Development and Optimization of Solar Fecal Sludge Dryer for Promoting Sustainable Urban Sanitation in Ethiopia

MSc. Thesis

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Jimma, Ethiopia

June, 2018

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Approval Sheet

We, the undersigned, members of the Board of Examiners of the final open defense by **Alebachew Amsalu Abebe** have read and evaluated her thesis in titled **"Development and Optimization of Solar Fecal Sludge Dryer for Promoting Sustainable Urban Sanitation in Ethiopia"** and Examined the candidate. This is therefore to certify that the thesis has been accepted in Partial Fulfillment for the Requirement for Masters of Masters in Environmental Health Science and Technology.

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Declaration

Declaration I, the undersigned, declare that this thesis is my original work, not presented for any degree in any universities, and that all the sources used for it are duly acknowledged.

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Abstract

From those not accessed to improved sanitation, 99% found in developing countries. Fast population growth, high urbanization and on site sanitation dependent with poor or lack of option for fecal sludge treatment are challenges for industrializing countries on the way of achieving improved sanitation. Urbanization without improved sanitation and dramatic fecal sludge reuse(disposal) in developing regions put urban residents and the environment at risk. Resource recovery approaches play a great role in the way of solving sanitation problems. The current study presents design, construction and evaluation of moisture content removal and pathogen inactivation efficiency of mixed mode passive solar fecal sludge dryer in Ethiopia. The drying system has two parts; solar collector and drying cabinet. The solar radiation was absorbed by both solar collector and through roof of drying cabinet simultaneously. The solar collector (air heater) used for absorbing sun light and convert to heat energy was improved by increasing contact of air with absorber and minimizing heat loss from solar collector. Fecal sludge sample was collected from pit latrine top layer to get high Ascaris eggs load and from vacuum truck to get high moisture content and mixed with equal ratio to get representative composite sample. Temperature in solar collector and inside drying cabinet are much higher than the ambient temperature during all the day. The useful heat energy gained from solar collector and drying cabinet was estimated 33% and ~ 4% respectively. The solar collector and system efficiency was also estimated as 34.3% and 26.2%. The drying rate determines as $3.3 kg H_2O/m^2$ day and $3 kg H_2O/m^2$ day of covered and open air sun drying respectively. Pathogen inactivation efficiency of the system revealed thatcomplete inactivation in covered and 63.5% open air sun drying. This indicates that covered dryer is better than open air sun dryer in all parameters. From these, it is possible to reuse dried fecal sludge from covered dryingfor all purposes.

Acknowledgment

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List of Abbreviations

FS	Fecal Sludge
IS	Improved Sanitation
OSS	On-Site Sanitation
FSM	Fecal Sludge Management
MC	Moisture Content
FST	Fecal Sludge Treatment
AD	Anaerobic Digestion
BSF	Black Soldier Flies
DFS	Dried Fecal Sludge
OSD	Open Sun Drying
SED	Solar Energy Drying
DC	Drying Cabinet
SC	Solar Collector
HO	Helminth Ova

1 Introduction

1.1 Background

Improved sanitation (IS) is complete hygienic separation of human excreta from human contact and it includes all sanitation chains from generation to re-use or safe disposal of fecal sludge [$URL : https : //en.wikipedia.org/wiki/Improved_sanitation,$2017]. Now a day, there is a progress in collection of fecal sludge (FS) at site of generation through on-site sanitation (OSS) installations or sewer system. OSS installations are pre-dominantly used in developing countries which need fecal sludge management (FSM) and a challenge for these countries (Kone Peter, 2008). FS is a byproduct of OSS installations which comprises all liquid and semi-liquid contents of OSS installations(Pillay, 2015). Worldwide, 2.7 billion people (a billion urban residents) served by OSS facilities which need fecal sludge management (FSM) and the figure to raise around 5 billion by 2030 (Linda Strande, 2014). The main targets in fecal sludge treatment (FST) are high moisture content (MC) in the range of $77.6-94\%$ and hazard of pathogenic organisms mainly originated from feces such as helminthes, protozoa, fungi, viruses and bacteria which pose risks to human and animals (Veses, O. et al, 2016: Williams, AR Overbo, A., 2015).Uncontrolled and indiscriminate disposal of undigested or partially digested FS to the environment will lead to surface and/or ground water pollution and soil contamination which have direct and indirect adverse impact on the environment and public health. By considering risk to human health, the priority of FS treatment from higher to lower risk can be; living in a dense community without basic sanitation, use of untreated pathogen contaminated waste water or excreta for irrigation of crops and soil conditioner respectively (Ronald J. LeBlanc, 2008). FSM includes sanitation values of containment/collection, transports, treatment and re-use or safe disposal FS. FS is generated in high amount and is rich in nutrients; for instance an individual generates $400l$/year of urine which contains 4.0kg nitrogen, 0.4kg phosphorous, and 0.9 kg potassium which can replace chemical fertilizer. Fecal matter also contains undigested organic matter like carbon and 25 to 50 kg per person/year generated (Peter, 2008). FST mainly focusing on solid-liquid separation and pathogen reduction for handling and minimizing transportation cost and to meet requirements of re-use and safe disposal of FS implemented in developing countries are still not effective. Waste is a resource and OSS is more affordable than sewer based systems to provide sustainable sanitation if they are well managed. To fill the gap and ensure sustainability of sanitation services, technologies should focus on profitable business based approaches. Potentially existing fecal sludge treatment (FST) options in developing countries mainly has two phases focusing on solid âĂŞliquid separation and treatment of solid and liquid to re-use and/or recovery. Settling tanks and sedimentation ponds, planted and unplanted drying beds, combustion, solar drying, anaerobic digestion, co-composting and black soldier fly productions are the common solid-liquid separation and treatment options (Peter, 2008). The primary objectives of the mentioned treatment technologies are to use treated FS (solid) for agriculture or disposed to land and to use liquid part for irrigation or discharge to surface water but both the effluents (solid and liquid) should be with standards before re-use for agriculture or to discharge to surface water (Kone Peter, 2008). Pathogen inactivation and moisture content (water) reduction in FSM can be achieved by drying. The concern on drying of FS for mentioned solutions is the high energy consumption in drying process and is difficult for developing countries. To fulfill energy demand in drying, solar energy is the proposed option because of free, non-polluting, evenly distributed, renewable energy and effective in drying and pathogen inactivation(Bennamoun, L., 2011). Inactivation of pathogens and solid-liquid separation using simple and available treatment options to produce dried FS for combustion, co-composting, pyrolysis, anaerobic digestion, fertilizer and construction materials will highly contribute for the process of improving sanitation.

1.2 Problem Statement

Lack or inadequate and poor performance of FST technologies in developing countries and discharging indiscriminately of partially treated or untreated FS haphazardly causes a severe impact on environment and public health (Linda Strande, 2014). Surface and ground water pollution, high level of pathogen prevalence in the urban environment and unpleasant odour are major problems related with poor FSM in low and middle income countries (Mara, D. et al., 2010). Globally, around 2.6 billion people waiting for access to improved sanitation and 99% found in developing countries and a billion people still practice open defection (Niwagaba,C.B.et al., 2014). A problem being addressed in current study is on FST; specifically focusing pathogenic organisms inactivation and moisture content removal by developing and optimization of solar fecal sludge dryer in Ethiopia. Pathogenic organisms exist in FS such as helminths, protozoa, fungi, viruses and bacteria pose risks to human and animals (Niwagaba, C. B. et al., 2014). In developing and middle income countries FS used by farmers illegally, disposed to close areas and discharged to water bodies without treatment (Veses, O. et al, 2016). Sanitation coverage (FS containment) will not be a guarantee for improved sanitation;

for instance in Ethiopian, urban sanitation coverage is 72% but overall improved sanitation is 16% (CSA [Ethiopia] and ICF, 2016). FS treatment in developing countries such as in Ethiopia largely depends on open sun drying (Scott, R., Ross, I. & Hawkins, P., 2016). The problems of this method are large area required, difficulty of drying process control, leachate management, unknown drying rate and pathogen inactivation efficiency, insect infestation and exposed to rain. Unfortunately, this dried FS without determination of helminths ova level, used by farmers illegally (Scott, R., Ross, I. and Hawkins, P., 2016). Multi-purpose handling and application of FS without treatment may cause infection to humans and animals. Worldwide, 1.6-2.5 million deaths and 1 in 5 children die related with diarrhea diseases and improving sanitation and hygiene can reduce diarrhea risk by 36% and 48% respectively (Mara, D. et al., 2010). If it is continue in this fashion, even there is a problem in achieving sustainable development goals (SDG) particularly, goal six (Ensure availability and sustainable management of water and sanitation for all) if the trend continues. The new paradigm shift on the use of FS as resource by inactivation of pathogens in recommended rage and adjusting moisture content for intended use could solve sanitation problem.

2 LITERATURE REVIEW

2.1 Characterization of Fecal Sludge

Fecal sludge is a combination of human waste, waste water, debris and other parts from OSS and characteristic varies due to climate, toilet type, diet and other factors. FS contains Nitrogen (N), potassium (K) and phosphorous (P) which are main nutrients for plant and pathogens such as bacteria, viruses, protozoan and helminthes (Padhi, S. K., 2016). The common parameters used to characterize FS includes biological oxygen demand (BOD), total suspended solids (TSS), chemical oxygen demand (COD), pH, moisture content (MC) and pathogens (Williams, AR and Overbo, A., 2015).

Parameters	Public toilet
pH	6.55-9.34
MC	77.6-94 %
TS (mg/l)	30,000-52,500 (>3%)
TVS	(as % of TS) 65-68
Ascaris eggs	67-151 /10g TSa
	13 eggs/g TSb
	6 eggs/g TS b

(Williams, AR & Overbo, A., 2015), Debela, T.H., et al, 2017, Kone and Peter, 2008.

Table 1: Fecal sludge characterization from On-Site Sanitation facilities

2.2 Fecal Sludge Utilization

2.2.1 Organic Fertilizer Production

Organic fertilizers overtakes advantages of chemical fertilizers by improve soil texture and structure, soil nutrients like nitrogen, potassium, phosphorous, zinc and increase productivity by preventing crop diseases and also increasing beneficial microorganisms (URL: http://www.brac.net/sites). Each year a person generates 700 kg of urine and 90 kg feces with 94%, 2.2 kg, 3 kg, 0.7 kg and 0.7 kg and 75%, 11 kg, 1 kg, 1 kg and 1 kg of water content, carbon, nitrogen, potassium and phosphorous respectively. Soil conditioner can be produced in different ways from FS such as slurry from biogas and co-composite with other substrates. To produce high quality of organic fertilizers in aerobic process carbon to nitrogen ratio (20-30:1) and moisture contents of between 40-60% should be ensured (Niwagaba,C. B. et al., 2014). The study (Nikiema,J., Cofie, O. & Impraim, R.,2014) on production of pellet fertilizers from fecal sludge showed promising quality. In this study, the moisture content of fecal sludge greatly affected production of fertilizers. The recommended moisture content is different and based on the technologies used to produce fertilizers and if the moisture is less than 30% there is a fear of breakage of pellet and if it is higher than 50%, there is a problem of pellet stuck together and drainage of water from pellets. Based on source types urine, back-water and fecal based fertilizers were produced and showed different efficiency (Winker, M. et al., 2009). The application of FS as a fertilizer is the most common but most of the time it is informal regarding pathogen concern and (WHO, 2006), as 1 viable eggs/g TS for irrigation application.

2.2.2 Anaerobic digestion (AD)

Anaerobic digestion (AD) is the microbial breakdown of biodegradable materials in the absence of oxygen aiming to produce fuels like biogases and a digestate used as fertilizer (Forbis-Stokes, A. et al., 2016). In this case sludge from septic tank has long retention time and there is probability of less gas production compared to pit latrine. Maximum gas production is possible in anaerobic digestion (AD) when optimum operating conditions are fulfilled. Over a temperature range of $15-30c^0$, there a possibility of harvesting 14-87 ml of gas per gram of fecal sludge (Ddiba, D. I. W., 2016). Mostly, the actual biogas production and theoretical estimation shows great gap and this may be because of feedstock characters, temperature, retention time and other important parameters including moisture content (Diener, S. et al., 2014). Generally AD process runs in lower temperature range than killing or inactivation of pathogenic organisms and in public health point of view it is important to eliminate pathogens before using AD slurry by any means.

2.2.3 Animal Protein Production

FS contains significant amounts of phosphorus and nitrogen which are important for plant growth. When plant species like E. pyramidalis planted on or near to wastewater treatment plants, then it can produce high amounts of animal feed like for horse, sheep, goats, dairy cows and even for rabbits. FS treatments ponds can used as fish production site because of ponds are good for plankton growth which used for fish feeding. The fish can be used for animal feeding and in some instance used directly as for human food. But when fish used as direct for human consumption there is possibilities of transmission of some pathogenic microorganisms from waste to human (Niwagaba, C. B. et al., 2014). FS can use as feeding for insect larvae which used as protein source for animal feeding. BSF (Black Soldier Fly) larvae (Hermetia illucens) can decay any form of organic waste by considerably. In BSF life cycle (it takes one month) there are 6-larval stages and the last stage of larva called prepupa used as alternative for fish meal. In FS treatment by BSF, there is negligible reduction of enterococcus Spp and eggs of helminth Ascaris suum. BSF larva can readily grow on FS and municipal organic waste has a significant volume reduction (55%) of importance. The moisture content adjustment is required because BSF can only grow with a dry mater of 40% (Kengne et al., 2014).

2.2.4 Construction Materials

FS can improve the quality of bricks by introducing small cavities for free-thaw expansion and bonding adherence to mortar (Ddiba, D. I. W., 2016). Using FS as a building material still not used at large but Studies using fecal sludge as raw materials for brick production investigated that possible to produce similar bricks of other raw materials such as cements, bricks, clay products and ceramics. Addition of up to 20% by weight of dried FS in clay bricks did not have a significance impact on functional characteristics of products. 1 – 10% of fecal sludge ash from incineration can integrated with limestone to produce cement and in clay based products (Niwagaba, C. B. et al., 2014). In the production of construction materials there is no fear of pathogens because of destruction in the process but need to control moisture content.

2.2.5 Combustion

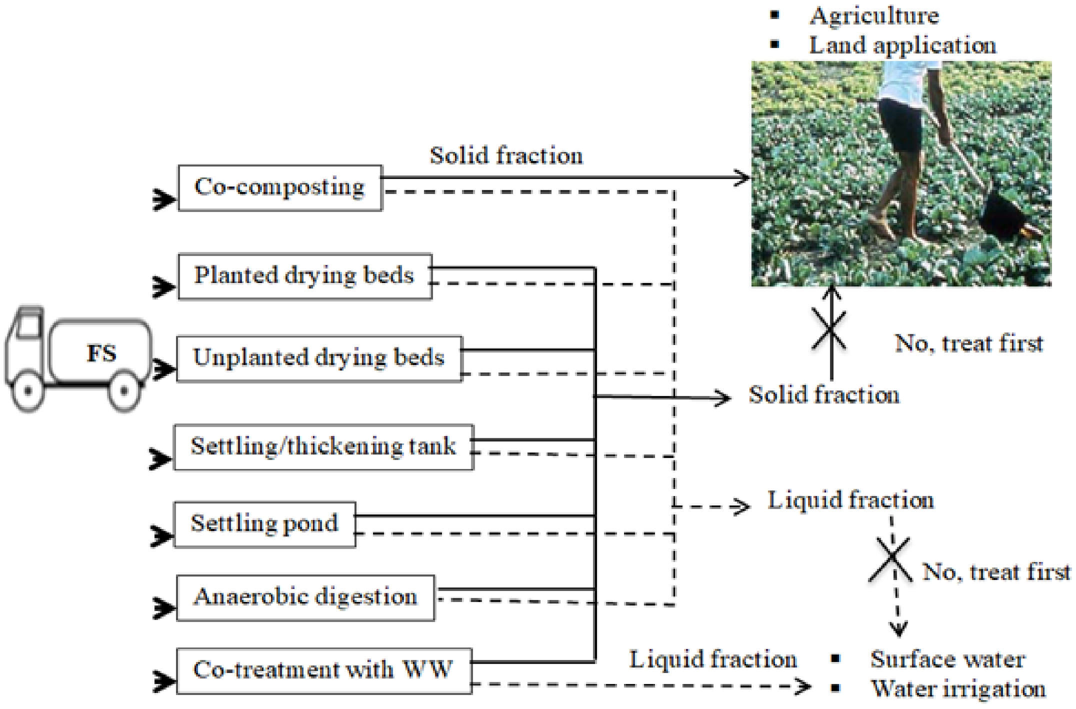
Combustion is a chemical process in which a substance reacts rapidly with oxygen and gives off heat. Industries use original substance called fuel such as coal, petroleum coke, wood, municipal waste, etc. as energy source (Ddiba, D. I. W., 2016). Average calorific value of raw FS was stated in the range of 16.2 MJ/kg to 19.1 MJ/kg TS or 17 GJ/ton and is comparable with other fuel source (Muspratt, A.M. et al., 2014). To get energy benefit, sludge must be adequately dried to a minimum of 28% dried solid (DS). Sludge can be combusted or co-combusted with different biomasses like municipal solid waste and with coal. The main potential market was identified in the use of sludge as fuel for industries but mostly industries meet their demand by using electricity and diesel kerosene. Companies in Dakar up to $10,090 m^3/year$ liquid fuel and FS can meet this demand up to 35% (Ddiba, D. I. W., 2016). In Ethiopia there are 7 operating and 39 ongoing cement industries and their main energy source currently depends on furnace oil. Mugher cement industry is one of the known cement industry in Ethiopia and the minimum specific energy consumption of the pyro processing system to be 4.2 MJ/kg of cement. In 2003 the fuel consumption of Mugher cement industry was 61,080,215 liters of furnace oil and this cost up to 134,129,435 Ethiopian birr (Seboka, Getahun Haile-Meskel, 2009). Fuel switching from conventional fossil fuels to biomass is a feasible and attractive option for Ethiopian cement industries.

2.2.6 Pyrolysis/ Gasification

Pyrolysis is the thermal decomposition of organic substance at elevated temperature in oxygen starved environment. A wide range of biomass feedstock can be used in pyrolysis processes but the process is very dependent on the moisture content, which should be around 10% and particle size of the feedstock. At higher moisture contents, high levels of water are produced and at lower levels there is a risk that the process only produces dust instead of oil. Gasification is a process that converts organic or fossil fuel based carbonaceous materials into carbon monoxide, hydrogen and carbon dioxide. The resulting gas mixture is called syngas (from synthesis gas or synthetic gas) or producer gas and is itself a fuel Kegne et al.,2014.
Generally, re-use of FS largely depends on moisture content adjustment and pathogenic microorganisms inactivation. FS for fertilizer production (aerobic process and pellet production), animal protein production (black soldier fly), combustion and pyrolysis, the moisture content should be ensured $40-60\%, 60\%, < 70\%$ and $< 10\%$ respectively. In case of fertilizer production from FS, the main concern is the presence of pathogen and it should be inactivated as $1 HO/g$ TS (WHO, 2006).

2.3 Fecal Sludge Treatment

Fecal sludge management is a must activity for adequate operation of OSS systems. The main goal of FS treatment is to ensure public health and protect the environment by reduction of pathogenic microorganisms and stabilization of organic matter and nutrients (Teresa da Costa Cabral Hazel, 2014). FS is typically rich in water and pathogens concentration and the treatment and fecal sludge management focuses on solid-liquid separation and pathogens inactivation (Thammarat Koottatep, (year not mentioned)). Solid-liquid separation is useful because sludge volume reduction is inversely related to solid contents and the dewatered sludge volume to be transported would be smaller than the raw FS volume (IRC International Water and Sanitation Centre-Delft, 2003). Potentially existing FS solid-liquid separation and treatment technologies are explained in the figure 1.



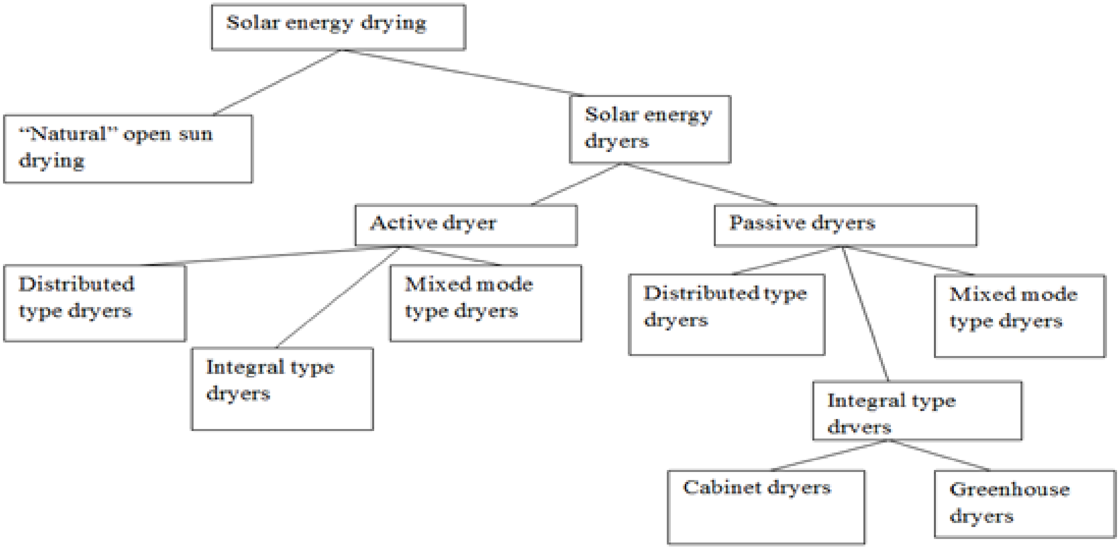
(Strauss et al., 2002)

Figure 1: Potentially existing FS treatment options in developing countries

As shown in fig. 1, FS treatment has two main phases of primary treatment for stabilization and solid-liquid separation and post treatment for further treatment of separated liquid and solid fractions.

2.4 Solar Drying

Solar drying is an old method and starts since time immemorial to dry different products. Solar drying is chosen because free, renewable energy source, well distributed and non-polluting (Winker, M. et al., 2009). Based on heat transferring to wet solids, solar dryers can be classified as passive solar energy dryer (natural) and active solar energy dryer.

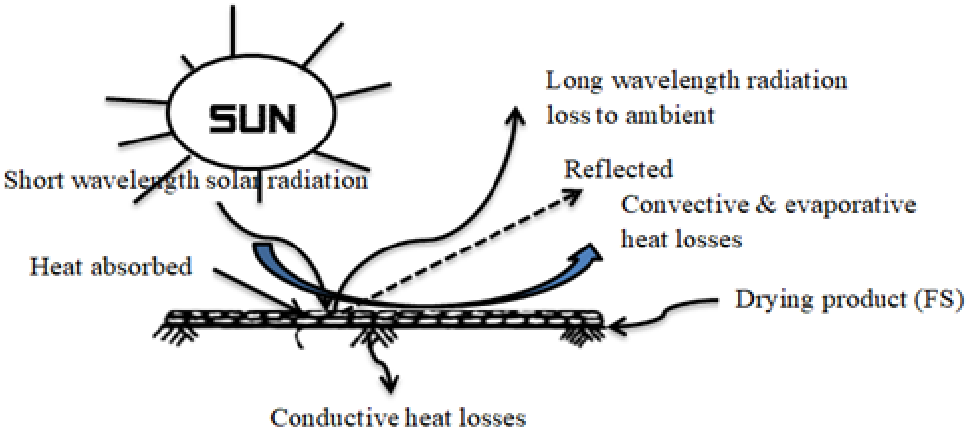


(Ekechukwu, O. & Norton, B., 1999)

Figure 2: Classification of dryer and drying modes

2.4.1 Open Sun Drying (natural)

The working principle of open sun drying (OSD) is shown in the figure 3. The drying product spread on drying surface and drying is due to the short wavelength solar energy and natural air circulation. The short wavelength reached to the surface of drying product can absorbed to increase drying product temperature and loss due to long wavelength radiation to ambient, reflected, and by conductive and convection heat loss (Sharma, A., Chen, C. R., Lan, N. V., 2009).



(Sharma, A., Chen, C. R., and Lan, N. V., 2009)

Figure 3: Working principles of natural open sun drying

The limitations of this method are; large area requirement, lack of ability to control drying process, insect infestation and possible degradation due to biochemical reactions (long time) are the common mentioned. Fecal sludge drying in developing countries largely depends on dewatering and open sun drying simultaneously and is the only option for FS treatment in Ethiopia

Drying bed in use

Drying bed at rest

Dried FS being removed

(Scott, R., Ross, I. and Hawkins, P., 2016)

Figure 4: Fecal sludge treatment plant drying beds in Hawassa Ethiopia

In this drying bed, nothing mentioned about the drying time it taken and the dried FS sanitation level. In addition to mentioned limitations, their functionality depends on season and no monitoring activities.

Damaged retaining walls and FS by-passing

Sludge “pond” at lower edge of the site

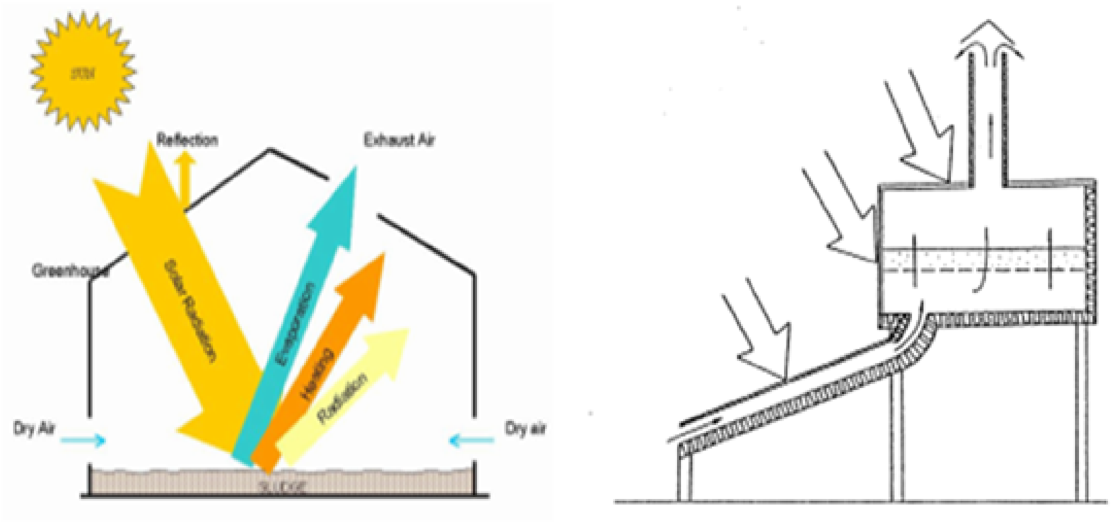
Figure 5: Conditions of FS drying beds in rainy season in Hawassa Ethiopia

Source: Alebachew A., 2018

Figure 6: Fecal sludge disposal system in Jimma, Ethiopia

2.4.2 Solar Energy Drying (SED)

Solar energy drying (SED) is the amendment of open sun drying and generally constructed in greenhouse structures with transparent covers, concrete basins and walls. (Niwagaba, C. B. et al., 2014). Solar drying can batch or continuous operations and can be influenced by solar variation, air temperature, ventilation rate, initial moisture content and air mixing.



(Niwagaba, C. B. et al., 2014)

Figure 7: Working principles of direct and mixed mode passive solar dryer and mixed mode passive solar dryer

2.5 Optimization of solar energy dryer

Air temperature and humidity are main factors in solar drying process and there is a considerable shortening of drying time by increasing air temperature and decreasing humidity. Improving solar collecting performance will enhance drying process efficiency. Temperature is the most important factor on drying process. Increasing the temperature of dryer will shorten drying time and moisture removal efficiency varies from product to product based on product nature, shape and moisture content nature (Al-Neama M Farkas .I, 2018). The dryer can be enhanced by increasing heat transfer area, increasing air turbulence, insulating non transparent parts of dryer etc (Al-Neama M Farkas .I, 2016; Bolaji B.O Olalusi A.P, 2008).

2.6 Efficiency of Solar Energy Dryer

When the solar dryer contains no items to dry, the ambient air temperature T_a and relative humidity H_a varies from the solar dryer air temperature T_d and relative humidity H_d. The increase in temperature (T_d>T_a and decrease in relative humidity (H_d<H_a) increases the tendency of hot air to pick more moisture. Greenhouse structure is the common solar sludge drying option and there are different results stated based on its drying efficiency. The application of greenhouse for sludge drying needs further study on its effectiveness and the study in rainy season (summer) (Seck et al., 2015), concluded that there is no difference between greenhouse structure and open sun drying and the effect of greenhouse is to rain protection only. (SypuÅĆa, M., Paluszak, Z., and Szala, B., 2013), stated opposite finding from the former and revealed that the temperature and relative humidity inside drying hall remained an average of $3c^o$ higher and lower than outside environment respectively. Many studies are supporting that the effect of greenhouse on drying shows better performance than open natural drying. (Bennamoun, L. 2012,: Mathioudakis, V.L. et al., 2013: Bennamoun, L., Arlabosse, P., Leonard, A., 2013, Muspratt, A.M. et al., 2014), Direct solar drying of sludge, 95% TS achievement within 8 to 31 days with drying rate of 8 to $12kgH_2O/m^2$day in summer and 94% moisture content was dried to 70% within 2 weeks in Kampala and 63%, 51% and 42% within 1, 2 and 3 weeks in Senegal and similarly 60% TS was achieved with 15 days at different depth (6, 8 and 10cm). In the drying of food item by mixed solar dryer (Adelaji and Babatope, 2013), indicated solar collector and system efficiency was raised up to 46% and 78.73% respectively. The average drying rate in this study was mentioned 0.184kg/hr and the study (Bolaji B. and Olalusi A.P., 2008), revealed the system efficiency was 57.5% which is lower than 78.73%, but higher drying rate of 0.62kg/hr.

2.7 Pathogen Inactivation Efficiency

Ascarisspp. can be used as an indicator of biological contamination in wastewater and sludge (Maya et al, 2012). Drier conditions lead to increased inactivation of Ascaris egg and temperature and dryness are the main parameters in the process of pathogen inactivation. The common pathogen inactivation (sanitization of sludge) methods are composting, liming and application heat treatment. Composting and liming of sludge can significantly reduce pathogen even class A limit. From heat treatment methods, solar drying is the common method for sanitization of sludge. Based the inactivation efficiency of solar dryer, there are different arguments. The study (Paluszak et al, 2012) mentioned that, solar drying canâĂŹt achieve biosafety of products for the purpose of agricultural use. But most of the literatures concluded that it is possible to reduce pathogen load up to EPA class B level but canâĂŹt eliminate pathogens to a sufficient degree (SypuÅĆa, M., et al, 2013). Even if solar drying is effective in microbial reduction up to EPA class B, it is more convenient for volume reduction and handling of sludge (S. Ozdemir, 2012).

2.8 Fecal Sludge Use and Requirement

United state environmental protection agency (USEPA) adopted two classes of sludge quality to assure public health (40 CFR parts 503).

Category	Reuse conditions	Helminth (no./g TS)	eggs FC (no./100 ml)
A	Unrestricted irrigation	≤ 1	<1000
	Home lawns andgardens		
	Public contact sites		
	Urban landscaping		
	Agriculture		
	Forestry		
	Soil and site rehabilitation		
	Land disposal		
	Surface land disposal		
B	Restricted use	1≤ 1	10^5
	Public contact sites		
	Urban landscaping		
	Agriculture		
	Forestry		
	Soil and site rehabilitation		
	Land disposal		
	Surface land disposal		

Category	Reuse conditions	Helminth (no./g TS)	eggs FC (no./100 ml)
C	Restricted use 2	$\leq 3 - 8/TS$	Not applicable
	Agriculture		
	Forestry		
	Soil and site rehabilitation		
	Land disposal		
	Surface land disposal		

(WHO, 2006: URL:https://cgi.tuharburg.de/~awwweb/wbt/emwater/documents/lesson$_d$1.pdf,2018)

Table 2: Guidelines for using treated faecal sludge

2.9 Conceptual Framework

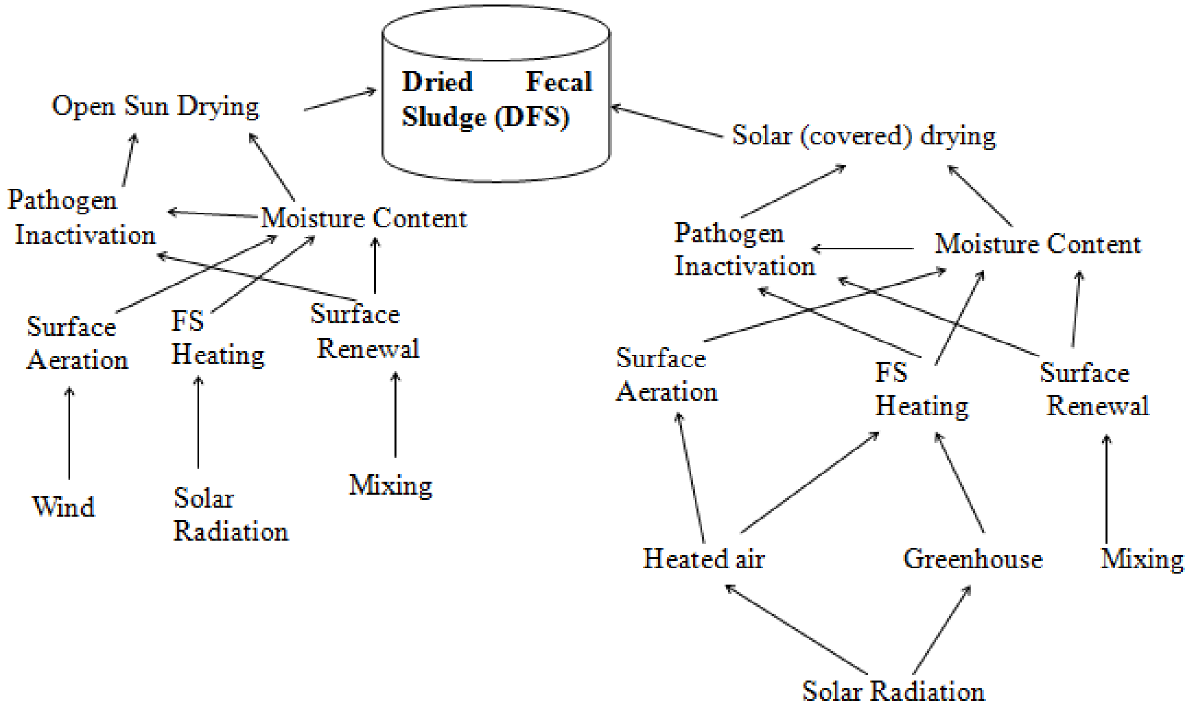


Figure 8: Conceptual framework of solar fecal sludge drying

3 SIGNIFICANCE OF THE STUDY

The study focuses on fecal sludge treatment particularly moisture content removal and pathogen inactivation for better fecal sludge management. The finding of this study will assist urban dwellers and authorities to overcome the challenges of indiscriminate and uncontrolled disposal of fecal sludge. Adjusting moisture content for intended use with in short time and re-using fecal sludge will have significant effect for sustainable sanitation. Inactivation of pathogenic organisms to meet requirements to re-use fecal sludge for agriculture or production of organic fertilizer play significant role to increase crop productivity. This study results will also contribute for local authorities and private pit emptying service providers to make informed decisions. The current study used as baseline for further researches on exploration of fecal sludge and its management.

4 OBJECTIVES

4.1 General Objective

- To Develop and Optimize Solar Fecal Sludge Dryer for Promoting Sustainable Urban Sanitation in Ethiopia, 2018.

4.1.1 Specific Objectives

- To optimize solar fecal sludge dryer
- To evaluate drying efficiency of solar fecal sludge dryer
- To evaluate pathogenic organisms inactivation efficiency of solar fecal sludge dryer

5 MATERIALS AND METHODS

5.1 Experimental Arrangements and Procedures

An experimental mixed mode passive solar fecal sludge dryer was designed and constructed as shown in the figure 9.

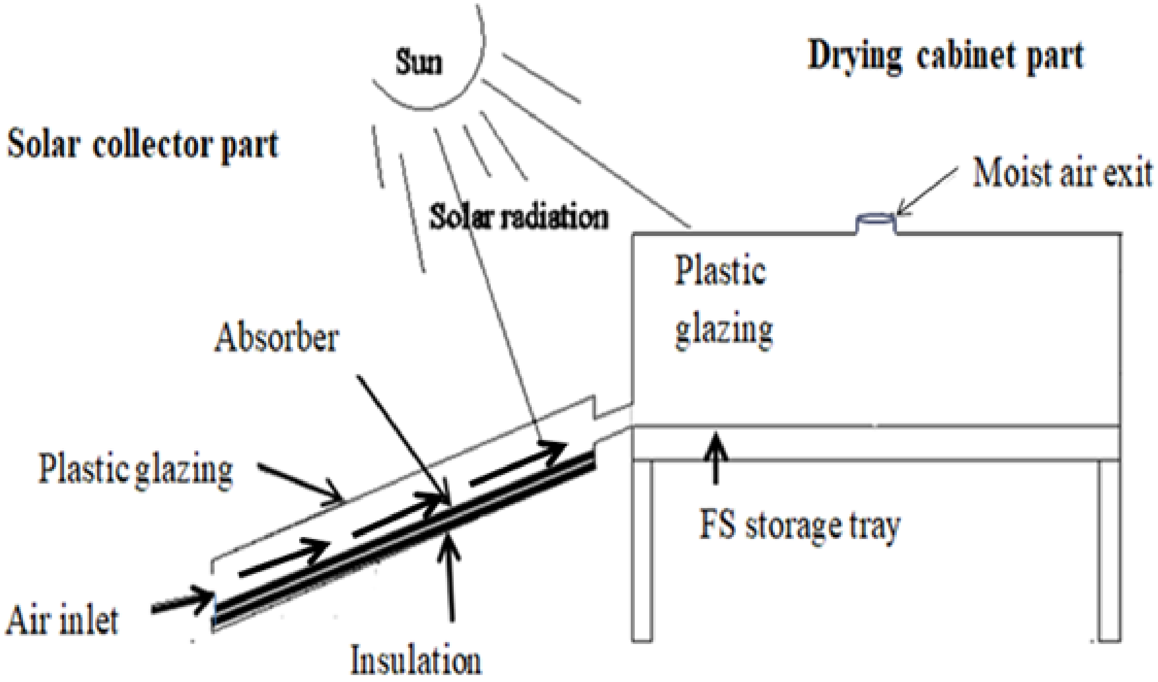


Figure 9: Scheme of solar fecal sludge drying experimental arrangement

5.2 Optimization of Solar Fecal Sludge Dryer

5.2.1 Solar Collector Optimization (SCO)

The solar collector part of the drying system was constructed with area of $0.7m^2(1m \times 0.7m)$ and $0.62m^2(0.95m \times 0.65m)$ active area and transparent plastic cover as a glazing. The non-transparent parts (side walls and bottom) were constructed from 2.5cm thickness plywood. To minimize heat loss from solar collector, the inside walls of sides and surface of floor insulated by cardboard and aluminum foil. For optimum solar radiation exposure, the solar collector was tilted at 17 degree to horizontal and positioned south to north. Black painted seven 90cm length PVC tubes with 4cm radius were used as an absorber and heat converter.

The heated air or heat energy conducted from solar collector to drying cabinet by 7cm radius insulated tube. The air inlet of solar collector provided with area of $0.03m^2(5cm \times 60cm)$.

5.2.2 Drying cabinet Optimization (DCO)

The second part of drying system is drying cabinet and constructed in greenhouse structure of half circle with 36cm radius and glazed by plastic cover. The drying cabinet was designed and constructed with two boxes of 3cm gap and the outer and inner box made from stainless steel with area of $0.8m^2(1m \times 0.8m)$ and $0.7m^2(0.94m \times 0.74m)$ respectively. The outer box was modified with opening at the center and allowed the entrance of heated air from solar collector to contact with drying tray (inner box). Again the outer box edge was bended inward to inner with 3cm and aiming to distribute heated air to surface of drying FS as surface aeration. After surface aeration, the moist air was exit to surround by chimney of 14 cm diameter at the center of drying cabinet roof.

5.3 Sampling

Before sample taking, all materials were washed and sanitized and personal protective equipment prepared for safety. The sample was taken to characterize fecal sludge based on %MC, Ascaris eggs, pH Temperature. To understand characteristics of fecal sludge, sample from pit latrine and truck is preferable and composite sample will be prepared by taking fecal sludge at beginning, middle and end of discharging of truck (Linda Strande, 2014). After making composite sample, pH & Temperature were measured onsite, close to prevent contamination, immediately transported to laboratory for analysis as possible and kept at four degree centigrade (not more than three days) to limit microbial activities. Half liter of raw fecal sludge for initial Ascaris egg analysis and 10g TS of DFS for final Ascaris egg analysis were taken (I.D. Amoah et al., 2017). In addition, the sample were taken from both open air sun fecal sludge dryer and coveredfecal sludge dryer during drying for moisture content analysis and at the end of drying period for moisture content and dried fecal sludge sanitization determination.

5.4 Analysis

Moisture Content(MC)

A well-mixed sample is evaporated in a weighed dish and dried to constant weight in an oven at 103 to 105^0C for overnight (Eugene W. Rice, 22nd ed.).

$$\%Moisture = \frac{(M_i - M_f)}{M_i} * 100 \tag{1}$$

Where:

M_i =weight of sample before drying (mg) , M_f = weight of sample after drying (mg)

Temperature of inlet air, heated air from solar collector and drying cabinet air were measured using couple thermometer. Temperature and pH of raw fecal sludge and fecal sludge temperature during drying of open air sun fecal sludge dryer and solar (covered) dryer were measured by pH meter and wet couple thermometer respectively.

Solar Insolation (I), estimated based on average daily radiation (H) on horizontal surface and average effective ratio of solar energy on tilted surface to that on the horizontal surface R as: R= 1.0035

$$I_c(\frac{w}{m^2}) = HR \tag{2}$$

Angle of Tilt (β) of Solar Collector/Air Heater

It states that the angle of tilt (β) of the solar collector should be

$$\beta = 100_0 + 1at\phi \tag{3}$$

Where, $lat\phi$ is the latitude of the collector location.

5.4.1 Efficiency of Solar Fecal Sludge Dryer

Energy Balance

Energy balance is a conservative process and obtained as of total input energy in to drying process to total out from the drying system.

Solar Collector Analysis

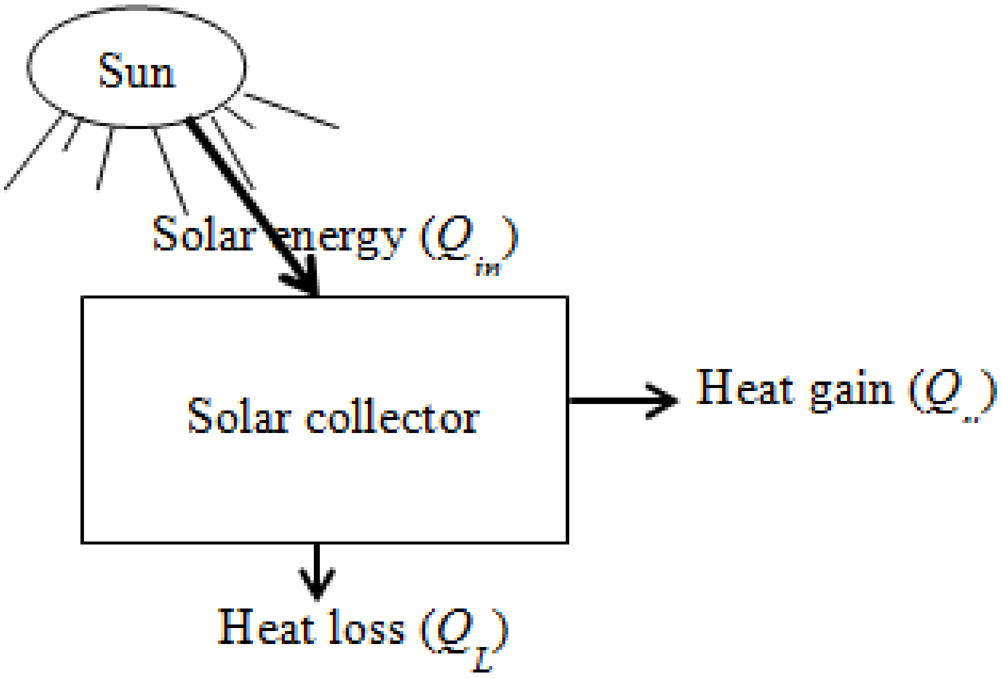


Figure 10: Scheme of solar collector energy input and output in fecal sludge drying system

The total energy obtained by collector (Bolaji, B. O., Olalusi, A. P., 2008)

Total input energy (Q_{in}):

$$Q_{in} = I_c A_c \tag{4}$$

where,

I_c = tilt solar insolation (W/m^2),

A_C = Collector area (m^2).

If τ and α are the transmittance of the glazing and solar absorptance respectively:

$$Q_(in) = \alpha\tau I_c A_c \tag{5}$$

$$I_c A_c \alpha\tau = Q_U + Q_L \tag{6}$$

Where

Q_U =The useful energy gained by solar collector,

Q_L =Heat lost from solar collector,

τ =Transmittance of plastic,

α = Solar absorptance of absorber.

$$Q_L = I_c A_c \alpha\tau - Q_u \tag{7}$$

$$Q_u = m_a C_p (T_c - T_a) \tag{8}$$

Where

T_a = Ambient air temperature,

T_c = Solar collector temperature,

ma = Mass flow rate of air (kg/s),

C_p = Specific heat capacity of air (KJ/kg.k)

The collector heat removal factor, F_R, is the quantity that relates the actual useful energy gained of a collector,

$$F_R = \frac{(m_a C_p (T_c - T_a))}{(A_c [\alpha\tau I_c - U_L (T_c - T_a)]} \tag{9}$$

Where U_L = Overall heat transfer coefficient of absorptance ($W_m^{-2} K^{-1}$)

$$U_L = \frac{(I_c A_c \tau\alpha - m_a C_p \triangle T)}{(A_c \triangle T)} \tag{10}$$

If the heated air leaving the collector is at collector temperature, the heat gained by the air Q_g is:

$$Q_g = A_c F_R [(\alpha\tau) I_c - U_L (T_c - T_a)] \tag{11}$$

Collector Efficiency η_c:

$$\eta_c = \frac{Q_g}{\alpha\tau A_c I_c} \times 100\% \tag{12}$$

Drying Cabinet Analysis

$$Q_{in} = \alpha\tau I A_d \tag{13}$$

Where

I=horizontal solar insolation (drying bed is positioned horizontally)

$$Q_U = m_a C_p (T_d - T_c) \tag{14}$$

$$Q_L = Q_{in} - Q_U \tag{15}$$

$$\eta_d = \frac{Q_u}{\alpha\tau A_d I_d} \tag{16}$$

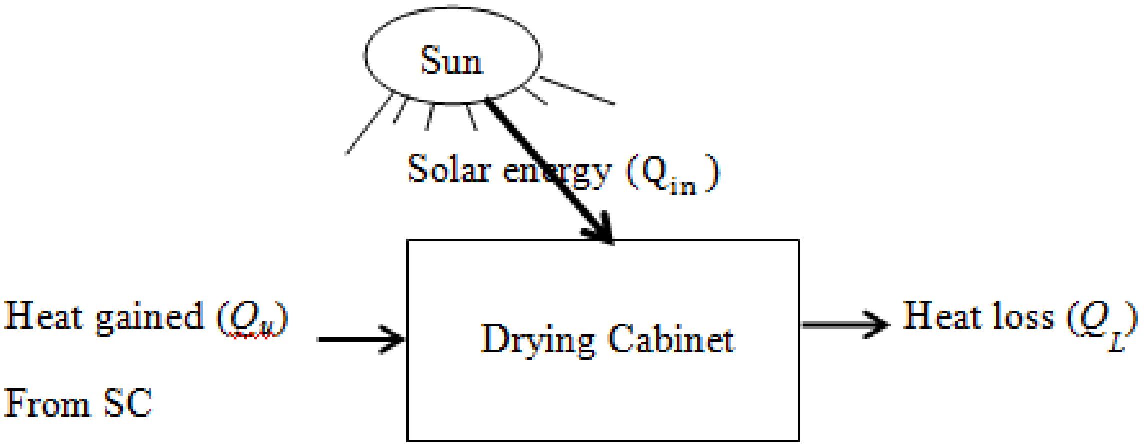


Figure 11: Scheme of drying cabinet input and output energy in fecal sludge drying system

System efficiency, η_s

$$\eta_s = \frac{Q_{Ut}}{Q_{in} + Q_g} \times 100\% \tag{17}$$

Where Q_{Ut} = Total useful energy gained by system

Drying Analysis

Experimental procedures and measurements before and after loading of sample and during drying in drying process are as shown in the fig. 12.

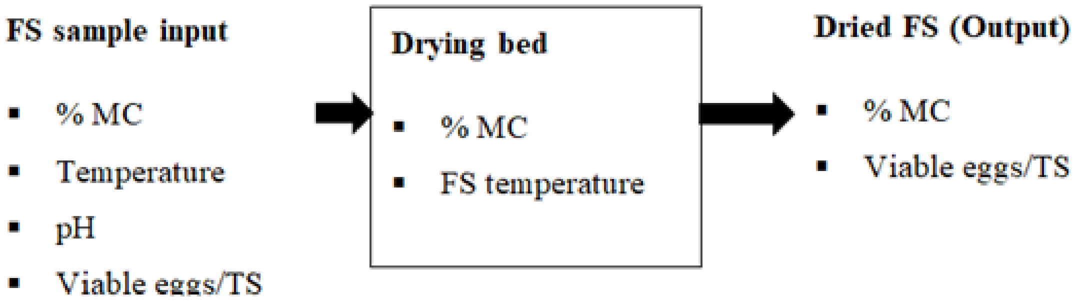


Figure 12: Scheme of drying cabinet mass balance input and output in drying process

Parameters	Descriptions
Location	$7^0 40' 0'' N / 36^0 50' 0'' E$
	Jimma, Ethiopia (7.67 latitude)
Drying period	May
Solar radiation, Jimma (May)	5.29 kWh/m^2
Annual relative humidity of Jimma	56
Drying product	Fecal sludge (FS)
Mode heating	mixed
No. of glazing	one
Glazing material	plastic
Loading provision	Batch
Air outlet provision	Chimney at the top middle of drying cabinet
Air circulation	Passive (natural convection)
Drying capacity	10 kg
Thickness of drying FS	3 cm
Insulation used	Wood, Cardboard, aluminum foil
Transmittance of plastic (τ)	0.86
Initial moisture content of FS (m$_i$)	97%
solar absorber used	Black painted 4cm diameter PVC tube
Solar absorptance (α)	0.9
Mass flow rate of air (kg/s)	0.038
Specific heat capacity of air (KJ/kg.k)	1.005

Table 3: Design considerations and assumptions

Percentage Moisture Removed from Product, γ%

$\gamma\% = \frac{(m_w - m_d)}{m_w} \times 100\% (wb) (18)$

Where

m_w = initial mass of the product (kg)

m_d =mass of dried product.

Final Percentage Moisture Content of Product, m_f:

$$m_f = \frac{(100-\gamma)}{100} \times m_i \tag{19}$$

Where

m_i = initial moisture content (dry basis)

The mass of water evaporated is calculated, m:

$$m = \frac{m_w(m_i - m_f)}{100 - m_f} \tag{20}$$

5.4.2 Purification and quantification of Ascaris viable eggs

Indicator selection criterion may vary based on the intended use of products, species behavior and others. Helminth species can be selected as an indicator for fecal sludge treatment efficiency because of the following reasons. The minimum infective dose, even a single helminth exposure develops parasite-associated diseases, resistance structure for inactivation process and wide spread in low and middle income countries. Nematode Ascaris is the most refractory to treatment processes and its inactivation can serve as indicator for efficiency of the inactivation processes (Moodley et al., 2008; M.C.V. Rocha et al., 2016). Breaking the bond between helminth eggs and particles in the sample will be done by anionic detergents like ammonium bicarbonate and try to shorten the contact time to avoid damage of eggs by detergent.

Filtration of samples

Filtration allows the eggs of interest to pass into the filtrate for further analysis using pore size between $20\mu m - 125\mu m$ because most nematode eggs dimension is in the range of$25\mu m - 150\mu m$.

Concentration

Sedimentation

Sedimentation is aiming torecover eggs that present in the solution and remove coarse residue from the sample. Separate parasite eggs from liquid part can be achieved through centrifugation of 1000g for 15 minutes followed by sieving 4(20-504 mesh size) for repeated times.

Flotation

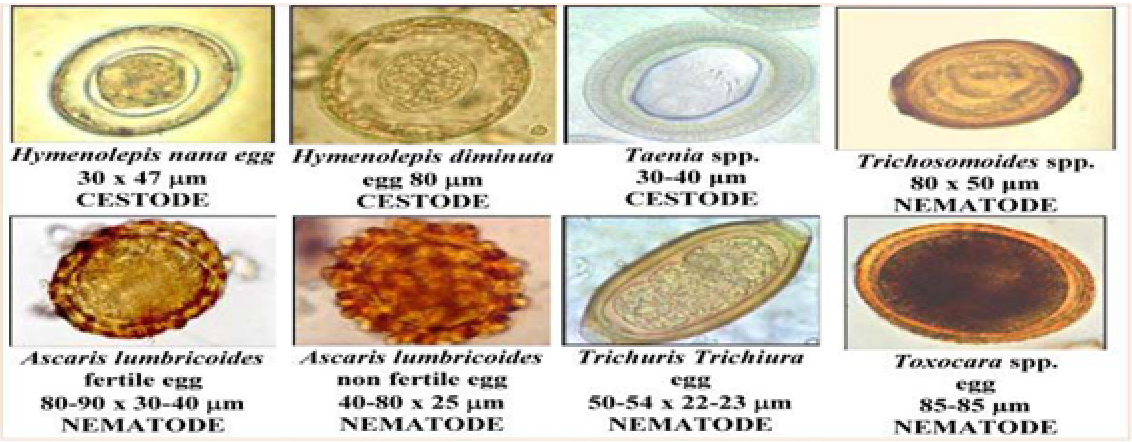
To remove materials that were not removed during filtration or sedimentation steps. The density of eggs is the range of 1.05 – 1.23 specific gravity (SG). Creating gravity gradient to float eggs using Z_nSO_4 that allows eggs to float while heavier particles to settle.

Phase extraction

Removing lipid soluble and ether soluble materials from the sample using reagent like ethyl acetate and diethyl ether and sample form different layers and the pellet (containing eggs) will find at the bottom.

Viability testing

To determine viable eggs per amount of sample, incubation method will be used. After all process done, the final deposit will be incubated using $0.1H_2SO_4$ at a temperature of 26^0c for three to four weeks. Once the incubation time is over, homogenize the deposit and proceed to quantify the eggs. Examine microscopically using 10x objective and the 40x objective for any unsure diagnoses. Only those ova where the larva is observed considered as viable.



(Jimenez et al., 2016)

Figure 13: Identification of viable Ascaris lumbricoides eggs

- Broad oval in shape, brown in color and size 60 × 45μm.
- The shell is thicker and consists of chitinous layer, and mammillated coat stained brown by bile.
- There is a new-moon (crescent) shape clear space at the each end inside the shell.

Unfertilized egg

- Narrower and longer and measure 90 Îijm in length and 55 Îijm in breadth.
- They are bile stained and brown in color.
- The chitinous layer and albuminous coat are thinner and irregular than those of the fertilized eggs.
- The content is made of small atrophied ovum surrounded by many refractable granules of various size.
- Heaviest of all the helminth eggs.

The equation used to estimate the number of eggs in the sample (Sharafi, K. et al., 2015):

$$N = \frac{AX}{PV} \tag{21}$$

Where

N= Number of helminth eggs per liter of sample

A= Average number of helminth eggs counted on slides under microscopic observation

X= Final volume of product (ml)

P=The volume on the McMaster slide

V= Original sample volume in (litres)

6 ETHICAL CONSIDERATION

Before the start of sample collection, ethical clearance was obtained from Ethical clearance committee of Jimma University. A formal letter was written to all concerned bodies and permission was secure at all levels. Informed verbal consent was also obtained.

7 RESULTS

This study presents design, construction and performance evaluation of mixed-mode passive solar fecal sludge dryer based on moisture content removal and pathogen inactivation.

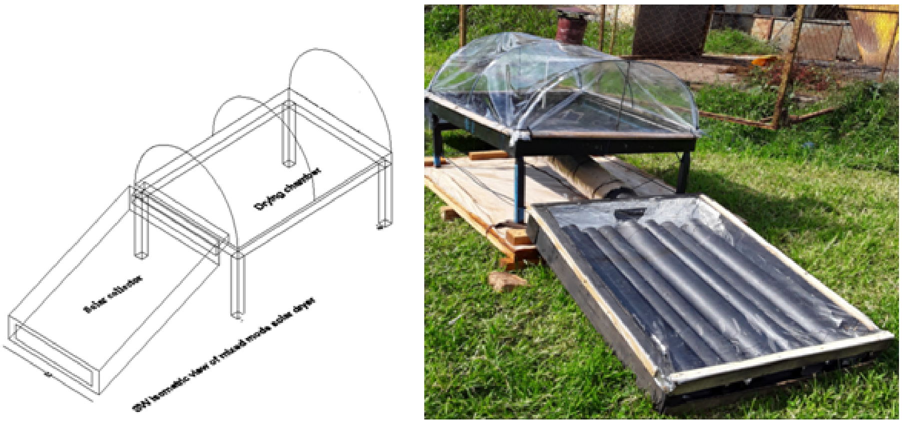


Figure 14: Design and construction of solar fecal sludge dryer

7.1 Optimization

The dryer was optimized taking in to consideration of heated air supplying by solar collector, tilt of solar collector at an angle of 17 degreein relation to latitude of the experiment was conducted for optimum solar radiation absorption and minimizing heat loss from the solar collector by insulating non transparent parts. One moist air exit chimney at the middle of drying cabinet with diameter of 13.5cm and 50cm length was installed.

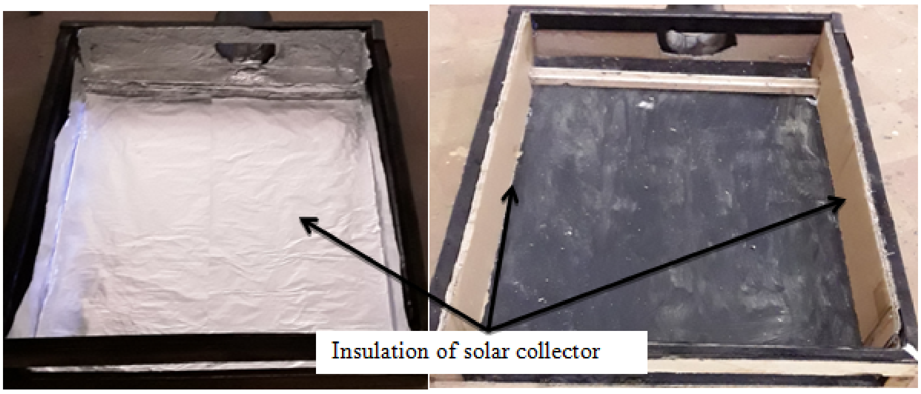


Figure 15: Insulation of non-transparent parts of solar collector

Figure 16: Insulation of heat air conducting tube to minimize heat loss from tube

7.2 Performance evaluation of solar fecal sludge dryer

In the drying system, the heated air from a separate solar collector is passed through a tube to fecal sludge drying tray in the drying cabinet, and at the same time, the drying cabinet absorbs solar energy directly through the transparent roof. The results obtained during the test period revealed that the temperatures inside the drying cabinet and solar collector were much higher than the ambient temperature during all hours of the day-light. As shown in the fig. 17, the temperature of solar collector and drying cabinet are much higher than ambient temperature during all hours of the day and the maximum temperature of 69^0c was recordedat 1:00 (noon) by drying cabinet.

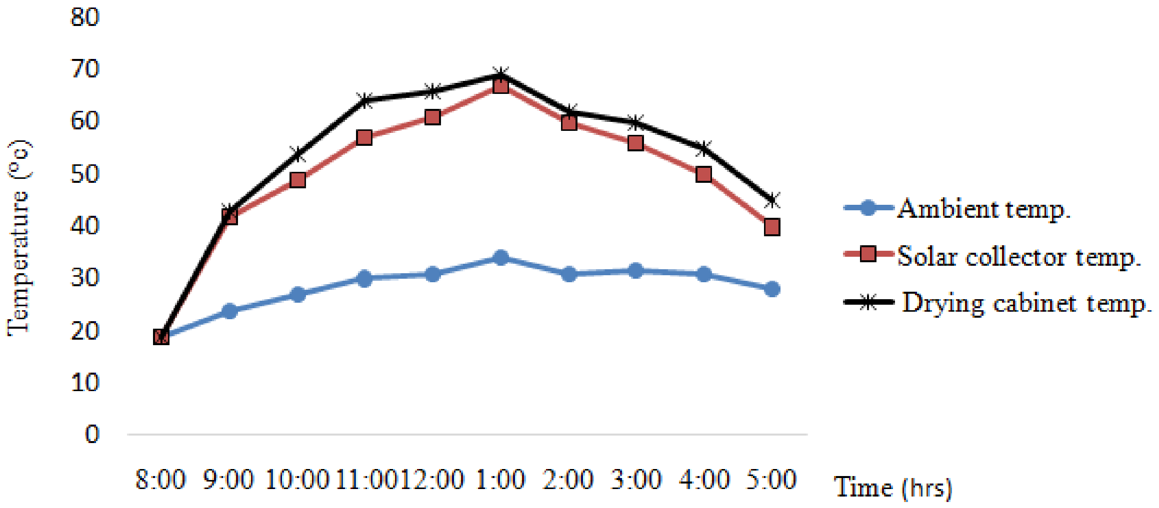


Figure 17: Time (hrs) vs temperature (ambient, collector and drying cabinet)

7.2.1 Energy and Mass Balance

The performance of the constructed solar fecal sludge dryer was estimated based on energy balance and moisture removal.

The heat absorbed (Q_{in}), useful heat gained (Q_g), efficiency (η_c) and heat lost (Q_L) of solar collector was estimated as 2.5kw, 856.6w, 37%, and 1.67 kw respectively. The heat absorbed (Q_{in}), useful heat gained (Q_u), and efficiency (η_d) of drying cabinet estimated as 2.86kw, 107w and 4% respectively. The overall system efficiency of the solar fecal sludge dryer is 26.2%.

Parameters	Values	Equation used
Total solar input (I)(w/m^2)	5308.5	1
Angle of tilt of solar collector	17.6	2
Heat absorbed by solar collector(Q_{in})	2.5kw	5
Useful heat gained from solar collector (Q_u)	869 w	8
the heat gained by the air (Q_g)	856.6 w	11
Heat loss from solar collector (Q_L)	1.67 kw	7
Collector efficiency (η_c)	37%	12
Heat absorbed by drying cabinet (Q_{in})	2.8 kw	13
Useful heat gained from drying cabinet (Q_u)	107 w	14
Heat loss from drying cabinet (Q_L)	2.7 kw	15
Drying cabinet efficiency (η_d)	4%	16
System efficiency (η_s)	26.2%	17
Percentage moisture removed from product for open drying (%)	89.7	18
Percentage moisture removed from product for covered drying (%)	94.7	18
Final moisture content of product (m_f) for open drying (kg)	7.3	19
Final moisture content of product (m_f) for covered drying (kg)	2.3	19
Amount of moisture content removed (m) for open drying (kg)	8.97	20
Amount of moisture content removed (m) for covered drying (kg)	9.47	20

Table 4: Performance evaluation of the drying system

7.2.2 Moisture Content Removal

Before starting drying, fecal sludge was characterized based on the objectives of the study as shown in table 5.

Parameter /variable	Value
%MC	97
pH	6.8
Temperature	$22.1^0 c$
Ascaris eggs	11.23/g TS or 229.1/L

Table 5: Characterization of fecal sludge

As shown in table 5, the temperature, pH and moisture content of fecal sludge is close to atmospheric, neutral and high respectively. The number of Ascaris eggs was determined from fecal sludge collected from on-site sanitation installations and the result is 11.23/g TS

The initial mass of fecal sludge used for both open air sun and covered drying was 10kg. The initial moisture content of fecal sludge is 97% and based on this moisture content and initial mass of fecal sludge, the amount of moisture (water) was 9.7 kg and 0.3kg total solids. The final moisture content of fecal sludge after drying period (5 days for moisture analysis) was 2.3% and 11.2% for covered and open air sun drying respectively.

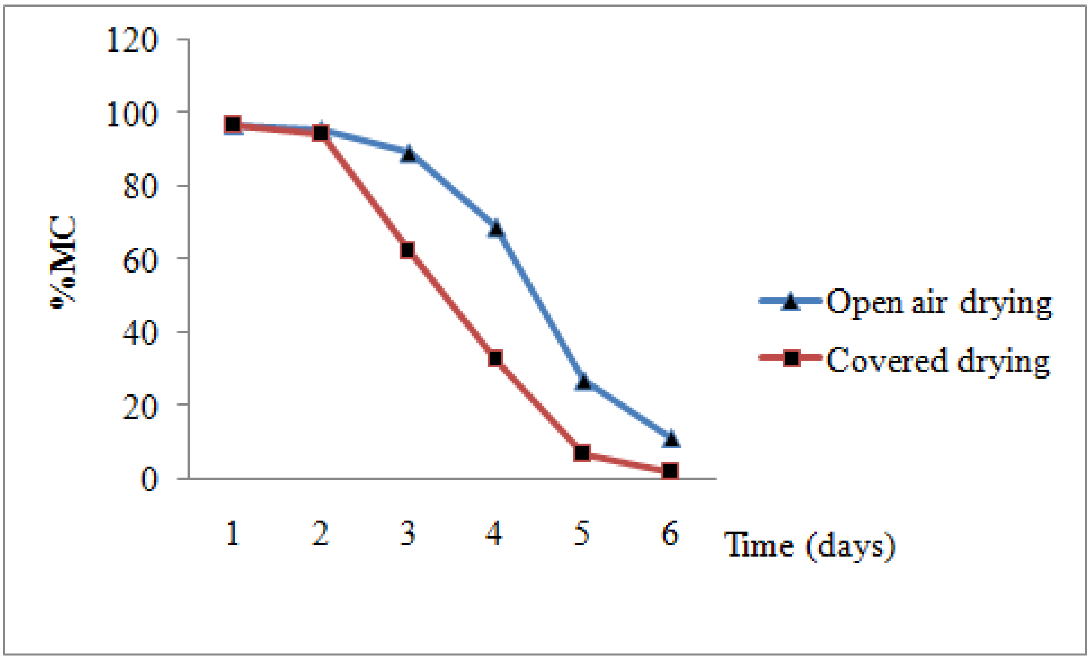


Figure 18: Local time (days) vs moisture content (db))

During fecal sludge drying, moist drop was observed inside of the drying cabinet roof which may limit the transparent efficiency of plastic glazing.

The water removed after drying period was 9.47kg for covered drying and 8.57kg for open air drying. From the water removed and drying period taken, the drying rate was$2.4 kg H_2O/m^2$day and $2.7 kg H_2O/m^2$day for open air and covered drying respectively. In the case of fecal sludge management, weight reduction of fecal sludge is very important like cost of transportation. In this study, weight loss in both covered and open air sun dryer was monitored. As shown in fig. 19, there is a rapid weight reduction of fecal sludge in covered dryer than open air sun dryer.

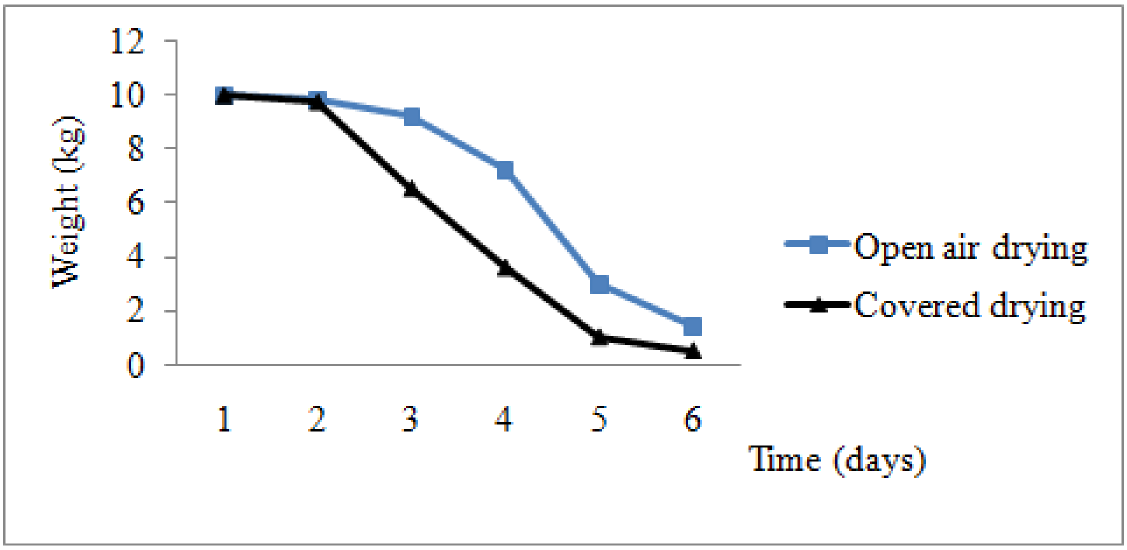


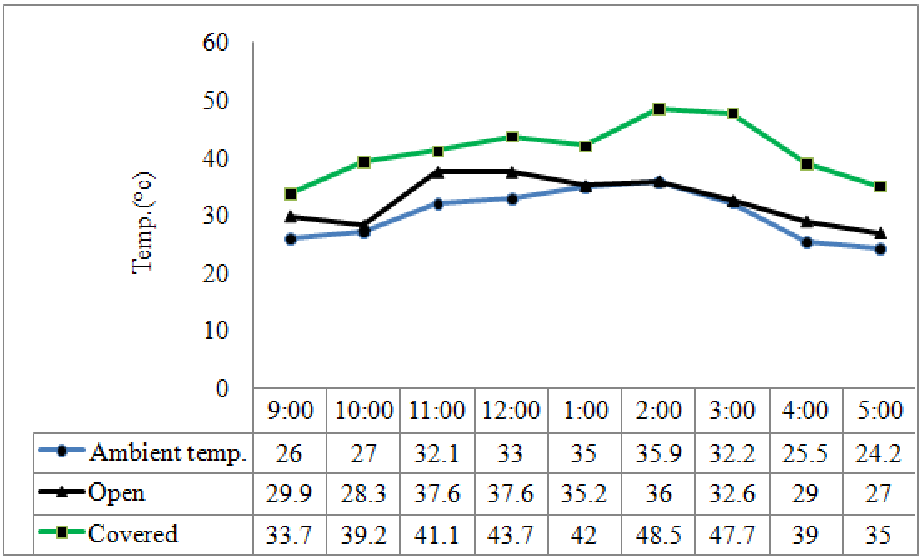
Figure 19: Weight reduction in open air sun drying vs covered drying

7.2.3 Pathogen inactivation

After loading fecal sludgesample, the ambient temperature, open air sun drying fecal sludge and covered drying fecal sludge temperature was recorded and it is shown in the fig. 21

Figure 20: Covered and open air sun drying

The covered fecal sludge temperature is much higher than open air sun drying fecal sludge temperature throughout the day and the maximum temperature recorded 48.5 at 2:00 (noon) by covered dryer.



	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	5:00
Ambient temp.	26	27	32.1	33	35	35.9	32.2	25.5	24.2
Open	29.9	28.3	37.6	37.6	35.2	36	32.6	29	27
Covered	33.7	39.2	41.1	43.7	42	48.5	47.7	39	35

Figure 21: Time (hrs) vs ambient and FS temperature (open and covered)

The pathogen inactivation performance of solar drying system was checked based on by determination of initial load of Ascaris ova in fecal sludge sample and after treatment. The raw fecal sludge collected from onsite sanitation installation contained 229.1 Ascaris eggs/literof fecal sludge or 11.23/g TS of fecal sludge and there is no Ascaris egg observedin covered dryer. There was reduction of Ascaris eggs from 11.23/g TS of initial Ascaris eggs load to 4.1/g TS final load which is 63.5% reduction in open air sun dryer.

8 DISCUSSION

(Al-Neama M.and Farkas I.,2016) revealed that, optimization activities can improve drying efficiency in shortening of drying time and pathogen reduction. Optimization of solar fecal sludge dryer in the current study was started by designing mixed mode passive solar dryer. Passive solar fecal sludge dryers are operating by natural air velocity and are independent of auxiliary energy and this make passive solar dryer to implement at decentralized level. In the current study,insulating non-transparent parts, increasing heat transfer area by selecting type of absorber, use black painted absorber, direct contact of heated air coming from solar collector to fecal sludge storage tray to heat bottom of fecal sludge storage tray, adjusting inclination of solar collector and position of dryer south to north for optimum solar absorption were implemented to enhance system efficiency. From those parameters that directly affect drying process, temperature is the most one. The developed solar fecal sludge dryer performance was evaluated based on energy balance system. Before starting of drying process, ambient air temperature (T_a), solar collector temperature (T_c)and drying cabinet temperature (T_d) were measured. The result revealed that the temperatures inside the dryer (T_d) and the solar collector (T_c) were much higher than the ambient temperature (T_a) during all hours of the daylight. The study (Seck et al., 2015), concluded that there is no difference between closed and open dryers and the advantage of covering is only for rain protection. The increase in temperature increases the tendency of hot air to pick more moisture (Sypula M.,Paluszak Z. Szala B., 2013).This indicates the covered dryer has better performance than open air sun drying system.

This result can be more explained by using energy analysis for covered dryer. The system has solar collector and drying cabinet which makes the system mixed. The increase in temperature of the absorber increases internal energy of the absorber. The heat energy absorbed by solar collector part (Q_{in}) was 2.5kw but all this energy cannot be used for drying because of heat loss (Q_L) from solar collector (Adelaji & Babatope, 2013). The useful heat energy gained (Qg) by solar collector was estimated only 856.6 wand 67% of (Q_{in}) lost from solar collector and the collector efficiency (η_c) was 34.3%. The drying cabinet also absorbed heat energy (Q_{in}) through transparent roof and is about 2.866 kw. The heat lost from drying cabinet which is 96% was very high. The fecal storage tray and external box of drying cabinet were made from metal sheet and these parts were not insulated which increases heat loss from drying cabinet. The total system efficiency (η_s) of solar fecal sludge dryer was estimated 26.2%. The efficiency of the current study is lower compared with other studies (Adelaji Babatope, 2013; Bolaji B. & Olasusi A.P., 2008) and inadequate insulation of non-transparent parts and heat lost by reflection from glazing are the main reasons.

The other performance evaluation for solar fecal sludge dryer is its moisture content removal efficiency. The moisture content removal analysis of dryer was conducted for four days with 3cm fecal sludge depth of both covered and open air sun dryers. The initial moisture content of fecal sludge sample was 97% and the sample was loaded in both covered and open dryers. The final moisture content for covered drying and open air sun drying was reached 2.3% and 11.3% within four days, respectively. The dried product achievement in the current (97.7% TS) within four days is better than the study (Muspratt A.M., et al, 2014) which was 95% TS within 8 to 31 days. There is high moisture content reduction of covered dryer than open and this indicates that solar drying can shorten the drying time of fecal sludge and the current study result is similar to studies ((Bennamoun, L. 2012,: Mathioudakis, V.L. et al., 2013: Bennamoun, L., Arlabosse, P., and Leonard, A., 2013, Muspratt, A.M. et al., 2014) but vary from the study (Sock et al, 2015) and this possibly because of low solar radiation in the former study.From the water removed and drying period taken, the drying rate was $2.4 kg H_2O/m^2$day and $2.7 kg H_2O/m^2$day for open air and covered drying respectively and is similar to (Adelaji & Babatope, 2013) but lower than (Bolaji B. & Olasusi A.P., 2008) and there is nothing mentioned the area related with drying rate in the previous studies.

From this result, it is possible to adjust moisture content of fecal sludge to reuse as input for other purposes and weight reduction for fecal sludge management. Fecal sludge for fertilizer production (aerobic process and pellet production), animal protein production (black soldier fly), combustion and pyrolysis, the moisture content should be ensured 40-60%, 60%, $< 70\%$ and $< 10\%$ should be ensured respectively (Niwagaba, C. B. et al., 2014:Kengne et al., 2014:Muspratt, A.M. et al., 2014) and this can be achieved by solar fecal sludge dryer in short period of time.

The pathogen inactivation performance of the solar fecal sludge dryer was evaluated based on the initial and after treatment load of Ascaris eggs. The initial load of Ascaris for fecal sludge collected from pit latrine and tank indicated that it is not safe to re-use or dispose to the environment. For treatment of Ascaris, the temperature and moisture content of the product should be raised to $> 40^0 c$ and /or 95% TS (Jimenez, 2009). In the current study, the fecal sludge temperature was raised above 40 oc from 11:00 to 3:00 and the maximum temperature was recorded 48.5^0c at 2:00. In addition the moisture content was rapidly reduced to 2.3% in covered and 11.2% for open air sun dryer. Based on this; covered drying can achieve pathogen inactivation but the fecal sludge temperature was not maintain above 40^0c for optimum days. In determination of Ascaris eggs, the result showed that 11.23/g TS and this result is in the rage stated by (Debela, T.H., et al, 2017), determined Ascaris Ova (67-151 /10g TS) of fecal sludge based on pit depth and the load of Ascaris eggs is higher at the top layer. The Ascaris load was determined after 10 days experimental period for both covered and open air sun drying and it was not observed and 4.1/g TS respectively. Pathogen inactivation efficiency of the system revealed that 100% and 63.5% for covered and open air sun drying respectively. This indicates that it is possible to reuse dried fecal sludge from covered drying up to unrestricted reuse 1(WHO, 2006). The study (Paluszak et al, 2012), was concluded that solar drying does not guarantee biosafety of products for agricultural purpose. This finding is contradicted with the current study result and the main probable reason can be there is very low solar radiation intensity in the previous study. Temperature and dryness are the main variables for complete inactivation of pathogens and there is only 3^0c of temperature difference between ambient and covered dryer in the previous study but it was 25.55^0c in the current study.

9 CONCLUSIONS

Simple and inexpensive mixed-mode passive solar dryer was designed and constructed using locally available resources. The hourly variation of the temperature in solar collector and inside drying cabinet are much higher than the ambient temperature during all the day. The higher temperature difference between covered dryer and ambient indicates that covered solar dryer better performance than open air sun drying. Insulating non-transparent parts and increasing of air contact with solar absorber in solar collector improves collector efficiency up to 34.3% but still approximately 67% of the energy absorbed is lost from solar collector. The useful heat gained from drying cabinet (Q_u) is only 112.7 w (~4%) and is reduced the system efficiency to 26.2%. The drying rates of fecal sludge were $2.7 kg H_2O/m^2$day and $2.4 kg H_2O/m^2$day for covered and open air sun drying respectively. There was also higher percentage weight reduction occurred in covered fecal sludge solar dryer. The fecal sludge temperature of covered drying was very higher than open air sun drying during drying period and it was above 40^0c for four hours. There is complete pathogen inactivation efficiency for covered drying and 63.5% for open air drying and this indicates that it is possible to use dried fecal sludge from covered dryer for irrigation, agriculture, forestry, soil and site rehabilitation, land disposal and surface land disposal.

10 RECOMMENDATIONS

Based on the experimental results obtained, the following recommendations suggested.

- Because of high energy lost from the dryer especially from the drying cabinet, it is better to further improve insulation of both the solar collector and drying cabinet.
- For long operation of drying and to maintain high fecal sludge temperature, storage of energy should be done
- To avoid moist droplet inside drying cabinet and to increase air velocity, addition of vent opening and increasing chimney length implemented
- Encourage use of fecal sludge dried by covered dryer for all purposes like irrigation, public contact sites, urban landscaping, agriculture, forestry, soil site rehabilitation, land disposal and surface land disposal.
- Because the main concern to use fecal sludge is its high moisture content, industries can use dried fecal sludge with other fuel options.
- Policy makers to establish standards for disposal and reuse of fecal sludge.

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