BEHAVIOUR OF ACIDITY, TOTAL NITROGEN AND TOTAL PHOSPHORUS IN FERMENTED SOLID ORGANIC WASTE FROM PIG-REARING COMPLEX

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Abstract. The research aim was to establish the mathematical dependencies between the acidity, total nitrogen content, and total phosphorus content in the starting mixture and resulting organic fertiliser and the fermentation time of the organic waste from the pig-rearing complex. The starting mixture consisted of the solid fraction of pig slurry coming from the screw separator, the solid fraction of pig slurry coming from the decanter centrifuge and the grain mechanical cleaning waste. The fermentation of the mixture into an organic fertiliser lasted for seven days. The fermenter operating mode included the aeration time of 5 $\text{min}\cdot\text{h}^{-1}$, air supply rate of 10 $\text{m}\cdot\text{s}^{-1}$, and the drum rotation interval – every 12 hours. The samples of the processed mixture were taken every day to determine the acidity, total nitrogen and total phosphorus content. The average pH of the processed mixture during the experiment increased by 5 % – from 8.8 to 9.2, uniformly by 1 % per day average. The total phosphorus content in the resulting organic fertiliser was 11 % higher than that in the starting mixture – 3863.3 $\text{mg}\cdot\text{kg}^{-1}$ against 3506.3 $\text{mg}\cdot\text{kg}^{-1}$. During fermentation, the total phosphorus content in the processed mixture increased uniformly, in proportion to the mixture mass and moisture content decrease. The average total nitrogen content in the resulting organic fertiliser was 28 % higher than that in the starting mixture – 7840.7 $\text{mg}\cdot\text{kg}^{-1}$ against 6128 $\text{mg}\cdot\text{kg}^{-1}$. During fermentation, the total nitrogen content in the processed mixture increased uniformly by 4 % per day average. Thus, the solid organic fertiliser with higher nutrient content against the starting mixture was produced in seven days. The general conclusion is that the established mathematical dependencies allow forecasting and controlling the fermentation process aimed to obtain products with tailored properties.

Keywords: pig rearing complex, slurry, nutrients, organic fertiliser, fermentation.

Introduction

Currently, the country pursues the policy of intensifying its farming and this affects the sustainability of the natural environment. Consequently, there is a growing need for developing uniform approaches to identifying the impact on all environment components and for creating the most efficient machine-based farming technologies. As of 2018, out of 581.2 million tons of organic livestock waste produced in Russia, no more than 242 million tons were processed and used in compliance with environmental regulations. Nutrient loss due to inefficient use of organic waste amounted to 2.2 million $\text{t}\cdot\text{year}^{-1}$ of nitrogen and 0.36 million $\text{t}\cdot\text{year}^{-1}$ of phosphorus. The total environmental and economic damage exceeded 140 billion $\text{roubles}\cdot\text{year}^{-1}$ [1]. A survey of currently applied farming technologies, machines and equipment revealed the “hot” technological operations, which required smart and environment-oriented practices in the first place. Processing of organic waste from pig-breeding complexes into a high-quality organic fertiliser is one of such operations [2].

An additional point is that the organic waste from pig-breeding complexes may contain a large number of pathogenic microorganisms besides the nutrients. Therefore, its processing mode should ensure both nutrient conservation and elimination of pathogens [3]. The process modelling is of great importance in this context. It was performed for different types of raw materials, poultry manure included [4-5]. The models related to pig-breeding waste will gain a better understanding of the mixture state during its processing.

Analysis of relevant technological solutions proved the accelerated processing, fermentation in drum-type units, in particular, to be a promising technique in this respect [6-8].

Agricultural production generates a significant amount of waste. The processing of waste by fermentation results in a high-quality organic fertiliser within short timeframes. This practice shows a good promise, as the installations do not have direct contact with the environment and therefore do not feature the adverse environmental impact.

The study focused on the fermentation process of organic waste generated on a pig-breeding complex and obtained the values of acidity, total nitrogen and phosphorus content in the fermented mixture. They became the basis for deriving the mathematical dependencies, which would help achieve the required relevant indicators in the resulting organic fertiliser depending on the fermentation time.

The statistical mathematical dependencies were obtained by Microsoft Excel and Statgraphics Centurion software packages.

Materials and methods

The experimental research methodology was elaborated in IEEP – branch of FSAC VIM in cooperation with the specialists of the pilot pig-rearing complex. The complex was located in the North-western Federal District of the Russian Federation and had the overall animal stock above 101 thousand head. This methodology allowed justifying the optimal operating modes of closed installations for accelerated fermentation of multicomponent organic waste with the resulting exportable solid organic fertilisers [9].

The experiments were conducted in the IEEP – branch of FSAC VIM from February to June 2019. The initial organic waste mixture from the pig-rearing complex included 60 % of the solid fraction of pig slurry coming from a screw separator, 32 % of the solid fraction of pig slurry coming from a decanter centrifuge, and 8 % of the grain mechanical cleaning waste. Such a composition demonstrated the ability of self-heating and maintaining the required temperature [9].

According to the previous studies, when the fermented mixture had the recommended physical and chemical parameters, such as 65 % to 70 % moisture content, 400 $kg \cdot m^{-3}$ to 600 $kg \cdot m^{-3}$ density, and C/N ratio of (15-30)/1, the fermentation process proceeded with high intensity, ensuring complete processing and guaranteed disinfection of the material [9; 10]. At the first experiment stage, the initial components were mixed and loaded in the fermenter (Fig. 1).

Fig. 1. **Loading the initial mixture in the drum fermenter**

Fermentation, i.e. the mixture processing into an organic fertiliser, lasted for seven days. The optimization criterion was the fermentation temperature. The temperature threshold of + 55 ºC ensured complete processing and guaranteed disinfection of the organic waste.

The temperature inside the processed material was measured by a TCM 9410/M2 thermometer at six points once a day every 24 hours from the mixture loading. A dipstick temperature sensor measured the temperature of the mixture inside the fermenter through special holes. Fig. 2 shows the arrangement of measuring points.

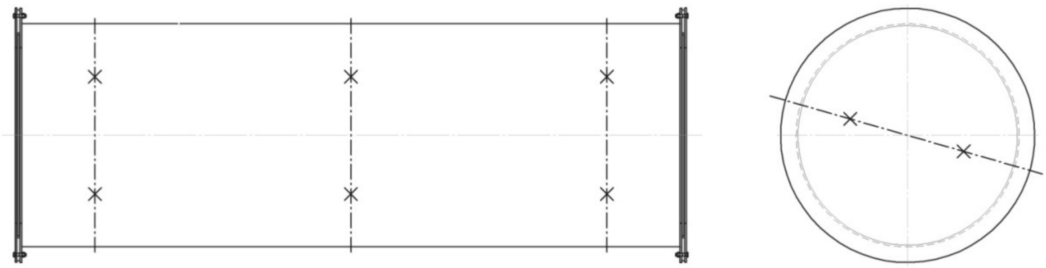

Fig. 2. **Arrangement of temperature measuring points in the fermenter**

The fermenter operating mode included the aeration frequency of 5 min·h^{-1}, the air supply rate of 10 m·s^{-1}, and the drum rotation interval – every 12 hours.

The aeration frequency and the drum rotation interval were set by a programmable TPU-2K timer. The air supply rate was measured by a TKA-PKM/60 device at the junction of the outdoor air duct and the perforated pipe.

The processed mixture samples were collected every day to determine pH, total phosphorus (P_{total}) and total nitrogen (N_{total}), mg·kg^{-1}, content. The samples were analysed in the Laboratory of Analytical Methods of Environmental Engineering of IEEP – branch of FSAC VIM, using the appropriate analytical equipment and in compliance with the relevant state standards [11-13].

These sampling and analysing methods associated with manure and organic fertilisers are consistent with generally accepted European ones [14-15].

The experiment had three replications. The experimental data were processed in *Microsoft Excel* and *Statgraphics Centurion* software packages.

The mean accuracy was determined by Student's t-test. The true value of the mathematical expectation with probability *P* was in the range

$$P\left[\bar{x} \pm t_V \cdot \frac{\sigma}{\sqrt{n}}\right] = 1 - \alpha \tag{1}$$

where $\bar{x}$ – mean value;
t_V – tabular value for Student's t-test (for probability of 0.9 the value is 2.92);
$1–\alpha$ – pre-chosen probability (for the fermentation process the value is 0.9);
n – number of array elements (for this experiment n = 3);
σ – mean-square deviation [16].

Results and discussion

The experiment started on 28 February 2019. Under the previously justified operating mode of the fermenter, the temperature rapidly increased – by the end of the first day the mixture warmed up from + 5.0 ºC to + 22.8 ºC. On the second day, the temperature of the mixture increased to + 48.5 ºC, and on the third day the threshold of + 55 ºC was overcome – the temperature of the mixture rose to + 58.2 ºC.

At the beginning of the experiment, the pH value in the loaded mixture averaged over three replications was 8.8; the total phosphorus content was 3506. mg·kg^{-1}; the total nitrogen content was 6128 mg·kg^{-1}, the moisture content was 68.7 %.

The obtained experimental pH data in the mixture and the results of their statistical analysis are presented in Table 1.

Table 1

Experimental pH data in the fermented mixture and the results of their statistical analysis

Fermentation stage	Average pH $\bar{x}$	Dispersion, *D*	$\bar{x}+\sigma$	$\bar{x}-\sigma$	Confidence interval for probability *P* = 0.9	
					Upper interval limit, *P*1	Lower interval limit, *P*2
Mixture loading into the fermenter	8.8	0.0025	8.85	8.75	8.9	8.7
Fermentation, day 1	8.7	0.0025	8.75	8.65	8.8	8.6
Fermentation, day 2	8.9	0.0025	8.95	8.85	9	8.8
Fermentation, day 3	8.9	0.0025	8.95	8.85	9	8.8
Fermentation, day 4	9	0.0025	9.05	8.95	9.1	8.9
Fermentation, day 5	9	0.0066	9.08	8.91	9.1	8.9
Fermentation, day 6	9.1	0.0025	9.15	9.05	9.2	9
Fermentation, day 7, mixture unloading	9.2	0.0025	9.25	9.15	9.3	9.1

The mathematical dependence of the average pH in the processed mixture on the fermentation time was obtained using the *Statgraphics Centurion* software package (Fig. 3). The correlation coefficient was 0.94, the determination coefficient was 89.4 %.

The mathematical dependence of the average pH in the processed mixture on the fermentation time is described by the following expression:

$$pH = 8.67 + 0.062 \cdot t \tag{2}$$

where pH – mixture acidity;
t – fermentation time, day.

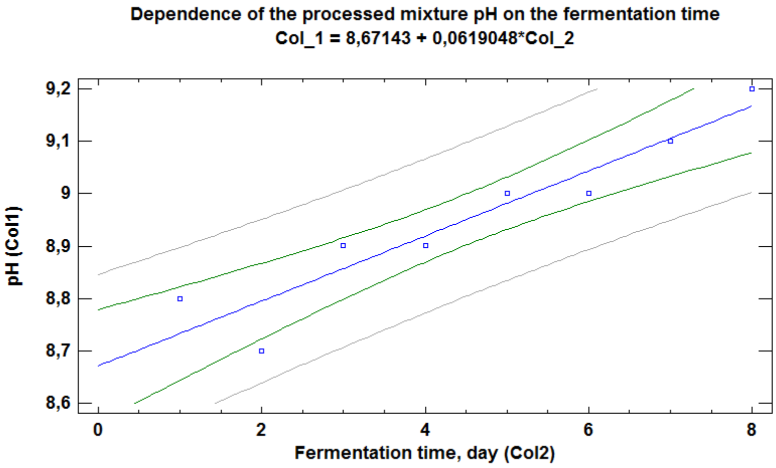

Fig. 3. **Dependence of the processed mixture pH on the fermentation time**

As shown by Fig. 4, the average pH in the processed mixture during the experiment increased by 5 % – from 8.8 to 9.2, uniformly by 1 % per day average.

The obtained experimental data on the total phosphorus content in the mixture and the results of their statistical analysis are presented in Table 2.

Table 2

Experimental data on the total phosphorus content in the fermented mixture and the results of their statistical analysis

Fermentation stage	Average total phosphorous $\bar{x}$, mg·kg^{-1}	Dispersion, D	$\bar{x}+\sigma$	$\bar{x}-\sigma$	Confidence interval for probability P = 0.9	
					Upper interval limit, $P1$	Lower interval limit, $P2$
Mixture loading into the fermenter	3506.3	7353.56	3592.05	3420.55	3651	3361.6
Fermentation, day 1	3550	1666.67	3590.82	3509.18	3618.9	3481.1
Fermentation, day 2	3576.7	2422.22	3625.92	3527.48	3659.8	3493.6
Fermentation, day 3	3640	2066.67	3685.46	3594.54	3716.7	3563.3
Fermentation, day 4	3738.3	505.56	3760.78	3715.82	3776.2	3700.4
Fermentation, day 5	3802	1234.67	3837.14	3766.86	3861.3	3742.7
Fermentation, day 6	3821.3	443.56	3842.36	3800.24	3856.8	3785.8
Fermentation, day 7, mixture unloading	3863.3	2022.22	3908.27	3818.33	3939.2	3787.4

The mathematical dependence of the total phosphorous content in the processed mixture on the fermentation time was obtained using the *Statgraphics Centurion* software package (Fig. 4). The correlation coefficient was 0.98, the determination coefficient was 97.6 %.

The mathematical dependence of the total phosphorous content in the processed mixture on the fermentation time is described by the following expression:

$$P_{total} = 3439.2 + 55.1 \cdot t \tag{3}$$

where P_{total} – total phosphorous content in the processed mixture, mg·kg^{-1}
t – fermentation time, day.

As shown by Fig. 4, the total phosphorous content in the resulting organic fertiliser was 11 % higher than that in the initial mixture: 3863.3 mg·kg^{-1} versus 3506.3 mg·kg^{-1}. During fermentation, the total phosphorous content increased uniformly in proportion to the decrease in the mixture mass and moisture content.

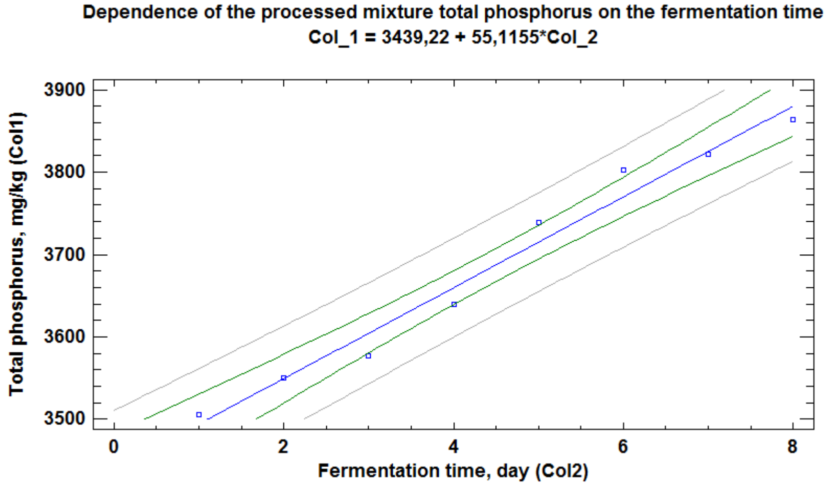

Fig. 4. **Dependence of the processed mixture total phosphorous on the fermentation time**

The obtained experimental data on the total nitrogen content in the mixture and the results of their statistical analysis are presented in Table 3.

Table 3

Experimental data on the total nitrogen content in the fermented mixture and the results of their statistical analysis

Fermentation stage	Average total nitrogen $\bar{x}$, mg·kg^{-1}	Dispersion, D	$\bar{x}+\sigma$	$\bar{x}-\sigma$	Confidence interval for probability P = 0.9	
					Upper interval limit, $P1$	Lower interval limit, $P2$
Mixture loading into the fermenter	6128	8.67	6130,94	6125.06	6133	6123
Fermentation, day 1	6156.7	1355.56	6193.52	6119.88	6218.8	6094.6
Fermentation, day 2	6743.3	1755.56	6785.2	6701.4	6814	6672.6
Fermentation, day 3	7114	6528.67	7194.8	7033.2	7250.4	6977.6
Fermentation, day 4	7276.3	84,22	7285.48	7267.12	7291.8	7260.8
Fermentation, day 5	7306.7	54.22	7314.06	7299.34	7319.1	7294.3
Fermentation, day 6	7356	378	7375.44	7336.56	7388.8	7323.2
Fermentation, day 7, mixture unloading	7840.7	80.89	7849.69	7831.71	7855.9	7825.5

The mathematical dependence of the total nitrogen content in the processed mixture on the fermentation time was obtained using the *Statgraphics Centurion* software package (Fig. 5). The determination coefficient was 99.6 %, the correlation coefficient was 0.96 %.

The mathematical dependence of the total nitrogen content in the processed mixture on the fermentation time is described by the following expression:

$$N_{total} = 7004.9 - 1649.15 \cdot t + 905.9 \cdot t^2 - 157.6 \cdot t^3 + 8.9 \cdot t^4 \quad (4)$$

where N_{total} – total nitrogen content in the mixture, mg·kg^{-1}
t – fermentation time, day.

The coefficients in formula 4 were obtained using the Statgraphics Centurion software package. The experiment had three replications. All obtained values were taken into account during the simulation.

As shown by Fig. 5, the average total nitrogen content in the resulting organic fertiliser was 28 % higher than that in the initial mixture: 7840.7 mg·kg^{-1} against 6128 mg·kg^{-1}. During fermentation, the total nitrogen content in the processed mixture increased uniformly by 4 % per day average in proportion to the decrease in the mixture mass and humidity.

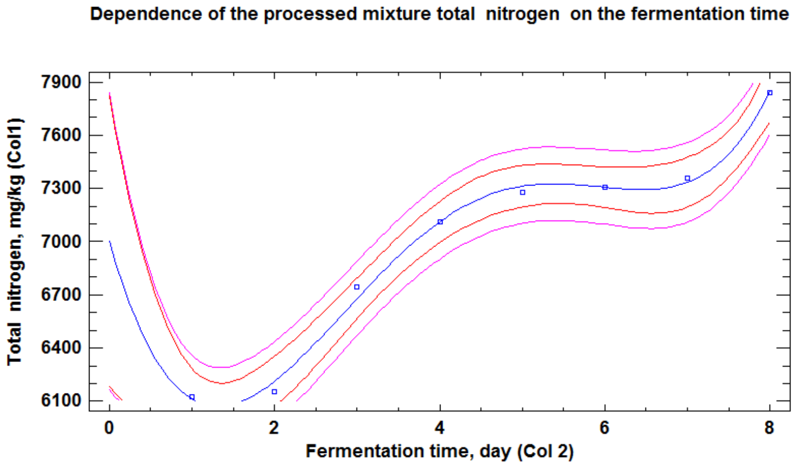

Fig. 5. **Dependence of the processed mixture total nitrogen on the fermentation time**

The mean value graphs for all dependencies were within the margin of error; therefore, the mean values and mathematical models developed on their basis might be regarded as reliable. The mean value graphs for all dependencies also fell within the range of standard deviations, therefore, the experimental data were reliable and no suspect data were available.

The investigations of international research teams associated with intensive aerobic fermentation of organic waste also revealed higher nutrient concentration in the resulting product with a decrease in the starting material mass [17-19]. Although the experiments used other types of organic waste from livestock breeding complexes, the nutrient behaviour patterns were much similar. Our study confirmed the established patterns and described in more detail the changes in the total nitrogen and phosphorus content during aerobic fermentation of the solid fraction of pig slurry.

Conclusions

1. Fermentation of organic waste from the pig-rearing complex located in the Northwestern Federal District of Russia was tested on the laboratory-scale equipment in IEEP - branch of FSAC VIM.
2. During the experiment, the following operating mode of the fermentation unit was applied: aeration frequency – 5 min·h^{-1}; air supply rate – 10 m·s^{-1}; drum rotation interval – every 12 hours. The optimization criterion was the mixture temperature; the controlled factors were the aeration frequency, air supply rate, and the drum rotation interval.
3. The average pH in the processed mixture during the experiment increased by 5 % – from 8.8 to 9.2, uniformly by 1 % per day average. The total phosphorus content in the resulting organic fertiliser was found to be 11 % higher than that in the initial mixture – 3863.3 mg·kg^{-1} against 3506.3 mg·kg^{-1}. During fermentation, the total phosphorus content in the processed mixture increased uniformly, in proportion to the decrease in the mixture mass and humidity. The average total nitrogen content in the resulting organic fertiliser was found to be 28 % higher than that in the initial mixture – 7840.7 mg·kg^{-1} against 6128 mg·kg^{-1}. During fermentation, the total nitrogen content in the processed mixture increased uniformly by 4 % per day average.
4. The experimental data were used to create the mathematical models describing the dependence of the acidity, total nitrogen and total phosphorus content in the processed mixture on the fermentation time. These models allow forecasting and controlling the fermentation process aimed to obtain the final product, an organic fertiliser, with tailored properties.

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