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SIMULATING LAGOON SLUDGE DRYING IN SOLAR-ASSISTED GREENHOUSE DRYING SYSTEMS

PIYUSH PATIL, MAHMOUD SHARARA

Highlights

- Solar-assisted greenhouse drying is impacted by weather, moisture content and sludge mixing.
- Average drying rates over 34 days ranged from 2.2 to 2.9 kg m^{-2} d^{-1}.
- Maximum carbon and nitrogen lost during drying were 12% and 14%, respectively.
- A neural network model successfully simulated (R^2 > 0.91) lagoon sludge greenhouse drying.

ABSTRACT. *Greenhouse sludge drying is gaining wider acceptance in agricultural and municipal applications due to the low cost, low energy inputs, and simple operation involved. This approach leverages weather and management practices to facilitate drying. This study evaluated greenhouse sludge drying and the impacts of weather conditions, air exchange rate and material properties on drying rate. Excavated swine lagoon sludge, loaded at 158-177 kg m^{-2}, was dried in two greenhouses (488.9 m^2 each) near Warsaw, North Carolina. The impact of ventilation rate, ranging between 1.1 and 4.6 m^3 m^{-2} min^{-1}, was evaluated during the 34 day (d) drying test. A two-phase drying process was observed: average drying rate during the first phase was 4.3±2.0 and 4.5±1.7 kg m^{-2} d^{-1} for GH#1 and GH#2, while the second phase showed rates between 0.6±1.9 and 0.1±2.3 kg m^{-2} d^{-1}. The following factors were significant predictors of the drying rate: solar radiation, sludge moisture, ambient temperature and relative humidity, time since mixing event, and ventilation rate. Cumulative carbon and nitrogen loss during the process was up to 12 and 14%, respectively. Statistical models developed to predict drying using process variables and management decisions performed well (R^2>0.80), but the absolute penalty neural network model outperformed other models' predictions in both greenhouses (R^2> 0.91, RASE <33.5 kg$_{H2O}$ hr^{-1}). This study is a first of its kind to evaluate feasibility of greenhouse sludge drying in Southeastern US. Findings and models developed in this study will increase process efficiency and incentivize adoption of on-farm greenhouse drying.*

Keywords. *Swine Lagoon, Neural Network, Solar greenhouse drying, drying rate,*

INTRODUCTION

North Carolina is a leading US swine producing state with more than 1,400 permitted farms, majority of which are feed-finish farms, all heavily concentrated in the Southeastern region of the state. The sector produced an average of 18.9 million heads per year from 2000 to 2022 (NASS, 2023). Anaerobic lagoons are the primary method of manure management on these farms where manure is stored and treated for use as two fractions: liquid supernatant and sludge. A median sized feed-finish farm in North Carolina, with 3,500 finishing heads (Aghdam, 2022), produces 70.4 Mg of sludge dry matter each year (Bicudo et al., 1999; John P. Chastain, 2006) containing ~9.7 Mg of P_2O_5 (Owusu-Twum and Sharara, 2020). Regulatory guidelines stipulate sludge removal if it occupies more than 50% of the designed lagoon treatment volume. Without affordable practices for the management of lagoon sludge nutrients, however, many farms opted to allow sludge accumulation and, if feasible, remove enough sludge to stay in compliance. The NC swine industry, at the current production rate, generates 52,372 Mg of P_2O_5 annually in sludge, which is equivalent to 56% of 2011 NC fertilizer P_2O_5 purchase (Commercial Fertilizer Purchased, EPA). A major hurdle facing recycling this valuable asset, however, is the difficulty of recovering these nutrients in a compact and transportable form. Current sludge management practices recover sludge at a total solid (TS) content between 8% and 12%, which greatly limit transportation. Another challenge in swine sludge use in NC is its high P concentration and elevated soil phosphorus index (P-I) (Johnson, 2004) in areas surrounding animal operations. Export of swine sludge nutrients where they will be valued and could be agronomically utilized will results in its sustainable use. However, transportation costs escalate for longer hauling of wet substrates. Treatment initiatives that reduce weight and volume without losing or diluting nutrients are hence needed for sustainable swine sludge management.

Drying is a potential alternative that can be employed to reduce sludge volume and moisture content. It can concentrate and retain sludge nutrients, hence producing a marketable and nutrient-rich product. Other applications for dried swine lagoon sludge include its use as a combustion feedstock, or co-ingredient, for renewable electricity generation, or pyrolysis for biochar and syngas production. Drying, however, is a capital and energy intensive process and is not typically economical for residual materials and agricultural byproducts like lagoon sludge, especially when expenses are borne by producers. A detailed analysis of several commercial drying systems, conducted by Sharara (2022), reported drying costs between \$90 and \$156 Mg^{-1} dry matter (DM), with additional costs associated with sludge removal and aggregation (centralization). Another crucial observation was the high demand of electricity (27 to 170 kWhr Mg^{-1}_{H2O} evaporated) and natural gas (1,550 to 2450 MJ Mg^{-1}_{H2O} evaporated) for conventional drying. Furthermore, farm scale systems may lose the advantage of economies-of-scale and energy use efficiency making conventional drying systems unsuitable for swine lagoon sludge management.

Drying using enclosed, ventilated solar greenhouse systems present a simpler alternative and can achieve comparable results with added benefits. These systems use incident solar radiation and ambient weather conditions, coupled with forced ventilation, material mixing, and optional supplemental heating to facilitate drying (Seginer et al., 2007; Seginer and Bux, 2006). Variability in these factors, however, results in slow and variable performance, unlike conventional drying systems (Bennamoun, 2012). While solar systems have lower energy consumption (24-28 kWhr Mg^{-1}_{H2O} evaporated) (Bux et al., 2002), they require a larger footprint. They are typically considered to be economical due to low infrastructure, machinery and maintenance costs (Boguniewicz-Zablocka et al., 2021a). While these systems have been studied for managing industrial waste and wastewater treatment sludges, no studies have reported the performance of these systems for animal manure or sludge in Southeastern US. In addition, no tools are currently available to help optimize the operation of such systems.

This study aimed to address this knowledge gap through evaluating the drying performance of swine lagoon sludge in a pilot scale ventilated greenhouse system that was newly built in Eastern NC. The main objective is to understand the impact of weather conditions, material mixing and ventilation rates on drying rates. Furthermore, this study developed and evaluated different empirical models to predict drying using process variables and management decisions. The findings in this study provide necessary information and tools to help researchers, producers, and stakeholders evaluate the economic and environmental performance of this technology as an option for animal producers in the state and beyond.

MATERIALS AND METHODS

SWINE LAGOON SLUDGE REMOVAL AND HANDLING

Lagoon sludge was sourced from a farrow-wean swine farm (4,719 allowable heads) in Duplin County, North Carolina, USA. The Sludge was removed using an excavator (313F, Caterpillar, Inc., Peoria, Illinois, USA) equipped with a modified skeleton bucket attachment (Teran Industries, Miami Florida, USA) and mounted on a floating barge. The barge navigated across the lagoon using guided cables and the excavator arm. The excavated sludge was collected in a roll-off dumpster stationed on the barge, the capacity of which was 11.5 m^3 (15 yd^3), then emptied into a lorry at the end of each removal cycle. Sludge samples were collected during transfer to characterize as-removed sludge. Subsequently, the excavated sludge was transported to an open, contained storage where it was stored for less than two weeks. The required amount of sludge was transported 25 km to the greenhouses site where it was staged before the commencement of the drying study. The sludge was spread through the greenhouses using a skid steer. The material loading rate was 177.2±9.7 for greenhouse #1 (GH#1) and 158.2±9.7 kg m^{-2} for greenhouse #2 (GH#2).

GREENHOUSE, VENTILATION AND SLUDGE TILLING SYSTEM

Two greenhouses (pointed-arch design) were employed to study sludge drying. Each greenhouse had a drying area of 444.5 m^2 (For dimensions refer Figure 1). Each greenhouse had entrances at both ends (garage-style), which were primarily used for material loading, unloading, and handling. Greenhouse ventilation was facilitated through mechanical tunnel ventilation, i.e., flexible louvers to allow air entrance on inlet side (4.5 m^2 louvered area), and four ventilation fans on exit side (HS9084, Hog Slat, Newton

Grove NC, USA), each had 504 m^3 min^{-1} airflow rate and 0.75 kW power rating.

Figure 1 Picture of sludge excavation, greenhouses, onsite weather station and sludge mixing.

A programmable logic system (PLC) was developed to control fan operation during drying process for both greenhouses using air temperature and relative humidity sensors (DOL 104, Aarhus, Denmark), which were used to calculate air psychrometry via a code block in the PLC. The PLC was programmed to control fans in each greenhouse based on the difference in absolute humidity between ambient air and exhaust air. Fan operations ceased when absolute humidity difference was less than 1.6 g m^{-3} (0.1 lbs. 1,000 ft^{-3}). Two fans would operate when absolute humidity difference was greater than 3.2 g m^{-3} (0.2 lbs. 1,000 ft^{-3}) and all four fans would be operational when absolute humidity difference rises to 6.4 g m^{-3} (0.4 lbs. 1,000 ft^{-3}). When ambient air relative humidity exceeds 90%, a system override terminates all fan operations to minimize risk of rewetting the sludge.

In this study, only one greenhouse (GH#1) was managed using the PLC logic detailed earlier. Fan operations in the second greenhouse (GH#2) were changed manually, with each interval between 48 and 72 hours. The manual fan scheduling started with one fan (1F) in the first interval, followed by two fans (2F), then three (3F) and finally four fans (4F). The same fans sequence was repeated in a cyclic manner until the end of drying. In both greenhouses, the sludge was mixed using a tractor-operated rotary tiller (55 HP, John Deere) at the start of each interval. These fan settings correspond to a nominal air velocity of 1.1. 2.3, 3.4 and 4.6 m s^{-1}

DATA COLLECTION AND ANALYSIS

Temperature and relative humidity of exhaust air were measured and recorded every 30 seconds using HOBO sensors (UX100-003, Onset, Bourne, MA, USA) fitted on each fan in both greenhouses. An additional sensor recorded local ambient temperature and relative humidity conditions. Uptime for each ventilation fan was logged by the PLC system on an hourly basis. A nearby weather station, i.e., Horticultural Crops Research Station, which is part of the state climate monitoring network (18 km from experiment site) was also used to retrieve ambient temperature, relative humidity, and solar radiation observations every minute throughout the experiment duration. Ambient and exhaust air properties and ventilation rate were used to determine vapor loss (VL) on hourly basis as follows:

$$VL = Q \times \left[\frac{W_{ext}}{V_{ext}} - \frac{W_{amb}}{V_{amb}}\right] \quad (1)$$

where Q = ventilation rate (m^3 h^{-1}), W= average humidity ratio (kg $_{H2O}$ kg $^{-1}$ $_{dry\ air}$), and V = specific volume of air (m^3 $kg^{-1}{}_{dry\ air}$), with ext and amb subscripts represent exhaust air and ambient air properties, respectively. Values for humidity ratio and specific volume were determined from psychrometric air properties using temperature and relative humidity observations. A workflow using MATLAB (R2021a, 9.10), Oracle Crystal Ball (Version 11.1) and Microsoft Excel (Version 16.65) was used to conduct the necessary computations.

For sampling purposes, the greenhouse was into gridded into nine grid cells representing front, middle and end of greenhouse (each cell is 3.6m by 15m). One sludge sample was collected from each grid cell at the beginning of each airflow interval. Each of the nine samples were analyzed for moisture and volatile solids content. In addition, for each sampling event, homogenous subsamples representing each zone: '*front*', '*middle*', and '*exit*' was composited from corresponding grid cells. Theses samples were analyzed to determine elemental composition, i.e., carbon (C), nitrogen (N), phosphorus (P), zinc (Zn) and copper (Cu) concentrations. Four sludge height observations were recorded for each grid cell at the start of every interval. Bulk density was measured in triplicates using grab samples from across the greenhouse during start, end of experiment and at select sampling events. The experiment was terminated when the sludge moisture content on wet basis reached less than 30% in both greenhouses. The total weight of dried sludge removed each greenhouse was determined and recorded.

STATISTICAL ANALYSIS

Analysis of variance (ANOVA), mean's comparisons, and predictive models' development were carried out using JMP-Pro 16 software (SAS Inc., Cary, NC). The dataset for GH#2 was divided into training (60%), validation (20%) and test (20%) for predictive modeling purposes. Three models predicting the rate of drying were developed, i.e., multiple linear regression, decision tree, and neural network (NN). Multiple linear regression was developed using stepwise analysis to include relevant independent variables. Decision tree analysis partitions data based on response and predictor relationships with decreasing importance. It was chosen considering the ease in result interpretation with findings directly used in PLC algorithm development. The NN model was developed with one hidden layer that had three activation functions: hyperbolic tangent (tanH), linear identity function and Gaussian function. An absolute penalty method with ten tours was used to determine appropriate prediction model. This method avoids overfitting by refitting the model a given number of times (tours) with random starting parameter estimates to determine best estimates. The observations from GH#1 were used to validate the best model generated and evaluate reliability of predictions.

RESULTS

SUBSTRATE PROPERTIES

The floating barge excavator facilitated sludge removal without significant dilution from lagoon liquid (supernatant) resulting in a higher dry matter content (Table 1). However, the wide range of dry matter observed was attributed to the non-compacted (fluid-like) portion of the recovered sludge. The variability between compacted and fluid-like portions of the sludge was visually observable during sampling. This variability was also reflected in the elemental analysis of the excavated sludge samples. This variability, however, was not relevant in the sludge at drying commencement. This can be attributed to the staging period where pooled substrate from multiple excavation tours was combined resulting in a more homogenous mixture. At the start of the experiment, the average dry matter content was 33.0% ± 1.1% and 29.4% ± 1.7% in GH#1 and GH#2, respectively.

Table 1. Characteristics of freshly excavated and initial sludge used in Greenhouses 1 and 2 (GH#1, GH#2).

		Initial wet sludge		Dried Sludge		
Parameter	**Excavated Sludge**	**GH#1**	**GH#2**	**GH#1**	**GH#2**	**Analytical method**
DM (% of wet mass)	29.0 ± 13.2	33.0 ± 1.1	29.4 ± 1.7	68.7 ± 6.7	78.7 ± 1.8	APHA 2015
VS% (% of DM)	NA	39.7 ± 2.0	46.4 ±5.2	41±2	44±3	APHA 2015
pH	8.0 ± 0.1	8.1 ± 0.1	8.2 ± 0.0	7.2 ± 0.1	7.3 ± 0.1	EPA 9045D
EC	3.2 ± 0.1	4.0 ± 0.2	4.2 ± 0.0	4.3 ± 0.5	5.0 ± 0.2	EPA 9045D
C (g/kg)	227.8 ± 117	185.1 ± 10.1	200.9 ± 3.1	170.3 ± 6.8	175.7 ± 6.2	AOAC 972.43
N (g/kg)	49.9 ± 26.3	37.4 ± 2.4	41.4 ± 1.1	33.5±1.3	35.7±0.8	AOAC 972.43
NH_4-N (g/kg)	24.6 ± 15.2	14.8 ± 1.4	16.6 ± 3.7	10.5±0.4	11.9±0.3	EPA 350.1
C/N	4.6 ± 0.0	4.9 ± 0.2	4.9 ± 0.1	5.1 ± 0.0	4.9 ± 0.0	NA
P (g/kg)	73.8 ± 6.2	67.9 ± 2.3	73.5 ± 1.6	66.4 ± 1.7	72.0 ± 0.4	EPA 200.7
K (g/kg)	5.6 ± 0.4	5.6 ± 0.3	6.2 ± 0.1	5.7 ± 0.2	6.4 ± 0.1	EPA 200.7
Zn (g/kg)	3.6 ± 0.8	3.4 ± 0.05	4.9 ± 0.4	3.7 ± 0.6	4.9 ± 0.2	EPA 200.7
Cu (g/kg)	2.1 ± 0.1	1.6 ± 0.04	1.8 ± 0.2	1.6± 0.1	1.9± 0.1	EPA 200.7

NA: Not available, mean ±SD (n= 3), all concentrations are specified on dry basis unless mentioned otherwise.

Effect of drying on Moisture content, material height and bulk density

The drying progress was tracked through moisture content change (d.b., MC_{db}) as shown in figure 2a. By the 15th day, the dry-basis moisture content decreased to 110.2±24.4% and 103.7±23.6% in GH#1 and GH#2, respectively. Additional 19 days were needed to reach 41.4±16.6% and 25.5±7.2% moisture content in GH#1 and GH#2 respectively. The variability in moisture content at each interval, indicated by reported standard deviation values, is attributed to the spatial variability in drying along airflow path from front to exit and, the gap in material loading. The average initial moisture content of samples in the front, middle and end grid cells in GH#2, were 256.0±64.8%, 192.5 ± 9.4%, 176.7±30.9% respectively, which was primarily due to gap in material loading as the material in the end section was loaded a week before the study commencement while the rest was loaded 24 hours earlier. At the end of the experiment, moisture contents in the GH#1 at the front, middle and end grid cells were 23.8±4.2%, 60.2±5.2% and 40.3±8.3% respectively, although all the material was loaded at the same time i.e., 24 hours before the commencement.

Average daily drying rate estimates show two distinct drying phases that represent the first and second falling rates (figure 3a, 3b). The constant rate drying phase was not observed in this study which could be attributed to the absence of free moisture in the sludge. The average drying rate during the first phase, i.e., MC_{db} > 100%, was 4.3±2.0 and 4.5±1.7 kg m^{-2} d^{-1} for GH#1 and GH#2, respectively. The drying rate dropped to 0.6±0.9 and 0.1±1.1 kg m^{-2} d^{-1} during the second phase. The maximum drying rates observed in the first phase was 7.2 and 6.5 kg m^{-2} d^{-1} in GH#1 and GH#2 respectively, while the maximum drying rates in the second falling phase were 2.1 and 4.3 kg m^{-2} d^{-1} for GH#1 and GH#2 respectively.

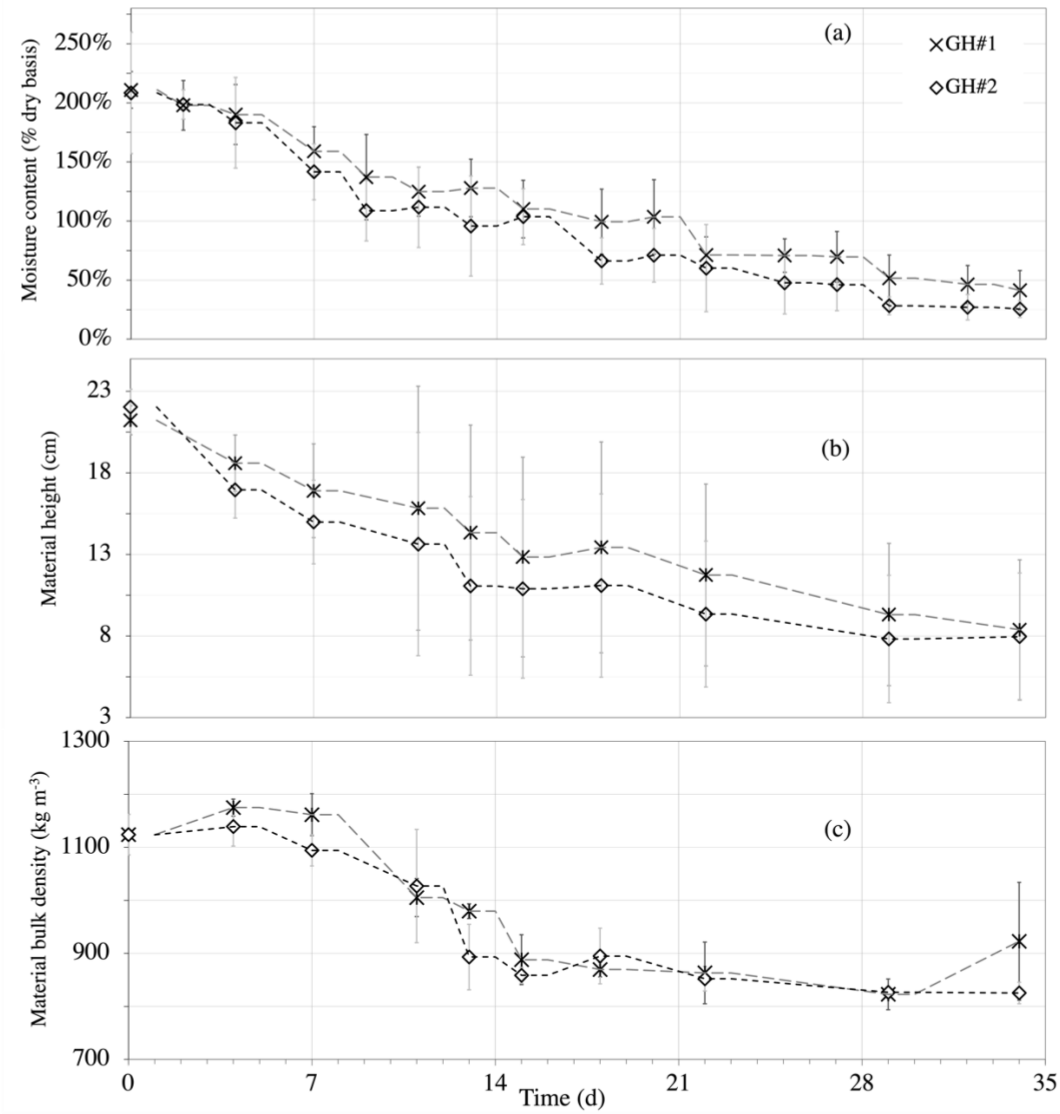

Figure 2. Observed changes in a) sludge height and b) bulk density, c) moisture content (dry basis) because of ventilated greenhouse drying.

Sludge height and bulk density were monitored during the drying period to correlate weight loss and with volume reduction (shrinkage). Sludge height on the 15th day, 12.8 ± 4.0 cm in GH#1 and 10.8 ± 1.7 cm in GH#2, was 40 to 51% lower than at the start of drying. Correspondingly, a decrease between 21-24% in material bulk density was also observed during this period. Figures 2b and 2c track average material heights and bulk density during the 34-d drying period. Variation in material height primarily indicates the spatial variability in material loading across the greenhouse. Variation in bulk density was attributed to the transition in sludge physical properties from paste-like to granular.

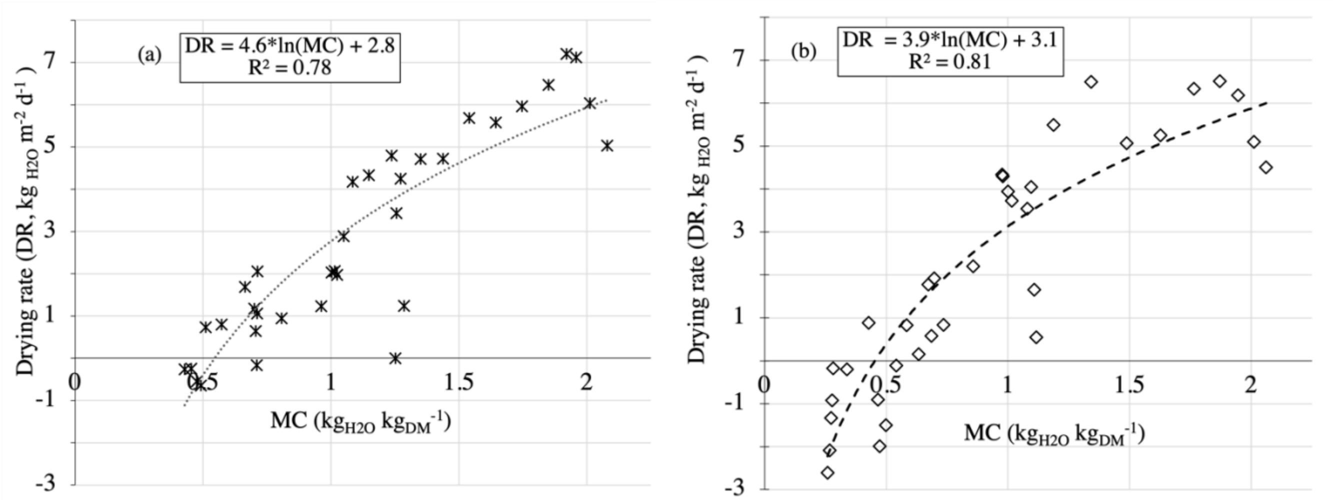

Figure 3. Observed average drying rate in a) GH#1, b) GH#2 as a function of moisture content (dry basis).

ACCOUNTING OF MASS AND VAPOR LOSSES

Sludge sampling and analysis were used to track losses of water, organic matter, and nutrients during the drying process. While the final weight of material recovered from GH#1 and GH#2 was recorded, i.e., 36.2 and 28.8 Mg respectively, logistical challenges prevented measuring initial total wet weights in both greenhouses. The initial wet weight of sludge was back-calculated using properties of initial and final sludge and assuming no change in ash content. The variability in material properties was incorporated into the initial weight estimates using Monto-Carlo simulation. On the other hand, cumulative water vapor loss was calculated using air properties along with hourly ventilation rates. We observed carbon loss of 12 ± 6% and 4±6% during drying from GH#1 and GH#2 respectively. Nitrogen losses were estimated to be 14±7% in GH#1 and 5±6% in GH#2. Differences in the carbon and nitrogen losses between GH#1 and GH#2 were observable however, not statistically significant ($p > 0.05$) indicating no effect of different ventilation techniques employed. Figure 4 illustrates the overall mass balance for both greenhouses, calculated water vapor loss amounted to 104±10% and 79.5±8% of weight loss estimated in GH#1 and GH#2 respectively. These mass balance estimations indicate the methodology used to track water loss on hourly basis via mechanical ventilation was adequate to represent the entire drying process.

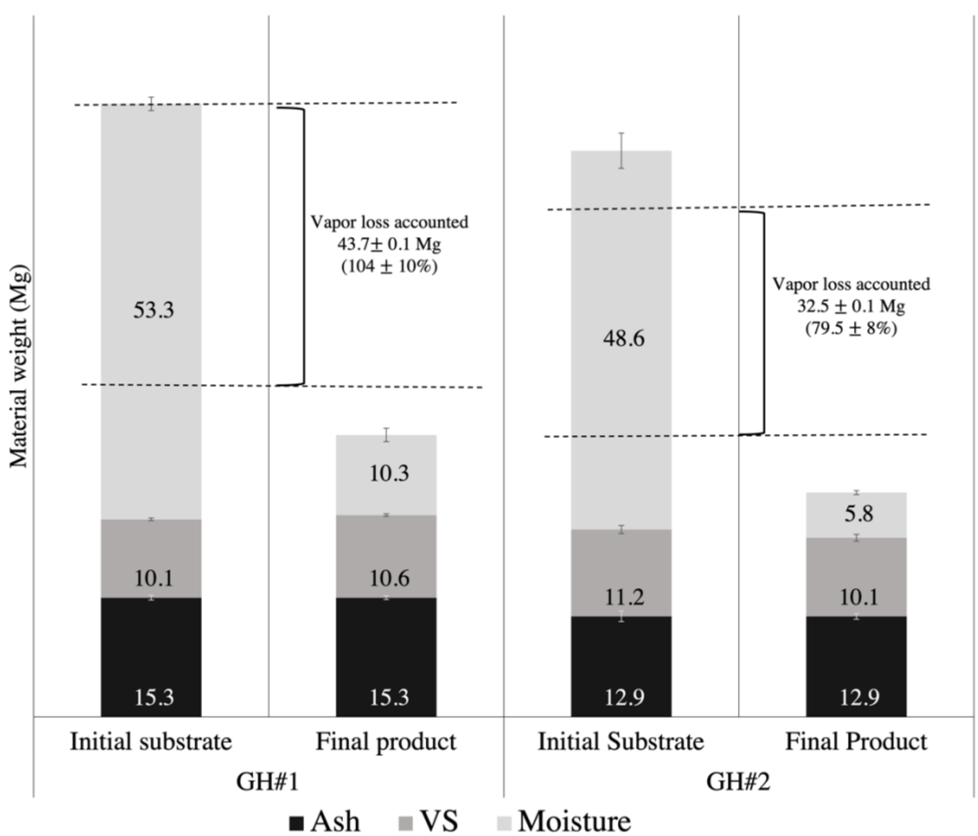

Figure 4. Observed mass loss (vapor and organic matter) and accounted vapor loss in greenhouses (GH#1, GH#2).

DRYING PROCESS FACTORS

Statistical analysis and model development were conducted using hourly dataset collected from GH#2 split into training set (457 observations), validation set (174 observations), and test set (181 observations). Factors observed to be statistically significant in drying rate estimation (p <0.05) were ambient temperature, relative humidity, solar radiation, sludge moisture content and time elapsed since last tillage (mixing). Seginer and Bux (2006) and Krawczyk, (2016) reported weather conditions and management significantly impacted drying process in solar drying of wastewater sludge . Ventilation rate (Q) was not observed to be statistically significant, although at least one fan was operational throughout the entire experiment duration in GH#2. As such, the results indicate that incremental changes in ventilation rate did not significantly affect water vapor loss rate.

The multi linear regression model was the simplest model developed to estimate the drying rate (refer to Appendix for model parameters). The decision tree (partition) model resulted in 66 logical data splits with decreasing importance of predictors. To reduce model complexity while maintaining prediction power, the decision tree was pruned resulting in 15 crucial splits. The neural network with learning rate (10%) and 10 trials was the most complex model developed, resulting in 30 individual equations with 10 equations for each of the three nodes (i.e., tanH, Linear, Gaussian). The coefficient of regression *(R^2)* and root averaged square error (*RASE)* values for the various models are listed in table 2. All models provided a fair prediction ability for training, validation, and test sets with R^2 between 0.80 and 0.92. The absolute penalty NN model was the superior model, outperforming other models across all datasets.

Table 2. Performance summary of Greenhouse drying prediction models

Category	Model	R^2	*RASE*[$] ($kg_{H2O}.h^{-1}$)
Training	Multiple linear regression	0.80	33.1
	Decision tree*	0.87	26.7
	Neural Network (absolute penalty)	0.93	19.3
	Neural Network (10% learning rate)	0.92	21.5
Validation	Multiple linear regression	0.82	33.4
	Decision tree*	0.87	28.1
	Neural Network (absolute penalty)	0.93	21.1
	Neural Network (10% learning rate)	0.92	22.4
Test	Multiple linear regression	0.85	35.0
	Decision tree*	0.86	33.7
	Neural Network (absolute penalty)	0.94	21.5
	Neural Network (10% learning rate)	0.92	24.7

*Pruned tree with 15 splits, [$]Root average squared error (for forecasts)

Model validation using GH#1 operation

Drying in *GH#1* was automated by using difference in humidity ratio between incoming and exhaust air as feedback to drive mechanical ventilation (using PLC controller). As a result, ventilation settings were changing at a faster rate than the hourly basis used for our data analysis and model development. Nonetheless, we sat out to test the absolute penalty NN model developed using *GH#2* dataset to predict the drying rate in *GH#1*. The model predicted hourly vapor loss using the following inputs: [1] predicted initial wet mass, [2] hourly ventilation records, [3] sludge mixing time records, and [4] weather conditions (temperature, relative humidity, and solar radiation). Predicted vapor loss was used to continuously update sludge moisture content for subsequent model evaluations until the moisture content reached the termination moisture content (experimental observation). Figure 5a illustrates predicted versus measured water vapor loss in *GH#1*. The coefficient of regression *(R^2)* indicated a good agreement between predicted and measured hourly water vapor loss rates. The model predictions were consistently below observed values, i.e., on average 17% lower than measured values.

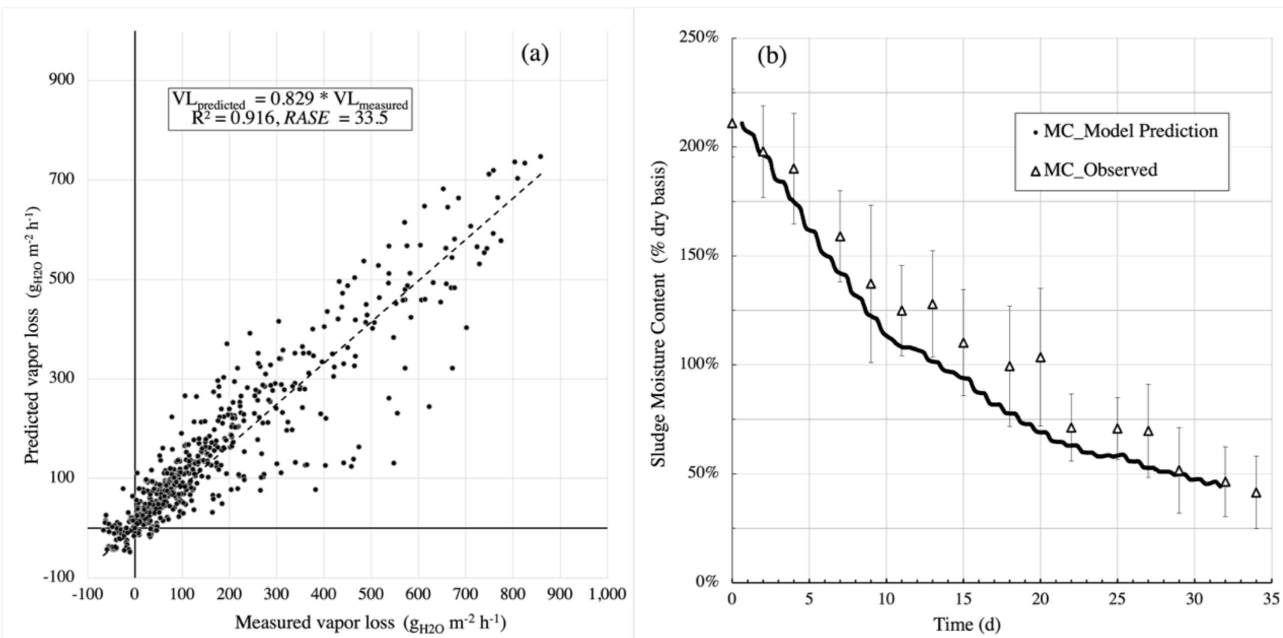

Figure 5. Summary of model predictions, a) vapor loss, b) moisture content for greenhouse drying.

The instantaneous prediction model could better predict drying at peak conditions which are averaged to an hourly basis in the current model. Predicted moisture content (solid line, Figure 5b) were comparable to measurements made at sampling intervals (hollow triangles, Figure 5b). These results demonstrate good prediction ability for the absolute penalty NN model to predict drying performance of a PLC controlled greenhouse system. Such model is a valuable tool to study the impact of PLC set points on drying performance and energy consumption. However, it should be noted that this model was developed based on observations for a part of the year and would need further data to improve performance and prediction ability for year-round drying performance.

DISCUSSION

Changes in sludge physical properties (height and bulk density) were observed to correlate to drying progress and can be potentially employed by operators as indicators of the drying phase. On average the sludge layer lost 50% of its height throughout the drying process. The high variability we observed, primarily due to variable spatial distribution of sludge initially and the implement used for sludge mixing (modified tiller), limited the ability to use these properties to estimate initial sludge mass in the greenhouse.

Drying swine lagoon sludge did not significantly change its volatile solids content. Limited information is available on volatile solids loss during greenhouse drying. A few studies that analyzed drying aerobic wastewater treatment sludge (Bux et al., 2002, Sorrenti et al., 2022) have reported reduction of VS from 74 to 41% during solar greenhouse drying. Swine lagoon sludge, unlike aerobic primary sludge, is a byproduct of anaerobic digestion after which it was continually stored for years. This results in a heavily degraded residue with marginal potential for further decomposition (Patil and Sharara, 2022), which is a positive attribute in this context as it eliminates concern for volatile organic compounds (VOC) emissions or abatement during drying.

Although, no studies have previously reported reduction in carbon content during greenhouse drying, it is safe to assume that fraction of carbon reduction to be co-related to VS reduction from microbial pathway. The carbon and nitrogen loss estimates in this study were higher in GH#1 compared to GH#2, although not statistically significant. This could be due to differences in ventilation between greenhouses. Intermittent fan operation in GH#1 led to solar thermal energy accumulation and consequently higher internal temperatures boosting aerobic activity and leading to increased C and N losses. The average nitrogen losses observed in this study (4-12%) are comparable to observations in previous studies. O'Shaughnessy et al., (2008), analyzed nitrogen losses from open-bed drying of dewatered sludge from aerobic and aerobic wastewater treatment, and observed 23% N loss from anaerobically tilled sludge, and up to 74% N loss from aerobic tilled sludge. N losses were observed to be impacted by tillage and substrate type. Szypulska et al., (2021) observed ~11% N loss from thermal drying of dewatered wastewater treatment sludge. Due to the agronomic importance of N and concerns over its volatilization as NH_3, additional efforts to estimate and reduce N losses are needed to quantify and mitigate these losses.

Mass balance indicated higher agreement between water vapor loss and estimated weight loss for GH#1 than in GH#2. Differences in ventilation strategy (PLC controlled vs. continuous) is suspected to be the driver for this observation. GH#1 also had an additional override to shut-off ventilation when ambient relative humidity was greater than 90%, unlike GH#2, which limited the risk of moisture addition to the system. Since, the HOBO sensors have a 5% error in relative humidity measurements when operated above 90% compared to 2.5% error below 90%, continued operation at high humidity conditions was a likely cause of the mass balance disagreement.

The drying was affected by the sludge moisture content, weather conditions, and sludge mixing. Seginer and Bux, (2006) observed ventilation rate was also a critical factor. Other factors that impact drying rate is sludge mixing time. Rates of drying for wastewater treatment sludge in Poland was observed to vary from 0.5 to 2.5 kg m^{-2} d^{-1}, depending on weather conditions (Boguniewicz-Zablocka et al., 2021b). Bux and Baumann, (2003) analyzed performance of 25 European solar sewage sludge drying plants in Germany, Austria, and Switzerland. They observed an average annual drying rate from 1.6 to 3 kg m^{-2} d^{-1}. The drying rate increased to 9.6 kg m^{-2} d^{-1} with supplementary heating. The average rate of drying observed in the current study, 2.2 to 2.9 kg m^{-2} d^{-1}, exceeds values reported in European systems due to favorable conditions for solar drying in Southeastern US. However, the reported rates reflect a short interval in annual operation cycle (Sept 19 - Oct 23, 2022) and continued monitoring is needed for more reliable performance estimates.

Our results indicated the drying rate spiked in the first four to eight hours after mixing, followed by a gradual diminishing effect. The mixing was carried out at the start of every interval i.e., once in 48-72 hours. As such, increasing the frequency of mixing can improve drying performance. Internal air circulation system, found to be an important variable in the process (Boguniewicz-Zablocka et al., 2021b), was a missing feature in the current system. Internal mixing increases the vapor gradient resulting in higher mass transfer across the sludge-air interface. Optimal ventilation system operation based on sensors and automation will further increase energy savings.

CONCLUSION

Swine sludge drying in mechanically ventilated solar greenhouses was evaluated in this study. Weather conditions, mixing events, and material moisture content impacted the drying rate. The height and bulk density served as indicators of drying progress during initial stages but did not provide reliable estimates of total mass in the greenhouse. This study is a first of its kind to investigate solar greenhouse sludge drying in Southeastern US and observed a drying rate of 2.2 to 2.9 kg_{H2O} m^{-2} d^{-1}. Continuous drying process monitoring using sensors provided fair estimate of water vapor loss (79% to 100% mass balance closure). Absolute penalty neural network model effectively predicted drying performance (R^2 = 0.92) based on dominant predictors and was shown to be an effective tool in simulating and optimizing the process when integrated into a programmable logic controller (PLC) system. Ventilated greenhouse sludge drying is a promising alternative for swine lagoon sludge to reduce mass and volume and wider distribution of manure nutrients for sustainable recycling. Further technoeconomic and environmental assessments are needed to benchmark the potential of this technology compared to established and emerging ones.

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