INVESTIGATION OF SUBSTRATE MIXING PROCESS IN ROTATING DRUM REACTOR
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ДОСЛІДЖЕННЯ ПРОЦЕСУ ЗМІШУВАННЯ КОМПОНЕНТІВ СУБСТРАТУ В ОБЕРТОВОМУ РЕАКТОРІ БАРАБАННОГО ТИПУ

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ABSTRACT

The results of the research on the influence of the drum type reactor design-technological parameters and the substrate`s physical-chemical parameters on the substrate`s components mixing evenness, that influence the quality of the received compost, are presented in this paper. By the method of the multifactor experiment rational values of the drum rotation speed, the blades (mounted on the inner drum surface) angle and the substrate`s moisture content are defined at which the components distribution homogeneity in the substrate reaches maximal value. The abovementioned, in turn, provides high compost quality by the agrichemical indices. The recommendations are given to pick the design parameters and operational modes of the drum type reactor.

РЕЗЮМЕ

Представлено результати дослідження впливу конструкційно-технологічних параметрів реактора барабанного типу і фізико-хімічних властивостей субстрату на рівномірність змішування компонентів у субстраті, що впливає на якість виробленого компосту. Методом проведення багатофакторного експерименту визначено раціональні значення частоти обертання барабану реактора, кута нахилу нерухомих лопатей, розташованих на внутрішній поверхні барабану, та вологості субстрату, при яких рівномірність розподілу компонентів в субстраті досягає максимальних значень. Зазначене, в свою чергу, забезпечує високу якість компостів за агрохімічними показниками. Наведені рекомендації щодо вибору конструктивних параметрів та режимів реактора барабанного типу.

INTRODUCTION

Widespread use of pesticides and fertilizers in agricultural production has provided a significant increase in crop yields. In Western Europe the yield of cereals has reached 5-6 t/ha due to the agrochemicals usage *(Fernández et al., 2010; Golub et al., 2017)*. However, the excessive fertilizer application and unbalanced plant nutrition constantly reduce the quality of crop products, and improper chemicals storage and usage leads to reduction of the natural soil fertility and its degradation, and as a result – to environmental pollution *(Golub et al., 2017)*. One way to improve soil fertility is to use organic fertilizers *(Toledo et al., 2020).*

Composting is one of the most important technological methods of high-quality organic fertilizers production. It is necessary to preserve nutrients in some fertilizers during their mineralization (manure, etc.) and to improve nutrients' accessibility in a more complex ones like peat, straw or other inert organic *(Geethamani et al., 2020).*

Although composting technologies have been developing intensively in the last few decades, the main obstacle of its wide application is its low efficiency because of how long it takes to produce it especially when composting in compost bins *(Liu et al., 2020).*

One of main methods of composting process intensification is a compost production in closed chambers *(Fahad et al., 2018; Liu et al., 2020).* Process intensification is reached by keeping optimal thermal conditions on each stage, use of aeration and development of rational parameters and modes of operation *(Jiang-Ming, 2017; Kalamdhad and Kazmi, 2008).*

Creating horizontal rotating drum reactors was a determinative step in the modernization and mechanization of composting in closed chambers *(Aboulam et al., 2006; Jain and Kalamdhad, 2018).* Inner reactor space often equipped with bulkheads, mixing shaft or welded scrapers *(Arora et al., 2018).* Process intensification is reached by the use of contraflow aeration that provides thermophilic bio-thermal composting mode *(Jain et al., 2019).* At such conditions and adequate thermal insulation the overall composting cycle can only take seven days *(Kalamdhad et al., 2008; Wang et al., 2016*). In reactors 200…300 litre big a periodic aeration is used, as a rule. It is done to provide even substrate saturation with the oxygen and to avoid the process from becoming anaerobic *(Kalamdhad et al., 2008*). Daily productivity of a single reactor is 20–50 t (*Kauser et al., 2020).* Nevertheless, use of the rotating reactors has some disadvantages. In some cases, this technology involves an extra stage of treatment in bins from several weeks to three months. Also, a high requirement is set for initial raw material, especially to agricultural biomass. The abovementioned leads to significant grow of investment in this technology which, in some cases, exceeds 5-10 times composting in compost bins *(Arora et al., 2018; Kalamdhad and Kazmi, 2008).*

In modern times creating and setting-up new technologies is narrowed to find optimal parameters of technological process and modes of correspondent equipment *(Liu et al., 2020).* Solving this type of problems requires a row of experiments since only practical experience gives possibility to objectively estimate process on any stage and is a basis for the creation of adequate mathematical models.

Papers *(Arora et al., 2018; Golub et al., 2019; Kauser et. al., 2020)* analysis indicates that reaching high evenness of component`s mixing is one of the methods of reaching the high quality of the end product.

Hence, it is actual the question of reactor design development and the optimal operational parameters definition, according to the physical-chemical substrate composition, at which the maximal mixing evenness and, as a consequence, high compost quality by the agrochemical indicators are reached.

MATERIALS AND METHODS

The goal of the work is to research the influence of the drum speed, the blades angle and the substrate`s moisture content on the substrate components distribution unevenness. In the same time, a requirement of agrichemical quality of compost should be maintained. To achieve this goal, the functional dependencies between factors of compost production should be found. Rational values of composting process which provide proper compost quality and minimal energy consumption should be defined.

To run experiments an experimental specimen of a drum type reactor was designed, which is shown in Figure 1. The reactor is designed for composting organic waste of agricultural origin.

a *b*

Fig. 1 – Experimental installation: *a* – general view of a drum type reactor; *b* – blades installation
1 – electric motor; 2 – gear; 3 – frame; 4 –bearing support; 5 – reactor; 6 – loading lid; 7 – axle; 8 – regulated stand; 9 – coupling; 10 – connector with inner threads; 11 – blades (pipes with jets unmounted)

The experimental installation consists of an air-tight drum type reactor *5*, that have a cylindrical shape and is installed horizontally on hollow axles *7*. The reactor *5* is equipped with the lid *6* for loading substrate and unloading treated compost. Thanks to the lid *6* the reactor *5* is easy to maintain, clean from residues, wash, etc. Loading the substrate and unloading the compost is done periodically, which is acceptable for an experimental installation.

Also, the lid *6* is equipped with a check valve set at *2* bar. To mix the substrate on an inner surface of the reactor *5* concave blades *11* and four longitudinally located tubes with jets for substrate aeration are fixed.

Axles *7* with bearings are installed in supports *4*. The axle where the electromechanical power train is connected by the coupler is blind; the other axle has a connector *10* with inner threads. A coupler *9* serves also for feeding air into reactor during its rotation. The drum type reactor *5* is actuated with the electromechanical power train that is mounted on a frame *3*. The electromechanical power train consists of a 3.5 kW electric motor *1*, a planetary gear *2* and a variable frequency drive (not shown) to adjust reactor RPM.

During reactor rotation, due to the combined action of its working units, substrate components experience mixing. The concave blades and four longitudinally located pipes with jets create contraflow particles movement that helps even distribution of components in the substrate.

To improve the substrate saturation with air, the mixing process is combined with the periodical forced aeration. The forced air supply into the reactor helps avoiding a negative phenomenon of anaerobic zones appearance, that is responsible for the nitrogen loses in the compost. Also, oxygen is necessary for the metabolism and breathing of the aerobic microorganisms and for the organic molecules' oxidation in a fermented substrate. At the beginning, the O_2 concentration in the pores is around 20% that corresponds to its normal concentration in the air. The same time the CO_2 concentration varies between 0.5…5%. With the rise of the microbiological activeness the O_2 concentration drops, and the CO_2 concentration – rises. When the O_2 concentration drops to 5% the anaerobic processes become prevalent. According to *(Rabinovich, 2006)* the air to substrate ratio is chosen as 4:1. The substrate mixing happens every 55 min and lasts for 5 min. The time between consequent aerations should be sufficient for the oxygen concentration to drop to 5…12%, in the thermophilic stage *(Kalamdhad et al., 2008)*. The air is supplied into the drum via the hollow axis by the compressor. Air supply is controlled. During the pumping, the bypass valve opens automatically so that the pressure inside the drum does not exceed 1.1 bars. In case if bypass valve is stuck, due to debris, and pressure rises, the relief valve is activated to drop pressure. After the mixing and aeration stopped the relief valve opens momentarily to equalize pressure inside the drum with the atmospheric one.

Stand *8* is regulated and that makes possible to change the height of reactor support. Such design provides changing reactor rotation axle tilt between 0…20 degrees from horizontal plane. The angle regulation is discrete with *5* degrees step. Due to this the substrate can be moved along the reactor that provides additional mixing during composting process. Overall net weight of an installation is 92 kg, reactor`s volume is 220 L.

At the beginning of experiments, to minimize thermal loses into the environment, a reactor was thermally insulated. Experimental installation was located in small room with minimal air flow. The room temperature was +18…+20°C, humidity was 40…60%, the wind speed was less than 0.1 m/s. When the reactor was not rotating the check valve was connected to the ventilation system.

For research, a substrate consisting of 50% of manure with chopped straw (moisture content 45%), 20% bird guano and 30% plant raw material (15% peat and 15% deciduous trees wood shavings). Research was done for the abovementioned substrate with three different moisture contents. The substrate moisture content had the following values W – 50%; 60% and 70%. The reactor *5* was filled with a substrate of abovementioned composition by 50%.

Temperature measurement during the experiment was only for reference to know what phase of fermentation was, and served as an indication of the end of the experiment. To measure the composted substrate temperature thermal probes TCP 1-8 was mounted on an inner surface of the reactor, which were providing temperature in different zones. Measurement results were averaged. Whereas the reactor was rotating the thermocouple connection and temperature measurements were done periodically. For the lag phase the temperature was between 18…20°C; for the mesophilic phase – 20…42°C; for the thermophilic phase – 42…65°C; for the maturation phase – the temperature was dropping to the ambient temperature. In general, on the thermophilic phase the maximal temperature did not exceed 65°C and varied between 62…64°C.

To provide substrate movement in longitudinal direction a reactor`s axle tilt changed periodically, setting the angle in a range from 0 to 10 degrees alternately.

A dependence of the coefficient of variation *k* of the control component`s distribution in the substrate on the substrate moisture content *W*, the reactor`s rotation speed *n* and blades angle α were researched.

To determine the connection between independent factors (*W, n,* α) and a dependent factor (*k*), to find a mathematical equation to describe this connection a multifactor experiment was done *(Golub et al., 2018; Melnikov et al., 1980)*.

At the beginning of experiment substrate moisture content was *W=50%.* The substrate moisture content was defined according to EN 14774-2:2009. Blades *11* on the inner surface of drum were fixed at angle α=15°. Whereas drum rotation speed was *n*=5 rpm. Experiments were repeated for drum rotation speeds *n*=10 rpm and *n*=15 rpm. Then, blades' angle was changed to α=27°, then to α=39° and experiments were repeated for the same rotation speeds. According to the plan of experiment, the investigations were repeated for substrates with moisture content *W=60%* and *W=70%.*

Red granules of the polyphenylsulphide 1.5 mm in diameter were taken as a controlled component for determination of mixing unevenness. Polyphenylsulphide granules' density was equal to a substrate density and was around 300–360 kg/m^3 depending on the substrate moisture content 50, 60 or 70 %. Controlled component distribution was defined from 42 samples, 50 gr each. Samplings were made in different points of the drum on each stage of composting. Samplings were made over equal time periods, namely every 6 hours. Samplings were made according to GOST 13496.0-80. Controlled component content in samples was determined according to GOST 21560.0.

The content of the nitrogen, potassium, phosphor, total carbon of the humus acids, ash and moisture were defined according to DSTU ISO 4176-2003, DSTU ISO 5310-2003, DSTU EN 15922:2015, DSTU 8454:2015, GOST 26714-85 and GOST 26713-85 respectively. Investigations were done in a certified laboratory of the educational-scientific centre of ecology and environmental protection of the Polissya National University.

As an indicator of mixing unevenness a coefficient of variation of controlled component actual distribution in samples (%) was taken. Measurements were done with 3% of controlled component in the total mass of material in the drum (*Golub et al., 2019*).

The coefficient of variation *k* of the control component's distribution was defined by calculating the:

$$k = \bar{l} \cdot 100\% / \bar{C}_m \tag{1}$$

where:

$\bar{l} = \sum_{i=1}^{n} \left| C_{mi} - \bar{C}_m \right| / n$ – is mean linear deviation of the control component concentration in samples;

C_{mi} – control component concentration in the i-th sample within each sampling session;

$\bar{C}_m$ – mean control component concentration, $C_m=3\%$.

Factors encoding: $X_1=W$, $X_2=n$, $X_3=\alpha$. Variation levels of factors are given in table 1.

Table 1

Variable factors and limits of their variation for definition of evenness of substrate components mixing

Factor variation level	Substrate moisture content *W*	Drum speed *n*	The blades angle α
	[%]	[rpm]	[degree]
Lower level (-)	50	5	15
Middle level (0)	60	10	27
Upper level (+)	70	15	39

To hold an experiment, a 5-level plan of second order was used. Experiments for plan realization were repeated tree times *(Golub et al., 2018; Melnikov et al., 1980).* The experimental plan included variation of three independent factors, which influence the unevenness of the mixing process.

Planning stage included the following steps: factor encoding, scheduling, randomization tests, implementation plan of the experiment, testing of reproducibility of the experiments, calculation of regression coefficients, assessment of the significance of regression coefficients and adequacy of the test model *(Melnikov et al., 1980)*. The experiment consisted of 15 tests at threefold repetition in each of them.

The main measuring equipment was: the sample weight was measured with a laboratory scales FEH-320; substrate moisture content with an instrument ZD-05 (error 0.2 %); substrate temperature was measured with the thermal probe TCP 1-8 (error 0.15 %); blades angle was measured with the laser goniometer Bosch

GAM 220 MF (0 601 076 200) (error 0.1 %); drum rotation speed with the portable optical tachymeter Testo 465 (error 0.02 %).

According to the plan of multifactor experiment the values of the model`s relative error are lower than 1.83% *(Melnikov et al., 1980)*. This is the case for all experiments. The values of mean relative deviation are lower than 0.9% *(Melnikov et al., 1980)*. Thus the relative error value is less than 5 % *(Melnikov et al., 1980)*. Such relative error value is considered acceptable in modelling. Therefore, it can be concluded that presented model predicts a degree of substrate components mixing unevenness with high accuracy.

RESULTS

As a result of laboratory experiments and statistical computation, the coefficient of variation *k* of controlled component distribution in samples was obtained and it is shown in table 2.

Table 2

Planning matrix of a multifactor experiment

№	**Experiment planning method**			**Experiments results**				**Model adequacy check**		
	X_1	X_2	X_3	k_1	k_2	k_3	k_{med}	$k_{med.com}$	$(k_{med} - k_{med.com})$	$(k_{med} - k_{med.com})^2$
1	+	+	0	19.882	19.659	19.473	19.671	21.546	-1.874	3.513
2	+	–	0	21.211	21.478	21.673	21.454	20.621	0.833	0.693
3	–	+	0	20.103	20.682	20.421	20.402	21.235	-0.833	0.693
4	–	–	0	22.848	22.633	22.779	22.753	20.879	1.874	3.513
5	0	0	0	11.320	11.264	11.857	11.480	11.417	0.064	0.004
6	+	0	+	19.278	19.032	19.013	19.108	18.538	0.570	0.324
7	+	0	–	21.214	21.106	21.041	21.120	20.669	0.451	0.204
8	–	0	+	19.853	19.359	19.482	19.565	20.016	-0.451	0.204
9	–	0	–	18.674	18.573	18.456	18.568	19.137	-0.570	0.324
10	0	0	0	11.541	11.838	11.952	11.777	11.417	0.360	0.130
11	0	+	+	16.973	16.871	16.736	16.860	15.734	1.126	1.267
12	0	+	–	17.087	17.163	17.222	17.157	15.914	1.244	1.547
13	0	–	+	13.474	13.026	13.712	13.404	14.648	-1.244	1.547
14	0	–	–	14.372	14.678	14.734	14.595	15.720	-1.126	1.267
15	0	0	0	10.979	10.987	11.012	10.993	11.417	-0.424	0.180

Regression coefficients: b_0=11.417; b_1=0.013; b_2=0.32; b_3=-0.313; b_{12}=0.142; b_{13}=-0.752; b_{23}=0.223; b_{11}=6.87; b_{22}=2.784; b_{33}=1.304.

After processing the experimental data in “Statistica” a regression equation in a coded form was obtained and the correlation coefficient was determined:

$$\begin{aligned} k_{(W,\,n,\,\alpha)} &= 11.417 + 0.013 \cdot W + 0.32 \cdot n - 0.313 \cdot \alpha + 0.142 \cdot W \cdot n - \\ &-0.752 \cdot W \cdot \alpha + 0.223 \cdot n \cdot \alpha + 6.87 \cdot W^2 + 2.784 \cdot n^2 + 1.304 \cdot \alpha^2 \end{aligned} \tag{2}$$

where:

W – substrate moisture content, [%];

n – drum reactor rotation speed, [rpm];

α – blades angle, [degree];

k – coefficient of variation of controlled component distribution in samples, [%].

The coefficient of correlation is R^2=0.9613.

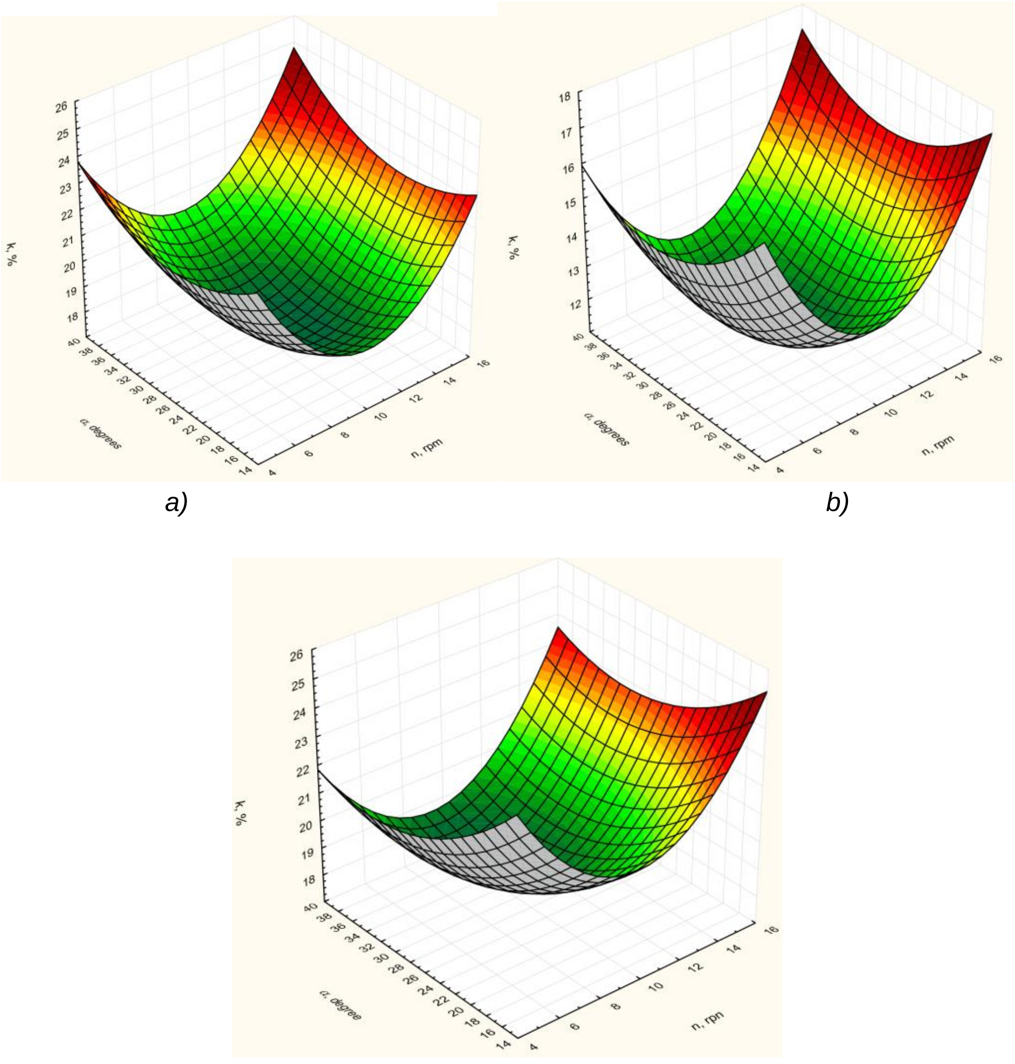
The Cochrane criterion and Student test were used to determine the homogeneity of variances and the confidence intervals for regression coefficients respectively. In our case we have a 5% level of significance for the number of freedom degrees f_2=2 and number of experiments f_1=15.

For these values, the tabulated value of Cochrane criterion was $G^{tabl}=0.3346$ and the tabulated value of Student coefficient was $t=4.3$ *(Melnikov et al. 1980)*. As we have got that $G^{com}=0.203<G^{tabl}(0.05;\ 15;\ 2)=0.3346$ the process is reproduced. The significance of regression coefficients was tested according to the established confidence intervals and covariance. Adequacy test of hypotheses of obtained regression equation was performed by the Fisher criterion. The estimated value of the Fisher criterion in the dispersion of inadequacy $S^2_{inadeq}=1.078$ was $F^{com}=6.88$, since $F^{com}=6.88<F^{tabl}(0.05;\ 15;\ 2)=19.38$. The hypothesis by the adequacy of the regression equation is confirmed.

After processing the experimental data in “Statistica”, graphs were built to show dependencies of optimization criterions from factors variation levels, which are quadratic response surfaces. In particular, dependencies of the coefficient of variation *k* of the control component`s distribution in the substrate on its moisture content *W*, reactor rotation speed *n* and blades angle α were built. Graphical representations of the abovementioned equation are given in Figures 2–4.

According to Eq. (1) the biggest influence on the coefficient of variation of controlled component distribution *k* in samples, namely an unevenness of substrate components mixing, has drum rotation speed *n*, blades angle α has a little less influence, and moisture content *W* has the lowest influence.

According to the graphs in Figure 2, between substrate moisture content *W=50…70%* rational drum rotation speed is $n=10$ rpm. Rational blades angle is $\alpha=27…29°$. Lower blade angles works better with lower moisture content. When moisture content rises to *W=70%*, to provide less mixing unevenness, blade angle should be set at $\alpha=29°$.

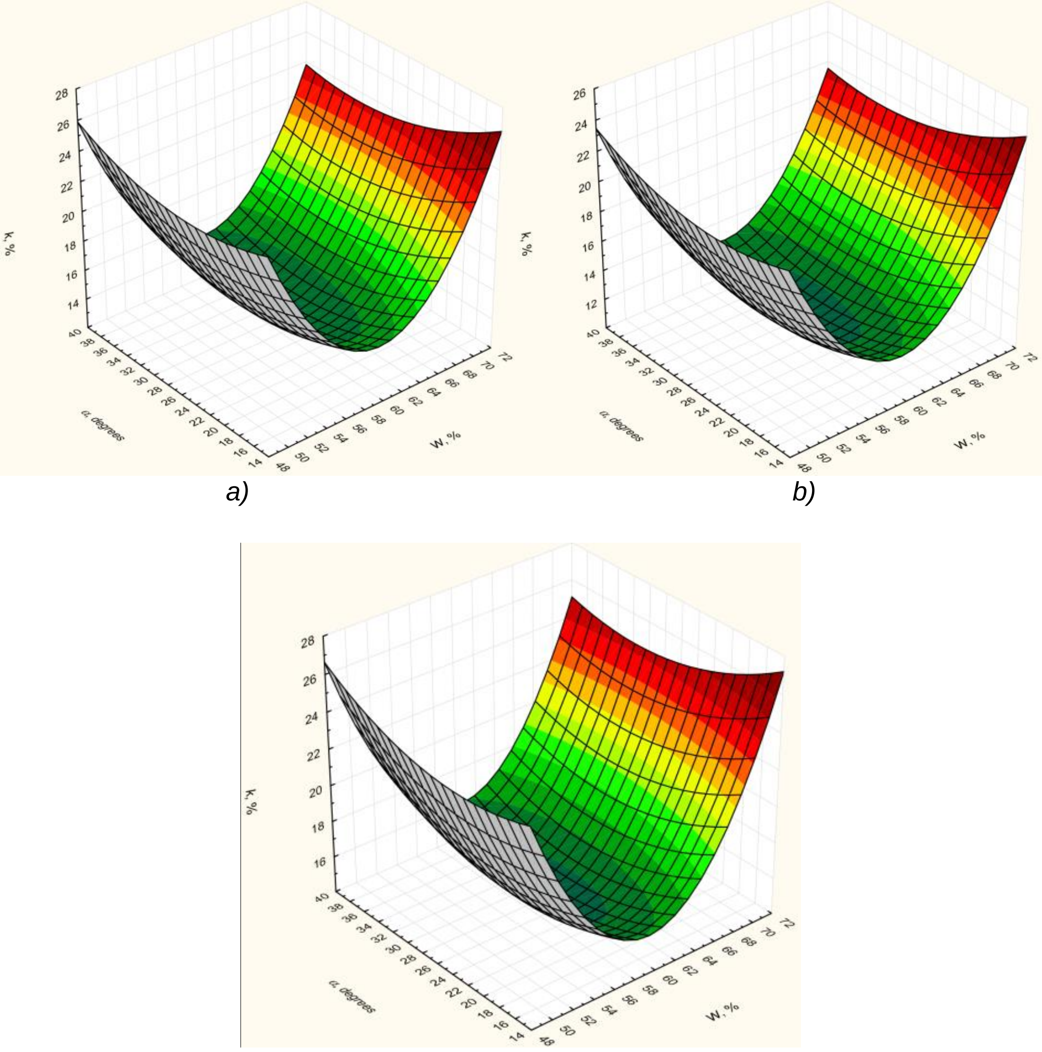


a) *b)*

c)

Fig. 2 – Response surfaces of the change in the values of k from the simultaneous change of two factors *k=f(n, α)*: a – *W=50%*; **b –** *W=60%*; **c –** *W=70%*

According to the graphs in Figure 3, between drum rotation speed n=5…15 rpm, the best substrate components mixing was observed at moisture content W=62% with blades angle changing between α=27…29°.



a) b)

c)

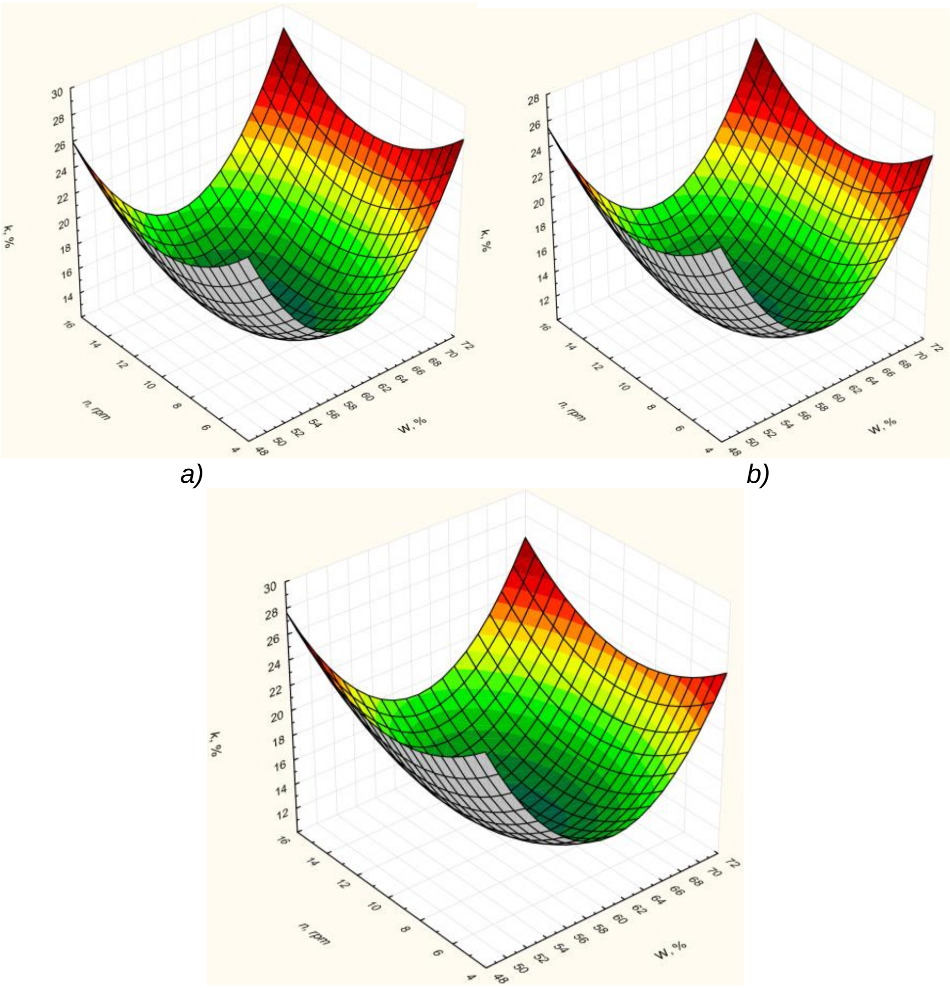
Fig. 3 – Response surfaces of the change in the values of k from the simultaneous change of two factors *k=f(W, α):* a – *n=5%*; **b –** *n=10%*; **c –** *n=15%*

According to the graphs in Figure 4, for blades angles α=15…39°, the best mixing was observed for moisture content W=57…62% while drum rotation speed was within n=9…11°rpm.

By analysing the received dependencies it was found that while rising drum rotation speed up to n=9 rpm the substrate unevenness is lowering, however further rising above 11 rpm leads to the raising of the substrate unevenness. This could be due to predominance of component segregation over mixing.

The range of rational values of substrate moisture content is W=57…62%. At this values of moisture content, while rising blades angle to α=27° substrate unevenness is lowering. However rising blades angle over 29° leads to raising substrate unevenness. This is explained by the fact that rising blades angle on reactor working surface improves holding substrate components in ascendance zone preventing it from sliding and widening mixing zone due to involving space over sliding surface. When rising angle above 29° partial substrate sliding is observed, it is returned into general flow instead of spraying in drums' free space hence degrading component distribution.

It should be marked that reactor rotation speed n has the biggest influence compared to substrate moisture content W and blades angle α. The lowest substrate unevenness (coefficient of variation of controlled component distribution in samples k=11%) was observed at substrate moisture content W=61%, reactor rotation speed n=10 rpm and blades angle equal to α=28°.



a) b)

c)

Fig. 4 – Response surfaces of the change in the values of k from the simultaneous change of two factors *k=f(n, W):* a – *α=15%*; b – *α=27%*; c – *α=39%*

From the graphs in Figures 2–4, it can be concluded that: to provide even mixing of substrate and receive high bio-chemical quality of compost the substrate moisture content should be between *W*=57…62%, rotation speed *n*=9…11°rpm and blades angle equal to α=27…29°.

To estimate the fertilizing characteristics of the fermentation product, the following agrichemical criteria were used: total nitrogen (N) content, mobile forms of phosphorus (P_2O_5) and potassium (K_2O) content, total carbon of the humus acids (C_{HA}) content, ash and moisture content in compost. The content was defined in % to dry weight. So, nitrogen content in the compost was 2.4% (initial substrate – 1.87%); P_2O_5 – 2.12% (init. sub. – 1.53%); K_2O – 1.68% (init. sub. – 1.2%); C_{HA} – 16.5% (init. sub. – 11.8%); ash – 14.27% (init. sub – 10.17%). Compost moisture content was 54% for the substrate moisture content 61%. This compost quality was received at parameters like: mixing with forced aeration was going at drum speed 10 rpm and blades angle 28°; the air to substrate ratio was 4:1; pressure inside was near equal to the atmospheric one; ambient temperature was +18°C. The process duration was 252 hours.

For the minimal drum speed and blades angle (*n*=5°rpm and α=15°C) and other conditions being identical, the produced compost had poorer agrichemical characteristics. Content per dry weight was: N=1.62%; P_2O_5=1.84%; K_2O=1.44; C_{HA}=16.3%; ash – 12.7%; moisture 50%.

For the maximal drum speed and blades angle values (*n*=15°rpm and α=39°C) and other conditions being identical, the produced compost was worse. Content per dry weight was: N=1.54%; P_2O_5=1.71%; K_2O=1.36; C_{HA}=15.8%; ash – 11.8%; moisture 45%.

In the future, basing on the dependencies of influence of the design-technological parameters of the fermentation process and substrate`s moisture content on mixing unevenness (final compost quality), it is planned to find optimal time of the process. Also, to find the influence of mixing time and amount of aeration air on the substrate`s maturation process and the change of its temperature modes on every fermentation phase.

CONCLUSIONS

The rational parameters and modes of reactor operation are substantiated by multifactor experiment. Namely, the influence of substrate moisture content, drum rotation speed and blades angle on substrate components mixing evenness and specific energy consumption of the process:

a) Substrate components mixing evenness is more dependent on rotation speed *n* opposed to moisture content *W* and blades angle α*;*

b) Even mixing of substrate components was observed at such rational factors ranges: *W*=57…62%, *n*=9…11°rpm, α=27…29°;

c) Minimal value of the coefficient of variation *k* of control component distribution in samples was 11% at substrate moisture content *W*=61%, rotation speed *n*=10 rpm and blades angle α=28°;

For the abovementioned rational factors ranges the compost with high agrichemical characteristics was produced: N=2.4%; P_2O_5=2.12%; K_2O=1.68; C_{HA}=16.5%; ash – 14.27%; moisture – 54%. The reactor`s operation beyond the mentioned parameters range results in worse mixing quality. This, in turn, leads to the need of changing the mixing modes: either reducing the time between consequent mixing or rising the periodical mixing duration.

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