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Effect of a Dehumidifier on the solar drying of sewage sludge-based biomixtures

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Abstract: One of the methods for treating sewage sludge is drying. In the Polish climate, the period from autumn to spring presents a challenge, rendering the natural sludge drying process inefficient. As an auxiliary measure, a dehumidifier can be employed, which, when combined with the use of biocomponents added to the sludge intended for drying, significantly improves the outcome of the process. The drying of sludge mixtures with additives was conducted during the autumn-winter period in a 10 m² polytunnel, divided into two sections: one unassisted and the other assisted by a dehumidifier. Sludge mixtures supplemented with walnut shells, wood chips, and sawdust, as well as sludge without additives serving as a control sample, were dried. It was found that the application of a dehumidifier, even solely during the initial phase of drying, facilitated a final reduction in the moisture content of the mixtures to 30–20% after just 40–60 days, which is sufficient for their storage, transport, or further utilization. The amount of water evaporated from the mixtures with additives in the assisted section, along with the drying rate, was several times greater. For the sludge without additives, the difference in the amount of evaporated water was as much as 30-fold. The final result achieved for the mixtures with biocomponents, owing to the initial moisture content and the structure of the material being dried, was considerably superior to that of the sludge without additives, a finding previously confirmed in earlier studies conducted under natural conditions during the spring-summer period.

Introduction

One of the stages in the sewage sludge treatment chain is drying, which significantly reduces its volume, alters its structure, promotes sludge hygienization, and increases its calorific value compared to the wet material (Bennamoun 2012; Trojanowska et al. 2012). Due to the high costs associated with drying sewage sludge using conventional methods, there has been growing interest in alternative drying techniques (Hurynovich et al. 2021, Mehrdadi et al. 2007, Przydatek et al. 2020).

Legislative developments require EU Member States to develop and implement sewage sludge management technologies, with particular emphasis on restricting landfill disposal and increasing the proportion of recovery processes. Consequently, processes involving the drying and conversion of sewage sludge into energy or fertilizer products are attracting increasing attention (Werle 2015).

Sewage sludge must be appropriately prepared prior to its natural utilization or thermal treatment (Khan et al. 2023,

Mehrardi et al. 2007, Smol et al. 2020). This is necessary primarily due to its high water content, variable concentrations of heavy metals, and varying degrees of sanitary risk (Cesaro et al. 2022, Yusuf et al. 2023). Among the available drying technologies, solar systems are gaining increasing prominence, as they facilitate a reduction in water content with minimal external energy consumption. Under temperate climate conditions, solar dryers can evaporate 1 ton of water while consuming only 13–28 kWh of electrical energy, which is substantially less than conventional thermal dryers, which consume up to 1.2 kWh per kilogram of evaporated water. An additional advantage of solar drying is its suitability for small and medium-sized wastewater treatment plants, particularly in rural areas lacking access to waste heat or district heating networks (Jat Baloch et al. 2023).

The efficiency of solar drying depends on meteorological conditions, meaning that during the winter period, especially in temperate climates, it frequently requires additional support. Another crucial factor is the structure of the material being



Fig. 1. Materials used in the drying tunnel

dried; therefore, the application of additives such as wood chips, walnut shells, or sawdust can substantially improve the efficiency of water evaporation (Kujawiak et al. 2024, Makowska et al. 2025). Furthermore, the use of supplementary biocomponents can improve drying conditions during unfavorable periods, thereby enhancing the physicochemical properties of the resulting biomixture, which can subsequently be utilized for both energy recovery and fertilizer applications (Boguniewicz-Zabłocka et al. 2021, Czekala et al. 2016, Kujawiak et al. 2024a).

Structural additives optimize heat exchange within the system, limit material agglomeration, and facilitate mixing, thereby enabling the entire layer to dry uniformly throughout its cross-section (Li et al. 2021). The importance of the dryer's design and its internal microclimate parameters was highlighted by Sorrenti et al. (2022), Mathioudakis et al. (2013), and Salihoglu et al. (2007). These authors demonstrated that, particularly during periods of low insolation and high relative humidity, the use of a dehumidifier, in addition to mechanical ventilation, can be highly beneficial. It not only stabilizes the relative humidity but can also positively affect the moisture reduction in the deeper layers of the sludge, which typically dry at a significantly slower rate and are more susceptible to clumping.

Krawczyk (2019) demonstrated a clear linear correlation between the so-called drying potential of the ventilation air (defined as the difference between the water vapor saturation level at a given temperature and the current water vapor content) and the instantaneous drying rate of the sludge, particularly during the initial phase of the process, when the moisture gradient between the sludge and the ventilation air is at its peak. As the material dries and cumulative drying

potential increases, the efficiency of the process decreases, which is consistent with the classical thin-layer drying model and confirms the existence of clearly defined drying phases: the rapid evaporation of free water, the transitional phase, and the final removal of bound water (An-nori et al. 2020, Bennamoun 2012). Sorrenti et al. (2022) and Bennamoun (2012) indicated that introducing additional assistance to the drying process is most effective during the first 10–20 days of the process. Therefore, the level of process assistance should be adapted to external conditions, the characteristics of the dried material, and the specific phase of drying phase.

The objective of this study was to determine the impact of employing a dehumidifier on the efficiency of the solar drying process of sewage sludge mixed with biocomponents. The study aimed to verify the hypothesis that the use of a dehumidifier as an auxiliary drying aid would improve the microclimatic parameters within the dryer, increase the rate of water evaporation from the sludge mixtures, and consequently reduce the overall drying time.

Materials and methods

The research was conducted in a naturally ventilated polytunnel measuring 2.5 x 4.0 m, located at the experimental farm of the Department of Horticulture, Poznań University of Life Sciences. Two zones were established within the tunnel: one equipped with a dehumidifier and a reference zone without a dehumidifier. Four containers measuring 0.8 x 0.9 m were placed in each zone, containing the biomixtures prepared for drying in four variants: sewage sludge supplemented with walnut shells, sewage sludge supplemented with mixed wood chips, sewage sludge supplemented with sawdust, and sewage sludge without additives (reference sample). The

Table 1: Characteristics of the dried mixtures

Symbol of the mixture	Type of supplement	Sewage sludge mass, kg	Supplement mass, kg	Total mass of the mixture, kg
MS1, BS1	Walnut shells	58.17	17.01	75.18
MS2, BS2	Wood chips	58.17	17.55	75.72
MS3, BS3	Tree sawdust	58.17	8.37	66.54
MS4, BS4	none	116.34	0	116.34

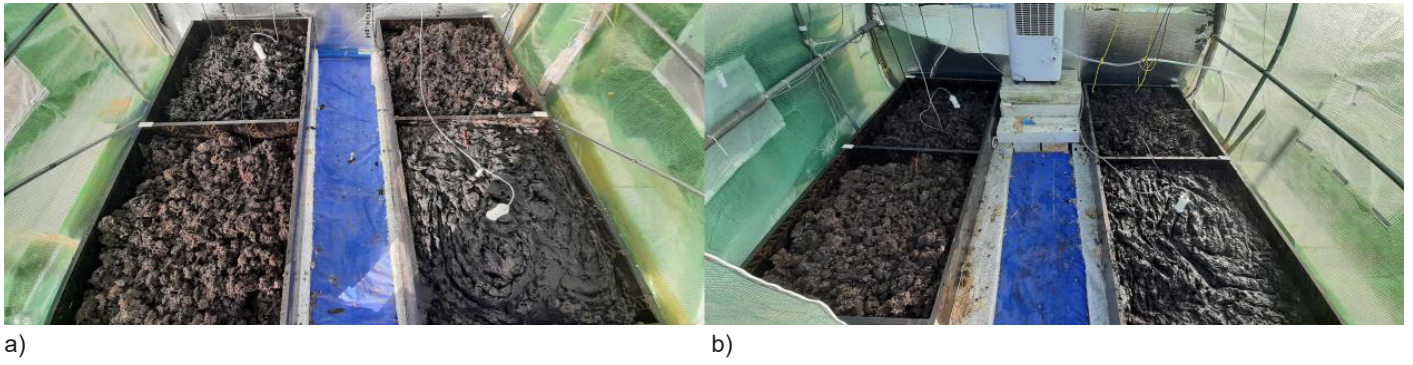


Fig. 2. Mixtures prepared for drying; a – zone B, b – zone M

initial thickness of the mixture layer was 15 cm, and the drying surface area of each container was 0.72 m². The materials used in the study are presented in Fig 1.

The arrangement of the containers with the mixtures was designed to ensure a similar layout in both zones (Fig. 2).

In zone B, drying was carried out under natural conditions without assistance. In zone M, drying also occurred under natural conditions but was supplemented with a dehumidifier rated at 0.8 kW and equipped with adjustable capacity, which operated continuously during the first 30 days of the process. The capacity of the dehumidifier was 270 m³ of air per hour. The mixtures in both zones were manually turned once a day. A maximum of 60 liters of leachate was collected over a 24-hour period.

To monitor the air parameters inside the tunnel, automatic sensors measuring air temperature and relative humidity were installed both beneath the roof of the dryer and directly within the material being dried in each container. Measurements were recorded continuously, enabling the analysis of daily variations in temperature and humidity. External meteorological data (air temperature, relative humidity, and insolation) were obtained from the official meteorological station of the Department of Horticulture located at Poznań–Ławica. The experiment lasted 80 days, from the end of September to mid-December 2024.

The moisture content of the mixtures was analyzed at regular intervals of 2–3 days. A composite sample was collected from each container and transported to the analytical laboratory of the Department of Water and Sanitary Engineering at Poznań University of Life Sciences. The determination of total and organic suspended solids was conducted using the direct gravimetric method in accordance with the PN-EN 872 standard. Based on these measurements, the following parameters were calculated using Eqs. (1-7):

$$H_{\%} = \frac{m_{aq}}{m_w} \cdot 100\% \quad (1)$$

where: $H_{\%}$ – moisture content of the mixture, %,
 m_{aq} – mass of water contained in the mixture, g,

$$m_{aq} = m_w - m_{og} \quad (2)$$

m_w – mass of the wet mixture, g,
 m_{og} – total dry mass of the mixture, g,

$$W = \frac{m_{aq}}{m_w} \cdot 1000 \quad (3)$$

where: W – water content in the mixture, kg/kg,

$$\Delta W = (W_0 \cdot M_0 - W_k \cdot M_k) \cdot 10^{-3} \quad (4)$$

where: ΔW – amount of water evaporated from the mixture, kg,
 W_0 – water content of the mixture before drying, g/kg,
 W_k – water content of the mixture after drying, g/kg,
 M_0 – total initial mass of the mixture before drying, kg,
 M_k – final total mass of the mixture after drying, kg,

$$\Delta W_m = \frac{\Delta W}{M_0} \quad (5)$$

where: ΔW_m – amount of water evaporated from the mixture per unit of the total initial mass of the mixture, kg/kg,

$$\Delta W_p = \frac{\Delta W}{A} \quad (6)$$

where: ΔW_p – amount of water evaporated from the mixture per unit of drying surface area, kg/m²,

A – drying surface area, m²,

$$\Delta W_{sm} = \frac{\Delta W}{M_{sm}} \quad (7)$$

where: ΔW_{sm} – amount of water evaporated from the mixture per unit of the dry mass of the mixture, kg/kg dm,

M_{sm} – dry mass of the mixture, kg.

The research results were compiled and presented in tabular and graphical form. The coefficient of determination (R^2) was calculated for the drying curves.

The energy consumption to support the drying process was also determined in relation to the overall results achieved. The resulting indicators, calculated per unit of sludge volume, evaporated water volume, and drying surface area, were compared with data available in the literature.

Results

The course of the drying process is directly influenced by the air parameters both outside and inside the dryer. Table 2 presents the environmental parameters of the mixtures being dried in both zones of the dryer, including insolation, air temperature, and air humidity. These environmental conditions directly influenced the temperature and moisture content of the mixtures being dried.

Figure 3 presents the average daily values of air temperature inside and outside the tunnel. During the initial phase of drying, the external air temperature fluctuated from a few to over a dozen °C, and the air temperature inside the tunnel was a few degrees higher, with the MS zone containing higher temperatures than the BS zone. During the second phase of drying, when the external air temperature fell below 10 °C and occasionally below 0 °C, the temperatures inside the tunnel

Table 2: Parameters of the environment and the examined mixtures

Drying zone		Zone BS				Zone MS			
Mixture		BS1	BS2	BS3	BS4	MS1	MS2	MS3	MS4
Insolation, MJ/m ²	min.	0.0039				0.0039			
	max.	9.3786				9.3786			
Temp. outside, °C	min.	-1.34				-1.34			
	max.	17.51				17.51			
Temp. inside, °C	min.	- 1.07				- 1.25			
	max.	25.82				27.90			
Humidity outside, %	min.	49.68				39.57			
	max.	100.00				100.00			
Temp. of mixture, °C	initial	25.32	26.15	24.67	26.09	21.63	21.62	21.64	21.64
	final	7.49	8.12	6.85	4.44	7.98	7.98	7.99	9.02
	min.	1.20	1.00	0.73	1.34	- 0.31	- 0.51	- 0.01	0.32
	max.	25.32	36.85	26.44	26.09	28.65	43.37	36.56	28.29
Humidity of mixture, %	initial	67.44	68.38	76.31	86.14	72.86	69.38	77.22	86.86
	final	52.19	50.69	58.82	84.84	20.83	21.12	22.67	65.13
	min.	47.80	50.56	56.81	84.48	18.46	20.41	16.81	65.13
	max.	68.05	68.38	76.31	86.59	72.86	69.38	77.22	86.86

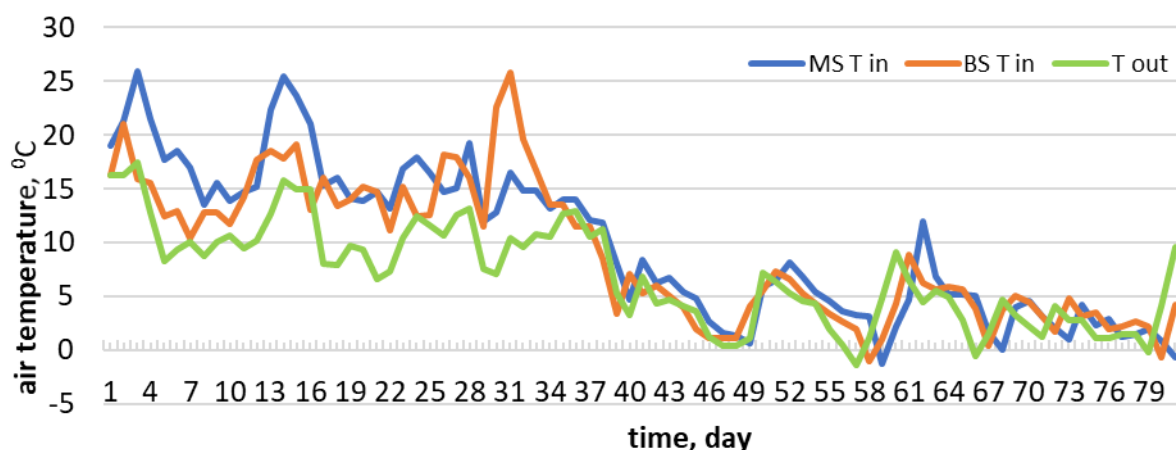
became comparable in both zones. Similar to the external conditions, the air temperature inside the tunnel decreased from more than 20 °C at the beginning of the process to only a few °C at the end. Overall, the difference between the initial and final air temperatures, both outside and inside the tunnel, exceeded 10 °C.

Fig. 4 presents the measured changes in air humidity inside and outside the dryer. This parameter exhibited considerable variability; however, during the operation of the dehumidifier, the humidity in the assisted MS zone was up to 40% lower than that in the unassisted BS zone. During the late autumn and winter periods, the air humidity in both zones periodically reached 100%.

The changes in air temperature and the temperature of the mixtures being dried were influenced by the variation in

solar radiation intensity during the autumn-winter study period (Fig. 5).

Figure 6 illustrates the changes in the temperature of the mixtures in the BS and MS zones during the drying process, as measured by the installed sensors. Similar to the ambient air temperature, the temperature of the mixtures gradually decreased from maximum values of 30–40 °C to minimum values below 10 °C. However, in the assisted MS zone, the diurnal temperature fluctuations and the differences between consecutive days were less pronounced. A direct comparison of mixtures with identical initial compositions dried under different conditions indicates that, during the initial phase of drying (approximately the first 20–30 days), the temperature of the assisted mixtures was higher for most of the time. This was associated with the more rapid evaporation of water, further

**Fig. 3.** Changes in air temperature inside and outside the drying room

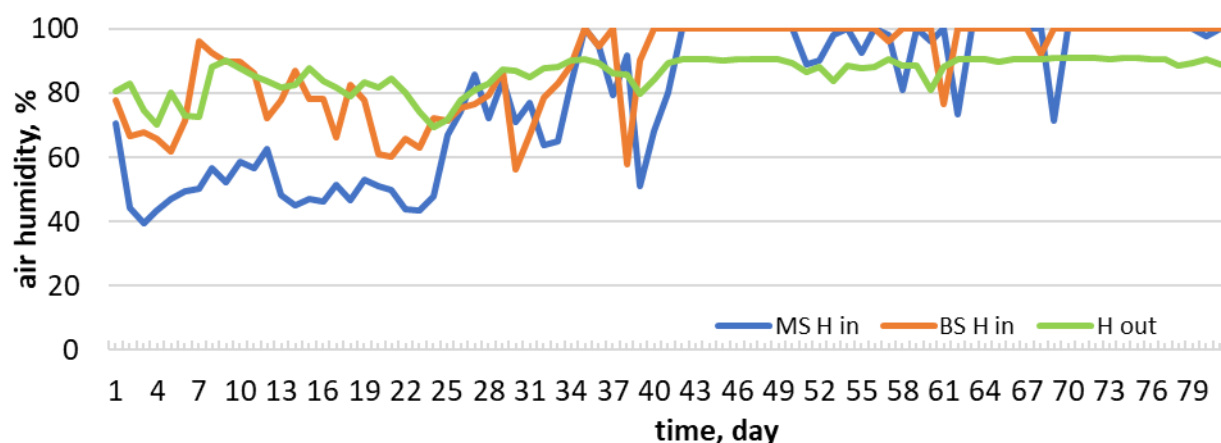


Fig. 4. Changes in air humidity outside and inside the drying room

enhanced by the operation of the dehumidifier. Although the dehumidifier was switched off after the first four weeks of the experiment, the elevated temperature of the assisted mixtures persisted for several additional days. During the second phase of drying, the temperature of the mixtures that had received assistance during the initial phase was lower than that of the unassisted mixtures.

Based on laboratory analyses of the moisture content of the mixture samples, drying curves were constructed using Eqs. (1) to (3), (Fig. 7). The drying of the mixtures in the tunnel section without the dehumidifier proceeded very slowly and inefficiently. After 80 days of the experiment, the moisture content of the sludge mixtures containing additives had decreased by more than 20 percentage points relative to the initial value, resulting in a final water content of 50–60%. In contrast, the moisture content of the sludge without additives decreased by only a few percentage points.

The drying of the identical mixtures in the tunnel section assisted by a dehumidifier proceeded considerably faster and with greater efficiency. After only 60 days, the moisture content of the mixtures had decreased to approximately 20% and was 30–40 percentage points lower than in the unassisted zone, representing a highly

favorable result under autumn-winter conditions. No further significant reduction in moisture content was observed during the subsequent 20 days of drying. The drying of the sludge without additives was less effective, confirming the previously reported positive effect of additives on the efficiency of sewage sludge drying (Makowska et al. 2025). The dehumidifier was switched off after 30 days of the experiment; however, this did not adversely affect the final drying outcome, indicating that the initial drying period is crucial for modifying the structure of the material being dried and promoting water removal. Similar observations have been reported in Germany, where the application of underfloor heating or forced-air ventilation increased drying efficiency by 20–30% (<https://www.eurotech.net.pl/ist.php>).

Fig. 8 presents the drying rate curves for the examined mixtures. During the initial phase of the process, the drying rate in the assisted MS zone was approximately three times higher than that in the unassisted BS zone. Approximately a dozen or so days after the deactivation of the dehumidifier, the drying rate of mixtures MS1, MS2, and MS3 continued to increase. In contrast, the drying rate of the mixtures in the unassisted zone was highest in the initial phase of drying and subsequently showed only a marginal increase.

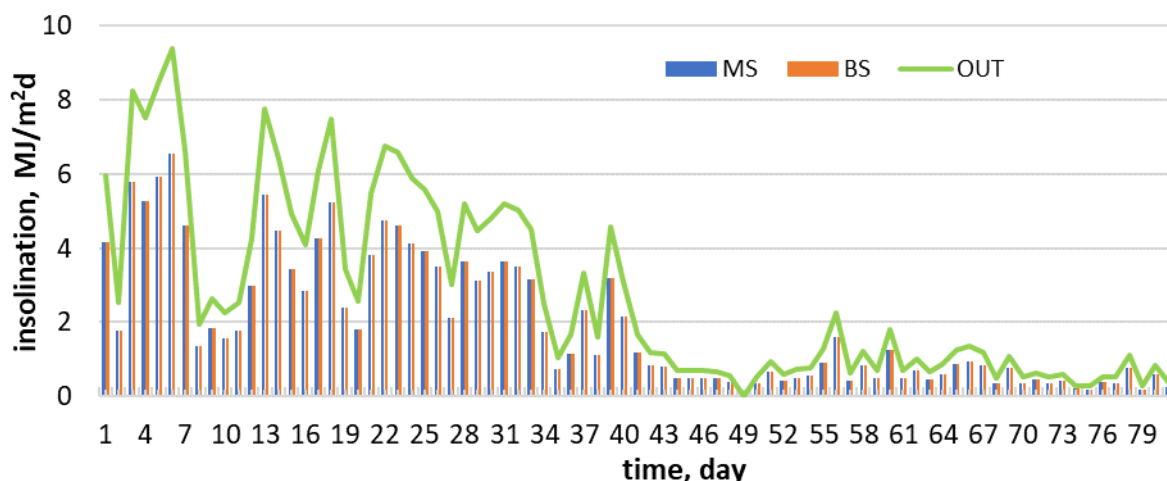


Fig. 5. Variation in solar radiation intensity during the research period; MS – assisted section, BS – unassisted section, OUT – outside the tunnel

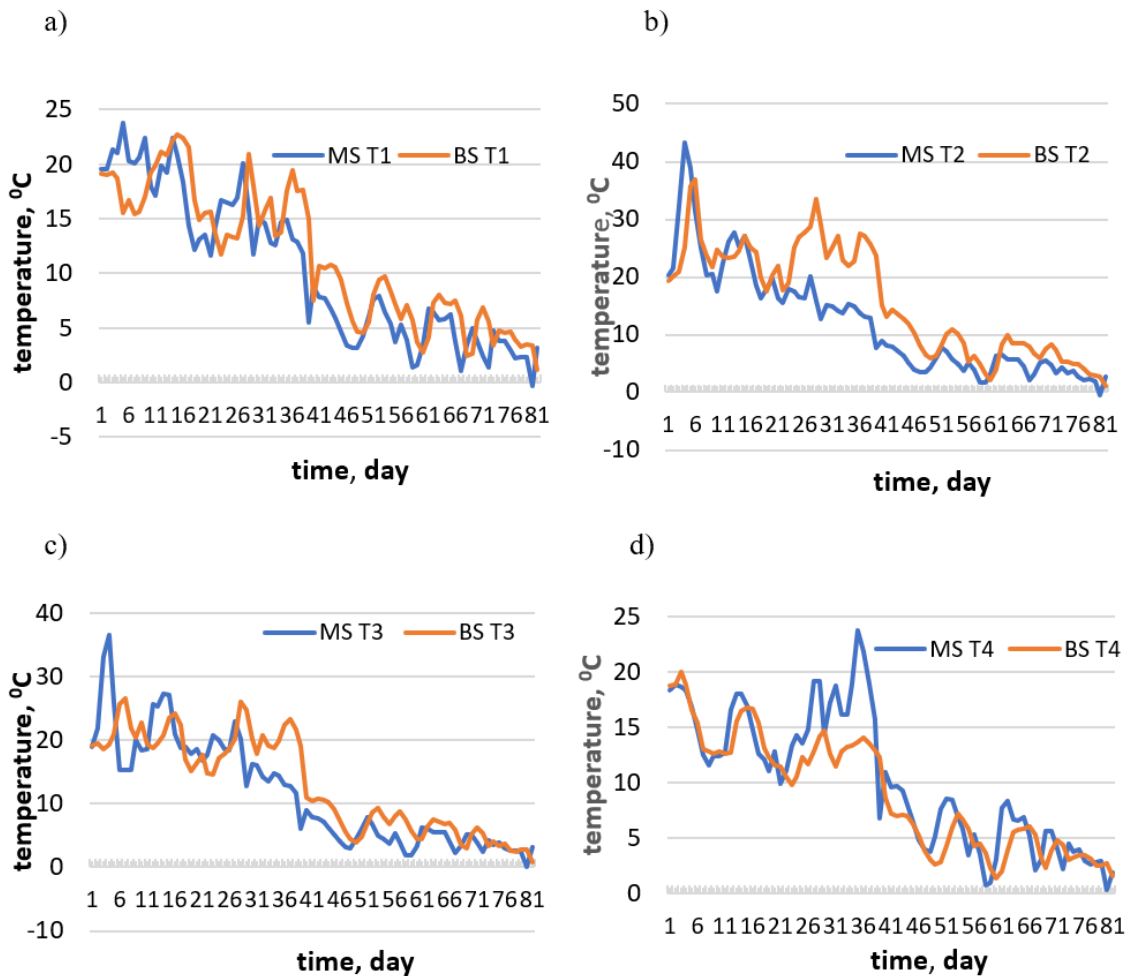


Fig. 6. Changes in the average daily temperature of the mixtures over time:
a – MS1 and BS1, b – MS2 and BS2, c – MS3 and BS3, d – MS4 and BS4

A coefficient of determination greater than 0.8 is considered to indicate good fit, whereas values between 0.6 and 0.8 indicate a satisfactory fit. These correspond to correlation coefficients (the square root of the coefficient of determination) of 0.7746 and 0.8944, respectively. In general, a correlation coefficient exceeding 0.7 is regarded as indicative of a good fit. According to Szydlowski (1978), for a significance level of $\alpha = 0.05$ and the number of points in the graphs—16 and 23—the corresponding critical correlation coefficients are 0.4227 and 0.4683, respectively. In conclusion, the fitted models can be considered statistically significant and representative of the experimental data.

The drying rate of the sludge without additives in the assisted zone was comparable to that observed in the unassisted zone, demonstrating that the application of additives was responsible for improving the drying performance of the sewage sludge mixtures.

Using Eqs. (4) to (7), the amount of water evaporated during the drying of the mixtures was calculated (Fig. 9). The results showed that the total amount of evaporated water, as well as the amounts expressed per unit of the total mass and dry mass of the mixtures, was consistently greater under assisted drying than under unassisted drying. For the mixtures containing biocomponents, the amount of evaporated water in the MS zone was 1.3 to 3.4 times greater than that in the

BS zone. The highest values were obtained for the mixtures containing sawdust and walnut shells in the MS zone and for the mixtures containing sawdust and wood chips in the BS zone. In the case of the sludge without additives (control sample), the difference was as much as 30-fold.

During the drying process, the organic matter content in the mixtures was also analyzed. Fig. 10 illustrates the organic matter content of the examined mixtures, expressed on a dry matter basis, at the beginning and end of the drying process. A decrease of several percentage points indicated that mineralization of organic substances occurred during drying.

An important aspect of the process is the amount of energy required to support drying. During the study, the energy consumption amounted to 1.235 kWh/kg of evaporated water. Compared with the value of 1.750 kWh/kg of evaporated water reported by Trojanowska (2010) for a dryer equipped with underfloor heating, this represents a favorable result for the proposed solution. The energy consumption per unit of drying surface area was 97.24 kWh/m², which is significantly higher compared to 311 kWh reported for the dryer in Kłodzko (Trojanowska et al. 2012). Comparison with studies conducted in regions characterized by substantially higher solar radiation are less meaningful due to the much greater contribution of solar energy, including its storage, as reported, for example, in Chile (Poblete and Pinemal 2020).

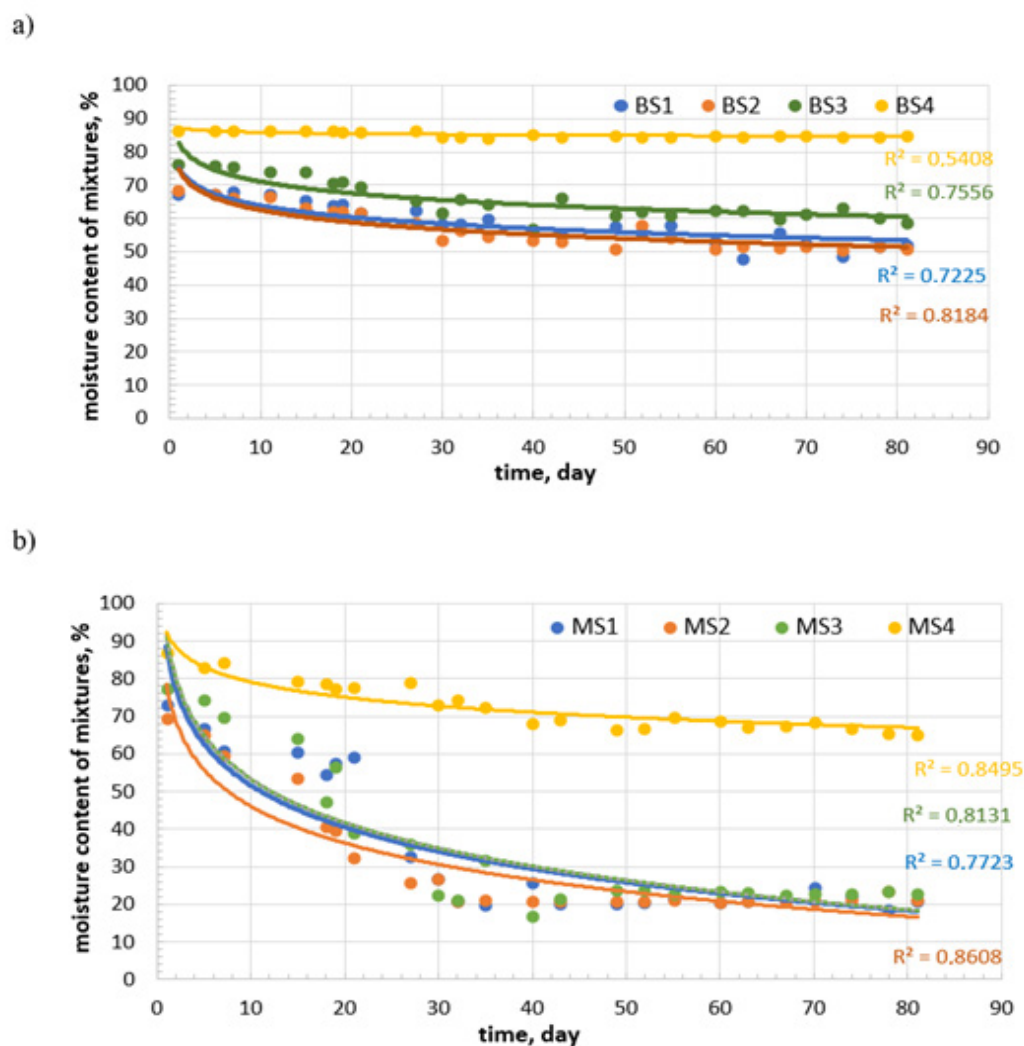


Fig. 7. Drying curves of the mixtures: a – unassisted BS section, b – assisted MS section

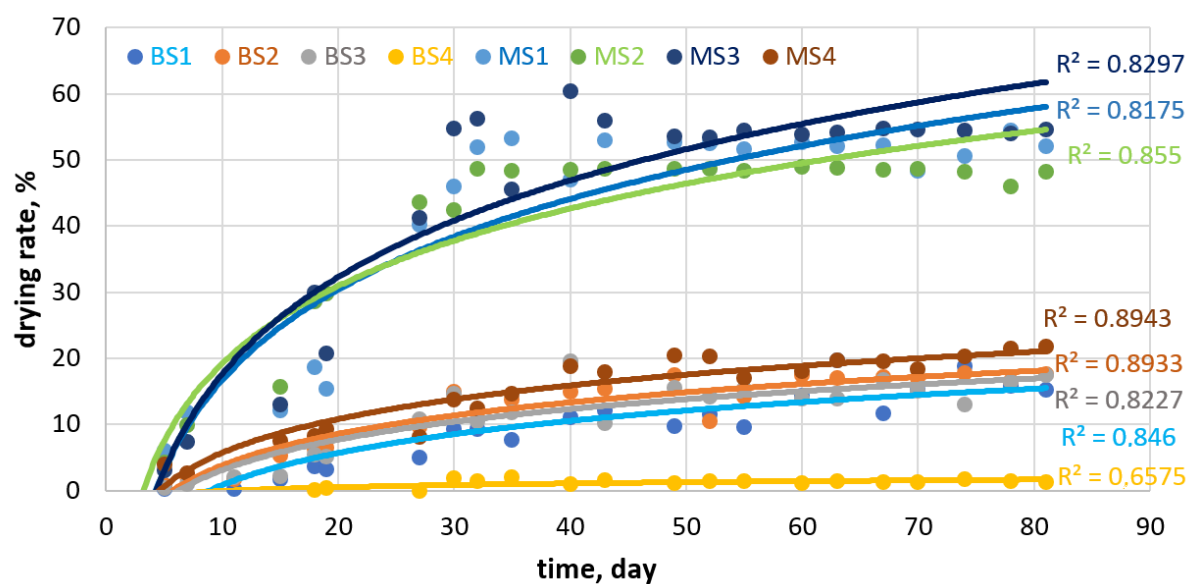


Fig. 8. Drying rate curves of the tested sludge mixtures with biocomponents

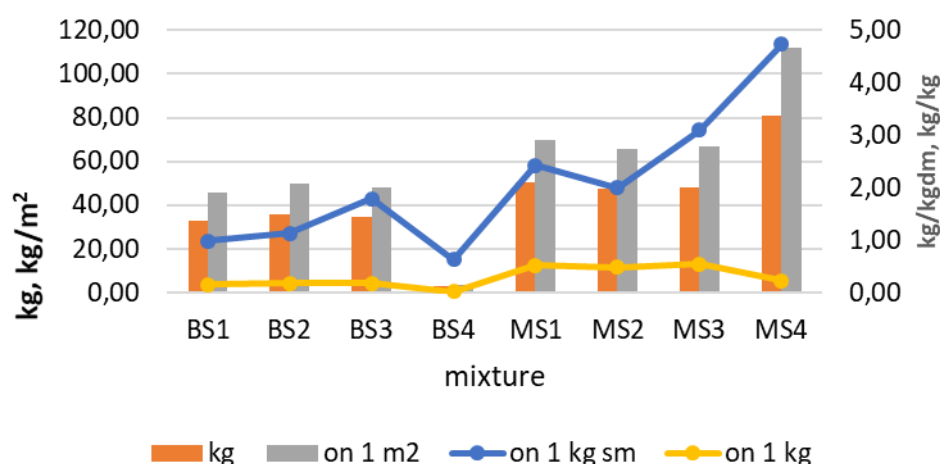


Fig. 9. Amount of water evaporated from the mixtures being dried

Conclusions

The pilot-scale study on the drying of sewage sludge with biocomponents in a polytunnel dryer clearly demonstrated the positive effect of using a dehumidifier as an auxiliary component in the drying process. During the initial 30-day drying period, the relative humidity in the assisted zone was lower, whereas the air temperature was higher than in the unassisted zone, resulting in improved drying conditions and enhanced process efficiency. After 30 days of the dehumidifier operation, the moisture content of the mixtures in the assisted zone was 20 to 30 percentage points lower than that in the unassisted zone, despite identical initial values. Although the dehumidifier was switched off after this period, the moisture content of the assisted mixtures decreased to approximately 20% during the subsequent 30 days, a level sufficient for the transport and further utilization of the dried material. The uniform progression of drying following the deactivation of the dehumidifier indicates that the initial stage of the process is critical to the final drying outcome. The amount of water evaporated from the mixtures in the assisted zone was more than three times greater than in the zone without dehumidifier assistance. The study also confirmed the beneficial impact of the bio-additives on the drying process. Although drying of

the sludge without additives proceeded more effectively in the assisted zone than in the unassisted zone, the process remained slow, resulting in a final reduction in moisture content of only 20%. The application of a dehumidifier as an auxiliary drying device is a simpler and less energy-intensive solution than a hybrid system based on heat pumps and underfloor heating. Combined with the use of structural additives, it may represent a favorable option for small and medium-sized wastewater treatment plants.

The proposed system is easy to implement in solar sewage sludge dryers of any size. When combined with the dryer's ventilation system (air inlets and exhaust vents) and a sewage sludge turner, it can significantly reduce the sludge drying time. A considerable reduction in the moisture content of the sludge also decreases its volume, facilitating storage when immediate utilization is not possible and reducing transport costs. Furthermore, the dried sludge can be used for energy recovery, for example, through co-incineration, provided that it meets the combustion requirements for this type of material.

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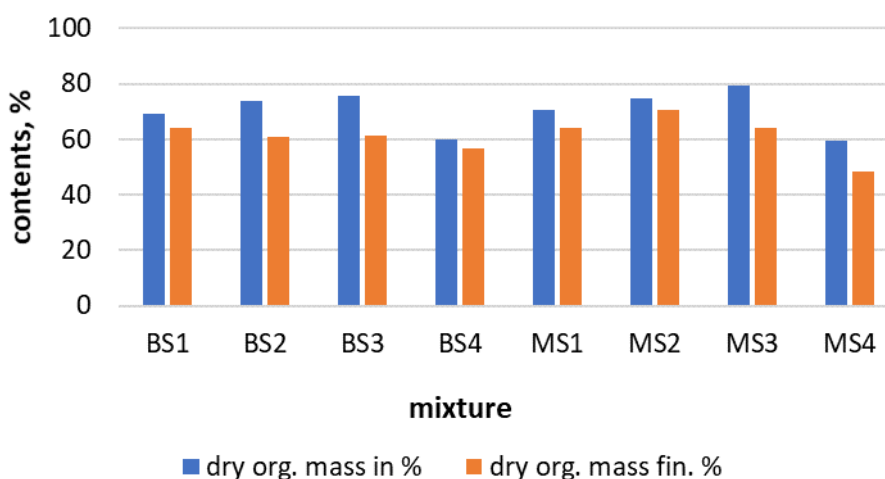


Fig. 10. Change in the dry organic matter content in the tested mixtures

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Patents

The results presented in this publication formed the basis of Polish patent application No. P.445919, entitled „Technology for the use of natural materials in the solar drying of sewage sludge and production of sewage sludge-based briquettes”.

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Wpływ pochłaniacza wilgoci na proces suszenia solarnego biomieszanek na bazie osadu ściekowego

Streszczenie: Jedną z metod przeróbki osadów ściekowych jest ich suszenie. Wykorzystanie w tym celu energii słonecznej jest korzystne pod względem ekonomicznym oraz umożliwia stosowanie procesu suszenia w małych i średnich obiektach oczyszczających ścieki. Jednak w polskim klimacie problemem jest okres roku od jesieni do wiosny, kiedy intensywność promieniowania słonecznego i temperatura powietrza spadają i proces naturalnego suszenia jest mało efektywny. Jako wspomaganie, zamiast dodatkowego ogrzewania suszarni słonecznej, można zastosować pochłaniacz wilgoci, który w połączeniu z wykorzystaniem biokomponentów dodawanych do osadu przeznaczonego do suszenia zdecydowanie poprawia efekt procesu. Suszenie mieszanek osadu z dodatkami przeprowadzono w okresie jesienno- zimowym, w tunelu ogrodowym o powierzchni 10 m², podzielonym na dwie sekcje: bez wspomagania i ze wspomaganie pochłaniaczem wilgoci. Suszono mieszanki osadu z dodatkiem łupin orzecha włoskiego, zrębków drzewnych i trocin oraz osad bez dodatków będący próbą kontrolną. Stwierdzono, że zastosowanie pochłaniacza wilgoci już tylko w pierwszej fazie suszenia pozwoliło na końcowe obniżenie wilgotności mieszanek do 30-20% już po 40–60 dniach, co jest wystarczające dla ich magazynowania, transportu lub dalszego wykorzystania. Ilość odparowanej wody z mieszanek z dodatkami w sekcji ze wspomaganie, podobnie jak szybkość suszenia, była kilkukrotnie większa. Dla osadu bez dodatków różnica w ilości odparowanej wody była nawet 30-to krotna. Efekt końcowy uzyskany dla mieszanek z biokomponentami ze względu na wyjściowe uwodnienie i strukturę suszonego materiału był zdecydowanie lepszy, niż dla osadu bez dodatków, co stwierdzono już we wcześniejszych badaniach, prowadzonych w warunkach naturalnych w okresie wiosenno-letnim.