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Enhanced Biosolids Drying with a Solar Thermal Application

Domènec Jolis[1] **and Natalie Sierra**[1*]

[1]San Francisco Public Utilities Commission 750 Phelps Street, San Francisco, California, USA

Abstract

Covered, green-house type biosolids solar drying facilities provide a low-energy option with operational simplicity and reduced cost. However, their large footprint consequence of low water evaporation rates make them unattractive for large wastewater treatment plants in urban areas with limited available space. This project investigated whether recent advances made in solar thermal technology conferred sufficient benefit in water evaporation rates that solar drying of wastewater biosolids may be feasible. A demonstration solar drying chamber was constructed with warm air from a solar thermal panel being routed to the chamber to aid in evaporation. Experiments were conducted with water alone to measure water evaporation rates in a range of weather conditions and to develop a regression model for evaporation. Experiments were also conducted with digested, dewatered biosolids to measure evaporation rates when drying biosolids. Total solids concentration in biosolids samples reached 42.3% after 102 hours in the dryer. Data showed that evaporation rates strongly depend on the temperature inside the dryer chamber but also on biosolids mixing. Measured evaporation rates were more than twice those previously reported in the literature for solar dryers and imply that with an experimental setup optimized for mixing, humidity control and energy recovery, still higher rates could be achieved. If confirmed in larger scale demonstration projects, the results from this study would allow for compact solar dryers to be located in urban settings.

Keywords: Solar drying; Solar thermal; Beneficial reuse; Biosolids; Compact treatment technologies; Evaporation rates

Introduction

Solar drying has long been used as a method employed in the reduction of water and pathogen content from biosolids. Traditionally, this took the form of open air drying beds, but as odor and air emissions have become more pertinent issues for many facilities, covered solar drying beds and greenhouse-type installations have replaced some of these installations. In addition, as biosolids transportation costs have risen, utilities have sought ways to reduce the volumes of biosolids hauled to final disposal/reuse sites. While conventional thermal drying is a proven solution to volume reduction, solar drying provides a low-energy alternative with operational simplicity.

Solar drying technology makes use of renewable solar energy to dry biosolids in greenhouse type installations. In this type of installation, biosolids are loaded into a greenhouse manually or via a conveyer, and dried in a batch or continuous process. The greenhouse serves to capture and contain heat generated by solar radiation. In addition to enhancing the available heat generated by solar energy, the greenhouse helps to contain odors that might be generated by the drying biosolids. To enhance drying, the newer generation of solar dryers employs automated mixing and control of the climate within the greenhouse [1]. There are three commercial examples, distinguished by mixing systems and number of commercial scale installations. One company uses an "electric mole," or small robot, to mix the biosolids, a second uses a system of conveyer belts, and a third uses a proprietary mixing machine. The system using the electric mole is able to process solids with solids concentrations as low as 3%, while the other two methods require a total solids concentration (TS) of 20% or greater [2]. Overall, these systems have been used in smaller plants, ranging from those serving 1000 population equivalents (PE) to those serving 300,000 PE [1].

Evaporation factor is a function of outdoor solar radiation, outdoor air temperature, and ventilation flux [3]. In sizing the area required for solar drying in any geographical location, the solar radiation is a key factor. The corresponding temperature and relative humidity inside the greenhouse are also pertinent factors. As solar radiation can vary throughout the year, the evaporation rate will vary leading either to a variation in the moisture content of the dried cake or in the time required to achieve target percent solids. The ventilation system set-up in any biosolids solar drying unit should allow free exchange of air between the interior and exterior of the greenhouse gas unit, in order to ensure that the air absorbing moisture from the biosolids does not reach a point of saturation so that the drying process continues to be driven by humidity. Figure 1 shows an image of a typical ventilation system in a solar drying unit.

While different models of evaporation rate have been explored in the literature, generally speaking, evaporation rate can be correlated to solar radiation, ventilation rate, air temperature, and relative humidity [2,4]. Performance, as defined by evaporation rate, thus varies widely in the literature, depending on the location and climate of the experiment, and maximum evaporation rates reported range from 1 kg/m^2-day to 8 kg/m^2-day [2,5-8].

Seginer and Bux [4] have put forth several models for evaporation rates from solar dryers. In general, they describe the evaporation rate as a function of weather, "state of the sludge" (e.g. dry solids content, sludge temperature), and control within the greenhouse (e.g. ventilation rate, mixing rate) [9-11]. Seginer and Bux used the vapor balance method in their initial modeling efforts, which consists of measuring the humidity ratio, w, of the ventilating air at the inlet and outlet of the unit; multiplying the difference, wo-win, by the density of air and the

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***Corresponding author:** Natalie Sierra, RMC Water & Environment, 222 Sutter Street, San Francisco, California, USA; Tel: 415-9204914 E-mail: djolis@sfwater.org

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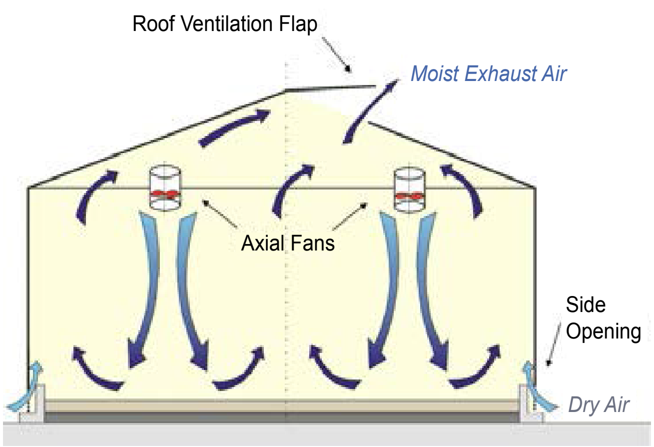

Figure 1: Solar Drying ventilation system [4].

discharge of the ventilation fans. Based on experimental data, they also proposed a linear equation, for evaporation rate as follows:

$$E= 0.000461R_o + 0.001010Q_v + 0.00744T_o - 0.220\sigma + 0.000114Q_m$$

Where:

E = evaporation rate (mm/h)

R_o = outdoor solar radiation (W/m^2)

Q_v = ventilation rate (m^3/m^2-h)

T_o = air temperature (°C)

σ = dry solids content of the sludge (kg solids/kg sludge)

Q_m = air mixing (m^3/m^2-h) [4]

The first three variables demonstrated a strong effect on the evaporation rate, while the last two demonstrated a smaller effect, based on the researchers' available data.

Solar drying installations have advanced in the last decade, largely by introducing automation to mixing and ventilation within a controlled greenhouse setting. The environmental controls offered by these greenhouse systems has enabled researchers to better predict evaporation rates, given measurements of solar radiation, temperature, ventilation rate, dry solids content of the sludge, and mixing rate. While individual results for evaporation rate vary, researchers reported rates between 1-9.6 kg/m^2-day. The ability to model evaporative behavior within the greenhouse setting further enables the optimization of such an installation depending on the site specific characteristics and needs of the agency employing this drying technology.

Objectives

This project investigated whether recent advances made in solar thermal technology conferred sufficient benefit in water evaporation rates that solar drying of wastewater biosolids may be feasible in densely populated urban areas. This work was done as proof of concept for a potential urban solar drying facility.

Materials and Methods

Chamber construction

A chamber (Figure 2) was constructed to allow a supported solar panel to heat the interior, thus drying the biosolids. This chamber was constructed of wood and measured 122 cm×46 cm×61 cm. The chamber design reflected the air-volume to sludge-area ratio as well as the air cross-flow to sludge-area featured in the low temperature (60°C) tunnel sludge drying technology developed by Aquology STC, Castellon, Spain. Aquology STC has tunnel sludge drying installations in France, Ireland and Spain with capacities of up to 500 metric tons per day. However, for simplicity, ease of construction and cost, no energy recovery features were incorporated in the experimental chamber beyond passive insulation, and mixing of the sludge inside the chamber was done manually. A four foot solar panel designed and sized to provide heat to a small bedroom, was mounted on the chamber, and with warm air generated by the panel traveling via a short length of four-inch ductwork to the chamber. The solar panel selected was designed to absorb 95% of the available solar energy and produce up to 100W of heat energy per linear foot. The panel was outfitted with a 12 volt DC fan attached to the intake vent; the fan is intended to turn on automatically when the inside temperature reaches 38°C. The chamber was insulated on the inside with commercially available household insulation. Temperature inside and outside of the chamber was measured using a data logger capable of taking and recording periodic temperature measurements. Relative humidity inside the chamber was also measured through the data logger. The unit was installed and tested outdoors in San Francisco.

Experiments to evaluate water evaporation rates

The initial phase of work sought to optimize the maximum achievable temperature inside the chamber. Factors that were tested include vent fan speed, insulation, and angle of the solar panel. The second phase of work sought to measure potential evaporation rates across representative outdoor temperatures and sun exposure. Six plastic cups were filled with approximately 50 mL of water each morning and their weights were recorded along with the current weather condition and time. Each cup measured 7.5 cm tall and had a diameter of 6.5 cm, providing an identical surface area (33.16 cm^2) to ensure uniform testing conditions. Three of the cups were placed inside the drying chamber of the solar dryer at three different locations. Cups 2 and 3 were offset on either side of the chamber's center where the sludge holding pans can be seen in Figure 2, while Cup 1 was placed between Cup 2 and the wall towards the outside edge of the dryer chamber. The two remaining cups were set outside of the drying chamber with Cup 4 placed in the shade and Cup 5 receiving direct sunlight.

Experiment to evaluate biosolids drying efficiency

Once adjustments to the chamber had been made and approximate

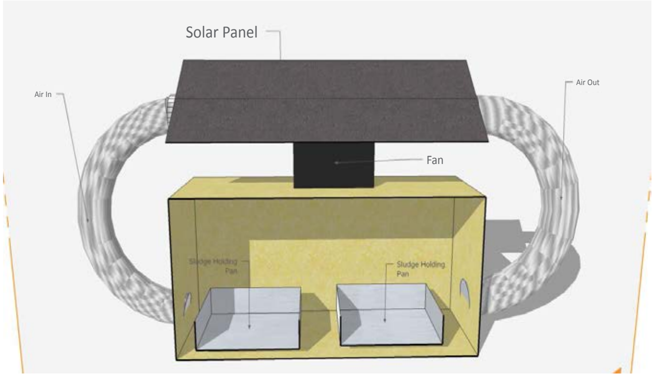

Figure 2: Test chamber with solar panel.

evaporation rates established, the efficacy of solar thermal drying on biosolids was tested. Three aluminum tins (33cmx23cmx5cm) were filled to a depth of two and one half centimeters with biosolids collected from the belt presses at one of San Francisco's wastewater treatment plants. The treatment plant incorporates a pure-oxygen activated sludge system and anaerobic digesters operated at mesophilic temperature and more than 20 days of hydraulic retention time. After digestion, the total solids (TS) and volatile solids (VS) of the stabilized sludge range between 2.3 and 2.7%, and 60 and 65%, respectively. Since the temperatures inside the drying chamber were not sufficient to significantly volatize the organic fraction of the biosolids, the VS content of the dried cake remained unchanged at 60-65%. Two of the tins were placed inside the solar dryer and the third was left as a control in the partial sun. Biosolids were mixed twice daily in one of the tins inside the solar dryer while the other tin inside the solar dryer and the outside control tin were left unmixed. The tins were left in the solar dryer 24 hours per day for four days.

Experimental conditions

As relative humidity, temperature, and solar radiation can all affect the efficacy of drying, establishing evaporation rates under different weather conditions was critical to the understanding of the applicability of a larger solar thermal installation. Table 1 summarizes the conditions for the three experiments conducted.

Data collection and statistical analyses

During Experiments 1 and 2, the five cups were removed every afternoon, weighed, and the evaporation losses were calculated.

Temperature data were recorded each day in three different places: inside the drying chamber, outside the chamber in the ambient air (with sensor placed on top of the drying chamber), and inside the conduit that delivers the heated air from solar heater to the drying chamber. Temperatures were recorded using a data logger with data recorded every ten minutes. The rate of evaporation was measured in kg/m^2-day. The total weight of water evaporated each day was divided by the total number of hours the dryer was run per day to give an average rate of evaporation per surface area. Paired T-tests of the observed evaporation rates were used to determine whether results for Cup 1 were different from Cup 2 or Cup 3 results, given the uneven exposure to air flow inside the dryer chamber.

During Experiment 3, biosolids samples were collected each afternoon at approximately 3 PM to be analyzed for %TS. As biosolids dry from top to bottom and the non-mixed tins dry unevenly, care was taken to sample at a depth of 1.2cm to achieve an average %TS for the sample. Temperature data were recorded inside the drying chamber every ten minutes using a data logger. Ambient temperature data was recorded every 15 minutes.

Result

An increase in temperature, often doubling, was observed in the chamber during daylight hours. Figure 3 shows this difference for a typical experimental day. Since the chamber's insulation was not optimized, diurnal variation, correlated with peak daytime temperatures and sun exposure, is evident. Figure 4 shows the temperature and average evaporation rates for Cups 2 and 3 inside the chamber, along with the average evaporation rates for cups placed outside the dryer in the shade and direct sun. The data presented in Figure 4 does not represent the evaporation rates recorded for Cup #1. Lower evaporation rates were observed in Cup #1 and are most likely attributed to its corner position in the drying chamber, putting it out of reach of the air currents generated by the fan. In fact, paired T-tests of the observed evaporation rates revealed that Cup 1 results were statistically different from Cup 2 or Cup 3 results at the 95% confidence level ($T=0.0005<T_{crit}=2.3$) and will not be further considered.

The results of Experiment 3 are detailed in Table 2. At the end of five days of testing, the mixed dryer sample was 42.3% solids (a 25 % increase), the unmixed dryer sample was 34.7% solids (a 17.4% increase), and the unmixed outside sample was 32.9% solids (15.6% increase).

Discussion

Initial work performed indicated that the interior of the chamber could get up to 38°C during daylight hours, with significant heat losses overnight. Evaporation rates (daily averages) for greenhouse applications range from 1 kg/m^2-day (Bux and Bauman 2003) to 2.2 kg/m^2-day [6]. Success of the pilot unit was therefore measured against these industry figures, while also acknowledging that the chamber was not constructed as an ideal solar dryer would be. For example, a more demonstration scale model would be better insulated to protect against

	Experiment #1	Experiment #2	Experiment #3
Media tested	Water	Water	Biosolids mixed and unmixed
Ambient temperature range, °C	11.5-19.1	12.7-26.8	5.7-17.4
Maximum Solar Irradiation, W/m^2	855	771	505
Maximum wind speed, m/s	5.2	5.4	3.3
Weather	Partly cloudy	Sunny	Cloudy

Table 1: Summary of experimental conditions.

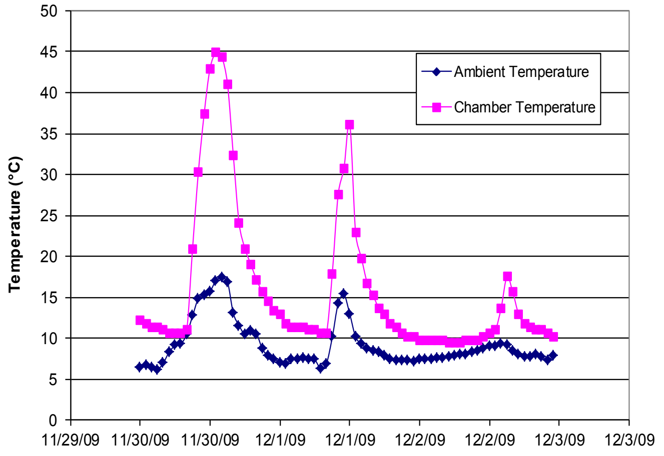

Figure 3: Typical Difference Between Dryer and Ambient Temperature during Experiments.

Date	Elapsed Time (hour)	Mixed Dryer (% TS)	Unmixed Dryer (% TS)	Unmixed Outside (%TS)
30-Nov-09	0	17.31	17.31	17.31
1-Dec-09	30	21.29	20.09	18.60
2-Dec-09	54.25	27.92	25.16	23.75
3-Dec-09	67.75	37.54	32.86	29.18
4-Dec-09	102	42.32	34.72	32.92

Table 2: Increase in %TS Over Experiment.

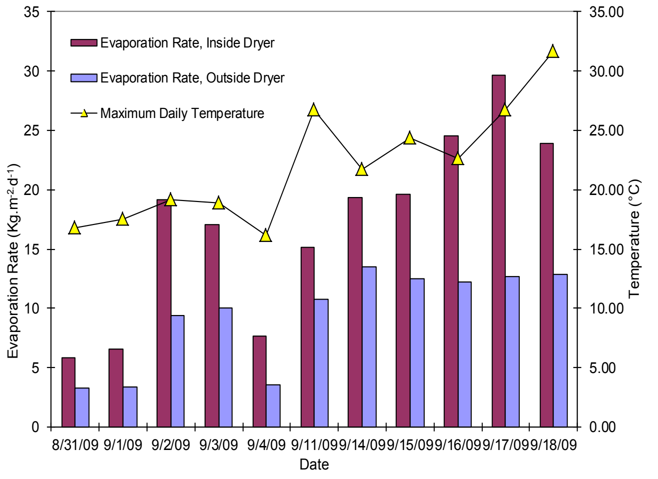

Figure 4: Evaporation Rates for Experiments 1 and 2.

the heat losses experienced during this experiment. Figure 3, however, indicates the increase in temperature experienced inside the chamber as compared to ambient temperature, often nearly doubling during peak sunlight hours. If the insulation of the chamber had been better optimized, this difference would likely have been greater.

Evaporation rate data in Experiment 1 is somewhat flawed due to the strong winds present at the time, which likely aided the evaporation rates of the cups set outside the chamber. The evaporation rates observed for Experiment 1 ranged from a low of 5.9 kg/m^2-day to a high of 19.2 kg/m^2-day. On cooler, cloudy days (8/31, 9/1, 9/4) these evaporation rates ranged from 78% to 116% improvement over the cups placed outside (which were not shielded from wind effects). On sunny days, the difference between the chamber samples and the outside samples is similar, ranging between 70% and 105% greater than the cups placed outside, indicating that the dryer's superior performance was maintained over a range of weather conditions. The evaporation rates measured during Experiment 2 ranged from 15.1 kg/m^2-day to 29.7 kg/m^2-day, a considerable difference from the values seen under the cooler conditions of Experiment 1 and much higher than those reported in the literature for biosolids.

As expected, a strong correlation exists between evaporation rate and the temperature inside the chamber for Experiments 1 and 2, which explains almost 80% of the variation in the data; the remaining variation is likely dependent on variations in relative humidity (not controlled in our experiments) and fan operation (i.e, air circulation). The regression equation (Figure 5) confirms the strong suspicion that evaporation rates for samples outside of the chamber were grossly overestimated, most likely due to evaporative cooling. Thus, for Experiment 2, the Cup #4 results would have required air temperatures inside the chamber between 24 and 27°C, but the recorded air temperatures outside the chamber ranged between 10 and 17°C.

Data in Table 2 can be used to calculate the evaporation rates for the duration of the experiments. These were 5.3 kg/m^2-d for the mixed sample and 4.6 kg/m^2-d for the unmixed one, clearly indicating the importance of mixing. Although the biosolids drying experiment could not be repeated under warmer conditions, it can be reasonably assumed that the evaporation rates in the biosolids samples could be nearly double when conditions similar to those of Experiment 2 were present.

However the limitations of the experiment as conducted, the evaporation rate for the mixed sample is 121% higher than current state of the art for solar biosolids dryers [6].

For Experiment #3, the higher rates of TS% increase inside the solar dryer are primarily due to the heating of the air inside the drying chamber as well as the flow of air over the biosolids produced by the solar dryer's fan. When the air inside the heating unit in the solar panel reaches a trigger (set at 75% for this study), a fan is switched on which circulates the heated air into the drying chamber and recycles the air into the heating unit. Insulation was included to contain the heated air inside the drying chamber and minimize losses to the ambient air.

Combining temperature profiles such as that shown in Figure 4 with the regression equation developed in Figure 5, the evaporation rates for different temperature and solar irradiation conditions can be calculated. Using this same approach for the five days, from November 30th to December 4th, when the biosolids drying experiment was conducted yields an average evaporation rate of 6.2 kg/m^2-d which compares favorably with the observed value for the mixed sample (17% difference) and validates the approach. Better mixing of the biosolids would have likely improved the rate of evaporation during the experiment, since the difference in rates between the mixed (twice per day) and unmixed samples was 14%, and would have brought it even closer to the calculated value.

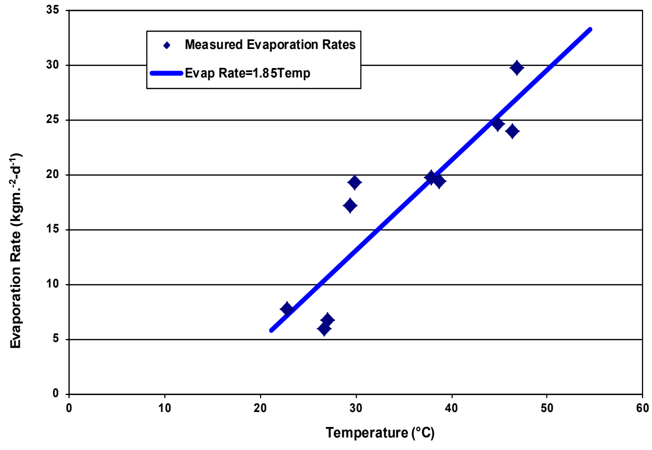

Figure 5: Observed Regression between Evaporation Rate and Chamber Temperature.

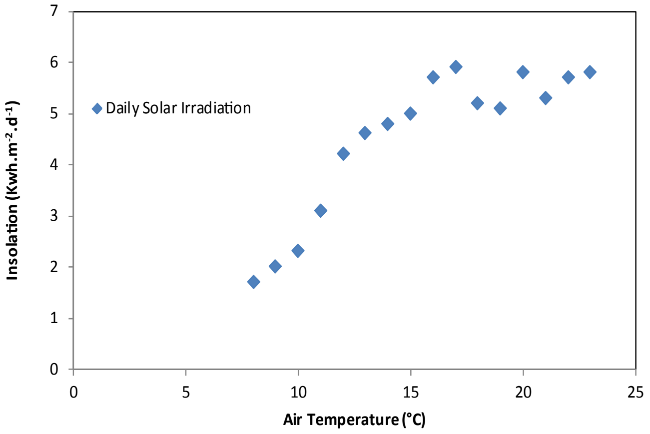

Figure 6: Daily Solar Irradiation for San Francisco, CA.

The solar dryer consistently provided higher evaporation rates inside the drying chamber over a wide range of weather conditions, but at times the increase was small while at other times the benefit was substantial. The weather along the coast in San Francisco can be extremely varied with the coldest temperatures seen in the fog-filled summer and rainy winter and the warmer temperatures seen in the sunnier spring and fall. Due to the varied weather conditions in San Francisco, the feasibility of installing a large scale solar biosolids dryer hinges in part on the unit's drying effectiveness in relation to the outside weather and temperature.

The solar dryer provides higher increases above ambient air temperature on days when the ambient temperature is higher due to increased solar irradiation. On November 30th, when the maximum ambient air temperature reached 18°C, the difference between ambient and chamber temperatures reached 82%. On December 2nd, the coldest day with a maximum ambient temperature of 9°C, the temperature difference only reached 31%. This relationship exists because high ambient air temperatures are typically correlated with high levels of solar energy reaching the earth's surface from the sun, so the solar heater runs for greater periods of time. Also, the fan is operated on a switch that turns on when the air inside the fan unit reaches approximately 24°C. So with increased solar energy the solar heater delivers more warm air and the fan is turned on for longer periods of time, creating more air flow at higher temperatures. These two changes create the maximum temperature differences between the chamber air and the ambient air and thus maximize the increased biosolids TS percent rates. A weakness of this experiment is that the relative humidity within the chamber could not be controlled, as would be true in a full-size installation. Greater evaporation rates would be observed if this factor could be optimized.

In addition, higher evaporation rates would be expected for more typical San Francisco weather conditions. In fact, the average temperature (9°C) and solar irradiation (2.0 Kwh/m^2-d) during the period of November 30th to December 4th were at the low end of annual values for San Francisco, CA (Figure 6). If instead, the median conditions for San Francisco of 14.6°C and 4.8 Kwh/m^2-d were used to estimate the temperature inside the chamber throughout the day and then the equation in Figure 5 is employed to calculate the evaporation rate for those temperatures, the predicted result is 17.8 kg/m^2-d or 236% higher than the value for the period of the biosolids drying experiment. Certainly, these estimates will need to be confirmed with further experimental results.

Conclusions

The solar dryer consistently provided elevated evaporation rates over a wide range of weather conditions. The evaporation rate measured during Experiment 3 (i.e., biosolids drying with mixing) was more than twice the current state of the art for solar dryers. The solar dryer increases biosolids TS% rates by altering two main factors inside the solar chamber: temperature and air flow. The solar dryer maximizes its heating efficiency on hot, sunny days when more solar energy reaches its panel and both the heating device and fan run for longer periods of time. The influence of local weather, particularly fog and cloud cover, often diminished the efficacy of the panel, as would be expected. Due to the varied weather conditions in San Francisco, the feasibility of installing a large scale solar biosolids dryer hinges in part on the unit's drying effectiveness in relation to the outside weather and temperature. Further studies to establish conservative drying rates (e.g. in the absence of idealized insulation and humidity conditions) and preliminarily size such a unit for a large wastewater treatment plant (500,000 to 1,000,000 PE) are needed.

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