Optimizing Sludge Drying Rate Inside Structurally Integrated Greenhouse Cells

Maher Adnan Kahil & Ahmed Souhail Youssef

Abstract

The rapid transformation in Dubai's lifestyle and infrastructure to become world's most sustainable city encompass to have proper sludge management system. The key focus of the city is to get rid of the massive sludge generated from the growing population and developmentwhile considering lowest environment footprint. One mean to effectively reach this challenging goal is through integrating solar energy into Dubai's sewage treatment plants. In this paper, solar heat energy is utilized inside greenhouse cells to dry sludge.The principle behind sludge drying is the absorption of solar radiation provided with air renewal and convective exchanges. However, to achieve the optimum performance of sludge drying all year-round, light transmittance should be maximized. Therefore, to optimize sludge drying rate in Dubai city, roof angle in conjunction with six different covering materials have been studied. The results showed that by setting the roof angle to 30^{o}measured from the horizontal along with using corrugated polycarbonate cover material, the sludge drying rate will reach its optimum drying performance all year-round.

Keywords

Solarenergy; transmissivity; sludge drying; light transmittance; heat transfer coefficient; sludge management.

Introduction

Sludge waste management occupies a challenging position for most municipalities dealing with sewage treatment plant. As part of being considered as waste product from the treatment process of wastewater and characterized neither economical nor environmental, sludge contributes a major issue

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with the rapid population growth and urbanization. In the past, cities used to find land disposal an easy way to get rid of excess sludge. This practice, although it didn't meet any measure for environmental protection, was favored due to low cost associated with the transportation and uncontrollable disposal of sludge. With the increase of sludge production and reinforcement of environmental regulations, drying nowadays takes an integral part in wastewater sludge management processes for their significance in reducing sludge weight and volume hence lowering disposal space and transportation costs.

Since the 1970s energy crisis and as global warming became a serious threat issue, the use of solar energy had attracted many researchers and scientists for major reasons including free cost, indefinite energy source, and sustainability. Dubai, one of the cities that has been key driver in recognizing the long term negative effects on the city due to the intensive consumption of fossil fuels,is seen today toincorporatestrategic policies and actions to remark its way in solving real environmental issues and concerns. Being aware of the significance of environment and energy as one of the three basic pillars of sustainable development, Dubai municipality devoted great effort on incorporating sustainable practices related to sewage wastewater and solids management.The high energy consumption for drying sludge in sewage treatment has opened the doors for solar sludge drying system. Considering Dubai's geographical location, solar energy occupies an important position as an energy alternative source that can be implemented in high energy applications such as sewage treatment plants. Since December 1994 and after the development of the first covered solar dryer in the municipal sewage treatment plant of Kandern-Hammerstein, Germany (Luboschik 1999), solar drying inside a greenhouse structure has been widely used in various developed and non-development regions. Solar sludge drying facilities are characterized by a greenhouse (cells) type with transparent roof cover over a yard. The fundamental principle behind drying system is through heat transfer to the sludge from solar energy and release of moisture from the interior of the sludge to the surrounding air. To limit transfer of bad odors to nearby residential areas, solar sludge drying greenhouses are supplied with bio-filter to detect and control any offensive odor and toxic gases present inside the cells. The objective of covered solar drying is to induce and conservethe heat transmitted inside the greenhousethan what is available under ambient conditions. This will lower sludge volume and mass by diminishing the bound water in the sludge resulting in lower transportation cost, handling, and storage. In fact, the removal of water from sludge can increase its value, which in return can be used as a material in landscape rehabilitation and agricultural fields, depending on the sludge quality generated, local laws and regulations.In the green house cells, sludge is spread on the floor in 25 cm layersfor effective drying and to avoid anoxic zones which typically create odors. In this process, solar radiation plays a significant role in warming the sludge to mitigate its moisture content. However, the indoor structure can minimize solar radiation leading to lower drying rate especially in cold seasons. Thus, thisstudy will examinethe effect ofcover material and roof inclination angle on sludge drying inside the greenhouse.

In a study to determine evapotranspiration inside greenhouse, it is revealedthat evapotranspiration is around 60 to 80% of that verified outside (Montero et al. 1985; Rosenberg et al. 1989; Fernandes et al. 2003).Also, it was noticed that reference evapotranspiration were 80& 85% of the reference evapotranspiration verified outside for greenhouses oriented east/west and north/south respectively (Braga &Klar 2000; Fernandeset al.2003). These factors can be due to the shape of the greenhouse which affects its indoor environment but other factors includes but not limited to roof angle and orientation(Giacomelli& Roberts 1993). Considering the use of solar energy inside greenhouse to dry the sludge, greenhouse design shall attempt to increase solar radiation availability inside the cells, decrease energy loss to ambient environment, and increasing storage capacity of greenhouse component. Since transmissivity is determined only by the light transmission of the roof and to lower extent of the sides (Kozai 1977), this paper aims to study and compare the sludge drying rate in relation with the transmission of radiant energy on the six cover materials (glass single layer, polyethylene single layer, fiberglass, air bubble, double acrylic panels, and corrugated polycarbonate) and roof inclination angle based on site climatic conditions in Dubai.

Orientation

Kozai et al. 1977 predicted the effects of orientation and latitude on the overall transmissivity of greenhouses. It was found out that transmissivity of east-west (E-W) and north-south (N-S) orientation varies at higher latitudes where E-W orientation was greater by 22% for 52.3oN in Amsterdam and 7% for Tokyo35.7oN (Kozai et al. 1977). Also Coffin et al.1988 greenhouse measurements showed higher overall light level for E-W models than N-S during winter months from October to March with effective transmissivity of 0.67 and 0.61 respectively. Effective transmissivity can be defined as the amount of solar radiation received on an inside horizontal surface as a percent of that falling on an outside horizontal surface of the same area (Lau & Staley 1989). In addition, Waaijenberg 2004 studied the influence of greenhouse orientation on the daily sum radiation. The result was higher daily sum of radiation in winter with east-west orientation than with north-south orientation. On the other hand, N-S orientated greenhouses allow more light to transmit inside in the summer (Waaijenberg 2004). In addition, Kozai 1977 numerical model tested on different greenhouse shapes at different latitude reveals that the effect of orientation on direct solar light transmission into a single-span greenhouse varies with the shape of the house, its structure, and latitude where the greenhouse is built. It was found that difference in light transmittance between E-W and N-S is larger in lower ridge greenhouse then in higher ridge one. Also light transmittance in E-W orientation are much the same at different latitudes where those in N-S are very different (Kozai 1977).

Greenhouse Structural Arrangement

Transmissivity depends on the length of the greenhouse even if the cross sections are the same (Kozai 1973). On the other hand, Gupta et al. 2003 analyzed the effect span on the weighted solar fraction. The results showed that even span shape gives higher weight solar fraction than uneven span shape at latitude of 16o-34o. Furthermore, structural members can account for 60-70% of total light loss in greenhouse (Kozai 1973).

Roof Inclination Angle

Solar radiation energy varies according to the tilt of the surface receiving the radiation. Many researchers have studied the effect of solar radiation on inclined surfaces. Noorian et al. have tested the hourly diffused solar radiation on inclined surfaces and compared it with two tilted surfaces 40o and 45o south and west facing respectively measured in the same period. Kumar at al.1944 shows that for the same glass area, more solar radiation will be transmitted when south glass is tilted than the case of vertical glass.Soriano et al. 2004 measured and calculated the light transmittance of greenhouse with different roof slopes for the Mediterranean region all year-round. Roof inclination at 27o revealed the highest transmittance in winter, and the most uniform transmittance throughout the year.

Cover Material

Cover material plays a significant role in achieving an optimal controlled environment, particularly relating to the solar radiation intensity and wavelengths (Giacomelli& Roberts 1993). Amsen 1980 measured the light intensity for single glasshouse in comparison with two covering types double glass and double acrylic one. Transmittance was found out to be 20% and 22% less under double glass and double acrylic respectively. Also, the covering material can significantly change the radiation balance relatively to the external environment because of the absorption and reflection of the incident of solar radiation resulting in a reduction of the internal radiation balance and consequently affecting evapotranspiration (Sentelhas 2001; Fernandes et al. 2003). Not only cover material affects radiation balance but it can also reduce the heat absorbed inside the greenhouse. Heat Transfer coefficient is a measure of thermal transmittance. From a thermal point of view, materials with high heating transfer coefficient can permit extensive heat losses during colder winter nights because due to poor insulating properties. Thus, the higher the heat loss coefficient, the less insulation the covering material provides (Jahns, &Smeenk 2009).

Several materials have been used for greenhouse covering. One type used is glass which is known for its high translucence and resistance to ultra violet light. Another material is acryl glass which is synthetic transparent thermoplastic and therefore break-proof and shock-resistant. Although single acrylic sheets are available, they are rarely used because of their high cost and deflection under high load and size restrictions (Siemens 1981). Instead double acrylic glazing is used which has the same physical properties as the single one but with added benefit of double glazing and ability to withstand higher loads. Other type used is corrugated polycarbonate which is a thermoplastic material with a low weight and higher break resistance. Although corrugated polycarbonate can be more expensive than acrylic glazing sheets, they are durable and more impact resistant since they are more flexible than acrylic glazing sheets. Furthermore,polyethylene can be an option whichis flexible and inexpensive greenhouse material that is widely used in the greenhouse market. However, its main disadvantage is their short lifetime due to deterioration and breakdown associated by the radiation in the sun's rays. Air bubble on the hand are revolutionary polyethylene film that are transparent, durable and can offer UV protection in addition to their capability in withstanding extreme climatic conditions.

Material & Methods

For the purpose of determining the greenhouse cover material with the optimum roof inclination angle, solar –drying rate model has been created to examinesite climatic conditions forDubai at 25.159 latitude,55.432 longitude, and 40m elevationfrom mean sea level. Dubai has a minimum yearly average temperature of 28oC and relative humidity of 44.61% (Atmosphere Science Data Center 2015). Fig. 1represents the site climatic data associated to Dubai.The increase in drying rate will serve to reduce the sludge weight and volume while meeting local health risks reduction and pathogenic destruction guidelines.

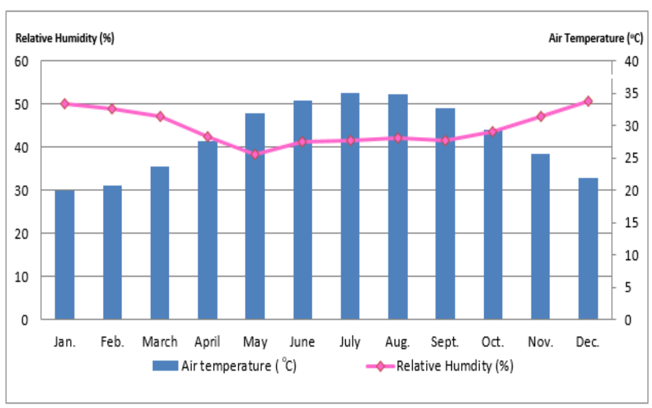

Fig. 1. Site Climatic Data (Atmosphere Science Data Center 2015)

The study was undertaken by studying characteristics ofsix cover glazing materials (glass single layer, polyethylene single layer, fiberglass, air bubble, double acrylic panels, and corrugated polycarbonate) and their effect on sludge drying rate in accordance with roof inclination angle.In general, most weather solar radiation data are available either for normal incidence or for horizontal surfaces. Therefore it is significant to determine and convert solar radiation based on tilt angle. Thus, several models can be used for this purpose such as Reindl1990 model, Badescu2002 model, and Liu and Jordan 1960 model. However, it was yielded that Reindl 1990 modelgives the highest amount of incidentsolar radiation in the whole year and Badescu2002 model established the lowest(Jakhrani et al. 2012). On the other hand, Liu and Jordan 1960 model performs well at the time of bad weather conditions and can be also used for the estimation of solar radiation on tilted surfaces in overcast skies conditions (Jakhraniet al. 2012). In this study, the Liu and Jordan 1960 modelwhich is considered to be the most suitable for estimating the daily diffuse radiation (Srivastava et al. 1995) was integrated in our solar – drying rate model topredict solar energy irradiation on the tested tilted surfaces. The total radiation for a tilted surface in Liu and Jordan 1960 model is the sum of horizontal beam, ground reflectance and diffuse radiation. Therefore, to compute monthly average daily total radiation on the tiled surface, equation 1 hasbeen used (Jakhrani et al. 2012).Since Dubai is located in the northern hemisphere, northern hemisphere equations were used.

$$H_t = \overline{H}.[\left(1-\frac{\overline{H}_D}{\overline{H}}\right)\overline{R}_B + \frac{\overline{H}_D}{\overline{H}}\left(\frac{1+cos\beta}{2}\right) + \rho_G\left(\frac{1-cos\beta}{2}\right)]$$

Equation 1. Monthly Average Daily Total Radiation on Tilted Surface

According to Liu and Jordan 1961, $\overline{R}_B$ can be estimated using equation 2& 3 in the northern hemisphere.

$$\overline{R}_B = \frac{\cos(L-\beta)\cos(\delta)\sin(h'_{ss}) + \left(\frac{\pi}{180}\right)h'_{ss}\sin(L-\beta)\sin(\delta)}{\cos(L)\cos(\delta)\sin(h_{ss}) + \left(\frac{\pi}{180}\right)h_{ss}\sin(L)\sin(\delta)}$$

Equation 2. Monthly Mean Beam Radiation Tilt Factor

$$h'_{ss} = \min\{h_{ss}, cos^{-1}[-\tan(L-\beta)\tan(\delta)]$$

Equation 3. Sunset Hour Angle on Tilt Surface

- $H_t$is the monthly average daily total radiation on a tilted surface (MJ/m2/d).
- $\overline{H}$is the monthly average daily total radiation (MJ/m2/d).
- $\overline{H}_D$is the monthly average diffuse radiation (MJ/m2/d).
- $\rho_G$is ground reflectance.
- $\beta$is roof inclination angle (degrees).
- $\overline{R}_B$is the monthly mean beam radiation tilt factor.
- L is latitude (degrees).
- $\delta$is declination (degrees).
- $h_{ss}$is sunset hour angle (degrees).
- $h'_{ss}$is sunset hour angle on the tilted surface (degrees).

In order to determine the monthly average sludge drying rate inside the greenhouse cells for the various cover glazing materials, the American Society of Civil Engineers (ASCE) standardized Penman-Monteith (ASCE Standardization of Reference Evapotranspiration Task Committee 2000) equation 4 was used.

$$ET = \frac{0.408\Delta(R_n - G) + \gamma C_n u_2 \frac{(e_s - e_a)}{(T)}}{\Delta + \gamma(1 + C_d u_2)}$$

Equation 4. Reference Evapotranspiration

ET is the reference evapotranspiration, (mm/d).
Rn is the net radiation, (MJ /m2/d).
G is the soil heat flux, (MJ/m2/d).
es is saturation vapor pressure of the air, (kPa).
ea is the actual vapor pressure of the air, (kPa).
Δ is the slope of the saturation vapor pressure temperature relationship, (kPa/oC).
T is the average temperature, (oC).
γ is the psychrometric constant, (kPa/ oC).
λ is latent heat of vaporization, (MJ/ kg).
u_2 is the wind speed, (m/s).
C_n is the numerator constant for the reference crop type and time step.
C_d is the denominator constant for reference crop type and time step.

Discussion& Results

The effect of absorption of solar radiation is dependent on the product light transmissivity and intensity of solar radiation. However, light transmissivity is dependent on material type and on incidence angle. Fig. 2 to 7represent the drying rate on the basis of roof inclination angle for the various cover materials used. As solar heat in the form of light transmits through the material, drying rate increases, causing sludge to dry at a higher rate. In Dubaicity, drying rate peaked as summer months (March to September) commenced and temperature increased. It can be clearly seen that in all materials, the 0ohorizontal roof inclination angle showed the highest dryingrate during hot months (April to September) while drying rate gradually decreased as roof inclination angle increases.In contrast, 60o roof inclination presented the highest drying rate in cold months (October to March) while it drops considerably as roof inclination angle decreases. Thus, it can be noticed that more solar radiation on tilted surfaces can be anticipated than on horizontal ones in cold months (October to March) due to low angle of incidence. However, in hot months (April to September) the solar radiation on tilted surfaces revealed lower than horizontal surface because of higher angle of incidence of solar radiation.

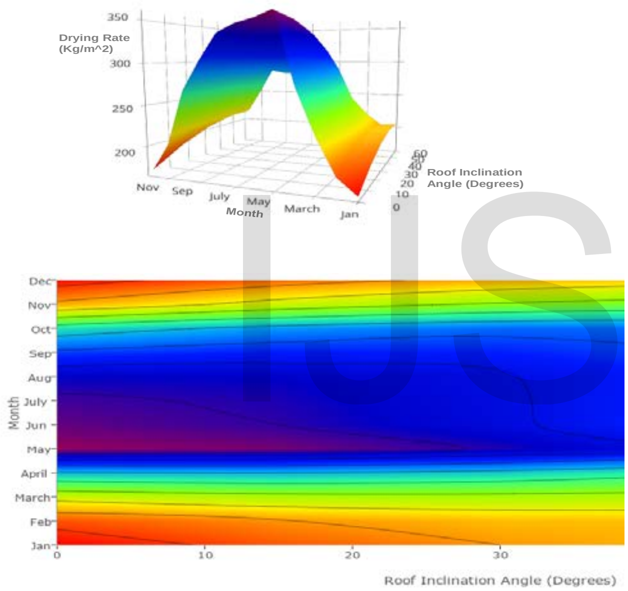

Fig. 2. Drying Rate for Glass Single LayerGlazing Material

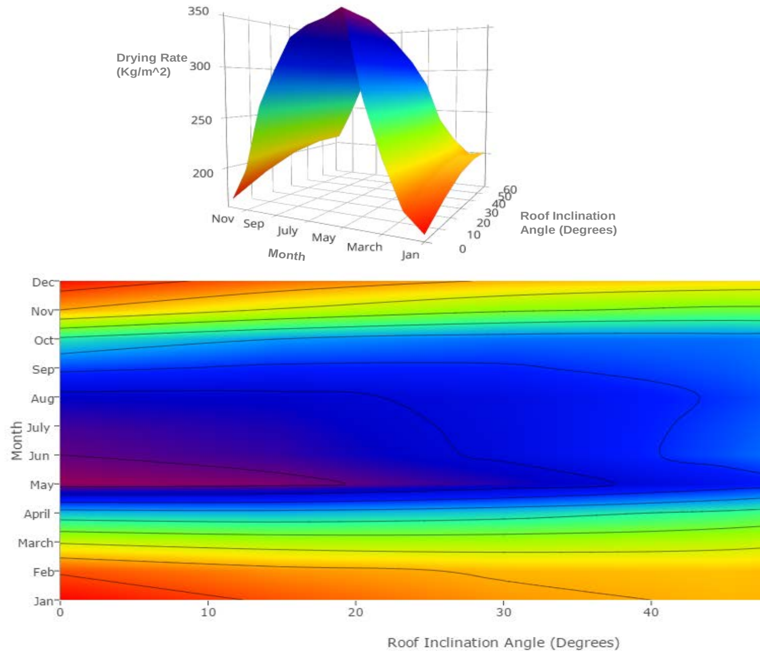

Fig.3. Drying Rate for Polyethylene Single LayerGlazing Material

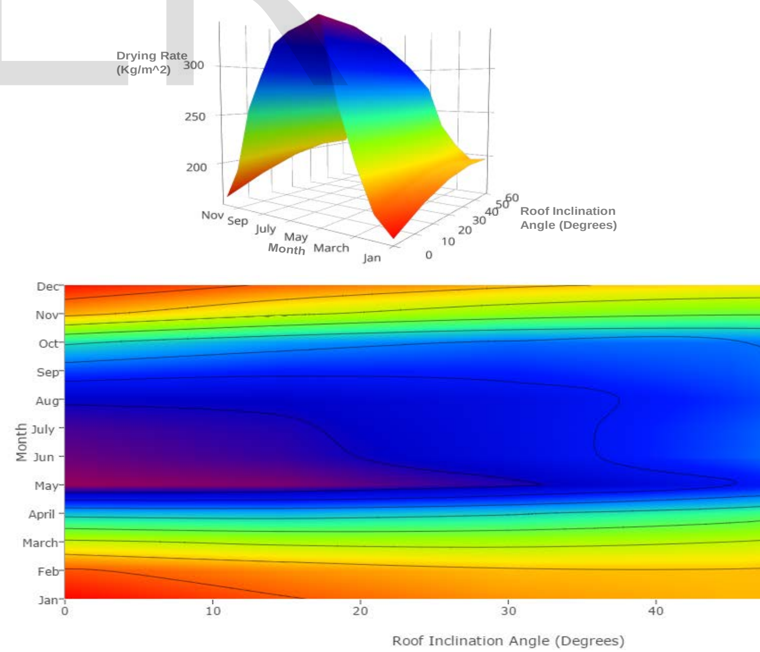

Fig.4.Drying Rate for Fiberglass Glazing Material

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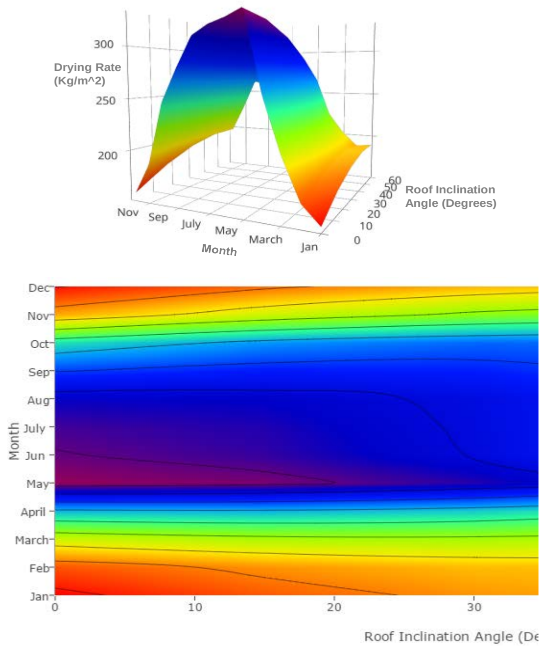

Fig.5. Drying Rate for Air Bubble Glazing Material

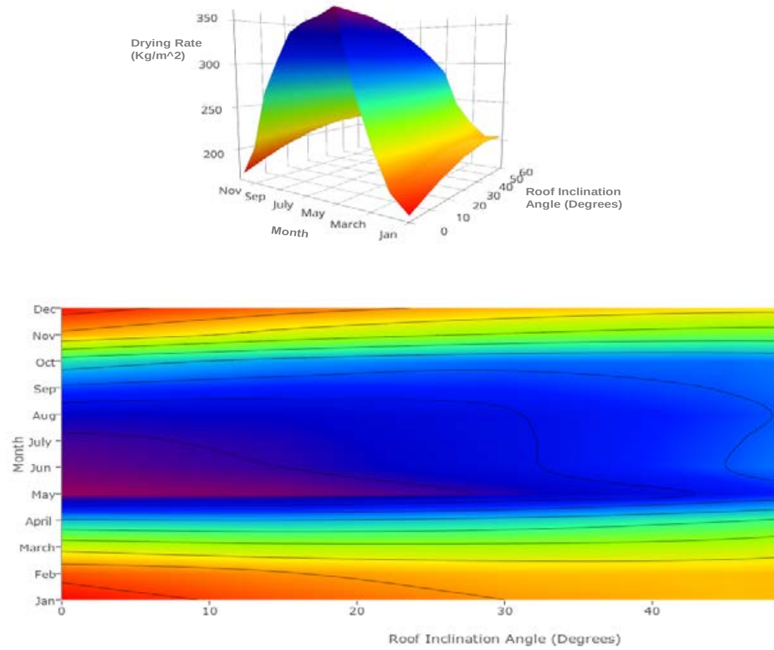

Fig.7. Drying Rate for Corrugated Polycarbonate

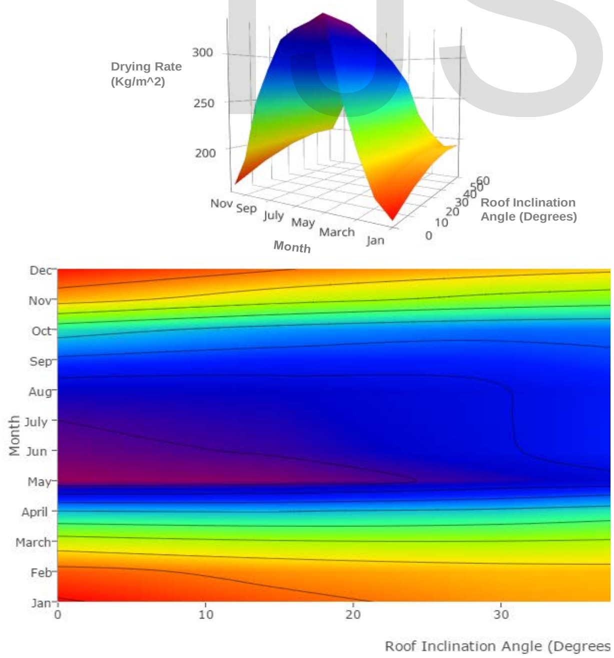

Fig.6. Drying Rate for Acrylic

By recognizing the importance of sludge drying on average yearly basis, both 15o and 30o gave equal and highest yearly average sludge drying rate. However, in some situations where sludge drying in winter time is more critical and there is restriction on minimum sludge moisture content prior to discharging in addition to quantity of sludge that can be stored inside the greenhouse due to maximum sludge bed level height, it is recommended to take 30o as the roof inclination angle since it can give higher winter drying rate than 15o from October to March. Although 45o has higher drying rate in winter than 30o, the 45o performance was lower on yearly average basis. Thus, it can be revealed that 30o can be the optimum angle required to get the optimum sludge drying rate and performance in Dubai on yearly basis.

To effectively optimize sludge drying rate inside greenhouse, another pillar to consider is heat transfer coefficient which is an indicator on how effective the material to act as an insulator. Heat transfer is the exchange of thermal energy from one medium to another. The rate at which heat transfers depends on temperature and the material intervening through which the material is transferred. The higher the coefficient value, the greater is the insulation. Fig. 8 represents the yearly average sludge drying rate at 30o roof inclination angle measured from the horizontal and the heat transfer coefficient (adapted from Bellows 2008) for the six materials studied. The single glass and corrugated polycarbonate shows the highest sludge drying rate (273 kg/m2/month) while polyethylene (267 kg/m2/month) comes after, followed by fiberglass (261 kg/m2/month), double acrylic (255 kg/m2/month), and the leastair bubble (252 kg/m2/month). The double acrylichas the lowestheat transfer coefficient(3.12 W/m2oC), making it the richest insulating material among the other materials used. Air bubble and corrugated polycarbonate comes after in the insulation level (3.29 & 3.70 W/m2oC)respectively. In contrast, fiber glass shows to have the lowest insulating material due to having the highest heating transfer coefficient (8.85 W/m2oC) followed byglass and single polyethylene(6.41 and 6.47 W/m2 oC) respectively. Thus, it can be noticed that corrugated polycarbonate covering material is the optimal radiation –absorption material for trapping and saving the highest amount of thermal radiation from a greenhouse for our case due to high sludge drying rate (273 kg/m2/month) and low heat transfer coefficient (3.70 W/m2 oC) .

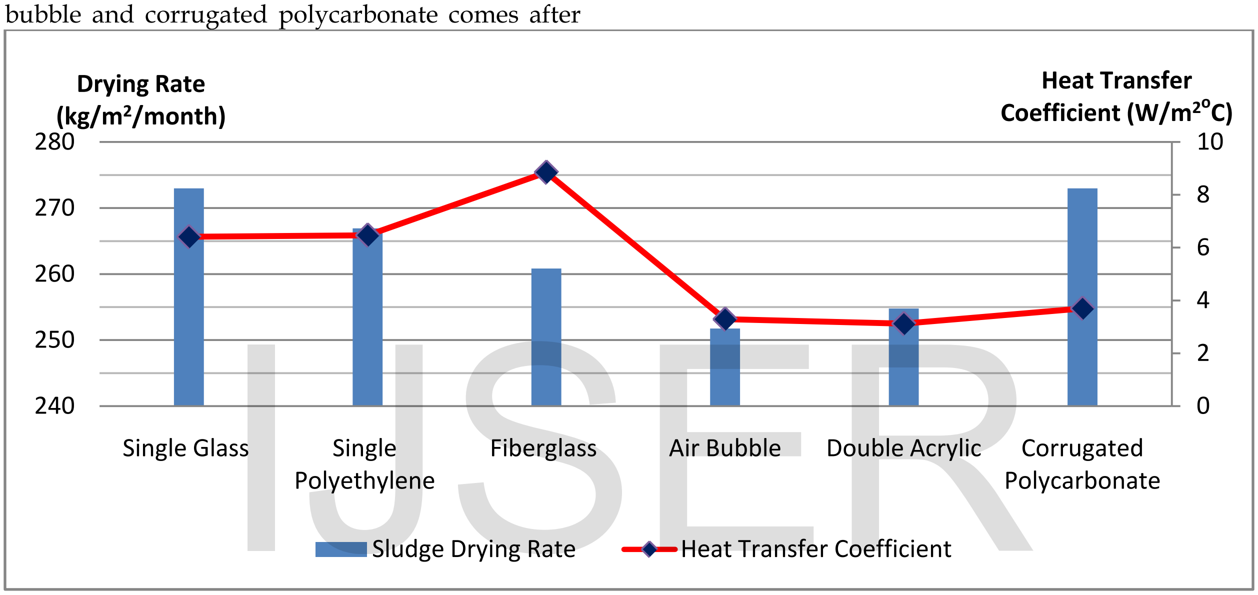

Fig.8.Yearly Average Drying Rateat 30o Roof Inclination & Heat Transfer Coefficient for Various Cover Glazing Materials

Conclusion

In this study, solar drying was applied as an economical and efficient mean to effectively overcome sludge management issues related to high volume, transportation and handling costs with the increase in population and urbanization. However,certain factors if not met can lower sludge drying rate especially in cold months. Thus,to maximize sludge solar drying rate, site climatic data fromDubai were examined in solar radiation model with the use of Liu & Jordan model and ASCE standardized Penman-Monteith equation to study the effects of roof inclination angle and cover materialon sludge drying rate. The ultimate goal was to compare and select the cover material and roof inclination angle that will reveal maximum solar radiation transmission, thus helping to increase sludge drying rate.The resultsdisplayed thatin order to maximize exposure of sun and its available energy, corrugated polycarbonate glazing materialshould be used with a 30o roof inclination angle to perform the optimumdrying rateyearly.

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