). We compared means of GHGE per unit of fat-and-protein-corrected milk (FPCM) produced in the rainy and the dry season. We evaluated the implication of number of farm visits on the variance of the estimated GHGEI, and on the variance of GHGE from different processes. GHGEI was higher in the rainy (1.32 kg CO_2-eq kg^{-1} FPCM) than in the dry (0.91 kg CO_2-eq kg^{-1} FPCM) season ($P < 0.05$). The between farm variance was 0.025 kg CO_2-eq kg^{-1} FPCM in both seasons. The within farm variance in the estimate for the single farm mean decreased from 0.69 (1 visit) to 0.027 (26 visits) kg CO_2-eq kg^{-1} FPCM (rainy season), and from 0.32 to 0.012 kg CO_2-eq kg^{-1} FPCM (dry season). The within farm variance in the estimate for the population mean was 0.02 (rainy) and 0.01 (dry) kg CO_2-eq kg^{-1} FPCM (1 visit), and decreased with an increase in farm visits. Forage cultivation was the main source of between farm variance, enteric fermentation the main source of within farm variance. The estimated GHGEI was significantly higher in the rainy than in the dry season. The main contribution to variability in GHGEI is due to variation between observations from visits to the same farm. This source of variability can be reduced by increasing the number of visits per farm. Estimates for variation within and between farms enable a more informed decision about the data collection procedure.

1. Introduction

The consumption of dairy products in Indonesia is rising due to population growth, a growing middle class and dietary shifts (Priyanti and Soedjana 2015). However, the national milk production only fulfils 17% of the national demand of dairy product (BPS, 2019). The Indonesian government policy aims to fill this gap between production and demand by, among others, increasing the number of dairy cattle on smallholder dairy farms (from 2-3 to 7 heads per farm) (Kemenko Ekon, 2016). Policies targeted at smallholder farms may have significant effects on national milk production because 88% of national milk production originates from these farms (Morey 2011).

Depending on Indonesia's strategy taken to increase domestic milk production, greenhouse gas emissions (GHGE) from dairy production may further increase, particularly if the numbers of cattle are to be increased (Tubiello et al. 2014; de Vries et al. 2019). Life cycle assessment (LCA) is a well-known method to assess GHGE along the production chain of milk and is mainly used to identify emission hotspots and potential mitigation options. In the calculation of GHGE from dairy farms, three main sources are identified: enteric fermentation (major GHG: methane (CH_4)), manure management (major GHGs: nitrous oxide (N_2O) and CH_4), and feed production including cultivation, processing and transportation (major GHGs: carbon dioxide (CO_2) and N_2O) (FAO and GDP 2018). Feed is a major contributor to global estimates of GHGE from dairy production because it is associated with CH_4 emission from enteric fermentation (47% of total GHGE) and emissions related to feed production (19%) (Gerber et al. 2013). Manure management is another important contributor, accounting for 26% of total emissions in the global dairy chain (Gerber et al. 2013).

Most LCA studies on smallholder farms in tropical regions use data that is collected at one particular moment in time (i.e. cross-sectional observation) to estimate the annual average of GHGE related to milk and live weight production (e.g. Garg et al. 2016; Taufiq et al. 2016). The main reason for this is that data collection is difficult and time consuming. To address variation in farm management practices over time, researchers often ask farmers to recall the situation over a particular year or season (e.g. de Vries et al. 2019). However, both cross-sectional observations and farmer recall could hamper an accurate assessment of the exact situation on a farm. For example, a study by Migose et al. (2020) showed that assessment of milk yield based on farmers recall was less accurate than those based on recordings, while milk yield explains a significant part of the variation in GHG emission intensity (e.g. de Vries et al. 2019; Wilkes et al. 2020). As the climate of Indonesia is characterized by a dry and a rainy season, dairy farmers adapt their practices to these seasons, mainly with regard to the amount and type of feed offered to dairy cattle (de Vries and Wouters 2017). In addition, dairy farmers in other tropical countries also adapt their manure management practices across seasons (Zake et.al. 2010; Paul et al. 2009). Seasonal differences in management practices and in the quantity and quality of available feed (Lanyasunya et al. 2006; Maleko et al. 2018; Richard et al. 2015) can be an important source of variability of GHGE estimates of smallholder dairy farms in the tropics.

To address the variation in farm management practices over time in the assessment of GHGE, longitudinal observations are preferred over a single observation. As frequent sampling from smallholder farms in tropical countries is time-consuming and costly, however, the number of visits (observations) per farm required for accurate estimation of GHGE should be optimized. To decide on the number of visits per farm, insight into the relation between the visits per farm and the variation in the estimated GHGE per kg milk is required. This study, therefore, aimed to assess seasonal differences in GHGE per kg milk of Indonesian dairy farms by means of longitudinal observations, and subsequently evaluate the implications of the number of visits per farm on the variation of the estimated GHGE per kg milk for a single farm, and for the population mean (as estimated by the mean over several farms).

2. Methods

2.1 Study area and farms selection

The LCA study was done in the Lembang district area, West Java, Indonesia. This area is the second largest dairy production region in Indonesia and provides 14% of the total national milk supply (Kementan 2018; KPSBU 2018). The area is an equatorial zone according to the Köppen-Geiger climate classification, with an average daily temperature above 18,□ a rainy season from October to March (monthly precipitation > 60 mm) and a dry season from April to September (monthly precipitation < 60 mm).

We selected 32 dairy farms from 300 randomly selected smallholder dairy farms surveyed by De Vries and Wouters (2017). To address variation in farm management that is likely to affect GHGE, we assigned these 300 farms to one of four feeding systems according to land size and milk yield, and to four manure management systems (MMSs). Because land size and milk yield, and consequently the feeding systems of the selected farms were not the same as recorded by De Vries and Wouters (2017) upon our farm visit, categorization based on feeding system was dismissed. The four MMSs were: apply manure for forage cultivation, sell manure, use manure for bio-digester (which could subsequently be used as fertilizer), and discharge manure. The classification of MMSs was based on the main part of faeces being collected. If farmers collected manure, they only collected faeces and discharged urine. Initially, we selected 8 farms randomly within each MMS, but some farms changed their MMS in between the study of De Vries and Wouters (2017) and our farm visits, hence we allocated them to a different MMS. Consequently, the number of farms differed between MMSs. Throughout the period of data collection all farmers stuck to the MMS they practiced at the start of the farm visits.

2.2 System description

Figure 1 provides an outline of the dairy farming system and all activities included in our LCA. The system boundary of our LCA includes upstream and on-farm activities. The upstream activities include the production (cultivation and processing) and transportation of the inputs to the farms. The inputs are purchased feeds (concentrate, tofu by-product, cassava pomace and rice straw), inorganic fertiliser (urea) used for forage cultivation, fuel, and electricity. On-farm activities include management of the dairy herd (lactating cows, dry cows, heifers, female and male calves, and male cattle), manure management, and forage cultivation. The outputs from the dairy farms are milk, live animals, and sold manure. Most of the produced milk (95%) is sold to the dairy cooperative in the Lembang district, whereas the remainder is consumed by households or fed to calves. Farmers sell cattle occasionally to the slaughterhouses or other farmers. Crop cultivation for human consumption and households is excluded from our system boundary as these processes are considered not to be part of the dairy production system. The utilisation of biogas to replace liquid petroleum gas (LPG) at the household is included within the system boundary of this study.

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2.3 Data collection

We visited each of the 32 smallholder dairy farms every two months from December 2017 till October 2018. The farm visits (FVs) from December 2017 to April 2018 (FV1 to FV3) were considered visits in the rainy season, whereas the FVs from June to October 2018 (FV4 to FV6) were considered visits in the dry season.

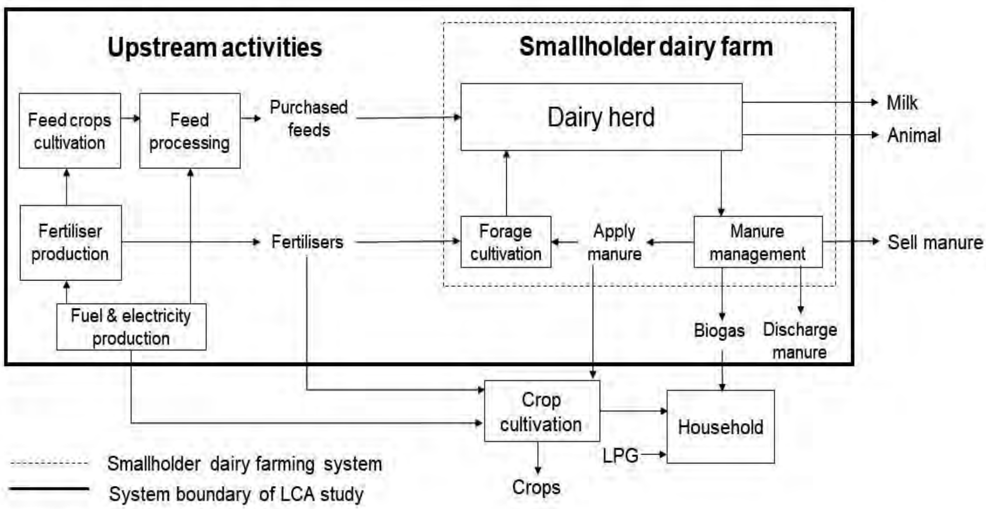

Figure 1. Outline of the smallholder dairy farming system in the Lembang district, Indonesia, and all activities included in our system boundary.

During each FV, we assessed feed intake of the cows, daily milk yield, and cattle body weight. To assess daily feed intake of the cows, we measured the offered feed and subtracted the feed refusal collected on the following day. To calculate the milk yield, we weighed the milk yield at morning and afternoon milking time. We also weighed the amount of milk fed to calves. The milk output from the farm was estimated as the total daily milk yield minus the amount of milk fed to calves. To estimate the cattle body weight, we measured the length and girth of the cows and used the Schoorl equation (Kusuma and Ngadiyono 2017).

We sampled forage and milk at each dairy farm once in the rainy season (at FV1) and once in the dry season (at FV5). Samples of tofu by-product and cassava pomace were collected only in the rainy season because these feeds are produced by food processing industries using standardized procedures and similar ingredients throughout the year, so we assumed that the variation of nutrient composition was minimal. In the case of concentrate, the dairy cooperative in Lembang district produced the concentrate for all dairy farms in the district and regularly analysed the nutritional composition of the concentrate. We observed that the nutritional composition of concentrate tested by the dairy cooperative showed minimal variation although the composition of ingredients varied slightly throughout the year. Hence, we analysed a concentrate sample only once in the rainy season. The proximate analysis was performed to assess the concentrations of dry matter, crude protein, crude fibre, and crude fat of feed samples (AOAC 1990). A milk sample was collected from each lactating cow for analysis of protein and fat content. All laboratory analyses were performed at the laboratory of the Faculty of Animal Science, IPB University (Bogor Agricultural University), Indonesia.

At each FV, we asked the farmers about current herd composition, manure management, forage cultivation and price of purchased feeds. Regarding herd composition, we asked the number of animals present, the number of purchased and sold animals in the two months prior to the FV, and animals' age. In terms of manure management, we asked the farmers to estimate the proportion of faeces currently being collected, the proportion of faeces being used in the biodigester, the proportion of applied faeces on the forage cultivation area, the proportion of sold faeces and the proportion of manure being discharged (including urine). To gain insight into forage cultivation, we asked about land size, quantity of applied fertilisers, and period of fertilisation. In addition, we asked the farmers about the usage of LPG for cooking in the household to be able to calculate the amount of LPG used before and after installation of an anaerobic digester.

Only at one FV, we asked the farmers about the size of the bio-digester, and the origin of rice straw, tofu by-product, and cassava pomace. The origin of these products was used to calculate the distance of transportation to the farms, which we subsequently used to calculate the emission from transportation of purchased feed. We interviewed the staff members of the dairy cooperative in charge of concentrate production to collect information about variation in the composition of concentrate throughout the year, annual energy use for concentrate production, and total annual production of concentrate.

2.4 Calculation of emissions

Emission factors from databases and information from literature were used to calculate GHGE from upstream activities. In case of purchased feeds, we used the LEAP database (FAO 2015) to estimate GHGE from cultivation of various feed crops (e.g. soybean, cassava, wheat, maize; see Table 1). In case of GHGE from rice straw, we also included CH_4 emissions from rice fields (IPCC 2019). The emissions related to energy use to process and transport purchased feeds to the smallholder dairy farms were based on Ecoinvent Version 3 (Wernet et al. 2016).

All assumptions to calculate emissions related to cultivation, transportation and processing of feed crops are provided in the Supplementary material (Table S1). The GHGE from purchased feeds are presented in Table 1 and are all calculated based on economic allocation (see section 2.5).

The CH_4 emissions from on-farm activities included those from enteric fermentation and manure management (including the storage, application and discharge of manure, and the production of biogas). For enteric fermentation, we used IPCC (2019) Tier 2 to estimate the conversion of gross energy intake into enteric CH_4 emissions. The gross energy intake was calculated by multiplying

Table 1. Greenhouse gas emissions (GHGE) in kg CO_2 equivalent per kg of feed in dry matter.

Feeds	Emission factor	Reference
Wheat pollard	0.26	FAO (2015); personal communication with staff of Bogasari Flour Mill, Indonesia
Rice bran	0.61	Agatha (2016); IPCC (2019); Wernet et al. 2016
Corn gluten feed	0.37	Vellinga et al. (2013)
Copra meal	0.16	Vellinga et al. (2013)
Palm kernel meal	0.20	Vellinga et al. (2013)
Coffee hull	0.10	Personal communication with coffee farmers in Lembang, Indonesia
Tofu by-product	0.76	FAO (2015); Liu et al. (2017); Wernet et al. (2016); Zannah (2017)
Cassava pomace	0.24	FAO (2015); Suroso (2011); Wernet et al. (2016)
Concentrate	0.25 - 0.30*	Wernet et al. (2016); personal communication with staff of dairy cooperative in Lembang, Indonesia
Rice straw	0.42	Agatha (2016); IPCC (2019); Wernet et al. (2016)

*the emission factor of concentrate varies due to different composition and energy use in the feed mill throughout one year feed intake and gross energy content of feed. The latter was estimated based on the concentration of carbohydrates, protein, and fat in the collected feed samples (NRC 2001). To calculate CH_4 emission from manure management, we multiplied the quantity of faeces being collected with the methane conversion factor (MCF) of different manure management systems (IPCC 2019). In the case of faeces stored for sale, the MCF of the IPCC-category liquid/slurry was used. In the case faeces stored in the digester for biogas generation, MCF of the IPCC-category anaerobic digester was used. In the case faeces or digestate (the by-product of bio-digester) applied for forage cultivation, and in the case of faeces or digestate to be discharged, MCF of the IPCC-category daily spread was used. Emissions from the bio-digester also included biogas loss that is not used for cooking in households. Ideally, households use the biogas to reduce or fully replace LPG-use for cooking. In some cases, however, biogas yield outweighed LPG-use for cooking, or was not fully utilized, resulting in an additional loss of CH_4.

The biogas loss was calculated by subtracting the biogas used for cooking from the biogas yield, and assuming a CH_4 content of 65% (IRENA 2006). The biogas used for cooking was calculated based on the difference between LPG-use before and after installation of the bio-digester. The biogas yield was calculated based on IRENA (2016). The parameters of temperature and retention time (IRENA 2016), the volatile solid (IPCC 2019), and the volume of the digester, were used to calculate the biogas yield. On-farm N_2O emissions are attributed to manure management, and to urea application for forage cultivation. To calculate N_2O emission from manure management, we first estimated the production of manure-N on farm. This was done by subtracting total N retained for milk, growth, and pregnancy from the total N intake. We calculated the total N intake from feed by multiplying the total daily feed intake of the cows on dry matter basis with the N content of the feed. To calculate N retention for lactating cows, we quantified N in milk by multiplying the total milk yield with the N content in milk. To calculate N retention for heifers, female and male calves, and male cattle (<24 months old), we estimated the retained N for growth, and to calculate N retention for dry cows we estimated the retained N for pregnancy (on 190-279 days) based on NRC (2001). Since the faeces and urine are treated separately in smallholder dairy farms (i.e., 100% urine being discharged), the quantity of faecal N and urinary N were calculated separately as described by Zahra WA et al. (2020).

The quantity of faecal-N was obtained by multiplying the proportion of faecal-N in the manure-N with the production of manure-N. To calculate the quantity of faecal-N collected, we multiplied the quantity of faecal N with the proportion of faeces collected. To calculate N_2O emissions from manure management, we multiplied the quantity of faecal-N collected with the N_2O emission factors of different manure management systems (IPCC 2019). To estimate direct N_2O emissions from manure storage (i.e. for manure that is stored and being sold), the N_2O emission factor of the IPCC-category liquid/slurry was used. To estimate direct N_2O emissions from production of biogas, the N_2O emission factor of the IPCC-category anaerobic digester was used. To estimate direct N_2O emissions from applied faeces and applied digestate for forage cultivation, and to calculate direct N_2O emissions from discharged faeces and discharged digestate, the N_2O emission factor of the IPCC-category daily spread was used. To calculate direct N_2O emissions from discharged urine, also the N_2O emission factor of the IPCC-category daily spread was used.

Indirect N_2O emissions are related to N losses in the form of NH_3, NO_x volatilization and in the form of NO_3^- leaching. To estimate volatilization of NH_3 and NO_x from manure that is stored and sold, the emission factor of the IPCC-category liquid/slurry was used. For production of biogas, the emission factor of the category anaerobic digester was used. For applied faeces and applied digestate for forage cultivation, and for discharged manure and discharged digestate, the emission factor of the daily spread was used. For discharged urine, also the emission factor of the category daily spread was used. The fraction of N losses in the form of NO_3^- leaching for specific manure management systems were based on personal communication with experts (De Vries et al. 2019). To estimate leaching of NO_3^- from manure storage, a leaching fraction of 18% was used. For applied faeces and applied digestate for forage cultivation, a NO_3^- leaching fraction of 30% was used. For discharged manure including discharged digestate, the NO_3^- leaching fraction was calculated by subtracting N losses in the form of N_2O, NH_3 and NO_x, from the total amount of N excreted. The default emission factor of 0.01 for indirect N_2O emissions from N volatilization, and 0.0075 for indirect N_2O emissions from N leaching and runoff was used (IPCC 2006). In addition, CO_2 emissions related to urea application were included based on IPCC Tier 1 (IPCC 2006).

2.5 Allocation methods

Some of the processes along the production chain yield multiple outputs, such as rice cultivation yielding rice and straw, and dairy production yielding milk and meat. This study used different methods to deal with allocation of GHGE for such processes. To allocate emissions related to feed production economic allocation was used, which means that emissions from processes with multiple outputs were allocated to the outputs based on their relative economic value (Table S2, Supplementary material).

To allocate GHGE to milk, we applied economic allocation with bimonthly data on body weight gain of the animals serving as an estimate for meat output. Prices of meat and milk were based on farm surveys and the body weight gain was calculated by the difference in body weight of individual animals (young stock and male cattle) between two sequent FVs. As another means to reduce data requirements, we explored the implications of using a method that prevents allocation by dividing the herd into milk and meat producing animals. This method seems justified because young stock and male cattle were generally sold to generate additional income, and not kept for replacement. In case of this alternative method, all GHGE from the adult cows (i.e., lactating and dry cows) are attributed to milk production, and all GHGE related to heifers, female and male calves, are attributed to meat production. The advantage of this method is that data requirements are reduced to a minimum (e.g., all data related to young stock, such as data on feed intake, manure production, and productivity, as well as economic data to calculate allocation factors can be discarded), being beneficial for studies in tropical regions that are often characterized by data scarcity and uncertainty. This method will be further referred to as system division.

In addition to milk and meat, some of the dairy farmers also sell manure (sold faeces) to crop farmers. We did not allocate any emissions to sold faeces, nor apply another method to account for this output for two reasons. First, the economic benefit from sold faeces is very low in comparison with milk and sold animals; applying economic allocation would not have changed the results and conclusions of this study. Second, although sold faeces is used by other farmers as organic fertilizer, it is not replacing synthetic fertilizer (personal communication with local crop farmers), which means that system substitution or system expansion does not apply here. In case of faeces that is used to produce biogas, however, system substitution was found to be most suitable as biogas replaces the use of LPG in farmer's households. Foregone emissions related to the production and combustion of this LPG were therefore subtracted from the total GHGE on those farms.

2.6 Impact assessment and interpretation

GHGE from different processes, from all farm visits, at the upstream (i.e., purchased feed and fertilizers) and on-farm (i.e. enteric fermentation, manure management, and forage cultivation) processes were converted into CO_2-equivalents (CO_2-eq) using the weighing factors 1 for CO_2, 265 for N_2O and 28 for biogenic CH_4 (Myhre et al., 2013). Subsequently, GHGE from all processes (i.e., upstream and on-farm) were summed up into total GHGE. To calculate greenhouse gas emission intensity (GHGEI), we divided total GHGE by milk yield (Eq. 1).

$$\mathrm{GHGEI} = \frac{\sum \mathrm{GHGE\ from\ different\ processes}}{\mathrm{milk\ yield}} \tag{1}$$

where ∑GHGE from different processes are the total GHGE from enteric fermentation, manure management, forage cultivation, and purchased feed (kg CO_2-eq), and milk yield is the milk output from a farm in kilogram of fat- and protein-corrected milk (kg FPCM) according to IDF (2015) (Eq. 2).

$$\mathrm{FPCM} = \mathrm{measured\ milk\ yield\ (kg)\ x\ [0.1226\ x\ milk\ fat\%} + \mathrm{0.0776\ x\ milk\ protein\%} + 0.2534] \tag{2}$$

2.7 Statistical analysis

Means of characteristics of the smallholder dairy farms in the rainy and the dry season were compared by the paired sample t-test. Means of GHGEI of the four different MMSs in the rainy and the dry season were compared using ANOVA. Means of GHGEI in the rainy and the dry season were also compared by the paired sample t-test. To understand the relation between the GHGEI based on economic allocation and GHGEI based on system division in both seasons, we did a Pearson correlation analysis.

For analysis of the data collected per farm and season a linear mixed model was used. Initially this model comprised five dispersion parameters: separate components of farms (between farms component of variance) and error (within farms component of variance) per season and a covariance between random effects of the same farm within the two seasons. A likelihood ratio test (Cox & Hinkley, 1979), comparing this model with a reduced model with a single component of variance for farms and for error for both seasons showed heterogeneity of variance between seasons (P-value = 0.005). Estimated components of variance for farms in the two seasons were found to be virtually the same and a second likelihood ratio test comparing with a model with a common variance component for farms and different error components for seasons was not significant at all (P-value = 1.0). Therefore, for the final calculations a linear mixed model was used with the same component of variance for farms in both seasons but different within farm variance in the two seasons. In addition, all linear mixed models considered comprised fixed effects for the two seasons, allowing for a difference in expected response between seasons. Components of variance were estimated by restricted maximum likelihood (REML, e.g. McCulloch, Searle & Neuhaus, 2008). Facilities from R routine glmmTMB (Brooks et al., 2017) were used for the calculations, i.e. to obtain deviances to calculate the likelihood ratio tests.

The estimated components of variance per season allow for the evaluation of the following criteria to compare sampling schemes with 1, 2 or 3, and even more visits collected per farm. In addition to the sampling schemes with 1, 2, or 3 visits we therefore also compared a hypothetical scheme with a number of 26 visits (weekly) collected per farm per season. Criteria considered were: (1) expected width of a 0.95 confidence interval (CI) of the mean of a single farm: $2 \times 1.96 \times \sqrt{\frac{\sigma^2_{error}}{n}}$;(2) expected width of a 0.95 confidence interval of the population mean based upon a number of randomly selected farms: $2 \times 1.96 \times \sqrt{\frac{\sigma^2_{farm}}{m} + \frac{\sigma^2_{error}}{nm}}$; (3) repeatability per farm, expressed as the correlation between (hypothetical) repeated farm means: $\sigma^2_{farm}/(\sigma^2_{farm} + \frac{\sigma^2_{error}}{n})$, where n is the number of visits per farm, e.g. n = 1, 2, or 3, m is the number of farms, and components of variance are replaced by their REML estimates. In all expressions, per season, the same estimated component of variance for farms (i.e., between farm variance) was used for both seasons, but different estimates for the error variances (i.e., within farm variance). To understand the importance of variation in GHGE from different processes, including enteric fermentation, manure management, purchased feed, and forage cultivation the same procedure was followed.

3. Results

3.1 Comparing GHGEI of milk between seasons

Table 2 shows the characteristics of the farms in the rainy and the dry season based on all six FVs. The average herd size of the 32 farms was 4 adult cows. On average, the dry matter intake (DMI) of lactating cows was 15% lower in the dry season than in the rainy season. The DMI of heifers was 35% lower in the dry season than in the rainy season. The proportion of elephant grass in the ration for lactating cows was lower whereas the proportions of rice straw, concentrate, and tofu by-product were higher in the dry season than in the rainy season. The content of gross and metabolizable energy in diets for lactating cows during the dry season was lower than during the rainy season, but the protein content was similar in both seasons. The daily milk yield per cow did not differ between seasons. The amount of N applied via inorganic fertiliser (faeces) was 55% lower in the dry season than in the rainy season. The proportion of collected faeces on farm was 14% lower in the dry season than in the rainy season. The proportion of faeces being collected had an important impact on the estimated direct and indirect N_2O emissions related to manure management.

Table 3 shows the GHGEI per kg milk produced, the contribution of different processes, and proportion of the different GHGs in each season. The different processes are enteric fermentation, manure management, forage cultivation, and the cultivation, transport and processing of purchased feeds. The average GHGEI was higher in the rainy (i.e. 1.32 CO_2-eq kg^{-1} FPCM) than in the dry (i.e. 0.91 kg CO_2-eq kg^{-1} FPCM) season (P-value < 0.05). This difference between seasons was explained by differences in emissions related to enteric fermentation (being 23% higher in the rainy season than in the dry season), manure management (being 38% higher in the rainy season than in the dry season), and forage cultivation (being 80% higher in the rainy season than in the dry season). The CH_4 from enteric fermentation was the major portion of the total sum of GHGs emitted in both seasons. The GHGEI between the four different MMSs did not differ in the rainy and the dry season (Table S3; Supplementary material). Therefore, we do not further distinguish between farms with different MMS in the present study.

Table 4 shows GHGEI per kg milk at each FV in the rainy and the dry season. The mean GHGEI at each FV ranged from 0.84 (FV6) to 1.40 (FV2) kg CO_2-eq kg^{-1} FPCM. Within seasons, GHGEI did not differ between FVs. The results of the GHGE calculations per unit of meat can be found in the Supplementary material (Table S4).

Table 2. Characteristics of 32 smallholder dairy farms in Lembang district, Indonesia in the rainy and the dry season, based on six farm visits from December 2017 to October 2018.

Characteristics	Rainy season*	Dry season*
Farm size (ha)	0.4 (0.38)	0.4 (0.36)
Herd composition (number per farm)		
Adult cows (lactating and dry cows)	4.2 (2.1)	3.8 (1.9)
Female calves and heifers	1.5 (1.8)	1.8 (1.8)
Male cattle (6 - 24 months old)	0.2 (0.5)	0.3 (0.8)
Male calves (≤ 6 months old)	0.6 (1.2)	0.8 (1.5)
Dry matter intake (kg animal^{-1} day^{-1})[1]		
Lactating cows	15.1^{a} (3.4)	13.1^{b} (3.6)
Dry cows	10.9 (3.9)	10.0 (4.5)
Heifers (6-24 months old)	10.6^{a} (4.9)	6.3^{b} (3.5)
Male cattle (12 - 24 months old)[2]	9.1 (5.8)	8.2 (4.7)
Male cattle (6 - 12 months old)[2]	4.4 (2.6)	3.5 (2.7)
Dietary proportion for lactating cows in dry matter		
Roadside grass	0.06 (0.14)	0.06 (0.11)
Elephant grass	0.28^{a} (0.18)	0.19^{b} (0.16)
Rice straw	0.09^{b} (0.13)	0.13^{a} (0.14)
Concentrate	0.35^{b} (0.15)	0.39^{a} (0.17)
Tofu by-product	0.13^{b} (0.15)	0.16^{a} (0.18)
Cassava pomace	0.09 (0.10)	0.07 (0.09)
Crude protein intake (g cow^{-1} day^{-1})	136.0 (18.0)	137.0 (16.7)
Gross energy (GE) intake (MJ cow^{-1} day^{-1})	252.4^{a} (44.2)	214.8^{b} (47.0)
Metabolisable energy (ME) intake (MJ ccow^{-1} day^{-1})	161.8^{a} (22.6)	143.3^{b} (28.5)
ME/GE (fraction)	0.62^{b} (0.05)	0.63^{a} (0.03)
Estimate of GE intake based on IPCC (2019) (MJ cow^{-1} day^{-1})	320.3 (37.7)	319.6 (43.5)
Body weight of adult cow (kg)	450.9 (34.9)	462.7 (37.8)
Milk production (kg cow^{-1} day^{-1})	14.1 (3.5)	15.3 (4.4)
Milk fat content (%)	4.0^{a} (0.5)	3.3^{b} (0.6)
Milk protein content (%)	2.9^{b} (0.2)	3.6^{a} (0.7)
Inorganic fertiliser for forage cultivation (kg N farm^{-1})	12.4^{a} (7.7)	0^{b}
Faeces application for forage cultivation (kg N farm^{-1})	9.3 (29.4)	4.1 (10.4)
Collected manure on farm (% of faeces)	69^{a} (26)	59^{b} (35)

*value between the brackets presents standard deviation (n = 32); superscripts show significant difference (P-value < 0.05).
[1]The DMI for calves (<6 months old) was excluded because the farmers fed only milk.
[2]The DMI for male cattle was classified into two categories of age because high variation of the DMI if the data being presented in one category

Table 3. Greenhouse gas emission intensity (GHGEI) per kg of fat-and-protein-corrected milk (FPCM), emissions per process, and contribution per gas per process in the rainy and dry season.

Items	kg CO_2-eq kg^{-1} FPCM		GHG	Contribution (%) to GHGEI	
	Rainy season	Dry season		Rainy season	Dry season
Total GHGEI	1.32^a (0.39)	0.91^b (0.22)			
Emissions per process:					
Enteric fermentation	0.70^a (0.20)	0.54^b (0.11)	CH_4	55	60
Manure management	0.19^a (0.16)	0.12^b (0.12)	CH_4	10	8
			N_2O	5	5
Forage cultivation	0.19^a (0.19)	0.05^b (0.12)	N_2O	13	5
			CO_2	1	0
Purchased feeds	0.22 (0.12)	0.20 (0.08)	CO_2	12	15
			N_2O	1	2
			CH_4	3	5

*values between brackets present the standard deviation (n = 32); superscripts show significant difference (P-value < 0.05)

3.2 Comparing GHGEI of milk within seasons

Figure 2a and b illustrate the GHGEI for each of the 32 smallholder farms at all visits in the rainy (a) and the dry season (b). These figures show that the estimates of GHGEI of each farm varied between FVs within seasons. Variation in GHGEI within a farm can be explained by fluctuations in milk yield across FVs, which could be related to the lactation stage of the cows, and fluctuations in DMI, being related to feed availability. The GHGEI of individual farm visits ranged from 0.3 to 4.3 kg CO_2-eq kg^{-1} FPCM. The highest value was explained by a low milk yield (e.g., end of lactation), and a high DMI (i.e., abundance of feed in the rainy season). The lowest value was explained by a high milk yield (e.g., beginning of lactation), and a low DMI (i.e., lack of feed in the dry season). In addition to stage of lactation, milk yield is also related to the parity of a cow (i.e., first, second). Since information about parity was based on farmers' interview, it was regarded to be uncertain. The missing data of GHGEI (Figure 2) relates to a situation where milk yield was zero because cows were in their dry period.

Table 4. Mean and standard deviation of greenhouse gas emission intensity (GHGEI) per kg of fat-and-protein-corrected-milk (FPCM) at each farm visit (FV) in rainy and dry season.

Season	Farm visit	GHGEI (kg CO_2-eq kg^{-1} FPCM)*
Rainy	FV1	1.25 (0.51)
	FV2	1.40 (0.68)
	FV3	1.27 (0.51)
Dry	FV4	0.91 (0.44)
	FV5	0.89 (0.37)
	FV6	0.84 (0.37)

*values between the brackets present the standard deviation (n = 32)

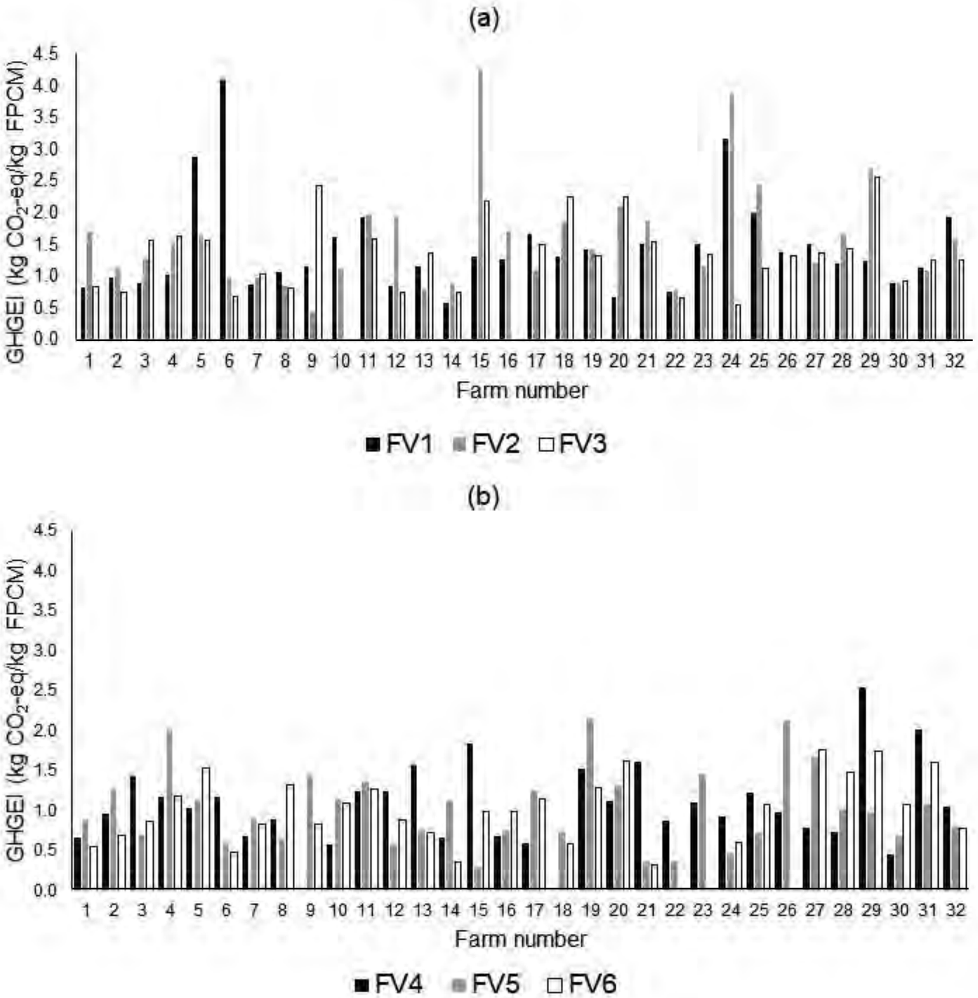

Figure 2. Greenhouse gas emission intensity (GHGEI; kg CO_2-eq kg^{-1} FPCM) for each of the 32 smallholder farms in the rainy season (a) and the dry season (b).

3.3 Relation between number of farm visits and variability of GHGEI estimate

Table 5 shows the between farm variance and the within farm variance of the estimated GHGEI for a single farm mean and for the population mean (32 farms), in the rainy and dry season based on 1, 2, or 3 visits per farm, and based on a hypothetical number of 26 (i.e., weekly) visits. The between farm variance was 0.025 kg CO_2-eq kg^{-1} FPCM in both seasons. The within farm variance of the estimate for a single farm mean and for the population mean decreased with an increased number of visits per farm in both seasons. In the rainy season, the within farm variance of the estimate for a single farm

Table 5. The between farm variance and the within farm variance of the estimated greenhouse gas emission intensity (GHGEI) per kg of fat-and-protein-corrected-milk (FPCM) for a single farm mean and for the population mean in the rainy and dry season with a sampling scheme of 1, 2, 3, or 26* visits per farm.

Between farm variance (kg CO_2-eq kg^{-1} FPCM)	Within farm variance (kg CO_2-eq kg^{-1} FPCM)			
		Number of visits	Rainy season	Dry season
0.025	Of the estimate for a single farm mean	1	0.69	0.32
		2	0.34	0.16
		3	0.23	0.10
		26*	0.027	0.012
	Of the estimate for the population mean	1	0.02	0.01
		2	0.01	0.05
		3	0.008	0.004
		26*	0.002	0.001

*Hypothetical number of visits per farm

mean decreased from 0.69 kg CO_2-eq kg^{-1} FPCM (1 visit) to 0.34 kg CO_2-eq kg^{-1} FPCM (2 visits), to 0.23 kg CO_2-eq kg^{-1} FPCM (3 visits) and to 0.027 kg CO_2-eq kg^{-1} FPCM (26 visits). In the dry season, the within farm variance decreased from 0.32 kg CO_2-eq kg^{-1} FPCM (1 visit) to 0.16 kg CO_2-eq kg^{-1} FPCM (2 visits), to 0.10 kg CO_2-eq kg^{-1} FPCM (3 visits), and to 0.012 kg CO_2-eq kg^{-1} FPCM (26 visits). As a result of a decrease in the within farm variance, the width of the 95% CI in the estimate for a single farm mean became narrower with an increase in the number of visits (Table 6). The width of the CI decreased from 3.25 kg CO_2-eq kg^{-1} FPCM (1 visit) to 0.64 kg CO_2-eq kg^{-1} FPCM (26 visits) in the rainy season, and from 2.21 kg CO_2-eq kg^{-1} FPCM (1 visit) to 0.43 kg CO_2-eq kg^{-1} FPCM (26 visits) in the

Table 6. Width of the 95% confidence interval (CI) and repeatability of the estimated greenhouse gas emission intensity (GHGEI) per kg of fat-and-protein-corrected-milk (FPCM) for a single farm mean and for the population mean in the rainy and dry season with a sampling scheme of 1, 2, 3, or 26* visits per farm.

	Rainy season			Dry season		
Number of visits	Width of CI of the estimate for a single farm mean	Width of CI of the estimate for the population mean	Repeatability	Width of CI the estimate for a single farm mean	Width of CI of the estimate for the population mean	Repeatability
1	3.25	0.58	0.03	2.21	0.40	0.07
2	2.30	0.42	0.07	1.56	0.29	0.14
3	1.87	0.35	0.10	1.28	0.25	0.19
26*	0.64	0.16	0.49	0.43	0.13	0.67

*Hypothetical number of visits per farm

dry season. The repeatability per farm increased when more farm visits were performed (Table 6). In the rainy season, the within farm variance in the estimate for the population mean decreased from 0.02 kg CO_2-eq kg^{-1} FPCM (1 visit) to 0.01 kg CO_2-eq kg^{-1} FPCM (2 visits), to 0.008 kg CO_2-eq kg^{-1} FPCM (3 visits) and to 0.002 kg CO_2-eq kg^{-1} FPCM in case of 26 visits. In the dry season, the within farm variance decreased from 0.01 kg CO_2-eq kg^{-1} FPCM (1 visit) to 0.005 kg CO_2-eq kg^{-1} FPCM (2 visits), to 0.004 kg CO_2-eq kg^{-1} FPCM (3 visits) and to 0.001 kg CO_2-eq kg^{-1} FPCM (26 visits). As a result of a decrease in the within farm variance, the width of the 95% CI in the estimate for the population mean became narrower with an increase in the number of visits (Table 6). The width of the 95% CI decreased from 0.58 kg CO_2-eq kg^{-1} FPCM (1 visit) to 0.16 kg CO_2-eq kg^{-1} FPCM (26 visits) in the rainy season, and from 0.40 kg CO_2-eq kg^{-1} FPCM (1 visit) to 0.13 kg CO_2-eq kg^{-1} FPCM (26 visits) in the dry season.

Table 7. The between farm variance and within farm variance of the estimated greenhouse gas emissions per kg of fat-and-protein-corrected-milk (FPCM) per process for a single farm mean and for the population mean in the rainy and dry season with a sampling scheme of 1, 2, 3, or 26* visits per farm.

Process	Between farm variance (kg CO_2-eq kg^{-1} FPCM)	Number of visits	Within farm variance (kg CO_2-eq kg^{-1} FPCM)			
			Of the estimate for a single farm mean		Of the estimate for the population mean	
			Rainy season	Dry season	Rainy season	Dry season
Enteric fermentation	0.007	1	0.18	0.09	0.005	0.003
		2	0.09	0.04	0.003	0.002
		3	0.06	0.03	0.002	0.001
		26*	0.007	0.003	0.0004	0.0003
Manure management	0.012	1	0.036	0.016	0.002	0.0008
		2	0.018	0.008	0.0009	0.0006
		3	0.012	0.005	0.0007	0.0005
		26*	0.0014	0.0006	0.0004	0.0004
Purchased feeds	0.002	1	0.008	0.004	0.0003	0.0002
		2	0.004	0.002	0.00018	0.00012
		3	0.002	0.001	0.00015	0.00010
		26*	0.0003	0.0002	0.00007	0.00007
Forage cultivation	0.017	1	0.093	0.023	0.0034	0.0012
		2	0.046	0.011	0.0019	0.0008
		3	0.031	0.007	0.0015	0.0007
		26*	0.004	0.0009	0.0006	0.0006

*Hypothetical number of visits per farm

Table 7 shows the between farm variance and within farm variance of the estimated GHGE per process, of the estimate for a single farm mean and for the population mean in the rainy and dry season based on 1, 2, 3 or 26 visits per farm. Forage cultivation has the highest between farm variance, followed by manure management, enteric fermentation and purchased feed. In both seasons, enteric fermentation has the highest within farm variance, both for the estimate for a single farm mean and for the population mean, followed by forage cultivation, manure management, and purchased feed. For all processes, the within farm variance in the rainy season was higher than in the dry season. In both seasons, the within farm variance of the estimate for a single farm mean and for the population mean decreased with an increase in number of visits per farm.

Table 8 shows the width of the 95% CI and repeatability of the estimated GHGE per process in the rainy and dry season with a sampling scheme of 1, 2, 3 or 26 visits per farm. The CI is directly related

Table 8. Width of the 95% confidence interval (CI) and repeatability of the estimated greenhouse gas emissions per kg fat-and-protein-corrected milk (FPCM) per process in the rainy and dry season with a sampling scheme of 1, 2, 3, or 26* visits per farm.

		Rainy season			Dry season		
Process	Number of visits	Width of CI of the estimate for a single farm mean	Width of CI of the estimate for the population mean	Repeatability	Width of CI of the estimate for a single farm mean	Width of CI of the estimate for the population mean	Repeatability
Enteric fermentation	1	1.66	0.29	0.04	1.17	0.21	0.07
	2	1.17	0.21	0.07	0.83	0.15	0.13
	3	0.96	0.17	0.10	0.67	0.13	0.19
	26*	0.32	0.082	0.50	0.23	0.07	0.67
Manure management	1	0.74	0.15	0.25	0.49	0.11	0.43
	2	0.52	0.12	0.40	0.35	0.098	0.60
	3	0.42	0.10	0.50	0.28	0.091	0.69
	26*	0.14	0.08	0.90	0.09	0.07	0.95
Purchased feed	1	0.35	0.07	0.20	0.24	0.05	0.33
	2	0.24	0.05	0.33	0.17	0.04	0.50
	3	0.20	0.04	0.43	0.14	0.04	0.60
	26*	0.06	0.03	0.87	0.05	0.03	0.93
Forage cultivation	1	1.19	0.22	0.15	0.59	0.13	0.43
	2	0.84	0.17	0.27	0.42	0.11	0.60
	3	0.69	0.15	0.35	0.34	0.10	0.69
	26*	0.23	0.09	0.83	0.11	0.09	0.95

*Hypothetical number of visits per farm

to the within farm variance and, as a result, the width of the CI of the estimate for a single farm mean and for the population mean is largest for enteric fermentation, followed by forage cultivation, manure management, and purchased feed, in both seasons. Repeatability is associated with the between farm variance and the within farm variance. Repeatability of enteric fermentation was the smallest compared to other processes followed by forage cultivation, purchased feed, and manure management in the rainy season. In the dry season, repeatability of enteric fermentation was the smallest compared to other processes followed by purchased feed, forage cultivation, and manure management. Repeatability of all processes were categorized as low and became higher when more farm visits were performed.

3.4 Comparing GHGEI based on economic allocation and system division

The economic allocation factor for milk in the rainy season was 0.79 and 0.74 in the dry season. Based on system division, a fraction of 0.82 of total farm emissions were related to adult cows (lactating and dry cows) in both seasons. The average GHGEI based on economic allocation was 1.32 kg CO_2-eq kg^{-1} FPCM in the rainy season and 0.91 kg CO_2-eq kg^{-1} FPCM in the dry season (Table 3). The average GHGEI based on system division was 1.37 kg CO_2-eq kg^{-1} FPCM in the rainy season and 1.05 kg CO_2-eq kg^{-1} FPCM in the dry season. The correlation between the average GHGEI of milk per farm per season based on economic allocation and the average GHGEI of milk per farm per season based on system division was strong (i.e., r = 0.85 in the rainy season, r = 0.90 in the dry season; Figure 3.a. and 3.b).

4. Discussion

4.1 Seasonal GHGE from smallholder dairy farms

The average GHGEI of milk from all farm visits in our study (1.19 kg CO_2-eq kg^{-1} FPCM) was lower than results of the previous studies in the same region of West Java (Taufiq et al. 2016; De Vries et al. 2019) and in other tropical countries (Wilkes et al., 2020). The difference is mainly explained by the higher average daily milk yield in our study (14 kg/cow in dry season, and 15 kg/cow in the rainy season) than the studies of De Vries et al. (2019) (12 kg/cow) and Taufiq et al. (2016) (10 kg/cow).

The GHGEI was lower in the dry than in the rainy season, mainly because differences in emissions from enteric fermentation, being associated with dietary composition and a lower DMI. In this study, the farmers increased the fraction of rice straw, concentrate, and tofu by-product in the diet during the dry season to compensate for the low availability of elephant grass. Consequently, feed digestibility was improved, as indicated by the higher ratio of metabolizable energy to gross energy

(ME/GE), reducing emissions from enteric fermentation. No significant difference in dietary protein content and milk yield was found between the rainy and the dry season. These findings suggest that altering the diet for lactating cows could potentially reduce GHGE. Changing to a diet with a reduced proportion of fibre, however, potentially increases the risk for acidosis in dairy cattle in the long term if fibre content becomes too low, and health aspects need to be considered (Lean et al. 2008). Although not accounted for in this study, it should furthermore be acknowledged that feeding crop residues such as rice straw and by-products, including the concentrate ingredients used in this study, to dairy cattle, can contribute to avoiding GHGE from straw burning in the rice field and prevention of food waste (Soam et al. 2017). However, using feed ingredients that could potentially be used as food, for instance the tofu by-product that was used in this case, could cause food-feed competition and impair overall food security (Van Zanten et al. 2016).

Manure management was another important contributor to GHGE in this study. The emission factors for manure management (i.e., those for discharged faeces and sold faeces) were based on those closest to our situation (i.e. daily spread and liquid/slurry), as emission factor for discharged faeces are not available. Emissions related to manure management were generally lower in the dry season than in the rainy season as farms discharged more manure during the dry season and the emission factor for discharged manure is lower than for the other MMSs. However, we highlight that discharged manure leads to other environmental impacts, such as eutrophication that poses a significant risk to the aquatic ecosystems and groundwater source (Van Es et al. 2006; Amachika et al. 2016). In the rainy season, more manure is collected for use in the bio-digester, leading to higher CH_4 emission related to biogas losses. Optimizing the production and use of bioenergy, therefore, can avoid unnecessary losses and reduce GHGE. Furthermore, in relation to forage cultivation, in the rainy season the amount of applied manure is higher than in the dry season. In an attempt to maximise plant growth during high rainfall, however, farmers do not reduce the application of inorganic fertiliser, accordingly, generally leading to overfertilization and higher N losses, including those in the form of N_2O. Therefore, we suggest the reduction of inorganic fertiliser when farmers apply manure to the forage cultivation area and highlight the importance of precision fertilization (including better distribution of manure across the field) to reduce GHGE as well as nutrient losses.

We used economic allocation to allocate GHGE between milk and meat, but also explored an alternative method in which we divided the herd into milk producing animals and meat producing animals, avoiding the application of allocation. In case of this alternative method, all GHG emissions from adult cows were attributed to milk, and all GHGE from young stock and male cattle were attributed to meat. We explored this alternative method for two reasons. First, the method seems a legitimate option because according to our observations, Indonesian smallholder dairy farms are rather specialized dairy farms that tend to maintain a constant number of adult cows to support the output of milk, being their main source of income, while young stock and male cattle are generally sold to generate additional income, and not kept for replacement. Based on this observation, attributing emissions from adult cows to milk, and from young stock and male cattle to meat, is in line with the principle of LCA to divide the system into sub-processes to avoid allocation. For the female calves that are ultimately kept or bought for replacement, we argue that the method could still hold under the assumption that the mass quantity of the replacement heifer is similar to that of the culled cow at the moment of replacement. The second reason to explore this alternative method is that the data requirements for calculating GHGE related to milk production are reduced to a minimum. All data related to young stock and male cattle, their diet, manure production, growth, and all the emission calculations to it, can be disregarded using this method. Similarly, economic data to calculate allocation factors, being often debated because of their variability in time, are not needed. Exploring this method as an alternative to economic allocation provides additional information to make an informed decision about the data collection procedure in situations of data scarcity, where cost and time constraints often also play a role. In this particular study, the correlation between GHGEI based on economic allocation and GHGEI based on the alternative method, referred to as system division, was found to be high. It was also shown, however, that economic allocation factors differed between seasons (0.79 in the dry and 0.74 in the rainy season), while in case of system division a fraction of 0.82 of the total farm emissions were related to milk production in both seasons. Compared to economic allocation, the average GHGEI per kg milk based on system division was almost 4% higher in the rainy season, and about 15% higher in the dry season. It was concluded that, although the correlation between methods was high, results based on system division cannot be compared directly to those based on economic allocation. Based on the difference in results between methods, and the fact that young stock and male cattle are generally not kept for replacement, economic allocation might underestimate the GHGEI of milk produced on smallholder farms with a similar structure.

4.2 Longitudinal observation for LCA

Our study shows the relation between the number of farm visits and the variability in estimated GHGEI per kg milk produced on smallholder dairy farms in Indonesia. While the variability in GHGEI between farms refers to a systematic difference in emission estimates across farms, the variability in GHGEI within farms refers to differences in emission estimates across visits to the same farm. The between farm variance, therefore, provides information about the GHG reduction potential by implementing management practices of the best performing farms across all farms within the population. The within farm variance of the estimate for a single farm mean describes the variability in GHGEI per kg milk within a farm based on a known distribution (i.e., Gaussian distribution). This within farm variance provides important information to interpret results related to the performance of an individual farm, e.g., compared to that of another farm, or over time. The within farm variance in the estimate for the population mean describes the variability in GHGEI per kg milk of a specific farm population, in this case of the 32 farms incorporated in this study.

The within farm variance can be reduced by increasing the number of visits per farm (See and Holmes, 2015), resulting in a more precise estimate of GHGE of a particular farm, or in a more precise estimate for the population mean. In this study, the within farm variance of the estimate for a single farm mean and the population mean was found to be higher than the between farm variance (i.e., within farm variance > 90% of the total variance in both seasons). This indicates that the farms in this study are rather homogeneous in terms of their GHGEI per kg milk, and that the main source of variation in GHGEI relates to the within farm variance, i.e., variation in emission estimates across visits to the same farm. Although increasing the number of visits per farm could be a solution to reduce the within farm variance, the required number of replications (visits) to achieve a desired precision is unknown in advance (Adewunmi and Aickelin 2012). The within farm variance of the estimate for the population mean reduces not only with an increase in visits per farm, but also with an increase in the number of farms visited. In our specific case, however, increasing the number of farms would probably not have resulted in a better estimate for the population mean, given the relatively small between farm variance, whereas increasing visits per farm would have. This provides an important indication for future studies that aim to assess the GHGEI for a small population of rather homogeneous farms rather than increasing the number of farms they might aim for increasing the number of visits per farm to improve the accuracy of their assessment. As a last aspect, results indicate a larger need to collect more data in the rainy season than in the dry season, because the within farm variance was higher in the rainy than in the dry season.

The width of the CI is an indicator for the precision in the estimate (Liu 2010). In both seasons, the width of a 95% CI was narrower when more visits per farm were performed because the standard error decreased due to the increase of n. In both seasons, the repeatability within a farm was considered low, being related to the high within farm variance. The repeatability increased based on a hypothetical number of 26 visits per farm, from low to moderate, because the increase of n reduces the within farm variance.

We investigated the variation in GHGE per process, in relation to its contribution to the GHGEI of milk. Forage cultivation was found to have the largest between farm variance in estimated GHGE among the four processes (Table 7). Potential explanations for this relatively large variation are systematic differences in the type and amount (i.e., land area and yield) of on-farm produced feed per kg milk, and in the quantity of fertilisers applied including urea, faeces and digestate. The between farm variance in GHGE from manure management can potentially be explained by either variability in the estimated amount of collected manure between farms with the same MMS, or by differences in MMS between farms. Comparing GHGEI between farms with different MMS, however, did not show a significant effect of MMS. This lack of statistical difference is likely related to the fact that most of the farms, regardless their MMS, discharge (part of) their manure, and emissions from discharged manure were calculated based on the same emission factor as the one that was used for applied manure for forage cultivation. The within farm variation in GHGE from manure management is therefore larger than the between farm variation. Furthermore, as the data about forage cultivation and manure management were obtained via interviews, variation in the estimated GHGE might also be explained by systematic differences in farmers estimates. The between farm variance of estimated GHGE from enteric fermentation indicates that there is no clear systematic difference in feeding strategy between farms, that, based on the calculation method used, affects the level of enteric CH_4 per kg milk. Of all processes, purchased feed was found to have the lowest between farm variance.

In case of within farm variance of the estimated GHGE per process, enteric fermentation was found to have the largest variance among the four processes. The variation could be explained by changes in diet composition over time, being related to the availability of forage across the year. In addition, enteric fermentation is the largest contributor to the GHGEI of milk, and any change in this parameter will have a significance effect on the GHGEI. As a result of the relatively large within farms variance, the width of the CI was wider, and the repeatability was lower for enteric fermentation than for other processes. For all processes, the within farm variance of the estimated GHGE of the estimate for a single farm mean and for the population mean was higher in the rainy than in the dry season.

Overall, this study shows the relation between the number of visits per farm and the variances of the estimated GHGEI of milk produced on smallholder dairy farms in Indonesia. Dependent on the objective of the study, i.e., estimating emissions of an individual farm or of a population of rather homogenous farms, such information can help to make a well-informed choice on the data collection procedure, being often constraint by money and time issues. We observed that weekly data collection (i.e., a hypothetical number of 26 visits per season) could improve the accuracy of the estimated GHGEI immensely, which underlines the importance of an intensive recording system to collect data at smallholder dairy farms to improve the accuracy of GHGE estimates.

5. Conclusions

The estimated GHGEI of milk produced by smallholders in Lembang district, Indonesia, was higher in the rainy season than in the dry season. The lower GHGEI in the dry season was explained by differences in dietary composition for lactating cows, resulting in lower enteric CH_4 emissions, and differences in manure management practices, including applied manure for forage cultivation. The primary source of variation of the estimated GHGEI per kg milk relates to within farms variability, which can be reduced by increasing the number of farm visits. Performing multiple visits, therefore, reduces the within farm variance of the GHGE estimate, reduces the width of the confidence interval, and increases the repeatability per farm. Looking at the individual processes, this study showed that the estimated GHGE from forage cultivation was the main source of variability between farms, whereas the estimated GHGE from enteric fermentation was the main source of variability within farms. Insight into the relation between the number of visits per farm and the variance of the GHGE estimate can help to make a well-informed decision on the data collection procedure. Implementing an intensive recording system to collect data at smallholder dairy farms would improve the accuracy of GHGE estimates significantly.

Appendix 4.1

Table S1. Assumptions to estimate greenhouse gas emissions from production, processing, and transportation of purchased feeds.

Product	Chain	Assumption
Wheat pollard	Cultivation	Wheat farm in Australia of which conventional practice and rainfed irrigation (FAO 2015)
	Processing	Wheat flour processing in PT. Bogasari Flour Mill, Jakarta, Indonesia (interview)
	Transportation	Imported from Western Australia Port to Jakarta Port
Rice bran	Cultivation	Rice cultivation in West Java, Indonesia of which conventional system (Agatha 2015)
	Processing	Rice mill in West Java, Indonesia (Agatha 2015)
	Transportation	From Karawang, West Java to Lembang, West Java, Indonesia
Corn gluten feed	Cultivation	Corn cultivation in USA (Vellinga et al. 2013)
	Processing	Corn gluten feed processing in USA (Vellinga et al. 2013)
	Transportation	Imported corn gluten feed from New York Port to Jakarta Port (Liu et al. 2017)
Copra	Cultivation	Coconut cultivation in Indonesia (Vellinga et al. 2013)
	Processing	Manual extraction of coconut oil in Indonesia (Vellinga et al. 2013)
	Transportation	Transported from processing in Surabaya, East Java to Lembang, West Java, Indonesia
Palm kernel meal	Cultivation	Oil palm plantation in Indonesia (Vellinga et al. 2013)
	Processing	Palm oil extraction in Indonesia (Vellinga et al. 2013)
	Transportation	Transported from Jambi to Lembang, West Java, Indonesia
Coffee hull	Cultivation	Coffee plantation in Lembang, Indonesia (personal communication with coffee farmers in Lembang district, Indonesia)
	Processing	Coffee bean processing in Bandung, Indonesia (personal communication with coffee roastery in Bandung, Indonesia)
	Transportation	Transported from Bandung to Lembang, West Java, Indonesia
Tofu by-product	Cultivation	Soybean cultivation in USA of which conventional system, rainfed irrigation (FAO 2015)
	Processing	Tofu industry in Bandung, Indonesia (Zannah 2017)
	Transportation	Imported soybean from New York Port, USA to Jakarta Port, Indonesia (Liu et al. 2017); tofu by-product from Bandung to Lembang
Cassava pomace	Cultivation	Cassava cultivation in Indonesia of which conventional system, rainfed irrigation (FAO 2015)
	Processing	Tapioca industry in Lampung, Indonesia (Suroso 2011)
	Transportation	Transported from Lampung to Lembang, West Java, Indonesia
Concentrate	Processing	Processing by feed mill owned by dairy cooperative in Lembang district
Rice straw	Cultivation	Rice cultivation in West Java, Indonesia of which conventional system (Agatha 2015)
	Transportation	Transported from Subang, to Lembang, West Java, Indonesia

Appendix 4.2

Table S2. Reference of economic value for main products and by-products of feed production.

Feed	Main products	By-products	Reference of economic value
Wheat pollard	Wheat flour	Wheat pollard	Kemendag (2018)
Rice bran	Rice	Rice bran	Kemendag (2018); BPS (2018)
Tofu by-product	Tofu	Tofu by-product	Zannah (2017)
Cassava pomace	Tapioca	Cassava pomace	Kemendag (2018); on-farm interview (2017-2018)
Rice straw	Rough rice	Rice straw	BPS (2018); on-farm interview (2017-2018)

Table S3. Greenhouse gas emissions intensity (GHGEI) per unit of fat-and-protein-corrected milk (FPCM) from Indonesian smallholder dairy farms with different manure management systems (MMS) in the rainy and the dry season.

MMS	Rainy season* (kg CO_2-eq kg^{-1} FPCM)	Dry season* (kg CO_2-eq kg^{-1} FPCM)
Manure for forage cultivation	1.54 (0.47)	0.94 (0.24)
Sell manure	1.36 (0.06)	1.01 (0.29)
Manure for bio-digester	1.42 (0.50)	0.93 (0.21)
Discharge manure	1.08 (0.24)	0.80 (0.14)

*value between the brackets presents standard deviation (n = 32)

Table S4. Greenhouse gas emissions intensity (GHGEI) per unit of meat from Indonesian smallholder dairy farms at each farm visit (FV) in the rainy and the dry season.

Period	GHGEI* (kg CO_2-eq kg^{-1} meat)
FV1	7.76 (6.21)
FV2	10.80 (8.46)
FV3	9,71 (6.95)
Rainy season	10.25 (5.88)
FV4	8.18 (4.79)
FV5	7.71 (4.15)
FV6	9.04 (5.47)
Dry season	8.50 (2.59)

Chapter 5

Entry points for reduction of greenhouse gas emissions in small-scale dairy farms: looking beyond milk yield increase

A smallholder dairy farmer feeds the cows

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Abstract

Increasing milk yield per cow is considered a promising climate change mitigation strategy for small-scale dairy farms in developing countries. As it can be difficult to increase cow productivity, mitigation options beyond this production strategy need to be identified. The aim of this study was to identify entry points for mitigation of GHG emissions in small-scale dairy farms in Lembang Sub-district, West Java, Indonesia. Data on herd composition, productivity, feeding and manure management were collected in a survey of 300 randomly selected dairy farms. Characteristics of farms with the 25% lowest (<3291 kg milk $cow^{-1}y^{-1}$), medium 50% (3291-4975 kg milk $cow^{-1}y^{-1}$), and 25% highest milk yields (≥4976 kg milk $cow^{-1}y^{-1}$) were compared. Life cycle assessment was then performed to estimate the cradle-to-farm gate GHG emission intensity (EI) of farms. The relationship between EI and milk yield per cow for all farms was modeled and farms with an EI below and above their predicted EI were compared ('low' and 'high' EI farms). Results showed that milk yield explained 57% of the variance in EI among farms. Farms with medium and high milk yields were more often specialized farms, fed more tofu waste and compound feed, and had higher feed costs than farms with low milk yields ($P<0.05$). Farms with high milk yields also applied less manure on farm land than farms with low milk yields ($P<0.05$). Low EI farms had fewer cows, and fed less rice straw, more cassava waste, and more compound concentrate feed (particularly the type of concentrates consisting largely of by-products from milling industries) than high EI farms ($P<0.05$). In addition, low EI farms discharged more manure, stored less solid manure, used less manure for anaerobic digestion followed by daily spreading, and applied less manure N on farmland than high EI farms ($P<0.05$). Some associations were affected by confounding factors. Farm management factors associated with milk yield and the residual variation in EI were considered potential entry points for GHG mitigation. Feeding less rice straw and discharging manure, however, were considered unsuitable mitigation strategies because of expected trade-offs with other environmental issues or negative impacts on food-feed competition.

1. Introduction

Global livestock production is estimated to contribute 14.5% to the total anthropogenic greenhouse gas (GHG) emissions, with dairy production systems being responsible for about 30% of these emissions (2.1 gigatonnes of CO_2-eq per year; Gerber et al., 2013; Opio et al., 2013). The global demand for dairy products is expected to increase in the next decade, with the majority of the increase in milk production being anticipated in developing countries (OECD/FAO, 2017). This development is expected to be accompanied by considerable increases in GHG emissions, all the more because GHG emission intensities (i.e., emissions per unit of milk output) from current dairy production systems in developing countries are often relatively high compared to the global average (Opio et al., 2013)

Because of the large contribution of dairy production systems to climate change, many studies have been conducted to evaluate options for mitigation of GHG emissions. Dairy cattle produce methane from enteric fermentation, and methane and nitrous oxide from manure. Besides this, dairy production also drives additional emissions from feed production, land use change, processing, and transports. At the farm level, one mitigation option is to increase milk yield per cow, which shows a non-linear negative association with GHG emissions per unit of milk output (Gerber et al., 2011). Increasing milk yield per cow is considered a promising strategy for reducing emissions intensity (emissions per unit of milk or meat output) even though absolute emissions per animal increase. This strategy is particularly effective for small-scale dairy farms in developing countries, as reductions in GHG emission intensity are largest for yield increases at the lower end of the milk yield range. The livelihood benefits for poor farmers can also be significant (e.g. Brown, 2003; Delgado, 2003).

Increasing milk yield requires improved herd management through combinations of feed supply and quality, animal health, cow fertility, and improving genetic potential (e.g. Capper et al., 2009). Although the level of variation in milk yield among farms in developing countries suggests there is much potential for improvement, in practice, it often appears difficult to improve milk production levels. A lack of high-quality feed sources, poor access to credit and poor herd management are examples of common constraints.

Alternative measures for mitigation should therefore also be considered, including, for example, improved manure management, low-emission crop cultivation (e.g. efficient nitrogen uptake, soil carbon sequestration), and avoided land use change (Capper et al., 2009; Van Middelaar et al., 2013; De Vries et al., 2018; Mostert et al., 2018; Vellinga and de Vries, 2018). The potential effectiveness and suitability of mitigation options depends on the specific characteristics of dairy farming systems targeted, and their agro-ecological and socio-economic context. Comparing farms within the same context should help to explain why some farms are more successful in increasing milk yield, and to identify farm-specific mitigation options beyond this production strategy (Mu et al., 2018).

The aim of this study was to identify suitable entry points for mitigation of GHG emissions in small-scale dairy farms in West-Java, Indonesia. We used a two-stage approach in which farms were first compared in terms of milk yield levels, followed by an analysis of the variance in farms' GHG emission intensities that could not be explained by milk yield levels and the implications for additional mitigation options.

2. Materials and Methods

2.1 Data collection

2.1.1 Survey

Three hundred 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 Sub-district, West Java, Indonesia. A structured questionnaire was developed for dairy farms with questions about herd composition and performance, cow fertility and health, land use, feed ration and feeding practices, manure management and crop nutrient management practices, other farming practices, and farmers' perceptions and motivations. Questions were asked in Indonesian, with translation to the local language, Sundanese, when needed. Five enumerators (bachelor students from the University of Padjajaran (UNPAD)) with knowledge of farming systems and familiar with local languages and culture were trained in a five-day course, including two days of field testing of the questionnaire. The questionnaire was administered in person on the 300 farms between November and December 2016. An informed written consent was obtained from all respondents. An ethics approval was not required as per applicable institutional guidelines and Indonesian law. Written informed consent was obtained from all participants.

Overall results of the survey showed that dairy farms in Lembang had an average herd size of four adult cows and two young stock. Herds were housed in tie-stalls with no access to grazing (zero-grazing systems). Most farms were specialized dairy farms (84%), and there were some mixed crop-livestock farms as well (16%). In nearly all farms the main purpose of keeping cattle was to produce milk for sale. Few farmers had other sources of income. The feed ration of lactating 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 was 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. Manure (either feces, urine, or both) was discharged to the environment from most farms, or used as a soil amendment, sold or given away to other farms. More details about the results of the survey can be found in the following sections and in De Vries and Wouters (2017).

2.1.2 Milk sales

For each of the 300 farms in the survey, the total amount of milk sold in 2016 was obtained from databases kept by the dairy cooperative KPSBU. The amount of milk sold to KPSBU could not be obtained for 12 farms, which were therefore excluded from the analysis, leaving a sample of 288 farms.

2.1.3 On-farm measurements

On 50 farms from the list of 300 surveyed farms, heart girths of cattle and absolute quantities of feed and fodder fed to cattle were measured during one full day in December 2016. Collection of farm data was done after obtaining approval of the farmer. An ethics approval was not required as per applicable institutional guidelines as well as Dutch and Indonesian law. Heart girths, measured slightly behind the shoulder blade, were used to estimate live weights of cattle using an equation derived from measurements on the same approximate size and breed of cattle (Heinrichs et al., 2007). Amounts of concentrate feed, wet by-products, and fodder per head of cattle were weighed over a 24-hour period using scales. Further details about the on-farm measurements can be found in Verweij (2017).

2.1.4 Nutritional values of feed ingredients

To determine the nutritional value of feed ingredients, two samples per feed ingredient were taken from several farms in Lembang in 2016 and analyzed in the EUROFINS laboratory. Sampled farms were not necessarily farms in the baseline survey or farm assessment.

2.2 Calculation of milk yield

Milk production per farm was based on the total amount of milk sold to KPSBU in 2016, corrected for the share of milk kept at home (e.g., for home consumption or calves). To calculate the average annual milk yield per cow per farm, the total amount of milk was divided by the number of adult cows. The average number of adult cows in 2016 was estimated based on the number of adult cows at the time of the survey and farmer recall of the number of adult cows culled, purchased, and that died in the past year. Since we did not obtain information about the date animals were culled, purchased, or died, we assumed the event took place halfway through the year.

Because of expected bias in the estimated number of adult cows, farms with an unrealistically high milk yield per cow were excluded from the analysis as outliers. Outliers were detected using the interquartile range (IQR; i.e., the difference between the 25th and 75th percentiles). Farms were excluded where average milk yield was 1.5 IQR above the third quartile (≥7659 kg milk cow^{-1}y^{-1}). There were no outliers in the lower range (1.5 IQR below the first quartile). Five cases were excluded

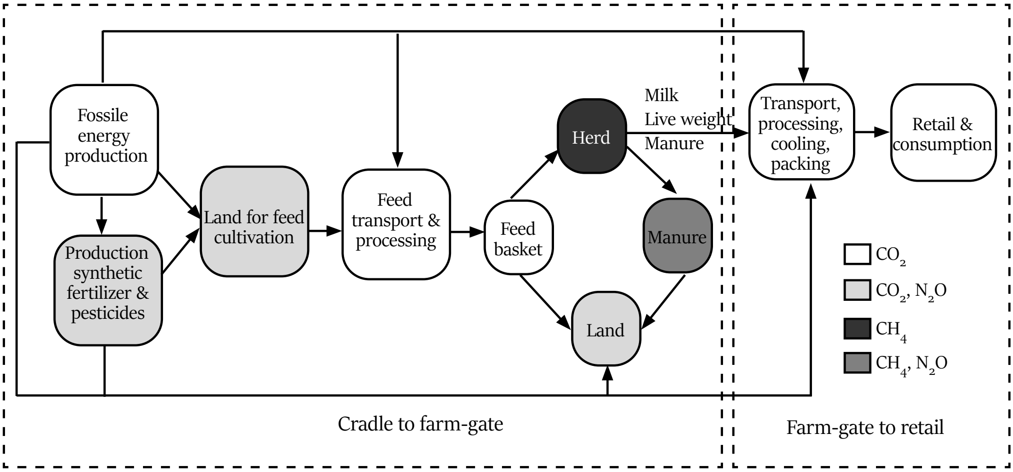

Figure 1. Cradle to farm-gate system boundaries (indicated by white rectangle with dashed lines) used for the analysis of greenhouse gas emissions in this study.

from the analysis, leaving 283 farms for the final analysis.

2.3 Calculation of GHG emission intensity

A life cycle assessment (LCA) was carried out to estimate GHG emission intensity of each of the 283 dairy farms. GHG emissions related to land use and land use change (LULUC) were not included in the LCA.

2.3.1 System boundaries

All processes up to the dairy farm gate (i.e., cradle-to-farm gate) were included in the LCA. This included production of farm inputs and on-farm production activities, but excluded transport and processing of the milk (Figure 1). Since we focused on the impact related to milk production, system boundaries included young stock kept for replacement of dairy cows, but excluded surplus calves and cows kept for fattening purposes.

2.3.2 Data Inventory

Primary, farm-specific data was used where available (Table 1). Where primary data were not available or biased, secondary data were used from existing databases or the literature (Table 2a-c).

Table 1. Farm-specific input data used in LCA analysis.

GLEAM module	Input parameter	Source
Herd module	Average number of adult cows on the farm in 2016[1]	De Vries and Wouters, 2017 (survey)
	Average milk yield per cow (kg $year^{-1}$)[2]	KPSBU Jabar (dairy cooperative), De Vries and Wouters, 2017
Manure module	Fraction of animal excreta per MMS (solid storage, compost, drylot, daily spread, anaerobic digestion, discharged, or exit livestock)	De Vries and Wouters, 2017
Feed module	Fraction (dry matter) of feed ingredient in total herd feed ration (homegrown grass, roadside grass, rice straw, cassava waste, tofu waste, brewers spent grain, rice bran, compound concentrate feed (type A or B))	De Vries and Wouters, 2017, Verweij, 2017 (on-farm measurements)
	Average nitrogen (N) application rates from animal manure (kg ha^{-1})[3]	De Vries and Wouters, 2017
	Land used for grass, fodder, and food crop production (ha)	De Vries and Wouters, 2017

[1] Based on the number of adult cows present at the farm at the time of the survey, and the farmer-reported number of adult cows that were culled, purchased, or died in 2016.

[2] Based on the amount of milk sold to the local dairy cooperative KPSBU Jabar (kg $farm^{-1}$ $year^{-1}$), the percentage of milk kept at home, and the average number of adult cows on the farm in 2016.

[3] Based on Tier 2 estimates of N excretion rates and amount of agricultural land.

2.3.3 Primary data

Data sources for calculation of annual milk yield per cow are described in section 2.2. The survey (De Vries and Wouters, 2017) yielded data on number of adult cows, land size, manure management and application, and feed rations. Land size included both owned and rented land for grass, fodder and food crop production.

The share of animal excreta allocated to different types of manure management systems (MMS) was estimated by farmers using a 1-5 scale (from 'almost none' to 'nearly all'). MMS included solid storage, composting, dry lot, daily spread, anaerobic digester, exit livestock (manure sold or given away), and discharge of manure (a description of these manure management systems can be found in IPCC, 2014). In case of manure discharging, farmers flushed from the cow barn the feces and urine, which were either washed away directly to ground- and surface water or lied deposited initially next to the barn, depending on the location and weather conditions (e.g., dry vs. rainy season).

With regard to feed rations, absolute amounts of industrial by-products and concentrates fed to lactating cows were derived from the survey and reported separately for the dry season and the rainy season. As it is difficult for farmers to estimate absolute amounts of fodder (grass and crop residues), farmers were asked about the relative share of each type of fodder in the total amount of fodder fed in the wet and dry season. Fodder contributing less than 5% was ignored (e.g., banana stalks, vegetable waste). Amounts of compound concentrate feed fed to lactating and dry cows were based on the survey (De Vries and Wouters, 2017), and for young stock, using on-farm measurements (Verweij, 2017). Nutritional values of feed ingredients were based on laboratory analyses of feed samples from farms in Lembang Sub-district (Section 2.1.4). For some feed ingredients, nutritional values were based on expert opinion or Feedipedia (details specified in Table 2b footnote).

Table 2a. Fixed values used as input data in LCA analysis.

GLEAM module	Input parameter	Value	Source
Herd module	Fertility rate (%)	75.0	Opio et al. (2013)
	Replacement rate (%)	15.0	Expert opinion
	Age at first calving (mo)	31.0	Anggraeni and Rowlinson (2005a,b)
	Death rate, perinatal (%)	22.0	Opio et al. (2013)
	Death rate, older (%)	4.2	Expert opinion
	Live weight adult cows (kg)	503.3	Verweij (2017)
Feed module	Nutritional values per feed ingredient (dry matter content, crude protein, organic matter, organic matter digestibility, gross energy)	(see other tables)	EUROFINS laboratory analyses, expert opinion, Feedipedia database[1]
	Gross yields, application rates of synthetic and animal fertilizer, and pesticides used in crop production.		De Vries and Wouters (2017), Gautier (2017), Badan Pusat Statistik (average rice yield Indonesia 2011-2015), IRRI, 2004, FAOSTAT (2014), Norton and VanderMark, (2016), IPNI (2011), Vellinga et al., (2012), FAO (2005), expert opinion. Vellinga et al. (2012)
	Energy requirements of processing feed		Vellinga et al. (2012)
	Transport distances feed		KPSBU Jabar (dairy cooperative)
System module	Milk fat (%)	4.0	KPSBU Jabar (dairy cooperative)
	Milk protein (%)	2.9	

[1] Website: www.feedipedia.org, accessed February 2017.

2.3.4 Secondary data

Average fat and protein contents of milk from farms in Lembang were acquired using data from the local dairy cooperative KPSBU (Table 2a). Because of expected bias we did not use the self-reported data from the survey (De Vries and Wouters, 2017) for herd reproductive performance as input for the LCA. Reproduction parameters were based on literature and expert opinion instead (Table 2a).

Crop yields, fertilizer use and pesticide use were based on national statistics (Badan Pusat Statistik), FAOSTAT, expert opinion, and the literature (Table 2c). Data for field work emissions, energy use of road transport, allocation of processed crops, and market prices were collected from databases of the Global Livestock Environmental Assessment Model (GLEAM; Opio et al., 2013), EcoInvent (using Simapro), FeedPrint (Vellinga et al., 2012), and the dairy cooperative KPSBU. For rice cultivation, we assumed pre-cultivation flooding of fields, continuous flooding during cultivation (irrigation via canal systems), no application of animal manure, and 200 days of cultivation per year (pers. comm. Huib Hengsdijk, November 2017).

The composition of compound concentrate feed and information about the production locations were obtained from the local dairy cooperative KPSBU. Two types of compound concentrate feed were used in dairy farms: quality A [wheat pollard (80%), corn gluten feed (13%), dregs of soy sauce (3%) and $CaCO_3$ (3%)] and quality B [wheat pollard (40%), corn gluten feed (13%), dregs of

Table 2b. Nutritional values of feed ingredients.

Feed ingredient	Dry matter content[1](%)	Nutritional value[2,3] per kg DM			
		CP (%)	OM (%)	OMD (%)	GE (MJ)
Fresh cut grass (road side)	12.3	11.7	85.4	56.9	16.0
Fresh cut grass (home grown)	12.5	14.9	83.3	58.7	17.4
Rice straw	28.6	4.0	79.9	46.5	15.5
Tofu waste	12.5	20.7	96.9	79.6	19.7
Cassava waste (pommace)	13.1	1.7	96.3	79.6	17.7
Brewers spent grain	23.5	25.8	97.0	67.7	19.7
Rice bran	90.2	12.7	90.6	63.8	20.2
Compound concentrate feed	86.0	17.0	93.0	74.8	18.9

[1] Dry matter content of fresh cut road side grass was assumed to be 14.8% in the dry season. Dry matter content of fresh cut home grown grass was assumed to be 15.0% in the dry season. Except for dry matter content of fresh cut grass, nutritional values of feed ingredients were assumed to be the same in the rainy season and the dry season. [2] CP = Crude Protein, OM = Organic Matter, OMD = Organic Matter Digestibility, GE = Gross Energy, [3]Sources: expert opinion (DM% tofu waste; OMD% cassava waste; CP% rice straw and compound concentrate feed), Feedipedia (DM%, CP% and OM% of cassava waste and rice bran; OMD% rice bran; GE of all feed ingredients, except road-side grass; P content cassava waste and rice bran), EUROFINS laboratory analyses (other values).

soy sauce (3%), $CaCO_3$ (3%), rice bran (7%), palm oil dregs (23%), coffee hulls (6.7%), and corn bran (3%)]. We assumed an equal amount from both types (50/50) in case farms used both types of compound concentrate feed. Dry matter content of fresh cut grass (road-side and home-grown) was assumed to be 25% lower in the rainy season than in the dry season.

2.3.5 Calculation of LCA input parameters

Numbers of young stock were estimated using rate parameters on reproduction, growth, and mortality based on expert opinion or literature (Table 2a). Numbers of young stock were not based on the survey, because these data did not distinguish between animals for replacement of dairy cattle and surplus animals kept for fattening on farms, a distinction required for the delineation of the system's boundaries.

In the survey farmers were asked about relative shares of fodder only. Absolute amounts of fodder were estimated based on energy requirements in four steps. First, gross energy requirements of adult cows per year were calculated using IPCC guidelines (IPCC, 2014). Second, total annual dry matter (DM) intake of adult cows was predicted based on their gross energy requirements and feed ration composition. Third, DM intake from fodder was estimated by subtracting DM intake from concentrates and by-products from the total DM intake (amount of concentrates and by-products fed were reported by farmers in the survey). Fourth, DM intake from fodder was subdivided to types of fodder (roadside grass, homegrown grass, rice straw) based on proportions reported by farmers in the survey. In case DM intake from concentrates and by-products (reported by farmers) exceeded 75% of the total DM intake, DM intake from concentrates and by-products was rounded to 75% of the total DM intake. The method of estimating fodder intake based on energy requirements is commonly used (e.g., Aarts et al., 2015), since estimating intake from forage is difficult.

Table 2c. Assumed crop yields, fertilizer use, and pesticide use.

	Gross yield (kg DM ha^{-1})	Synthetic fertilizer (kg ha^{-1} y^{-1})			Animal manure (kg N ha^{-1} y^{-1})	Pesticides (kg ha^{-1})
		N	P_2O_5	K_2O		
Grass (road side)	7,500[1]	-	-	-	-	-
Grass (home grown)	15,000[1]	277[2]	-	-	(farm-specific)	-
Rice	10,997[3]	202[4]	10[4]	-	-	2[4]
Wheat	2,360[5]	39[6]	25[6]	22[6]	29[6]	3[6]
Corn	4,954[5]	82[7]	-	-	2[7]	2[7]

[1] Personal communication Bram Wouters, August 2017, [2] De Vries and Wouters, 2017, [3] Bandan Pusat Statistik (average rice yield Indonesia 2011-2015), [4] IRRI, 2004, [5] FAOSTAT (2014; wheat yield Australia, maize yield); Norton and VanderMark, 2016; IPNI, 2011, [6] Vellinga et al., 2012 [7]FAO, 2005

For young stock, we assumed the same feed ration as for adult cows, but in lower amounts: the DM intake of fodder and by-products by young stock was assumed to be 60% and 40% of the DM intake by adult cows, respectively (percentages were based on on-farm measurements in the study of Verweij (2017); see section 2.1.3). A fixed amount of 2.4 kg compound concentrate feed was assumed for young stock (based on Verweij, 2017).

Farm-specific nitrogen (N) application rates from animal manure were calculated based on Tier 2 estimates of N excretion rates and the area of agricultural land in the farm, corrected for manure discharged, sold or given away. In three farms with missing data on the area of agricultural land, missing values were replaced by the mean land size of all other farms (i.e., mean imputation). Outliers in N application rate were detected using the interquartile range. Where the N application rate was greater than 1.5 IQR above the third quartile, outliers were defined as being above the value of 1.5 IQR above the third quartile (i.e., 1803 kg N per hectare per year; 21 farms). In these farms, the remaining N was considered to be discharged manure.

2.3.6 Emission calculations

For each farm, GHG emission intensity was estimated using the Global Livestock Environmental Assessment Model (GLEAM; MacLeod et al., 2017) based on an attributional approach. In GLEAM, GHG emissions are calculated based on IPCC Guidelines (IPCC, 2014), using Tier 2 methods where data permit. The GLEAM model consists of five modules, of which salient features are described below (a detailed description of the model can be found in MacLeod et al. (2017)):

- Herd module: Herd structure, dynamics, and production are characterized. Herd totals are disaggregated into four cohorts of animal classes: adult females, adult males, female younstock, and male young stock. The herd model computes the number of young stock to maintain the adult stock, using rate parameters on reproduction, growth, and mortality, as well as live weight (LW) output.
- Manure module: The proportion of manure in each MMS is specified. Results are used as input to the system module (calculating emissions from manure management) and the feed module (calculating emissions from manure applied to crops and grasses).
- Feed module: The total herd feed ration is specified (in percentage of total DM intake per feed ingredient at the herd level) and CO_2, CH_4, and N_2O emissions arising during feed production, processing and transport are calculated. Emission sources include direct and indirect N_2O and CO_2 from crop cultivation and cultivation inputs (e.g., synthetic fertilizer), CH_4 from rice cultivation, and CO_2 from energy use associated with field operations, crop processing and transport. CO_2 emissions arising from land use and land use change (LULUC) are not included. Total emissions per feed ingredient are allocated between the grain and its co-products using

economic or digestible fraction allocation, depending on the type of feed ingredient (MacLeod et al., 2013). In addition, average digestible energy and N content of the feed ration as a whole are calculated, which are used in the System module to determine total DM intake per animal cohort.

- System module: DM feed intake per animal cohort is calculated based on cattle energy requirements and the digestible energy and N content of the ration from the Feed module. Subsequently, N and P retention in animal products (milk and LW) and volatile solids are determined, and N and P excreted in dung and urine (IPCC, 2014). Emissions arising from enteric fermentation (CH_4), manure management (CH_4 and N_2O), energy use in housing (CO_2), and the production, processing, and transport of feed (CO_2, CH_4 and N_2O) are calculated using Tier 2 approaches (IPCC, 2014). For enteric methane the emission factor is adjusted for ration digestibility (details can be found in MacLeod et al. (2017)). For GWP characterization, factors of 1, 28, and 265 were used for CO_2, biogenic CH_4, and N_2O, respectively (IPCC, 2014) to sum up emissions.
- Allocation module: GHG emissions are allocated to milk and live weight, using biophysical relationship allocation (Thoma et al., 2013). In the present study, emissions were not allocated to other functions of cattle (non-edible outputs or services), because the survey among dairy farms in Lembang showed cattle were predominantly kept for edible outputs (milk and meat).

The System module was adjusted to enable calculation of emissions related to discharging of manure, either as fresh feces and urine, or as digestate based on the following assumptions:

- For manure discharged daily from barns, CH_4 and N_2O emission factors of 'pasture/range/paddock' were used (IPCC, 2014) with an N leaching factor of 65%.
- For manure discharged after anaerobic digestion (discharged digestate), the CH_4 conversion factor of anaerobic digestion was used for CH_4 emissions, and the emission factor of daily discharging of manure for N_2O emissions (see previous bullet).

2.4 Comparison of farms by milk production level

To compare characteristics of the 283 farms with distinct milk production levels, farms with the 25% lowest milk production per cow were classified as 'low' milk yield (i.e. <3291 kg milk cow^{-1} y^{-1}), and farms with the 25% highest milk production per cow were classified as 'high' milk yield (i.e. ≥4976 kg milk cow^{-1} y^{-1}). The remaining 50% of farms with were classified as 'medium' milk yield (i.e. 3291 to 4975 kg milk cow^{-1} y^{-1}). Medians and ranges per milk yield class are given in Table 3.

Farms in the three milk yield classes were compared according to herd size, household characteristics, land use, herd performance, feed ration, and manure management (Table 3). Since the assumption of normality was often not appropriate for these variables, the Kruskall-Wallis test was used to compare farms across milk yield classes, and the Mann-Whitney U test was used for post hoc comparisons of classes. The Chi-square test was used for discrete variables.

2.5 Comparison of farms by GHG emission intensity level

To identify factors influencing GHG emission intensity (EI) of farms other than milk yield, characteristics of farms were compared based on the deviation of their EI from the curve describing the relationship between milk yield per cow and EI of all 283 farms in the analysis (Gerber et al., 2011). In the present study the relation between milk yield per cow and EI was described as follows:

$$EI = 379.0 \times Y^{(-0.674)} \qquad \text{(Equation 1)}$$

where EI = GHG emission intensity (kg CO_2-eq kg^{-1} milk), given a milk yield Y (kg cow^{-1} y^{-1}).

Farms with an EI below and above their predicted EI (using Equation 1) were compared in terms of LCA input parameters, using Mann-Whitney U tests and Chi-square tests. In addition, to test if differences depended on milk yield level, farms with an EI below and above their predicted EI were compared within milk yield classes (low, medium, and high milk yield) using the same statistical tests. Spearman correlations were used to identify potential confounding variables.

3. Results

As expected, average EI differed significantly among all milk yield classes ($P<0.001$), ranging from 2.1 kg CO_2-eq kg^{-1} milk in the lowest milk yield class, to 1.4 and 1.1 kg CO_2-eq kg^{-1} milk in the medium and high milk yield class (SD = 0.7, 0.4, and 0.2). The fitted curve of Equation 1 (Figure 2), explained only 57% of the variance in the data, however, suggesting that the EI was influenced by other factors than milk yield. A large residual variance was observed, especially in farms in the low milk yield class (coefficient of variation (CV) 34%) compared to farms in the medium and high milk yield class (CV 25% and 17%).

3.1 Characteristics of farms by milk production level

Farms with medium and high milk yields were more often specialized dairy farms, in contrast with farms that had low milk yields, which were more often mixed crop-livestock farms (Table 3). With regard to feed ration composition, farms with medium and high milk yields fed a higher amount of tofu waste and compound concentrate feed, and had higher feed costs per cow than farms with low milk yields. In farms with high milk yields a lower percentage of manure was spread daily on farmland compared to farms with medium and low milk yields (these differences cannot be directly observed from Table 3 because median values were zero in all groups).

Table 3. Characteristics (median (range), or frequencies) of surveyed dairy farms, and differences between farms with the 25% lowest ('low'), medium 50% ('med'), and 25% highest ('high') milk yields.

	All farms	Milk yield class			
Herd	(n=283)	Low (n=71)	Medium (n=141)	High (n=71)	Overall P-value
Herd size (LU)[1]	4.5 (1.0-38.5)	4.5 (1.5-38.5)	4.5 (1.0-22.5)	4.3 (1.0-15.5)	N.S.
Fraction adult cows in herd (LU/LU)	0.8 (0.2-1)	0.8 (0.4-1.0)	0.8 (0.2-1.0)	0.8 (0.4-1.0)	N.S.
Household					
Household members (persons)	3 (1-8)	4(1-8)	4 (1-6)	3 (2-6)	N.S.
Respondent age (years) [2]	43 (20-76)	45(22-76)	42 (20-74)	43 (24-65)	N.S.
Female respondent (vs male; % of farms) [2]	15.9	21.1	15.6	11.3	N.S.
Land					
Farm type mixed (vs specialized; % of farms)	16.6	29.6[a]	12.1[b]	12.7[b]	0.003
Land size (ha)	0.2 (0-2.0)	0.2 (0-1.0)	0.2 (0-2.0)	0.1 (0-1.3)	N.S.
Land tenure (%)	28.6 (0-100)	50.7 (0-100)	20.0 (0-100)	28.6 (0-100)	N.S.
Herd performance					
Average milk yield (kg $cow^{-1}y^{-1}$) [3]	4151 (882-7636)	2652[a] (882-3291)	4151[b] (3304-4974)	5734[c] (4976-7636)	0.000
Average number of open days per cow (d)[4]	102 (40-410)	100 (50-313)	105 (40-410)	105 (60-403)	N.S.
Average AI services per cow[4]	2 (1-12)	2 (1-6)	2 (1-12)	2 (1-5)	N.S.
Costs of purchased feed (1000 IDR LU^{-1} mo^{-1}) [1,5]	652 (107-2794)	520[a] (107-2794)	657[b] (161-1605)	754[c] (199-1608)	0.000
Feed ration adult cows[6]					
Tofu waste (kg DM $cow^{-1}d^{-1}$)	0.1 (0-2.7)	0[a] (0-2.2)	0.1[b] (0-2.7)	0.9[b] (0-2.7)	0.003
Cassava waste (kg DM cow^{-1} d^{-1})	0.5 (0-2.3)	0.3 (0-2.3)	0.6 (0-2.0)	0.6 (0-1.7)	N.S.
Compound concentrate feed (kg DM cow^{-1} d^{-1})	3.4 (0-7.1)	2.5[a] (0.3-7.1)	3.4[b] (0-7.1)	3.4[b] (0.2-7.1)	0.020
Compound concentrate feed type A (vs B; % of farms)[7]	71.4	71.8	70.2	73.2	N.S.
Share of roadside grass in fodder ration (%)	40.0 (0-100)	36.7 (0-100)	42.9 (0-100)	37.5 (0-100)	N.S.
Share of rice straw in fodder ration (%)	0 (0-100)	20.0 (0-100)	0 (0-100)	0 (0-100)	N.S.
Manure management system (% of manure)[8]					
solid storage	0 (0-50.0)	0 (0-30.8)	0 (0-41.2)	0 (0-50.0)	N.S.
daily spread	0 (0-100)	0[a] (0-100)	0[a] (0-100)	0[b] (0-100)	0.039
digester w/ daily spread	0(0-51.3)	0 (0-50.0)	0 (0-51.3)	0 (0-50.0)	N.S.
discharged	66.7(0-100)	66.7 (0-100)	64.5 (0-100)	80.0 (0-100)	N.S.
exit livestock	0 (0-100)	0 (0-100)	0 (0-100)	0 (0-100)	N.S.

[a,b,c] Medians or frequencies within a row with different superscripts differ between milk yield classes (P < 0.05).
[1] Number refers to number of cattle (expressed in livestock units; LU) present at the farm at the time of the survey (including cattle kept for fattening). [2]Respondent was likely to be the person in charge of the farm, as enumerators requested so before starting the interview. [3] Milk yield (kg/cow/y) was estimated from the total amount of milk sold to the dairy cooperative in 2016, and the share of milk kept at home and the average number of adult cows present at the farm in 2016. [4]Based on average number of open days and average number of artificial insemination (AI) services per conception of (maximum) 3 randomly chosen adult cows in the herd. [5] Costs of purchased feed and fodder over the month before the interview took place (including transport costs).[6]Rice bran and brewers spent grain not shown because of low prevalence (<5 farms per milk yield class). [7]Two types of compound concentrate feed were used in KPSBU dairy farms: i) quality A: wheat pollard (80%), corn gluten feed (13%), dregs of soy sauce (3%) and $CaCO_3$ (3%), and ii) quality B: wheat pollard (40%), corn gluten feed (13%), dregs of soy sauce (3%), $CaCO_3$ (3%), rice bran (7%), palm oil dregs (23%), coffee hulls (6.7%), and corn bran (3%).[8] Manure management system (IPCC, 2014) included only if applied in at least 5 farms per cell (excluded were dry lot and composting).

3.2 Characteristics of farms by deviation from their predicted emission intensity

Farms with a 'low' EI (an EI below their predicted EI based on milk yield level, using Equation 1) had fewer cows than farms with a 'high' EI (an EI above their predicted EI; Table 4). In addition, low EI farms fed less rice straw, more cassava waste, and more compound concentrate feed, and less often fed compound concentrate feed type A than high EI farms. With regard to manure management, low EI farms discharged more manure, stored less solid manure, used less manure for anaerobic digestion followed by daily spreading, and applied less manure N on farmland than high EI farms (some of these differences cannot be directly observed from Table 4 because median values were zero in both groups).

Table 4. Differences [median (range); $P < 0.05$] between farms with a greenhouse gas (GHG) emission intensity below and above their predicted emission intensity based on milk yield.

GHG emission intensity	Below predicted EI (n=171)[1]	Above predicted EI (n=112)[1]	P-value
Adult cows (average heads y^{-1})	3.0 (1-15.0)	4.0 (1-25.5)	0.048
Milk yield (kg $cow^{-1}y^{-1}$)[2]	4221 (882-7206)	4077 (1325-7636)	N.S.
Land size (ha)	0.2 (0-1.3)	0.1 (0-2.0)	N.S.
Feed ration adult cows (kg DM $cow^{-1}y^{-1}$)[3]			
Roadside grass	2.2 (0-11.0)	2.2 (0-9.5)	N.S.
Home-grown grass	1.8 (0-9.1)	1.2 (0-9.6)	N.S.
Rice straw	0 (0-2.9)	2.8 (0-12.9)	0.000
Tofu waste	0.1 (0-2.7)	0.1 (0-2.7)	N.S.
Cassava waste	0.7 (0-2.3)	0.1 (0-2.0)	0.005
Compound concentrate feed	3.4 (0-7.1)	2.8 (0.2-7.1)	0.050
Compound concentrate feed type A (vs B; % of farms)	66.1	79.5	0.010
Manure management system (% of manure)[4]			
Solid storage	0 (0-41.2)	0 (0-50.0)	0.003
Daily spread	0 (0-100)	0 (0-66.7)	N.S.
Digester, daily spread	0 (0-100)	0 (0-100)	0.016
Digester, discharged	0 (0-100)	0 (0-100)	N.S.
Digester, exit livestock	0 (0-50.0)	0 (0-100)	N.S.
Discharged	72.0 (0-100)	46.0 (0-100)	0.015
Exit livestock	0 (0-100)	0 (0-100)	N.S.
Manure N application rate (kg ha^{-1})[5]	0(0-1803)	156 (0-1803)	0.002

[1]Maximum number of farms per category (for some variables the number of farms per category was lower).
[2]Milk yield (kg $cow^{-1}y^{-1}$) was estimated from the total amount of milk sold to the dairy cooperative in 2016, and the share of milk kept at home and the number of adult cows present at the farm at the time the interview took place.
[3]Rice bran and brewers spent grain not shown because of low prevalence.
[4]Dry lot and composting not shown because of low prevalence.
[5]A cut-off value was used for N application rate from animal manure in case of outliers (1803 kg N ha^{-1}).

Results of the correlation analysis showed that the association between herd size and residual variation in EI was likely affected by confounding factors, including amount of rice straw fed to cows and manure N application rates (both positively associated with herd size; $P < 0.05$). Both for discharging of manure and the amount of solid manure stored the association with residual variation in EI was likely affected by the amount of manure N applied to farm land as a confounding factor ($r_s = -0.68$ and 0.39, resp., $P < 0.001$). Excessive manure N fertilization was more common in farms with a higher amount of fresh manure and digestate spread to land daily ($r_s = 0.66$ and 0.42, resp., $P < 0.001$).

Comparing 'low' and 'high' EI farms within milk yield classes showed that differences in EI between these two groups depended on milk yield class (Annex 1). An exception was the amount of rice straw fed, which differed between low and high EI farms in all milk yield classes, and herd size and amount of discharged manure, which were not significantly different between 'low' and 'high' EI farms in any of the milk yield classes. Besides rice straw, in the low milk yield class, low EI farms less often used a solid storage for manure than high EI farms. In the medium milk yield class, low EI farms fed more cassava waste and more compound concentrate feed, and applied less digestate and total manure N to farmland than high EI farms. In the high milk yield class, low EI farms had lower milk yields and applied less manure N to farmland than high EI farms.

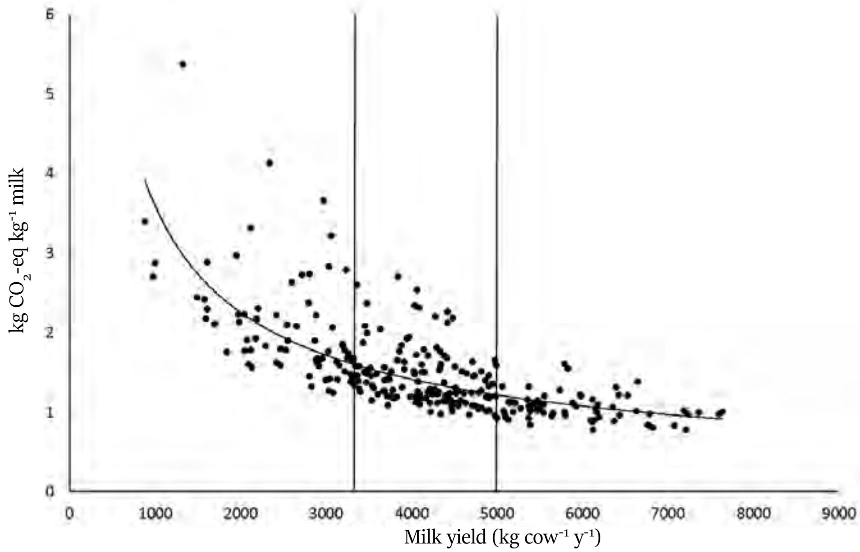

Figure 2. Milk yield and greenhouse gas emission intensity of 283 dairy farms in Lembang Sub-district, West Java.

4. Discussion

Average EI of farms in this study was 1.5 kg CO_2-eq kg^{-1} milk, which is lower than estimates of the EI of dairy production systems in SE Asia found by Opio et al. (2013) and Gerber et al. (2013). Enteric methane emissions and emissions from feed production per kg milk in our study were lower than in Opio et al. (2013), probably because of a higher milk production level (4166 kg cow^{-1} y^{-1} versus 2515 kg cow^{-1} y^{-1} in Opio et al. (2013)) and use of better quality by-products. EI in an LCA study by Taufiq et al. (2016) in the same region in Indonesia (Pangalengan) ranged from 1.5 kg CO_2-eq L^{-1} milk in 'modern' dairy farms to 2.3 kg CO_2-eq L^{-1} milk in small-scale dairy farms. Average EI of small-scale farms in our study was lower than what was found by Taufiq et al. (2016), partly due to a higher milk production of small-scale farms in our study (12 versus 10 L cow^{-1}day^{-1}).

The non-linear relationship between EI and milk yield of dairy farms in Lembang found in this study (as shown by the curve in Figure 2) is consistent with the relationship between EI and milk yields for a wide range of dairy production systems worldwide (Gerber et al., 2011). Like Gerber et al., we found that emissions steeply decreased at the lower end of the milk yield range, until about 2 to 3 kg CO_2-eq kg^{-1} milk at 2000 kg milk cow^{-1} year^{-1}, at which point reductions in EI slowed down as productivity increased further. Country average emission intensities were used in the study of Gerber et al. (2011), however, thus excluding between-farm variation. This may explain the smaller proportion of variance in EI due to milk yield in the present study compared Gerber et al. (57% versus 89%). For comparison, Christie et al. (2012) found that milk yield accounted for 70% of the variance in EI among Australian dairy farms.

The fact that milk yield explains only part of the variation in EI suggests mitigation strategies other than milk yield increase are relatively important, and also highlights the limitation of using milk yield as a single proxy for estimating EI (e.g. Christie et al., 2012; FAO & ILRI, 2016; Lorenz et al., 2019). In the following paragraphs we discuss methodological limitations of the present study, options for reducing EI by improving milk yields and mitigation options beyond this production strategy.

4.1 Methodological limitations

Availability and quality of livestock data are common issues in developing countries and were also an important methodological limitation of the present study. Like in any survey, responses to the questionnaire were likely subject to self-reporting bias, particularly farmers' estimates of feed ration composition, land size, amounts of farm inputs purchased, and amounts of manure per storage type. Furthermore, the recall period of one year was too short to make accurate estimates of amount of LW output from herds, because LW output of small herds can fluctuate substantially from year to year. Using one-year data can lead to too optimistic or too pessimistic estimates of the amount of

LW output from herds. Also, as is common in developing countries, availability of secondary data in Indonesia was limited, particularly for data on local crop yields and field inputs (fertilizers, pesticides). In future studies, farm data susceptible to self-reporting bias should be collected through on-farm measurements rather than surveys, and farms should be monitored more regularly and over several years to estimate LW output more accurately.

The limited data availability and quality likely affected the results of this study in two ways. First, estimates of milk yields and GHG EI of farms were likely less accurate due to the limited availability and quality of data. For example, some farms had low inputs but high milk yield levels, which might explain why we found relatively low emission intensities for some farms. Second, because only a few farm parameters were farm-specific, the differences between farms with distinct milk yields and GHG emission intensities were likely underestimated. More differences among farms may be expected where more farm-specific data are included, e.g., farm-specific field inputs (e.g. synthetic fertilizer), reproductive performance, and animal health.

4.2 Options for reducing EI by improving milk yields

Specialization in dairy production, and feeding higher amounts of tofu waste and compound feed were associated with higher milk yield levels, and can be considered entry points for mitigation as average EI reduced considerably when shifting to a higher milk yield class (26-32% reduction). It is important to consider that specialization can increase the risk of adverse environmental impacts, however, especially if animal manure is not efficiently recycled as a fertilizer and nutrient losses are not managed properly (e.g. Oenema et al., 2007; Petersen et al., 2007). In our study, specialized farms discharged significantly more manure than mixed farms. The positive effects of compound concentrate feed and tofu waste on milk yield were likely caused by a higher intake of energy and protein. An increased use of compound concentrate feed, furthermore, can lead to a net increase in EI if the increase in milk yield is not sufficient to compensate for the increase in emissions from feed production. This is particularly relevant when feed rations do not match with the dairy cow's requirements, as is the case in many farms in Lembang (De Vries and Wouters, 2017). Feeding concentrates in excess may also carry animal health risks such as subacute ruminal acidosis (Kleen et al., 2003). Increasing the amount of compound concentrate feed to enhance productivity of dairy cows, therefore, should be part of a balanced ration. Feeding balanced rations has shown considerable potential for reduction of EI (De Vries et al., 2017; Garg et al., 2018). The use of tofu waste as part of a balanced diet for cows is not only advantageous because of its positive effects on milk yield, but also because utilizing these co-products as animal feed prevents food-feed competition and contributes to circularity of food systems (Vellinga et al., 2012; Van Zanten et al., 2018).

4.3 Mitigation options beyond the milk production strategy

Nine management practices were identified as statistically significant for mitigation based on analysis of the residual variation. Our statistical approach allowed to distinguish between the variation in EI associated with milk yield, and the residual variation in EI. Some farm management factors, however, influence EI both via changes in milk yield and the residual variation in EI. A better quality feed, for example, can lead to a higher milk yield but can also influence total dry matter intake and carry relatively high embedded emissions from its cultivation and processing.

The positive association between the amount of rice straw fed to cows and EI can be explained by the relatively high emission factor of rice straw (0.9 kg CO_2-eq kg^{-1} DM), associated with the assumptions made on CH_4 and CO_2 emissions from paddy rice cultivation and processing. However, since rice straw is commonly burned after harvesting, omission of rice straw in the cow diet does not necessarily reduce emissions embedded in rice straw, just that the emissions are no longer allocated to the dairy sector. Open burning of rice straw is associated with the release of black carbon, which is the second largest contributor to global warming after carbon dioxide, and leads to human health problems (e.g., Hafidawati et al., 2017). Also, whereas use of rice straw (being a crop residue) does not require additional land, other higher-quality fodders might require additional land (e.g., grass, maize silage). In this context, technical solutions that can improve the nutritional quality and digestibility of rice straw have a high potential for reduction of GHG emissions from agriculture. Fungi treatment of rice straw is an example of such a technique (e.g., Tuyen et al., 2013).

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The negative association between the amount of cassava waste fed and EI was due to the relatively low emission factor of cassava waste (<0.1 kg CO_2-eq kg^{-1} DM), which was low because no upstream emissions were assumed for wet by-products except for those related to the processing and transport of the wet by-product itself (Vellinga et al., 2012). Similar to tofu waste, utilizing these by-products from industrial food processing can reduce food-feed competition and contribute to circularity of food systems (Vellinga et al., 2012; Van Zanten et al., 2018). The potential for increased use of cassava waste in cattle diets is low, however, due to its poor nutritional value.

Even though compound concentrate feed was the feed ingredient with the second highest emissions per kg DM (0.4-0.5 kg CO_2-eq kg^{-1} DM), we found a negative association between the amount of compound concentrate feed fed to cows and EI. This was because total dry matter intake was lower in farms feeding more concentrates (8.2 and 9.2 kg DM $cow^{-1}d^{-1}$ in 'low' and 'high' EI farms; Table 4), due to the high energy content of concentrates. Feeding feed ingredients with a low carbon footprint per unit of nutritive value (e.g., energy), therefore, can contribute to reducing EI.

Feeding compound concentrate feed type A was positively associated with EI because it contained more wheat pollard, and less palm oil dregs, coffee hulls, and corn bran than concentrate type B, and the emission factor of wheat pollard was assumed to be higher than of palm oil dregs, coffee hulls, and corn bran. Similar to wet by-products, increasing the use of nutritious by-products from milling industries in compound concentrate feed can reduce GHG emissions from feed production (e.g., Bannink, 2009) and reduce food-feed competition. Hence, feeding the same or better quality feed with relatively low embedded emissions from feed production should be preferred to reduce EI while maintaining high milk yield levels.

Paradoxically, manure discharging was associated with a lower EI, and storing solid manure and daily spreading of digestate were associated with a higher EI. Assumptions on CH_4 and N_2O emissions from discharged manure were highly uncertain, however, and emissions may vary considerably depending on the location and weather conditions and the fate of the discharged manure. Moreover, discharging manure implies a loss of nutrients, and can cause other environmental issues besides global warming such as eutrophication and pollution of drinking water sources. Recycling manure as a fertilizer can reduce GHG emissions when it replaces synthetic fertilizer. The positive associations between manure management practices and EI was were likely confounded with amount of manure N applied on farmland. In other words, manure storage and application more often led to excess manure application and higher associated N_2O emissions than discharging of manure.

Although not significant in the present study, daily spread shows large potential for mitigation of GHG emissions because of relatively low associated N_2O emissions from storage (IPCC, 2014), provided that excess manure application is avoided. Other low-emission manure management options for dairy farms in Lembang need to be explored for situations where daily spread is not possible. Part of the manure needs to be sold or given away to other sectors because dairy farmers in Lembang own too little land to apply all manure (De Vries and Wouters, 2017). Changing to other manure management practices may be challenging, however, because collection, storage and transport of manure requires more labour and space, and may be more costly than the current practice of discharging manure.

4.4 Recommendations

Several mitigation options were identified in the present study, but many were expected to have trade-offs outside the dairy production chain or with other environmental issues. Feeding more compound concentrate feed (type B) and tofu waste seemed promising mitigation options for farms with low and medium milk yields, provided that these are part of a balanced ration and food-feed competition is avoided. Preventing excess manure N fertilization seemed a promising mitigation option for farms with medium and high milk yields.

To support sustainable development of the Indonesian dairy sector potential trade-offs with other environmental issues such as eutrophication, land use and biodiversity should be assessed before introducing options to reduce GHG emissions. Given the high livestock stocking densities in West Java, spatial policy or a manure policy at regional level might be required. Consequential LCA can help to identify environmental trade-offs outside the dairy production chain, e.g., an increase in GHG emission related to burning of rice straw as a result of changes in the dairy cow's diet. A final point of consideration is that options to reduce GHG emissions could impair food security. Feeding highly nutritious feed products such as grains to livestock, for example, might decrease emission intensity compared to feeding by-products, but also contributes to food-feed competition.

5. Conclusion

This study showed that 57% of the variance in EI among dairy farms in Lembang Sub-District could be explained by milk yield. Farm management factors associated with increased milk yields and the residual variance in EI were considered potential entry points for mitigation. Specialization towards dairy production, and feeding higher amounts of tofu waste and compound feed were associated with higher milk yield levels. Feeding less rice straw, more cassava waste, and more compound concentrate feed (particularly type B, consisting largely of by-products from milling industries) were feeding practices negatively associated with the residual variance in EI. Discharging more manure, storing less solid manure, using less manure for anaerobic digestion followed by daily spreading, and applying less manure N on farmland were manure management practices negatively associated with the residual variation in EI. Feeding less rice straw and discharging manure, however, were not considered to be suitable mitigation strategies because of expected trade-offs with other environmental issues or negative impacts on food-feed competition. More research is needed to evaluate these potential trade-offs.

Appendix 5.1

Milk yield	Low			Medium			High		
GHG emission intensity	Below predicted EI (n=42)[1]	Above predicted EI (n=29)[1]	P-value	Below predicted EI (n=83)[1]	Above predicted EI (n=58)[1]	P-value	Below predicted EI (n=46)[1]	Above predicted EI (n=25)[1]	P-value
Adult cows (average heads year^{-1})	3.5 (1-12.5)	4.0 (1-25.5)	N.S.	3.0 (1.0-12.5)	4.0 (1.0-18.0)	N.S.	3.0 (1.0-15.0)	4.0 (1.0-12.5)	N.S.
Milk yield (kg cow^{-1} y^{-1})[2]	2467 (882-3291)	2809 (1325-3268)	N.S.	4214 (3304-4974)	4120 (3310-4954)	N.S.	5495 (4986-7206)	6116 (4976-7636)	0.009
Land size (ha)	0.1 (0-1.0)	0.2 (0-1.0)	N.S.	0.2 (0-1.3)	0.1 (0-1.9)	N.S.	0.1 (0-1.0)	0.1 (0-1.3)	N.S.
Feed ration adult cows (kg DM cow^{-1} d^{-1})[3]									
roadside grass	1.7 (0-8.7)	1.8 (0-9.3)	N.S.	2.5 (0-10.2)	2.3 (0-9.5)	N.S.	2.4 (0-11.0)	2.6 (0-6.4)	N.S.
home-grown grass	1.7 (0-7.9)	0.5 (0-8.2)	N.S.	1.6 (0-9.1)	1.1 (0-9.6)	N.S.	1.9 (0-8.5)	2.1 (0-7.2)	N.S.
rice straw	0 (0-2.6)	2.9 (0-12.9)	0.000	0 (0-2.9)	2.8 (0-11.2)	0.000	0 (0-2.2)	3.0 (0-6.3)	0.000
tofu waste	0 (0-2.2)	0 (0-1.6)	N.S.	0.1 (0-2.7)	0.1 (0-2.7)	N.S.	0.2 (0-2.7)	0.9 (0-2.7)	N.S.
cassava waste	0.6 (0-2.3)	0.1 (0-1.7)	N.S.	0.7 (0-1.7)	0.1 (0-2.0)	0.005	0.7 (0-1.7)	0.6 (0-1.7)	N.S.
compound concentrate feed	2.6 (0.4-7.1)	2.3 (0.3-6.6)	N.S.	3.7 (0-7.1)	2.6 (0.3-7.1)	0.037	3.5 (0.3-7.1)	3.4 (0.2-7.1)	N.S.
Compound concentrate feed type A (vs B; % of farms)	64.3	82.8	N.S.	65.1	77.6	N.S	69.6	80.0	N.S.
Manure management system (% of manure)[4]									
solid storage	0 (0-24.5)	0 (0-30.8)	0.017	0 (0-41.2)	0 (0-30.6)	N.S.	0 (0-25.5)	0 (0-50.0)	N.S.
daily spread	0 (0-100)	0 (0-66.7)	N.S.	0 (0-100)	0 (0-100)	N.S.	0 (0-100)	0 (0-50.0)	N.S.
digester, daily spread	0 (0-25.0)	0 (0-75.0)	N.S.	0 (0-100)	0 (0-100)	0.045	0 (0-75.0)	0 (0-50.0)	N.S.
digester, discharged	0 (0-100)	0 (0-75.0)	N.S.	0 (0-50.0)	0 (0-100)	N.S.	0 (0-50.0)	0 (0-50.0)	N.S.
digester, exit livestock	0 (0-50.0)	0 (0-75.0)	N.S.	0 (0-50.0)	0 (0-50.0)	N.S.	0 (0-50.0)	0 (0-100)	N.S.
discharged	71.0 (0-100)	50.0 (0-100)	N.S.	66.7(0-100)	32.1 (0-100)	N.S.	100 (0-100)	60.0 (0-100)	N.S.
exit livestock	0 (0-100)	7.7 (0-50.0)	N.S.	0 (0-100)	0 (0-100)	N.S.	0 (0-100)	0 (0-100)	N.S.
Manure N application rate (kg ha^{-1})[5]	0 (0-1803)	140 (0-1803)	N.S.	55 (0-1803)	225 (0-1803)	0.043	0 (0-1803)	154 (0-1803)	0.021

[1] Maximum number of farms per category (for some variables the number of farms per category was lower).

[2] Milk yield (kg cow^{-1}y^{-1}) was estimated from the total amount of milk sold to the dairy cooperative in 2016, and the share of milk kept at home and the number of adult cows present at the farm at the time the interview took place.

[3] Rice bran and brewers spent grain not shown because of low prevalence (<5 farms per milk yield class).

[4] Manure management system (IPCC, 2014) included only if applied in at least 5 farms per cell (excluded were dry lot and composting).

[5] A cut-off value was used for N application rate from animal manure in case of outliers (1803 kg N ha^{-1}).

Chapter 6

Constraints on manure management on Indonesian smallholder dairy farms

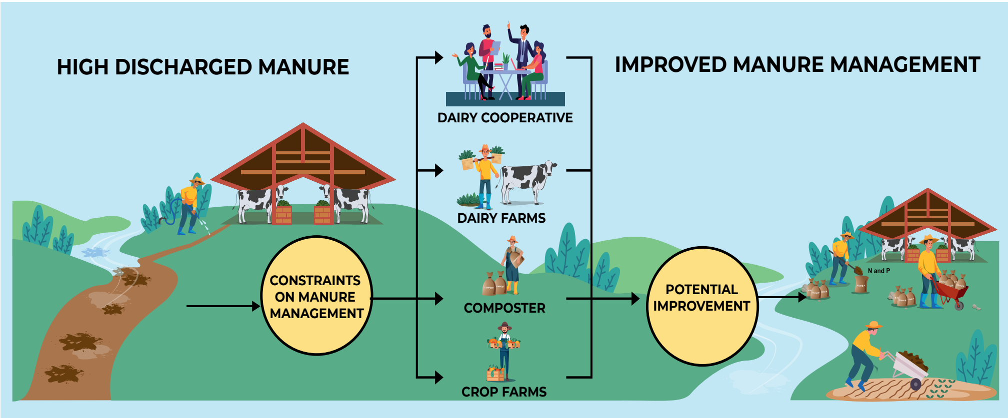

Illustration of poor manure management and improved manure management

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To be submitted

Abstract

The high rates of discharged manure in smallholder dairy farms in the Lembang region of West Java are linked to constraints on manure management. Understanding these constraints and what prevents them from being resolved is essential to improving manure management. This study aims to analyse and identify the constraints on manure management in smallholder dairy farms and find potential opportunities for improvement. We conducted two Focus Group Discussions (FGDs) and interviewed 30 farmers practicing one of the following four different manure management systems (MMSs): applying manure directly on forage land without treatment (ADL), selling manure (SEL), using manure as substrate for anaerobic digestion (ADI), and discharging manure (DIS). The FGDs included stakeholders that interacted with manure management in this region (i.e., the dairy cooperative (n = 5), dairy farmers (n = 15), crop farmers (n = 11) and composters (n = 4). We identified 20 constraints on manure management, of which availability of space to store manure on the farm, and costs of manure management are regarded most important. Stakeholders proposed strategies to improve manure management: communal manure storage (CMS), a structured manure market, and supports. The cost of manure management is high, and SEL and ADI had higher net total cost than DIS. Total revenue (TR) differed between MMSs and ADL had lower TR than SEL. All MMSs had negative net gross margins which could be explained by the high costs attributed to labour (i.e., family labour) and low revenue from manure. To conclude, working with concerned stakeholders is important and better insight into constraints gives insight to improve manure management.

1. Introduction

In response to the increasingly high national milk demand, the Indonesian government plans to expand the dairy cattle population, especially at smallholder dairy farms (Kementrian Pertanian, 2019; 2017). A larger dairy cattle population will lead to higher manure output, which has become a reason for concern in dairy cattle regions. High manure production must be accompanied by a proper manure management to avoid adverse environmental problems (e.g., greenhouse gas emissions and nutrient losses) (Uddin et al., 2020; Tanh et al., 2020; Biagni et al., 2018; Anzai et al., 2016).

Proper manure management utilises the benefits of manure both on- and off-farm, and avoids undesirable social, economic, and health and environmental impacts (Baiyeri et al., 2020; Bradley et al., 2019; Malomo, et al., 2018). Proper manure management can be achieved if manure management starts with good collection, includes proper storage, manure treatments, and ends with manure application (Teenstra et al., 2014). Manure storage at the farm refers to the facility used to hold manure before its application to the soil, ensuring that manure will not be discharged. Applying manure to crop land is an essential part of proper manure management. Hence, crop farmers and manure processors such as composters are important players in the process of attaining better manure management, and dairy cooperatives can support this endeavour.

Most dairy farms in Indonesia are smallholders; in fact, small farms account for 90% of the country's dairy production (Sulistiyati et al., 2013). This type of farming system is characterised by having 2-4 dairy cows per farm, each producing 12-14 L day^{-1} (de Vries et al., 2017). All the dairy farms in the Lembang region of West Java produce a total of about 150 tonnes of milk day^{-1}, equal to 14% of national milk production (Kementrian Pertanian, 2019). Most of the dairy farms in this region are landless, with little to no land for manure application. This leads to fresh manure often being discharged from the farms, polluting the environment. Previous studies about manure management in smallholder dairy farms in this region showed that 80% of the farms discharged some part of the total manure produced, resulting in an estimated annual loss of 1,061 tonnes of N and 290 tonnes of P over an area of about 9,560 ha (Zahra et al., 2021; de Vries et al., 2017). Improper manure management at the farm level contributes significantly to environmental problems at the regional level (i.e., the pollution of the Citarum river; Zahra et al., 2021).

It is crucial that Indonesian dairy farms work with the stakeholders associated with manure management (i.e., crop farmers, composters, and dairy cooperative), because dairy farms are small and suffer constraints when it comes to performing proper manure management. Stakeholders may also be affected to some degree when dairy farmers are unable to perform proper manure management. For example, crop production may be affected if crop farms do not use manure due to an inconsistent manure supply. Moreover, the stakeholders also have constraints that limit them from utilising the benefits of manure (e.g., the bulkiness of manure).

Manure management is vulnerable to constraints. Understanding these constraints and what prevents them from being resolved may contribute to policy making for improving manure management at the farm level and subsequently decreasing environmental impacts at the regional level (i.e., the Lembang region). Currently, the constraints on manure management at Indonesian smallholder dairy farms are not well recognized. Therefore, this study aims to analyse and identify the constraints on manure management on smallholder dairy farms and find potential opportunities for improvement.

2. Methods

2.1 Focus group discussions (FGDs)

Two FGDs were performed to gain insight into the constraints on manure management, as well as to discover potential solutions to overcome these constraints. Both FDGs were performed in November 2018 on separate days in the Lembang region of West Java. We invited key stakeholders related to manure management: dairy farmers (represented by group leaders), composters, the dairy cooperative (KPSBU), and crop farmers. The first FGD involved 3 representatives from KPSBU and 15 dairy farm group leaders. The second FGD involved 2 representatives from KPSBU, 11 crop farmers, and 4 composters.

KPSBU is the largest dairy cooperative in the West Java province, with more than 4,000 active members, covering ~90% of the dairy cattle population in the Lembang region. KPSBU collects milk and provides supplies and services (compound feed, veterinary care, on-farm supplies, etc.) for the dairy farms. Moreover, they support manure management through loans for biodigester construction, providing manure management training for the farmers, and participating in manure-related research. KPSBU was represented in both FGDs by the secretary, members of the advisory board, and the extension staff.

Dairy farmers are the only cattle manure producers in the region. The dairy farmers are organised in farmer groups (i.e., 120 sub-regionally organized groups in total), each with a group leader. We received the list of group leaders from KPSBU and selected 15 of 120 at random to be represented in the first FGD.

Crop farms are the major organic fertiliser (compost) user, accounting for about 36% of total land use in Lembang (BPS, 2018). KPSBU provided information about the Lembang Agri crop cooperative most of whose 250 members use compost for crop farming. These crop farmers were organized in seven groups, each of which had a group leader. We invited the board of the crop cooperative and group leaders.

Composters are dairy farmers that operate manure processing businesses. The composters transform fresh dairy cattle manure into usable compost for sale. The composters use manure from their own farms, and they may purchase manure from other dairy farmers. We received the list of 40 active composters in the region from KPSBU. With help of KPSBU we selected four composters for the second FGD.

In FGD 1, KPSBU first described measures they took related to manure management. KPSBU and dairy farmers' group leaders were asked about the constraints involved in proper manure management. We then had a series of open questions with follow-up discussions to find potential solutions for improving manure management.

In FGD 2, KPSBU, again, first described measures related to manure management. Then crop farmers were asked to describe the use of the organic fertilisers on their crops and the related difficulties or challenges. After this, the composters were asked to discuss the compost supply and related constraints. Similar to the FGD 1, an open question and answer period was offered, aimed at finding potential solutions to improve manure management.

Both FGDs were held in the Bahasa Indonesia language and recorded; notes were also taken. Both FGDs were facilitated by the researcher (first author), who was prepared with and guided by a list of questions and a schedule for that purpose. The FGD was organized such that all invited participants were given the opportunity to voice their opinions (Bloor et al., 2001). The first FGD lasted 90 minutes and the second FGD lasted 120 minutes.

To analyse the FGD data, we identified aspects and sub-aspects in the discussions. An aspect is an important facet of manure management, such as surplus manure production and a sub-aspect is a smaller component of the aspect. We then grouped the aspects and sub-aspects into overarching themes. A constraint is a characteristic that restricts efficacy in the present or is expected to do so in the future (modified from Boogaard et al. 2008). For manure management, we identified constraints as aspects and sub-aspects mentioned by stakeholders' multiple times and potentially hampering proper manure management.

2.2 Farm surveys

A farm survey was conducted to assess the environmental impacts of smallholder dairy farms in the Lembang district of West Java. This data collection occurred on a bi-monthly basis over the course of a year from December 2017 to October 2018, to a total of six times (Zahra et al., 2021). As part of this study, data about costs and revenues related to manure management were also collected. Fresh manure (i.e., the faeces) is partly collected whereas all urine is discharged. Each of the 30 dairy farms involved was classified to one of following manure management systems (MMSs): (1) applying manure directly – i.e. without treatment – on HGF (home grown feed) areas, whereby faeces are collected and used as organic fertiliser for the cultivation of HGF (ADL; n= 6 farms); (2) selling or exporting manure, whereby faeces are collected in sacks and sold to manure traders or to other farms (SEL; n= 7 farms); (3) using manure as substrate for anaerobic digestion, whereby faeces are collected to produce bio-energy (methane) in a biodigester (ADI; n= 8 farms); (4) discharging manure, whereby faeces are not collected and in most cases was flushed from the barns into the surroundings (DIS; n = 9 farms). If more than 40% of the faeces was managed according to one of the MMSs, the farm was assigned to that MMS. The 30 selected dairy farms with different MMSs had comparable farm characteristics: on average 3.5±1.7 lactating cows, 0.4±0.3 dry cows, and 2.0±0.4 young stock, with an average milk production of 5,376±826 kg animal^{-1} yr^{-1}, and terrain size of 0.32±0.2 ha. Further details about the selection and allocation of the farms to each MMS group including on-farm data collection procedures (e.g., milk yield) can be found in the study of Zahra et al. (2021).

During each farm visit, we asked about the supplies required for manure management and their cost price. Labour input per MMS was assessed during each farm visit, by observing farm activities for one day and recording time spent on manure management activities (i.e., collecting, storing, applying manure to HGF areas, etc.). The labour input for ADL and ADI included labour for collecting manure from the barn, storing it in sacks or in the bio-digester, or in a manure heap, delivering and applying manure to the HGF areas. The labour input for SEL included the work of collecting manure from the barn and storing it in sacks. The labour input for DIS included the work of flushing manure from the barn. We asked the farmers about who was in charge of the manure management activities. If manure management activities were performed by family members, the cost was classified as family labour. If manure management activities were performed by hired employees, the cost was classified as hired labour. Additionally, during one of the six visits per farm, we asked ADI farmers about the cost to construct a bio-digester.

To collect data about farm revenue, during each farm visit, we asked the farmers about the quantity of manure sold, the selling price of manure, urea usage on HGF, and the cost of urea. We also asked the farmers to recall the monthly consumption of the Liquefied Petroleum Gas (LPG) tubes before and after installation of their bio-digester.

2.3 Calculating costs of manure management

We identified the total costs of manure management (TC), which included the total production cost for manure management (TPC) and labour cost (LC). TPC consisted of the total fixed costs (TFC) and total variable costs (TVC). TFC were supplies that were purchased only once, such as the cost of constructing a bio-digester. TVC were supplies, like shovels, buckets, hoses, etc, that might be repeatedly purchased throughout the year based on the farmer's needs. TFC refers to the total fixed cost, which is derived by multiplying the price of the supply item with its depreciation rate (%), which we assumed to be 10%.

LC was defined as the cost that the farmers spent on labour for manure management activities. This was calculated as the wage rate per day in smallholder dairy farms multiplied by hours a day spent working on manure management related activities for an entire year (IDR yr^{-1}). With regards to labour, we distinguished between family labour and hired labour. Studies have shown that family labour is a determining factor in generating profits in smallholder farms (Posadas-Dominguez et al., 2014; Espinoza-Ortega et al., 2007). In smallholder farming systems, the farmer often allocates his own or his family's labour without taking costs into account (Picazo-Tadeo et al., 2005). In this study, ADI, ADL, and DIS had family labour, and SEL had a combination of family labour and hired labour. Hence, in TC, we presented TC without family labour and TC with family labour (net TC). Similarly, we also presented GM without family labour and GM with family labour (net GM). In the net TC and net GM, we computed the family labour as costs.

To calculate revenue from manure management, we identified three forms of potential revenues from manure management: (1) savings from replacing urea with manure (UreaS), (2) savings from substituting LPG with biogas (LPGS), and (3) direct income (DI). Total revenue (TR) was the sum of all potential revenues from MMS. UreaS (IDR yr^{-1}) equalled the cost of the substitution of urea by manure, which we calculated by first multiplying the amount of applied N from manure (i.e., N from solid manure in the case of ADL and N from digestate for ADI) to HGF areas (kg N yr^{-1}) with the N-working coefficient of organic fertiliser divided by the N- content of urea (kg kg^{-1}). Next, we multiplied this value (kg N yr^{-1}) with the urea price (IDR kg N^{-1}) to determine the cost of substituting urea with manure (IDR yr^{-1}). The N-working coefficient was 0.43 for solid manure and 0.65 for digestate (Zahra et al., 2021).The N-content of urea was 0.46 kg kg^{-1} and the price of urea (1,800 IDR kg^{-1}; 828 IDR kg^{-1} N) was the price of subsidised urea (Indonesia 2011).

LPGS (IDR yr^{-1}) equalled the cost of substituting LPG with biogas, calculated as the difference between monthly LPG tubes used before and after the construction of the bio-digester multiplied by the price for LPG tubes (IDR $tube^{-1}$). The price was based on that of subsidized LPG (30,000 IDR $tube^{-1}$; 1 tube = 3 kg). DI (IDR yr^{-1}) was calculated based on kg manure sold per year, multiplied by the price of manure (IDR kg $manure^{-1}$). The gross margin (GM) was calculated to estimate the gross profit at different MMSs and expressed as the difference between TR and TC.

To analyse the economic data from the farm surveys, we compared the means of TC, TR, and GM of the four different MMSs. We also compared the means of TR, which included UreaS, LPGS, and DI of four different MMSs using a Kruskal-Wallis test. The Dunn test was performed to analyse differences of these parameters between MMSs.

3. Results

3.1 FGDs findings

We identified 11 aspects and 3 themes of manure management (Table 1). Overall, we identified 20 constraints on manure management which will all be discussed further in the following sub-section.

3.1.1 Manure surplus

In the manure surplus theme, dairy farmers and dairy cooperatives indicated high manure production as being a constraint for them. High manure production is linked to the regulation of the Indonesian government to increase numbers of dairy cattle per farm. High manure production and the limited opportunities (e.g., land for storage and application) to use manure causes the surplus of manure on the farm. The surplus of manure is discharged and leads to environmental emissions (e.g., greenhouse gas emissions and nutrient losses). Due to the high levels of discharged manure in the region, the dairy cooperative received complaints from households near dairy farms about odours and from urban centres about contaminated water.

3.1.2 Manure management

In the theme of manure management, we identified 11 constraints on manure management. Dairy farmers reported constraints during manure collection and storage, processing, transport, and application. Manure collection is performed manually, using shovels, buckets, and hoses, and the high labour and time costs constitute the constraint. The farm size is small, and the farmers have limited to no space for storing manure, which was perceived as a constraint for them. Current storing systems (e.g., solid storages with no storage for urine) are often insufficient to store the surplus of manure production, which then leads to discharging manure.

The dairy farmers and/or composters process manure via composting and anaerobic digestion. The constraint on manure processing is related to the availability of manure technology. The dairy cooperative indicated that the currently available technology (e.g., bio-digester) is inadequate and unaffordable, leading to low adoption rates. KPSBU attributed the low rates of adoption of technology by dairy farmers to limited financial capital and high initial investment costs. Composters indicated that current composting practices are inadequate for meeting the quality of compost required by

Table 1. Identified themes and summarised aspects of manure management, including the constraints.

No	Themes	Aspects	Sub-aspects	Stakeholders[1]
1	Manure surplus	1.1 High production *	-	Dairy farmers, Dairy cooperative
		1.2 Limited use of manure*	-	
		1.3 Environmental pollution	-	
2	Manure management	2.1 Collection and Storage	Space availability*	Dairy farmers, Composters
			Cost of labour *	
		2.2 Processing	Space availability*	
			Cost of investment*	
			Cost of labour*	
			Availability technology*	
			Adoption technology*	Dairy cooperative
		2.3 Transport	Equipment *	Dairy farmers, Composters
			Cost of labour*	
		2.3 Application	Space availability*	Dairy farmers
			Cost of labour*	
3	Manure market	3.1 Competition with other fertilisers	Chicken manure *	Dairy farmers, Composters
			Artificial fertiliser*	
		3.2 Price	Subsidies *	
		3.3 Market requirement	Constant supply-demand*	Crop farmers
			Quality of product*	
			Preference for compost*	
		3.4 Structure and organization*	-	Dairy farmers, Composters, Crop farmers

*Constraints on manure management, [1]Constraints for specific stakeholders

consumers: due to poor drying processes, which are in turn linked to the limited financial capital to access drying technologies, the products are dried manually and thus highly dependent on weather, leading to substandard products.

The dairy farmers and composters indicated the space for manure processing is a constraint for them. Manure processing (i.e., bio-digester) requires space, and not all dairy farmers have the space to construct a bio-digester due to the small size of the farm. To optimize the benefits of the bio-digester, farms need additional land for storing digestate (a by-product of anaerobic digestion), which subsequently can be used as organic fertiliser on HGF areas and cropland. However, the land for storing the digestate is not available, leading farmers to discharge digestate instead. On the other hand, the composting process requires ample space for storing, drying, mixing, and grinding, which is often a constraint for composters.

There are substantial investment costs attached to processing manure. The dairy farmers admitted that the current manure technology (e.g., bio-digester) is often costly, particularly the initial investment. According to the composters, manure processing also requires a high investment (e.g., buildings and equipment). Composters reported on the high labour cost for processing manure. Composting is a labour-intensive activity because most of the processes are performed manually (i.e., collecting, mixing, and drying). Hence, the composters mainly perceived the high cost for labour as the constraint.

The cost of transporting fresh manure is high because the dairy farmers transport manure to their land either using a wheelbarrow or a motorbike, further limiting the delivery capacity. Lack of manure transportation equipment (e.g., truck for transporting manure) is a particularly severe constraint for dairy farmers located in rural areas. The composters also indicated high transportation costs because they had to collect fresh manure from many farms.

Dairy farmers indicated that the available space for manure application is a constraint for manure management. The dairy farmers have little to no HGF areas for manure application, and most of the HGF areas are located on marginal land (steep hills with limited road access), making manure application difficult. In addition, manure application is labour-intensive and is perceived as an economic constraint for dairy farmers. Dairy cattle manure is bulky and wet, and limited storage for storing manure causes the applied manure to the HGF areas to often be in the form of fresh manure or semi-dried manure. Applying these products is impractical and time-consuming, generating high labour costs.

3.1.3 Manure market

In the theme manure market, we identified six constraints on manure management. Compost and fresh manure must compete with other fertilisers such as chicken manure and artificial fertiliser. The use of chicken manure was favoured among our respondents; they reported that it is lighter and not as bulky as fresh cattle manure, which makes it easier to apply and therefore lowers labour

costs. Artificial fertiliser is also easier to apply than fresh manure. In addition, dairy farmers and composters indicated that the subsidy on artificial fertiliser is a constraint for use of fresh manure. The Indonesian government subsidies artificial fertilizer by 60%, which makes the price of this fertilizer low which is an incentive for farmers to use it on croplands and HGF areas.
In the theme manure market, crop farmers mentioned that they prefer to use compost to fresh manure because they believe the composted manure is better for their crops and more beneficial for the soils than fresh manure. The compost supply-demand and quality of compost are the constraints for them. At the beginning of the cropping season, mainly in the rainy season, the crop farmers require large amounts of compost. The composting process in the rainy season takes longer than in the dry season. According to the crop farms group, the compost demand for major crops was roughly 51,580 Mg yr^{-1} (Table 1; Supplementary material 1). The supply of compost was estimated as lower than this amount.

The absence of a structured manure market was perceived as a constraint for dairy farmers, crop farmers, and composters. Currently, an informal manure market exists that involves all three aforementioned stakeholders. In this informal manure market, dairy farmers sell or give fresh manure to crop farmers. In this instance, crop farmers themselves process it into compost before using it as organic fertiliser. The dairy farmers also sell fresh manure to composters. In addition to buying manure from other dairy farmers, composters use manure from their own farms and process it into compost to subsequently sell it to crop farms. The current informal manure market does not solve the issue of discharged manure because of the demand and supply of compost and fresh manure not being aligned, leading to unreliable profits from selling manure. Because of this, crop farmers said that the supply of compost and fresh manure is inconsistent, and composters reported that they struggled to maintain a consistent income. The dairy farmers, the crop farmers, and the composters indicated the importance of a structured and well organised manure market, which is currently unavailable because stakeholders are not taking the initiative to create one due to limited financial capital for the required investments.

Because of the uncertainty of compost supply, the quality and compost price are affected to a degree. When there is insufficient compost supply, composters may deliver or supply unfinished compost to meet the demand from crop farmers. This, however, compromises the compost quality. In addition, the price for compost may vary a lot, for example from 10,500- 20,300 IDR per 35 kg of product. The variation of quality and price of compost is unfavourable for crop farmers, as it negatively impacts production costs. Composters agreed that the prices of compost varied due to the variable production capacity at relatively small processors (the production capacity of the four composters participating in the FGD ranged from 20 to 540 Mg yr^{-1}, fluctuating selling price of fresh manure by dairy farmers (i.e., 5,000-7,000 IDR per 50 kg), and the volatility of demand for compost (Table 2; Supplementary material 2).

3.2 Farm survey findings

Table 2 shows TC, TR, and GM of the four different MMSs. The TC without family labour differed among MMSs with DIS having a lower TC without family labour than SEL and ADI. Similarly, net TC differed among MMSs with DIS had lower net TC than SEL and ADI. The family labour cost accounted for 3.37 to 6.73 million IDR year^{-1} or 95-98% of the total net TC. The family labour cost of DIS was lower than of SEL and ADI. The hired labour cost was only found in SEL (Confidence Interval (CI) = -0.7 – 3.2) and the mean did not differ from zero. TPC differed among MMSs, with DIS having a lower TPC than ADI. TPC in ADI was associated with the investment in the bio-digester and it was a supply cost such as for purchase of shovels, buckets etc for ADL and SEL

We also discovered that TR differed between MMSs with ADL having lower TR than SEL. UreaS from ADL (CI = 0.06 – 0.30) and ADI (CI= 0.01 – 0.08) did not differ but the means differed from zero. ADL only received revenue from UreaS, and ADI received revenue from UreaS (5% of TR) and LPGS (95% of TR). TR from DI was only found in SEL (CI = -1.9 – 11.7) and the mean did not differ from zero, while DIS had no revenues from manure management. GM without family labour differed between MMSs, and DIS had the only negative GM. SEL had higher GM without family labour than DIS. The net GM was negative for all MMSs and did not differ among MMSs.

Table 2. The mean of total cost, revenue, and gross margin of four different manure management systems (million IDR yr^{-1}) (Standard error between brackets).

	MMS			
Parameters	ADL[1](n= 6)	SEL[2](n= 7)	ADI[3,9](n= 8)	DIS[4] (n= 9)
TC[5] without family labour	0.17^{ab} (0.06)	1.36^{b} (1.04)	0.44^{b} (0.05)	0.06^{a} (0.01)
Net TC[5]	4.50^{ab} (0.57)	7.23^{b} (1.63)	7.17^{b} (0.77)	3.43^{a} (0.43)
LC[6,7]				
• Family labour cost	4.33^{ab} (0.60)	5.88^{b} (1.13)	6.73^{b} (0.75)	3.37^{a} (0.43)
• Hired labour cost	-	1.25 (1.04)	-	-
TPC[8,9]	0.17^{ab} (0.06)	0.11^{ab} (0.02)	0.44^{b} (0.05)	0.06^{a} (0.01)
TR[10]	0.18^{a} (0.06)	4.93^{b} (3.5)	0.86^{ab} (0.17)	-
1. UreaS[11]	0.18^{a}(0.06)	-	0.05^{a} (0.02)	-
2. LPGS[12]	-	-	0.81 (0.18)	-
3. DI[13]	-	4.93 (3.5)	-	-
GM[14] without family labour	0.01^{ab} (0.10)	3.58^{b} (2.49)	0.42^{ab} (0.19)	-0.06^{a} (0.01)
Net GM[14]	-4.33 (0.56)	-1.05 (3.45)	-6.32 (0.75)	-3.43 (0.43)

[1]Applying manure directly on HGF areas, without treatment; [2]Selling manure to the manure traders; [3]Using manure as substrate for anaerobic digestion; [4]Discharging manure; [5] Total cost; [6] Labour cost; [7]Wages were 110,000 IDR day^{-1} for 8-hour days, [8] Total production costs; [9]The average cost of construction for bio-digester is 7.14 million IDR and this was divided by three, as KPSBU gave a three-year loan to dairy farmers to build the bio-digester; [10]Total revenue, [11]Savings from replacing urea with manure; [12]Savings from substituting LPG with biogas; [13]Direct income; [14]Gross margin; Different superscripts letter show significant difference (P-value < 0.05)

3.3 Stakeholders' ideas for improving manure management

During the FGDs, the stakeholders came up with three potential ideas to improve manure management: 1) communal manure storage, 2) structured manure market, and 3) support.

1. **Communal manure storage**. Most of dairy farmers had limited space to store manure. They indicated the importance of centralized manure storage, and a communal manure storage (CMS) was proposed. A CMS is a storage unit in a communal area operated by a dairy farmers' group where manure from individual farms is transported to and stored. A CMS would have to be large enough to absorb all manure being produced per dairy farmers' group. The cost of transportation for composters would decrease since the manure will be collected from a single location.

2. **Structured manure market.** The collected manure at a CMS needs to be sold, and a good and structured manure market is essential for this. Dairy and crop farmers, as well as composters, suggested a role for the KPSBU cooperative to develop a structured manure market. Such a structured manure market should help to regulate manure prices and stability of manure supply and demand, and to control product quality.

3. **Support.** To improve manure management, institutional and economic support is needed. This support includes access to credit to invest in manure management and financial incentives as a reward for good manure management.

4. Discussion

4.1 Constraints on manure management

This study explored constraints on manure management on smallholder dairy farms and find potential opportunities for improvement. The FGD being performed in this study was effective to identify constraints on manure management. FGD bridges communication between participating stakeholders (Soltani et al., 2015; Bani et al., 2009; Morgan et al., 1996). Stakeholder involvement was believed to be key to sustainable waste management (Le et al., 2018; Rajablu et al., 2014; Heidrich et al., 2009). In our study, stakeholders shared that they have clear roles in manure management and use, and that there are interdependencies among stakeholders. Crop farmers, for example, rely on the dairy farmers to supply compost, and dairy farmers rely on the crop farmers for manure application on the crop land. Such dependency connections show that manure management improvement at the regional level requires the involvement of multiple stakeholders.

Having a structured (for example a centralized and better regulated) manure market could act as an important step to stop discharging manure. The local government can play a role by providing support and regulations related to manure management. Currently, the Indonesian government regulates manure management for the livestock sector, by having made mandatory for the livestock sector to build storage facilities and perform manure management to avoid exceeding the maximum limit of wastewater (e.g., maximum biological oxygen demand is 100 mg L^{-1} or 20 g $head^{-1}$ d^{-1}) (Ministry of Agriculture no 11, 2014; Ministry of Environment no 11, 2019). The medium- and large-scale farms (i.e., > 20 dairy cattle per farm) need to regularly report their environmental performances. In line with the current study, the studies of Dinh et al. (2017) and Teenstra et al. (2015) indicated that countries in South Asia such as Vietnam and the Philippines placed emphasis on manure policies for medium- and large-scale farms. Nevertheless, they also showed that most countries in southeast Asia are weak in their enforcement of manure policies and that there are only few or no regulations for smallholder farms. The Indonesian government might consider implementing regulations for smallholder farms, as the aggregate pollutions from these farms are considerable (Zahra et al., 2021).

4.2 The economics of manure management

The negative economies, caused by high cost and low revenue, made structured MMSs less appealing for smallholder dairy farms. The average net GM was low and negative for all MMSs, unless for few farmers in SEL, and this was caused by the high costs for labour (i.e., family labour) and low revenue from manure. Family labour accounted for 78-100% of the total labour cost and this was comparable to the other studies in which family labour accounted for 80-100% of the total labour cost (Salina-Martinez et al., 2020; Posadas-Dominguez et al., 2014; Hemme et al., 2000). In the situation where labour is scarce, family labour costs should be taken into account because family labour lends value to the system. In addition, during the FGDs, dairy farmers and composters indicated the cost for labour is high, and this implies that a labour scarcity exists in the region, which is likely linked to the decreasing number of young employees in Indonesian agricultural sectors (Sulistiowati et al., 2016). Postive net GM in at least few farmers in SEL indicated that the selling of manure is economically attractive when the direct income from selling manure is higher than the total production costs.

Low revenue for ADL and ADI could be explained by low substitution of urea by manure due to the low price of subsidized urea. Farmers using fresh manure or compost did not replace urea but gave additionally. In addition, LPG was similarly subsidized (Arze del Granado et al., 2012; OECD, 2019). Because of the subsidies, farmers may be reluctant to use manure and utilize anaerobic bio-digesters. In addition, high initial investment costs also limit adoption of these improved manure management practices. The high cost of investment for bio-digesters was also an issue in the biogas programme in Vietnam (Roubik et al., 2018). Improper bio-digester protocols lead to environmental issues such as the release of CH_4 from the excessive production of biogas (Apdini and Zahra, et al. 2021) and nutrient imbalances at farm and regional level when the digestate is being discharged (Zahra et al., 2021). Low revenue for SEL was linked to the low price per kilogram of manure.

Ultimately, all MMSs had economic shortcomings. SEL seemed to be the most attractive compared to others but the revenue of selling manure was limited by the absence of a structured manure market and the competition with artificial fertiliser. ADI required an expensive initial investment and thus may not be feasible for all farmers without access to credit and/or private or governmental aid. ADL was limited by the availability of land for manure application. DIS was limited by labour costs and, at the same time, had no revenues, while aggravating environmental and social issues (FAO 2003).

4.3 Improvement options

Performing proper manure management is essential to minimize environmental pollution (Wiesner et al., 2020; Ndambi et al., 2019; Navarrete-Molina et al., 2019). The attitudes of farmers towards manure are important and should not be overlooked. The majority of the farmers in this region saw manure as a valuable product but experience constraints on manure management, which leads to high rates of discharged manure. Space availability and cost are considerable constraints on manure management at smallholder dairy farms, as it is found in many sub-aspects.

Manure management must be improved, and improvement options should strive to solve the relevant issues (i.e., space and cost). All improvement options being addressed by stakeholders could be valid. The presence of CMS could solve the issue related to space for storing manure and benefit dairy farmers by better manage manure without each farmer incurring additional cost for storage facilities, and by increase manure collection at regional level. A CMS requires land and marginal lands belonging to the local community as communal land under the local government could be used. The dairy cooperative could play a role to arrange the agreement between the local government and dairy farmers to use these lands. The technical aspects (e.g., exact size and capacity of a CMS) will depend on the location and the size of farmer groups and require further research and analysis that lie outside the scope of the current study.

The establishment of a structured manure market is important, and the market could increase manure use at regional level and beyond and increase the value of manure. The dairy cooperative could take the lead to create a structured manure market, starting with arranging a formal agreement between stakeholders. This formal agreement could be done by approaching the stakeholders (e.g., crop farmers) to identify their needs (i.e., demand for compost, and its quality, and price etc.). The exact structure of the formal agreement will require further investigation and cooperative work between stakeholders to design a plan to benefit all parties involved. The market for fresh manure is limited because fresh manure is mostly used by the dairy farmers as organic fertiliser to fertilise HGF areas while the major user (i.e., crop farmers) prefer to use compost. To overcome this issue, the number of composters in the region needs to be increased in order to transform more manure into compost, and the presence of a structured manure market is important. Moreover, use of compost made from dairy cattle manure needs to be encouraged on a larger scale and application in the plantation and forestry sectors should be explored (Zahra WA et al., 2021).

Providing financial support, such as access to credit, would allow dairy farmers or farmers groups to purchase equipment and facilities, required for proper manure management. The credits will only be useful if they can be paid back. Hence, manure collection and marketing either by individual farmers of by a farmers group with a CMS needs to be commercial and a business plan is required. At the beginning of transition of better manure management, providing financial incentives could help to increase on-farm manure collection. Studies have shown the impact of financial incentives in motivating smallholder farmers to adopt recommended manure management practices (Roubik et al. 2018; Dinh et al., 2017). The incentive could be based on the quantity of manure being managed relative to the total quantity produced and could be paid via a premium to the milk being produced. For this strategy, the role of KPSBU is essential.

Training of farmers and extension could help to get successful plans and operations of manure management. Training improves the farming skills and the abilities of the farmers in adopting technologies (Paltasingh et al., 2018; Weir et al., 1999). Dairy farmers and/or composters need to be taught for better drying process in order to achieve a good and standardized compost for the market. Moreover, dairy farmers are hardly having knowledges on organizational and business aspects of manure management and for this reason, the current farmers groups should learn how to organize a CMS and running a manure business (e.g., quantifying the coming in-out manure to CMS and recording the selling manure, etc.). Organization and support from both the dairy cooperative and the local government would help ensure a smooth transition to better manure management practices for smallholder dairy farms.

Overall, the existing constraints that prevent stakeholders from creating symbiotic relationships must be solved. Since there are social, environmental, and economic aspects to manure management, it is not enough for dairy farmers to change; the stakeholders they interact with must also be willing to change. For change to truly take hold, all agricultural industries must be represented and impacted.

5. Conclusions

Our study explored the constraints on manure management on smallholder dairy farms. We discussed these constraints with stakeholders involved in manure management and identified 20 constraints on manure management. Space availability and costs are considerable constraints as it is indicated in many sub-aspects. The cost of manure management is high, where SEL and ADI had higher net total cost than DIS. The high cost of manure management was primarily associated with labour cost and on average all MMSs had negative GMs. Even so, based on stakeholders' opinions, the opportunities for improving manure management are plentiful, such as communal manure storage, a structured manure market and institutional and economic support. Our study also showed the importance of working with concerned stakeholders, as the dairy farmers cannot stand alone if they are to overcome manure issues.

Appendix 6.1

Supplementary material 1

Table 1. The estimated demand for organic fertiliser for major crops in the Lembang region according to crop farmers during the FGDs.

Crop types	Organic fertiliser rate (Mg ha^{-1} Yr^{-1})	Land size of the crops (Ha)[1]	Total Organic fertiliser requirement (Mg Yr^{-1})[2]
Chili	30	336	10,080
Tomato	15	321	2,385
Green beans	45	287	12,915
Leeks	30	237	7,110
Broccoli	30	210	6,300
Cabbage	30	164	5,740
Chinese cabbage	20	159	6,420
Lettuce	30	42	630
Total	--	--	51,580

[1]Based on Lembang statistics (2018). [2]The total organic fertiliser requirement was based on a multiplication of organic fertiliser rate with the land size of the crop

Supplementary material 2

Table 2. Potential manure supply from four composters

Composter	Capacity of manure production (Mg yr^{-1})[1]	Price (IDR kg^{-1})[2]	Gross margin from manure business (million IDR yr^{-1})
Farm A	20	300	6.00
Farm B	60	450	27.00
Farm C	125	500	62.50
Farm D	540	580	313.20

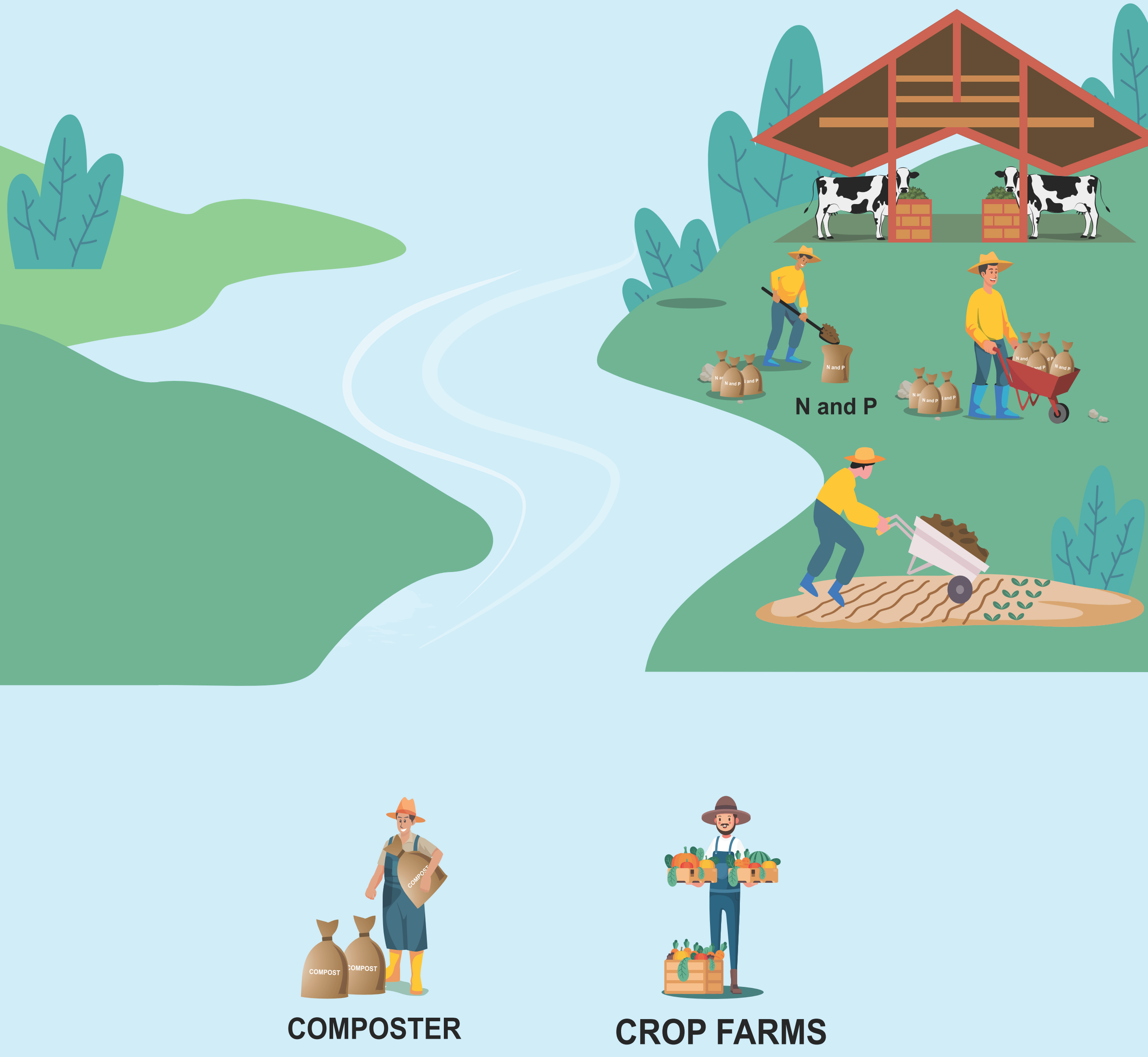
[1)]Compost product, [2)]1 euro = 16,000 IDR

DAIRY COOPERATIVE

DAIRY FARMS

Chapter 7

General discussion



1. Introduction

The governmental policy to increase the dairy cattle population in Indonesia has increased manure production of the dairy cattle sector. Most of the manure that is produced on dairy farms is discharged to ditches, to end up in rivers, including the Citarum river, causing pollution of these waterbodies. The practice of discharging manure has been ongoing for decades and has caused nuisances such as complaints from people living near dairy farms about odour, and from people living in urban centres about contaminated water sources. Moreover, release of gaseous emissions and nutrient leaching from poor manure management generates environmental impacts such as climate change through greenhouse gas emissions (GHGE), and acidification and eutrophication through acidifying and eutrophying compounds such as ammonia and nitrate.

Manure management at Indonesian smallholder dairy farms must be improved. Focussing on environmental issues, this thesis aimed to evaluate emissions to the environment associated with manure management and to identify improvement options on smallholder dairy farms in Indonesia. The evaluation of emissions is performed at multi-levels (i.e., animal, farm, regional, and value chain). In this general discussion, I first present the main findings of each research chapter and thereafter I discuss some methodological issues. Following this, I discuss improvement options and suggest ways to create an enabling environment for better manure management on smallholder dairy farms.

2. Main findings

The study in Chapter 2 developed mathematical models to quantify nitrogen (N) and phosphorous (P) excretion at animal level based on farm data that are relatively easy to collect. It was concluded that the proposed models can be used with reasonable accuracy to predict N and P excretion of dairy cows on smallholder farms in Indonesia under various circumstances. The models can contribute to improving manure management and to reducing related environmental impacts. The models predicted that on average, N excretion was 197 g animal^{-1} d^{-1} and P excretion was 56 g animal^{-1} d^{-1}. The nutrient use inefficiency (NUI) at animal level was found to be 78% for N and 88% for P.

The study in Chapter 3 evaluated environmental emissions of dairy farms with different manure management systems (MMSs) at farm and regional level by quantifying their nutrient balances. The N balances of all 30 dairy farms averaged 222 kg N farm^{-1} yr^{-1} and did not differ between MMSs. The P balances of the farms did differ between MMSs; balances were highest for farms that discharge manure (DIS) (83 kg P farm^{-1} yr^{-1}) and lowest for farms that sell or export manure (SEL) (-25 kg P farm^{-1} yr^{-1}). Annually, all dairy farms in the Lembang region caused a loss of 1,061 tons of N and 290 tons of P into the environment and they extracted 8 tons of P from soils. It was concluded that the main cause of nutrient losses related to dairy production in the Lembang region is discharging manure into the environment and to reduce these losses dairy farmers should improve the collection and on-farm use of manure and sell excess manure to crop farms. The decoupling of animal and crop production is seen as one of the main reasons of high nutrient pollution at regional level.

The study in Chapter 4 evaluated environmental emissions at value chain level. I analysed seasonal differences in greenhouse gas emissions (GHGE) from Indonesian dairy farms by means of longitudinal observations and evaluated the implications of number of farm visits on the variance of the estimated GHGE per kg milk (GHGEI) for a single farm mean, and for the population mean. The results showed that GHGEI was higher in the rainy (1.32 kg CO_2-eq kg^{1} FPCM) than in the dry season (0.91 kg CO_2-eq kg^{-1} FPCM). Based on the between and within farm variance of the estimated GHGEI, it was concluded that variation between observations at different visits to the same farm is the major source of variability of GHGEI. Variability of GHGEI can be reduced by increasing the number of visits per farm.

The study in Chapter 5 evaluated environmental emissions at value chain level and aimed to identify strategies to reduce GHGE at smallholder dairy farms beyond productivity (milk yield per cow) increases. The results showed that farms with a low GHGEI generally use less rice straw, more cassava waste, and more compound feed than farms with a high GHGEI. They furthermore discharge more manure, store less solid manure, use less manure for anaerobic digestion, and apply less manure N on farmland. Hence, good manure management practices (which is beneficial for reduction of N and P losses to the environment) showed a trade-off with reduction of GHGEI.

The study in Chapter 6 identified constraints on manure management on smallholder dairy farms in Lembang, and potential improvement options at farm and regional level. The results showed that there are 20 constraints to improve manure management, of which availability of space to store manure on the farm, and costs of manure management are regarded most important. High cost of manure management is primarily associated with labour cost. The net gross margin of all manure management systems is negative. Stakeholders proposed strategies to improve manure management such as communal manure storage (CMS), a structured manure market, and providing economic and institutional support such as access to credits and financial incentives for good manure management.

3. Methodological issues

The availability and quality of data are often issues in livestock studies in Indonesia. These issues stem from the absence of farm monitoring and data recording. The mechanisation level is low, implying that there is hardly any equipment used, let alone equipment with sensors or data recording. Consequently, many animal and farm data that are generally available in developed countries are not available in Indonesia. To perform research on livestock systems in developing countries, researchers often rely on information or models from livestock studies in developed countries. This potentially results in under- or overestimated values as the prediction models, e.g. of feed intake, growth, or milk yield, are built on relations between parameters assessed under conditions in developed countries. To overcome such biases for one of the most important issues with regard to manure management on smallholder dairy farms namely the estimation of the amount of excreted nutrients, I developed and tested models for the Indonesian situation. In this case, the so-called Lucas principle (Weisbjerg et al., 2004; NRC, 2001), as used in developed countries, gave relatively accurate predictions under the Indonesian conditions.

Studies of smallholder farming systems in tropical regions often use data that are collected at one particular moment in time (i.e., cross-sectional observation) or use data based on farmer's recall (i.e., farmers retrieve information from the past through memory; Migose et al., 2020). Seasonal and within season differences in management practices, however, can be an important source of variability and there is a risk that such differences are not well captured in farmer's recall. To overcome bias in a situation where farm recordings are absent and seasonal and within season differences may affect estimates of farm characteristics such as milk yield, nutrient balances and GHGE, I performed longitudinal observations (Chapters 3 and 4). In the following sub-sections, I discuss the advantages and limitations of the approaches that I used, and future research approaches to consider.

3.1 Models to predict nutrient excretion from dairy cows

The models to predict nutrient excretion from dairy cows (Chapter 2) were developed and tested according to the Indonesian situation. The advantage of the models developed in Chapter 2 is that most of the data required for the model were collected (and can relatively easily be collected), on-farm, thus representing the actual situation. Such on-farm data are feed intake, milk yield, and bodyweight of individual animals whereas on farm collected feed, milk and manure samples were taken for analysis of composition. The Lucas principle was tested under Indonesian conditions and it showed to be a generally applicable principle to estimate N digestion (Weisbjerg et al., 2004; NRC, 2001). The remaining part of my models were built on general equations based on NRC (2001). The advantage of using such a model is that the baseline for further calculations is known, well documented, and robust. Moreover, the Q_{FN} model (i.e., the model to estimate the quantity of faecal nitrogen) developed in Chapter 2 is relatively easy to apply and low-cost because data requirements are limited to information on dry matter intake (DMI) and nitrogen content of the intake (NI).

However, the model to estimate Q_{FN} has parameters for which the values have to be derived from literature. The digestibility of dry matter (DDM) is an example of such a value. The availability of specified information of DDM for many feed types is limited for the Indonesian situation. Moreover, one literature value does not cover for the variation in DDM quality of feeds in time or among farms. In the model evaluation, the actual quantity of faecal N from the independent data set (Q_{FNACT}) is assumed without error. In reality, Q_{FNACT} also has an estimation error because of errors related to sampling, to laboratory analysis, and to the assumed DDM values used to estimate $Q_{FNACT.}$ Hence, evaluation of the predicted quantity of N in the faeces when evaluated against a real direct assessment (full collection of faecal and urinary excretion separately and compositional analysis of each fraction) would have been a better evaluation than the one in Chapter 2. However, collecting and analysing both faecal and urinary excreta is difficult, costly, and time consuming.

The models in Chapter 2 use feed intake data to predict nutrient excretion. Other studies often use empirical models to estimate nutrient excretion solely based on milk yield or body weight of the animals (Qu et al., 2018; Nennich et al., 2005). In my study (Chapter 2), I assumed that feed intake has a stronger correlation with nutrient excretion than milk yield and body weight and used all three parameters to determine urinary N excretion. Although data on milk yield and/or body weight are relatively easy to collect (Chapter 3; Chapter 4), variation in milk yields has been reported in Chapter 4 and Chapter 5 and should be taken into account when developing models based on milk yield. The estimation for milk yield can vary between data collection methods (i.e., longitudinal observations in Chapter 4 and cross-sectional observation in Chapter 5). The difference between data collection methods is discussed further in the following sub-section. Developing nutrient excretion models using readily available data, such as milk yield, body weight, feed intake, or a combination of those, could provide potential users the opportunity to select the model that is most reliable and accurate given the study and site-specific circumstances. The accuracy of different models (i.e., the models from Chapter 2, or models solely based on milk yield or body weight), however, should be evaluated and tested to allow comparison and final selection of models.

In addition, the data used to calibrate and evaluate the models were collected from one season only (i.e., the rainy season). The effect of seasonality on farm practices and emission estimates is later recognized in Chapter 4. Seasonality could potentially also affect the parameters that were used to calibrate and evaluate the nutrient excretion models in Chapter 2. However, since I use the (generically applicable) Lucas principle in which N digestion depends on DMI and N concentration of the diet, and all of these parameters are assessed at the moment of the farm visit, I expect that the models proposed in Chapter 2 will have no seasonal bias and are applicable throughout the year.

3.2 Frequent data collection

In Chapter 4, I demonstrated the importance of frequent data collection (i.e., longitudinal observations) by evaluating the impact of the number of farm visits on the variability of GHGEI estimates for a single farm mean and for the population mean. In longitudinal observations, data collection is repeated over prolonged periods—it could be multiple years or even decades (Caruana et al., 2015). The advantage of this approach is that it provides insight into potential differences in on-farm management practices across and within seasons. Longitudinal observations, therefore, could improve the reliability of the data and the accuracy of the results.

Performing longitudinal observations raises the question how many observations are needed to obtain a certain level of accuracy of the results. To answer this question, in Chapter 4, a linear mixed model was used to understand the impact of the number of farm visits (observations) on the variability of the estimated GHGEI. Results yielded insights into the between and within farm variances in GHGEI estimates across seasons. This information provides insights into the impact of the number of farm visits on the accuracy of GHGEI.

In Chapter 4, the between farm variance was lower than the within farm variance in both seasons, which means that the variation in the estimated GHGEI across visits to the same farm is higher than the variation in the estimated GHGEI across farms. The results show the importance of performing multiple observations on the same farm. Increasing visit per farm decreases the within farm variance and narrows the confidence interval (CI) of the estimated GHGEI for a single farm mean and the population mean. In Chapter 4, I furthermore looked at the between and within farm variance of the estimated GHGE per process, which provides insight into the relative importance per process for reducing the variability of the estimated GHGEI. For example, emissions from purchased feed did not differ between seasons and had the lowest within farm variance, so collecting data to estimate this parameter multiple times is hardly needed. On the contrary, emissions related to enteric fermentation differed between seasons and the within farm variance of the emission estimate was larger than that for manure management and purchased feed. Collecting data to calculate emissions from enteric fermentation (e.g., feed intake of the animals) is therefore needed at least once in the dry and once in the rainy seasons.

Performing longitudinal observations, however, is time-consuming and costly. As a result, longitudinal observations are often performed on a limited number of farms, which could compromise the representativeness of the results for the entire population of farms in the region (Sharma et al., 2017). The study in Chapter 5 included a larger number of farms (300 out of about 4,500 dairy farms in the region of Lembang) than the study in Chapter 4 (32 of about the same 4,500 farms). The estimated GHGEI in Chapter 5 may therefore be more representative for the entire population of dairy farms in the region than the estimated GHGEI in Chapter 4. However, data collection in Chapter 5 was performed once (i.e., cross-sectional observation) and most data were based on farmer's recall. As a result, detailed information obtained by measurements such as those performed in Chapter 5 (e.g., on milk yield and feed intake of individual cows), as well as variation of management practices across seasons was not included or included to a lesser extent. Milk yield is an important determinant of GHGEI. Collecting daily milk yield based on on-farm measurement of individual lactating cows (Chapter 4) resulted in a higher average daily milk yield (14 kg cow^{-1} day^{-1} in dry season, and 15 kg cow^{-1} day^{-1} in the rainy season) than the daily milk yield based on the farmer's recall in Chapter 5 (12 kg cow^{-1} day^{-1}). In Chapter 5, it was shown that 57% of the variance in GHGEI was explained by milk yield. Hence, the difference in estimated milk yield between Chapter 4 and 5 may have caused a difference in the final emission estimates. It is difficult, however, to conclude which method (i.e., method in Chapter 4 or method in Chapter 5) is closest to the actual average daily milk yield, as daily milk recordings throughout the lactation period are lacking. The most accurate method to estimate average daily milk yield is based on daily recording throughout lactating periods such as is being done in automatic milking systems (Migose et al., 2019; Ojango et al., 2017). Implementing automatic milking systems would therefore be a step towards improving emission estimates.

When research aims to collect information for a baseline study, cross-sectional observations are preferred over longitudinal observations. Cross-sectional observations can cover a large number of farms within a relatively short time frame and at lower costs than a longitudinal study, and covers variation in farm practices across systems to provide a representative picture of a population of farms at a certain moment in time. When the research aims to understand variation in management practices or changes in emissions over a period of time (Chapter 4), however, longitudinal observations are preferred. In my study, I started with a cross-sectional observation to understand the GHGEI of milk produced on smallholder dairy farms in the Lembang region (Chapter 5), and subsequently set up a longitudinal study for a subset of the farms to understand the variation of GHGEI within and across seasons (Chapter 4).

Although I did not analyse the effect of seasonal differences or the importance of more frequent data collection on estimating annual nutrient excretion (Chapter 2) or nutrient balances (Chapter 3), it is likely that also for this type of calculations longitudinal observations increase the accuracy of the excretion/emission estimates. An important reason for this is that seasonal differences affect DMI (Chapter 4) and DMI defines nutrient intake of purchased feed. Nutrient intake from purchased feed is the major nutrient inflow in dairy farming systems (Chapter 3). Further research is required to understand the importance of seasonality in calculating annual nutrient excretion and nutrient balances of smallholder dairy farms.

4. Improvement options

In the following paragraphs, I will address potential options to improve manure management on smallholder dairy farms in Indonesia at the various aggregation levels that were included in my thesis. In line with the study of Šebek et al. (2014), I address issues and improvement options at different aggregation levels and interactions (i.e. synergies and trade-offs), between aggregation levels in order to picture a broad and rich perspective of improving manure management at smallholder dairy farms.

Animal level

At animal level, a step towards improving manure management is to reduce NUI of dairy cows. The higher the NUI of a cow, the higher the N-P excretion (Chapter 2). Below, I will provide more details on relevant strategies to reduce the N-P excretion on smallholder dairy farms through reducing NUI of dairy cows, including strategies related to providing a balanced ration, and strategies related to improving cow management. I selected those strategies because they are relatively easy to adopt by smallholder dairy farms.

1. **Providing a balanced ration**

   To reduce N-P excretion, the dairy farmers need to provide a balanced ration. From Chapter 2, the high NUI could be explained by overfeeding of crude protein (CP) and P, being offered to the animals through the diets. Overfeeding is relative. Actually, too much feeding of certain nutrients in the diet implies that the cow ingests more nutrients than she can utilize. This may occur when other nutrients are too low in the diets (hence the diet is unbalanced) or when the production of the cow is limited by other factors such as high ambient temperatures, or the genetic potential of the animal. Overfeeding increases feed cost and excretion per cow (Hynes et al., 2016; Dijkstra et al., 2013; NRC, 2001).

   A balanced feed ration means that protein, energy, minerals, and vitamins from dry fodders, green fodders, concentrates, mineral supplements and other feed ingredients, should be provided in appropriate, balanced quantities to enable the animal to perform optimally and remain healthy (de Vries et al., 2017; Garg et al., 2013; FAO, 2012). Improving the quality of home-grown feed (HGF), using specific agro-industrial by-products, and using least-cost ration optimization models could all help farmers to achieve a balanced ration.

   Feed quality is often an issue in tropical regions (Oosting et al., 2014), including Indonesia. When overfeeding of protein occurs, diets are often too low in energy. Improving feed quality (i.e., digestibility) of home-grown feed (HGF) is important to overcome this issue. Quality of HGF can be improved by using forages with a high digestibility in combination with improving soil, fertilization, harvesting and storage (e.g., silage) practices (Pretz et al., 2016; Wouters et al., 2013). Improving the quality of HGF will affect feed cost. Feed expenses are the single most important expense of dairy farmers (Wolf et al., 2010), accounting to >70% in many Asian countries (Alqaisi et al., 2014). Jahroh et al. (2020) estimated that feed costs account for 72% of the total variable cost on smallholder dairy farms in the Lembang region, West Java Province. The higher the feed cost, the lower the profit dairy farmers receive. To increase farmer's profit, therefore, the costs for improving the quality of HGF should be kept as low as possible.

Moreover, to balance the diets by increasing the energy content, farmers can use agro-industrial by-products with high energy and relatively low protein content (Miyagi et al., 2012). This will help to reduces NUI of the cows (Chapter 2) and subsequently also reduce the GHGEI of milk production (Chapter 4; Chapter 5). Farmers could use energy rich agro-industrial by-products that are locally available in the region such as brewer waste, coffee husk, and coconut meal. Such products, however, are only limitedly available. If these agro-industrial by-products are imported from other regions, a reduction of NUI at the animal level would still be possible, but trade-offs with other environmental impacts at farm and regional level might be expected (Chapter 3). Importing nutrients from other regions may cause nutrients extraction in the regions where the feed is being produced and nutrient accumulation in the regions where it is fed. To avoid this, coupling of animal and crop production is preferred. Alternatively, transporting human excreta back to the region of feed production is also an option (Harder et al., 2019; Andriani et al., 2015).

Finally, using least-cost ration optimization models could help farmers to achieve a balanced ration. Using such models could result in low cost rations and a lower NUI concomitantly. Such a model optimises the combination of feed ingredients that supplies the required levels of nutrients at least cost (Rosi et al., 2004). Chakerdza et al. (2006) demonstrated the use of a least-cost ration optimization model in smallholder dairy farms in Africa. The steps to come to an optimal ration included the creation of a feed database, specification of dietary requirements, and optimizing the diet by selecting the combination of feed ingredients based on nutritional aspects and prices. The model is inexpensive but is likely inaccurate because the variation related to nutrient requirements of the animals are often not captured. The main reason for this is that information about the physiological status of the cow determining the nutrient requirements is often lacking on smallholder dairy farms. Nevertheless, dairy cooperatives, via their extension staff, could assist farmers to determine the least-cost ration for their farm based on most appropriate assumptions in order to provide insight into potential improvement options for their current feeding strategy.

2. Improving cow management

A) Heat stress

Though the climate in Java is suitable for dairy farming, specifically in the high lands, dairy cows may experience heat stress during several periods. Improving cow management to prevent heat stress in dairy cows can help to reduce NUI of a dairy cow. This strategy refers to keeping the animals comfortable (Sutton et al., 2016). High ambient temperature leads to heat stress. Heat stress reduces animal productivity and decreases feed efficiency, markedly by reducing DMI and diminished milk synthesis (Kaufman et al., 2020; Rhoads et al., 2008). At high ambient temperatures, a lower milk protein content and higher urinary N excretion were observed (Kamiya et al., 2005).

Without a proper adaptation strategy, the health, behaviour, and performance of dairy cattle will be affected by heat stress (Schütz et al., 2012). The adaptation strategy to reduce heat stress is providing adequate clean drinking water to keep the dairy cow hydrated. A dairy cow requires about 0.73-0.90 kg of water per kg of milk being produced. An increase in temperature, from 18 ^{0}C to 30^{0}C, increases water consumption by 29% (NRC, 2001). In addition, smallholder dairy farmers in Indonesia “wash” their cows regularly before milking. They perform this practice in order to ensure the cows are clean and neat, and to avoid bacterial contamination in milk. This practice helps also in reducing heat stress of the cows and potentially reduces N-P excretion by improving DMI and feed efficiency. However, the water being used to wash the cows ends up with the unmanaged manure on the farm, and is subsequently discharged into the environment as wastewater. As a result, the current practice of washing cows has a trade-off with environmental impacts at farm level by contributing to the runoff of nutrients in manure. Providing shade and ventilation are also means to reduce heat stress.

b) Health

Optimizing health of dairy cows will improve the efficiency of nutrient use for production (e.g., milk), to subsequently reduce NUI at animal level (Chapter 2) and GHGE at value chain level (Chapter 4; Chapter 5). Improving animal health (at animal level) will improve animal welfare, reduce treatment costs (e.g., lower antibiotic use), and reduce GHGE at value chain level by maintaining the productivity of the dairy cows which is reduced when the health is poor (Moestert et al., 2018; MacLeod et al., 2019). There are many ways to support health of dairy cows, such as establishing herds with genetic resistance to diseases, preventing the entry of diseases to a farm, having an effective herd health management program, and using veterinary medicines as directed (FAO, 2011). In Chapter 6, it is reported that the dairy cooperative contributes to maintaining the health of the dairy cows by providing access to veterinary care.

c) Genetic potential

When diets are balanced, heat stress is minimized and health care is maximal, cows could still underutilize their diets when their genetic potential limits higher production (Van der Linden et al., 2017). Indonesian dairy farmers use the high productive Holstein Frisian breed. For many years, the bulls, and semen, have been imported largely from temperate regions, being used to improve the genetic merit of cows to improve productivity. Artificial insemination (AI) is widely used in the Lembang region and the AI centre is government-operated. Breeding and genetic selection within the Indonesian Holstein Frisian population and breeding with semen of bulls with high genetic potential for milk under Indonesian conditions could result in increased genetic potential of Indonesian dairy cows and subsequently, improve the utilization of diets and reduce NUI and GHGEI (González-Recio et al., 2019; Pryce et al., 2017). Herath et al. (2009) reported that the absence of a coordinated system for data collection and record-keeping, and the maintenance of databases for the livestock sector, including a mechanism for feedback and exchange among the stakeholders for development of livestock-related policies, have been identified as a major constraint for genetic improvement of livestock in many countries in South Asia-Pacific, including Indonesia. Hence, developing a data collection system and record-keeping is crucial, even on a limited scale, to support genetic improvement at smallholder dairy farms.

Farm level

At farm level, a step towards improving manure management is to reduce the farm's nutrient imbalance (Chapter 3). Furthermore, improvements can be made to reduce the GHGEI of milk (Chapter 4; Chapter 5). I propose relevant strategies to improve manure management at farm level including: 1) increasing manure collection, 2) using manure as fertilizer, 3) and optimizing the use of bio-digesters. I selected those strategies because they are relatively easy to adopt by smallholder dairy farms. In addition, facilitating wide adoption of bio-digesters on smallholder farms is part of the Indonesian National Determined Contribution (NDC) strategy to reduce GHGE from manure management (Kementrian Lingkungann Hidup dan Kehutanan, 2017). Optimizing the technology and use of bio-digesters, therefore, could support the Indonesian government in their plan to reach a national emission reduction target of 29% by 2030 compared to 2010 levels.

1. Increasing manure collection

Most farmers collect a proportion of 0-20% of the faeces produced on their farm. One of the reasons for this proportion being low is the limited availability of space to store the faeces. One of the improvement options is therefore to facilitate a communal storage. In Chapter 6, the communal manure storage (CMS) has been introduced. The presence of the CMS will increase faeces collection which could subsequently reduce nutrient imbalances (Chapter 3) at the farm, because the manure stored in the CMS will likely be used as fertilizer and not be discharged. The option is further discussed in the next section about improvement options at regional level.

In addition to improving the collection of faeces, it is important to collect urine. Managing urine is more difficult than managing faeces because urine is liquid. For now, all urine from smallholder dairy farms is discharged. Urine contains valuable nutrients (Laubach et al., 2013; NRC 2001) and discharging urine has caused high nutrient imbalances at farm and regional level (Chapter 3). Collecting urine is therefore very important and could be achieved by collecting the urine in a tank. Urine can also be sold if a structured manure market is available (Chapter 6). The difficulty of collecting urine is related to the housing system. The tie-stall is the most common housing system at smallholder dairy farms. In the tie-stall system, cows are tied continuously, and manure is collected in a gutter behind the cows (Powel et al., 2007). In the tie-stall system, urine and faeces are naturally separated because the urine drains of through the gutter to the ditches. In this tie-stall system, the contact between urine and faeces is minimal and this could be a practical approach to reduce urea hydrolysis by urease which is abundantly present in faeces and results in the formation of NH_3 emissions (Vadella et al., 2010; Van Horn et al., 1994). Since the current tie-stall system is not designed to capture urine, some modifications in this tie-style system are required to capture urine, such as the use of innovative floor types to store the faeces and urine separately (Galama et al., 2020).

2. **Using manure as fertilizer**

The collected manure should be used. In Chapter 2, it is shown that a high proportion of N-P in the feed ends up in manure. Any nutrients that end up in excreta should subsequently be used to fertilize on-farm cropland as much as possible, so nutrients can be recycled back to the cows via feed production, reducing N-P imbalances at farm level through reducing the need for purchased feed and fertilizers (Chapter 3). When manure exceeds the fertilizer application capacity of on-farm land, manure must be exported, potentially to crop farmers in the region (see next section).

3. **Optimizing the use of bio-digesters**

In Chapter 4, it was shown that manure management contribute about 9 to 14% to overall GHGEI of milk production, and that it is an important activity to consider for GHG mitigation. Chapter 4, furthermore, report on the losses of methane related to biogas production. Those losses consist of intentional losses and other losses. Intentional losses occur when biogas production is greater than consumption and methane is released. Other losses include those related to pressure relief valves, biogas upgrading units, ventilation from buildings, leaks in pipes, and tanks, and are estimated to count for 0.4-14.9% of the methane being produced (Kvist et al., 2019; Scheutz et al., 2019; Liebetrau et al., 2017; Vu et al., 2015). Both intentional losses and other losses are emitted to the atmosphere. In Chapter 4, the estimated intentional losses were 28% of the total methane produced in the bio-digester and were lower than in the study by Bruun et al. (2014) who estimated the intentional losses to be 36% of the total methane produced in the bio-digester in smallholder households in southern Vietnam.

The intentional losses of methane from bio-digesters can be reduced or completely avoided by assuring a constant energy supply from biogas, so that households can adjust their energy consumption (Bruun et al., 2014). Adding manure to the bio-digester is done manually and sometimes farmers do not have the time and labour available to execute this activity, resulting in an inconsistent supply of biogas. In addition, an inconsistent supply of biogas can also result from malfunctioning of the bio-digester. The study of Zahra et al. (2021) reported that malfunctioning of biodigesters on smallholder farms in West Java is common. Hence, maintenance of bio-digesters should be performed frequently, to avoid defects.

To avoid emissions, the biogas surplus should be used. Currently, dairy farmers only use the biogas yield as energy source for cooking and the surplus is emitted to the atmosphere. The surplus of biogas can be used as energy source for electricity. The chemical energy of the combustible gases is converted to mechanical energy in a controlled combustion system by a heat engine (Sacher et al., 2020). The mechanical energy then activates a generator to produce electrical power. When the surplus of biogas cannot be used as electricity, this surplus should be distributed to the neighbourhood. Support from local government and dairy cooperative are required, for example to facilitate the investment in the generator to utilize the biogas surplus.

Moreover, the biogas digestate (i.e., by-product from biogas production) is rich in nutrients and organic material (Bonten et al., 2014). Biogas digestate needs to be managed well and should not be discharged. Biogas digestate is produced mostly in liquid form (i.e., DM content of 3.0 to 4.1%; Zahra et al., 2021; Risberg et al., 2017), making it difficult to handle. Hence, most of the biogas digestate is discharged. The collection and application of biogas digestate for fertilizing on-farm cropland is preferred because it reduces nutrient imbalances at farm level (Chapter 3). In addition, some studies propose digestate to be managed and used for other applications. Digestate, for example, can be used for soaking seeds (e.g., faba beans), having a positive effect on seed germination and seedling growth (Zhao et al., 2014). A study of Kupper et al. (2006), furthermore, showed that the digestate can be used in disease and pest control in case of Citrus black spot disease. The interaction between diverse microorganism in the digestate is believed to control this plant disease by activating resistance mechanisms when applied to plants.

Utilizing digestate as a media to cultivate microalgae is another option (Bastabak et al., 2020; Logan et al., 2019). This latter application is likely suitable for the Indonesian situation because microalgae are relatively easy to grow in Indonesia due to climatic conditions. Microalgae are widely used for biodiesel production and producing biodiesel supports the governmental policy in Indonesia to increase the production and use of renewable energy (Kristiana et al., 2021; Hadiayanto et al., 2012; Mata et al., 2010).

Regional level

Various interventions could be introduced in order to facilitate good manure management at farm level, which will help to reduce nutrient imbalances at farm and regional level. Regional interventions could therefore contribute to reducing the pollution of the Citarum river (Chapter 3), and include: 1) introducing a communal manure storage, 2) using manure as fertilizer for local crop production, and 3) composting manure. Interventions can result in improvements at regional level if many or all farmers practice the improvement options. Hence, regional interventions require the involvement of many farmers and other stakeholders.

1. **Introducing a communal manure storage**

   One of the main reasons for farmers only collecting a small part of the faeces is the limited availability of space for storage. Facilitating a CMS could help to overcome this problem. In Chapter 6, the CMS has been introduced. The presence of the CMS will increase faeces collection which could subsequently reduce nutrient imbalances (Chapter 3) because the manure stored in the CMS will likely be used as fertilizer and not be discharged. The transportation cost for composters will decrease when they can collect the fresh manure from one central place and contribute to increase the value of manure (Chapter 6). Land is required to construct a CMS. This land (e.g., marginal land) could be provided by the local government to support manure management improvement. Land for CMS must be accessible for dairy farmers because they need to deliver manure to the CMS using a wheelbarrow or motor bike. The distance from the farm to CMS, will affect the labour and transportation costs. The costs of constructing and maintaining a CMS can be considerable and should be shared among the local government, the dairy cooperative, and dairy farmers. If the CMS is commercially managed, however, it could also generate revenues for the dairy farmers. One of the dairy farmers groups located in the upstream of the Citarum river managed to set-up and run a CMS successfully. The aim of setting up this CMS was to support the Indonesian government's program in cleaning the Citarum river. The Indonesian army is actively monitoring manure collection in this farmers group and helps the farmers in collecting and composting manure. Compost is then sold to crop and flower farmers in the Lembang region, generating revenues for dairy farmers in this group.

2. Using manure as fertilizer for local crop production

When manure produced on dairy farms exceeds the application capacity of on-farm cropland, it needs to be exported to crop farmers in the region. Applying manure to cropland in the region is preferred over application to other plantations, because by-products from crop production are used as feed for dairy cattle (e.g., leftover of crop production). Returning manure to local cropland therefore facilitates the recycling of nutrients. In Chapter 3, it is shown that in the region, there is sufficient land available to apply manure from the entire dairy sector in the Lembang region if crop farmers replace artificial fertiliser with manure. If crop farmers are only willing to substitute part of the artificial fertilizer, other agricultural sectors covering about 25% of the total area of West Java province, offer possibilities to utilize dairy cattle manure as fertiliser (BPS, 2018). The study of Zahra et al. (2021), for example, explored opportunities of utilizing dairy cattle manure at coffee plantations and the forestry sector. The study showed that dairy cattle manure is needed to improve soil productivity at coffee plantations and can increase coffee production. In case of the forestry sector, dairy cattle manure is needed to optimize the multiple functions of the forest area, including the utilization of the forest production area for forage cultivation.

3. Composting manure

Composting fresh dairy cattle manure could be a solution to improve manure management at farm and regiional level. The market for compost is big because the crop farmers in the region prefer to use compost over fresh manure (Chapter 6). Composting benefits the environment because manure nutrients are converted to more stable and nutrient-dense forms and are less likely to reach groundwater or move in surface runoff (Larney et al., 2006). In addition, compost is lighter than fresh manure, making it easier to apply and to transport to croplands, while also reducing labour cost for application.

In Chapter 6, some issues related to facilitating composting of manure at the region level have been reported including difficulties to assure the quality of the end product, uncertainties about supply and demand, price, and high cost for labour and investment. At the beginning of the cropping season, mainly in the rainy season, the crop farmers require large amounts of compost. The composting process in the rainy season takes longer than in the dry season, leading to insufficient compost supply. When there is insufficient compost supply, composters may deliver or supply unfinished compost to meet the demand from crop farmers. This, however, compromises the compost quality. The prices of compost varied due to the variable production capacity at relatively small processors. These issues point to the importance of having good composting practices and the presence of a structured manure market.

Good composting practices start with selecting a proper site for composting and end with a successful composting process. Composting should take place on an area that drains well, where runoff or leachate will not reach waters of the state, and preferably have slopes of 2 to 4% which consist of concrete or packed soil or gravel (Augustin et al., 2016). A successful composting process depends primarily on the ability of the composter to control variables such as temperature, moisture content, aeration, pH, carbon to nitrogen (C/N) ratio, and feedstock mixtures. The optimum temperature is 55–60 °C (during the thermophilic stage), moisture content in the mixture is 40–60%, pH is 5.0–8.0, and initial C/N ratios is 25:1 to 30:1 (Macias-Corral et al., 2019; Vochozka et al. 2017; Gao et al. 2010). As the C/N ratio of dairy cattle is between 19:1 to 21:1, amendments should be added to achieve the required C/N ratio (Macias-Corral et al., 2019). Preferably, the amendment should be locally available to avoid importing nutrients to the region. The amendment such as postal (i.e., broiler manure consisting of dry chicken manure and rice husk) is abundant in West Java province. The use of amendment affects the price of selling compost. Hence, amendments need to be used in an optimal ratio so that the desired quality of compost is obtained, nutrient losses are minimized, and economic benefits are maximized (Sefeedpari et al., 2020). Good composting practices are essential, however, it was reported that up to 77% of initial N of manure can be lost if done improperly (Tiquia et al., 2002).

High costs for labour and investment are inevitable because currently, composting of manure is labour intensive, and technology to facilitate the process of composting is lacking. For example, turning compost is an essential stage during the process of composting. Turning compost incorporates oxygen into the system, homogenizes the pile, breaks up clumps, and allows more contact of manure with microbes (Augustin et al., 2016). Turning of compost, however, is performed manually by using a shovel and is often difficult to monitor and evaluate, which leads to a sub-optimal final product. Composting can only be profitable if the final product meets the market requirements and a structured manure market is available. The presence of a manure market being voiced by stakeholders in Chapter 6 should be forced not only institutionally but should also be supported by improving technical aspects to meet market's requirement. When a structured manure market is formed and the process of composting is standardized to assure the quality of the final product, it is expected that the number of composters in the region will increase. The results in an increased rate of manure being composted, which can subsequently reduce or avoid the amount of manure being discharged at regional level.

Value chain

Improvement options being made at animal, farm, and regional levels will affect environmental impacts at value chain level. At animal level, for example, changing feeding practices and improving cow management could affect GHGE and other environmental emissions of processes along the value chain level, such as feed production. Feeding strategies to reduce NUI at animal level, for example, could either reduce or increase emissions related to feed production. When improved NUI is reached by changing towards feed products with a higher emission intensity, the emission reduction gained by reducing feed intake per kg milk could be (partly) offset by an increase in emissions during feed production. At the same time, however, reduced NUI will reduce the amount of N excretion and therefore likely reduce GHGE from manure management. To assure that an improvement option results in a net reduction of emissions at value chain level, changes in emissions along the entire production chain need to be taken into account. Analysis at chain level, on its turn, however, has its limitations because it does not capture the interlinkages between the various sectors and product chains of the entire agricultural sector. A food system approach would be preferable to address issues such as food-feed competition, and optimizing the use of by-products. The above mentioned issues give a glance of the complexity and the need to consider the consequences of improvement options across scales to move towards a sustainable dairy sector in Indonesia.

5. Creating an enabling environment for good manure management

A proper enabling environment is required for development of proper manure management at smallholder dairy farms. I propose relevant strategies to setting up an enabling environment including: 1) educating farmers, 2) encouraging collaboration between stakeholders, 3) relocating dairy farming, and 4) phasing out subsidies. I suggest these four strategies because it supports the implementation of the manure management practices suggested in section 4. Below, I further describe these four strategies.

1. **Educating farmers**

   Most smallholder dairy farmers have a low education level. For example, the highest level of education completed by 57% of the members of one of the farmer's groups in the Lembang region was middle or high school, whereas for the remaining members it was elementary school (Apriman et al., 2017). Educating dairy farmers to raise awareness on the importance of proper manure management is needed. The dairy farmers must be informed continuously about the benefits of manure and the drawbacks of emissions from improper manure management. Moreover, dairy farmers need to be educated on how to balance the ration in order to reduce N-P excretion at animal level (Chapter 2) and to optimize the use of bio-digesters in order to reduce GHGE at value chain level (Chapter 4). The CMS being suggested in Chapter 6 needs to be commercial and a business plan for manure management is required. Therefore, it is important to teach dairy farmers to professionally organize the CMS in order to gain economic benefits from manure and reduce nutrient imbalances at farm and regional level (Chapter 3; Chapter 6).

As a major user of manure (Chapter 3; Chapter 6), crop farmers believe that crop yields are higher when applying artificial fertiliser is used instead of manure. To facilitate the uptake of a strategy that aims to increase the use of manure on crop farms, farmers need to be educated to understand differences between artificial fertilizer and manure and the short and long-term effects of both on crop yield and soil productivity. The composters need to be educated as well, especially to ensure the quality of the final product. Educating dairy farmers, crop farmers and composters can be done by means of seminars and training. The role of the dairy cooperative, their extension staff, and the local government is crucial to create this enabling environment.

2. **Encouraging collaboration between stakeholders**

The study in Chapter 6 has shown the importance of working together with stakeholders. It is not only the dairy farmers who are responsible for reducing environmental emissions associated with manure management, but also other stakeholders, including the Indonesian government. To encourage collaboration between stakeholders, the economic benefits from utilizing manure should be increased and shared among stakeholders by initiating a manure market (Chapter 6). Moreover, in Chapter 6 it is also reported that the dairy cooperative needs to start a structured manure market by arranging a formal agreement between stakeholders and identifying their needs (i.e., demand for compost, quality, price etc.). Financially speaking, this strategy could increase the value of manure and increase the revenues for all farmers.

3. **Relocating dairy farms**

Limited availability of land for manure application has been reported as the main reason for the high amounts of manure being discharged in the region of Lembang (Chapter 6). Currently, 90% of the dairy farms in Indonesia are located on Java Island. The expected increase of the cattle population on the island will increase the environmental impacts related to dairy production further. In the future, the Indonesian government should consider developing the dairy sector in other islands that have a suitable climate for raising dairy cows and land availability to couple livestock to land. This option may be not easy because developing a dairy sector means that the infrastructure, such as milk processing facilities and a dairy cooperative, must be built. Massive investment and involvement of private sectors are required. Moreover, to increase national milk production, the Indonesian government has on short term no other way than increasing the dairy cattle population on Java Island. For the long-term, dairy production should be developed in a sustainable way. Relocating and developing dairy farms outside Java Island could be a more sustainable solution to support Indonesian dairy production.

4. **Phasing out subsidies**

The subsidies on artificial fertiliser and LPG hamper the increase of manure use (Chapter 3) and reduce the revenues from manure (Chapter 6), respectively. The subsidies on artificial fertiliser have begun in 1971 and aimed at achieving rice self-sufficiency at that time (Hedley et al., 1989). Unlike the subsidies for artificial fertiliser that has been running for almost 50 years, the subsidies for LPG rapidly increased since 2007 when the program to convert kerosene to LPG was initiated to promote clean and efficient energy use. The energy demand is growing faster at around 5% each year, and in the case of LPG, the subsidies have supported more than 25 million poor and vulnerable households. In addition, the biogas losses being reported in Chapter 4 are linked to the low price of subsidized LPG being reported in Chapter 6. For farmers, it is easier to buy LPG rather than obtaining biogas from the bio-digester. The same holds for artificial fertiliser, which is cheaper, easier, and more practical to use than manure to fertilise the HGF areas. However, subsidies are costly. Subsidies for LPG accounted for 37% and artificial fertilisers accounted for 13% of the whole budget for subsidies of the Indonesian government (Sekretaris Kabinet Republik Indonesia, 2020). For sustainable dairy production, the subsidies should be reduced, although this option may be not easy. Some studies (Kuehl el al., 2021; OECD 2020; Sudaryanto et al., 2014) recommend phasing out subsidies, and the budget can be reallocated to long-term investment in essential public services such as infrastructure, education, health, and social protection.

Finally, in this thesis, I addressed many important aspects of manure management on Indonesian smallholder dairy farms. The presentation, interpretations, and conclusions about environmental impacts, constraints for improvement, and improvement options in this thesis are based on scientific observations, and the results could be informative for users. Shifting from poor manure management to better manure management may not be easy, may take time to realize, and will not be feasible without involving many stakeholders. This process, however, must be started now for a sustainable Indonesian dairy production in the future

General conclusions

- The models to predict nutrient excretion from a dairy cow using readily available farm data show reasonable accuracy and can be used to improve manure management at animal level.

- Nutrient imbalances at farm level are high and are associated with high nutrient inputs-low outputs and poor manure management. Nutrient imbalances at farm and regional level show that, on the one hand, enormous amounts of nutrients are lost to the environment, but on the other hand, soil mining is limited.

- Increasing the number of farm visits improves the accuracy of estimated GHGEI of milk production on smallholder dairy farms.

- Paradoxically, discharging of manure is associated with low GHGEI while this practice leads to high nutrient losses and related to environmental impacts at farm and regional level.

- The economics of manure management is not appealing for dairy farmers. Communal manure storage, developing a structured manure market and support may increase economic benefits of manure management. Stakeholders' involvement is essential to achieve these benefits.

- Strategies to improve manure management at animal level include balancing the ration and improving cow management, whereas strategies at farm level include increasing manure collection and use and optimizing the use of bio-digesters. Chain level analysis is needed to assure a net improvement of environmental impacts along the entire chain. Creating an enabling environment supports the transition towards better manure management.

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Summary

As a response to a high demand for milk and low national milk supply, the Indonesian government aims to increase national milk production by, among others, increasing the dairy cattle population. This will have consequences especially for manure production. Manure is an inevitable by-product of dairy production and has a number of benefits if it is appropriately managed, but can also cause environmental impacts when high manure production is followed by improper manure management. The losses of nutrients from manure, mainly nitrogen (N) and phosphorus (P), are harmful to water bodies and can contribute to eutrophication. In addition, methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3) and nitrogen oxides (NO_x) are released during the storage, treatment, and application of manure, and contribute also to climate change and acidification. To avoid these adverse environmental impacts, manure needs to be managed appropriately. Smallholder dairy farms in Indonesia, however, are currently characterized by poor manure management, and with the expected increase in manure production, the importance of improving manure management is increasing. Improving manure management on smallholder farms involves many aspects, such as feed management, land for storing and applying manure, and costs associated with manure management. Knowledge about many of these aspects is lacking. The overall aim of the studies in this PhD thesis was to evaluate emissions to the environment associated with manure management and to identify improvement options on smallholder dairy farms in Indonesia. To this end, the studies in this PhD thesis analysed various aspects of manure management at different aggregation levels (i.e., the animal, farm, regional, and value chain level).

Improvement at animal level requires accurate estimation of N-P excretion from dairy cows, since this cannot be easily assessed at dairy farms. **Chapter 2** developed models to accurately predict N-P excretion of dairy cows on smallholder farms in Indonesia based on readily available farm data. The model to quantify faecal N (Q_{FN}) was based on the principles of the Lucas equation, describing the relation between dry matter intake (DMI) and faecal N excretion. Excretion of urinary N and faecal P were calculated based on National Research Council recommendations for dairy cows. The model was validated by comparing the predicted quantity of faecal N with the actual quantity of faecal N (Q_{FNACT}) based on measurements. The parameterization of the Lucas equation for Indonesia was almost similar to the ones given in literature. Overall, the model predicted actual nutrient excretions with reasonable accuracy. The total N excretion of dairy cows in Indonesia was on average 197 g animal^{-1} d^{-1}, whereas P excretion was on average 56 g animal^{-1} d^{-1}.

N-P losses from dairy farming systems in West Java province lead to environmental problems, such as eutrophication of the Citarum river. In **Chapter 3**, nutrient balances from dairy farming systems with different manure management systems (MMSs) were analysed. Furthermore, nutrient balances

from farm level were upscaled to regional level to determine the sector's contribution to the pollution of the Citarum river and to identify potential options for improvement. N-P balances were derived from differences between N-P in- and outflows at farm and sub-system level. Results showed that the N balances of all 30 dairy farms averaged 222 kg N $farm^{-1}$ yr^{-1} and did not differ between MMSs. The P balances of the farms differed between MMSs; balances were highest for farms that discharge manure (83 kg P $farm^{-1}$ yr^{-1}) and lowest for farms that sell or export manure (-25 kg P $farm^{-1}$ yr^{-1}). Annually, all dairy farms in the Lembang region caused a loss of 1,061 tons of N and 290 tons of P into the environment and they extracted 8 tons of P from soils.

Greenhouse gas emissions (GHGE) emitted from dairy farming systems contribute to climate change, which is a global environmental impact. **Chapter 4** and **Chapter 5** evaluated GHGE at the value chain level by means of life cycle assessment (LCA). LCA studies on smallholder farms in tropical regions generally use data that is collected at one moment in time. To evaluate the importance of longitudinal observations, Chapter 4 assessed seasonal differences in GHGE from Indonesian dairy farms by means of longitudinal observations and evaluated the implications of number of farm visits on the variance of the estimated GHGE per kg milk (GHGEI) for a single farm mean, and for the population mean. Results showed that GHGEI was higher in the rainy (1.32 kg CO_2-eq kg^{-1} FPCM) than in the dry (0.91 kg CO_2-eq kg^{-1} FPCM) season. The between farm variance was 0.025 kg CO_2-eq kg^{1} FPCM in both seasons. The within farm variance in the estimate for a single farm mean and the population mean decreased with an increase in number of farm visits. Variability in GHGEI can therefore be reduced by increasing the number of visits per farm. Forage cultivation was the main source of between farm variance, enteric fermentation the main source of within farm variance. Chapter 5 identified mitigation strategies of GHGE at smallholder dairy farms. The relationship between GHGEI and milk yield per cow for all farms was modelled and farms with an GHGEI below and above their predicted GHGEI were compared ('low' and 'high' GHGEI farms). Results showed that milk yield explained 57% of the variance in GHGEI among farms. Low GHGEI farms had fewer cows, and fed less rice straw, more cassava waste, and more compound concentrate feed (particularly the type of concentrates consisting largely of by-products from milling industries) than high GHGEI farms. In addition, low GHGEI farms discharged more manure, stored less solid manure, used less manure for anaerobic digestion followed by daily spreading, and applied less manure N on farmland than high GHGEI farms.

The high rates of discharged manure on smallholder dairy farms in the Lembang region of West Java are linked to constraints on manure management. **Chapter 6** analysed and identified constraints on manure management on smallholder dairy farms and potential opportunities for improvement were identified. Focus Group Discussions (FGDs) with stakeholders related to manure management were performed to identify the constraints. In addition, data about costs and revenues related to manure management were collected. There are 20 constraints on manure management, of which availability of space to store manure on the farm, and costs of manure management are regarded most important. Stakeholders proposed strategies to improve manure management: communal manure storage (CMS), a structured manure market, and providing economic and institutional support such as access to credits and financial incentives for good manure management. The cost of manure management was high, and farms that sell or export manure, and farms that have a bio-digester had higher net total cost than farms that discharge manure. Total revenue (TR) differed between manure management systems and farms that apply manure had lower TR than farm that sell or export manure. All MMSs had negative net gross margins which could be explained by the high costs attributed to labour (i.e., family labour) and low revenue from manure.

Chapter 7 first discusses the methodological issues of the study, including the scope of the models that were used. The advantage of nutrient excretion models developed is that the input data can be collected relatively easily. Therewith, they represent actual situations. Moreover, the models are based on known, well documented, and robust theory. Some model parameters, however, had to be derived from literature. The advantages of performing longitudinal data collection are that it provides insight into differences in on-farm management practices across and within seasons thus improving the reliability of data and the accuracy of the results. However, longitudinal studies are time-consuming and costly, and are, consequently, often performed with small sample sizes which challenges representation of the whole population by the studied sub-population.

Second, Chapter 7 integrates the knowledge gained in the various studies and identifies a series of improvement options that connect the aggregation levels animal, farm, region, and value chain. It further suggests ways to create an enabling environment required to implement and effectuate the improvement options. The strategies to improve manure management at animal level include balancing feed and improving cow management. Feed balancing can be achieved by using least-cost ration optimization models, by growing and feeding high quality forages, and by expanding use of high-quality agro-industrial by-products. Cow management can be improved by preventing heat stress, and improvement of animal health, and genetic potential. The strategies to improve manure management at farm level include increasing manure collection, increased use of manure as fertilizer, and optimizing use of bio-digesters. The strategies to improve manure management at regional level include introducing a communal manure storage, using manure as fertilizer for local crop production, and composting manure. The presence of a communal manure storage could increase faeces collection at farm and regional level whereas providing tanks and modifying the tie-stall system could increase urine collection at farm level. At farm level, manure should subsequently be used to fertilize on-farm cropland as much as possible. Using manure as fertiliser at other agriculture sectors such as plantation and forestry sectors could increase manure use at regional level. Processing of manure to compost is essential to increase the market for manure. Optimization of the bio-digester at farm level by ensuring a continuous supply of energy, avoiding biogas surplus, and managing digestate will reduce GHGE from manure management. Reduction of GHGE from manure management at farm level will impact GHGE at value chain level. Analysis at chain level is needed to understand the integrated environmental consequences along the entire production chain. For a good enabling environment for improved manure management education of farmers, collaboration between stakeholders, relocation of dairy farms, and phasing out subsidies are essential. Shifting from poor manure management to better manure management may not be easy, may take time to realize, and will not be feasible without involving many stakeholders. This process, however, must be started now for a sustainable Indonesian dairy production in the future.

Ringkasan

Sebagai respon terhadap tingginya permintaan susu dan rendahnya suplai susu nasional, pemerintah Indonesia berencana meningkatkan produksi susu dalam negeri (SDN) dengan berbagai cara, diantaranya adalah dengan upaya meningkatkan populasi sapi perah. Upaya ini memiliki konsekuensi terutama pada peningkatan produksi limbah dari peternakan sapi perah. Limbah (feses dan urin) sapi perah merupakan produk sampingan yang tidak bisa dihindari dari sistem peternakan sapi perah. Limbah peternakan sapi perah memiliki banyak manfaat jika dikelola dengan baik, namun juga bisa memberikan dampak lingkungan yang buruk jika tidak dikelola dengan baik. Hilangnya berbagai nutrient yang bermanfaat seperti nitrogen (N) dan posfor (P), yang berbahaya bagi sistem perairan karena dapat menimbulkan fenomena eutrofikasi. Gas methan (CH_4), nitrous oxide (N_2O), ammonia (NH_3) dan nitrogen oxides (NO_x) dilepaskan selama proses penyimpanan, pengolahan, dan pengaplikasian limbah, dan dapat berkontribusi terhadap dampak lingkungan seperti perubahan iklim dan asidifikasi. Dampak negatif dari limbah peternakan sapi perah dapat dihindari dengan melakukan pengelolaan yang baik dan benar. Peternakan sapi perah rakyat saat ini belum mengelola limbah sapi perah secara baik dan benar, dan dengan adanya peningkatan produksi limbah, upaya pengelolaan limbah yang baik dan benar harus ditingkatkan. Upaya peningkatan pengelolaan limbah melibatkan berbagai aspek, seperti pengolahan pakan, tempat untuk menyimpan dan mengaplikasikn limbah dilahan serta biaya yang terkait dengan pengolahan limbah. Pengetahuan mengenai aspek tersebut masih sangat kurang, sehingga secara keseluruhan tujuan dari penelitian dalam buku PhD ini adalah untuk mengevalusi emisi lingkungan yang terkait dengan manajemen limbah peternakan dan mengidentifikasi upaya-upaya untuk meningkatkan manajemen limbah peternakan sapi perah di Indonesia. Penelitian-penelitian pada buku PhD ini juga menganalisa berbagai aspek terkait manajemen limbah pada level agregasi yang berbeda (ternak sapi perah, *farm*, wilayah, dan rantai pasok).

Perbaikan manajemen limbah peternakan sapi perah dimulai dari ternak sapi perah, dimana dibutuhkan model pendugaan ekskresi N-P secara akurat dari seekor ternak sapi perah. Model ini tidak tersedia, sehingga pada **Chapter 2,** dikembangkan model pendugaan ekskresi N-P dari ternak sapi perah di peternakan rakyat kecil di Indonesia berdasarkan data yang tersedia. Model digunakan untuk mengkuantifiksi N pada feses (Q_{FN}). Model ini dikembangkan berdasarkan prinsip *Lucas equation* yang menggambarkan hubungan antara asupan bahan kering (DMI) dan ekskresi N pada feses. Ekskresi N pada urin dan P pada feses dikembangkan berdasarkan rekomendasi dari *National Research Council* untuk sapi perah. Model divalidasi dengan membandingkan hasil prediksi N pada feses (Q_{FNACT}) dan hasil aktual N pada feses berdasarkan hasil pengukuran. Hasil parameterisasi berdasarkan Lucas equation untuk Indonesia memiliki hasil yang hampir sama seperti pada literatur. Secara keseluruhan, model pendugaan memiliki akurasi yang dapat diterima. Total ekskresi N dari sapi perah di Indonesia memiliki rata-rata 197 g ekor^{1} hari^{-1}, sedangkan ekskresi P memiliki rata-rata 56 g ekor^{-1} hari^{-1}.

Hilangnya nutrient seperti N-P dari sistem peternakan sapi perah di Provinsi Jawa Barat mengakibatkan permasalahan lingkungan seperti eutrofikasi pada sungai Citarum. Pada **Chapter 3**, keseimbangan nutrient dari sistem peternakan sapi perah dengan sistem pengelolan limbah yang berbeda (MMSs) dibandingkan. Selanjutnya, keseimbangan nutrient di *farm* level di tingkatkan ke tingkat wilayah untuk menentukan kontribusi peternakan sapi perah terhadap polusi sungai Citarum dan mengidentifikasi upaya-upaya perbaikan yang dapat dilakukan. Keseimbangan N-P dihitung melalui perbedaan aliran masuk N-P dan aliran keluar N-P pada *farm* dan *sub-farm* level. Hasil penelitian menunjukkan bahwa keseimbangan N dari keseluruhan 30 peternak memiliki rata-rata 222 kg N farm^{-1} yr^{-1} dan tidak berbeda diantara MMSs. Keseimbangan P berbeda di antara MMSs, dengan nilai surplus paling tinggi untuk peternak yang membuang limbah (83 kg P farm^{-1} yr^{-1}) dan paling rendah untuk peternak yang menjual limbah (-25 kg P farm^{-1} yr^{-1}). Setiap tahun peternakan sapi perah di Lembang menyebabkan kehilangan 1,061 ton N dan 290 ton P ke lingkungan, dan sebesar 8 ton P di ekstrak dari tanah.

Gas rumah kaca (GHGE) yang dikeluarkan dari sistem peternakan sapi perah berkontribusi terhadap perubahan iklim yang memberikan dampak lingkungan ditingkat global. Pada **Chapter 4** dan **Chapter 5**, GHGE di evaluasi ditingkat rantai pasok dengan menggunakan *life cycle assessment* (LCA). Metode LCA pada peternakan sapi perah di daerah tropis biasanya menggunakan data yang dikumpulkan hanya pada satu kali pengumpulan. Untuk mengevaluasi pentingnya pengamatan secara longitudinal, pada **Chapter 4** dilakukan analisa pengaruh perbedaan musim terhadap GHGE dari peternakan sapi perah di Indonesia dengan menggunakan pengamatan longitudinal. **Chapter 4** juga mengevaluasi dampak dari jumlah *farm visit* terhadap *variance* pendugaan GHGE per kg milk (GHGEI) untuk nilai tengah sebuah farm dan populasi. Hasil menunjukkan bahwa GHGEI lebih tinggi pada musim hujan (1.32 kg CO_2-eq kg^{-1} FPCM) dibandingkan pada musim kering (0.91 kg CO_2-eq kg^{-1} FPCM). *Variance* di antara peternak sebesar 0.025 kg CO_2-eq kg^{1} FPCM pada kedua musim. *Variance* pendugaan nilai tengah didalam peternak pada sebuah *farm* dan populasi menurun dengan meningkatnya jumlah *farm visit*. Variabilitas dalam GHGEI bisa diturunkan dengan meningkatkan jumlah kunjungan per *farm*. Pakan hijauan merupakan sumber variasi utama untuk *variance* di antara peternak sementara fermentasi enterik merupakan sumber utama *variance* di dalam peternak. **Chapter 5** mengidentifikasi strategi-strategi mitigasi GHGEI pada peternakan sapi perah di Indonesia. Hubungan antara GHGEI dan produksi susu dimodelkan. Peternak dengan GHGEI yang berada di bawah dan di atas prediksi GHGEI kemudian dibandingkan (*'low' and 'high' GHGEI farms)*. Hasil menunjukkan bahwa produksi susu menjelaskan 57% dari *variance* GHGEI di antara peternak. Peternak dengan nilai GHGEI yang rendah memiliki lebih sedikit ternak, memberi pakan jerami lebih sedikit, memberi lebih banyak limbah singkong, dan memberi lebih banyak pakan konsentrat (terutama untuk konsentrat yang memilki *by-products* dari indutri penggilingan) dibandingkan dengan peternak yang memiliki nilai GHGEI yang tinggi. Selanjutnya, peternak dengan nilai GHGEI yang rendah membuang lebih banyak limbah, menyimpan lebih sedikit limbah padat, menggunakan lebih sedikit limbah untuk *anaerobic digestion* yang diikuti dengan pembuangan limbah, dan mengaplikaskan lebih sedikit N pada lahan pertanian dibandingkan dengan peternak yang memiliki nilai GHGEI yang tinggi.

Tingginya angka pembuangan limbah di peternakan sapi perah di wilayah Lembang, Jawa Barat dikaitkan dengan hambatan-hambatan dalam pengelolaan limbah. **Chapter 6** menganalisa dan mengidentifikasi hambatan-hambatan dalam pengelolaan limbah dan menggali lebih jauh peluang-peluang dalam upaya meningkatkan pengelolaan limbah. Focus Group Discussions (FGDs) dilakukan bersama stakeholders terkait dengan pengelolaan limbah untuk mengidentifikasi hambatan-hambatan tersebut. Ada 20 hambatan dalam pengelolaan limbah pada peternakan sapi perah yang teridentifikasi, utamanya adalah ketersediaan tempat untuk menyimpan dan biaya dalam pengelolaan limbah peternakan. Stakeholders menyarankan strategi-strategi dalam upaya meningkatkan pengelolaan limbah peternakan, diantaranya membangun sistem penyimpanan limbah secara terpadu (CMS), membangun pasar limbah yang terstruktur, dan menyediakan dukungan ekonomi dan institusi seperti akses terhadap kredit dan insentif finansial untuk pengelolaan limbah yang baik. Biaya untuk pengelolaan limbah sangat tinggi, dan peternak yang menjual limbah serta peternak yang mengelola limbah dengan menggunakan bio-digester memiliki *net* biaya total yang lebih tinggi dibandingkan dengan peternak yang membuang limbah. Total penerimaan (TR) berbeda diantara sistem pengelolaan limbah dan peternak yang menggunakan limbah sebagai pupuk organik di kebunnya memilki TR yang lebih rendah dibandingkan dengan peternak yang menjual limbah. Semua MMSs memilki nilai *net gross margin* yang negatif karena tingginya biaya tenaga kerja (tenaga kerja keluarga) dan rendahnya penerimaan dari limbah.

Chapter 7 mendiskusikan tentang isu-isu terkait metodelogi dalam tesis ini, termasuk isu yang ditemukan pada model eksresi N-P yang dibangun. Keunggulan dari model ekskresi N-P yang dibangun adalah data input untuk model relatif mudah untuk dikumpulkan, sehingga model tersebut menggambarkan kondisi aktual. Model juga dikembangkan berdasarkan model yang sudah diketahui dan didokumentasikan dengan teori yang *robust*. Beberapa model parameter harus diturunkan dari literatur karena keterbatasan informasi yang tersedia. Keunggulan dari pengumpulan data secara longitudinal adalah adanya informasi dari perbedaan sistem manajemen di dalam dan di antara musim sehingga dapat meningkatkan reliabilitas data dan memberikan hasil yang lebih akurat. Bagaimanapun, pengumpulan data secara longitudinal membutuhkan banyak waktu dan biaya, sehingga lebih sering menggunakan ukuran sample yang lebih kecil yang mungkin akan memilki tantangan dalam mempertahankan keterwakilan populasi.

Selanjutnya, Chapter 7 mengintegrasikan informasi yang didapatkn dari chapter sebelumnya dan mengidentifikasi upaya perbaikan yang berkaitan dengan level agregasi di tingkat ternak, *farm*, wilayah, dan rantai pasok. Dukungan untuk menciptakan lingkungan yang kondusif dibutuhkan dalam rangka perbaikan manajemen limbah peternakan. Strategi untuk meningkatkan manajemen limbah di tingkat ternak sapi perah dimulai dengan menyeimbangkan pakan dan perbaikan manajemen ternak. Upaya menyeimbangkan pakan bisa dilakukan menggunakan *least-cost ration optimization models*, menanam dan memberikan pakan hijauan yang berkualitas tinggi, dan menggunakan *by-product* yang berkualitas tinggi. Manajemen ternak perah bisa diperbaiki dengan mencegah *heat stress,* memperbaiki kesehatan ternak, dan memperbaiki potensi genetik. Strategi untuk meningkatkan manajemen limbah peternakan sapi perah di tingkat farm level diantaranya adalah meningkatkan pengumpulan limbah, meningkatkan penggunaan limbah sebagai pupuk, dan mengoptimalkan fungsi bio-digester. Strategi untuk meningkatkan manajemen limbah peternakan sapi perah di tingkat wilayah diantaranya adalah membangun tempat penyimpanan limbah komunal, menggunakan limbah sebagai pupuk untuk tanaman pangan, dan melakukan pengomposan limbah. Keberadaan tempat penyimpanan limbah secara komunal dapat meningkatkan koleksi feses di tingkat *farm* dan wilayah sementara menyediaan *tank* dan memodifikasi *tie-stall system* dapat meningkatkan koleksi urin di tingkat *farm* level. Di tingkat *farm* level, limbah harus dapat digunakan sebagai pupuk pada lahan-lahan pertanian secara optimal. Menggunakan limbah peternakan sapi perah pada lahan-lahan pertanian lainnya seperti lahan perkebunan dan kehutanan dapat meningkatkan penggunaan limbah di tingkat wilayah. Melakukan pengomposan adalah hal yang penting untung meningkatkan pasar limbah. Optimasi penggunaan bio-digester di tingkat *farm* level dengan menjamin keberlangsungan suplai energi secara kontinue, menghindari surplus biogas, dan mengelola *digestate* akan mengurangi GHGE dari pengelolaan limbah peternakan. Pengurangan GHGE dari pengelolaan limbah peternakan pada tingkat *farm* level akan memberikan dampak terhadap menurunnya GHGE di tingkat rantai pasok. Analisa di tingkat rantai pasok dibutuhkan untuk memahami dampak lingkungan secara terintegrasi di sepanjang rantai produksi peternakan sapi perah. Untuk menciptakan lingkungan yang kondusif dalam upaya memperbaiki pengelolaan limbah peternakan sapi perah, diperlukan adanya pemberian pendidikan dan pendampingan bagi peternak, kerjasama antar *stakeholders*, relokasi peternakan sapi perah, dan pengurangan subsidi. Perubahan pengelolaan limbah peternakan sapi perah ke arah yang lebih baik tidaklah mudah, membutuhkan waktu, dan tidak akan mungkin tanpa melibatkan banyak *stakeholders,* namun proses ini harus dimulai saat ini untuk peternakan sapi perah yang berkelanjutan dimasa yang akan datang.

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Autumn 2016, we decided to move to the Netherlands, and the marathon began.

Just like a marathon, there is a route, and I called it the PhD route. The route seems long, may be tricky, may be easy; I didn't know. However, I know there is a finish line for every start, and I believe I can make it. After few years, I finally reached my PhD finish line. Throughout my marathon, I have received a great deal of support and assistance, and I sincerely thank them.

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Wageningen

Windi Al Zahra

About the author

Windi Al Zahra (Windi) was born on 14th of February 1989 in Bogor, West Java Province, Indonesia. In 2010 she received her BSc in Animal Production Technology, IPB University (Bogor Agriculture University), Indonesia. Her interest on the field of animal environment brought her pursuing MSc in Natural Resources and Environmental Management, IPB University, Indonesia. She pursued other MSc' in Animal Science, IPB University in collaboration with the Major of Regional and Environmental Sciences, Ibaraki University, Japan.

In 2014 she got permanent job as a lecturer at Department Animal Production Technology, Faculty of Animal Science, IPB University Indonesia. She joined the division of dairy production and focused on environmental aspects related to the dairy farming systems. In early 2016 she got an offer from Sustainable Intensification Dairy Production in Indonesia (SIDPI) project to pursed PhD at Wageningen University the Netherlands. The project focussed on improving manure management at smallholder dairy farms in Indonesia. In 2016 she received the Indonesia Endowment Fund for Education (LPDP) scholarship for her doctoral study.

In October 2016, she joined the Animal Production Systems group to work on her PhD as part of the SIDPI project. Her work investigated emissions related to manure management from smallholder dairy farms at different level analysis, under supervision of Prof. Imke de Boer, Dr. Simon Oosting, and Dr. Corina van Middelaar. After accomplishing her PhD, she will return to Faculty of Animal Science, IPB University Indonesia. She can be contacted by email: windialzahra@apps.ipb.ac.id

Publications

Refereed scientific Publications

de Vries M., Zahra W.A., Wouters A., van Middelaar C.E., Oosting S.J., Tiesnamurti B, Vellinga T.V. 2019. Entry Points for Reduction of Greenhouse Gas Emissions in Small-Scale Dairy Farms: Looking Beyond Milk Yield Increase. Frontiers in Sustainable Food Syst 3:1–13. https://doi.org/10.3389/fsufs.2019.00049

Zahra, W. A., van Middelaar, C. E., de Boer, I. J. M., Oosting, S. J. 2020. Predicting nutrient excretion from dairy cows on smallholder farms in Indonesia using readily available farm data. Animal Bioscience. 33(12), 2039-2049. http://doi:10.5713/ajas.20.0089

Zahra, W.A., Apdini, T. Oosting, S.J., de Boer, I. J. M., de Vries M., Engel B, van Middelaar C.E. 2021. Understanding variability in greenhouse gas emission estimates of smallholder dairy farms in Indonesia. International Journal Life Cycle Assessment. (26) 1160–1176. https://doi.org/10.1007/s11367-021-01923-z

Zahra, W. A., van Middelaar C.E., de Boer, I. J. M., Oosting S.J. 2021. Nutrient imbalances from smallholder dairy farming systems in Indonesia: the relevance of manure management. Submitted

Zahra, W. A., Rocha A., Oosting, S. J., van Middelaar C.E. 2021. Constraints on manure management on Indonesian smallholder dairy farms. To be submitted

Conference proceedings

Zahra, W. A., van Middelaar, C. E., de Boer, I. J. M., Oosting, S. J. 2017. Quantifying Environmental Impacts from Smallholders Dairy Farms in Indonesia. Wageningen Indonesian scientific Exposure (WISE). The Netherlands

Zahra, W. A., van Middelaar, C. E., de Boer, I. J. M., Oosting, S. J. 2020. Predicting nutrient excretion of dairy cows on smallholder farms in Indonesia using readily available farm data. WIAS Annual Conference. The Netherlands

Zahra, W. A., Apdini T. van Middelaar, C. E., de Boer, I. J. M., Oosting, S. J. 2020. Life cycle assessment of milk produced in Indonesian smallholder dairy farms: Greenhouse gas emissions associated with different manure management system. LCA Food. Germany

Scientific reports

Zahra, W. A., de Vries M., de Putter H. 2021. Exploring barriers and opportunities for utilization of dairy cattle manure in agriculture in West Java, Indonesia. Wageningen livestock research. Public Report No 1315. https://doi.org/10.18174/546091

Sefeedpari, P., M. de Vries, F. de Buisonjé, Suharyono, D., Wouters, B., Zahra, W.A., 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, Public Report No 1262. https://doi.org/10.18174/515335

Education Certificate

Completed training and supervision plan[1]

Basic Package	2 ECTS
WIAS Introduction Day	2018
Course on philosophy of science and/or ethic	2018
Disciplinary Competences	**16 ECTS**
WIAS writing research proposal	2016
Environmental Impact Assessment of Livestock System	2016
Life Cycle Assessment training	2017
Structural Equation Modelling	2018
Introduction to R for Statistical Analysis	2018
Statistic for life science	2018
Linier Models	2018
Farms economic of households	2019
Professional Competences	**8 ECTS**
Data management planning	2016
Information literacy including endnote introduction	2016
Societal impacts of your research	2019
Efficient Writing strategies	2019
Scientific Writing	2019
Scientific Artwork	2019
Organizing WIAS Science Day committee	2020
Presentation Skills	**3 ECTS**
Poster, WISE (Wageningen Indonesia Scientific Exposure), The Netherlands	2017
Poster, WIAS Science Day, The Netherlands	2020
Oral, LCA Food conference, Germany	2020
Teaching competences	**5 ECTS**
Thesis supervisor, 1 BSc thesis	2020
Thesis supervisor, 3 MSc thesis	2018-2020
Practical supervisor, Climate Smart Agriculture	2018
Education and Training total	**34**

With the listed activity, the PhD candidate complied with the educational requirements of Wageningen Institute of Animal Sciences (WIAS) a Wageningen University & Research graduate school. One ECTS equals a study load of 28 hours.

Colophon

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