Efficiency of using biological filtering material for environmental support of accelerated waste processing

Ivan Krivolapov¹, Sergey Shcherbakov¹, Konstantin Manaenkov¹, Artemy Korotkov¹, Aleksey Aksyonovsky¹
¹Michurinsk State Agrarian University, Internationalnaya str., 101, Michurinsk, 393760, Russia
E-mail: ivan0068@bk.ru

Abstract. Based on the data obtained during the studies, the concentration of ammonia and hydrogen sulfide released during the accelerated processing of livestock waste was established. The design of an experimental setup for modeling the composting process using a biological air filtration system is presented. To ensure effective purification of air from ammonia and hydrogen sulfide generated during the accelerated processing of livestock waste, a method for using organic filter material consisting of compost and wood chips in various ratios is proposed. Also, the optimal time for cleaning air passing through the filter material has been established. The optimum type of filtering material and its characteristics have been experimentally established, ensuring the efficiency of air purification from hydrogen sulfide and ammonia by 97 and 98%, respectively.

1. Introduction
Nowadays, the development of the livestock industry and related enterprises of the processing complex is characterized by a significant localization of production in a small area. This contributes to an increased concentration of pollution, both in atmospheric air and in soil and ponds.

In the process of storage and processing, manure has a serious biological effect on ecosystems by forming significant microbial contamination, provides a significant environmental burden on the environment: air, groundwater, soil, etc., creates an additional burden on the enterprise personnel, worsens the indoor climate in terms of keeping animals, reducing their productivity, the smell from livestock farms, which can spread over distances of up to 8...10 km, exerts no less influence [1-3].

At present, accelerated composting is a promising way of livestock waste processing, the technological process of which is carried out continuously in special, thermally insulated bioenzymes of various shapes and designs [4]. This process proceeds with constant contact of the mixture with atmospheric oxygen due to its continuous or periodic supply to the bioenzyme.

As a result of microbiological processes during the storage and processing of livestock waste, a significant amount of ammonia, hydrogen sulfide, carbon dioxide and organic compounds are released into the air, which negatively affect the cardiovascular and central nervous system of a person. So, in the course of previous studies [3,5] in plants, as a result of biochemical decomposition of its components, leading to an increase in temperature in the mixture to 60 ... 65 °C, a significant amount of gases is formed containing hydrogen sulfide and ammonia, the concentration of which varies from 15 to 22 and from 70 to 115 mg/m³, respectively, which exceeds the maximum permissible levels from 2 to 5.5 times.
A possible way to solve the problem of air pollution in the process of accelerated processing of livestock waste is the use of microbiological treatment technology [6-10], based on the oxidation of gaseous contaminants by microorganism enzymes that use decomposition energy for their growth and development.

The aim of the research is to determine the effectiveness of using the biological filtration system of polluted air from ammonia and hydrogen sulfide released during accelerated processing of livestock waste.

2. Objects and methods
As an object of study, filtering material consisting of compost and wood chips is defined in various ratios: 3:7; 1:1, respectively, these ratios are determined based on the analysis of a number of works [1-3, 8-15].

The moisture content of each type of filter material was 40, 50 and 60%. The contact time of polluted air with the material changed from 6 to 10 s.

As an optimization criterion, the efficiency of air purification from ammonia and hydrogen sulfide was determined using well-known formulas:

\[
\eta_{NH_3} = \left(1 - \frac{C(NH_3)_{out}}{C(NH_3)_{in}}\right) \times 100\% \tag{1}
\]

\[
\eta_{H_2S} = \left(1 - \frac{C(H_2S)_{out}}{C(H_2S)_{in}}\right) \times 100\% \tag{2}
\]

where \(\eta_{NH_3}\) and \(\eta_{H_2S}\) are the purification efficiency for ammonia and hydrogen sulfide, respectively, %, \(C(NH_3)_{in}\), \(C(H_2S)_{in}\) is the concentration of the ammonia and hydrogen sulfide at the biofilter inlet, mg/m³, \(C(NH_3)_{out}\), \(C(H_2S)_{out}\) is concentration of ammonia and hydrogen sulfide at the biofilter exit, mg/m³.

To conduct experimental studies, the installation was designed (Figure 1).

Figure 1. Scheme (a) and general view (b) of a laboratory installation for studying the biological filtration process, where: 1 - thermally insulated container; 2 – straw-manure mix; 3 - aluminum duct; 4 - exhaust fan; 5 - fan control unit; 6 - biofilter; 7 - metal mesh; 8 – filtering material; 9 - vent pipes.

The installation worked as follows, straw-manure mixture 2 in the ratio of straw, manure 1:1 by weight, humidity 65...70%, volume 1 m³ previously brought to a temperature of 45...50 °C, was loaded into a thermally insulated container 1, height 1.6 m and a side length of 1 m, located on a metal mesh with 25 mm cells, at a height of 0.3 m from the floor surface. Above this capacity, through the use of polymer material, the collection of contaminated air was carried out, which entered the aluminum duct 3.
For the implementation of forced ventilation of the composted mixture and the movement of air to the surface of the filter material, an exhaust fan 4 was used.

Air, through the use of an exhaust fan, entered the housing of the biofilter 6, in which it was evenly distributed over the surface of the filter material 8.

The principle and operation control of the installation are presented in more detail in [3, 16].

Based on the conducted experimental studies, a matrix of a non-compositional plan of the second order was built, table 1.

**Table 1.** Matrix of the non-compositional plan of the second order with the results of experimental data.

| Experience No. | $x_0$ | $x_1$ | $x_2$ | $x_3$ | $x_1x_2$ | $x_1x_3$ | $x_2x_3$ | $x_1^2$ | $x_2^2$ | $x_3^2$ | $E_{ev, NH_3}$ | $E_{ev, H_2S}$ |
|----------------|-------|-------|-------|-------|----------|----------|----------|----------|----------|----------|--------------|--------------|
| 1              | +     | +     | +     | 0     | +        | 0        | +        | +        | 0        | 98.0     | 98.7         |              |
| 2              | +     | +     | -     | 0     | -        | 0        | +        | +        | 0        | 97.3     | 94.3         |              |
| 3              | +     | -     | +     | 0     |          | 0        |          |          | 0        | 98.0     | 92.1         |              |
| 4              | +     | -     | -     | 0     | +        | 0        |          |          | 0        | 94.9     | 90.2         |              |
| 5              | +     | 0     | 0     | 0     | 0        | 0        | 0        | 0        | 0        | 97.9     | 95.5         |              |
| 6              | +     | +     | 0     | +     | 0        | +        | 0        | +        | +        | 97.5     | 98.1         |              |
| 7              | +     | +     | 0     | -     |          | 0        |          |          | 0        | 88.9     | 82.3         |              |
| 8              | +     | -     | 0     | +     | 0        | -        | 0        | +        | 0        | 93.7     | 93.7         |              |
| 9              | +     | -     | 0     | -     | 0        | +        | 0        | +        | 0        | 87.1     | 80.1         |              |
| 10             | +     | 0     | 0     | 0     | 0        | 0        | 0        | 0        | 0        | 97.6     | 94.8         |              |
| 11             | +     | 0     | +     | 0     | +        | 0        | +        | 0        | +        | 96.9     | 98.9         |              |
| 12             | +     | 0     | -     | +     | 0        | 0        | -        | 0        | +        | 94.3     | 94.0         |              |
| 13             | +     | 0     | -     | -     | 0        | 0        | +        | 0        | +        | 85.9     | 81.4         |              |
| 14             | +     | 0     | -     | 0     | 0        | +        | 0        | +        | +        | 81.2     | 84.9         |              |
| 15             | +     | 0     | 0     | 0     | 0        | 0        | 0        | 0        | 0        | 98.1     | 96.0         |              |

The determination of standard deviations, Cochren criterion values, variance and standard deviations of the values of the regression coefficients, as well as the adequacy of the obtained mathematical models were determined using generally accepted formulas using the MathCAD software package.

The reproducibility of the experiment was determined by the Cochren criterion, the obtained values of the Cochren criterion, respectively, were:

- when cleaning air from ammonia $G_{cal}=0.124$
- when cleaning air from hydrogen sulfide $G_{cal}=0.108$

The table value of the Cochren criterion, at a significance level of $\alpha=0.05$, the number of experiments $N=15$ and the replications of experiments $k=3$, is $G_{tab}=0.198$, since the condition $G_{cal}\leq G_{tab}$ is fulfilled the experiment can be considered reproducible.

The obtained values of the regression coefficients were:

- when cleaning air from ammonia: $b_0=97.878. \ b_1=1.008. \ b_2=1.458. \ b_3=3.658. \ b_{12}=-0.583. \ b_{13}=0.467. \ b_{23}=-0.683. \ b_{11}=-0.547. \ b_{22}=-0.264. \ b_{33}=-5.514$
- when cleaning air from hydrogen sulfide: $b_0=95.433. \ b_1=2.167. \ b_2=1.821. \ b_3=7.013. \ b_{12}=0.600. \ b_{13}=0.567. \ b_{23}=0.392. \ b_{11}=-1.421. \ b_{22}=-0.179. \ b_{33}=-5.446.$
The arithmetic mean of the response and variance in the center of the plan were:
- when cleaning air from ammonia: \( \sigma_{\text{quE}}=97.878, \sigma_{\text{uE}}=0.063 \)
- when cleaning air from hydrogen sulfide: \( \sigma_{\text{quE}}=95.433, \sigma_{\text{uE}}=0.404 \)
- where \( \sigma_{\text{quE}} \) is the variance in the center plan
  \( \sigma_{\text{uE}} \) - the arithmetic mean of the response

The variances characterizing errors in determining the regression coefficients were:
- when cleaning air from ammonia:
  \( \sigma_{\text{uE}}(b_0)=0.144. \sigma_{\text{uE}}(b_i)=0.088. \sigma_{\text{uE}}(b_{ij})=0.125. \sigma_{\text{uE}}(b_{ii})=0.130 \)
- when cleaning air from hydrogen sulfide:
  \( \sigma_{\text{uE}}(b_0)=0.367. \sigma_{\text{uE}}(b_i)=0.225. \sigma_{\text{uE}}(b_{ij})=0.318. \sigma_{\text{uE}}(b_{ii})=0.331 \)

The table value of the Student criterion with a confidence probability of \( \alpha=0.05 \) and a degree of freedom \( f=2 \) is \( t_{0.05}^{0.05}=2.92 \). then the confidence intervals of the regression coefficients are
- when cleaning air from ammonia:
  \( \Delta b_{E0}=0.422. \Delta b_{Ei}=0.258. \Delta b_{Eij}=0.365. \Delta b_{Eii}=0.380 \)
- when cleaning air from hydrogen sulfide:
  \( \Delta b_{E0}=1.072. \Delta b_{Ei}=0.657. \Delta b_{Eij}=0.928. \Delta b_{Eii}=0.966 \)

When assessing the significance of the regression coefficients, by comparing the values of the regression coefficient and its confidence interval by inequality \( |b_i|\Delta b_i \), significant coefficients were determined during air purification.

Thus, the following regression equations were obtained
- regression equation for the efficiency of air purification from ammonia
  \[ y_{E}=97.878+1.008x_1+1.458x_2+3.658x_3-0.583x_1x_2+0.467x_1x_3-0.683x_2x_3-0.547x_1^2-5.514x_3^2 \]
- regression equation for air purification from hydrogen sulfide
  \[ y_{E}=95.433+2.167x_1+1.821x_2+7.013x_3-1.421x_1^2-5.446x_2^2 \]

In these equations, the factors are encoded; for their decoding, expressions 3-5 were used, as well as an auxiliary Table 2:

\[ b_i x_i = \frac{b_i}{\varepsilon_i} x_i - \frac{b_i}{\varepsilon_i} x_{0i}, \quad (3) \]
\[ b_{ij} x_i x_j = \frac{b_{ij}}{\varepsilon_i \varepsilon_j} (x_i x_j - x_i x_{0j} - x_i x_{0i} + x_{0i} x_{0j}), \quad (4) \]
\[ b_{ii} x_i^2 = \frac{b_i}{\varepsilon_i} x_i^2 - 2 \frac{b_i}{\varepsilon_i} x_i x_{0i} + \frac{b_i}{\varepsilon_i} x_{0i}^2, \quad (5) \]

where \( x_i \) is the coded value of the factor; \( X_i \) is the natural value of the factor, \( X_{0i} \) is the natural value of the factor at the zero level; \( \varepsilon \) is the natural value of the variation interval of the factor.

Table 2. Auxiliary table for decoding coefficients in regression equations.

| The encoded value of the indicator | The decoded value of the indicator |
|-----------------------------------|-----------------------------------|
| \( x_1 \)                      | 0.1W-5                          |
| \( x_2 \)                      | 0.1t-3                          |
| \( x_3 \)                      | 0.05M-2.5                       |
| \( x_1 x_2 \)                  | 0.05Wt-0.4W-2.5t+20             |
| \( x_1 x_3 \)                  | 0.005WM-0.25W-0.25M+12.5        |
Using these expressions and a table, we obtain regression equations of the form:

- Decoded regression equation for the efficiency of air purification from ammonia:
  \[ y_E = -0.00547W^2 - 0.014M^2 - 0.029Wt + 0.0023WM - 0.017Mt + 0.765W + 3.042t + 1.581M + 17.048 \]

- Decoded regression equation for the efficiency of air purification from hydrogen sulfide:
  \[ y_E = -0.014(W^2 + M^2) + 1.638W + 0.910t + 1.712M - 9.781 \]

The adequacy of the obtained regression equations was assessed using the Fisher test, taking into account the variance of the mathematical model adequacy:

\[ F_{cal} = \frac{\sigma_{ad}^2}{\sigma^2} \]  \hspace{1cm} (6)

The adequacy variance is calculated by the formula [17]:

\[ \sigma_{ad}^2 = \frac{S_R - S_E}{N - k' - (n_0 - 1)} \]  \hspace{1cm} (7)

where \( k' \) is the number of regression coefficients; \( S_R \) is the sum of the deviation squares of the calculated values from the experimental at all points of the plan; \( S_E \) is the sum of squares, determined by the results of the experiment in the center of the experiment:

\[ S_R = \sum (y_u - \bar{y}_u)^2 \]  \hspace{1cm} (8)

\[ S_E = \sum (y_{u0} - \bar{y}_0)^2 \]  \hspace{1cm} (9)

The calculated value of the Fisher test \( F_{cal} \), compared with the table value at a given significance level \( \alpha \), if the ratio \( F_{cal} \leq F_{tab} \) is satisfied, the regression model is recognized as adequate and can be used to predict the values of the dependent variable \( y \) for all values of the independent variable \( x \) within its observed values.

The obtained value of the Fisher test was:

- When cleaning air from ammonia \( F = 16.451 \)
- When cleaning air from hydrogen sulfide \( F = 2.450 \)

The table value of the Fisher criterion \( F_{tab} \) for the number of degrees of freedom \( v_1 = 2 \) and \( v_2 = 14 \) and 5% significance level is \( F_{tab} = 19.42 \) (Spiridonov A.A., 1981; Spirin N.A., 2004). Thus, the condition \( F_{cal} \leq F_{tab} \) is performed. Therefore, the resulting regression equations are adequate.

3. Results and discussion

In accordance with the obtained regression equations, the dependences of the biological air filtration efficiency \( E \) on the contact time \( t \) and the moisture content of the filter material \( W \) with different mass fractions of compost \( M \) were determined.

These dependencies are presented in Figures 2-4.
Figure 2. Dependence of the purification efficiency of ammonia (a) and hydrogen sulfide (b) on contact time and humidity during filtration with a material with a mass fraction of compost of 30%.
Figure 3. Dependence of the purification efficiency of ammonia (a) and hydrogen sulfide (b) on contact time and humidity during filtration with material with a mass fraction of compost of 50%
A study on the purification efficiency of ammonia (a) and hydrogen sulfide (b) during filtration with material containing compost. The mass fraction of compost has a significant effect on the cleaning efficiency. It has been established that for air purification from ammonia, it is most effective to use a filter material consisting of compost and wood chips in a ratio of 1:1, with a humidity of 50% at which the cleaning efficiency is 98...99% at a contact time of 10 s.

When cleaning air from hydrogen sulfide, the most effective filter material is compost and wood chips in a ratio of 7:3, with a humidity of 60% at which the cleaning efficiency reaches 99% with a
contact time of 10 s.

However, when using filter material consisting of compost and wood chips in a ratio of 1:1 with a humidity of 50% for air purification from hydrogen sulfide, the cleaning efficiency is 97...98%, while the pressure loss during air movement in this filter material is lower than in the material consisting of compost and wood chips in a ratio of 7:3.

Graphic dependences also show that with increasing humidity of the filtering material, the cleaning efficiency increases, while the humidity in the range of 50...55% is the most optimal.

Based on the obtained regression equations using the MathCAD software package, graphical dependencies of air purification from ammonia and hydrogen sulfide when they were filtered with a material consisting of compost and wood chips in a ratio of 1:1, humidity 50% were constructed, these dependencies are shown in Figure 5.

![Figure 5](image_url)

**Figure 5.** Response surfaces of the efficiency of air purification from ammonia (a) and hydrogen sulfide (b) using filtering material with a mass fraction of compost 50%.

Analysis of the graphical dependencies presented in these figures shows that the efficiency of air purification increases with increasing contact time of contaminated air with filter material and its humidity.

A further increase in humidity contributes to the formation of zones in which air does not enter, which leads to a decrease in cleaning efficiency.

4. **Conclusion**

The process of biological filtration of air contaminated during the accelerated processing of livestock waste was studied experimentally, during which it was found that in order to ensure an optimal filtration process, an adaptation phase is necessary, which is aimed at the formation of a certain type of microorganisms, this phase established during laboratory research is within 3...4 days, depending on the type and humidity of the filter material.

At the same time, it was found that the filtering material consisting of compost and wood chips in a ratio of 1:1, humidity 55%, in which polluted air is kept for 10 s, is optimal for biological treatment. The use of this material provides cleaning efficiency for ammonia at 98%, for hydrogen sulfide at 97%.

An increase in the mass fraction of compost to 70% increases the efficiency of air purification from hydrogen sulfide by 1% compared to the filtering material, in which the mass fraction of compost is 50%, at a similar humidity level, when cleaning from ammonia, an increase in the mass fraction of compost to 70% reduces the efficiency purification by 3% due to the formation of anaerobic zones. In addition, a high proportion of compost in the filter material leads to high pressure losses during air movement.
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