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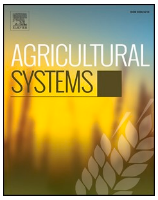

Nutrient imbalances of smallholder dairy farming systems in Indonesia: The relevance of manure management

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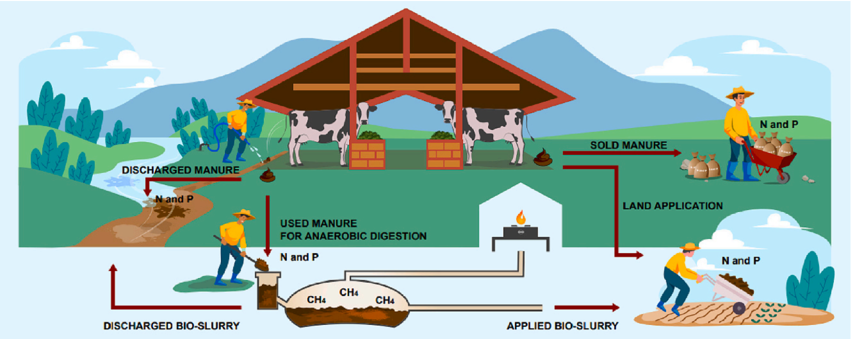
HIGHLIGHTS

- Poor manure management on Indonesian dairy farms pollutes the local river.
- We quantified nitrogen and phosphorus balances at farm, subsystems and regional level.
- Nitrogen balance averaged >1000 kg N ha^{-1} yr^{-1} and did not differ between farms.
- Phosphorus balance differed between farms with different manure management. Systems
- Transporting manure to local crop farms offers a solution to reduce losses.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Nitrogen (N) and phosphorus (P) imbalances from dairy farming systems (DFSs) lead to environmental problems, such as eutrophication.
OBJECTIVE: This study aimed to quantify nutrient deficits and losses from DFSs with different manure management systems (MMSs) at the farm level and at the levels of its sub-systems.
METHODS: 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). N—P balances were calculated based on differences between in- and outflows.
RESULTS AND CONCLUSIONS: Results showed that N balances at DFS averaged 222 kg N farm^{-1} yr^{-1} and did not differ between MMSs. Average P balances at DFS differed between MMSs; balances were highest for DIS (83 kg P farm^{-1} yr^{-1}), and lowest for SEL (−25 kg P farm^{-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 are estimated to cause a nutrient loss of ~1061 tons of N and ~ 290 tons of P, and extract 8 tons of P from soils. Overall, high NP imbalances are caused by discharging manure into the environment.

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SIGNIFICANCE: To reduce imbalances, collection and on-farm use of manure must be improved, and excess manure needs to be sold to crop farms. The carrying capacity for high-input high-output dairy farming is determined by the capacity of arable farms to apply the manure surpluses.

1. Introduction

The current dairy sector in Indonesia is responsible for supplying about 15–20% of the national milk demand. This national demand is projected to increase by 9% each year (Livestock Statistic, 2017). This increase is not only due to a rise in the number of middle-class consumers, but also due to an increase in perceived human health benefits of dairy products by consumers. To meet this increasing milk demand, the Indonesian government aims to increase the domestic production (Kemenko Ekon, 2016). At present, the increase of domestic production is mainly achieved by increasing the number of dairy cows and not by increasing productivity. Consequently, the dairy cattle population is growing 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 (Sampat et al., 2021; Adenuga et al., 2020; Clay and Garnett, 2020; Hoekstra et al., 2020; de Vries et al., 2015; Laubach et al., 2013).

The contribution of dairy farming to eutrophication of rivers and drinking water is mainly caused by leaching and runoff of nitrogen (N) and phosphorus (P). Leaching and runoff 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 and Lazzaroni, 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 6600 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 pollution originates from domestic and municipal activities and about one-third from agriculture activities, including dairy farming (Garg et al., 2018;Yoshida et al., 2017). 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 an average of two to four milking cows per farm. These farms are located in peri-urban areas and are mostly landless without grazing system. While homegrown feed is cultivated at most farms, the quantity produced is limited and often insufficient to meet the nutrient requirements of the cows, and, therefore, the farms import almost all feeds. Livestock density is high (about 12–15 livestock units per hectare). The cows are housed in tie-stalls with concrete floors and no bedding material. In these tie-stalls, cows are tied continuously, and manure (i.e., faeces) is collected in a gutter behind the cows while urine is discharged directly into the environment. Following this, manure is managed in different ways, including direct land application to the homegrown feed area, storage in sacks and selling it to manure traders, and using it as substrate for bio-energy production in biodigesters. However, large parts of manure are still being discharged. In such intensive dairy systems, proper manure management is essential to prevent environmental pollution. Although the relation between manure management and an imbalance between in- and output of nutrients, resulting in large nutrients surpluses at farm level, has been shown (Varma et al., 2021; Sefeedpari et al., 2019; Wei et al., 2018; Oenema et al., 2007), little is known about how different types of manure management systems influence nutrient flows and balances of dairy farming systems in Indonesia. With different manure management systems being present in this region (de Vries et al., 2017), such insight could be valuable to identify feasible improvement options for reducing environmental pollution.

The nutrient balance approach has been shown to be a valuable method to calculate nutrient surpluses or deficits at various levels, including those at regional, farm and field level (Taube and PÖtsch, 2001). Numerous studies exist that have calculated a nutrient balance at farm level (e.g., Mihailescu et al., 2014; Fangueiro et al., 2008), but most of these studies lack details about losses at sub-systems level which could help to explain how various management practices can contribute to reduce losses (Godinot et al., 2014). Even more, while the number of intensive dairy systems in Southeast Asia, including Indonesia, is increasing, so far nutrient balances in those world regions are limited to country level (Uwizeye et al., 2020; Gerber and Menzi, 2006). With this study, we aim to quantify nutrient deficits and losses from dairy farming systems with different manure management systems at the level of the farm and its sub-systems. This approach should improve our understanding of how to effectively reduce nutrient losses from smallholder dairy farms In Indonesia. Nutrient balances from farm level are furthermore upscaled to determine the sectors contribution to the pollution of the Citarum river and the potential options for improvement at regional level.

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 (Fig. 1). To quantify nutrient balances, we selected 32 farms from a previous study of de Vries et al. (2017). The study of de Vries et al. (2017) visited 300 randomly selected dairy farms in the Lembang region. On most farms, manure (faeces) is rinsed away with a hose during floor cleaning and, therefore, discharge of manure is common practice on these smallholder dairy farms. In case dairy farmers collect manure, it is only the solid part (faeces) that is collected. In all dairy farming systems, the liquid part (urine) is discharged. In addition, most of the dairy farming systems implement more than one manure management systems. We therefore first assigned each of the 300 farms from the study of de Vries et al. (2017) to a manure management system. If >40% of the faeces was managed according to one of the manure management systems, the farm was assigned to that manure management system.

We assigned the farms to one of the following manure management systems (See Table 1 for details):

1. Apply Directly to Land (ADL)
2. Selling (or exporting) (SEL)
3. Use of manure in Anaerobic Digester (ADI) and
4. Discharge (DIS).

We randomly selected 8 farms per manure management system out of the 300 available farms to have an equal number of farms per system. Selected farmers, moreover, confirmed to be willing to participate for the entire research period of one year. After the start of the assessment, one farm changed its manure management system from SEL to DIS, whereas two farms changed their system from ADL to ADI. We excluded these last two farms because they were breeding farms with >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 manure management system. Table 2 presents the characteristics of the dairy farming systems for the different manure management systems. Most dairy farming system characteristics did not differ among manure management systems; only the proportion of faeces collected differed among manure management systems.

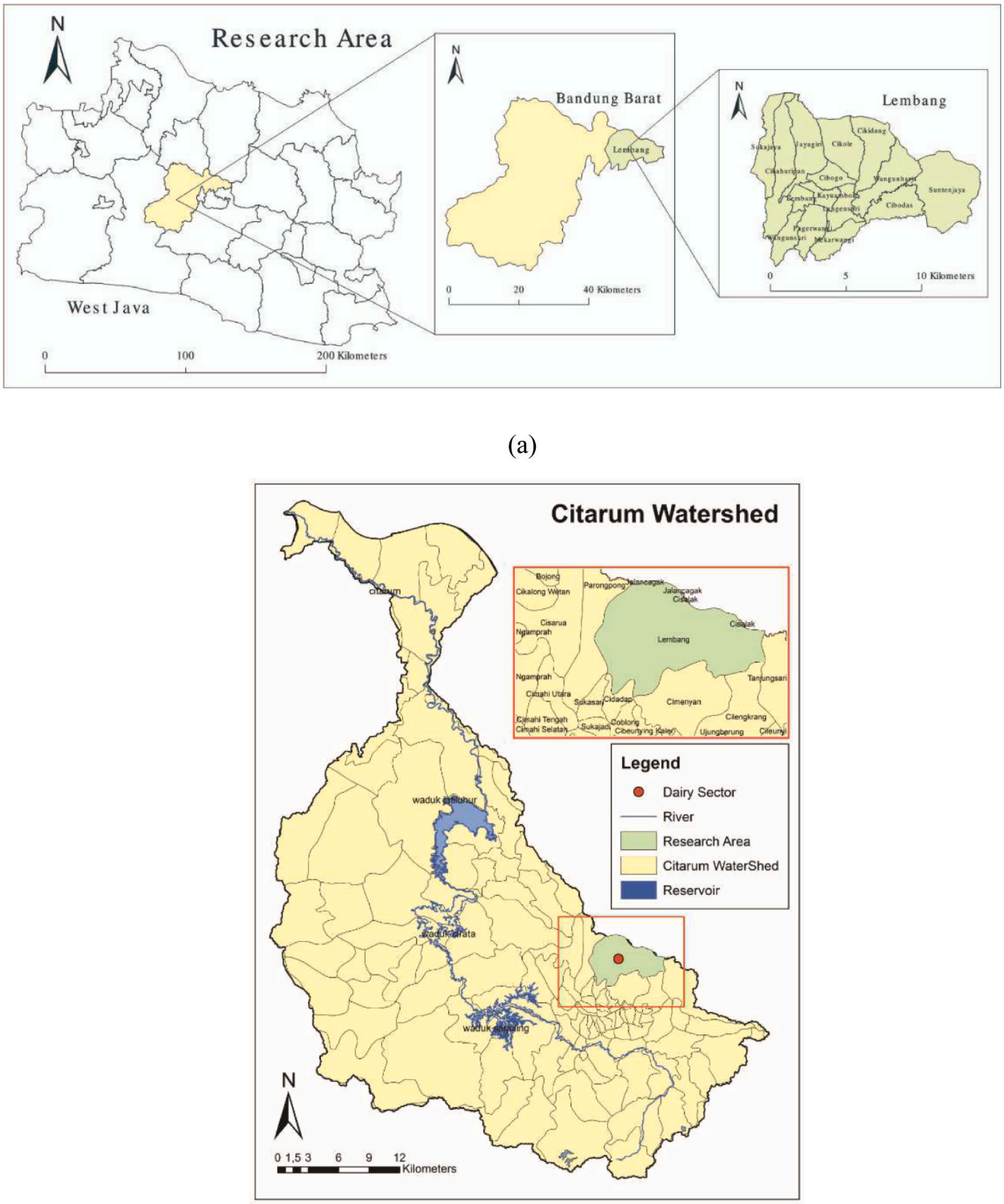
2.2. System description

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

Furthermore, nutrients flow into the dairy farming system via purchased feed, inorganic fertiliser, and flow out of the dairy farming system 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.

2.3. Data collection and quantification of nutrient balances

Nutrient balances of dairy farming system were determined as the



(a)

(b)

Fig. 1. The Lembang region was the sampled area for data collection (a); The area in the map represents the Citarum river basin; the red dot is the specific location of the dairy sector within the Lembang region where most of the dairy farms of Lembang are found (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Manure management systems.

No	Manure management systems	Definition	Abbreviation
1	Applying manure directly on forage land without treatment	Faeces is collected and used as organic fertiliser for cultivation of homegrown feed	ADL
2	Selling or exporting manure	Faeces is collected in sacks and sold to manure traders or used at crop farms outside the dairy farming system	SEL
3	Using manure as substrate for anaerobic digestion	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 homegrown feed or crops	ADI
4	Discharging manure	Faeces is not collected and, in most farms, flushed from the barns into the environment	DIS

Table 2
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})	4964 (221)	4863 (221)	4985 (342)	5798 (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 indicate significant differences among manure management systems (P-value <0.05).

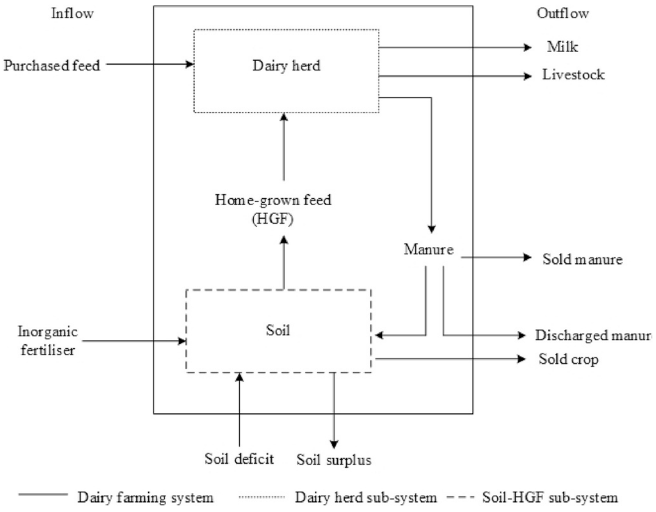


Fig. 2. Nutrient in- and outflows of the dairy farming system, and its sub-systems dairy herd and soil-homegrown-feed cultivation.

difference between nutrient inflows and outflows. We not only computed nutrient balances of the entire dairy farming system, but also of its sub-systems. Nutrient balances of the dairy sub-system were determined as the difference between nutrients in purchased and homegrown feed, and nutrients in milk and livestock. Nutrient balances from the soil-homegrown feed sub-system were determined as the difference between nutrients in inorganic fertiliser and manure, and nutrients in harvested feed. If the total input of inorganic nutrients into the soil exceeded the total output of nutrient in harvested feed, 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 input into the soil was lower than the output, the difference was assumed to be extracted from inorganic nutrient reserves in the soil (i.e., no change in soil organic stock in a short-time period).

To quantify above-described nutrient balances, we collected data through a farm survey. This survey was conducted during 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, homegrown feed area and production, and the quantity of inorganic fertiliser (i.e., urea) applied on homegrown feed 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.

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 3). These feed samples were collected at the first farm visit only, as

Table 3
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.

we assumed that the 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 homegrown feed (QN_{HGF}) equals the nutrients in the net ingested homegrown feed (presented in dry matter basis). To quantify nutrients in the net ingested homegrown feed, we followed the same procedure as described in case of purchased feed. The two types of homegrown feed were elephant grass and roadside grass (i.e., a mix of plants growing along the roadside). Most of the farmers used elephant grass, whereas only a few farmers used roadside grass. We collected samples of homegrown feed from each farm to determine the DM, and the content of nutrients N—P. The homegrown feed 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 homegrown feed was affected by season (Haegele and Arjharn, 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 manure management systems.

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 3). 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, 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 (National Research Council, 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 (Eq. 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}).

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 dairy farming system 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 manure management system, we multiplied the proportion of faeces being collected by the quantity of faecal N—P. To quantify the amount of faecal N—P being discharged in each manure management system, 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 presented 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 Eq. 2:

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

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 by the factor of 6.38 times 100.

2.4. Statistical analysis

To determine the impact of manure management systems on nutrient balances, we compared means of nutrient inflows, outflows, and balances per unit of farm, per unit of product and per unit of land across farms differing in manure management systems using ANOVA, followed by the Tukey's post hoc test with a critical significance level of 5% (Dean et al., 2017). We also compared means of total nutrient inflows, outflows, and balances of the dairy herd sub-system and the soil- homegrown feed 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-homegrown feed sub-system and dairy herd sub-system differed across manure management systems. All dairy farming systems 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 manure management systems. Hence, we summed the surplus and deficit farms and calculated the average in order to compare the soil N balance at soil-homegrown feed sub-system and N balance at dairy farming system across manure management systems. The proportion of farms with a negative and positive P balance, however, differed across manure management systems at both soil *($P = 0.0005$)* and dairy herd sub-system level *($P = 0.000005$)*. We, therefore, compared positive P balances (surplus) and negative P balances (deficit) of the soil-homegrown feed sub-system and dairy herd sub-system across manure management systems also separately. We presented the average of N—P balances across farms, the average of positive NP 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 manure management system among the 300 dairy farms in the study of de Vries et al. (2017) was multiplied with the number of dairy farms within the region (3985 dairy farms) to get the number of dairy farms at regional level in each manure management system. We assumed that the distribution of manure management systems among the 300 dairy farms reflected the distribution of manure management systems at regional level because the farm selection was performed at random.

The number of dairy farms at regional level in each manure management system was multiplied with the average nutrient balances per farm of that particular system 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 (Fig. 1).

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., 3419 ha from the total of 9560 ha). We made a scenario in which manure-N was applied to tomato, chili, long bean and green bean 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 by the N availability rate of organic fertiliser for each crop. The N availability rate of organic fertiliser for such crops ranges from 50 to 60% in Indonesia (Sari et al., 2019; Anggara et al., 2016; Sumarni et al., 2010). Subsequently, we multiplied the land size of each crop in the region with the quantity of applied manure-N ha^{-1} per year of each crop to estimate the total annual amount of manure-N potentially applicable per crop in the whole region.

3. Results

3.1. Nitrogen balances

Table 4 shows the average N inflows, outflows, and balances of the dairy farming system, as well as of the dairy herd and of the soil-homegrown feed sub-systems, per manure management system. At dairy farming system level, N inflows did not differ among manure management systems. On average, purchased feed caused the largest N inflow in all manure management systems (343 kg N farm^{-1} yr^{-1}), followed by inorganic fertiliser (35 kg N farm^{-1} yr^{-1}).

At dairy farming system level, total N outflows also did not differ among the four manure management systems. Milk caused the largest N outflow in ADL (Applying manure Directly on forage Land without treatment) which was 82 kg N farm^{-1} yr^{-1}, in ADI (using manure as substrate for Anaerobic DIgestion) which was 81 kg N farm^{-1} yr^{-1}, and in DIS (DIScharging manure) which was 99 kg N farm^{-1} yr^{-1}. In SEL (SELling or exporting manure) the largest outflow was sold manure (166 kg N farm^{-1} yr^{-1}). N outflow via sold manure in SEL was significantly larger than in other manure management systems, but, as said, this did not result in a difference in total N outflow, nor in a difference in total N balances between manure management systems. The average N balance of all farms at dairy farming system level was positive (surplus), equalled 222 kg N farm^{-1} yr^{-1}, 1007 kg N ha^{-1} yr^{-1} or 12 kg N ton FPCM^{-1} yr^{-1} and did not differ between manure management systems. All the dairy farms with different manure management systems had a N surplus at the dairy farming sub-system level.

In the dairy herd sub-system, total N inflows and N outflows did not differ between manure management systems. However, in the soil-homegrown feed sub-system, total N inflows differed between manure management systems. The largest 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 manure management systems were due to differences in applying manure to the homegrown feed area. Manure was applied in ADL (97 kg N farm^{1} yr^{1})

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

Dairy farming systems				
	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 (58.2)*
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)
Homegrown feed	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-homegrown 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})				
Homegrown feed 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.)*
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-homegrown feed sub-system.

[7] based on N balances across farms in each manure management system.

[8] N surplus are calculated when the total nutrient input into the soil exceeded the total output (Homegrown feed yield).

[9] N deficit are calculated when the total nutrient input into the soil is lower than the total output.

[10] N.A. is not applicable, Different superscripts indicate significant differences among manure management systems (*P*-value <0.05).

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 soil-homegrown feed 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 soil-homegrown feed 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-homegrown feed sub-system was negative (deficit) for all manure management systems and did not differ among 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}.

3.2. Phosphorous balances

Table 5 shows the average P inflows, outflows, and balances of the dairy farming system, as well of the dairy herd and of the soil-homegrown feed sub-systems, per manure management system. At dairy farming system level, P inflows did not differ among manure management systems. On average, purchased feed caused the largest P inflow in all manure management systems (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 manure management systems.

At dairy farming system level, total P outflows differed among the four manure management systems. Total P outflow in SEL (94 kg P farm^{-1} yr^{-1}) was largest, 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 larger in SEL than in other manure management systems. As a result, P balances at dairy farming system level also differed between manure management systems. At dairy farming system level, P balances differed among manure management systems. P balances (surplus) were largest 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 larger 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 dairy farming system 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 manure management systems. However, in the soil-homegrown feed sub-system, total P inflows differed between manure management systems. The largest 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 larger in ADL (68 kg P farm^{-1} yr^{-1}) than in other manure management systems. For two out of six farms, P outflows of soil-homegrown feed 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 soil-homegrown feed sub-system exceeded P outflows (soil surplus) (9 to 96 kg P farm^{-1} yr^{-1}). For all other farms, P outflows of soil-homegrown feed 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-homegrown feed sub-system (soil deficit) differed between manure management systems 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 manure management systems.

3.3. Nutrient balances at regional level

Table 6 presents estimated N—P balances from the dairy farms in the Lembang region which consists of the surplus and losses from the aggregate of dairy farming system and the soil-homegrown sub-system.

Table 5
Average P inflows, outflows, and balances of the dairy farming systems, as well of the dairy herd and of the soil-homegrown feed sub-systems, per manure management system, (standard error between brackets).

Dairy farming systems				
Parameters	ADL[1]	SEL[2]	ADI[3]	DIS[4]5
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[8]	44^{bc} (15.2)	*-25^{a} (5.7)*	36^{b} (9.6)	*83^{c} (11.8)*
P Surplus	*56^{ab} (13.2)*	*N.A.*[8]	*42^{a} (9.1)*	*83^{b} (11.8)*
P Deficit	*−16 (N. A.)*	*−25 (5.7)*	*−6 (N.A.)*	*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)
Homegrown feed	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-homegrown 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})				
Homegrown feed	51 (11.6)	30 (6.3)	31 (7.9)	35 (6.4)
P Balances[66] ***(kg farm^{-1} yr^{-1})***				
P Balances[7]	*17 (19.1)*	*−30 (6.3)*	*−24 (7.2)*	*−35 (6.4)*
P Surplus	*48 (25.5)*	*N.A.*	*N.A.*	*N.A.*
P Deficit	*-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-homegrown feed sub-system

[7] based on P balances accross farms in each manure management system

[8] N.A is not applicable, Different superscripts indicate significant differences among manure management systems (P-value <0.05)

The dominant manure management system 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 an annual surplus of 1061 tons N and 290 tons P from dairy farms in the Lembang region which potentially pollute the Citarum river. In contrast, we also estimated a deficit of about 8 tons P yr^{-1} from the soil-homegrown sub-system. . Total N

Table 6

The estimated N—P balances from dairy farms at the Lembang region.

Manure management systems	Number of dairy farms in baseline study (n)	Proportion of manure management systems [1] in dairy farming system (%)	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	3061	868	253	0
Total	300	100	3958	1061	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.

loading in the Citarum river was estimated at 51,555 ton yr^{-1}, of which 2182 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 7 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 availability rate of the organic fertiliser per crop, the potential amount of manure application to cropland in this region is 1350 tons of N yr^{-1}. This value exceeds the estimated total N balances (surplus) from the dairy sector (Table 6), 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. In addition, we estimated that 220 tons of N yr^{-1}can be saved in the region if DIS farmers would avoid N waste through applying ADL, ADI and SEL manure management systems. This N saving is equal to the average N-surplus from DIS farms minus the weighted average of N-surplus from ADL-, ADI- and SEL- farms multiplied by the number of DIS-dairy farms in the region.

4. Discussion

This study quantified N—P balances, and analysed differences between farms with different manure management systems. 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-homegrown feed subsystem. Identifying nutrient balances at each sub-system enables us to identify improvement options for nutrient management of the entire farming system and provide a meaningful assessment of the risk posed by a dairy farm to the environment (Harrison et al., 2021).

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 ammonia, nitrogen oxide, nitrous oxide and runoff 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. Especially 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, 2014).

Table 7

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	1125	361	1875	403
Tomato	321	600	202	1200	601
Green bean	287	405	116	810	232

[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).

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 dairy farming system level, SEL has a P deficit, implying more nutrients flow out than in the farm. Negative balances N—P (deficit) in the soil-homegrown feed sub-system can imply a depletion of the soil N or P stock. Godinot et al. (2014) argue that accounting for changes in soil organic matter should be included to improve the accuracy of a nutrient balances. We, however, could not exactly quantify the change in soil organic matter due to data limitations, and therefore, excluded changes in soil organic matter from our nutrient balances.

Our study showed that, at dairy farming system, P balances differed among manure management systems, whereas N balances did not. N balances did not differ between manure management systems, because all urine was discharged in all manure management systems. The classification of manure management systems was based only on the methods of faeces being collected. The fact that urine was discharged in all manure management systems made N balances among manure management systems largely comparable, because the N excretion via urine is larger than via faeces (Zahra et al., 2020; Jiao et al., 2014; Knowlton et al., 2010). At dairy farming system, P balances did differ between manure management systems 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 manure management system.

It is important to realize that whether or not manure is seen as a valuable output largely affects the calculation of nutrient balances at dairy farming system. 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 fertiliser, 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 manure management systems. 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., 1007 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 larger 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., 2014), 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 2513 kg N ha^{-1} 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 large 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 larger 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 larger 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., 2014). This larger average P surplus per unit of product at Indonesian smallholder dairy farms resulted from a larger 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-homegrown feed sub-system, some ADL farms need to sell the excess of faeces, whereas to avoid N—P deficits in the soil- homegrown feed 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 extracted 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-homegrown feed sub-system at the right rate and time could improve fertiliser use efficiency, mitigate soil depletion and improve soil productivity (Wu et al., 2020; Cai et al., 2019).

The Indonesian Government has set a seven-year (2018–2025) clean-up program of the Citarum river, called Citarum Bestari (Bappenas, 2020; Firdayani, 2020; Erianti and Djelantik, 2019; Belinawati et al., 2018). The results of this study can be used as an entry point for decision makers to come up with an action plan for improving nutrient management and avoiding pollution of the river. Our results show that nutrient losses from dairy farms in the Lembang region (about 1061 tons of N and 290 tons of P per year) potentially pollute the Citarum river. As mentioned earlier, however, we know that not the entire N surplus will either run-off or leach into the Citarum river; part of the N surplus is released to the air, via volatilisation of NH_3 or emissions of N_2O and NO_x, 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.

Financial constraints are the main barrier for improving manure management on smallholder farms. Effective manure collection, for example, requires substantial investment in technology (e.g., installation of drainage to collect urine) or would come with high labour costs especially when taking into account the transportation of collected manure from dairy farms to crop farms. Providing financial support, such as access to credit, is therefore seen as a first prerequisite to overcome the barriers for improvement and would allow dairy farmers or farmers groups to purchase equipment and facilities, required for proper manure management (Zahra, 2021).

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 and Yusuf, 2014), and are therefore an important constraint for farmers to replace inorganic fertiliser with manure from neighbouring farmers. Current legislation could result in a situation where crop farmers add the manure on top of the fertilisers they already use. In this case, the application of additional manure to crop cultivation areas will result in an increase in N input and N losses, which means that a large part of the nutrient losses resulting from poor manure management is simply moved to a neighbouring (crop) farm. The high density of dairy farms in this region has consequently contributed to large N losses and impose heavy environmental pressure on the Lembang region and the Citarum river and could furthermore rises public health issues (Li et al., 2022; Smit and Heederik, 2017). The problems related to current manure management practices will not be solved if dairy and crop farms are reluctant to collaborate. If such a collaboration also includes a proper fertilization plan so that nutrients in manure are either taken up by crops or stored in the soil, it could significantly contribute to reducing the environmental pressure of dairy farms in the Lembang region.

We furthermore need to realize that by importing purchased feed (e.g., concentrates) into the Lembang region, we 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 (de Vries et al., 2019;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 crop farms to apply excess manure.

5. Conclusion

We quantified nutrient flows and balances from smallholder dairy farms at the farm level and the level of its sub-system, and analysed differences in balances between farms with different manure management systems. All farms had a positive N balance, and we found no differences between manure management systems. Some farms had a positive, whereas other farms had a negative P balance. P balances differed between manure management systems, and were largest 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. The estimated potential N saved equals 220 tons of N per year in the region. The carrying capacity for high-input high-output dairy farming therefore is determined by the capacity of arable farms to apply excess manure from dairy farms.

CRediT authorship contribution statement

Windi Al Zahra: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Corina E. van Middelaar:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Simon J. Oosting:** Conceptualization, Formal

analysis, Methodology, Supervision, Writing – review & editing. **Imke J. M. de Boer:** Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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