Development and testing of solar thermal dryer technologies for the treatment of faecal sludge from onsite sanitation facilities

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Abstract

Solar thermal energy could be a cost-effective solution to supply the heat required for thermal drying. However, this type of technology has not been enough deployed for the treatment of faecal sludge from onsite sanitation facilities. The current project aims at developing pilot-scale solar thermal driers for faecal sludge drying, namely a greenhouse-type solar dryer and a screw conveyor. The prototype testing confirmed that solar drying in a thermal system is an interesting, cost-effective faecal sludge treatment. Drying occurred relatively fast if the weather conditions were favourable and with the correct operation of the ventilation, mixing and scraping systems.

Keywords: *Faecal sludge treatment; solar thermal drying; screw conveyor; greenhouse; prototype testing.*

1. Introduction

According to figures from the World Health Organization, 2 billion people worldwide did not have access to decent sanitation in 2021 [1]. On-site sanitation is the most viable option to provide sanitation to poor communities where this basic service is lacking. However, faecal sludge (faecal waste from onsite sanitation facilities) can represent a public health threat and pollution source for the environment if not well managed. The treatment of faecal sludge enables a suitable disposal of the waste without risks for the population and the environment, and with the possibility of resource recovery as the ultimate goal.

The removal of the moisture from the faecal sludge is an essential operation for the minimisation of the mass and volume of the waste, as well as for the deactivation of pathogens found in the faecal material. Drying beds are a low-cost method commonly employed for the dehydration of faecal sludge, but they usually take a long time for drying (a few weeks), and pasteurisation is not always achieved [2]. Thermal drying technologies can remove moisture from the sludge and ensure the destruction of pathogens. However, it requires a high input of energy for moisture evaporation, due to the high latent heat of water vaporisation, leading to high operating costs difficult to afford.

The use of solar thermal energy for drying purposes could drastically reduce energy consumption, leading to lower operating costs. The use of solar thermal energy has great potential for faecal sludge drying, as most of the countries relying on on-site sanitation are in tropical areas with abundant solar energy sources throughout the year. Solar thermal drying seems as a compromise between the conventional drying beds that are inexpensive but inefficient, and the thermal driers that show a good performance but usually at high costs.

Solar drying is one of the most ancient applications of solar energy, practiced particularly for food and crop conservation. Since then, there have been technological breakthroughs in this area with the development of thermal systems to harness efficiently the solar energy for its conversion into heat, but the deployment of solar drying technologies has not yet been widely commercialised [3]. This panorama may change soon, as the use of solar energy gains relevance in the actual context, with the stress of fossil fuel depletion and climate change.

Solar thermal energy has also been applied to wastewater sludge drying. By 2006, Seginer and Bux [4] identified approximately 70 solar driers in operation in European countries, the United States and Australia. This number has probably increased over the years in the developed countries, and solar drying has also gained interest in middle-income countries, such as Greece, Turkey, Algeria, Morocco and China. Large sewage sludge solar drying plants can be found at: (i) Mallorca, Spain, with a surface of 17,260 m^2 and a capacity of 30,000 tonnes of sludge per year [5]; (ii) Oldenburg, Germany, with a surface of 6,500 m^2 and able to treat 30,000 tonnes of sludge per year [6]; (iii) Managua, Nicaragua, with a total surface of 8,760 m^2 and a capacity of treatment of 26,000 tonnes per year [7]. In addition, an important number of Research & Development activities have been conducted to improve, optimize and develop technologies [8, 9]

In the faecal sludge sector, the use of solar energy for drying has been minimal, with only a few cases. Only a few cases have been reported, such as the testing of simple greenhouse drying beds in Rwanda, Uganda, Ghana and Senegal [10–12] or the development of toilet technologies with in-situ solar drying of the faecal waste [13, 14]. Muspratt et al. [12] shown that the use of greenhouse could reduce considerable the number of days required to achieve the desired moisture content. In contrast, Seck et al. [10]did not find that greenhouse shortened the drying period, which could be originated from a less efficient design, but they stated that a greenhouse offers protection to sludge against rehydration during rainfalls. Other applications of solar thermal energy other than drying exist for faecal sludge treatment, such as disinfection of faecal [15, 16] or bio-char production [17, 18].

Possible reasons for the low use of solar drying is the lack of awareness about this type of technology, as well as a lack of knowledge and data for the design of plants that could dissuade sanitation practitioners from using solar drying technologies. To cover the lack of data and understanding about faecal sludge solar thermal drying, a previous investigation was undertaken in a laboratory-scale solar drying rig to get valuable insight about the process [19, 20]. From the knowledge and lessons learnt in this investigation, two pilot-scale solar thermal drying technologies were developed, namely a greenhouse-type solar dryer and a screw conveyor. These systems are expected to offer a cost-effective solution to municipalities and sanitation stakeholders for the treatment of faecal sludge that could be applied as a decentralized solution or in a faecal sludge treatment plant. The first step of this work consisted of a preliminary study to perform an assessment of the solar resource in Durban for drying applications. Thereafter, the functionality of two solar thermal drying technologies of interest was tested using a simulant of faecal sludge.

2. Materials and Methods

A solar assessment and thermodynamic calculations were performed to evaluate the potential of solar thermal energy for drying applications in Durban. Then, the functionality tests were performed in the solar thermal drying prototypes through the measurement of temperature and relative humidity inside the driers, the evaporation of water and drying of a faecal sludge simulant.

2.1. Determination of the potential of solar thermal drying

A solar assessment was conducted in Durban during the last five years in order to evaluate the potential of solar energy resources. The irradiance values were obtained from an online database, SAURAN (Southern African Universities Radiometric Network), which is available at the following website: http://sauran.ac.za. SAURAN is an initiative from Stellenbosch University and UKZN to record weather and solar irradiance data through radiometric stations installed in different locations in South Africa, Namibia and Botswana, and make it available to the public [21]. The data used in this study were measured from a radiometric station located at the roof of the Mechanical Engineering building, at the University of KwaZulu-Natal, Durban, South Africa (latitude: 29°52'15.5" S; longitude: 30°58'37.0"E). It includes the solar irradiance, air temperature, relative humidity, wind speed and barometric pressure measured each hour from the 1st of April 2013 to the 31st August 2018. From the average irradiance data, thermodynamic calculations were done to determine the theoretical amount of water that could be evaporated using solar energy. The GHI (global horizontal irradiance) was selected as the irradiance reference parameter in this study.

2.2. Development and testing of the solar thermal drying prototypes

This section presents the initial concepts for the design of the solar dryer. Two configurations of solar drying technologies were tested: (i) a greenhouse-type solar dryer, and (ii) a screw conveyor solar dryer. The testing of the solar thermal technologies was done without feedstock, and with synthetic faecal sludge (mixture of psyllium husk, peanut oil, miso paste, polyethylene glycol, calcium phosphate, cellulose, ground dried vegetables and water). During the testing of the prototypes, the sludge moisture content and water activity were measured at different residence times. The moisture content was measured at 105°C by a *Radwag Max 50* moisture analyzer balance, and the water activity by *an AquaLab Tuneable Diode Laser* analyzer.

2.2.1. Greenhouse-type solar drier

In this configuration, the sludge was placed as a bed inside a transparent enclosure made in acrylic, on top of a suspended mesh. A door was created on one of the sides of the enclosure for the introduction of sludge and maintenance operations. A scraping system was designed to move across the surface of the sludge at intermittent intervals of time, to avoid a crust formation that can limit the process and lead to a mixing effect between the different layers of the bed for a more homogenized drying.

The solar dryer included a ventilation system to remove the evaporated moisture and renew the air inside the enclosure. The ventilation should have enough capacity to avoid the build-up of humidity inside the dryer, as this could hurt the drying process by limiting the ability of air to hold further vapor water molecules and by decreasing the driving force for the mass transfer of the evaporated moisture from the sludge to the environment. The air ventilation configuration allowed air flow above and below the support mesh to dry the top and bottom of the sludge bed. Circulating fans were installed inside the solar dryer to create a mixing movement of air, avoiding the formation of concentration gradients of humidity and improving the contact of air with the sludge for the enhancement of mass transfer for moisture evaporation.

The solar dryer included a solar collector inside the enclosure to maximize the amount of solar thermal energy harnessed in the system. The absorber consisted of a metallic sheet painted black covering the side face of the enclosure. A small gap was left between the absorbent and the wall of the dryer. Indeed, the air stream is introduced into the solar dryer through this space and will be heated by the absorber while flowing through the drying zone.

An illustration of the greenhouse solar dryer can be observed in Figure 1.

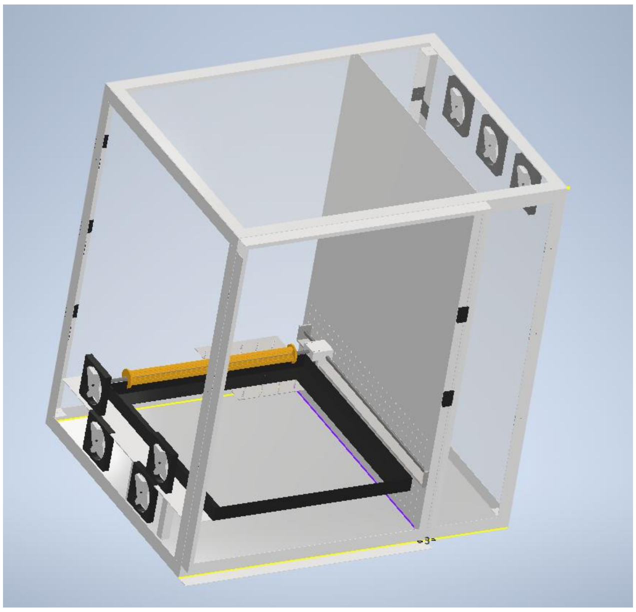

Fig. 2 Illustration of the greenhouse solar dryer

2.2.2. Screw conveyor solar drier

In this configuration, the sludge was placed inside a transparent screw conveyor where it dries by the heat absorbed from the solar radiation as it moves forward from the inlet to the outlet of the dryer. The enclosure was composed of a tube made of a transparent material, acrylic. An air stream was introduced within the screw conveyor to remove the evaporated moisture and enhance the mass transfer for moisture evaporation. The airflow moved in counter-current to the motion of the sludge to maximize the heat and mass transfers. A solar collector was designed to preheat the air before its introduction into the drying zone, and it was integrated into a commercial air dehumidifier. Solar reflectors were placed along the length of the tube to increase the amount of solar energy received by the sludge. To achieve better results, the solar dryer length was aligned in the east-west axis. Instrumentation was placed to monitor the key parameters from the process, namely the temperature, relative humidity, air flow rate and irradiance. The screw conveyor solar drier is illustrated in Figure 2.

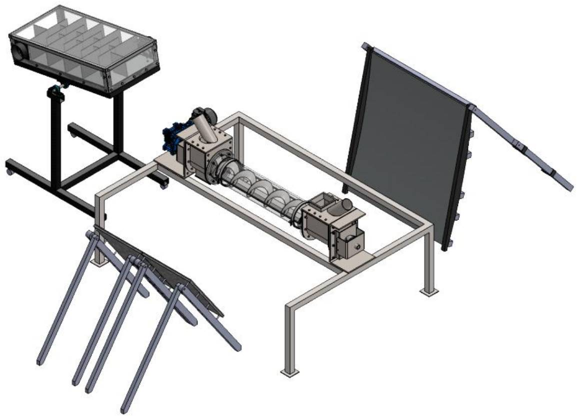

Fig. 2 Illustration of the screw conveyor solar drier

3. Results and discussions

3.1. Potential of solar thermal drying in Durban

Table 1 compiles the monthly sum and average of the GHIs during the period of the study. As could be expected, the lowest irradiances are obtained during the autumnal and hibernal periods. Depending on the year, the month with the lowest irradiance fell in May, June or July. On the contrary, the highest irradiances were observed during summer in December or January. A similar trend could be observed for the air temperature, pressure, relative humidity and wind speed: the winter recorded the lowest values while the summer presented the highest ones.

From the average GIH values, the theoretical moisture evaporation rate was calculated by dividing the solar irradiance to the latent heat of water vaporization (2,260 kJ/kg). According to these calculations, the evaporation rate varied from 4.3 to 7.5 kg/d/m^2 throughout the year, with an average of 5.8 kg/d/m^2. Considering the typical moisture content of 80% for faecal sludge from ventilated improved pit (VIP) latrines in the eThekwini municipality [22]. The theoretical annual capacity of a solar drying plant to reduce the moisture content to 20% would be 2.8 tonnes of sludge per m^2. If approximately 30 000 VIP latrines are served in a cycle of years (6 000 latrines/year) and that a pit can store up to 2 000 kg of sludge, a solar plant covering the area of 4 Olympic pools (around 5 000 m^2) would be required to treat all the VIP sludge generated within a year. Solar drying represents, therefore an interesting option for faecal sludge treatment, with low running costs and a reasonable land footprint.

Table 1. Monthly sum and average of the GHIs from 2014 to 2018

	2014	2015	2016	2017	2018	5 years average (kW/m²)
Month	GHI Month sum (kW/m²)					
January	171.44	151.59	163.93	165.30	181.61	167.01

February	144.77	126.42	153.72	136.87	151.53	142.66
March	90.26	154.35	146.10	135.20	133.38	142.10
April	109.23	123.45	113.69	116.32	130.77	118.69
May	57.41	100.58	107.75	109.47	104.46	105.25
June	94.40	75.87	89.53	93.25	93.90	92.48
July	103.40	92.71	91.00	86.71	104.47	95.66
August	102.76	112.22	122.87	111.38	112.47	112.34
September	119.33	112.48	87.46	109.02	134.22	116.51
October	151.81	132.54	8.78	153.14	127.39	138.50
November	151.50	140.76	118.75	143.58	123.07	135.53
December	145.49	147.01	167.45	153.83	149.17	152.59
Average	120.15	122.50	114.25	126.17	128.87	126.61

3.2. Field testing

The functionality tests showed that temperatures up to 40 °C and 50°C were obtained in the greenhouse and screw conveyor, respectively, without the introduction of synthetic sludge. These temperatures lead to low relative humidities, particularly in the screw conveyor solar drying prototype when it was connected to the air dehumidifier

During the solar drier tests, the sample changed from an initial wet look with a pasty-like consistency to a final dried granular solid aspect as drying proceeded, as can be observed in Figure 3. Sunny conditions were the most favourable for the drying of the synthetic sludge, which dried to low moisture contents after a few days of testing. The absorber wall and circulation fans had a positive effect on the faecal sludge drying in the greenhouse, as well as the reflectors, air collector and air dehumidifier in the solar screw conveyer dryer. Concerning the ventilation rate, an increase of this parameter decreased the temperature inside the dryer, leading to a lower vapor pressure for moisture, but it increased the mass transfer. An optimal point must be found for a faster drying.

Fig. 3 Evolution of the aspect of synthetic sludge during drying (from the left picture at the beginning of the tests to the right picture at the end of drying)

At the latest stage of drying, the water activity of the material decreased, suggesting that the remaining moisture was strongly bound to the solid, leading to a decrease of the drying rate. This result suggests that drying could be stopped before the drastic increase of moisture boundness to lead to higher performance. Some challenges were identified during operation of the prototypes, particularly the sticky behavior of the sludge, potentially leading to blockages and fouling of the screw conveyor and the scraping system in the greenhouse. This phenomenon must be taken into consideration in the operation of the mechanical components of the prototypes, and mitigation strategies could be applied to limit its adverse effects. Another challenge was the variability of the weather conditions, with the rainy and overcast days leading to slower drying rates.

4. Conclusions

The solar assessment confirmed that solar thermal drying is an interesting, cost-effective faecal sludge treatment method. In the greenhouse and screw conveyor solar thermal driers, faecal sludge drying could occur within a few days if the weather conditions are favourable, and with the optimal operating conditions. The process could be stopped before reaching a high level of bound moisture to gain in efficiency.

The next steps in the prototype testing will consist of tests with real faecal sludge. Measures to mitigate stickiness will be sought in future iterations of the prototypes, as well as heat storage systems could be considered to allow for drying during nights and cloudy days.

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