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APPLICATION OF MICROWAVE ENERGY TO THE HYGIENIZATION OF SEWAGE SLUDGE

The article deals with the possibilities of microwave energy utilization in the hygienization of sewage sludge. It presents the evaluation of the destruction effectiveness of selected microorganisms existing in sewage sludge as a result of microwave heating. Additionally, it describes the influence of the microwave energy dose on the selected physical-chemical indexes of sludge and on its structure.

The tests were conducted on secondary sludge and anaerobically digested sludge. Sewage sludge was heated with the microwave dose from 0.6 kJ/g up to 24 kJ/g of sewage. The frequency of microwaves was 2450 MHz. It was proven that microwaves could be applied to the hygienization of sewage sludge. They should be considered a highly efficient method of heating up sludge to the temperature of its pasteurization.

During microwave heating, microorganisms existing in sludge are destroyed. The most sensitive ones are *Salmonella* and *Coli* bacteria, whereas thermophilic bacteria and *Clostridium* demonstrate significant resistance to microwaves.

1. INTRODUCTION

Every treatment plant produces waste called sewage sludge. Sludge produced in municipal treatment plants is a reservoir of bacteria, viruses, intestinal parasites, sewage fungi and yeast [1], [2]. Before the agricultural or natural use, stabilized and dehydrated sludge is subjected to the process of hygienization.

The hygienization of sewage sludge may occur during liming, aerobic and anaerobic thermophilic stabilization, thermal drying, composting or pasteurization [3]–[5]. Microwaves can also be used for the hygienization of sewage sludge. Literature reports confirm a high effectiveness of microwave in the destruction of microorganisms in soil and liquid manure as well as insects in grain [6], [7].

Microwaves are electromagnetic waves of a frequency from 0.3 GHz up to 300 GHz, which correspond to a wavelength in air of 0.0001 meter and up to 1 meter, re-

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spectively. They can be reflected by the surface of the material, pass through it or be absorbed [8].

Materials which absorb the energy of microwaves are heated. This is a property of dielectric substances, for instance of water. In dielectrics, microwaves cause a dipole polarization. This leads to the rotation of molecules, which in the case of dielectrics have a dipole structure. The influence of microwaves causes a chaotic movement of molecules in relation to the travel direction of electromagnetic waves. The absorbed energy of microwaves causes dielectric heating. The increase of temperature is caused by dipole molecules, constituting dielectric materials, that are unable to align themselves in relation to the electromagnetic field [9]. The molecule ability of every substance to polarize is determined by a dielectric constant [10]. For 20 °C water, the dielectric constant is 80. On that account, water as well as other high moisture substances are heated very fast in the microwave field.

The effectiveness of the destruction of microorganisms using microwaves depends on the time of exposure and the power of the electromagnetic field used [11]. The influence of microwaves on microorganisms is the result of the thermal effect on water which is a part of their cytoplasm and the environment. It is also connected with non-thermal effects [11], [12]. The mechanism of non-thermal effect of microwaves on microorganisms is not precisely known. It is only known that it is not connected with breaking chemical bonds of substances from which microorganisms are built nor of compounds taking part in biochemical processes. The highest energy of microwave quantum equals 1.2 meV and is not adequate for breaking hydrogen bonds with the bond energy of 0.04–0.44 eV and covalent bonds (5 eV) [13].

In the USA, microwave hygienization of sewage sludge and other biologically contaminated organic wastes was classified as a method which may have a wider practical use in the future [14].

Taking the above mentioned reasons into consideration, laboratory tests were carried out to determine the possibilities of microwave energy utilization in the process of sewage sludge hygienization.

2. AIM AND SCOPE OF THE TESTS

The tests were conducted in order to define the effectiveness of microwaves in the destruction of selected groups of microorganisms. The microbiological composition of sludge was tested in the range of chosen types of microorganisms before and after their exposure to the microwave field. The microbiological analysis included a determination of an overall number of psychrophilic, mesophilic and thermophilic bacteria, bacteria from the *Coli* group, *Salmonella* and *Clostridium* bacteria. Additionally, the tests were conducted in order to determine the influence of microwave energy doses on chosen physical-chemical indexes of sludge and its structure. The samples used in tests were secondary sludge and anaerobically digested sludge. The microwave radiation doses used in the tests varied from 0.6 kJ/g up to 24 kJ/g of sewage.

The radiation dose D (kJ/g of sewage) was calculated from the formula:

$$D = \frac{M \cdot t}{m}, \tag{1}$$

where:

M – power of microwave energy supplied by the device manufacturer, kW;
t – time of microwave exposure, s;
m – sludge mass, g.

The survivability of bacteria R was calculated from the formula:

$$R = \log \frac{N_0}{N_t}, \tag{2}$$

where:

N_0 – number of microorganisms before hygienization;
N_t – number of microorganisms after hygienization.

In the following part of the research, $\log_{10}$ symbol was used to mark a unit of bacteria survivability. The expression 1 $\log_{10}$ describes a 10 times reduction of the microorganisms number after the process of hygienization in relation to the initial value.

The analysis of the results was conducted on the basis of logistic regression:

$$P(Y=1 \mid X_1, X_2, ..., X_k) = \frac{\exp^{\left(a_0 + \sum_{i=1}^{k} a_i x_i\right)}}{1 + \exp^{\left(a_0 + \sum_{i=1}^{k} a_i x_i\right)}}, \tag{3}$$

where:

a_i for $i = 0, ..., k$ regression coefficient;
$x_1, x_2, ..., x_k$ independent variables measured or quality variables.

The logistic function applies the value from a range of [0.1]. It allows us to estimate the probability of the event occurrence with independent variables' values.

The analysis also included the odds ratios for the estimation of the multiplicity rise of the success probability in the case of the increase of the value of 1 of the independent variable X_n and constant value of other variables. The odds ratios OR were calculated with the following formula on the basis of estimated values of logistic regression coefficients:

$$OR = \exp(a_n), \tag{4}$$

where a_n is a regression coefficient for the analysed independent variables.

3. RESULTS

The conducted tests proved that microwaves destroy microorganisms present in sewage sludge. The examples of changes in the number of chosen bacteria exposed to microwave energy are presented in figures 1–3. The highest effectiveness of microwave heating was proven in relation to *Salmonella* bacteria. These bacteria were not found in the samples exposed to microwave doses from 1.5 up to 4.8 kJ/g of sludge. Microwave heating, even at low energy doses, decreased the number of bacteria from the *Coli* group. A complete destruction of these bacteria was obtained with doses from 3 up to 12 kJ/g of sludge.

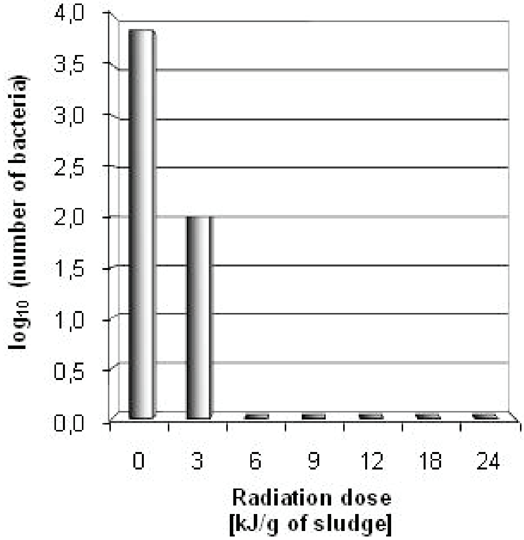

Fig. 1. Influence of microwave energy on the changes of the number of bacteria from the *Coli* group

Under the influence of microwaves, the number of mesophilic bacteria decreased, whereas at energy doses from 6.5 up to 16.8 kJ/g of sludge, the survivability equalled 4 $\log_{10}$. In the case of psychrophilic bacteria, the most significant changes of their overall number were noticed at microwave energy doses up to 9 kJ/g. The survivability of psychrophilic bacteria at these microwave energy doses was from 1.8 up to 4.1 $\log_{10}$.

Thermophilic bacteria and *Clostridium* showed a relatively high resistance to microwave heating. Even high doses of microwave energy caused slight decrease of these microorganism number. An average survivability of thermophilic bacteria equalled 0.9 $\log_{10}$. For *Clostridium* bacteria, an average survivability equalled 1.3 $\log_{10}$, while the highest value of 2.5 $\log_{10}$ was obtained at the microwave energy dose of 18 kJ/g of sewage. The present results can be explained by the adaptation of these bacteria to a high temperature environment.

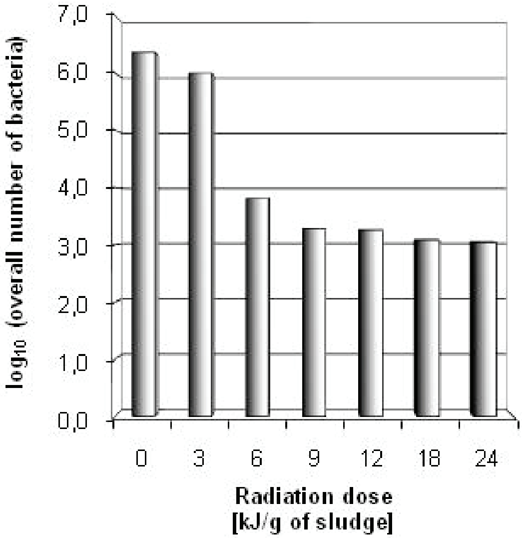

Fig. 2. Changes of the overall psychrophilic bacteria number at different microwave energy doses

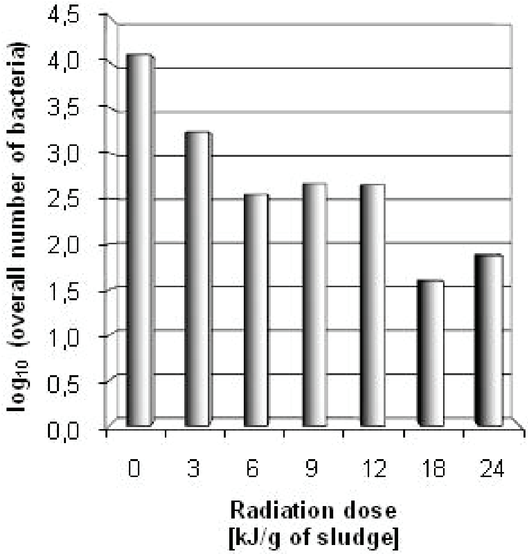

Fig. 3. Changes of the *Clostridium* bacteria number at different microwave energy doses

Figure 4a presents raw sludge before the application of the microwave energy radiation. In the picture, bacteria in their natural shape can be seen. At the microwave energy dose of 6 kJ/g of sludge, cracked and deformed bacteria cells were noticed (figure 4b).

a) b)

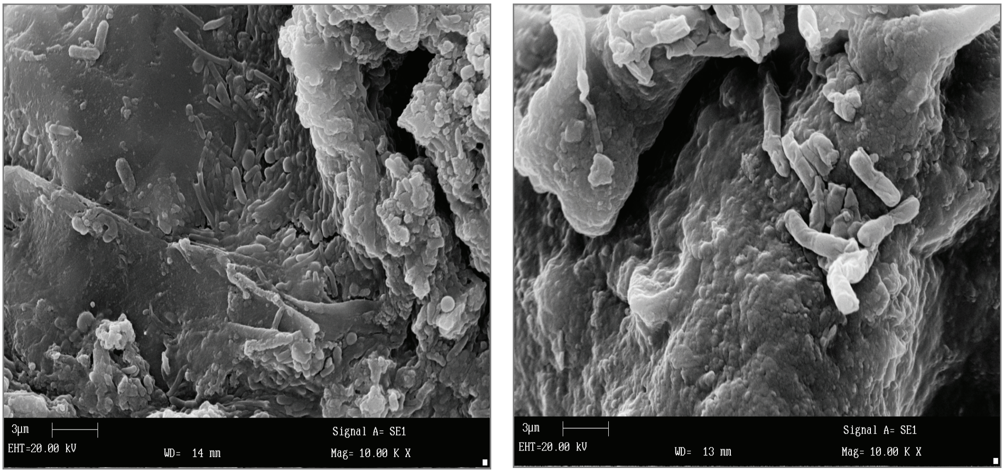

Fig. 4. Scanned pictures of sewage sludge before the application of the microwave energy radiation (a) and after the application of the microwave radiation dose of 6 kJ/g of sludge (b)

The obtained results allowed for the calculation of logistic functions:

$$P(Y = 1D) = \frac{\exp^{(a_0 + a_1 \cdot D)}}{1 + \exp^{(a_0 + a_1 \cdot D)}}, \tag{5}$$

defining the influence of the microwave energy dose D (kJ/g of sludge), and functions:

$$P(Y = 1D) = \frac{\exp^{(a_0 + a_1 \cdot D + a_2 \cdot U)}}{1 + \exp^{(a_0 + a_1 \cdot D + a_2 \cdot U)}} \tag{6}$$

describing the influence of the microwave energy dose D (kJ/g of sludge) and sludge hydration U (%) on the probability of individual bacteria survivability.

Figure 5 presents logistic functions described by equation (5) for the survivability of mesophilic bacteria, while figure 6 presents functions for the complete destruction of *Coli* and *Salmonella* bacteria.

The higher the microwave energy dose *D*, the greater the probability of *Salmonella, Coli* and *Clostridium* bacteria destruction as well as the reduction of the overall number of psychrophilic, mesophilic and thermophilic bacteria.

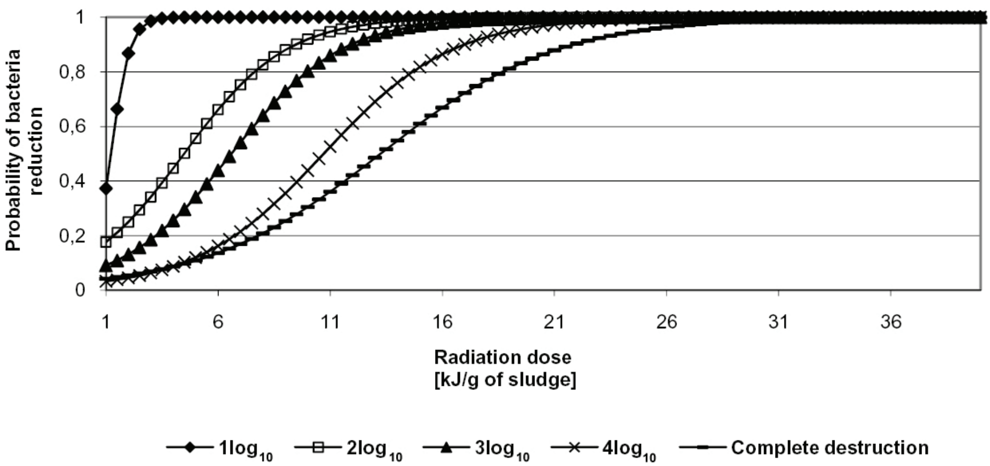

Fig. 5. Probability of the mesophilic bacteria overall number reduction in sludge at different microwave energy doses

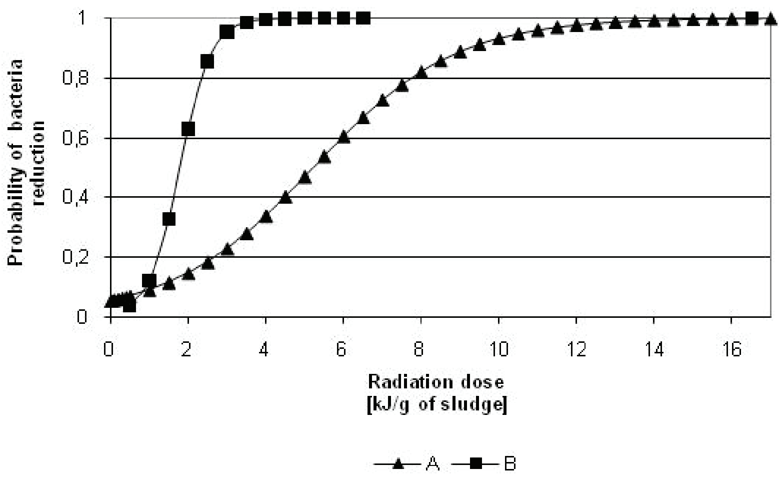

Fig. 6. Probability of the complete destruction of *Coli* (A) and *Salmonella* (B) bacteria at different microwave energy doses

The table presents the odds ratios for a microwave energy dose at different survivability levels and for individual microorganisms.

Table

The odds ratios for a microwave energy dose for the analysed bacteria

Microbiological test type	Reduction efficiency	Odds ratios
Salmonella bacteria	complete destruction	11.8
Coli bacteria	complete destruction	1.7
Clostridium bacteria	1 $\log_{10}$	1.2
	2 $\log_{10}$	1.3
Overall number of psychrophilic bacteria	1 $\log_{10}$	6.2
	2 $\log_{10}$	2.1
	3 $\log_{10}$	1.2
Overall number of mesophilic bacteria	1 $\log_{10}$	11.0
	2 $\log_{10}$	1.6
	3 $\log_{10}$	1.5
	4 $\log_{10}$	1.4
	complete destruction	1.3
Overall number of thermophilic bacteria	1 $\log_{10}$	1.2

Salmonella as well as mesophilic and psychrophilic bacteria are the most sensitive to microwave energy, but with the survivability of 1 $\log_{10}$. Under the influence of microwave energy the hydration of sludge is reduced (figure 7). At doses above 3 kJ/g of sludge, drying and changes of sludge structure were noticed. Nevertheless, the increase of microwave energy dose did not significantly influence the surviv-

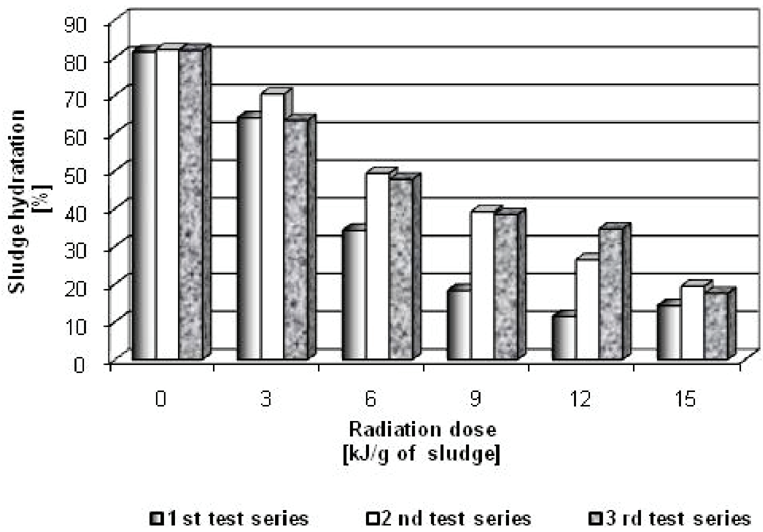

Fig. 7. The influence of microwave energy on sewage sludge hydration changes

ability of microorganisms, except for *Salmonella* bacteria. The effect of sewage sludge hygienization under the influence of microwave energy is connected with heating up a sludge mass and creating the conditions of conventional pasteurization. Sewage sludge should be heated up with the application of low microwave energy doses which do not cause any changes within sludge structure. High microwave energy doses resulted in the sintering and burning of sludge.

The conducted tests demonstrated a decrease of sludge alkalinity in direct proportion to the microwave energy dose. The decrease of alkalinity was probably caused by the effect of the ammonium acid carbonate decomposition and the escape of free ammonia from the sludge in consequence of the temperature rise.

4. CONCLUSIONS

The hygienization of sludge occurs during microwave heating. *Salmonella* and mesophilic bacteria are the most sensitive bacteria to microwave energy, whereas thermophilic bacteria and *Clostridium* demonstrate significant resistance to microwaves. Microwaves can be used as a highly efficient method of heating up sludge to the temperature necessary for its pasteurization.

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