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Original Research

Effect of Sewage Sludge Solar Drying Technology on Inactivation of Select Indicator Microorganisms

Małgorzata Sypuła, Zbigniew Paluszak, Beata Szala*

Department of Microbiology, University of Technology and Life Sciences,
Bernardyńska 6/8, 85-029 Bydgoszcz, Poland

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Abstract

The sanitization effectiveness of sewage sludge solar drying was examined in the aspect of limiting the transmission of pathogenic microorganisms into the environment. The survival rates of indicator bacteria *E. coli*, faecal streptococci, and rods of *Salmonella Senftenberg*$_{W775}$, as well as the eggs of the intestinal parasite *Ascaris suum* were assessed in dried sludge. The results indicate that the process of solar drying in the studied cycle was not effective and did not eliminated microorganisms to a sufficient degree. The number of the bacterial population of interest decreased only by 2 $\log_{10}$. The percentage of live eggs of *A. suum* after 28 days of the process was more than 90%.

Keywords: sewage sludge, solar drying, indicator microorganisms

Introduction

Every year large quantities of sewage sludge are produced in sewage treatment plants [1]. Due to high hydratation, the content of organic compounds susceptible to decomposition as well as the presence of pathogenic microorganisms and live eggs of intestinal parasite sludge is the type of troublesome waste that is difficult to manage [2, 3]. The majority of local sewage treatment plants reutilize municipal sewage sludge for use in agriculture and for land reclamation. To ensure the sanitary safety for people and animal health it is necessary to develop microbiological methods for validation of sludge sanitization. This will allow the control of transmission of pathogenic microorganisms to the environment [4, 5].

One of the technologies allowing reduction in the mass and volume of sludge produced in sewage treatment plants is drying. In the case of conventional drying, the most serious drawback is a high operational cost of thermal systems and the emissions of pollutants released to the atmosphere. For economical and ecological reasons, unconventional systems of sludge drying, such as solar drying plants, are starting to enjoy increasing popularity [6]. Sludge generated in drying plants can be reused for burning with conventional fuels in thermal systems or for agricultural purposes. Conditions that must be met when using sewage sludge in agriculture, including its microbiological and parasitological properties, are defined in the regulation of the Ministry of Environment of 13 July 2010 on municipal sewage sludge [7].

The aim of this study was to assess the sanitization effectiveness of the technology of sewage sludge solar drying by means of determining the survival rate of the indicator bacteria and the eggs of intestinal parasites *Ascaris suum*.

Materials and Methods

The experiment was carried out in a sewage sludge solar drying plant – a commercial system working at full

*e-mail: szabea@utp.edu.pl
szabea@op.pl

scale at the waste water treatment plant. The main principles of the drying operation is the solar effect and heating floor exploitation to water evaporation from sewage sludge. The structure of the hall allows the penetration of sun rays to the inside and generating the greenhouse effect. Inside the drying hall sludge is transported, aerated, granulated, and moved to the end of the drying hall by a sludge turning device. The automatic ventilation system, which consists of mechanical ventilators inside the hall and an automatic window in the top of the roof, ensures and improves water evaporation and humidity removal outside the drying hall. The drying process takes 30 days.

Microbiological Analysis

To study the inactivation of pathogenic microorganisms in the course of drying sludge, perforated steel probes were used in which carriers contaminated with selected indicator microorganisms were placed. The carriers contained 25 g weights of sewage sludge, and 1 ml of suspension: *Escherichia coli*, rods of *Salmonella Senftenberg*$_{W775}$, and faecal streptococci of group D were added to each of them. The concentration of bacteria in suspension amounted to 10^6-10^9 MPN/ml. Also, perlon sacks containing live eggs of *Ascaris suum* were placed inside the probes. The probes were filled with sludge from both sides, closed with blind stops, and placed in the pile of dried sludge at the end of the hall as well as on the shovels and frame of the sludge turner. Samples placed in the shovel had contact with a drying bed of sewage sludge. Samples placed on the frame of the turning device didn't have contact with drying bed and were affected only by climatic conditions such as humidity and temperature inside the drying hall.

During the whole drying process the carriers were removed at weekly intervals and subjected to microbiological analyses. The degree of inactivation of the studied bacteria was determined based on a change in their number in the course of the process. From 1-gram weights of sludge from the carriers, a series of 10-fold dilutions in 0.9% NaCl were made. In the case of *E. coli* the selective MacConkey's medium was applied (Merck, No.105396) [8]. Samples were incubated at 43ºC for 24 h. Following this, the material was sieved on the solid selective medium Lactose TTC agar with Tergitol® (Merck, No. 107680) [9] and the selective solid medium Endo (Merck, No. 104044) [10]. Samples were incubated at 43ºC for 24 h. To confirm the results, the material was analyzed using API 2 20E biochemical tests. For faecal streptococci, the selective liquid medium with sodium azide and glucose was used (Merck, No. 101590) [11]. The material was incubated at 37ºC for 24 hours. From the samples where turbidity of the medium was observed, an inoculation was made on the solid selective medium with canamycin, esculin, and sodium azide (Merck, No. 105222) [12]. Cultures were incubated for 24 hours at 37ºC. In the final phase of identification the serological test Phadebact D Strep Test (Phadebact strep D test Karo Boule Diagnostics AB, Huddinge, Sweden) was applied. To determine the number of rods of *Salmonella Senftenberg*, multiplying and selective media were used. After incubation in 1% peptonic water (37ºC, 24 h), 0.1 ml of the suspension from each tube was transferred to tubes containing 9 ml of the selective liquid multiplying medium acc. to Rappaport (Merck, No. 110236) [13]. The cultures were incubated at 43ºC for 24 h. Then the material was sieved on the solid selective medium BPLA acc. to Kauffmann (Merck, No. 107236) [14] (37ºC, 24 h). Additionally, in order to confirm the identification, a serological test was applied using the polyvalent serum HM. Determinations of the number of the studied bacteria were carried out in three replications using the method of the most probable number (MPN) in the 3-tube kit. The results obtained were subject to statistical analysis using Statistica Microsoft. Regression lines were drawn up based on which theoretical survival time of bacteria in the tested material was calculated.

During the experiment perlon sacks containing 1 ml of suspension of *Ascaris suum* live eggs also were placed in the carriers. During analyses the sacks were cut open, placed in Petri dishes, and subject to incubation for 21 days at 28ºC. After incubation the eggs were observed under the microscope and the percentage of invasive eggs, containing a live larva, was calculated.

Study of Climatic Conditions

In the research cycle, testing and measuring devices monitored the climatic conditions prevailing outside and inside the drying plant hall. A compact hydrothermometer was used to measure the humidity and temperature, a pyranometer to measure the intensity of dispersed solar radiation coming to the horizontal plane and the climatic station to control weather conditions such as the temperature, air humidity, wind speed, and rainfall detector. The temperature measurement in the sludge pile was taken using the intra-pile thermometer.

Physico-Chemical Analyses

Also, the following parameters were determined in sludge: dry weight, pH, the content of fertilizer components, including total nitrogen, ammonium nitrogen, total phosphorus, calcium, magnesium, and the content of heavy metals (Pb, Cd, Hg, Ni, Zn, Cu, Cr). Physicochemical analyses of sludge were carried out using reference methods contained in annex no.5 to the Regulation of Ministry of the Environment of 1 August 2002 on municipal sewage sludge (J. Law. No. 134, Item 1140) [15].

Results

In the research period, the conditions prevailing inside the drying plant and in the pile of dried sludge had a small effect on the inactivation of selected indicator microorganisms. The temperature outside the drying plant ranged from 9.1ºC to 15.7ºC, on average 12.6ºC. In the first three weeks, in the sludge pile a downward tendency in the temperature was recorded, from 16.5ºC to 13.2ºC, whereas in the last

Table 1. Number of studied microorganisms in sludge from the carriers [MPN·g^{-1}].

Sludge from the carriers placed on frame of the turner					
Indicator bacteria	Times of sampling (days)				
	0	7	14	21	28
Salmonella Senftenberg	7.83×10^{8}	6.83×10^{9}	2.17×10^{8}	3.17×10^{7}	2.5×10^{8}
E. coli	1.83×10^{6}	4.83×10^{6}	5.58×10^{5}	1.57×10^{6}	7.0×10^{4}
Faecal streptococci	5.5×10^{9}	3.17×10^{8}	7.83×10^{7}	6.17×10^{7}	6.0×10^{7}
Sludge from the carriers placed on shovels					
Indicator bacteria	Times of sampling (days)				
	0	7	14	21	28
Salmonella Senftenberg	7.83×10^{8}	2.48×10^{9}	2.32×10^{9}	5.4×10^{7}	5.17×10^{6}
E. coli	1.83×10^{6}	5.38×10^{6}	5.65×10^{3}	5.0×10^{5}	3.67×10^{4}
Faecal streptococci	5.5×10^{9}	4.82×10^{8}	1.08×10^{8}	1.08×10^{8}	4.5×10^{7}
Sludge from the carriers placed in sludge pile					
Indicator bacteria	Times of sampling (days)				
	0	7	14	21	28
Salmonella Senftenberg	7.83×10^{8}	3.17×10^{8}	3.0×10^{8}	3.17×10^{6}	1.23×10^{7}
E. coli	1.83×10^{6}	3.77×10^{7}	2.33×10^{5}	2.97×10^{4}	4.0×10^{4}
Faecal streptococci	5.5×10^{9}	1.13×10^{8}	2.67×10^{8}	5.17×10^{8}	6.17×10^{7}

week there was an increase to 17-18ºC. The temperature inside the hall remained on average 3ºC higher than that outside (Fig. 2).

Solar radiation was characterized by considerable diversification. Very low insolation was recorded on days 5, 7, 20, and 28 of the cycle, whereas on days 8, 10, 11, 19, and 21 it reached values above 210 W/m^2. The lowest value was observed on the 12th day of the cycle – 19.5 W/m^2, and the highest on day 18 – 299.7 W/m^2 (Fig. 3).

The relative humidity studied outside and inside the drying plant also showed considerable fluctuations. It was observed that its value inside the hall was lower than the outside air. Relative humidity in the drying plant during the 28 days of the cycle reached the lowest value (62%) on day 16, and the highest (86%) on days 20 and 28 (Fig. 4).

The changes in the number of indicator microorganisms in the tested cycle of sewage sludge drying are presented in Tables 1 and 2.

On the basis of the obtained results it was proved that the full sanitization of sewage sludge did not occur. The number of microorganisms introduced into the carriers showed slight fluctuations. The number of rods of *Salmonella Senftenberg*$_{W775}$ in the carriers placed on the frame of the turner was similar at the beginning and at the end of the experiment and amounted to 7.83×10^{8} and 2.5×10^{8} MPN·g^{-1}, respectively. Slight changes in the population count – by 1 and 2 $\log_{10}$, respectively– were observed in the pile and the sludge placed on shovels of the turner (Table 1).

The number of *E. coli*, after 28 days of the process of drying, in sludge collected for the study from all the control points, showed a downward tendency by 2 $\log_{10}$. A daily decrease in *E. coli* in the carriers placed in the pile and on the frame of the turner was 0.094 $\log_{10}$/day and 0.058 $\log_{10}$/day, respectively. The time needed for the total elimination of *E. coli* in the research material, determined on the basis of regression equations, amounted to 112 days on the frame and 98 days on the shovels of the device, whereas in the pile of sludge it was 72 days (Table 2).

During the research cycle a small decrease in the count of streptococci of group D from 10^{9} MPN/g to 10^{7} MPN/g was found. The longest survival time of faecal streptococci, amounting to 191 days, was observed in the probe

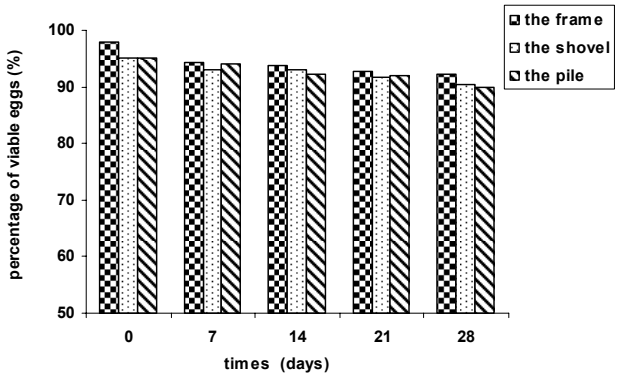

Fig. 1. Inactivation of *A. suum* eggs in the carriers.

Table 2. Regression line equations presenting dynamics of indicator bacteria inactivation in sludge from the carriers.

Sludge from the carriers placed on frame of the turner			
Indicator bacteria	Regression equat.	r^2 (%)	Survival of bacteria (days)
Salmonella Senftenberg	y=-0.047x+9.23	35.04	196
E. coli	y=-0.058x+6.52	56.44	112
Faecal streptococci	y=-0.066x+9.22	75.91	140
Sludge from the carriers placed on shovels			
Indicator bacteria	Regression equat.	r^2 (%)	Survival of bacteria (days)
Salmonella Senftenberg	y=-0.094x+9.54	66.81	101
E. coli	y=-0.062x+6.07	31.31	98
Faecal streptococci	y=-0.068x+9.25	78.77	136
Sludge from the carriers placed in sludge pile			
Indicator bacteria	Regression equat.	r^2 (%)	Survival of bacteria (days)
Salmonella Senftenberg	y=-0.083x+9.0	70.71	108
E. coli	y=-0.094x+6.81	60.86	72
Faecal streptococci	y=-0.048x+9.17	47.81	191

placed in the sludge pile, whereas the shortest – amounting to 136 days, in the sludge situated on the shovels of the turner (Tables 1 and 2).

Also, inactivation of the eggs of the intestinal parasite *A. suum* was not obtained. After 28 days of the process of sludge drying the count of eggs capable of further development was about 90% in all the carriers (Fig. 1).

The results of physico-chemical properties of sludge monitored during the conducted research were presented in Table 3. Prior to drying, the sludge was mechanically dewatered, according to the technological system of the sewage treatment plant. Dry weight of the sludge processed in the drying plant was on average about 15.94%. During the process of drying, the content of sludge dry weight in the pile increased from 34.7% on day 7 to 46.9% on the day 28 of the cycle. The pH value of sludge was 6.8 and was approaching neutral. Organic substance content in the sludge underwent a small decrease from 64.1% to 62.9% d.w. Also, a decrease in total nitrogen from 4.3 % to 3.87 % d.w. was observed in dried sludge.

Discussion

The former studies of sanitization of sludge subjected to solar drying were carried out both on the full technical scale (in Germany [16, 17] and Australia [18, 19]), and on the pilot scale, in miniature drying plants constructed specially for this purpose (in Turkey [20], in Greece [21], and in Mexico [22]). The conditions prevailing in Germany can be regarded as comparable to the climatic conditions of Poland. In the study conducted by Bux et al. [16] and Hertwig [17], a reduction in the bacteria count most often did not reach a level allowing unlimited use of dried sludge in agriculture, since it did not satisfy the defined standards established by the United States Environmental Protection Agency (US EPA 2003) [23]. For this reason, the process of drying was supplemented with additional methods, leading to the elimination of pathogens.

Also, the present study confirms an unsatisfactory degree of the inactivation of the observed microorganisms, hindering the use of dried sludge for agricultural purposes.

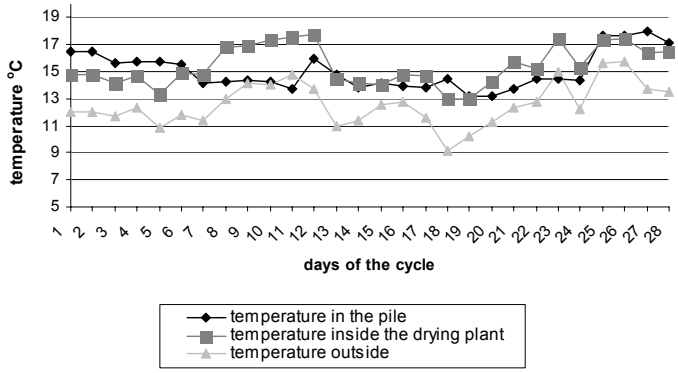

Fig. 2. Changes in temperature during the research cycle.

Table 3. Results of physico-chemical analyses of sewage sludge.

Studied parameter	Times of sampling [days]				
	0	7	14	21	28
Sludge dry weight (%)	15.94	34.7	39.4	46.3	46.9
Organic substance (% d.w.)	64.1	64.2	63.5	63.9	62.9
pH	6.80	6.80	6.81	6.81	6.81
Total nitrogen content (% d.w.)	4.30	4.30	3.97	3.80	3.87
Ammonium nitrogen content (% d.w.)	0.16	0.15	0.15	0.15	0.15
Total phosphorus (% d.w.)	2.00	2.02	2.01	2.02	2.02
Calcium content (Ca) (% d.w.)	1.09	1.08	1.10	1.09	1.09
Magnesium content (Mg) (% d.w.)	0.389	0.389	0.390	0.390	0.389
Heavy metals (mg/kg d.w.)					
Lead (Pb)	24.15	24.00	24.01	24.00	24.00
Cadmium (Cd)	1.62	1.62	1.61	1.60	1.59
Mercury (Hg)	0.09	0.09	0.09	0.09	0.09
Nickel (Ni)	15.74	15.74	15.76	15.74	15.74
Zinc (Zn)	1000.09	1000.00	1000.00	1010.00	1000.00
Copper (Cu)	270.00	270.15	270.12	270.12	270.12
Chromium (Cr)	31.23	31.00	31.20	31.20	31.20

In the case of faecal streptococci and *E. coli*, after a 4-week course of the drying process, a decrease in the count only by 2 $\log_{10}$ was found in carriers from three studied places. In contrast, the concentration of *Salmonella* remained the same at the beginning and at the end of the experiment and amounted to 10^8 MPN/g. Of the studied indicator bacteria, after 28 days of the experiment, the lowest concentration was obtained in the case of *E. coli* – of an order of 10^4 MPN/g. However, it is notable that the count of *E. coli* was by 2-3 $\log_{10}$ lower in comparison with the other bacteria already at the beginning of the experiment.

Bux et al. [16] in a study carried out during solar drying of sludge, working with the charging method, obtained a reduction in *E. coli* number only by 3 $\log_{10}$ during a cycle lasting 21 days. Radaidah et al. [24], in turn, observed a decrease in faecal coliforms from 4.6×10^8 to 2.0×10^4 cfu/g d.w. and a reduction in *Salmonella* bacilli from 8.4×10^8 to 4.3×10^3 cfu/g d.w. after 23 days of intensive solar drying of sludge. Salihoglu [25] obtained a reduction in bacteria of the coli group from 10^7 to 10^6 cfu/g d.w after 45 days of sludge drying in the summer period. Öğleni and Özdemir [20] report that during a fast solar drying of sludge, the con-

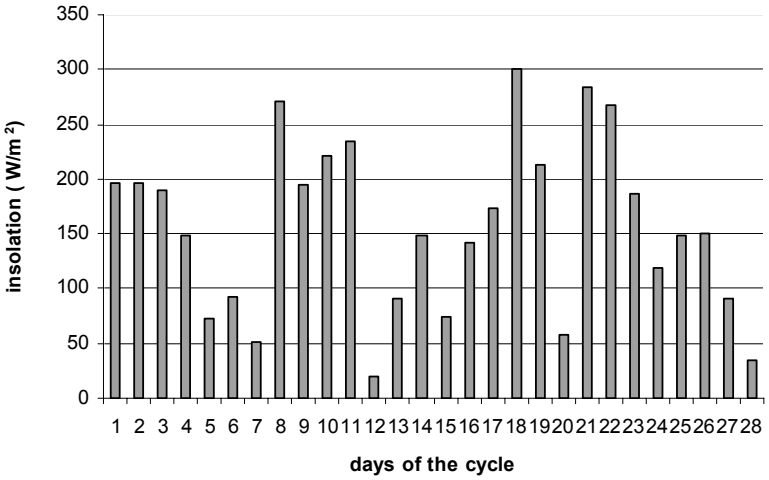

Fig. 3. Changes in insolation during the research cycle.

centration of faecal bacteria from the coli group decreased from the values 4.2×10^7 to 1.7×10^5 MPN/g d.w. after 2 days of drying. After 12 weeks of storage of dried sludge they did not obtain the full inactivation of the bacteria – they were still isolated in the amount $>10^3$ MPN/g.

The lack of the full sanitization of sludge subjected to solar drying, in spite of large insolation ranging from 950 to 1000 W/m^2, also was indicated by Mathioudakis et al. The authors obtained only a reduction in the total number of coli bacteria from 4×10^6 to 2×10^4 MPN/g d.w., and of coli bacteria of the faecal type from 3×10^5 to 10^3 MPN/g d.w. [21].

The theoretical time of inactivation of indicator bacteria selected for the study calculated on the basis of regression lines ranged from 72 days in the case of *E. coli* to 196 days in the case of *Salmonella*. The results indicate that the process of solar drying in the studied cycle was not effective. In this case additional action should be taken, improving the sanitary quality of sludge by liming or composting. Both Bux et al. [16] and Salihoghu [25], in order to increase the effectiveness of sanitization of sludge obtained during solar drying, subjected it to the liming process. After the addition of calcium oxide prior to the process of solar drying, already after 5 days Salihoghu obtained a decrease in bacteria of coli group below 10^3 cfu/g d.w.

Low temperatures generated during the process of sludge solar drying may be the cause of not only the lack of pathogenic bacteria elimination, but also their regrowth, particularly when dried sludge is rich in nutrients [26]. In the present study such a situation was observed in the case of rods of *Salmonella* and *E. coli*. After 7 days of the process, the count of *Salmonella* in carriers on the frame of the turner and on shovels increased by 1 $\log_{10}$. In the last week, another increase by 1 $\log_{10}$ was recorded in the carriers placed on the frame and in the sludge pile. In the case of *E. coli* another increase of their count was observed after 3 weeks of the process on the frame of the turner and on the shovels (Table 1). This phenomenon is often described in the literature [27, 28]. It is notable that a another increase in bacteria number depends not only on the temperature but also on humidity and the availability of nutrients [29].

In the present study, the humidity of sludge in the pile during the process of drying decreased by only 31.58% reaching a value of 53.1% at the end of the process. Too high humidity of sludge does not favour the inactivation of pathogenic bacteria. This is confirmed by the study by Salihoglu et al., who claimed that a reduction in sludge humidity below 50% increases the elimination rate of bacteria of the coli group [25]. Also, Liang indicates that 50% humidity is the threshold value, above which bacterial activity increases [30].

Taking into consideration that sewage sludge often contains eggs of internal parasites, a study concerning the survival rates of *A. suum* eggs as indicator organisms were also carried out. Similarly to the indicator bacteria, the demanded inactivation of parasite eggs was not obtained. After 28 days of the process of sludge solar drying, about 90% live eggs were observed in the sludge, both from carriers placed on the shovels and the frame, and from those in the pile. The direct cause of the lack of inactivation of parasite eggs was too low temperature during the drying process. Aitken et al. [31] remarks that thermal dewatering of sludge is an effective way of inactivation of helminth eggs in the biomass, on condition that a properly high temperature is provided. Experiments carried out during long-term storage of sludge, at a low temperature not exceeding 21ºC, confirm a high survival rate (80-99%) of *A. suum* eggs under such conditions [32]. Eggs of *Ascaris* are so resistant on the external factors that their survival rate in soil fertilized with improperly sanitized sludge amounts to even several years [33, 34]. This can pose a serious threat to human health, hence their presence constitutes an important criterion in a later way of sewage sludge utilization [35, 36].

The control of sludge chemical properties carried out during the experiment indicated that the concentration of fertilizer components – phosphorus, calcium, and magnesium – remained on the average level characteristic of municipal sewage sludge, and heavy metal content was low, which allowed the use of sludge in agriculture, in accordance with the directive of the minister of the environment of 1 August 2002 [15].

Solar drying of sewage sludge is one of many technologies used in recent years in sewage treatment plants. Microbiological and sanitary assessment of this technology based on indicator microorganism behavior during the process makes it possible to assess the risk of environmental contamination as a result of the application of sludge

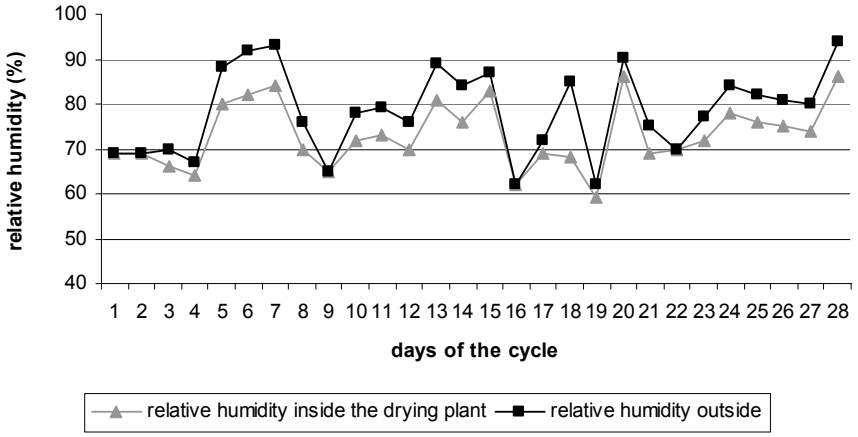

Fig. 4. Changes in relative humidity during the research cycle.

dried material for fertilization. Besides physico-chemical parameters and the quality control of the final product, a dynamic validation of sludge processing technology also is necessary, based not only on monitoring of the final product, but also on the potential abilities to eliminate pathogens during the process of drying, particularly in the case of extremely high contamination of the input material.

Under the conditions of the temperate climate that prevails in Poland, solar drying of sludge is a technology that does not guarantee obtaining a stable material without pathogenic microorganisms. The lack of positive results of the elimination of harmful microorganisms in drying plants located in different climatic conditions confirms that the solar drying technology cannot be regarded as an effective technology of sludge sanitization, safe for the environment. To obtain sanitary pure sludge, the vast majority of authors reports the necessity of subjecting it to additional sanitizing treatments.

Conclusions

1. The applied model of the study based on the inactivation of selected indicator bacteria and eggs of intestinal parasites allows validation of the solar drying method.
2. No clear effect of placing the carrier in the drying plant on the elimination rate of the studied indicator microorganisms was observed.
3. No significant differences in the inactivation of the applied indicator microorganisms were found.
4. The study proved the low sanitization effectiveness of sludge during solar drying. It does not ensure appropriate preparation of sludge for application in agriculture as a soil conditioner and for land reclamation.
5. It seems to be necessary to prolong the time of drying and to apply additional methods of sludge sanitization, such as liming or composting, in order to increase its biosafety.

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