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Advanced Techniques of Natural Dewatering of Sewage Sludge: An Innovative Solar Greenhouse for Enhanced Sewage Sludge Drying

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

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The cost of treatment and disposal of sewage sludge is expected to increase in the near future, primarily due to the growth of the urban population, the improvement in the quality of human life, and the development of agriculture and industry. It is necessary to develop new sustainable and efficient solutions to reduce the weight of sewage sludge from wastewater, aiming for dehydration to increase the dry matter content and reduce the amount of water in the sludge leaving treatment plants, thereby decreasing transportation and disposal costs. Considering this, the present work illustrates the design, implementation, and experimentation of solar greenhouse prototypes based on the principle of thermal convection to achieve greater sludge drying. The experimental phase was conducted in three different seasons (winter-spring-summer) and with different plant configurations to maximize sludge drying performance. This study has shown that solar greenhouses with warm air insufflation perform better than conventional greenhouses. Moreover, better performance was achieved during the summer trials. The greenhouse that demonstrated the best performance allowed for a weight reduction of the sludge by approximately 98%. Therefore, it can be stated that these sludge drying systems significantly minimize the volume of sludge destined for landfills.

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INTRODUCTION

Due to the increase in industrialization and the growth of the world population, projected to reach an additional 8.6 billion people by 2030, according to the United Nations, many countries are implementing stricter laws on wastewater discharge standards (Collivignarelli et al., 2019). To meet these, new wastewater treatment plants (WWTPs) will be constructed, and the existing ones will be retrofitted to enhance the treatment capacity. This will result in a significant increase in sewage sludge generation, whose treatment and disposal will pose several environmental and economic concerns. Considering this, researchers are focusing on innovative technologies to achieve excess sludge minimization, with the aim of reducing the amount of sludge to be disposed of (Morello et al., 2022).

Currently, both thermal and solar drying techniques are widely applied for sludge drying (Belloulid et al., 2017). Thermal drying implies significant energy consumption, either from electrical vectors or directly from fossil fuels, leading to increased energy consumption. In order to adopt eco-friendly practices and leverage renewable energy, employing solar greenhouse drying systems emerges as a viable and advantageous solution for medium-small WWTPs located in climate zones with high solar radiation. Conventional solar greenhouses utilize both solar-generated hot water and the greenhouse effect to harness energy.

Previous studies carried out on open and closed-static greenhouse dryers demonstrated that approximately 55–80% and 90%, respectively, of dry solid concentration could be obtained in less than 2 months (Mathioudakis et al., 2009; Salihoglu et al., 2007).

A recent study demonstrated that the use of a forced ventilation system to provide hot air for sludge drying instead of hot water below the wet sludge enabled to achieve approximately 95% of dry solid concentration in about 25 days (Sorrenti et al., 2022). This study has laid the groundwork for the development of a technology for solar greenhouses based on the use of hot air produced by a solar panel.

Considering this, the present work illustrates the design and testing of three different prototypes of solar greenhouses based on the principle of heat convection to obtain enhanced sludge drying. The main objective of this work was the development of an efficient and sustainable drying system for sewage sludge. Indeed, these prototypes were fed by a renewable energy source such as solar energy, allowing not only a direct environmental benefit in terms of sewage sludge reduction but also an indirect environmental benefit due to the use of a renewable energy source.

MATERIALS AND METHODS

In this section, the authors describe the three prototypes of solar greenhouses, that differ in the addition of equipment to improve heating performance for sewage sludge drying. To evaluate the efficacy of these prototypes and to optimize the setup configuration, four experimental tests have been performed.

The Greenhouse pilot

Three geometrically identical small-scale pilot greenhouses were designed and constructed using a polyvinylchloride (PVC) tank of 0.97 m length, 0.64 m width. The horizontal surface area of each greenhouse 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.
Each of the solar greenhouses was equipped with a forced ventilation system to provide hot air for sludge drying and to overcome hydraulic head losses through the drainage and wet sludge layers. To this end, a side-channel air blower (engine power of 0.2 kW, pressure of 20 mbar) was installed. Air was introduced through two different inlet points: a perforated pipeline with 6 mm medium-sized holes placed within the drainage sand layer and through three horizontally arranged orifices (6 cm in diameter) located above the sludge layer. A properly shaped stainless-steel profiled sheet was placed on the perforated pipeline to ensure a homogeneous distribution of the air and to avoid water percolation inside it. Hot air was produced by an aero-thermal flat solar panel of the SolarAir Enterprise (1.30 m^2) tilted at a 30-degree angle and south-oriented. Two dedicated flowmeters allowed for air flow control.

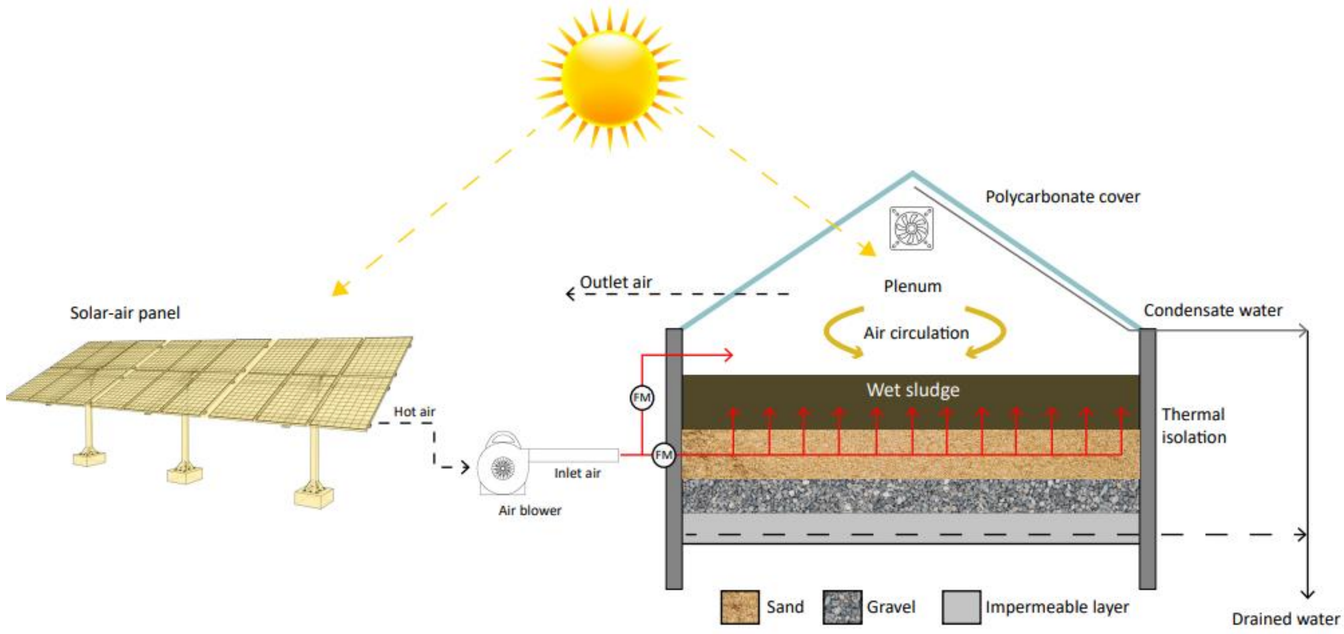

Figure 1. Schematic view of solar greenhouse

The main components of the solar greenhouse system are listed reported:

- solar hot air system: composed of a Twin Solar 1.3 solar collector with a surface area of 5.87 m^2 oriented to the south with a tilt of 40°.
- a PVC solar greenhouse with a maximum volume of 0.41 m^3 when the sludge thickness is about 3 cm. In contrast, the minimum volume of the solar greenhouse varies with the thickness of the sludge inside it. Specifically, with a sludge thickness of 28 cm, the minimum volume is about 0.25 m^3; with a thickness of 27 cm, the volume is 0.26 m^3; and with a thickness of 25 cm, the minimum volume is 0.28 m^3.
- mini-electro fans: installed to ensure adequate air turbulence inside the greenhouses, with a size of 80 mm × 80 mm × 25 mm, operating at a voltage of 12 volts with a current of 0.41 A.
- side channel blower: with an electrical power of 0.2 kW and a flow rate of 40 m^3/h. This system is timed using a timer, drawing air from outside to the solar collector and pushing it inside the solar greenhouse (inlet air).
- drained water and condensation water collection systems.
- photovoltaic system: feeding all electrical devices.

All three small-scale pilot greenhouses are equipped with all the components, although they operated in different mode. More precisely, “Greenhouse A” operated with warm air input over the sludge layer, “Greenhouse B” with warm air input under the sludge layer, and “Greenhouse C”, operated as a conventional greenhouse that is without warm air input.

Operating setup

During the four tests, the solar greenhouses operated in parallel always using the same excess sludge taken from the wastewater treatment plant where the greenhouses were installed, but under different operating conditions. The experiments were conducted with variable air flow rates and the average duration of the experimental periods was 25-30 days.

Test n.1

The first test was conducted during the winter season, with a duration of 30 days, from March 8 to April 6. The main operational parameters of this experimental test are reported in Table 1.

Table 1. Values of the main parameters of the test 1

	Greenhouse A	Greenhouse B	Greenhouse C
Initial sludge thickness, cm	25	25	25
Initial sludge weight, kg	155	155	155
Sludge moisture, %	97	97	97
Air flow rate above sludge, m/h	16	-	-
Air flow rate under sludge, m/h	-	16	-

Test n.2

The second test was carried out during the spring season, from April 19 to May 18, and, also, had a duration of 30 days. The main operational parameters of this experimental test are reported in Table 2.

Table 2. Values of the main parameters of the test 2

	Greenhouse A	Greenhouse B	Greenhouse C
Initial sludge thickness, cm	27	27	27
Initial sludge weight, kg	167	167	167
Sludge moisture, %	96	96	96
Air flow rate above sludge, m/h	25	-	-
Air flow rate under sludge, m/h	-	25	-

Test n.3

The third test was piloted again during the summer season, from August 22 to September 15, with a duration of 25 days. The main operational parameters of this experimental test are reported in Table 3.

Table 3. Values of the main parameters of the test 3

	Greenhouse A	Greenhouse B	Greenhouse C
Initial sludge thickness, cm	28	28	28
Initial sludge weight, kg	174	174	174
Sludge moisture, %	97	97	97
Air flow rate above sludge, m/h	16	-	-
Air flow rate under sludge, m/h	-	16	-

Test n.4

An additional test was carried out during the summer season, from June 21 to July 15, and lasted 25 days. The difference with the other summer test lies in the operation of Greenhouse C. In that warm air was provided both above and below the sludge layer. The main operating parameters of this experimental test are given in Table 4.

Table 4. Values of the main parameters of the test 4

	Greenhouse A	Greenhouse B	Greenhouse C
Initial sludge thickness, cm	25	25	25
Initial sludge weight, kg	149	149	149
Sludge moisture, %	97	97	97
Air flow rate above sludge, m/h	9	-	9
Air flow rate under sludge, m/h	-	9	9

Monitoring system

All the greenhouses were equipped with a dedicated monitoring system. This was composed of temperature and humidity sensors strategically placed throughout the setup. Additional sensors are positioned in other critical areas, including downstream of the solar panel and upstream of the blowers. Inside the greenhouses, temperature sensors are installed at different heights within the sludge layer to track temperature trends accurately. Climatic data, such as outdoor temperature and solar radiation, are recorded by the weather station mounted on top of a pole above the solar panel, enabling comprehensive monitoring of parameters that affect the drying process. In the laboratory, total suspended solids, volatile suspended solids, and moisture levels are analyzed by taking sludge samples from each greenhouse every three days.

RESULTS AND DISCUSSION

The results of the four experimental tests are showed and discussed in this section.

First Test

During the first test, an average outdoor temperature of 23.91°C was observed, while the daily solar radiation of 11.8 MJ/m^2 has been recorded. Sludge moisture was reduced from 97% to 6% in 30 days, and a 97.4% weight reduction was observed for greenhouse A. Next, we find greenhouse B with a moisture content of 7% and a weight reduction of 97.5%. Finally, we find the conventional greenhouse with a weight reduction of 87.7%. With reference to the total sludge treated in the greenhouse, mass balances revealed that for greenhouse A, 3% consists of the final sludge weight, 69% is the water evaporated during the test, and the remaining part, 28%, is drained water. In greenhouse A, therefore, water is mainly eliminated through evaporation. Greenhouse B and Greenhouse C have the same percentage of drained water, approximately 41%, while the percentages differ for evaporated water (55% for Greenhouse B and 47% for Greenhouse C) and final sludge weight (3% for Greenhouse B and 12% for Greenhouse C). The results are shown in Figure 2.

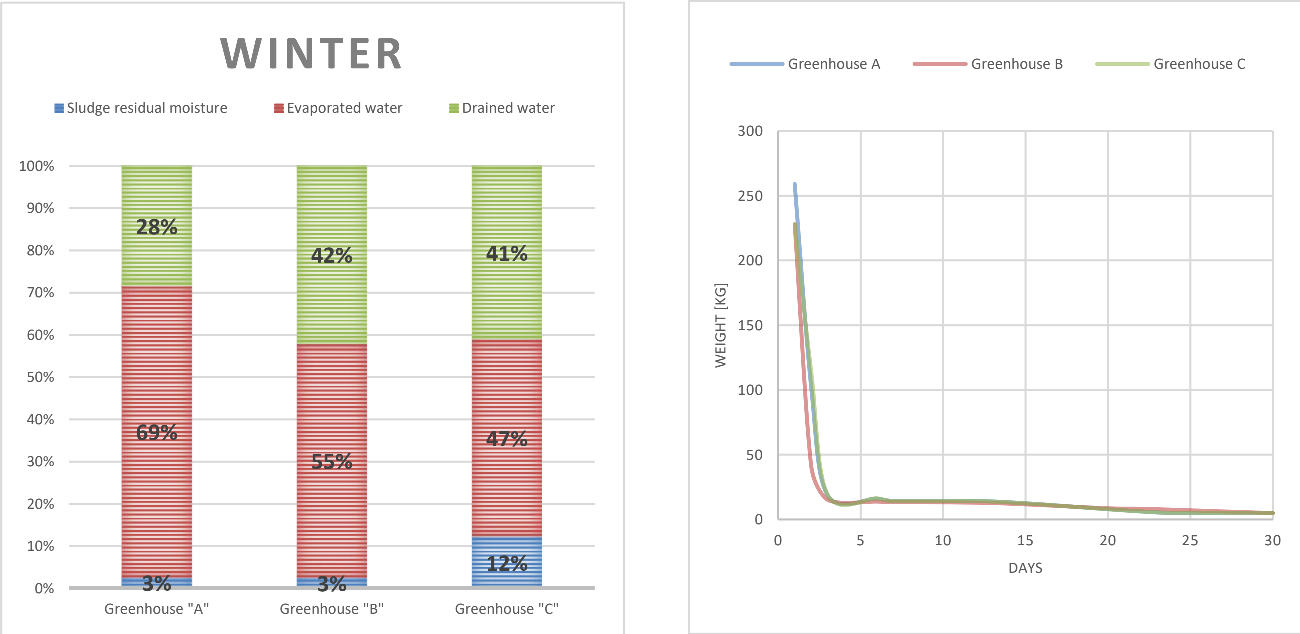

Figure 2. Results First Test

Second Test

The average outdoor temperature recorded during the second test was 28.14 °C with solar radiation of 21.5 MJ/m^2. During the second test, a weight reduction of 94.01% was recorded for the conventional greenhouse with a sludge moisture of 5.79%. This was followed by Greenhouse A and Greenhouse B with almost equal results, in fact Greenhouse A recorded a final sludge moisture value of 5.79% followed by Greenhouse B with a value of 4.92%. The reduction in weight was the same at 95.21%. The mass balances carried out with reference to the spring test allowed us to observe that, even during this test, greenhouse A loses water mainly through evaporation, unlike the other two greenhouses where the percentage of drained water (approximately 43%) and the percentage of evaporated water (approximately 52%) are almost equal. The results are shown in Figure 3.

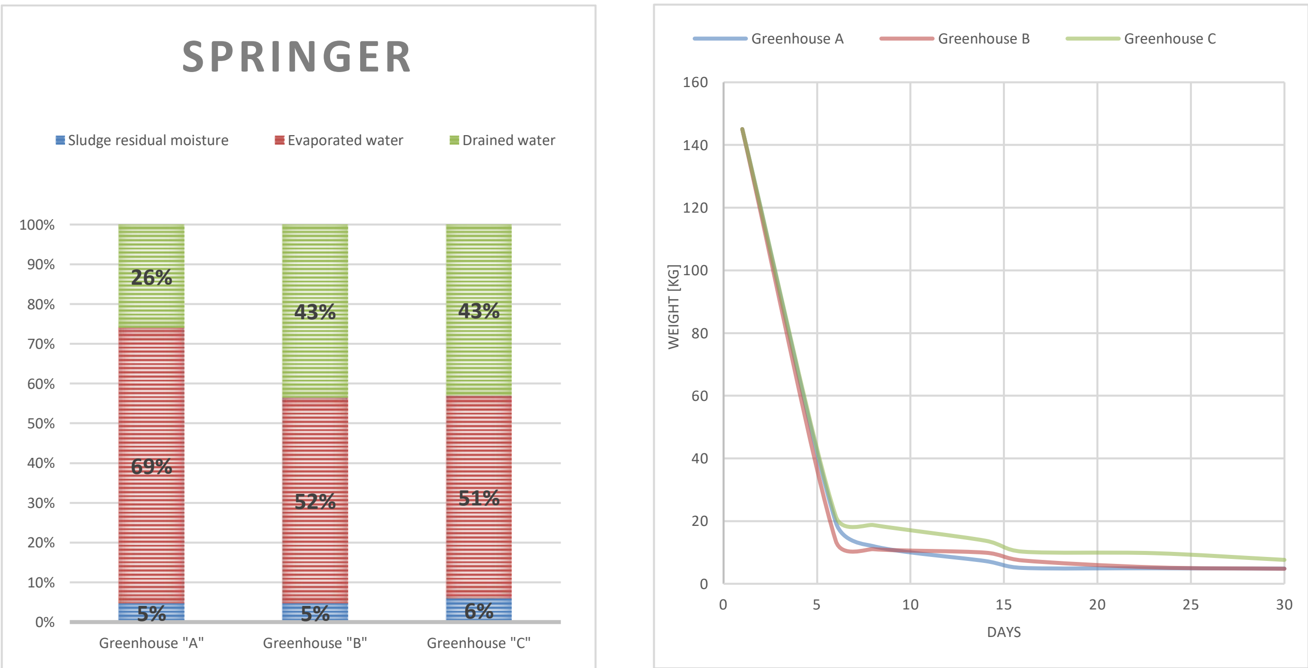

Figure 3. Results Second Test

Third Test

The results of the fourth test show how outdoor temperature affects the drying process. In fact, it accelerates the process. The average outdoor temperature recorded was 31.76°C with solar radiation 28.1 MJ/m^2.
Greenhouse B was the one that obtained the best results, in fact the moisture content of the sludge at the End of the test was found to be 4% with a 98.40% reduction in weight. Next, we find Greenhouse B which obtained a sludge with a final moisture content of 6% and a sludge reduction of 97.95% and finally the conventional greenhouse with a weight reduction of 96.43%. Instead, during the summer test, the mass balances showed that in all three greenhouses the percentage of evaporated water is higher than the percentage of drained water. The evaporated water (for all three greenhouses) constitutes about 68% of the treated sludge volume. The drained water, on the other hand, is around 29% for greenhouse A, followed by greenhouse B (36%), and finally greenhouse C with 31%. The results are shown in Figure 4.

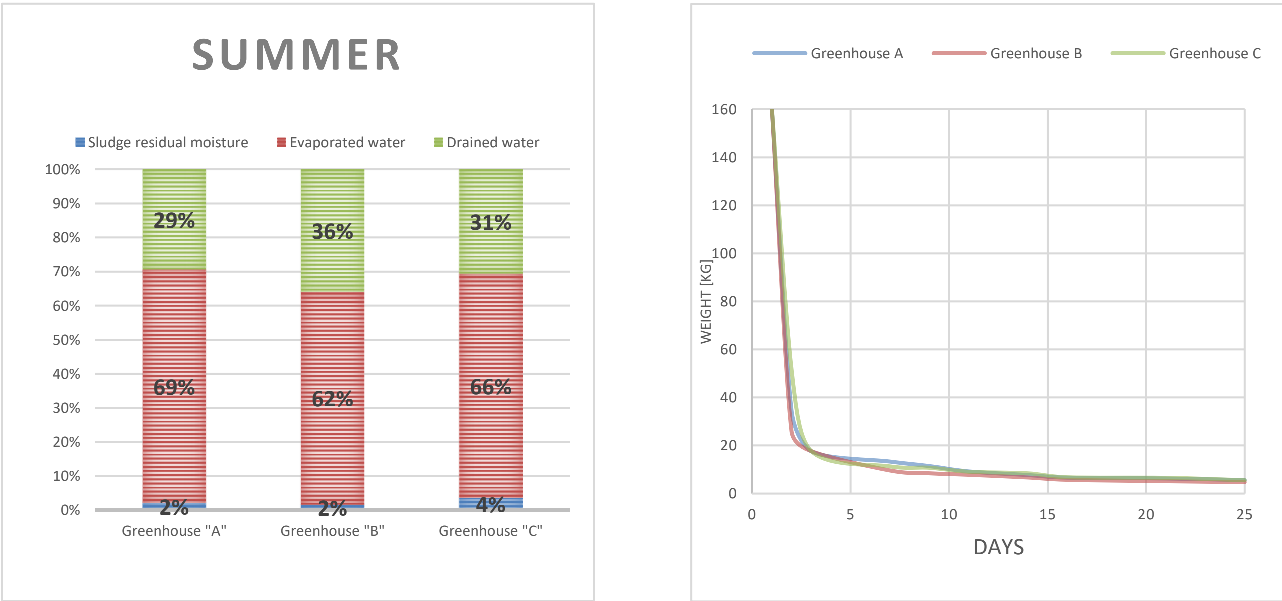

Figure 4. Results Thirth Test

Fourth Test

The fourth test was also conducted during the summer period, in fact the average temperature recorded was higher than the previous tests. The temperature was 34.33°C and the solar radiation was 30.8 MJ/m^2. Greenhouse A obtained a sludge with a moisture content of 5.78 percent followed by greenhouse B with a moisture content of 4.22 and finally greenhouse C with a moisture content of 4.12 percent. In contrast, in terms of weight reduction, the greenhouse that achieved the best reduction was Greenhouse B with a weight reduction of 97.19%. The results shown in Figure 5 of the mass balances highlight how in greenhouse C this time the percentage of drained water is greater than in the other two greenhouses (49%). While the percentages of both drained and evaporated water appear almost similar in Greenhouse A and Greenhouse B.

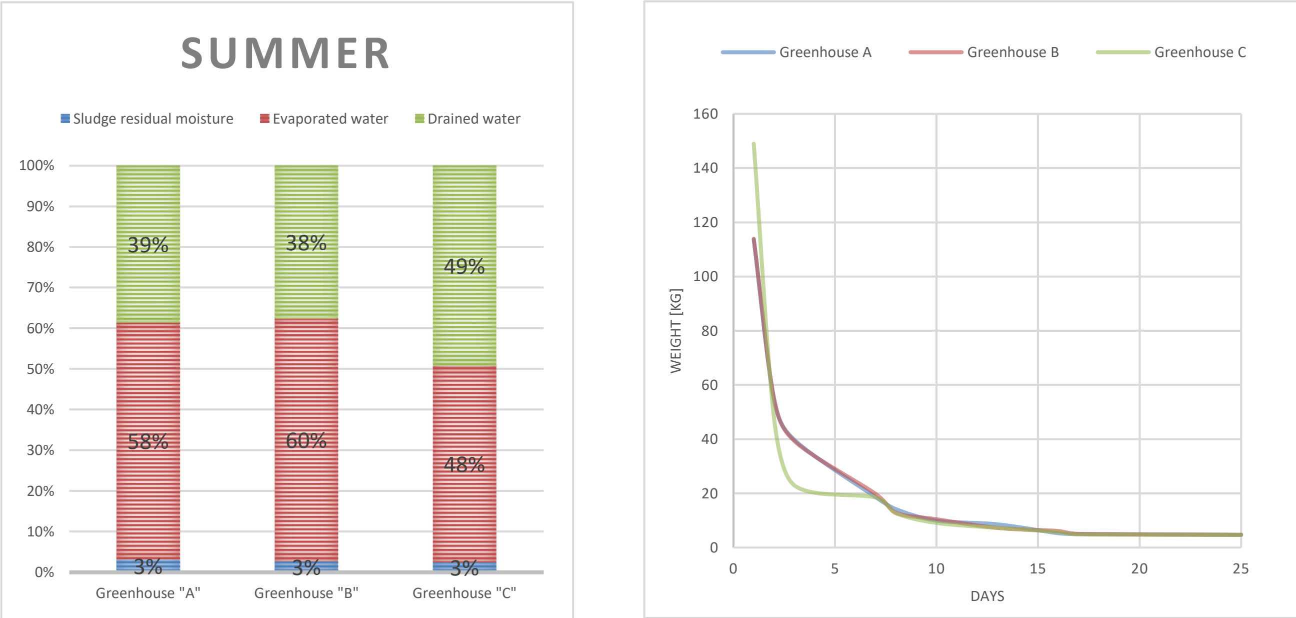

Figure 5. Results Fourth Test

Discussion

The values of the ratio between final and initial weights indicate that the prototypes perform well. Specifically, it was found that the conventional greenhouse C has lower performance compared to greenhouses with the introduction of hot air. The conventional greenhouse performs better in the summer season, where outdoor solar radiation is an important factor, and less so in the winter season, when it achieves a sludge weight reduction of 87.7 percent. Drained water is consistently around 30-40%. While solar greenhouses A and B showed similar results, the final percentages in terms of weight reduction, drained water, and evaporated water differ. Specifically, solar greenhouse A, with hot air introduced from above, shows a higher percentage of evaporated water than greenhouse B, regardless of the season. The evaporated water percentage is consistently around 69%, whereas the drained water is lower, approximately 28%. Thus, in this case, surface evaporation compensates for water drainage.

Greenhouse B is characterized by a higher percentage of drained water than evaporated water. In fact, it has a percentage of evaporated water of 55-60% and a percentage of drained water of 36-43%.

Solar greenhouse B achieves excellent results in the summer season where high external temperatures are measured. In conclusion, the system has demonstrated a positive outcome compared to conventional greenhouses, since it allows high dryness percentages to be achieved in a limited period of time.

Figure 6. Pictures of the Sludge at the beginning and the End of the test

Certainly, one of the fundamental aspects is the external temperature, which accelerates the drying process. Solar greenhouses have the advantage of exploiting solar energy, thereby reducing energy consumption.

CONCLUSIONS

The tests conducted highlighted the effectiveness of the system compared to conventional solar greenhouses. Considering the results discussed, it is evident that the performances of greenhouses equipped with hot air insufflation (Greenhouse A and Greenhouse B) differs significantly from that of the conventional greenhouse (without hot air insufflation). It was observed that blowing hot air from the upper part (Greenhouse A) or the lower part (Greenhouse B) of the sludge bed achieves better performance than the conventional greenhouse; however, the performances of greenhouses A and B are similar. By examining the results from different tests, the following observation can be made:

- in the winter season, the final weight of the sludge in Greenhouse A and Greenhouse B is equal to 20% of the final weight of the sludge in the conventional greenhouse.
- in the summer season, the final weight of the sludge in Greenhouse A and Greenhouse B is equal to 50% of the final weight of the sludge in the conventional greenhouse.
- in the spring season, the final weight of the sludge in Greenhouse A and Greenhouse B is equal to 80% of the final weight of the sludge in the conventional greenhouse.

The problem of the treatment and disposal of sludge produced by urban wastewater purification processes is currently one of the major critical issues in the purification cycle. The objective is to find efficient drying systems to enhance the dehydration process aimed at increasing the dry content and reducing the quantity of water present in the sludge. Furthermore, these are systems that exploit green and renewable energy, providing a significant environmental benefit in terms of reducing the quantity of sludge sent for disposal and utilizing a totally free energy source. The results of this work can help to better understand the drying processes that take place inside solar greenhouses, to identify theories and procedures that allow plant managers to continuously optimize the dehydration phases.

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