Front. Agr. Sci. Eng. 2021, 8(1): 58–71 https://doi.org/10.15302/J-FASE-2020371

RESEARCH ARTICLE

# NUTRIENT USE EFFICIENCY AND LOSSES OF INDUSTRIAL FARMS AND MIXED SMALLHOLDINGS: LESSONS FROM THE NORTH CHINA PLAIN

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## KEYWORDS

industrial farms, mixed smallholdings, pig, dairy, nutrient management

## HIGHLIGHTS

- Degree of integration of crop and livestock was insufficient on mixed smallholdings.
- Liquid manure discharges on industrial farms hamper the closing of nutrient loops.
- Coupling with local crop farms is encouraged to achieve integration of crop-livestock systems.

Received May 4, 2020;
Accepted November 12, 2020.

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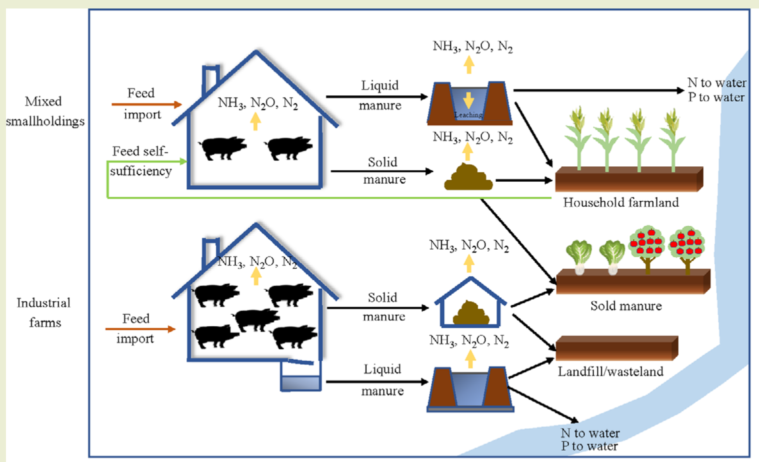
## GRAPHICAL ABSTRACT




## ABSTRACT

The proportion of industrial livestock in China has increased over the past 30 years, which increases animal performance but causes the decoupling of crop and livestock production. Here, we aimed to quantify nutrient flows, nutrient use efficiency, and nutrient losses in different livestock systems in the North China Plain based on the NUFER-farm model. Activity data were collected by face-to-face surveys on pig and dairy (41 livestock farms) during 2016–2018. The two systems included industrial farms and mixed smallholdings. In mixed smallholdings, 4.0% and 9.6% of pig and dairy feed dry matter (DM) were derived from household farmland, but 4.8% and 9.3% of manure DM recycled to household farmland. Nutrient use efficiency in industrial farms was higher than in mixed smallholdings at animal level, herd level, and system level. To produce 1 kg N and P in animal products, nutrient losses in industrial pig farms (2.0 kg N and 1.3 kg P) were lower than in mixed pig smallholdings, nutrient losses in industrial dairy farms (2.7 kg N and 2.2 kg P) were slightly higher than in mixed dairy smallholdings. Liquid manure discharge in industrial farms was the main losses pathway in contrast to mixed smallholdings. This study suggests that feed localization can reduce nutrient surpluses at the district level. It is necessary to improve manure management and increase the degree of integrated crop-livestock in smallholdings. In industrial farms, it is desirable to increase the liquid manure recycling ratio through cooperating livestock and crop production at the district level.



# 1 INTRODUCTION

The nitrogen (N) and phosphorus (P) losses from Chinese livestock systems in 2010 were 23 Tg and 4.6 Tg[1]. Pork and dairy milk production systems accounted for 23% and 8% of N losses and 18% and 7% of P losses[2,3]. Pig and dairy cattle production systems produce both liquid and solid manures. Livestock farms lack sufficient arable land area and suitable machinery to apply manures, especially liquid manures, thus it is usually directly discharge[4]. Direct discharges (manure to water bodies or landfill) of manure N and P in 2010 were 5.4 Tg and 1.9 Tg, direct discharges have become a major source of water pollution in China[1]. Also, considering the costs of manure treatment and application technology limitations, manure management is inappropriate and unregulated, resulting in environmental risk (e.g., atmospheric pollution, water pollution, and soil pollution)[5,6]. Therefore, there is an urgent need to evaluate the N and P balances of pig and dairy farms.

An ever-increasing demand for livestock products has prompted structural changes in livestock production. Chinese livestock production has undergone a huge transformation from mixed farms to industrial farms over the past 30 years. The changes have had a profound impact on national and global food supply, resource use, and nutrient flow[4]. The percentage of industrial pig systems (annual pigs slaughtered $\geqslant$150 LUs) increased from 8% in 1998 to 47% in 2017 and the percentage of industrial dairy systems (annual cattle stock $\geqslant$200 LUs) reached 24% in 2017[7]. However, in terms of farm numbers, mixed pig and dairy smallholdings accounted for 96% and 98%. Differences in nutrient management are influenced by farmer behavior and the scale of livestock systems[8]. It is necessary to analyze nutrient use efficiency and nutrient losses in industrial and smallholding pig and dairy systems to improve manure management and reduce environmental pollution.

Model analysis is an effective method in the assessment and analysis of nutrient flows and environmental losses in crop and livestock production systems and it provides strategic suggestions for improving nutrient management[9]. Some models have been developed to analyze nutrient balance at the farm scale. The NUANCES project mainly studies nutrient management and optimization in smallholder farms at Africa, but it focuses on cropping systems[10]. The De Marke dairy farm in the Netherlands adopted comprehensive management technologies and calculated the nutrient inputs, outputs, and balance of the whole farm through a model by combining land use, crop management, feed balance, and manure management. The whole-farm management can recycle nutrients, reduce imported nutrients, and mitigate environmental emissions[11–13]. However, the parameters of this model do not suit the actual situation in China. The NUFER-farm (Nutrient flows in Food chains, Environment, and Resources use-farm) model is a nutrient flow model for Chinese crop-livestock systems at the farm scale and can be used to analyze the nutrient balance of industrial and smallholding systems of pig and dairy production[14].

The objective of the present study was to assess nutrient flows of industrial farms and mixed smallholdings via model analysis and farm surveys in the North China Plain. The specific objectives were: (1) to assess the feed sourcing and manure distributing of industrial farms and mixed smallholdings; (2) to evaluate nutrient use efficiency and nutrient losses of industrial farms and mixed smallholdings.

# 2 MATERIALS AND METHODS

## 2.1 Field survey

### 2.1.1 Survey region

Hebei Province is a major province with crop and livestock production systems in the North China Plain. Hebei Province vigorously developed livestock production systems in response to the ‘Vegetable Basket Project’ and the proportion of industrial livestock systems gradually increased. The percentages of industrial pig and dairy systems reached 41% and 58% in 2017, but the number of smallholdings accounted for > 90%[7].

Hebei Province has geographical advantages, such as flat area, suitable mean temperature (~13°C), and precipitation (485 mm), these favor annual maize-wheat rotations.

### 2.1.2 Livestock production systems

Survey data were collected in Hebei Province from 2016 to 2018 through face-to-face questionnaires. The study encompassed 32 pig farms and 9 dairy farms. The interview time at each farm was 40–60 min. Survey data in crop production systems comprised synthetic fertilizer inputs, crop yields, irrigation, seeds, and manure inputs. Survey data in livestock systems consisted of feed inputs, manure storage, manure treatment, manure application rates, and animal products (milk yields and animal weight gains). Sample selection was based on the two different livestock pigs and dairy cattle) and two contrasting scales of livestock production (industrial farms and mixed smallholdings). Pig farms comprised industrial farms (150 LUs ⩽ annual pigs slaughtered < 1500 LUs) and mixed smallholdings (annual pigs slaughtered < 150 LUs). Here, industrial pig farms signed formal production contracts with pig enterprises which, in turn, were responsible for providing weaning pigs, feeds, medicines, and technical guidance while the industrial pig farms were responsible for feeding fattening pigs and manure management. Mixed smallholdings had livestock production and crop production in the same enterprise and they fed fattening pigs, breeding sows, and breeding boars. Dairy farms consisted of industrial farms (200 LUs ⩽ annual cattle stock ⩽ 5000 LUs) and mixed smallholdings (annual cattle stock < 200). The main characteristics of the systems are shown in Table 1.

## 2.2 System boundary and model calculations

### 2.2.1 NUFER-farm model

The nutrient flows, nutrient use efficiency, and environmental losses of the different livestock systems were calculated based on the NUFER-farm model[14]. The model used a bottom-up method to quantify the nutrient flows, nutrient use efficiency, and environmental losses of different crop systems, livestock systems, and mixed crop-livestock systems.

### 2.2.2 System boundary

Inputs of cropping systems comprise seed, irrigation, synthetic fertilizers, manures, returned crop residues, atmospheric deposition, and biological nitrogen fixation (BNF). The outputs consist of crop products, crop residues, and environmental losses. Livestock systems operate at three levels: animal, herd, and system levels (Fig. 1). The animal level considers only nutrient inputs and outputs of fattening pigs or lactating cows. Herd level considers nutrient inputs and outputs of total animal stages. The

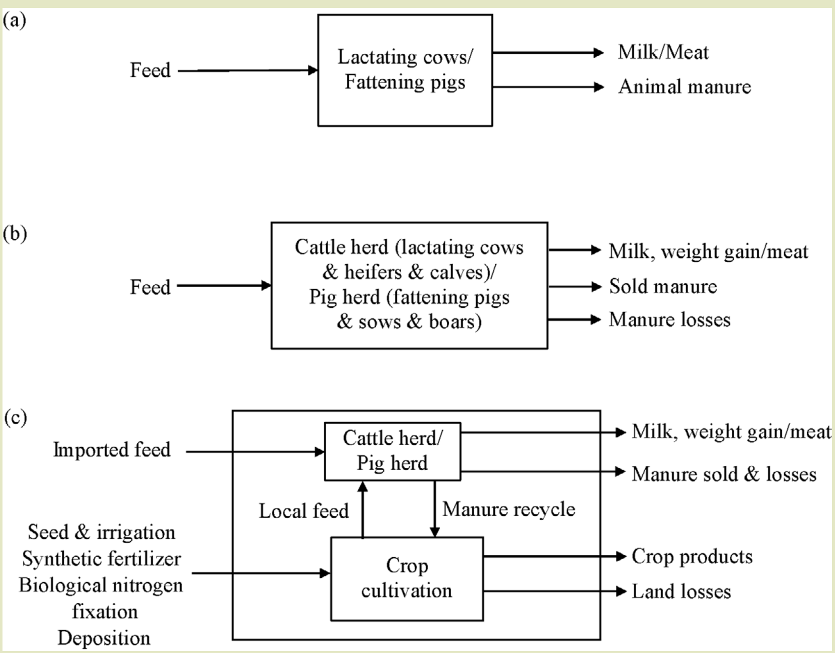



**Fig. 1** Research system boundary and nutrient flow of crop-livestock systems at different levels: (a) animal level, (b) herd level, and (c) system level (adapted from Ma[15]).

Table 1 Characteristics of different livestock production systems based on survey data (adapted from Ma[15])

| Characteristic | Industrial pig farms | Mixed pig smallholdings | Industrial dairy farms | Mixed dairy smallholding |
|---|---|---|---|---|
| Number of farms | 24 | 8 | 4 | 5 |
| Cultivated crop area (ha) | 0 | 0.52 | 0 | 15 |
| Number of animals (LU)[a] | 275 (slaughtered) | 136 (slaughtered) | 1400 (stock) | 114 (stock) |
| FPCM ($kg \cdot LU^{-1} \cdot yr^{-1}$)[b] | – | – | 7288 | 6276 |
| Feed/meat ratio ($kg \cdot kg^{-1}$) | 2.8 | 3.5 | – | – |
| Housing floor type (%)[c] | | | | |
| Solid cement floor | 96 | 100 | 75 | 60 |
| Slatted cement floor | 4 | 0 | 25 | 0 |
| Soil | 0 | 0 | 0 | 40 |
| Collection frequency (%) | | | | |
| Twice per day | 92 | 54 | 75 | 0 |
| Less than twice per day | 8 | 46 | 25 | 100 |
| Manure storage (%) | | | | |
| Solid manure | | | | |
| Aboveground covered | 0 | 40 | 50 | 0 |
| Aboveground uncovered | 0 | 60 | 50 | 100 |
| Slurry or liquid manure | | | | |
| Underground covered | 0 | 0 | 0 | 0 |
| Underground uncovered | 0 | 100 | 0 | 100 |
| Manure treatment (%) | | | | |
| Slurry or liquid manure | | | | |
| Anaerobic digestion | 20 | 0 | 25 | 0 |
| Oxidation pond | 80 | 0 | 75 | 0 |
| Solid manure | | | | |
| Composting | 100 | 0 | 0 | 0 |
| Manure return to household cropland | | | | |
| N ($kg \cdot ha^{-1}$) | 0 | 370 | 0 | 230 |
| P ($kg \cdot ha^{-1}$) | 0 | 71 | 0 | 25 |
| Land use of sold and discharge manure (ha)[d] | 17 | 7 | 247 | 31 |

Note: [a] LU, livestock units (one dairy cow is the standard unit and one pig is equivalent to 0.3 dairy cows). [b] FPCM denotes fat and protein corrected milk and the milk is standardized to 4% fat and 3.3% protein, calculated as FPCM (kg) = raw milk (kg) × (0.1226 × fat% + 0.0776 × true protein% + 0.2534)[16]. [c] Solid cement floors collect solid manure and liquid manure; slatted cement floors collect slurry; soil floors collect solid manure. [d] The additional land to apply sold and direct discharge manure. The manure applied amounts is 170 $kg \cdot ha^{-1}$ N in Europe[17] and it is used here.

system level considers the inputs and outputs of crop-livestock systems. System inputs are district feeds and imported feeds, the outputs consist of animal product exports, crop product exports, and environmental losses. The animal level reflects the nutrient management of fattening pigs or lactating cows, the herd level represents the structure and nutrient management level of livestock farms, and the system level represents the nutrient flows, resource demands, and environmental impacts of the crop-livestock production systems[2,3]. This study does not consider synthetic fertilizer production, imported feed production or energy use.

### 2.2.3 Definitions and calculation of key indicators

N and P flows, nutrient use efficiency and environmental losses were calculated by the NUFER-farm model[16],

$$\mathrm{N(P)I_{crop}} = \mathrm{N(P)I_{fer}} + \mathrm{N(P)I_{seed}} + \mathrm{N(P)I_{ir}} + \mathrm{NI_{BNF}} + \mathrm{NI_{dep}} + \mathrm{N(P)I_{Am}} + \mathrm{N(P)I_{st}} \quad (1)$$

where $\mathrm{N(P)I_{crop}}$ (kg) is the N or P inputs of crop systems, $\mathrm{N(P)I_{fer}}$ (kg) is N or P inputs via synthetic fertilizers, $\mathrm{N(P)I_{seed}}$ (kg) is N or P inputs via seeds, $\mathrm{N(P)I_{ir}}$ (kg) is N or P inputs via irrigation, $\mathrm{NI_{BNF}}$ (kg) is N inputs via BNF, $\mathrm{NI_{dep}}$ (kg) is N inputs via deposition, $\mathrm{N(P)I_{Am}}$ (kg) is N or P inputs via animal manure, and $\mathrm{N(P)I_{st}}$ (kg) is N or P inputs via crop residues.

$$\mathrm{N(P)I_{livestock}} = \mathrm{N(P)I_{FI}} + \mathrm{N(P)I_{HC}} \quad (2)$$

where $\mathrm{N(P)I_{livestock}}$ (kg) is N or P feed inputs in livestock systems, livestock = animal, herd, $\mathrm{N(P)I_{FI}}$ (kg) is N or P feed inputs via imported feed, $\mathrm{N(P)I_{HC}}$ (kg) is N or P feed inputs via household farmland products.

$$\mathrm{N(P)UE_C} = \frac{\mathrm{N(P)O_{crop}}}{\mathrm{N(P)I_{crop}}} \times 100 \quad (3)$$

In Eq. (3), $\mathrm{N(P)UE_C}$ (%) is N or P use efficiency in crop production systems, $\mathrm{N(P)O_{crop}}$ (kg) is outputs of N or P in crop products and $\mathrm{N(P)I_{crop}}$ (kg) is N or P inputs of cropping systems.

$$\mathrm{N(P)UE_{Animal}} = \frac{\mathrm{N(P)O_{Animal}}}{\mathrm{N(P)I_{Animal}}} \times 100 \quad (4)$$

where $\mathrm{N(P)UE_{Animal}}$ (%) is N or P use efficiency in livestock production at the animal level, $\mathrm{N(P)O_{Animal}}$ (kg) is N or P in animal products of fattening pigs/lactating cows, and $\mathrm{N(P)I_{Animal}}$ (kg) is N or P inputs via feeds of fattening pigs or lactating cows.

$$\mathrm{N(P)UE_{Herd}} = \frac{\mathrm{N(P)O_{Herd}}}{\mathrm{N(P)I_{Herd}}} \times 100 \quad (5)$$

where $\mathrm{N(P)UE_{Herd}}$ (%) is N or P use efficiency in livestock production at herd level, $\mathrm{N(P)O_{Herd}}$ (kg) is outputs of N or P from all stages of dairy herd (calves, heifers, lactating cows and dry cows) or pig herd (boars, sows and fattening pigs), and $\mathrm{N(P)I_{Herd}}$ (kg) is N or P inputs via feed at all animal stages.

$$\mathrm{N(P)UE_{c+a}} = \frac{\mathrm{N(P)O_c} + \mathrm{N(P)O_a}}{\mathrm{N(P)I_{fer}} + \mathrm{N(P)I_{seed}} + \mathrm{N(P)I_{ir}} + \mathrm{N(P)I_{BNF}} + \mathrm{N(P)I_{dep}} + \mathrm{N(P)I_{FI}}} \times 10 \quad (6)$$

In Eq. (6), $\mathrm{N(P)UE_{c+a}}$ (%) is N or P use efficiency in crop-livestock systems at the system level, $\mathrm{N(P)O_c}$ (kg) is N or P outputs of crop products, $\mathrm{N(P)O_a}$ (kg) is N or P outputs of animal products, $\mathrm{N(P)I_{fer}}$ (kg) is N or P inputs of crop systems via synthetic fertilizers, $\mathrm{N(P)I_{seed}}$ (kg) is N or P inputs of crop systems via seeds, $\mathrm{N(P)I_{ir}}$ (kg) is N or P inputs of crop systems via irrigation, $\mathrm{N(P)I_{BNF}}$ (kg) is N inputs of crop systems via BNF, $\mathrm{N(P)I_{dep}}$ (kg) is N inputs of crop systems via deposition, and $\mathrm{N(P)I_{FI}}$ (kg) is N or P feed inputs of livestock systems via imported feeds.

$$\mathrm{N(P)L_c} = \mathrm{NO_{NH_3}} + \mathrm{NO_{N_2O}} + \mathrm{NO_{N_2}} + \mathrm{N(P)O_{rf}} + \mathrm{N(P)O_{le}} \quad (7)$$

In Eq. (7), $\mathrm{N(P)L_c}$ (kg) is N or P losses in crop production systems, $\mathrm{NO_{NH_3}}$ (kg) is N losses through ammonia emission in crop production, $\mathrm{NO_{N_2O}}$ (kg) is N losses through $N_2O$ in crop production, $\mathrm{NO_{N_2}}$ (kg) is N losses through $N_2$ by denitrification in crop production, $\mathrm{N(P)O_{rf}}$ (kg) is N or P losses through erosion and runoff in crop production, $\mathrm{N(P)O_{le}}$ (kg) is N or P losses through leaching in crop production.

$$\mathrm{N(P)PL_a} = \frac{\mathrm{NO_{livestock\ NH_3}} + \mathrm{NO_{livestock\ N_2O}} + \mathrm{NO_{livestock\ N_2}} + \mathrm{N(P)O_{discharge}} + \mathrm{N(P)O_{livestock\ le}}}{\mathrm{N(P)O_{livestock}}} \quad (8)$$

In Eq. (8), $\mathrm{N(P)PL_a}$ ($\mathrm{kg \cdot kg^{-1}}$) is kg N or P losses of per kg N or P in livestock products, $\mathrm{NO_{livestock\ NH_3}}$ (kg) is N losses through $NH_3$ in livestock production systems, $\mathrm{NO_{livestock\ N_2O}}$ (kg) is N losses through $N_2O$ in livestock production systems, $\mathrm{NO_{livestock\ N_2}}$ is $\mathrm{NO_{livestock\ N_2}}$ (kg) is N losses through $N_2$ in livestock production systems, $\mathrm{N(P)O_{discharge}}$ (kg) is N or P losses through the direct discharge in livestock production systems, $\mathrm{N(P)O_{livestock\ le}}$ (kg) is N or P losses through leaching in livestock production systems, and $\mathrm{N(P)O_{livestock}}$ (kg) is animal outputs of N or P in livestock production systems.

$$\mathrm{N(P)PL_k} = \frac{\mathrm{N(P)O_{livestock\ k}}}{\mathrm{N(P)O_{livestock}}} \quad (9)$$

In Eq. (9), $\mathrm{N(P)PL_k}$ ($\mathrm{kg \cdot kg^{-1}}$) is when produced per kg N of P in livestock products, nutrient losses through k in livestock production systems, k = $NH_3$, $N_2O$, $N_2$, and discharge, $\mathrm{N(P)O_{livestock}}$ (kg) is animal outputs of N or P in livestock production systems.

The percentage of feed source and manure distribution.

$$\mathrm{P_i} = \frac{\mathrm{FI_i}}{\mathrm{FI_{Herd}}} \times 100 \quad (10)$$

$$\mathrm{R_i} = \frac{\mathrm{MO_i}}{\mathrm{MO_{Hard}}} \times 100 \quad (11)$$

where $P_i$ (%) is the feed sourcing ratio from region i of total feed, region i = within the farm, within the district, within the province, within the country and overseas, $FI_i$ (kg) is the feed dry matter amount from region i, $FI_{Herd}$ (kg) is the inputs of feed (based on DM) in livestock farms, $R_i$ (%) is manure returned ratio to region i, $MO_i$ (kg) is manure dry matter returned amount to region i, $MO_{Hard}$ (kg) is the manure output amount (based on DM) of livestock farms.

Districts and provinces are the administrative divisions in China. The district is defined where farmers can easily exchange crop products (animal feed) and animal manures without third-party service providers. In practice this would be within a radius of up to about 10 km. Province is defined where farmers can exchange crop products (animal feed) and animal manures and they need third-party service providers to produce feed (premix or concentrate) and process manures. In practice this would be farms within a radius of 10–100 km and the region should have an adequate road infrastructure.

#### 2.2.4 Model parameterization

Nutrient contents of animal products are taken from the NUFER model (Table 2)[18,19]. The coefficients of crop and livestock production are taken from Ma et al.[18], Hou et al.[20], and Wei et al.[21] (Tables 3 and 4).

#### 2.2.5 Statistical methods

Microsoft Access 2010 software was used as the data management platform and Rstudio 0.98.978 as the development platform. Average nutrient values and standard deviation were calculated using Excel 2016 and Origin 2017 software.

## 3 RESULTS

### 3.1 Feed sourcing and manure distributing

The spatial distribution feed sourcing and manure distribution differed between industrial farms and mixed smallholders (Fig. 2). The main feed source (dry matter (DM) basis) of industrial pig farms was outside the province (70%), followed by within the province (20%) and the local district (10%). In mixed pig smallholdings, only 4.0% of feed was from household cropland. In contrast to industrial pig farms, most of feeds in mixed pig smallholdings were sourced from within the province (60%), followed by within the country (26%). Only 4.8% of pig manures (DM basis) were recycled to household cropland in mixed pig smallholdings. The remaining manures were applied within the local district due to the high transportation costs. Industrial pig farms returned all manures to district croplands (Fig. 2(a)).

The main ingredients of the dairy feed formula were hay, silage, and concentrates. In industrial dairy farms, 3.3% of feeds were imported from overseas (alfalfa and soybean), 50% from outside the province (concentrates and hay), 37% from within the province (maize and wheat bran), and 10% from the local district (maize silage). In mixed dairy smallholdings, the feeds were mainly from within the province (42%) and outside the province (43%), with only 10% from household cropland, and 9.3% of cattle manures were returned to household cropland with 80% and 11% of cattle manure distributed to the local district and within the province, respectively. Industrial dairy farms cooperated with a manure processing company and 20% of manures were sold to the local province (Fig. 2(b)).

**Table 2 Nutrient contents of livestock animal products (adapted from Ma[15])**

| Item | Nutrient | Pig | Dairy cattle |
|---|---|---|---|
| Meat (%) | N | 1.5 | 2.8 |
| | P | 0.18 | 0.17 |
| Bone (%) | N | 1.9 | 1.8 |
| | P | 3.3 | 4.2 |
| Other (%) | N | 2.2 | 2.2 |
| | P | 0.07 | 0.01 |
| FPCM (%) | N | – | 0.52 |
| | P | – | 0.09 |

Note: The N and P content data of livestock products were obtained from the NUFER model[18,19].

**Table 3 Emission factors in crop production systems**

| Emission factor | Hebei Province |
|---|---|
| Biological nitrogen fixation ($kg \cdot ha^{-1}$ N) | 19 |
| Deposition ($kg \cdot ha^{-1}$ N) | 33 |
| $NH_3$-N of synthetic fertilizer (%) | 25 |
| $N_2O$-N of synthetic fertilizer (%) | 1.1 |
| $NH_3$-N of applied manure (%) | 25 |
| $N_2O$-N of applied manure (%) | 1.0 |
| Runoff and erosion of total N input (%) | 4.8 |
| Leaching ($NO_3^-$-N) of N surplus (%) | 19 |
| $N_2$-N of N surplus (%) | 15 |
| Accumulation of N surplus (%) | 66 |
| Runoff and erosion of total P input (%) | 2.6 |
| Leaching of P surplus (%) | 0.15 |
| Accumulation of P surplus (%) | 99.8 |

Note: The data were obtained from the NUFER model[18,19]. $N(P)_{surplus} = N(P)I_{crop} - N(P)O_{crop} - N(P)O_{straw} - N(O)_{NH_3} - N(O)_{N_2O} - N(P)O_{rf}$.

**Table 4 $NH_3$, $N_2O$, and $N_2$ emission factors of manure storage, storage, and treatment in livestock systems (adapted from Ma[15])**

| Manure management stage | | $NH_3$-N (%) | | $N_2O$-N (%) | | $N_2$-N (%) | |
|---|---|---|---|---|---|---|---|
| | | Pig | Dairy cattle | Pig | Dairy cattle | Pig | Dairy cattle |
| Housing | Solid cement floor | 18 | 23 | 0.5 | 0.5 | 5.0 | 5.0 |
| | Slatted cement floor | 15 | 15 | 0.5 | 0.5 | 5.0 | 5.0 |
| | Soil | 20 | 26 | 0.5 | 0.5 | 5.0 | 5.0 |
| Storage | Aboveground covered | 6 | 15 | 0.5 | 2.0 | 5.0 | 10 |
| | Aboveground uncovered | 30 | 17 | 0.5 | 0.5 | 5.0 | 5.0 |
| | Underground covered | 4 | 14 | 0.5 | 3.0 | 5.0 | 15 |
| | Underground uncovered | 20 | 17 | 0.5 | 0.5 | 5.0 | 5.0 |
| Treatment | Anaerobic digestion | 10 | 22 | 0.5 | 0.5 | 5.0 | 5.0 |
| | Oxidation pond | 20 | 26 | 0.5 | 0.25 | 5.0 | 5.0 |
| | Composting | 30 | 26 | 0.5 | 0.25 | 5.0 | 5.0 |

Note: Data obtained from Ma et al.[18], Hou et al.[20], and Wei et al.[21].

## 3.2 N and P flows in pig farms

There were differences in N and P flows between industrial pig farms and mixed pig smallholdings at three levels (Table 5). Industrial pig farms had higher nutrient use efficiency than mixed pig smallholdings (Fig. 3(a)). At the animal level, mixed pig smallholdings required more feed than industrial pig farms (16% N and 12% P) when 1 kg N and P were produced in pork. The NUE and PUE values of mixed pig smallholdings (28% and 36%) were lower than those of industrial pig farms (32% and 40%) (Fig. 3(a)). At the herd level, the feed N and P inputs in mixed pig smallholdings were 75% and 31% higher than in industrial pig farms. NUE and PUE in industrial pig farms (32% and 40%) were higher than in mixed pig smallholdings (18% and 26%). At the system level, all feed was imported and all manure was exported in industrial pig farms. In mixed pig smallholders, there was nutrient exchange through mixed crop and livestock production systems with 8.9% of N and 13% of P in feeds derived from household cropland products but only 8.7% excreted N and 14% excreted P in manure returned to household cropland

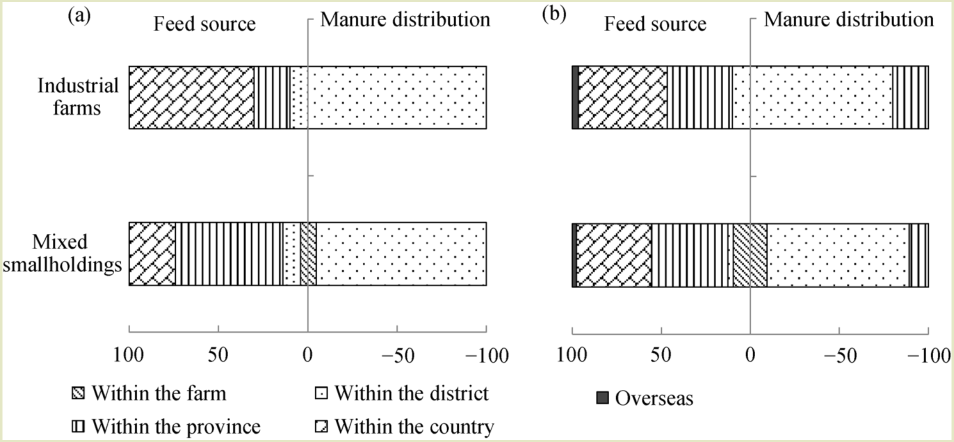



**Fig. 2** Feed source and manure distribution from (a) pig and (b) dairy production systems (adapted from Ma[15]).

**Table 5** N and P flows in mixed pig smallholdings and industrial pig farms (mean values±standard deviation for each farm type) (adapted from Ma[15])

| Input and output | Nutrient flow | N (kg N per kg product N) | | P (kg P per kg product P) | |
|---|---|---|---|---|---|
| | | Industrial pig farms | Mixed pig smallholdings | Industrial pig farms | Mixed pig smallholdings |
| Animal level | | | | | |
| Input | Feed | 3.1±0.31 | 3.6±0.96 | 2.5±0.27 | 2.8±0.35 |
| Output | Pork | 1.0 | 1.0 | 1.0 | 1.0 |
| | Manure excretion | 2.1±0.51 | 2.6±0.79 | 1.5±0.17 | 1.8±0.42 |
| Herd level | | | | | |
| Input | Feed | 3.2±0.57 | 5.6±1.12 | 2.9±0.38 | 3.8±1.03 |
| Output | Pork | 1.0 | 1.0 | 1.0 | 1.0 |
| | Manure excretion | 2.2±0.65 | 4.6±0.98 | 1.9±0.28 | 2.8±1.01 |
| System level | | | | | |
| Input | Import feed | 3.2±0.57 | 5.1±1.16 | 2.9±0.38 | 3.3±0.82 |
| | Synthetic fertilizer | 0 | 0.60±0.08 | 0 | 0.30±0.09 |
| | Others | 0 | 0.20±0.05 | 0 | 0 |
| Output | Crop products and residues | 0 | 0.35±0.06 | 0 | 0.05±0.01 |
| | Pork | 1.0 | 1.0 | 1.0 | 1.0 |
| | Manure export | 2.2±0.65 | 4.2±0.59 | 1.9±0.28 | 2.4±0.31 |
| | Crop losses | 0 | 0.25±0.03 | 0 | 0.02±0.005 |
| Recycle | Household feed | 0 | 0.50±0.08 | 0 | 0.50±0.08 |
| | Manure recycle | 0 | 0.40±0.05 | 0 | 0.40±0.07 |
| | Accumulation | 0 | 0.30±0.11 | 0 | 0.16±0.09 |

(Table 5). NUE and PUE values at the system level in mixed pig smallholdings were 24% and 29%, respectively, but these values remained lower than in industrial pig farms (Fig. 3(a)).

Industrial pig farms had lower nutrient losses than mixed pig smallholdings (Fig. 3(a)). To produce 1 kg pork (based on N and P), mixed pig smallholdings emitted 2.5 kg N and 1.6 kg P into the environment, while 2.0 kg N and 1.3 kg P were lost in industrial pig farms. Ammonia ($NH_3$) emission was the main pathway of N losses, accounting for > 60% of the total losses. The second losses pathway was direct discharge of manures in mixed pig smallholdings (0.6 $kg \cdot kg^{-1}$ N) and industrial pig farms (0.7 $kg \cdot kg^{-1}$ N). The main P losses pathway was direct discharge of manures (Fig. 3(b)).

## 3.3 N and P flows in dairy farms

Industrial dairy farms required lower feed nutrient inputs (Table 6) to produce 1 kg FPCM (based on N and P), had higher nutrient use efficiency (Fig. 4(a)), and lost more nutrients (Fig. 4(b)) than mixed dairy smallholdings. At the animal level, industrial dairy farms required less feed N (20%) and P (30%) inputs than mixed dairy smallholdings when producing 1 kg FPCM (Table 6). This explains the lower NUE and PUE (22% and 23%) of mixed dairy smallholdings than of industrial dairy farms (28% and 30%) (Fig. 4(a)). At the herd level, considering non-lactating cows (calves and heifers), industrial dairy farms required lower feed nutrient inputs than mixed dairy smallholdings. NUE and PUE in mixed dairy smallholdings were 15% and 14%, respectively, whereas in industrial dairy farms they were

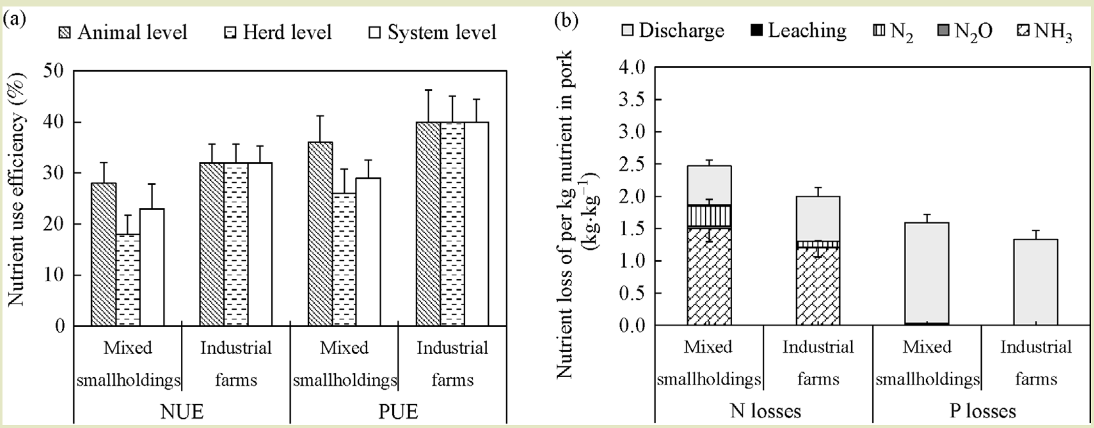



**Fig. 3** Nutrient use efficiency (a) and nutrient losses (b) in mixed pig smallholdings and industrial pig farms.

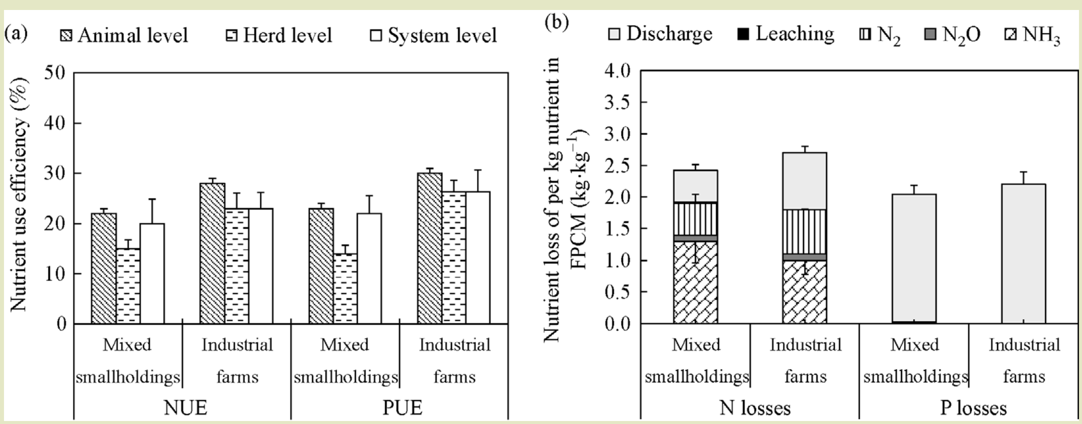



**Fig. 4** Nutrient use efficiency (a) and nutrient losses (b) in mixed dairy smallholdings and industrial dairy farms.

Table 6 N and P flows in mixed dairy smallholdings and industrial dairy farms (mean values±standard deviation for each farm type) (adapted from Ma[15])

| Input and output | Nutrient flow | N (kg N per kg product N) | | P (kg P per kg product P) | |
|---|---|---|---|---|---|
| | | Industrial dairy farms | Mixed dairy smallholdings | Industrial dairy farms | Mixed dairy smallholdings |
| Animal level | | | | | |
| Input | Feed | 3.6±0.64 | 4.5±0.27 | 3.3±0.56 | 4.3±0.63 |
| Output | Milk | 1.0 | 1.0 | 1.0 | 1.0 |
| | Manure excretion | 2.6±0.24 | 3.5±0.85 | 2.3±0.39 | 3.3±0.76 |
| Herd level | | | | | |
| Input | Feed | 4.3±0.53 | 6.7±0.44 | 3.8±0.67 | 7.1±0.86 |
| Output | Milk and meat | 1.0 | 1.0 | 1.0 | 1.0 |
| | Manure excretion | 3.3±0.14 | 5.7±0.27 | 2.8±0.71 | 6.1±1.24 |
| System level | | | | | |
| Input | Imported feed | 4.3±0.53 | 6.4±0.43 | 3.8±0.67 | 6.5±1.65 |
| | Synthetic fertilizer | 0 | 0.50±0.09 | 0 | 0.60±0.04 |
| | Others | 0 | 0.10±0.01 | 0 | 0 |
| Output | Crop products and residues | 0 | 0.4±0.12 | 0 | 0.57±0.05 |
| | Milk and meat | 1.0 | 1.0 | 1.0 | 1.0 |
| | Manure export | 3.3±0.14 | 4.9±0.29 | 2.8±0.71 | 5.1±1.08 |
| | Crop losses | 0 | 0.20±0.02 | 0 | 0.07±0.01 |
| Recycled | Household feed | 0 | 0.30±0.04 | 0 | 0.61±0.11 |
| | Manure recycled | 0 | 0.77±0.11 | 0 | 1.0±0.13 |
| | Accumulation | 0 | 0.63±0.07 | 0 | 0.40±0.10 |

23% and 26% (Fig. 4(a)). Nitrogen and phosphorus losses when producing 1 kg N and P in FPCM in mixed dairy smallholdings (2.4 kg N and 2.0 kg P) were 11% and 9% lower than in industrial dairy farms (2.7 kg N and 2.2 kg P). This was due to the higher manure discharge ratio (0.9 $kg\cdot kg^{-1}$ N and 2.2 $kg\cdot kg^{-1}$ P) in industrial dairy farms than in mixed dairy smallholdings (0.5 $kg\cdot kg^{-1}$ N and 2.0 $kg\cdot kg^{-1}$ P). The main pathway of N losses was $NH_3$ emissions in mixed dairy smallholdings (54%) and industrial dairy farms (37%) (Fig. 4(b)).

At the system level, NUE and PUE in mixed dairy smallholdings (20% and 22%) were lower than in industrial farms (23% and 26%) (Fig. 4(a)). In mixed dairy smallholdings, 4.5% of feed N and 8.6% of feed P were sourced from household cropland products, and manure N and P returned to household cropland were 14% and 16%, respectively. The animal products accounted for 71% of N and 64% of P in crop-livestock products (Table 6).

# 4 DISCUSSION

## 4.1 Nutrient flow characteristics of pig farms

Mixed pig smallholdings had lower imported feed dependency and reduced direct discharge of manures through coupling of crop and livestock production compared to industrial pig farms. In mixed pig smallholdings, feed self-sufficient DM was 4.0%, lower than the defined mixed systems level according to the FAO (feed self-sufficient DM>10%)[22]. In mixed pig smallholdings, 8.9% of feed N and 13% of feed P were sourced from household cropland products, and 8.7% of excreted N and 14% of excreted P were returned to household cropland, 370 $kg\cdot ha^{-1}\cdot yr^{-1}$ N and 71 $kg\cdot ha^{-1}\cdot yr^{-1}$ P were applied to household farmland in manures. These manure applied amounts were more than double the maximum European manure N (170 $kg\cdot ha^{-1}\cdot yr^{-1}$ N) and P (30 $kg\cdot ha^{-1}\cdot yr^{-1}$ P) application standards[16,23]. Also, these farms needed an extra 7 ha of land to accommodate sold and direct discharge manures and the extra land required was more than the household cropland area (0.5 ha) (Table 1). This shows that mixed pig smallholdings had insufficient cropland area to fully recycle animal manures[14]. Feed DM in industrial pig farms was sourced from outside the province (70%), but the manures from these systems were mainly returned to land within the province. This would increase N and P surpluses within the local province[24]. The main ingredients of pig feeds are maize, soybeans, and wheat bran (from survey data). Carrying out a corn-soybean rotation in intensive pig systems can reduce imported soybean and maize. Selecting and cultivating maize varieties that suit pigs can increase the regional feed supply ratio and increase animal feed intakes[25]. The NUE and PUE at the animal, herd, and system levels in industrial pig farms were all higher than in mixed pig smallholdings because the industrial pig farms did not rear sows and boars. Pig enterprises provide fattening pigs to industrial pig farms. Also, the pig enterprises unified the feed formula (e.g., the crude protein content of feed for fattening pigs was 14%) and reduced mortality by strict management. Industrial pig farms feed fattening pigs with centralized systems. The same batch of fattening pigs entered the house together and left the house together. Disinfection procedures were used to prevent epidemics in the animal houses. These measures enabled NUE and PUE at herd level in industrial pig farms (32%) to be higher than the national pig farm average (23%)[2], but still lower than the average level in the Netherlands (33%)[26]. Also, PUE at the animal level in industrial pig farms (40%) was higher than the national average (31%)[2] and in the Netherlands (37%)[27]. Ammonia emission (40%–60%) was the main contributor to N losses in pig production systems[28]. The manure discharge in mixed pig smallholdings was lower than in industrial pig farms because industrial pig farms could sell solid manures but liquid manures would not be used without household cropland. If direct discharge and sold manure returned to cropland, 17 ha of additional land would have been needed in industrial pig farms (Table 1). In conclusion, mixed pig smallholdings need to reduce the pig feed conversion ratio and improve manure management. The feed-to-meat ratio can be reduced by adding exogenous enzymes and reducing feed protein[29]. There are some methods to reduce $NH_3$ emissions in manure management such as increasing the frequency of manure removal at the housing stage, covering solid manures and acidifying liquid manures at the storage stage, and applying manures according to crop growth requirements[20]. Industrial pig farms need to deal with liquid manures, for example by renting cropland or cooperating with specialized crop farms. Building enclosed storage tanks to store liquid manures for 3–6 months and application liquid manures by band-spreading or injection can reduce $NH_3$ emissions[20].

## 4.2 Nutrient flow characteristics of dairy farms

Mixed dairy smallholdings had higher farm feed self-sufficiency and lower nutrient losses than industrial dairy farms through integrating crop and livestock production. In mixed dairy smallholdings, the percentages of N and P outputs in animal products accounted for 71% and 64% of crop-livestock products, exceeding the standard of mixed crop-livestock[30]. NUE and PUE in industrial dairy farms were higher than in mixed dairy smallholdings at animal and herd levels because industrial dairy farms had higher milk yields and lower nutrient inputs. At animal level, NUE in industrial dairy farms was 28%, higher than in Beijing (21%)[31] but lower than in the USA (35%)[32]. At herd level, NUE and PUE were 15% and 14% in mixed dairy smallholdings, lower than in the Netherlands (20% and 34%) because Chinese farms had higher feed nutrient inputs and lower milk production[33,34]. In mixed dairy smallholdings, external inputs such as synthetic fertilizers were included but the crop-livestock products showed a minor increase and therefore NUE and PUE were lower than in industrial dairy farms at the system level. Industrial dairy farms had higher N and P losses than mixed dairy smallholdings to produce 1 kg N in FPCM because of higher manure direct discharges, especially liquid manure. Notably, mixed dairy smallholdings had greater $NH_3$ emissions than industrial dairy farms (1.3 kg N vs 1.0 kg N per kg N in FPCM) due to poor manure management. Ammonia emissions (54%) in mixed dairy smallholdings were higher than the average level of dairy production in China (33%)[3]. In conclusion, manure direct discharge in industrial dairy farms should be avoided, while mixed dairy smallholdings should implement whole manure chain management such as optimizing manure collection and covering storage to reduce $NH_3$ emissions[20].

## 4.3 Uncertainties

The model uncertainties are due mainly to activity data and emission factors. To ensure the accuracy of activity, a balance of different animal types, growth stages, and breeding days was used to calculate solid manures and liquid manures here. The nutrient flows were calculated by nutrient balance and the results were close to real values. We calculated the coefficient of variation (CV) and found that the CVs of nutrient use efficiency and nutrient losses was usually $< 15\%$, thus there was uncertainty in the sample sizes but this would have little impact on the conclusions[35]. The $NH_3$, $N_2O$, $N_2$, and $NO_3^-$ emission factors in housing, storage, and treatment were collected from the published literature. Sensitivity analysis was conducted to determine how changes in emission factors would impact N losses (Fig. 5). Changes in emission factors had little effect on N losses and impacts were controlled within 3%. This study considered only the N and P flows in the crop-livestock production systems and did not estimate nutrient flows in feed production or manure sold. Industrial farms need longer transportation services than mixed smallholdings and environmental footprints (e.g., GHG) and expanding systems should be considered in the future. It would also be useful to analyze nutrient exchanges between industrial livestock farms and industrial crop farms at the district level.

## 5 CONCLUSIONS

This study emphasizes differences in nutrient flows and nutrient use efficiency between industrial farms and mixed smallholders based on the NUFER-farm model.

Feed DM in industrial farms was derived from outside the province and manures were applied within the province, resulting in nutrient surpluses at the district level. In mixed smallholdings, feed DM from household cropland in pig and dairy production was 4% and 9.6%, only 4.8% and 9.3% of the manure DM returned to the household cropland. For products, the percentages of N and P from animal products were 71% and 64% on dairy farms and 74% and 95% on pig farms, respectively. Thus, crop production and livestock production do not match in mixed smallholdings and the degree of integration in crop-livestock systems is insufficient.

NUE and PUE were higher in industrial farms than in mixed smallholdings at animal, herd, and system levels. To produce 1 kg N and P in animal products, N and P losses in industrial pig farms (2.0 kg N and 1.3 kg P) were lower than in mixed pig smallholdings (2.5 kg N and 1.6 kg P). Nutrient losses showed minor differences between industrial dairy farms and mixed dairy smallholdings. Direct discharge of manures was higher in industrial farms than in mixed smallholdings. The findings of this study suggest that district feed production can reduce the N and P surpluses at the district scale. For mixed smallholdings, they should first focus on reducing the feed-to-meat ratio and improving animal performance. Regarding manure management, covering and acidifying manures during storage can reduce $NH_3$ emissions. Industrial farms need to focus on improving the management of liquid manures and recycling of manures to district specialized crop farms. Environmental losses at the district level can be reduced by improving manure management and increasing district integration of crop and livestock production.

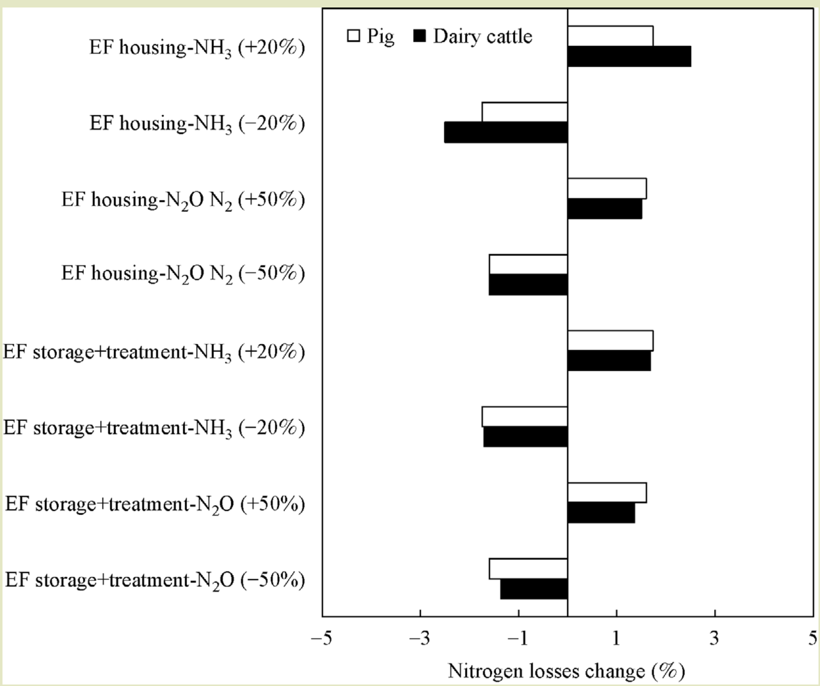



**Fig. 5** Impact of changes in emission factor on nitrogen losses in pig and dairy cattle production systems.

**Acknowledgements**

This study was funded by the National Natural Science Foundation of China (31772393), the National Key Research and Development Program of China (2016YFD0200401), and the National Key Research and Development Program of China funded by the Ministry of Science and Technology of the People's Republic of China (2016YFE0103100). The results and conclusions are those solely of the authors.

**Compliance with ethical guidelines**

Yifei Ma, Ling Zhang, Zhaohai Bai, Rongfeng Jiang, Yong Hou, and Lin Ma declare that they have no conflicts of interest or financial conflicts to disclose. All applicable institutional and national guidelines for the care and use of animals were followed.

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