Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 46 No. 3 (2025)

Development of a greenhouse and screw conveyor solar driers for the treatment of faecal sludge from on-site sanitation facilities

Santiago Septien[1], Pareshin Naidoo[1], Akhil Ramlucken[1], Adheesh Ganapathie[2], Yashlen Pather[2], Anusha Singh[2], Jonathan Pocock[2], Freddie Inambao[3] and Craig McGregor[4]

[1] WASH R&D Centre, University of KwaZulu-Natal, Durban, South Africa

[2] Chemical Engineering Discipline, University of KwaZulu-Natal, Durban, South Africa

[3] Mechanical Engineering Discipline, University of KwaZulu-Natal, Durban, South Africa

[4]STERG, University of Stellenbosch, Stellenbosch, South Africa

ABSTRACT

Thermal drying is an important unit operation in faecal sludge treatment. However, this process requires a high energy input, leading to high running costs due to high electricity or fuel consumption. Solar thermal energy can be used to decrease the costs of the drying process. This work aims to develop solar thermal drying technologies that efficiently harness solar thermal energy and are adapted to the sludge characteristics. Two different types of technologies were selected for their development, i.e. greenhouse-type solar drier and screw conveyor solar drier. After construction, the technologies were tested to measure their performance, find the optimum operating conditions, and identify improvement points. During the tests in the solar driers, it was observed that temperatures inside the enclosure were higher than the ambient conditions (+10-15°C for the greenhouse and +15-25°C for the screw conveyor drier), leading to relative humidities lower than 30%. An evaporation rate in the greenhouse was measured in the order of 0.8 kg/h/m^2 when conducting the tests with water. The drying tests with wetted soil in the screw conveyor solar drier resulted in a good performance with most of the moisture being removed from the soil after less than 30 minutes of operation. Testing with synthetic sludge also showed positive results, with moisture removal in the region of 20% to 50% in 2 hours. The most optimal conditions were obtained when the ventilation was operated at a low air flow rate, as the maximum temperatures achieved in the system were higher (after the solar air heater), leading to a higher moisture removal from the synthetic sludge. The results from the tests were promising. After the testing phase for both prototypes, improvements have been identified for the next round of iteration. In particular, the sludge stickiness is a critical problem that must be resolved to achieve sustainable long operation times.

Keywords: Faecal sludge; On-site sanitation; Solar thermal drying; Temperature; Drying rate

1. INTRODUCTION

The World Health Organization estimates that 50% of the worldwide population does not have access to safely managed sanitation services, among which over 1.7 billion people do not have basic sanitation services, causing 494 million still practice open defecation (WHO 2021). On-site sanitation is the most viable option to provide sanitation to poor communities where this basic service is lacking, as the high costs for the development and maintenance of a sewage system are usually unaffordable for developing countries. Moreover, many regions in the world already rely on onsite sanitation, with 2.7 billion people served by this type of sanitation technology (Strande et al., 2014). On-site sanitation can also serve in developed areas and cities to change the paradigm of sewage sanitation into a more water-sensitive, climate change-resilient and sustainable model.

One of the main challenges of onsite sanitation is the accumulation of faecal waste in the site of generation (i.e. faecal sludge). Methods must therefore be developed for its in-situ treatment, or its collection and transportation to a faecal sludge treatment plant for its disposal and eventual resource recovery. The implementation of safely managed onsite sanitation with the recovery of valuable resources (e.g., reuse water, nutrients and biofuel) can be a key factor to accomplish the Sustainable Development Goals, in particular Goal 6, ensuring safe water and sanitation for all (Andersson et al., 2018).

The removal of moisture in the sludge through drying is an important step in its treatment, as it reduces the mass and volume of the faecal waste and destroys pathogens that cannot survive without water and are deactivated at high temperatures. Conventional thermal driers present high operating costs due to the high energy demand for moisture evaporation in the form of electricity or fuel. The use of solar thermal energy for drying purposes is an interesting option because of several reasons: (i) high availability in the developing countries (including South Africa); (ii) sustainability, environmentally friendly and low greenhouse emissions; (iii) renewable and "free" energy.

The use of solar thermal energy for drying purposes could drastically reduce energy consumption, leading to a significant cost reduction. This should involve the setting up of a thermal system to harness in an efficient way the solar energy for its conversion into heat. Most of the solar drying applications are found in the agriculture and food industry sectors, for the preservation of grains and the dehydration of food products. Solar thermal energy has also been widely applied for sewage sludge drying in European countries, the United States and Australia (Seginer and Bux, 2006), and has gained interest in developing countries as Greece, Turkey, Algeria, Morocco and China. The largest sewage sludge solar drying applications consist in greenhouses with units that can process around 30,000 tons per year (Meyer-Scharenberg and Pöppke, 2010; Socias, 2011). Different types of solar thermal technologies are under development, such as solar roof dryers (Wang et al., 2019) and cabinet solar dyer (Ameri et al., 2018). Nonetheless, almost no information has been found in the literature for faecal sludge solar drying apart from some isolated cases where the sludge was dried in greenhouses with a simplistic design (Muspratt et al., 2014; Seck et al., 2015).

This work aims to develop solar thermal drying technologies that have been designed to harness the solar thermal energy efficiently and that are adapted to the sludge characteristics. Two different types of technologies were selected for their development, i.e. greenhouse-type solar drier and screw conveyor solar drier. The prototypes were built at pilot-scale to be able to process several kg of faecal sludge per day. After construction, the technologies were tested to measure their performance, find the optimum operating conditions, and identify improvement points. Based on these results, a technical-economic analysis will be performed for the upscaling and implementation of the technologies in faecal sludge treatment facilities.

2. MATERIALS AND METHODS

2.1. Description of the solar thermal drying prototype

The greenhouse prototype consists in a solar dryer where faecal sludge will be placed in a bed and dried using solar thermal energy. The prototype offers an enclosed space where the solar thermal energy can be collected through the greenhouse effect and the presence of an absorber wall. It includes a ventilation system and a sludge rake system to boost the drying process. The sludge bed will stand on a suspended grid, which will allow the sludge to dry also from the bottom. The prototype scheme can be found in Figure 1.

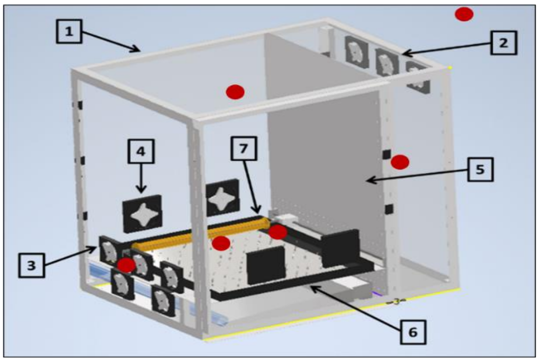

Figure 1. *Drawing of the greenhouse solar dryer (1: enclosure; 2: air inlet; 3: air outlet; 4: circulation fans; 5: absorber wall; 6: sludge bed support; 7: rake system; red points: sensors)*

In the screw conveyor solar drier prototype, the sludge will be dried during its passage through a transparent tube exposed to solar radiation (drying chamber). During this process, the sludge will absorb the solar thermal energy and use it as latent heat for moisture evaporation. An air stream will circulate inside the drying chamber to enhance the drying process. The air stream will be dehumidified and heated before being introduced into the drying chamber. Reflectors will be placed next to the drying chamber to increase the amount of solar radiation received by the sludge. Figure 2 schematizes the screw conveyor solar drier setup.

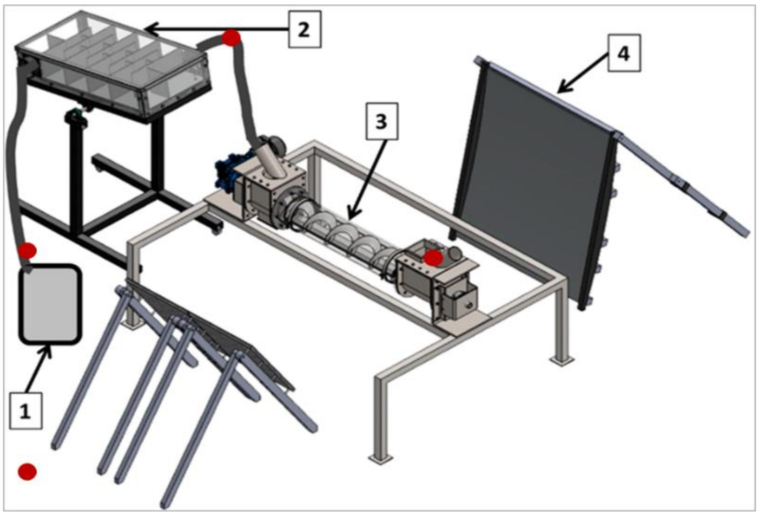

Figure 2. *Schematic representation of the screw conveyor solar drier prototype (1: air dehumidifier; 2: solar air heater; 3: drying chamber; 4: reflector; red points: sensors)*

2.2. Testing of the solar thermal drying prototypes

The greenhouse was tested initially without feedstock to assess the functionality of the system and find the optimal ventilation operating conditions based on the temperature measurements. Water evaporation tests were then carried out, where several 55 mm diameter containers with water (100 g/container) were placed inside the greenhouse. After a few hours of operation, the mass of evaporated water was measured by comparing the initial and final mass of the containers.

Concerning the screw conveyor solar drier, the first tests were carried out to test the individual components of the prototype and the integrated system without feedstock. Thereafter, the solar drier was tested using wetted soil (400 g water added per 1 kg of dry soil) and synthetic faecal sludge (with 80% initial moisture content) as feedstock, for 1 – 2 hours of operation. The synthetic faecal sludge recipe was made of water, psyllium husk, peanut oil, miso paste, ground dried vegetables, cellulose, polyethylene glycol and calcium phosphate (Penn et al., 2021). The effect of the ventilation rate was studied by the measurement of the temperatures obtained inside the system and the moisture content of the synthetic sludge at the outlet of the dryer.

The prototypes were placed on the roof of the Chemical Engineering building (latitude: 29°52'08.1" S; longitude: 30°58'46.6"E), at the Howard College campus, University of KwaZulu-Natal, Durban, South Africa. The prototypes were tested during May and June, corresponding to austral autumn, where the average irradiances are typically comprised between 90 to 105 W/m^2. The tests were carried out between 9:30 AM and 2:30 PM, a range where the solar irradiance has attained its peak value and does not vary significantly.

3. RESULTS AND DISCUSSIONS

3.1. Results of the greenhouse testing

Table 1 shows the temperature difference between the air inside the dryer as compared to the temperature of ambient air at different ventilation conditions.

Table 1. *Temperature measurement during tests of the greenhouse without feedstock*

Time	Outside Temp(°C)	GH Temp(°C) no ventilation	GH Temp(°C) ventilation full	GH temp(°C) ventilation half
09:30	34.4	42.9	41.2	40.2
10:00	34.3	43.7	38.3	37.5
10:30	34.4	43.1	38.1	37.6
11:00	32.2	42.9	38	38.7
11:30	31.3	42.4	38.5	39.6
12:00	30.0	41.4	37.6	36.8

It can be observed that temperatures higher than 10°C, considering the ambient conditions, can be obtained in the greenhouse without ventilation. If the fans are turned on, the temperature in the greenhouse decreases by a few degrees. There is no significant difference between the ventilation at full and half capacity. This result suggests that the increase in ventilation leads to lower temperatures inside the greenhouse.

During the evaporation tests, approximately 20 g of water was evaporated from each container after 4 hours of operation, demonstrating that evaporation occurred similarly at the different positions inside the greenhouse. The evaporation rate was then calculated at 2.1 kg/h/m^2 from the loss of mass of water, the time of the test and the surface area of the containers. From this result, it was estimated that the greenhouse would be able to dry faecal sludge in a bed of 1 m^2 surface area and 0.1 m of thickness (leading to a sludge volume of 0.1 m^3 and weight of 120 kg considering a density of 1000 kg/m^3) from an initial moisture content of 80% (typical value for the sludge from local pit latrines) to 20% in theoretically 35 h (equivalent to 7 days considering 6 hours of full sunlight per day). Nonetheless, in a real scenario, sludge drying takes more time than water evaporation, so the drying time will probably take longer than the calculated value above.

3.2. Results of the screw conveyor solar dryer testing

Table 2 displays the results from the tests without feedstock, with wet soil and synthetic sludge in the screw conveyor solar drier, including temperature measurements and final moisture content. The tests were conducted at different ventilation rates.

The dehumidifier increased the temperature of the air flow rate by a few degrees and led to a drop in the relative humidity to values around 35%, which is favourable for the drying process. After the solar air heater, the airflow gained a significantly higher temperature, and its humidity further decreased. Therefore, the combination of an air dehumidifier with a solar heater allowed the airflow temperatures up to 45°C and relative humidities almost as low as 25%. In the drying chamber, the temperature tended to drop, and the humidity rose, which could be due to heat losses and the drying process that absorbs heat and releases humidity.

During the wet soil tests, most of the added moisture in the solid was removed in less than 30 minutes, showing that the system was able to completely dry the sample in a relatively short amount of time. With synthetic faecal sludge as feedstock, it could be observed that a lower ventilation rate led to a slightly higher temperature at the inlet of the drying chamber and better moisture removal. Indeed, the airflow temperature at the inlet of the drying chamber was around 45°C at an airflow below 130 m^3/h, whereas it was measured at 40°C at an airflow of 203 m^3/h. In addition, the simulant was dried to 30% moisture content after 2 hours of residence time at 75 m^3/h air flow rate, whereas a final moisture of 55% and 60% was achieved at 130 and 203 m^3/h air flow rate, respectively. Therefore, operating the solar dryer at a low ventilation rate seems more optimal as the airflow is heated at a higher temperature inside the system, providing more thermal energy for moisture evaporation.

Table 2. *Results of the tests in the screw conveyer solar drier (SAH: solar air heater; DC: drying chamber)*

Feedstock	**Residence time**	**Ventilation rate**	**Temperature / humidity**				**Final moisture content**
			Ambient	**Outlet dehumidifier**	**Outlet SAH**	**Outlet DC**	
None	N.A.	203 m^3/h	24°C / 67%RH	32°C / 35%RH	38°C / 31%RH	34°C / 33%RH	N.A.
Wet soil	30 min	203 m^3/h	30°C / 80%RH	34°C / 53%RH	43°C / 30%RH	35°C / 70%RH	0%
	1 h	203 m^3/h	31°C / 67%RH	40°C / 45%RH	45°C / 30%RH	90°C / 67%RH	0%
Synthetic sludge	2 h	203 m^3/h	27°C / 98%RH	35°C / 58%RH	42°C / 39%RH	40°C / 62%RH	60%
		130 m^3/h	33°C / 85%RH	35°C / 52%RH	45°C / 30%RH	40°C / 55%RH	55%
		75 m^3/h	32°C / 80%RH	36°C / 52%RH	45°C / 67%RH	41°C / 650%RH	30%

During these tests, one of the major observations was how challenging it was to work with synthetic sludge. The sludge tended to stick to all surfaces within the dryer and coat the blades of the auger in a thin layer (Figure 3). As the sludge dried, it acquired a rubber-like consistency and stuck to the blades. This meant that a considerable amount of sludge tended to get stuck within the dryer and not exit the system (making its quantification difficult). However, the sludge stuck to the blades tended to dry well with time, due to how hot the auger gets while the reflectors were in place.

Figure 2. *Photograph displaying how synthetic sludge tended to stick to the auger surface*

4. CONCLUSIONS

The testing results were promising, with the functionality tests showing that the systems functioned well together. The solar thermal systems increased the temperature by 10-25°C concerning the ambient conditions, leading to relative humidities lower than 30%, which is favorable for the drying process. The temperature increase tended to be higher in the screw conveyor solar drier than in the greenhouse solar drier. The greenhouse could evaporate water at a rate of 0.8 kg/h/m^2, whereas the screw conveyor dried completely the wet soil (40% moisture content) in less than 30 minutes and reduced the synthetic sludge moisture content from 80% to 60 – 30%. The most optimal conditions were obtained when the ventilation was operated at a low air flow rate for both systems, as the temperatures achieved in the drying chamber were higher. This led to a higher moisture removal from the synthetic sludge in the case of the screw conveyor solar drier. It was suspected that a high ventilation rate led to a cooling effect on the system.

After the testing phase for both prototypes, improvements have been identified for the next round of iteration. In particular, the sludge stickiness is a critical problem that must be resolved to achieve sustainable long operation times.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the funders from this project (Water Research Commission through the K5/2852 project and the Royal Academy of Engineering through TSP2021_100224 Grant), as well as the eThekwini municipality and the administrative and technical staff from the WASH R&D Centre (in particular, Poovalingum Govender, Thabiso Zikalala, Kerry Lee Philp, Nombuso Mtshali and Lungile Ndlela).

REFERENCES

1. Ameri, B., Hanini, S., Benhamou, A., and Chibane, D., 2018. Comparative approach to the performance of direct and indirect solar drying of sludge from sewage plants, experimental and theoretical evaluation. Solar Energy, 159, 722-732.

2. Andersson, K., Otoo, M., and Nolasco, M., 2018. Innovative sanitation approaches could address multiple development challenges. Water Science and Technology, 77(4): 855-858.
3. Meyer-Scharenberg, U. and Pöppke, M., 2010. Large-scale Solar Sludge Drying in Managua/Nicaragua. Wasser und Abfall, 12(3):26.
4. Murray Muspratt, A., Nakato, T., Niwagaba, C., Dione, H., Kang, J., Stupin, L., Regulinski, J., Mbéguéré, M., and Strande, L., 2014. Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal. Journal of Water, Sanitation and Hygiene for Development, 4 (2): 223–230.
5. Penn, R., Ward, B. J., Strande, L., & Maurer, M., 2021. Faecal sludge simulants: review of synthetic human faeces and faecal sludge for sanitation and wastewater research. Methods for Faecal Sludge Analysis. IWA Publishing.
6. Seck, A., Gold, M., Niang, S., Mbéguéré, M., Diop, C., and Strande, L., 2015. Faecal sludge drying beds: increasing drying rates for fuel resource recovery in Sub-Saharan Africa. Journal of Water, Sanitation and Hygiene for Development, 5(1): 72-80.
7. Seginer, I. and Bux, M., 2006. Modeling solar drying rate of wastewater sludge. Drying Technology, 24(11): 1353–1363.
8. Shanahan, E. F., Roiko, A., Tindale, N. W., Thomas, M. P., Walpole, R., & Kurtböke, D. İ., 2010. Evaluation of pathogen removal in a solar sludge drying facility using microbial indicators. International Journal of Environmental Research and Public Health, 7(2), 565-582.
9. Socias, I., 2011. The solar drying plant in Mallorca: the drying process in waste management. European Drying Conference. Palma de Mallorca, Spain.
10. Strande, L., Ronteltap, M., and Brdjanovic, D., 2014. The global situation. Faecal Sludge Management: Systems Approach for Implementation and Operation. IWA Publishing, London.
11. Wang, P., Mohammed, D., Zhou, P., Lou, Z., Qian, P., and Zhou, Q., 2019. Roof solar drying processes for sewage sludge within sandwich-like chamber bed. Renewable Energy, 136, 1071-1081.
12. World Health Organization, 2021. Progress on household drinking water, sanitation and hygiene 2000-2020: five years into the SDGs.