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Effective application of mass balance method: case of organic fertiliser produced from pig slurry

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Abstract. The study aimed to verify the applicability of the mass balance method in calculating quantity and quality of an organic fertiliser produced from unseparated pig slurry in a pig-fattening complex in the Leningrad Region. The amount of manure at ex-animal level and its nutrient content, required for further calculations of ex-housing manure and resulting organic fertiliser at ex-storage, were calculated by applied diets and feed DM digestibility. Calculated values were compared with the norms from relevant Russian regulatory documents. The regulatory values of manure nitrogen were 22% smaller than the calculated ones. On the contrary, the standard values of manure phosphorus and potassium exceeded the calculated ones by 72% and 73%, respectively. The nutrient content of the organic fertiliser was calculated by the farm data on pig housing and slurry processing systems. The values calculated by the mass balance method were compared with those from the analysis reports issued by the certified laboratory. The difference did not exceed 20%: 11.2% for N, 13.3% for P, and 18.7% for K. This way, the mass balance method can be effectively used for calculating the characteristics of pig slurry-based organic fertiliser. On the contrary, the data from the current regulatory manure management documents showed the low reliability in the part of the physicochemical properties of fattening pig manure. These documents do not take into account the changes in the fattening pig diets with modern special concentrated feeds, which have a major effect on the manure nutrient content.

Key words: mass balance method, nutrient content, organic fertiliser, pig-rearing complex, slurry.

INTRODUCTION

Currently, the pig industry in the Russian Federation demonstrates active development - the operating complexes increase the pig stock and new complexes are constructed in some regions (Bondarenko & Miroshnikova, 2012; Lachuga et al., 2019). At the same time, the industry's intensification leads to a stronger anthropogenic load to the environment (Lenerts et al., 2019; Castrillón et al., 2020). In this sector, only specialised large-scale enterprises can bring competitive products to the market. However, slurry utilisation systems of such enterprises are the main environmental challenge (Zarebska, et al., 2014; De Vrieze et al., 2018; Molinuevo-Salces et al., 2020). Understanding the pressure of these systems on the nearby territories requires the aggregated estimates of the amount and nutrient content of organic fertilisers produced from the pig slurry (Paura & Jonkus, 2016; Grausa et al., 2020). The quantity and quality of organic fertilisers have a direct correlation with pig diets, housing systems, and slurry removal and processing techniques (Bittman et al., 2014; Shalavina & Vasilev, 2015; BAT reference book, 2017; Santonja et al., 2017; Jansons et al., 2020). The quantity of the organic fertiliser after the storage period and the total nitrogen, phosphorus and potassium content may be calculated by the relevant source data from the selected pig farms (Bewick, 1980; Poulsen & Kristensen, 1997; Luostarinen et al., 2018). The known nutrient content in the organic fertiliser, in turn, allows adjusting its application rates and the farm land area required.

The purpose of the study was to calculate the quantity and total nitrogen, phosphorus and potassium content of the pig slurry-based organic fertiliser after the storage period for a selected pig-rearing complex and to compare the data obtained with the values from the laboratory analysis reports and regulatory documents.

In case the calculation method proves applicable and accurate, it may be used for an aggregated estimation of the nutrient content of organic fertilisers produced at the district level and further assessment of relevant environmental risks to search for better mitigation solutions.

MATERIALS AND METHODS

The first study step was to collect the relevant information associated with the selected pig-rearing complex:

– the diets (dry matter content and digestibility, %; ash, total crude protein, phosphorus and potassium content, %);

– specialisation of the complex;

– characteristics of the pig housing system (number of pigs, head; duration of particular fattening period, days; initial body weight, kg; final body weight, kg);

– technique of slurry removal from the pig house;

– slurry processing technology into an organic fertiliser.

The second study step was to calculate the target indicators by the mass balance method (Luostarinen et al., 2017; Kaasik et al., 2019). This method was already tested in our studies on the cattle manure-based organic fertiliser (Shalavina et al., 2018; Briukhanov et al., 2020).

Regularly, these indicators are calculated by the source data from livestock farms for relevant animal categories. In our case, the pig-rearing complex had only one animal category - fattening pigs.

1. Quantity of manure ex-animal (M_E), kg day^{-1}/animal. The calculation was made for each diet used on the complex separately.

$$\mathrm{M}_E = (\mathrm{M}_{F1} - \mathrm{M}_{F2}) \cdot \frac{100}{100 - MC_F} + (\mathrm{M}_{F1} - \mathrm{M}_{F2}) \cdot \frac{100}{100 - MC_F} \cdot \frac{1}{\mathrm{K}} \quad (1)$$

where M_{F1} – quantity of feed dry matter supplied with the diet per animal, kg day^{-1}; M_{F2} – quantity of digested feed dry matter supplied with the diet per animal, kg day^{-1}; MC_F – feces moisture content, %; K – conversion coefficient of feces quantity to urine quantity, dimensionless.

2. Quantity of manure at ex-animal level of all animals, who received the same diet M_{Ei}, kg day^{-1}

$$M_{Ei} = M_E \cdot A_i \quad (2)$$

where A_i – number of animals on the pig-rearing complex, who received the same diet; i – diet identification number.

3. Quantity of manure at ex-animal level of all the animals on the pig-rearing complex $M_{E-compl}$, kg day^{-1}

$$M_{E-compl} = \sum_{i=1}^{n} M_{Ei} \quad (3)$$

where n – the number of diets used on the pig-rearing complex.

4. Average quantity of manure at ex-animal level per pig, $M_{E-average}$ kg day^{-1}

$$M_{E-average} = \frac{M_{E-compl}}{\sum_{i=1}^{n} A_i} \quad (4)$$

5. Total nitrogen quantity of manure at ex-animal level per pig, N_E g day^{-1}. The calculation was made for each diet used on the complex separately.

$$N_E = N_{FEED} - N_{ANIMAL} \quad (5)$$

where N_{FEED} – total nitrogen quantity in the feed supplied with the diet per pig, g day^{-1}; N_{ANIMAL} – nitrogen deposition to animal body, g day^{-1}

6. Total nitrogen quantity of manure at ex-animal level of all animals, who received the same diet N_{Ei}, g day^{-1}

$$N_{Ei} = N_E \cdot A_i \quad (6)$$

7. Total nitrogen quantity of manure at ex-animal level of all animals on the pig-rearing complex $N_{E-compl}$, g day^{-1}

$$N_{E-compl} = \sum_{i=1}^{n} N_{Ei} \quad (7)$$

8. The average total nitrogen quantity of manure at ex-animal level per pig $N_{E-average}$, g day^{-1}

$$N_{E-average} = \frac{N_{E-compl}}{\sum_{i=1}^{n} A_i} \quad (8)$$

The quantity of total phosphorus and potassium in the manure at ex-animal level are calculated in the same way as the total nitrogen by formula (5). The average quantity of total phosphorus and potassium in the manure at ex-animal level are calculated in the same way as the total nitrogen by formula (8).

Table 1 presents the default values for calculating the nutrient content in the manure at ex-animal level. As the pig-rearing complex under consideration had fattening pigs only, the data in Table 1 concerns only this animal category.

Table 1. Default values used in the calculations

Animal category	Indicator		Unit	Value
Fattening pigs	Weight gain	N	g kg^{-1}	29.6
		P		5.5
		K		2.2
	Digestibility	N	%	81
		P		55
		K		70

9. Quantity of manure (slurry) at ex-housing level ($M_{S\text{-}complex}$) at the exit from all pig houses on the pig-rearing complex, kg day^{-1}

$$M_{S-complex} = \mathrm{M}_{E-complex} + \mathrm{M}_{B-complex} + \mathrm{M}_{W-complex} - \mathrm{M}_{loss-complex} \quad (9)$$

where M_B – quantity of bedding material in all pig houses on the complex, kg day^{-1}; M_W – quantity of process water getting into the slurry in all pig houses on the complex, kg day^{-1}; M_{loss} – loss of the quantity of slurry on the whole pig-rearing complex, kg day^{-1}.

10. Average quantity of manure (slurry) at ex-housing level ($M_{S\text{-}average}$) at the exit from all pig houses on the complex $M_{S-average}$, kg day^{-1}

$$M_{S-average} = \frac{M_{S-complex}}{\sum_{i=1}^{n} A_i} \quad (10)$$

11. Quantity of total nitrogen in the ex-housing slurry in all pig houses on the complex $N_{S-complex}$, g day^{-1}

$$N_{S-complex} = N_{E-complex} + N_{B-complex} - N_{S\_loss-complex} \quad (11)$$

where $N_{B-complex}$ – quantity of total nitrogen in the bedding material in all pig houses on the complex, g day^{-1}; $N_{S\_loss-complex}$ – total nitrogen loss at ex-housing level from all pig houses on the complex, g day^{-1}.

12. Average quantity of total nitrogen in the ex-housing slurry per animal $N_{S-average}$, g day^{-1}

$$N_{S-average} = \frac{N_{S-complex}}{\sum_{i=1}^{n} A_i} \quad (12)$$

Average quantities of total phosphorus and potassium in the ex-housing slurry per animal were calculated in the same way as the total nitrogen by formula (12).

13. Quantity of manure at ex-storage level M_{OF}, kg day^{-1}

$$M_{OF} = M_{S-complex} \cdot \frac{100 - \mathrm{M}_{loss-storing}}{100} \quad (13)$$

where $\mathrm{M}_{loss-storing}$ – loss of slurry quantity during its processing into an organic fertiliser by long-term storing (maturing), %.

14. Quantity of total nitrogen in the manure after storing period N_{OF}, g day^{-1}

$$N_{OF} = N_{S-average} \cdot \frac{100 - N_{loss-storing}}{100} \quad (14)$$

where $N_{loss-storing}$ – loss of total nitrogen during the slurry processing into an organic fertiliser by long-term storing (maturing), %.

15. Total nitrogen content in the manure at ex-storage level $N_{OF\_content}$, %

$$N_{OF\_content} = \frac{N_{OF}}{M_{OF}} \cdot \frac{1}{10} \quad (15)$$

The total phosphorus and potassium content was calculated in the same way as the total nitrogen by formula (15).

The third study step was the comparison of the calculated data with the data

– from the regulatory documents governing the manure management (RD-APK 1.10.15.02-17, 2017; RD-APK 3.10.15.01-17, 2017) in terms of the average quantity of manure per animal, the average quantity of total nitrogen, phosphorus and potassium in the manure per animal,

– from the laboratory analysis reports in terms of total nitrogen, phosphorus and potassium content in the resulting manure at the ex-storage level. These are average values for multiple samples, which were collected in three replications in spring, summer and winter. The manure samples were analysed by a third-party accredited laboratory, with the reports being provided by the pig-rearing complex.

All calculations were performed in *Excel*.

RESULTS AND DISCUSSION

At the first study step the information was collected from the pig-rearing complex located in the Luzhskij District of the Leningrad Region.

The selected pig-rearing complex specialises in pig fattening. The overall animal stock at the time of the survey was 19,165 head. The initial body weight of piglets was 33–35 kg at the age of 75–77 days. The mean weight of the animals was 34 ± 0.6 kg. The final body weight of pigs was 115–117 kg. The fattening period lasted for 103 days. The mean final body weight was 116 ± 0.6 kg.

During this period the animals were housed in group pens on partly slatted floor without bedding. The housing conditions were in line with the general animal welfare requirements.

The slurry was removed by a gravity flow system of batched type and processed into an organic fertiliser by 12 months' storing (maturing) in the uncovered water-proof storage facilities.

At the second study step, the quantitative and qualitative characteristics of manure at ex-housing and ex-storage level were calculated.

The calculation of quantity of manure at ex-animal level and its total nitrogen, phosphorus and potassium content based on chemical composition of feeds applied on the complex (Table 2).

Table 2. Characteristics of feeds applied on the pig-rearing complex

Complete feed, target use	Dry matter (%)	DM digestibility, (%)	Ash content (%)	Crude protein (%)	Total phosphorus (%)	Total potassium (%)
SK-5 -39676/839 – pig fattening, 1st period	88.5	82.0	4.5	16.8	0.5	0.6
SK-7-39677/840 – pig fattening, 2nd period	88.3	78.0	4.4	15.1	0.5	0.6

Table 3. Calculation results of the qualitative and quantitative characteristics of fattening pig excrement (Ex-animal level) and organic fertiliser (Ex-storage level)

Indicator	Unit	Value
Ex-animal level		
Average excrement quantity per animal	kg day^{-1}	7.1
Average quantity of total nitrogen in excrement per animal	g day^{-1}	54.5
Average quantity of total phosphorus in excrement per animal	g day^{-1}	3.4
Average quantity of total potassium in excrement per animal	g day^{-1}	4.5
Ex-storage level		
Average quantity of organic fertiliser per animal	kg day^{-1}	8.6
Total nitrogen content in organic fertiliser	%	0.48
Total phosphorus content in organic fertiliser	%	0.052
Total potassium content in organic fertiliser	%	0.065

Table 3 shows the amount and chemical composition of manure at ex-animal, and ex-storage level. Moisture (technological and rainwater) and nutrient additions (bedding) and losses (dry matter decomposition, moisture evaporation and nitrogen volatilization) are also considered.

Fig. 1 shows the comparison of the calculated manure data to the regulatory data.

As can be seen from Fig. 1, the regulatory data on the total nitrogen content in fattening pig manure at Ex-animal level are below the calculated data by 22%. At the same time, the regulatory data on the total phosphorus and potassium content exceed the calculated data by 72% and 73%, correspondingly. These differences indicate that calculation results based on the regulatory data may not comply with the real state of things.

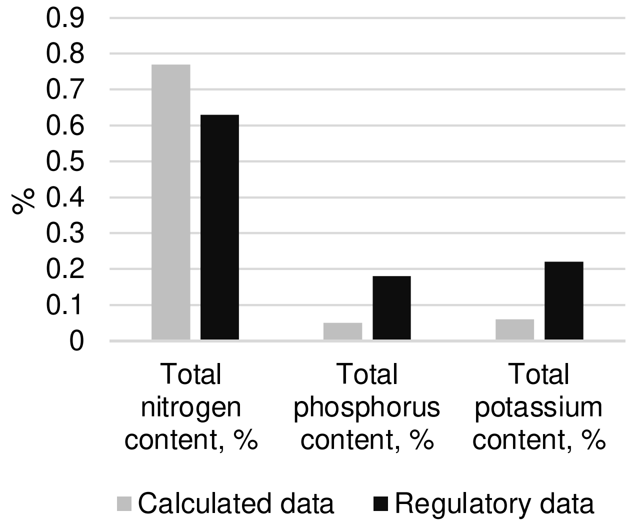

Figure 1. Total nitrogen, phosphorus and potassium content in the pig manure Ex-animal level.

Currently, animal diets are changing, concentrated feeds and different feed additives (synthetic amino acids, phytase) are used to improve the animal performance. These changes in feeds influence the quantity of pig manure and its nutrient content. The calculated data (ex-animal level) on the average manure quantity per animal exceed the regulatory data by 15% that is 7.1 kg day^{-1}versus 6 kg day^{-1}.

Fig. 2 shows the comparison of the calculated ex-storage manure data and the data from laboratory analysis reports.

As can be seen from Fig. 2 the difference between the calculated data and the data from the laboratory analysis reports does not exceed 20% - 11.2% for total nitrogen, 13.3% for total phosphorus, and 18.7% for total potassium. This may be explained by the inaccuracy of sampling procedure and sample analysis and the heterogeneity of the pig manure at ex-storage level.

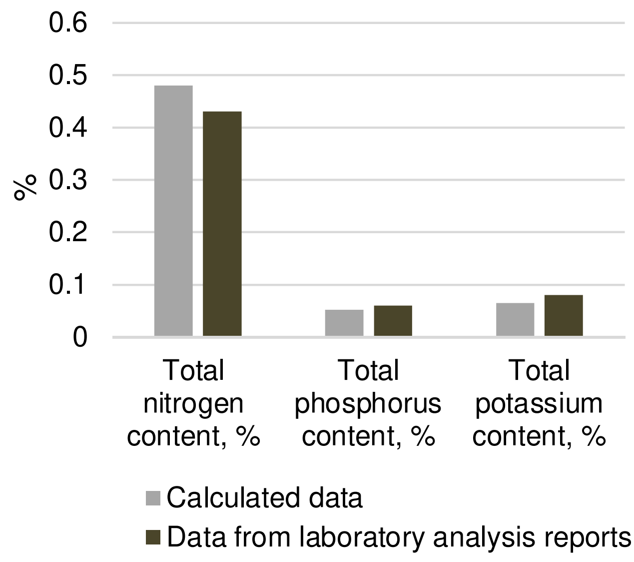

Figure 2. Total nitrogen, phosphorus and potassium content in the organic fertiliser (ex-storage manure).

The study findings indicate that the mass balance method, which was tested on unseparated pig slurry, is generally applicable for calculating the quantity and quality of organic fertilisers. However, for the fattening pig manure (Ex-animal level), the difference in total nitrogen, phosphorus and potassium content between the calculated data and the values from the regulatory documents may be up to 73%.

This difference may be explained by the introduction of concentrated feeds and different feed additives in the animal diets that are not considered in the current regulatory documents.

The calculated and experimental data from the study associated with characteristics of organic fertilisers were found to be in line with the values obtained by other researchers (Hatfield et al., 1998; Database, 2019). In particular, in the organic fertiliser produced from unseparated pig slurry in the United States the range of total nitrogen content was 0.4–0.7% and the phosphorus range was 0.05–2%. These values were obtained with the pig slurry processing technology much similar to that applied in the pig-rearing complex considered in our study, namely long-term slurry storing (maturing) in a storage. In our calculations, the total nitrogen content was 0.48% and the phosphorus content was 0.052%. In our opinion, this fact proves the validity of our calculation results.

CONCLUSIONS

The calculation of the quantity and quality of organic fertilisers produced from unseparated pig slurry by the mass balance method was tested on the example of a pig-rearing complex specialising in pig fattening.

Comparing the data on the organic fertiliser (Ex-storage level) showed that the difference between the calculated data and the data from the laboratory analysis reports in terms of total nitrogen, phosphorus and potassium content did not exceed 20% - 11.2% for total nitrogen, 13.3% for total phosphorus and 18.7% for total potassium. These differences can be explained by the sampling and analytical error, and by the heterogeneity of the organic fertiliser.

Comparing the data on the fattening pig manure ex-animal showed that the regulatory values related to the total nitrogen content were 22% smaller than the calculated ones. On the contrary, the regulatory values related to total phosphorus and potassium content exceeded the calculated ones by 72% and 73%, correspondingly.

This means that the values from the regulatory documents are hardly applicable for calculating the quantitative and qualitative characteristics of organic fertiliser produced from the pig slurry on the pig-rearing complex. This is because the current regulatory documents do not take into consideration the modern special concentrated feeds used for pig fattening, which have a major effect on the quantity and, especially, nutrient content of animal manure. However, additional research is needed on other types of pig complexes – multiplication farms and full-cycle farms.

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