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Enhanced Sewage Sludge Drying with a Modified Solar Greenhouse

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Abstract: This work reports the results obtained with an innovative configuration of a closed-static solar greenhouse for sludge drying. The novelty of the solar greenhouse configuration consisted in using a forced ventilation system to provide hot air for sludge drying and the utilization of solar irradiation for energy supply. Wet sewage sludge (97% humidity) was successfully dried up to a residual humidity close to 5% after 25 days during wintertime. The increase of the airflow rate supplied under the sludge bed improved the sludge drying rate. Moreover, the fraction of volatile suspended solids decreased from 70% to 41% after 13 days, indicating that air supply promoted the simultaneous stabilization of the sludge as a side-effect to the drying process. Overall, the specific energy consumption per ton of evaporated water was estimated to approximately 450 kWh/t, resulting in about 55% of energy demand lower than a conventional thermal drying system, while using only free solar energy. The achieved high weight reduction of up to 99% implies a noticeable reduction of the excess sludge handling costs, indicating that solar greenhouse drying is a highly interesting opportunity for sludge drying in medium-small sized WWTPs.

Keywords: excess sludge reduction; convective drying; greenhouse; renewable energy; solar sludge drying; sustainable sludge management

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1. Introduction

Nowadays, among the sensitive environmental problems in the wastewater treatment sector, the treatment and disposal of excess sludge is one of the most debated [1]. Sewage excess sludge arises from the treatment of wastewater because of the growth of bacteria, accumulation of inert solids contained in the wastewater and accumulation of endogenous residue [2]. The sewage sludge handling is related to high operating costs in a wastewater treatment plant (WWTP), which varies depending on the plant's location and the treatment technology implemented in both the wastewater and sludge handling units. Sludge treatment and disposal could account for up to 60% of the overall operating costs in a conventional WWTP [3]. It was estimated that the average price for sludge disposal (including transport cost) ranges between 200 and 600 EUR/t depending on dry percentage values [4]. After conventional dewatering processes, excess sludge is still characterized by a high water content (40–80% wt), which still results in a very large volume to be disposed [5]. Then, the dewatered sludge is transported to the disposal site by road tanker, generally. In medium-small sized WWTPs, the impact of sludge transportation on the total disposal cost could be significant, especially if the disposal site is placed far from the plant. With a view to a cost-reduction program, recent research pushed forward the implementation of innovative and cost-effective solutions aimed at reducing the excess sludge handling costs.

In this sense, the application of advanced dewatering processes aimed at reducing the sludge humidity is an interesting solution to reduce transport and disposal costs. In recent years, thermal drying methods were adopted to dry waste sludge [6]. The typical thermal methods include convection heat transfer of direct hot gas blasting and conduction heat transfer of steam inside screw conveyors. However, although thermal drying is an efficient method, it implies significant fuel consumption and potential emission of greenhouse gases (mainly CO_2). Indeed, a recent study estimated that the average energy requirement was in the range of 1.87–2.68 kWh/kg [7]. Thus, thermal drying is very energy intensive; therefore, it is economically convenient only when excess or waste heat is available [8].

With a view of implementing environmentally friendly processes and using renewable energy sources, the application of solar greenhouse drying systems appears a practical and beneficial solution for medium-small sized WWTPs located in climate zones characterized by high solar radiation. Conventional solar greenhouses exploit the combination of hot water generated by solar energy additionally to the energy given by the greenhouse effect [9]. In general, a static greenhouse for sludge drying is constituted by an impermeable floor, heated with hot water pipes, on which the wet sludge is disposed, and roof in transparent material (i.e., polycarbonate or glass) that create the greenhouse effect. In these systems, the wet sludge is placed within the solar greenhouse and no mixing systems are provided for sludge movement. A ventilation system located above the sludge powered by means of conventional energy sources provides the continuous air renewal and allows water evaporation from the sludge and the transport of the water out of the unit.

Previous studies carried out on open and closed-static greenhouse dryers demonstrated that approximately 55–80% [9] and 90% [10] of dry solid concentration could be obtained in less than 2 months by implementing a hot water recirculation circuit under the greenhouse gravel. Belloulid et al. [11] dried mechanically dewatered sludge in an open greenhouse pilot located at Marrakesh city, obtaining at least 80% volume reduction both during summer and winter. A recent study investigated a purely solar-driven greenhouse facility for sewage sludge drying under different conditions [12]. The authors obtained residual humidity lower than 10% with a low specific energy consumption close to 0.28 kWh/kg evaporated water. In these systems, heat conduction is the predominant method of transferring heat to the wet sludge. Indeed, sludge drying by heat conduction involves almost the entire mass of the sludge, whereas heat convection is limited to the superficial layers only. For higher potential installations, dynamic solar greenhouses can be used [13]. These are structurally similar to the static solar greenhouse but are equipped with a scarifying surface machine that turns over the sludge enabling to improve the sludge drying rate. Nevertheless, these systems could be more susceptible to wear and are not indicated for small installations. A recent study evaluated the feasibility to perform sludge drying in a solar greenhouse, achieving about 70% of residual dry content [14]. In the same study, the authors suggested the possibility of using solar panels to supplement additional energy requirements to reach a higher dry solid content. According to this study, the supplement of energy provided by the solar energy could allow obtaining higher dry solid content and resulting in a less costly solution for sludge drying.

To the best author's knowledge, static solar greenhouses for sludge drying based on the principle of heat convection were not proposed so far. Considering this, the present paper reports the first results obtained with an innovative configuration of a closed-static solar greenhouse for sludge drying. The main novelty of this solar greenhouse was the use of a forced ventilation system to provide hot air for sludge drying instead of hot water below the wet sludge, and the utilization of 100% green energy for the operation of the entire system. The innovative system proposed could be considered for retrofitting existing sludge drying beds in medium-small sized WWTPs for intensification of sludge drying with a low-cost process.

2. Materials and Methods

2.1. Solar Greenhouse Description

A pilot scale greenhouse was designed and constructed using a polyvinylchloride (PVC) tank of 0.97 m length, 0.64 m width. The horizontal surface area was equal to 0.62 m^2 and the overall volume was 0.42 m^3. The roof had a height of 1 m at the top and it was constituted by two 10 mm transparent polycarbonate sheets inclined at 45 degrees.

The bottom of the PVC tank was shaped by a thin concrete layer to provide a slope of approximately 1% toward a drainage pipe placed along the longitudinal axis of the tank. A drainage layer consisting of about 0.20 m of gravel with different particle size distribution (20–30 mm and 4–8 mm) and 0.05 m of sand was placed on the bottom of the tank.

The solar greenhouse was equipped with a forced ventilation system to provide hot air for sludge drying and to overcome the hydraulic head losses through the drainage and wet sludge layers. To this aim, a side-channel air blower (engine power of 0.2 kW, pressure 20 mbar) was installed. Air was introduced through two different inlet points: a perforated pipeline (6 mm medium-sized holes) placed within the drainage sand layer and above the sludge layer by means of three orifices (6 cm diameter) horizontally arranged. A properly shaped stainless-steel profiled sheet was placed on the perforated pipeline to ensure a homogeneous distribution of the air and to avoid the water percolation inside it. Hot air was produced by an aero-thermal flat solar panel (courtesy of SolarAir) (1.30 m^2) tilted at a 30 degree angle and south-oriented. Two dedicated flowmeters allowed the air flow regulation. A dedicated polysilicon photovoltaic panel (1.00 m^2) supplied energy to the air blower during daylight hours. The roof of the solar greenhouse was equipped with 5 microfans (3 W) to ensure the discharge of the saturated air and provided air renewal within the plenum. Moreover, a system for drainage of condensed water was installed on the inner walls of the roof.

The sidewalls of the tank were insulated with a polyurethane foam and an isothermal blanket to avoid heat dispersion and conductive heat transfer to the outside. Figure 1 depicts a schematic view of the solar greenhouse.

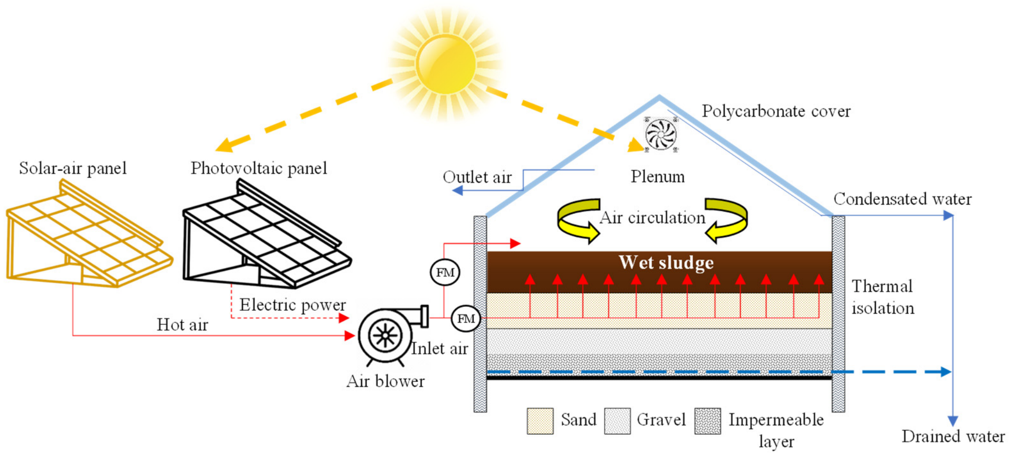

Figure 1. Schematic view of the static solar greenhouse.

2.2. Operating Conditions and Monitoring Activities

The experiments were carried out during the winter period, from 18 February to 12 March, in Palermo, Italy (38°6′20.3832″ N-13°20-49.7868″ E), and lasted 25 days. The excess sludge used for the experiment was collected downstream the pre-thickened unit from a municipal WWTP located in Palermo. The sludge was characterized by a humidity close to 97% and a ratio between volatile and total suspended solids (VSS/TSS) of 0.73. Then, the sludge was spread above the drainage layer that was previously wet with tap water to reach its water-holding capacity. The volume of the sludge placed within the solar greenhouse was 125 L, resulting in an initial thickness of approximately 16.5 cm.

The airflow rate over the sludge layer was set to approximately 15 m^3/h during the entire experiment, whereas that supplied through the perforated pipeline under the sludge was set to 2 m^3/h until the 19th day, and it was increased to 10 m^3/h for the remaining days. The air blower was operated only during the daytime, from 7 am to 4 pm; thus, the air was supplied for approximately 9 h a day.

Temperature was measured in four different points. Specifically, the outdoor and indoor air temperatures (in the plenum) were measured three times per day by means of a digital thermometer. Furthermore, the temperature in the air stream at the outlet of the solar panel was measured by means of a hot-wire anemometer equipped with a thermometer, whereas that above the sludge bed was recorded continuously by means of a specific temperature sensor. The humidity of the sludge at different depths was continuously monitored with 5 specific sensors (one every 4 cm from the bottom of the sludge layer) connected to an Arduino board. The volume of water drained was collected within a storage tank. Then, the trends of the residual humidity and the drainage curve of the sludge were daily assessed. The dry content of the sludge and the VSS/TSS was measured three times per week.

2.3. Analytical Methods

All analyses including the measurement of the sludge humidity and dry content, the total and volatile suspended solids concentrations, were performed according to the standard methods [15].

The maximum solar radiation was obtained from a free online database (SIAE-Sicilian Information Agro-meteorological Service). Other climatic parameters were collected from the meteorological control unit of the University of Palermo located about 50 m from the greenhouse installation's site.

2.4. Calculation

To assess the drying kinetic of the sludge, the drying curve was determined. This curve shows the variation in drying rate of the sample as function of the residual humidity of the sludge. The drying rate was determined by measuring the volume of water drained in a precise time interval, whereas the residual humidity of the sludge was calculated by subtracting to the initial water content the cumulative volume of water drained.

3. Results

3.1. Atmospheric and Solar Greenhouse Environment Parameters

The drying process of sewage sludge depends on weather conditions, which affect the solar radiation intensity, air temperature and relative humidity. The area's Mediterranean climate is characterized by mild, rainy winters and warm, sunny summers. Mean annual solar radiation ranges from 3.6 kW/m^2 in the north area to 4.7 kW/m^2 in central-southern Italy and 5.4 kW/m^2 in Sicily. Consequently, the entire territory has favourable characteristics for implementing innovative technologies based on solar energy utilization.

Figure 2 shows the trends of the average temperature measured at different points of the solar greenhouse and the maximum solar radiation as a function of the wheatear conditions during the experiment.

During the first 14 days, weather was sunny or slightly cloudy, whereas during the remaining part of the experiment, it changed to mostly cloudy with rainfall events occurring on days 23 and 24. The maximum daily incident solar radiation was influenced by the weather conditions (Figure 2b). Higher values were observed during sunny days, while lower ones in correspondence of cloudy or rainy weather. Overall, the average value of the daily incident solar radiation ranged between 1 and 3 MJ/m^2. The sum of the solar radiation falling on the surface of the sludge during the experiment was about 22.5 MJ/m^2, corresponding to 6.25 kWh/m^2.

The outdoor and the indoor temperatures measured in the plenum of the greenhouse were affected by the incident solar radiation, showing a variable trend in relationship with the outside wheatear conditions. Conversely, the temperature measured above the sludge layer was quite constant (37 ± 3 °C), and this resulted slightly lower than that measured in the external air stream (40.5 ± 4 °C), thus suggesting that the heat loss within the sludge bed was low. Therefore, the upflow of hot air and the greenhouse effect allowed maintaining the sludge at a quite constant temperature, about three times higher than the outside temperature. Moreover, the greenhouse effect enabled to avoid an excessive heat loss during the nighttime hours when no solar irradiation was available neither hot air was supplied.

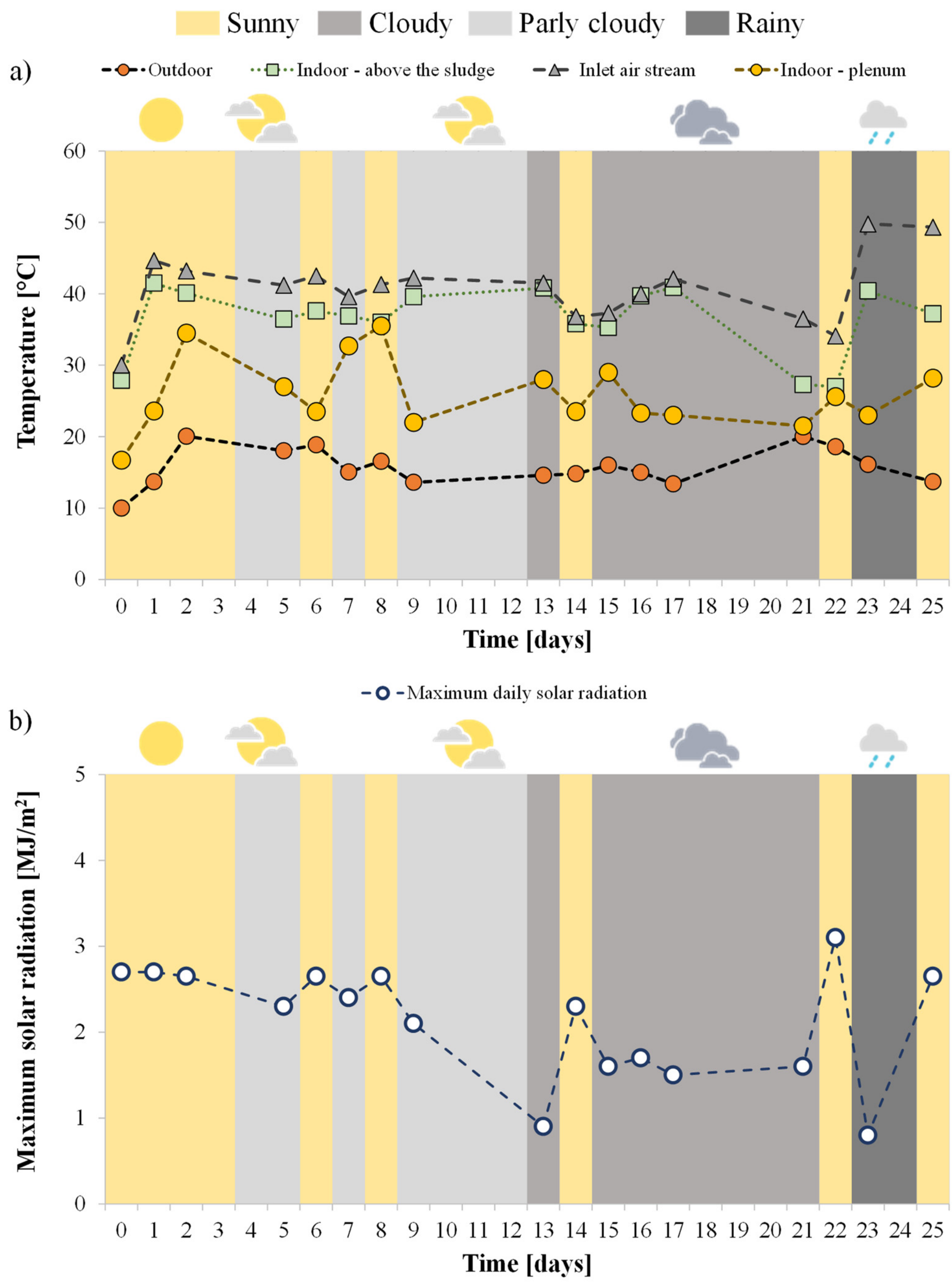

Figure 2. Wheatear conditions, trends of the average temperature measured in different points (**a**) and trend of the maximum daily solar irradiation (**b**).

3.2. Sludge Residual Humidity

The effect of different airflow rates supplied under the sludge layer on the sludge drying process was evaluated in this experiment. Figure 3 shows the trend of the residual humidity in relationship with the airflow rate blown below and above the sludge layer.

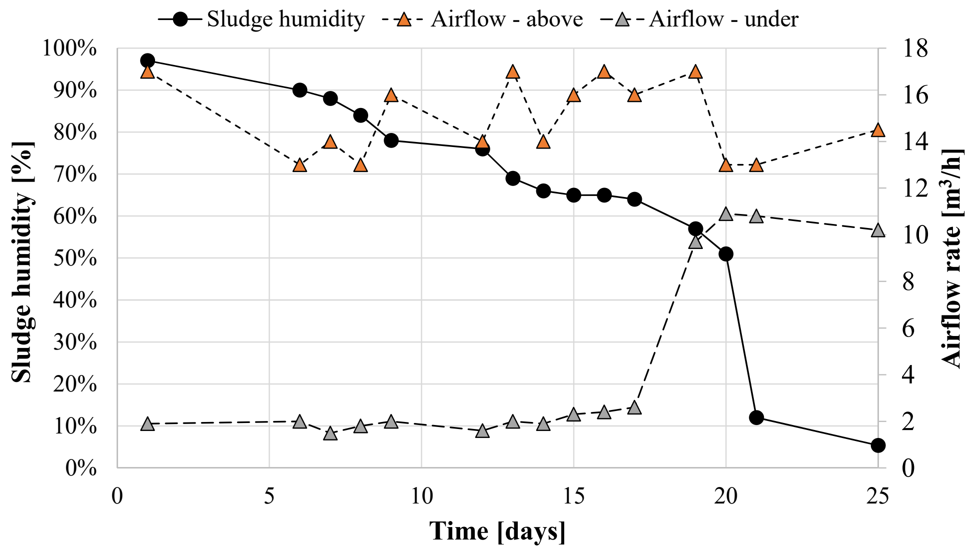

Figure 3. Trends of the residual humidity and the airflow rates during the experiment.

The drying rate was constant during the first 18 days, resulting equal to approximately 2.30% of humidity loss per day. Starting from the 19th day a very rapid increase in the drying rate was observed, which resulted in a much higher humidity loss, close to 4%/d. This suggested that the airflow rate supplied from the bottom of the sludge layer affected the sludge drying performances and kinetics. At the end of the observed period, the residual sludge humidity resulted close to 5%. The residual humidity obtained in this study was noticeable lower compared with that achieved with conventional thermal dryer and conventional solar greenhouses [16,17]. Moreover, the obtained results indicated that the proposed configuration enabled a faster drying kinetic than that obtained using conventional solar greenhouse. Indeed, Salihoglu et al. [9] obtained a final humidity close to 60% in 55 days in an open-static solar greenhouse with surface ventilation only, whereas approximately 20% of residual humidity was achieved by implementing a transparent coverage in the same system. Similarly, Lei et al. [18], using a greenhouse without forced ventilation under the sludge layer, obtained a residual humidity close to 44% in less than 25 days during wintertime, whereas in summer, the time required for achieving the same results decreased to less than a week. The findings of the present study indicated that the forced ventilation under the sludge promoted a significant improvement in the sludge drying process. A possible explanation could be related to the effect of the air speed blown under the sludge layer. Indeed, previous studies demonstrated that the increase of the air speed promoted the formation of shrinkage and cracks that speed up, significantly, the drying process also improving the result in terms of residual humidity [19]. In this respect, it was noted that when the airflow rate was increased, the number of cracks increased consistently and resulted in a much more efficient and quicker drying rate of the sludge. Recent studied found that providing air when the sludge thickness is small results in a significant increase of the drying rate [20]. Nevertheless, this aspect should be better elucidated in future studies.

The overall total solar radiation falling on the solar greenhouse during the experiment was equal to 36.3 kWh; that referred to the unit of the greenhouse surface resulted equal to 6.25 kWh/m^2. The energy consumption by the air blower was calculated by multiplying the power consumption (0.13 kW) for the usage time during the experiment (9 h per day for 25 days). This resulted equal to 29 kWh; that referred to the unit of the greenhouse surface resulted equal to 48 kWh/m^2. Thus, the specific energy consumption per ton of evaporated water (0.121 t) was estimated to approximately 450 kWh/t. This value was significantly lower than the energy consumption of conventional dryers, which is reported in literature as close to 1000 kWh/t [21]. Furthermore, the energy consumption in the solar greenhouse was fully covered by solar energy and is, therefore, free of charge.

3.3. Insights into Sludge Drying Process

To provide additional details about the sludge drying process and kinetics, the drainage curve and the sludge humidity at different levels were determined. Figure 4 shows the drainage curve obtained during the experiment (Figure 4a) and a detailed view of the several phases during the sludge drying process (Figure 4b).

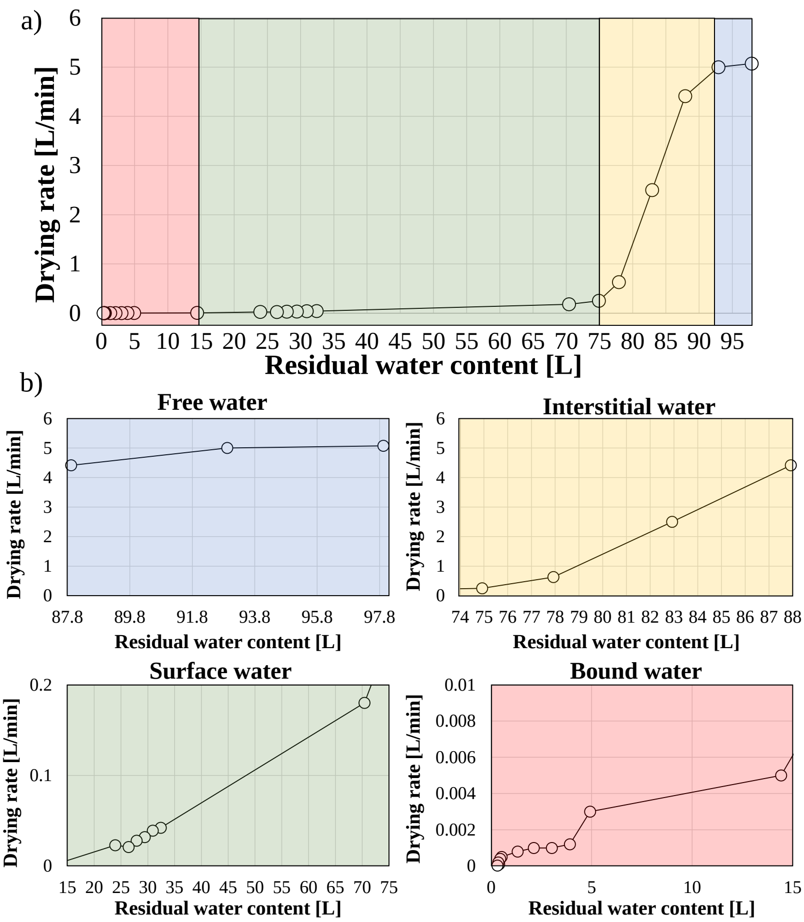

Figure 4. Sludge drying curve (**a**); detailed view of the several phases during sludge drying process (**b**).

The sludge drying curve (Figure 4a) showed the typical profile of wastewater sludge drying process reported in previous studies [22]. In detail, the beginning phase of the curve was characterized by a quite constant water loss rate close to 5 L/min, which corresponded to the removal of free water as reported in the literature [23]. This phase lasted about 3 min during which approximately 8% of the initial water content of the sludge was removed (Figure 4b). After this phase, two falling rates were noted, corresponding to the removal of the interstitial and surface waters [24]. More precisely, the first falling rate was characterized by a decreasing linear tendency of the water loss rate from 5 L/min to less than 0.20 L/min and determined the removal of approximately 17% of the initial water content. In the second falling rate, the water loss rate decreased by one order of magnitude from 0.20 L/min to 0.020 L/min, resulting in a decrease of the water content close to 50% of the initial humidity of the sludge. This result agreed with a previous study in which it was reported that approximately 50% of the overall sludge water content was the surface one [25]. Even the last part of the curve showed a further linear decrease of the water loss rate that decreased up to 0.20×10^{-3} L/min. In this phase, approximately 15 L of the residual humidity was removed, resulting in a final humidity of the sludge close to 5%. These results were in agreement with a previous study carried out with a solar greenhouse [26]. In general, the drying rate resulted higher than that reported in previous studies carried out with conventional solar greenhouses [9,27]. Nevertheless, similar drying rates than those reported in the present study were obtained using forced a ventilation system for sludge drying [28–30]. The results obtained in this study indicated that the implementation of a forced convective dryer of the sludge determined higher drying kinetics and a more efficient removal of the residual humidity than a conventional solar greenhouse.

Figure 5 depicts the trends of the sludge humidity registered by sensors located at different levels from the surface during nine operational days.

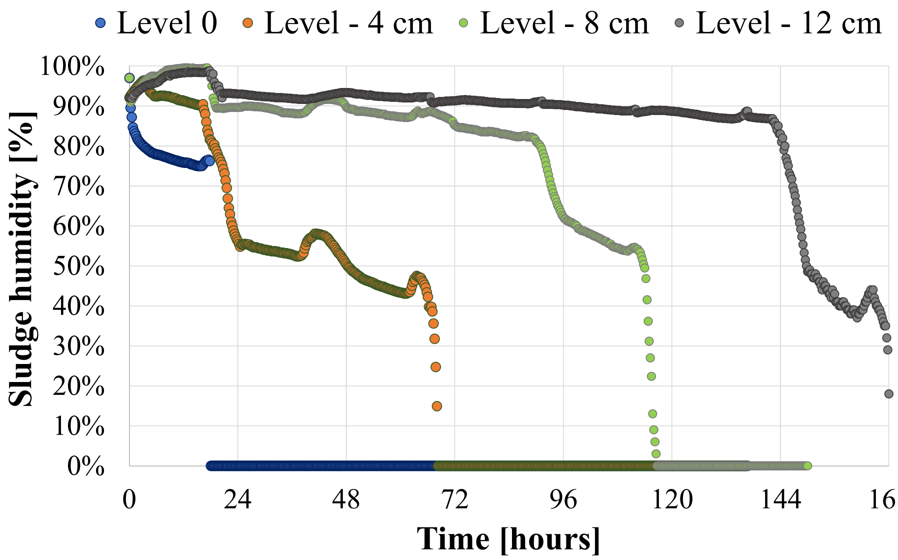

Figure 5. Trends of sludge humidity at different levels within the sludge.

Four different phases were observed, each of which characterized by a different drying rate and duration. The uppermost sensor revealed a very fast decrease of the humidity during the first minutes of operation. After that, the humidity decreased linearly, although showing a lower tendency than the previous one, until the sensor was not more in contact with the sludge. In the lower sludge layer (sensor at −4 cm from the surface), the humidity increased during the first 24 h of operation likely due the drainage of the water from the upper layers (phase 1).

Hereafter, the humidity decreased although showing different trends. Specifically, the humidity first reduced very rapidly with a humidity loss rate close to 1.1%/min (phase 2) and after, the tendency decreased resulting to a humidity loss rate close to 7×10^{-3}%/min (phase 3). The latter tendencies were replicated (phase 4 and phase 5) in the following two days, although characterized by a longer extent until the sensors were uncovered. The profiles of the humidity were replicated also in the lower layers of the sludge. More precisely, the length of phase 1 increased in the deeper layers, whereas the duration of phase 2 was similar and occurred simultaneously in the lower layers. Phase 3 was the longest and its length increased with depth, whereas phase 4 had a similar duration in all the layers. Finally, the duration of phase 5 decreased with depth and this was characterized by a temporary increase of the humidity during the night hours.

The phases characterized by the highest humidity loss were the second and the fourth. According to the literature, these phases corresponded to the loss of free and surface waters [25]. In more detail, it is interesting to highlight that the removal of the surface water was faster than that obtained from the conventional solar greenhouse based on heat conduction to the wet solids [12,22]. This suggested that the convective heat transfer principle contributed to enhance both the sludge drying performances and kinetics. Moreover, it is worth noticing that some of the above-described drying phases are quite short, whereas others are longer. This suggested that further studies are necessary to investigate the effect of process parameters on the duration of the longest drying phases to define the best operating conditions to obtain sludge drying in a shorter time. The data reported in this study could establish the basis for further research on this type of greenhouse to deepen the sludge drying through a mathematical approach with the aim of process optimization.

3.4. Reduction of Initial Sludge VSS and Weight

Figure 6 shows the initial and final values of VSS/TSS ratio and sludge weight. Wet sludge was characterized by an initial weight close to125 kg, whereas the fraction of volatile suspended solids was 73%.

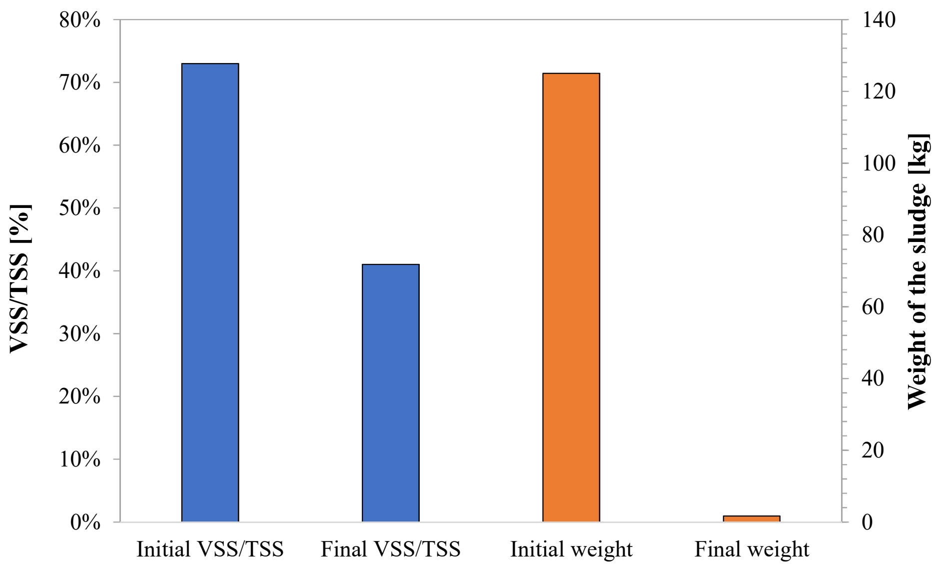

Figure 6. Initial and final values of VSS/TSS and weight of the sludge.

The fraction of volatile suspended solids dropped to 41% after 13 experimental days and remained constant until the end of the experiment.

This indicated that air supply determined the stabilization of the sludge as a side effect. This result is of considerable interest since simultaneous sludge dewatering and stabilization occurred in the modified solar greenhouse. It is possible that the synergistic effect exerted by aeration supply, solar irradiation and humidity reduction determined a stabilization and sanitation of the sludge contextual with its drying process. In previous literature, the lowest VSS/TSS ratio achieved with a solar greenhouse was close to 55–60% [21,30,31]. The obtained reduction of the volatile solids content by up to 40% guaranteed the production of a completely stabilized sludge. Therefore, the stabilization phase that takes place in aerobic digester could be likely reduced or omitted from the sludge handling units in small sized WWTPs, thereby enabling footprint and energy saving.

In Figure 7, two pictures of the sludge at the end of the experiment are reported.

Figure 7. Pictures of the dried sludge at the end of the experiments.

The sludge presented a highly porous structure with the presence of many cavities. This is related to the fact that during the drying process, channels of different sizes are created inside the sludge that allowed the water drainage. At the end of the experiment, the final weight of the sludge was 1.67 kg, which resulted in a reduction of approximately 99% of the initial sludge weight. The achieved reduction of weight could lead to a reduction of the transportation, handling and dumping costs, thus reducing the economic impact of sludge drying and disposal on the operating costs of a WWTP.

3.5. Costs Estimation and Economic Evaluation

To assess the economic feasibility of sludge drying through the modified solar greenhouse, the net present value (NPV) was calculated for 20 years. The variables considered for the NPV assessment were the investment costs for the solar greenhouse and all the equipment (e.g., sensors, air blower) and the solar energy facilities (e.g., photovoltaic and aero-thermal flat solar panel). All the above costs were normalized to the greenhouse surface. For solar greenhouse drying, a price of 300 EUR/m^2 was assumed [32]. Referring the photovoltaic and the aerothermal solar panel, it was assumed a specific cost equal to 3.5 EUR/kW and 800 EUR/m^2, respectively. The costs of the other equipment were estimated equal to 10% of the sum of the other facilities.

The calculations assumption was based on the drying with the solar greenhouse of a precise amount of sludge already dewatered (1000 kg/d), assuming a residual humidity of this equal to 75% according to landfilling disposal requirements. The further humidity reduction achievable with the solar greenhouse was considered a cost saving because of the lower amount of sludge to be disposed.

The treatment potential of the solar greenhouse was calculated based on the data obtained in this study; thus, considering that 125 kg of sludge could be dried up to 5% of residual humidity in approximately 25 days, if it is assumed that the initial humidity of the sludge was 75%. Therefore, the treatment capacity of the solar greenhouse resulted equal to 8.0 kg/m^2·d.

Assuming that the ratio between the surface of the solar greenhouse and that of the solar panel of the present study is constant, the specific surface requirement for the aerothermal panel referred to the surface unit of the solar greenhouse was 2.10 m^2/m^2. The power requirement for the photovoltaic panel was estimated based on the installed power referred to the air blower (0.32 kW/m^2).

The NPV was calculated according to the following equation:

$$NPV = -I_0 + \sum_{t=1}^{20} \frac{C_t}{(1+i)^t}$$

where I_0 is the initial capital investment, C_t are the net cash inflow–outflows during a single period t, "i" is the discount rate (5%) and t is the time of the cash flow.

The annual cash flows were calculated as the difference between the sludge disposal costs resulting from the dewatering process (residual humidity of 75%) and that from the solar drying (5%), assuming that the sludge disposal cost for landfilling was equal to 260 EUR/tons, according to the average European cost [33]. Therefore, starting from 1000 kg of sludge with a residual humidity of 75%, a humidity reduction from 75% to 5% results in a total weight of sludge to be disposed after the solar greenhouse of approximately 263 kg/d. Table 1 reports the annual values of the NPV.

Based on the economic analysis, it was concluded that the NPV after 20 years is largely positive; thus, confirming the feasibility of the investment. Moreover, the payback period was estimated between 6 and 7 years.

It is important to stress that the proposed solution for sludge drying is an environmentally friendly technique because free and clean energy was used. From an environmental point of view, different benefits could be identified. First, the energy requirements for sludge drying are lower than conventional drying systems and have completely zero impact on the environment since it is produced by solar technologies. Moreover, the smaller sludge amount could reduce the number of transports to the disposal site and the need of additional volume in the landfill for sewage sludge disposal. Future studies are necessary to estimate the carbon footprint of this system, in order to evaluate comprehensively the environmental benefit of sludge drying practices with solar greenhouses.

Table 1. Summary of the economic assessment though the NPV referred to a treatment potential of 1000 kg/d.

Year	Initial Capital Cost	Actual Cash Flow [EUR/Year]	NPV [EUR]
0	−EUR 365,200.60	EUR 0	−EUR 365,200.00
1		EUR 66,596.49	−EUR 298,603.51
2		EUR 63,425.23	−EUR 235,178.28
3		EUR 60,404.98	−EUR 174,773.30
4		EUR 57,528.55	−EUR 117,244.75
5		EUR 54,789.10	−EUR 62,455.65
6		EUR 52,180.09	−EUR 10,275.55
7		EUR 49,695.33	EUR 39,419.77
8		EUR 47,328.88	EUR 86,748.66
9		EUR 45,075.13	EUR 131,23.78
10		EUR 42,928.69	EUR 174,752.48
11		EUR 40,884.47	EUR 215,636.94
12		EUR 38,937.59	EUR 254,574.53
13		EUR 37,083.42	EUR 291,657.95
14		EUR 35,317.54	EUR 326,975.49
15		EUR 33,635.75	EUR 360,611.25
16		EUR 32,034.05	EUR 392,645.30
17		EUR 30,508.62	EUR 423,153.92
18		EUR 29,055.83	EUR 452,209.75
19		EUR 27,672.22	EUR 479,881.96
20		EUR 26,354.49	EUR 506,236.46

4. Conclusions

The performances of a modified solar greenhouse for sewage sludge drying were assessed. The results showed that a residual humidity close to 5% was obtained in 25 days. Moreover, a simultaneous effect of sludge stabilization was obtained due to the supply of hot air under the sludge bed. The achieved high weight reduction of up to 99% by drying leads to a reduction in sludge handling cost. Due to the moderate investment cost, the low energy consumption, thanks to the use of solar energy and low maintenance requirements, solar greenhouse is a highly interesting technology for sludge drying in small sized WWTPs. Moreover, the high dry solids content and the reduced total volatile concentration could open additional pathways of disposal such as thermal treatment for energy recovery. Further studies are necessary to provide more insights into the drying process and to evaluate the effect of some operating parameters on drying performance and process kinetics.

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