USE OF SOLAR AIR DRYER WITH PHASE CHANGE MATERIAL IN SLUDGE DRYING

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PhD THESIS
DEPARTMENT OF ENVIRONMENTAL ENGINEERING

BURSA – 2021

THESIS APPROVAL

This thesis titled "USE OF SOLAR AIR DRYER WITH PHASE CHANGE MATERIAL IN SLUDGE DRYING" and prepared by Zeinab AMIN has been accepted as a **PhD THESIS** in Bursa Uludağ University Graduate School of Natural and Applied Sciences, Department of Environmental Engineering following a unanimous vote of the jury below.

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ÖZET

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Her yıl, çeşitli evsel ve endüstriyel atık su arıtma tesislerinden yüksek miktarda atık çamur üretilmektedir. Çamurun nem içeriği tüm çamur arıtım süreçlerinde özellikle nakliye ve nihai bertarafında sorun oluşturmaktadır. Bu çalışmada, çamurun nem içeriğini azaltmak amacıyla tasarlanan güneş kurutucusunun verimliliğini arttırmak için yapılan iyileştirmeler ele alınmıştır. Bu araştırmanın amacı; çamuru sürdürülebilir, maliyet-etkin yöntem ile su içeriğini azaltılmasıdır. Tasarlanan sistemde güneş enerjisinden gelen ısıyı depolamak için su, hava ve parafin, gibi bir faz değiştiren malzeme kullanılarak iç ortam hava sıcaklığının kararlı halde kalması hedeflenmiştir. Bu sistemde, güneş enerjisinin çamura ısı olarak transferinde konveksiyon, kondüksiyon ve radyasyon işlemleri, birlikte kullanılmıştır. Çalışmada farklı nem oranlarına sahip, evsel atıksu arıtma tesisi çamuru (AAT), endüstriyel boya çamuru ve mermer atık çamurlarının kurutulma süreçleri incelenmiştir. Güneş kurutucusunun tasarımında yapılan iyileştirmeler sonucu birim alandan buharlaştırılan su miktarına göre arıtma çamurunda 20% den 28%, boya çamurunda 18% den 31% ve mermer çamurunda 6%dan 13% verim artışı gözlenmiştir. Ayrıca, AAT çamuru üzerinde yapılan mikrobiyolojik deneyler sırasında, güneş radyasyonuna maruz kalan E-coli mikroorganizmalarının 2 log oranında inaktive edildiği tespit edilmiştir. Yapılan Toplam Kjeldahl Azotu deneyinde amonyak miktarı 9000 mg/kg 'den 6800 mg/kg' a düşmüştür. Ayrıca çalışmada güneşle kurutulmuş çamurların Taramalı Elektron Mikroskobu ile elde edilen görüntülerinde gözenekli yüzey yapısının çamur suyun buharlaşmasına katkı sağladığı belirlenmiştir.

Anahtar Kelimeler: Güneş kurutucusu, Kondüksiyon, Konveksiyon, Radyasyon, Sürdürülebilir, Escherichia-coli, Toplam Kjeldahl Azot.

2021, x +121 sayfa.

ABSTRACT

PhD Thesis

USE OF SOLAR AIR DRYER WITH PHASE CHANGE MATERIAL IN SLUDGE DRYING

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Every year, large amounts of sludge from various domestic and industrial treatment plants are produced. The moisture content of sludge is a problem in all waste sludge treatment processes, especially in the transportation and final disposal. In this study, improvements made to rise the efficiency of the solar dryer to reduce the moisture content of the sludge are discussed. Aim of this research is to diminish the water content of the sludge with a sustainable, cost-effective method. By using water, air, and phase change materials such as paraffin, the indoor air temperature was kept stable. In this system, convection, conduction, and radiation processes are used together as heat transfer methods to transmit solar energy to the sludge. Wastewater Treatment Plant (WWTP), Paint and Marble sludge with assorted moisture content, drying processes were investigated. As a result of the improvements made in the design of the solar dryer, the efficiency increased from 20% to 28% for WWTP.sludge, from 18% to 31% in paint sludge, and from 6% to 13% in marble sludge, according to the amount of water evaporated from the unit area. In addition, during microbiological experiments on WWTP.sludge, it was determined that E-coli micro-organisms were inactivated by 2 logs. after solar radiatıon exposure. In the Total Kjeldahl Nitrogen experiment, the amount of ammonia decreased from 9000 mg/kg to 6800 mg/kg. In addition, it was determined that the porous surface structure of the dried sludges obtained by Scanning Electron Microscopy contributed to the evaporation of the sludge water.

Key words: Solar dryer, Conduction, Convection, Radiation, Sustainable, E-coli, Total Kjeldahl Nitrogen.

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ACKNOWLEGDEMENT

I would like to thank my deep acknowledgment to Prof. Dr. Nezih Kamil SALİHOĞLU my supervisor for his guidance, experience in the installation of the dryer system and, 4 years of his support.
I would also like to appreciate two consulting Prof. Dr. Fatma Olcay TOPAÇ, (Uludag University professor and consultant) and Prof. Dr. Mehmet İŞLEYEN (Bursa Technical University professor and consultant) for their valuable advice during the research, and Assoc. professor Sevil ÇALIŞKAN ELEREN (Uludag University academic staff) for her generous contributions to the microbiology lab. In the process of research, my grateful tanks to Ms. Melsa KORKMAZ, (Master of Environmental Engineering Student) for providing the sludge, Assoc. professor M. Akif ÇİMENOĞLU, (TÜBİTAK BUTAL Laboratory Staff) for SEM pictures and Prof. Dr. Veysel Turan YILMAZ (Uludag University professor) in Waste sludge (TGA) analyzing.
I am especially grateful to my parents for their unending support during my study.
Finally, I would like to thank and apologize to all the native animals and insects in the area, whose habitat was in the solar system installation site and I was disturbed their life's during the research, especially my dear tortoise.

Zeinab AMIN

07/09/2021

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SYMBOLS and ABBREVIATIONS

Symbols	Definition
A	Area (m^2)
˚C	Centigrade
α	Collector Slope
%	Percentage
h	Hour
KJ/Kg. K	kilojoule per kilogram per kelvin
kg/m^3	kilogram per cubic metre
min	Minutes
µS/cm	Microsiemens per centimeter
Qc	Heat loss
RH	Humidity
T	Temperature
U	Heat transfer Coefficient (W/ [m^2 x ˚C])
Sec	Second
ΔT	Temperature differential
θ	Collector floor angle
α	Angle of the sun with the ground

Abbreviation	Definition
Ag	Silver
Al	Aluminum
Al_2O_3	Aluminum oxide
As	Arsenic
B	Boron
BFP	Belt Filter Press
BUSKI	Bursa Water and Sewerage Administration
Cl	Chloride
Cd	Cadmium
Cr	Chromium
Cu	Copper
CaO	Calcium oxide
CO_2	Carbon Dioxide
CFU/gr	Colony-forming unit per gram
DTA	Differential Thermal Analysis
DM	Dry matter
DS	Dry solids
E-coli	Escherichia coli
EPA	Environmental Protection Agency

ETC	Evacuated Tube Collectors
ETHP	Evacuated Tube Heat Pipes
F	Fluoride
FAO	Food and Agriculture Organization of the United Nations
Fe	Iron
Fe_2O_3	Iron (III) oxide
FPC	Flat Plate Solar Collectors
FPSAH	Flat Plate Solar Air Heater
GSC	Glazed Solar Collectors
Hg	Mercury
LHS	Latent heat storage
MA	Moisture Analyzer
Mn	Manganez
MgO	Magnesium oxide
MPa	Megapaskal
Ni	Nickel
NO_3-N	Nitrate Nitrogen
NO_2-N	Nitrite Nitrogen
NH_4-N	Ammonium Nitrogen
Pb	Lead
PCM	phase change material
pH	potential of hydrogen
PV	Photovoltaic
SHS	Sensible heat storage
SAH	Solar Air Heating O4
SO_4	Sulfate
Sb	Antimony
Se	Selenium
SEM	Scanning Electron Microscopy
SET	Solar Energy Technologies
TES	Thermal Energy Storage
SiO_2	Silicon dioxide
Sn	Tin
TKN	Total Khejdahl Nitrogen
TG	Thermogravimetry
TN	Total Nitrogen
TP	Total Phosphorus
UN	United Nation
WEC	World Energy Console
WWTP	Wastewater Treatment Plant
Wh/m^2	Watt-hour per square meter
Zn	Zinc

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1. INTRODUCTION

One of the most important energies needed by societies is heat, which is easily obtained by using solar dryers. Dryers using solar energy are usually recommended to dry the agricultural products, heating the environment and other applications (Aravindh and Sreekumar 2014). In this developed world, the issue of renewable energy and the need for it are increasing every year. According to the World Energy Council (W.E.C) 2016, fossil fuels currently supply more than 80% of the world's required energy, and from this amount of energy, 31.1% includes petroleum, 28.9% from coal, and 21.4% from natural gas. The energy crisis has caused political and economic instability around the world (Sopian 2006; Janssen 2002; Ahuja and Tatsutani 2009). Usually alittle amount of solar power is consumed by humans (Idliman et al. 2016), so through the optimal use of solar energy the efficiency uses of solar systems increased. Researchers have focused on solar energy technologies due to low investment cost, lower environmental pollution, and high efficiency. Solar energy is used for different purposes and has many applications, especially in the environmental sector. An article published by Weliwaththage et al. (2020) briefly discusses the innovation of sludge solar drying technology. The designed dryer has been set up on the campus of Uludag University in Bursa/Turkey.

1.1. Background

Solar drying is an essential method for sludge management. Sludge is usually obtained during various industrial processes. As the sunlight increases, sludge moisture decreases and energy consumption increases. Large volumes of sludge are generated daily as waste by various treatment plants and industries, which must be disposed in a short time to avoid any problems (Kacprzak et al. 2017; Archer et al. 2017; Guo et al. 2009). Solar energy technologies (SETs) encourage to sustainable development of human activities. Reducing the amount of water in the sludge causes its excretion. Drying is a common method but it is one of the most challenging processes in removing moisture to produce a dry product (Idlimam et al. 2016). Sludge management has become problematic due to high humidity and the potential risk of trouble during transportation (Świerczek et al. 2018; Ying et al. 2012; Wang et al. 2019). Solar drying method is generally used more in food products and it has been found that it deteriorates the product quality when exposed to solar radiation for a long time, but there was no problem in the drying process. By increasing the evaporation of water from the sludge, a better result is obtained (Manara and Zabaniotou 2012). In the case of the dewatering process, undesirable changes in the quality of the dry product may occur, so the original qualities should be maintained as much as possible (Akpinar et al. 2003). As Grobelak et al. (2019) have been mentioned, the EU's annual sludge production is estimated at more than 10 million tonnes of dry solids, also according to United Nation Department of Economic and Social Affairs (UNDESA) 2014, sludge production in the union will increase to 13 million DM (dry matter) in 2020. Eurostat reported in 2018 that 318 503-ton sludges were produced in Turkey, so solar dryers are a good option to reduce sludge moisture content. Solar dryers are a low-cost way to produce high-quality products (Weiss and Buchinger 2002). The water trapped between the sludge particles is divided into four categories: free water, interstitial water, surface water, and bound (physically and chemically) water that is easily released during the solar drying process (Vaxelaire and Cézac 2004; Kopp and Dichtl 2000; Kopp and Dichtl 2001). Integrated solar dryers have been introduced as one of the leading methods in various studies (Lakshmi et al. 2019). Among the proposed requirements in greenhouse systems, to improve the absorption of solar waves is the use of solar collectors and reflectors (Campbell 2013; Kalbande et al. 2017). Another practical method to accelerate the heat and mass transfer proceeding to the system is the use of phase change materials (Wang et al. 2019). According to Darvishi et al. (2018) studies heat transfer from the inner sludge surface is determined the drying rate. Different phase change materials are used to store heat inside the drying systems. One of the most common phase change materials is paraffin, which is used at a high level due to its cheapness and ease of supply. The solar dryer system can be used efficiently in low and medium heat by allocating a lot of open space (karaca et al. 2019).

1.2. Aims

Waste sludge contains inorganic compounds, water, microorganisms, and some undigested materials (Zhipan et al. 2021). The aim of this research is decreasing the investment and operating cost of sludge treatment by minimizing the volume of sludge. By reducing the amount of water in the sludge, it causes a decrease in microorganisms and transportation costs and finally, the cost of sludge waste disposal is reduced as the main target, also the resulting material is obtained as a manageable substance. By collecting these pollutants and providing appropriate methods for waste management, the potential risks are minimized. During environmental assessment and related politics, the goal is is reducing the costs for risk management and provide appropriate methods/tools to create thermal balance in the system. By determining the performance of the dryer and comparing it with similar systems, it is considered that more solar radiation is absorbed per unit time and water evaporation increases. The purpose of designing the optimal and developed model in this study was to minimize the construction and operation costs of sludge dryers, in addition, in this optimized model, the amount of water evaporated per hour based on cumulative solar radiation is determined.

1.3. Research questions and problems

During drying, sludge changes to a paste and sticky form and it prohibited dewatering. The sticky phase causes difficulties within the drying unit and reduces drying performance. The solar drying method is an efficient way to release the water from this phase. The problem varies depending on the drying rate, so more extensive and detailed research is required. In this study, it was tried to find answers to the following questions:

- How to build an optimal solar dryer system for sludge dewatering?
- Can heat transfer into the system be increased?
- What is the relationship between solar radiation & evaporation?
- What is the effect of phase change materials in drying systems?
- Is it possible to dry different sludges with different water content and structure at the same condition?

1.4. Evaluation of Topic

The justification for solar dryers is more related to their operating cost, which is less expensive than mechanized dryers. According to the studies, it has been determined that solar drying systems are both environmentally friendly and less CO_2 emission compared to thermal drying systems. It is emphasized that solar drying systems will minimize greenhouse gas emissions and contribute to the clean development mechanism within the framework of the Kyoto protocol. The sludge treatment process is known as a carbon source due to greenhouse gas emissions and energy consumption. Carbon footprint is a method for assessing the path of sludge technology (Ji 2018). Environmental researchers in sludge treatment processes have examined the carbon footprint and life cycle from an environmental or energy perspective, also its analysis is very important in sludge management methods with reliable quality standards (Pradel and Reverdy 2013). Greenhouse solar drying systems, like thermal dryers, are implemented by manufacturers for different requests and purposes. To accelerate drying, a variety of processes are required that increase heat transfer. The drying time must be considered in the solar drying method. At the same time, drying time can be minimized by creating a suitable heat balance and preventing heat loss in the system.

Drying time varies according to weather conditions, but some required materials affect this process. Although solar dryers have a lower water evaporation rate than thermal dryers, so easy operation and maintenance are important. Another important physical property feature of sludge is water holding capacity (Aşkın and Aygun 2018). According to the characteristics of sludge water holding capacity after solar drying, it can be used to improve the soil quality. The protection feature of sludge stability is important in environmental and agricultural studies(Meral et al. 2015). As a result, due to the fact that sludge has a certain amount of water, it is applied as an effective factor in increasing soil fertility in land applications. The technology chosen must be environmentally friendly, applicable, sustainable, and economical.

2. THEORETICAL BASICS and LITERATURE REVIEW

2.1. The nature of sludge types

Due to the high volume of sludge waste produced, high energy needs are also observed for the removal of pollutants. Necessary operation requires controlling all types of sludge with optimal conditions. One of the sludge types is obtained from wastewater treatment plants which may be from domestic, industrial, and commercial effluents. The source of sludge is determined significantly by their composition. Paint sludge is kinde of hazardous waste that poses a serious threat to the environment, and its production is inevitable from industries. Today, paint sludge is industrial waste according to the specifications of various parties. Among the wastes from industrial activities, marble sludge from ornamental stones also leads to waste management problems. In this study, the drying of marble sludge formed as a result of cutting and grinding marble was investigated. Nowadays, efforts to produce energy from waste sludge have received a lot of attention, and the focus is on incineration and land spreading methods for sludge disposal, but, due to the high moisture of the sludge and transportation problems, drying the sludge is mandatory before any activity.

All operation requires drying, and after drying the water content of the sludge drops below 10%, which provides a great advantage. Various processes in sludge dewatering have been described in the literature. Heat transfer is a common process, also it relies on convection, conduction, or radiation procedures. In these methods, water is evaporated from a solid material. The Removal of water from the sludge depends on the ambient and sludge temperature, humidity, air velocity, time, and texture of sludge(Reinola 2007). In order to choose the appropriate drying method, investment and operating costs, commitment to safety, sludge contents, and environmental compatibility are taken into consideration (Reinola 2007). Depending on the type of sludge and the amount of water in it, moisture is discharged in several stages. The Warm-up phase is the process of heat and mass transfer and continues until the equilibrium value is reached.

The initial amount of water, which is the maximum water content in the sludge, and evaporates faster. In the second phase, the sludge enters a steady state of evaporation, and heat exchange occurs. The structure of sludge cell walls leads to the rapid movement of moisture to the surface (Jung et al. 2010). Drying time depends on the amount of water particles bond between the sludge grains. Sludge surface water evaporates faster than the inner part. During the drying of the sludge, it changes from the liquid to a sticky state. In the sticky phase, the sludge has 45-65% of dry solids (DS) (Chodur 2002). Factors affecting drying include: temperature, relative humidity, airflow rate, the specific heat of sludge, material selection, heat transfer coefficient, and resistance to mass transfer (Ruiz and Wisniewski 2008). The sludge water types is as follows:

- Free Water

Free water is free from solids and capillary forces and moves freely in the sludge (Vaxelaire and Cezac 2004). This water is independent of sludge particles and capillary phenomenon. Free water usually leaves sludge easily during mechanical processes. In a study about vacuum purification, sludge free water under pressure of $5 * 10^4$ Pa is easily released after 30 minutes (Smollen 1990) and at pressures above 28 MPa large volumes of sludge water evaporates (Pramanik 1994; Smith and Vesilind 1995).

- Interstitial Water

This type of water is trapped in the fluke structure by capillary forces (Tsang and Vesilind 1990; Vaxelaire and Cezac 2004). Intermediate water is easily released under mechanical processes(Kopp and Dichtl 2000).

- Surface Water

Surface waters are bound to solid particles by adhesion forces (Vaxelaire and Cezac, 2004; Smith and Vesilind 1995). This layer has powerful bonds of Van der Wals forces.

- Bound Water

Water is bound to sludge particles and is difficult to separate. Intracellular water is chemically bound to particles (Kopp and Dichtl 2001; Tsang and Vesilind 1990), and is known as hydration water (Halde et al. 1979). This water is attached to solid particles and be separated using thermal energy (Mahmoud 2010). All the explanations about the evaporation process depend primarily on the sludge types which are mentioned below and used in the research.

2.2. Sludge treatment methods and drying overview

Sludge is solid material with high humidity that is obtained during purification and industrial processes and usually contains a large volume of water that during the drying stage is reduced significantly. The wastewater treatment plant sludge is processed by the following steps:

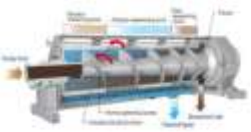
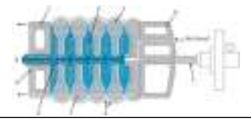
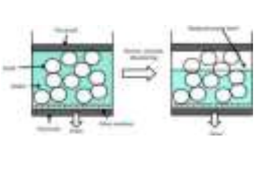
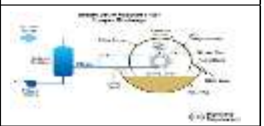
- Thickening:

The sludge obtained at this stage has a humidity above 97%. In this part, the sludge enters the gravity thickener tank. This method is the simplest and most basic ways to reduce the moisture concentration of sludge with low energy consumption. In this process, the total volume of sludge is reduced to 1,2 of the original volume (Schaum and Lix 2011).

- Dewatering:

The resulting sludge at this stage contains 20% solids content. Sludge dewatering and volume minimizing is a process for sludge disposal. During the sludge dewatering operation, its weight is significantly reduced. Due to the physical and chemical properties of sludge grains, various dewatering methods have been proposed in Table 2.1.

Table 2.1. Mechanical sludge dewatering methods

Dewatering Process Type	Description	Refrences	Picture
Belt-Filter Presses (BFP)	►Requires little energy and cost ►Easy to maintain and operate ► Fast process ►Expert personnel ►The primary separation is achieved by passing a pair of belts through the roller system ►Dehydrated sludge has between 12-35% solids matter	(Techobanoglous et al. 2014)	
Rotary Presses	►Lower speed ►Low cost ►Trap odors and airborne particles easily ►The screw system works as rotating machines	(Techobanoglous et al. 2014; kakoki, 2021)	
Recessed Plate Filter Presses	►Produce the highest amount of dry cake ► It is a simple process and requires skilled labor ►The feed pump of the system is stopped after obtaining the desired moisture	(Godwin et al. 2017; Suezwaterhandbook 1931)	
Electro-Dewatering	►Electric field dehydration or electro dehydration consumes three to five times more energy ►Includes electrophoresis, electro osmosis and electro-migration ►High cost	(Mujumdar et al. 2008; Mahmoud et al. 2010)	
Drying Beds	►Less expensive ►Low maintenance and low energy ►After dewatering, the concentration of solids reaches 60-50%	(Techobanoglous et al. 2014; Elbaz et al. 2020)	
Centrifuge	►Requires high energy ►Requires polymer ►Product contains between 16 and 35% solids ►The solid/liquid accelerate force is created in a conical cylinder at high speed (2500-3500 rpm)	(Young, 207).	
Geo-textile	►This system consists of high-strength permeable fabrics ►The sludge contains 15-45% solids matter	(Young, 2017)	
Rotary Vacuum	►This method is done through liquid suction ► This process is very slow ►The quality of the product is high ► The produced sludge contains 20-45% solids matter	(komline, 2021)	

- Drying:

The method of sludge drying is by transferring heat energy to the sludge to obtain sludge containing solids content above 90%. The solar drying process depends on technical solutions as a type of dryer and heat recovery method. Sludge is a solid waste with high moisture that is produced through various industries. The sludge produced at this stage is obtained in the form of granules with the least environmental impact, which makes it easier to store and transport. In this research, this method has been studied due to its special importance and cost-effectiveness. Choosing the right solar dryer depends on the type of product like sludge and how it is designed. According to experts, the use of dry sludge with 90% dry matter in furnaces for burning has a higher efficiency than wet sludge and less energy is consumed. In Poland, over the past ten years, 30 solar greenhouses have been built with a mixture of sewage sludge(Bożym and Bok 2017). The aims of sludge drying are mentioned in Table 2.2.

Table 2.2. The sludge drying aims in a different method

Using Methods	**Range of Drying**			**Drying Aim**
	30%-40%	60%-90%	>90%	
Agricultural	Unprofitable	Profitable	Profitable	Transporting &Storage Stabilization and Sanitation
Incineration	Profitable 35-45%DS	Unprofitable	Profitable	Autothermic Incineration
Co- Incineration With waste	Unprofitable	Profitable	Profitable	Easier Transportation &Storage

Solar air heaters are recommended to heat the air. These systems use renewable energy to heat indoor air, and also commercial and industrial applications as solar dryers are very cost effective (Ryan 2011).

2.3. Using phase change material in solar dryer

Solar energy is available and can be stored in materials. Solar air heaters (SAH) are divided into two main parts with storage and without storage, which is mentioned in Figure 2.1 (Goyal et al. 1998).

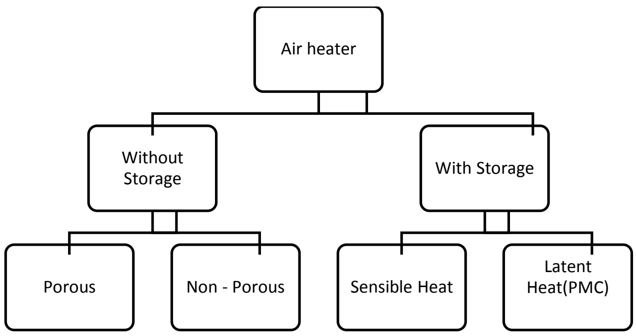


Figure 2.1. SAHs classification according to PCM

The most common materialfor heat storage is paraffin because it is also easily available and cheaper than other materials. Table 2.3 shows the comparative table of storage materials.

Table 2.3. Specifications of PCM types

Type of PCM	Advantages	Disadvantages
Organic Paraffins & non Paraffins	High latent heat	Low thermal conductivity
	Recyclable	Flammable
	Available in larg range temperature	
	Noncorrosive	
	Nondangerous	
	Low vapor pressure in melt form	
	Thermal and chemical stable	
Inorganic Hydrated Salts	High volumetric latent heat	Slightly Toxic
	Low Cost	Corrosive to most metals
	Lower Environmental Impact	Supercooling problem
	Nonflammable	High volum change
	High thermal conductivity	
Eutectic	No segregation	
	Sharp melting temperature	
	Congruent Phase change	

In Table 2.4. the thermophysical spesification of Paraffin-wax which is used in the research is shown.

Table 2.4. Paraffin-wax properties

Properties	Value
Melting Temperature ˚C	65-67
Flash Point ˚C	260
Penetration MM/S	11
Oil content	1%-0.5
Pour point ˚C	54-56
Viscosity at 100 ˚C	7-8 CST
Congealing point ˚C	56-58

In some studies, solar heaters integrated with PCM have been designed, and the convection process occurs by changing the phase of energy storage materials and ambient temperature (Mahmud, et al. 2010).

During the research, most of the models are active with thermal storage capacity. Paraffin-wax is used as a heat storage material due to its abundance and cheapness (Shameer and Nishath 2013). The thermal energy storage process (TES) helps to reduce energy demand. PCMs are the most suitable materials in the environment for energy storage (Shariah et al. 1999). Phase change materials are determined into the following three main groups.

- Sensible heat storage (SHS)

The temperature of a liquid or solid is stored with reasonable heat storage, and the appropriate heat capacity is used, also the changes in the material temperature is stored during the charging and discharging process. SHS is the best material due to its cheapness and special heat.

- Latent heat storage(LHS)

The phase transfer time of thermal energy from liquid to vapor is stored at latent heat during fusion and evaporation. Phase change material has been widely used due to its heat absorption and heat dissipation properties during the solidification and melting process. Heating the material causes the phase change to melt and stores energy as latent heat. PCMs release large amounts of energy during the freezing and absorb energy from the environment during thawing (Sharma et al. 2009; Sharma et al. 2005; Sharma et al. 2013; Sharma et al. 2014; Abhat 1983; Baetens et al. 2010).

The heat storage depends on the use of amount of storage material, the heat of the dehydration reaction, and the rate of conversion. Phase change materials have isothermal properties and can store high-density energy in the variable temperature range (Mofijur et al. 2019). During the study conducted by Kılıçkapa et al. 2018, the highest thermal efficiency in the solar collector inside the tank containing PCM at 13:30 reached 58%. Thermal energy storage is mostly used in places where the difference between the day and night temperatures is high (Srivastava 2017). The use of PCM leads to enhanced proper heat transfer to achieve greater heat energy storage density (Arslan and Ilbas 2019).

2.4. Heat and Mass transfer

Heat and mass exchange is done between dry sludge and air during the drying process is very important. Heat exchange is transmitted through solar radiation, convection, conduction (Srikiatden and Roberts 2008). The mass diffuses from a higher level concentration to a lower level. As the temperature increases, moisture evaporates from the surface of the sludge to the air. The highest rate of evaporation occurs in the first stage of drying. The maximum amount of water in the sludge is free water. The rate of evaporation also depends on the contact surface of the dry matter (Urbaniak and Hillebrand 2004). Studies have shown that the amount of solar radiation and mass flow significantly affects collector performance. To obtain a particular temperature during drying, the mass velocity is optimized (Hematian et al. 2012). Heat and mass transfer during the solar drying process, occur simultaneously (Feyzioğlu 2011). If the mass flow rate is low, the energy losses increase due to the large-temperature difference (Chamoli, 2013). As the moisture content decreases, and the density changes, the porosity of the sludge surface increases, and its volume decreases (Nadhari et al. 2014; De Lima et al. 2002), (Dissa et al. 2010; Talla et al. 2004). Porosity, shrinkage, and density are important factors influencing the heat transfer process. As the moisture content decreases, the shrinkage increases linearly (Koua et al. 2019). When water comes out of the sludge, due to the lack of pressure balance between the inner and outer part, stress is created and causes the sludge to deform and crack (De Lima et al. 2002).

2.5. Type of solar dryers

In recent years, various models of drying systems are developed to reduce energy consumption and make better the product quality, but only a limited number of them are widely used and commercialized (Müller et al. 2012).

Dryer systems are generally classified according to the amount of energy consumed. Systems must be optimal designed and scaled across different environments to achieve the desired quality and good performance.

- Active and Passive solar dryer

Solar dryers are divided in two types according to air flow conditions: Natural and forced convection solar systems (Brenndorfer et al. 1985). Systems based on natural drying methods use natural hot air (Green and Schwartz 2001). Forced or active convection dryers work during fan pressure differences (Brnendorfer et al. 1985).

- Active solar dryer:

The active solar system has a ventilation device for circulating hot air in internal of dryer system and is powered by electricity (Tiwari et al. 2016; Taylor and Weir 1985)
Active dryers are recommended for products with higher humidity and are more suitable than passive dryers and require more capital cost (Chua and Chou 2003). Energy cost should be balanced with system performance, dryer capacity and, drying time. According to Brenendorfer et al. (1985), the drying efficiency in natural convection dryers is 10-15% and in forced convection dryers is 20-30%.

- Passive solar dryer

Passive solar dryers are built as simple and inexpensive systems. Inactive systems consist of an insulated box-shaped dry chamber and a transparent glass or polycarbonate sheet (Seveda 2013). The heated air circulates inside the system (Tomar et al. 2017; Sivakumar and Rajesh 2016; Tiwari et al. 2016) and the humid air leaves through a chimney (Ghaffari and Mehdipour 2015; Chauhan and Rathod 2018; Müller et al. 2012). These types of dryers are commonly used for small-scale drying (Jayaraman et al. 2000). The passive dryer efficiency is between 20 to 40% depending on the product, location, and airflow (Kumar et al. 2016). If the passive dryer overheats, the product quality decreases and causes the color change (Milczarek et al. 2016).

Indirect passive dryers include a collector, dryer and air circulation units (Tiwari 2016). Passive dryer efficiency is on average 13-25%, which is lower than direct dryer efficiency

(Kumar et al. 2016). These systems are easy to build and install and also are located away from the power grid (Hughes and Oates 2011). Passive dryers are still used in many Mediterranean, tropical regions in small farming communities.

- Direct and Indirect solar dryer
- Direct solar dryer

In this method, direct sunlight is used to reduce the moisture of the product. Density differences lead to air movement inside the system. In this system, a thin layer of the product is redistributed in a large space. The roof of these systems is sloping to prevent water accumulation. Portable dryers can be made of wood or metal while building large and fixed systems can be used stone, brick, or concrete, especially the floor of the system is usually made of concrete or soil.

1- The efficiency of the system depends on the weather conditions.
2- It needs a lot of surfaces.
3- Drying time is longer.
4- It is not scientifically possible to control the drying process.
5- This product is exposed to attack by animals and birds.
6. Quality changes in the product occur when the product is exposed to direct sunlight.
7. The capacity of these systems is low, and they are used on a small scale.
8. Direct exposure to sunlight causes chemical reactions in the product.
9. The choice of coatings for the absorbent plate is limited.

- Indirect solar dryer:

In indirect solar drying, atmospheric air is absorbed by the collector, and this hot air flows into the drying chamber during this process and the moisture of the product is lost due to convection. The recirculation of air from the motor to the dryer chamber is performed to return hot air. The presence of a solar collector leads to an increase in system temperature and the possibility of controlling airflow (Kumar et al. 2016).

The heated air circulates around the product inside the dryer chamber, and the heat transfer occurs through convection and provides the evaporation process. Advantages and disadvantages of indirect solar drying:

1. Drying speed is faster than the direct method.
2. The drying process of the product is scientifically controllable.
3. The area required for drying is relatively less.
4. Product quality is largely maintained.
5. The initial cost is higher.
6. Heat loss reduced.
7. Drying time is reduced.

- Mixed- Mode solar dryer

Mixed-Mode solar system is a combination of direct and indirect methods. This system consists of three main components: air heater, dryer chamber, and chimney. The air is heated by the air heater and it has been heated in two ways: air passing through the absorber plate as an air heater and absorbs the solar radiation directly. The product is placed in the system compartment, and moist air is discharged through the chimney.

In a mixed solar dryer, both direct solar heating and preheating of the air with the help of additional energy sources such as biomass heaters lead to heat generation (Kumar et al. 2016; El-Sebaii and Shalaby 2012). In a Mixed-Mode system the product quality with less harmful, maintained (Kumar et al. 2016). Mixed-Mode dryers are complex systems and less commonly used (Sharma et al. 2009).

Maintain product quality with less damage in a Mixed-Mode system. Dryer trays are usually made of non-corrosive stainless steel, and for collectors usually, dark black corrosive paints are selected (Hii et al. 2012; Basumatary et al. 2013). Figure 2.2 Shows a simple view of all three dryer models (Ekechukwu 1999).

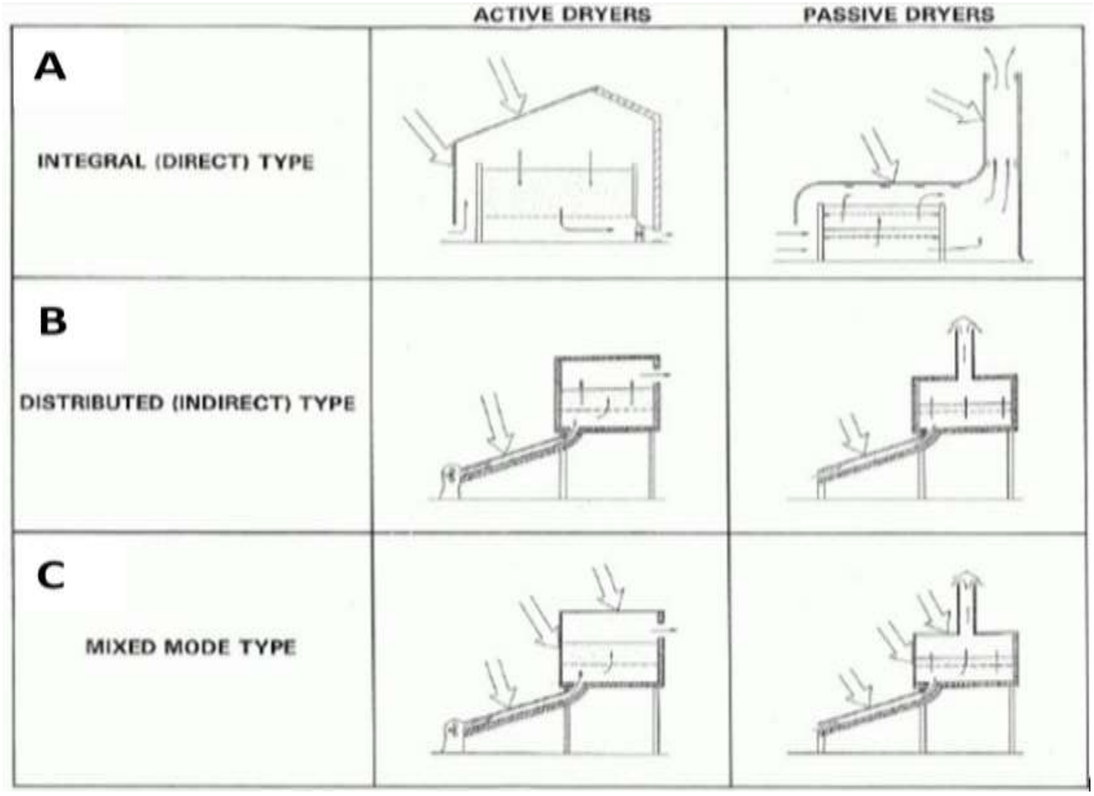
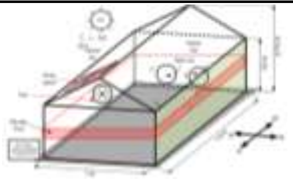
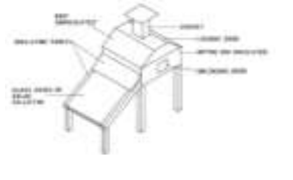
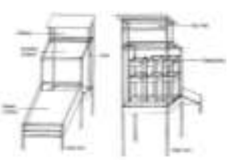
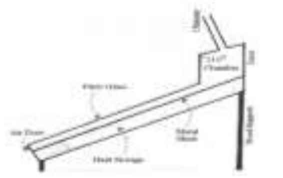


Figure 2.2. Basic modeles of solar dryers. **A)** Direct Type **B)** Indirect Type **C)** Mixed-Mode

Table 2.5 examines the types of solar dryer systems and their efficiency. According to previous studies, active and indirect, and mixed-mode systems have better performance than passive and direct systems.

Table 2.5. Different types of solar dryers along with system performanc

Dryer Model	Author	Product	Efficiency	Picture
Active	(Prakash and Kumar, 2014)	Vegetable Crops	Minimize the various losses and enhance the drying rate	
Passive	(Ekechukwu, 1999)	Maize crops	The moisture content reaches from 20% to 12% within 3 days.	
Direct and cabinet type	(Raju et al. 2013)	Chilly and Tomato	The weight of the product was reduced from 3000grams to 550 grams on the second day.	
Direct	(Medugu, 2010)	Tomato	Tomato with 90% moisture dried completely within 129 hours.	
Mixed Mode	(Forson et al. 2007)	Cassava	The drying efficiency was 12.3% with a drying time of 35.5 hours.	
Mixed Mode Solar cabinet Dryer	(Basumatary et al. 2013)	Chili	Within 7 hours, 48.72% moisture was removed from the upper tray and 33.3% from the lower tray containing pepper.	
Indirect	(Svenneling, 2012)	Pineapple	The moisture content was reduced from 90 % to 10 % within 16 hours.	
Indirect	(Alonge and Adeboye, 2012)	Pepper	Reduce the moisture content of the pepper to 24% during 51 hours.	

2.5.1. Type of solar collectors

Solar collectors convert solar energy flux into internal energy. The most important part of any solar dryer is collector, which absorbs solar energy and converts it into heat (Fudholi and Sopian 2018). Depending on the type of system, this heat can be transferred to the fluid inside the dryer as water or air (Kavoosi Balotaki and Saidi 2017). Different types of collector efficiency have been studied by calculations (Kalogirou 2004). One of the important functions of using solar collectors is to increase the temperature above the atmospheric temperature and create favorable conditions for different purposes. (Karim and Hawlader 2006). The temperature of hot air from solar radiation increases with the passage of the solar collector. Certain standards must be followed for good and reliable operation. The standards can be divided into three parts: collectors standards, systems standards and used components and materials standards (Fajgelbaum et al. 2020). The operating cost of a solar system depends on the resulting efficiency of the dryer installation and materials used (Obstawski et al. 2020).

- Flat Plate solar collectors (FPC)

Flat plate collectors collect solar energy and use it for heating. These typical collectors are relatively inexpensive due to their simple design and are economically viable, also, it consists of a large plate as an absorber made of black copper or aluminum plate. The efficiency of flat plate collectors with thermal storage is 5 to 10% higher than other collectors(Saravanakumar et al. 2012). The system is manufactured by a metal box with a glass or plastic cover sheet and an absorbent plate in dark color. The plate is placed between a glaze and an insulation panel. A flat plate collector is one of the basic models of the solar collector and is usually used in solar water heating systems to provide hot water for domestic or industrial use.

Application of these collectors is usually used for different temperature range between 60˚C to 100˚C (Tiwari and Mishra 2012). One of the advantages of using this system is its simple structure and cheapness. Thermal insulation in this dryer is located around the system and prevents heat loss. The performance of a flat plate solar collector integrated with energy storage material was studied by Walid et al. (2012). Flat collectors do not track the sun because they are stationary. Figure 2.3 shows a schematic picture of a flat plate collector and its various parts (Kalogirou 2004). The specifications of the FPSAH system are:

1- It has one-dimensional airflow
2. The airspeed inside the channels is constant.
3- Temperature drop is insignificant.
4. The temperature distribution is uniform in each section (Marathe et al. 2013).

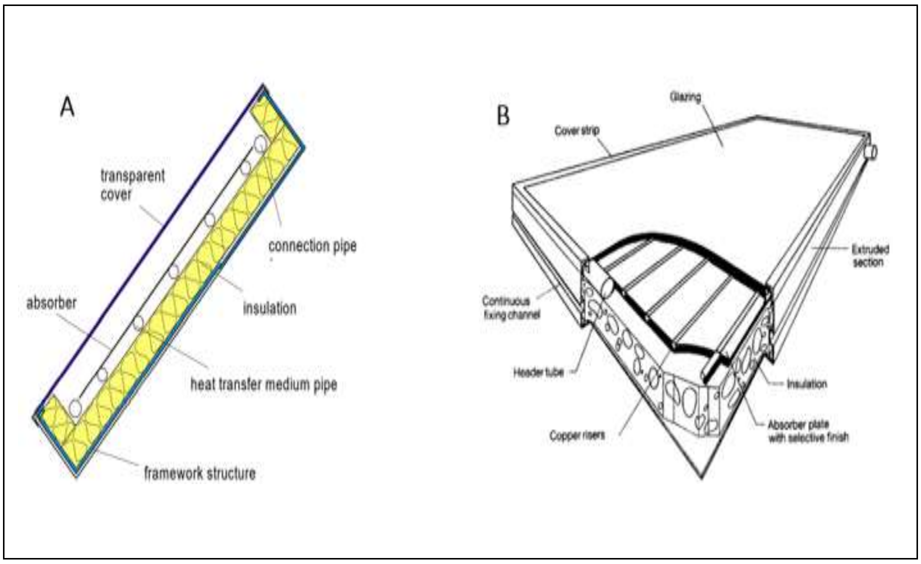


Figure 2.3. An overview of the flat plate solar collector structure. **A)** side view of the collector **B)** collector's interior view

- Parabolic solar collectors

The parabolic collector consists of three parts, including the receiver motor or absorber tube, solar reflector, and a mounting base. The parabolic reflector is a type of parabolic plate that concentrates the solar radiation at one point. Parabolic collectors are used to heating the pipe without reducing the collector efficiency due to the production of a temperature of about 300 ˚C. A parabolic reflector is mounted on a supporting structure (Khare et al. 2014).

This parabolic collector consists of a parabolic cylindrical mirror to reflect sunlight towards the receiver tube in the center of the parabolic cylinder, then it converts solar energy into thermal energy. This system also has high efficiency and low cost and is recommended for direct use of solar energy (Xiao 2007). Figure 2.4 is a view of a parabolic collector. Figure 2.4(A) shows the direction of the solar waves hitting the collector (Khare et al. 2014) and Figure2.4 (B) shows the actual view of the parabolic collector (Li and Dubowsky 2011).

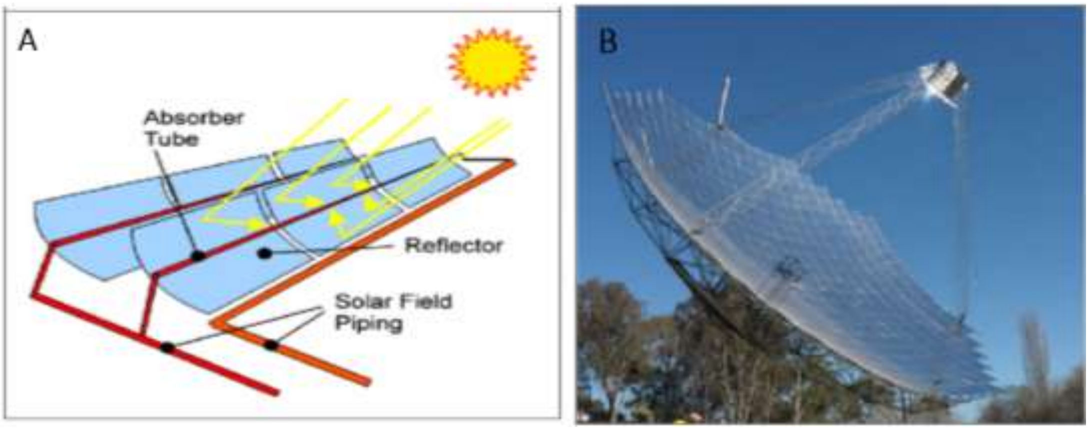


Figure 2.4. An overview of the parabolic solar collector structure. **A)** The image of the direction of sunlight exposure the parabolic collector **B)** Real image of parabolic collector

- Glass tube solar collector

Glass tube solar collectors are more commonly known as solar water collectors, also they are more efficient than flat plate collectors and can operate in cold weather without antifreeze. Air is trapped between the surfaces of the two inner glass tubes. Glass tubes have a cylindrical surface and this shape of the tubes does not affect the performance of collectors exposed to sunlight (Kumar et al. 2020). The outer pipe is made of borosilicate, transparent, and has sufficient resistance to rain and hail. The internal tube is coated with a thin sheet that has absorbed solar heat and minimizes the reflection.

Sunlight is absorbed by the inner glass surface, and preventing re-emitted operation. During one-way mirror acts, 93% of the sunlight hits the tube's surface and absorbed, and 7% is lost through reflection and redistribution. The glass tubes used are often known as Evacuated Tube Heat Pipes (ETHP).

As explained the glass tubes have optimized performance and consist of a centralized double-walled glass tube connected to each other on both sides. The coating between the two tubes is made of aluminum nitrite sputter or copper. This system works well at very low temperatures, unlike flat plate collectors. An overview of the Vacuum tubes is shown in Figure 2.5 (Papadimitratos et al. 2017). To change the efficiency of the system and store heat, phase change materials can be used in the space between copper pipes and glass tubes.

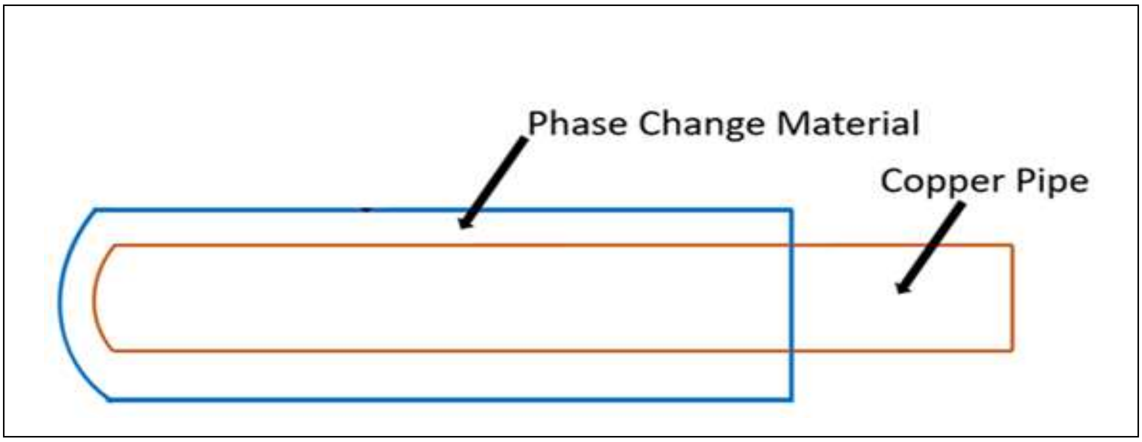


Figure 2.5. An overview of the glass tube solar collector

The absorbing surfaces of the glass tube solar collectors are proportional to the angle of the sun's rays. Figure 2.6 shows the direction of sunlight during the day.

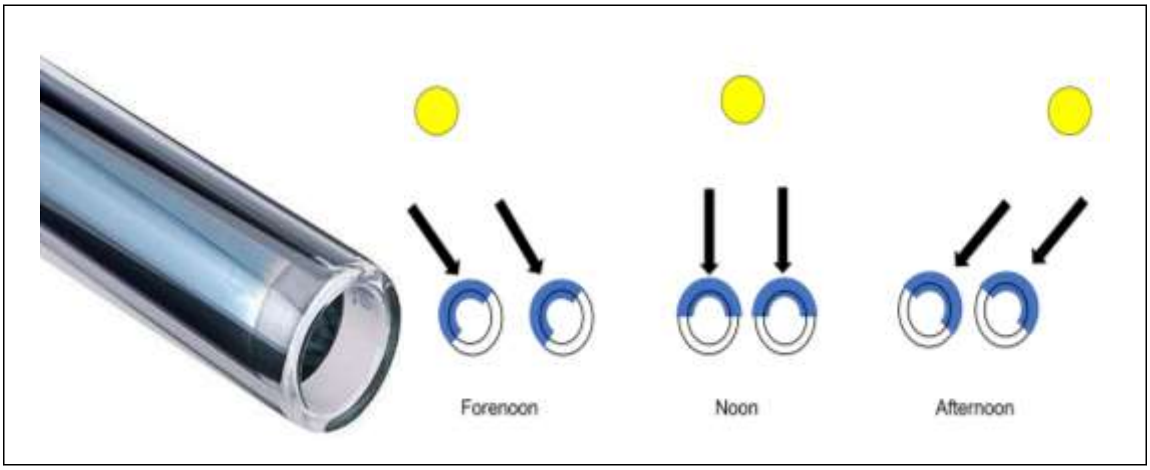


Figure 2.6. The path of sunlight hitting the glass tubes during the day

In this study, different efficiency values were obtained according to the ambient temperature, solar radiation, and the structure of the system. The important feature in these systems was the serial connection of the glass tubes. Glass tubes and Evacuated Tube Collectors (ETC) are better than conventional collectors. These collectors also increase system efficiency in hot weather. These systems can be widely used in warm up the place and agricultural products drying (Külcü 2017). Glass tube solar collectors are offered more frequently in colder seasons and allow a more stable thermal energy generation (Olczak et al. 2020). By installing reflectors around these tubes, the efficiency of absorbing sunlight increases. The solar radiation hit the absorber tubes directly and scattered. Reflector installation significantly increases the performance of the solar collector. Figure 2.7 shows the function of the tubes with reflectors and the direction of the solar radiation.

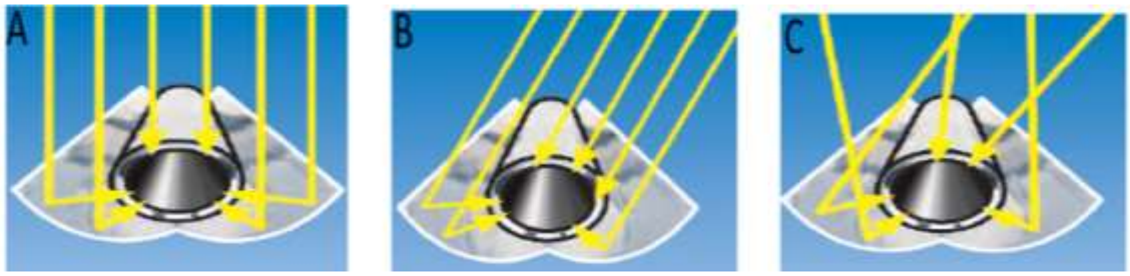


Figure 2.7. Sunlight reflection from the collector to the glass tubes during the day. **A)** Direct solar irradiation **B)** Angled solar irradiation **C)** Diffuse solar irradiation

- V-corrugated plate solar collector

V- Corrugation plate was produced by the aluminum sheet and the thicknesses are 1 mm (Sayigh 1977). The heat transfer improves in three ways by the corrugated absorber.

(1) The heat transfer zone is increased.
(2) Depending on the direction of the flow, it may increase in turbulence
(3) If the direction is correct, the orientation level may be selected (Lof 1954).

The airflow at the top of the adsorption plate is 30-60%, at the bottom of the absorber is 49-70% and under the absorber is 55-65% of the input temperature range (Yan 2014). The V-grove collector thermal efficiency was 4-15% more than the flat plate collector due to the porous medium structure. Depending on the collector type, different types of fins and baffles can be placed on them. The finned collector's efficiency depends on the mass flow rate, solar intensity, and surface geometry of the collector. The arrangement of turbulators is shown in Figure 2.8 (A) (Rajaseenivasan et al. 2015), and the pumping power increases. In Figure 2.8 (B) (Bekele et al. 2014), is mentioned the absorber plate with obstacles mounted. In Figure 2.8 (C) (Kumar et al. 2017), arc shape wire ribs arranged in “s” shape.

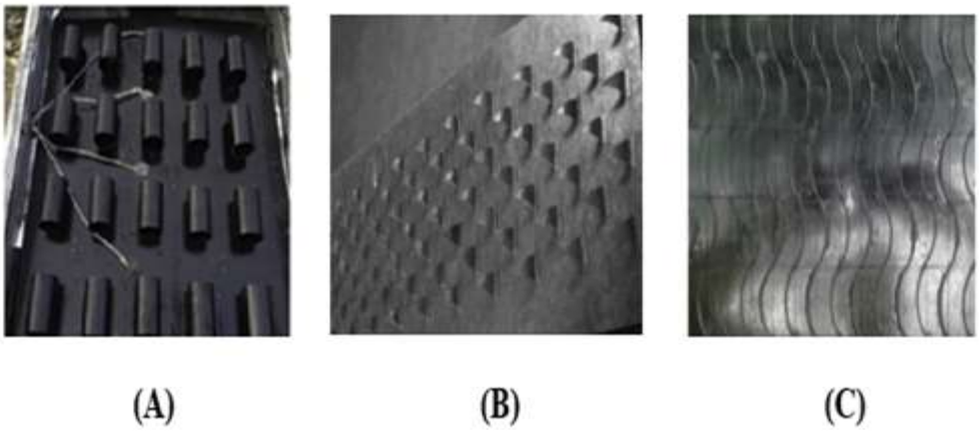


Figure 2.8. Types of fins used in collectors

The presence of fins in the dryer improves the efficiency of the system (El-Sebaii et al. 2011; Garg et al. 1989; Junqi et al. 2007). According to studies by El-Khawajah et al. 2011and Tsai et al. (1999) the use of 2, 4, 6 fins in double-pass solar dryers has been investigated. In another experiment, single-pass air heater performance with fins was evaluated by Mohammadi and Sabzpooshani (2013); Jang and Chen (1997).

The conventional solar air heater with double glazing, double pass finned, was investigated that they have better than the other types (Tao et al. 2007; Bhandari and Singh 2012; Wongwises and Chokeman 2005; Ramgadia and Saha 2012). Wavy fins (sinusoidal) were analyzed in heat exchangers experimentally and theoretically and are shown in Figure 2.8 (C) wavy fins improve heat transfer surface and heat transfer coefficient(Yeh and Ting 1986; Junqi et al. 2010). Wavy fins are popular because they increase the airflow length of the heat exchanger (Wang et al. 2002; Sheik et al. 2009), also, these are cheap and easier to install. Herringbone wavy fins performance is studied by Wongwises and Chokeman (2005). The herringbone wavy fin increases the contact surface and mixes the airflow. The use of fins increases the air velocity in the solar air heater and increases the efficiency of pressure drop. Various researches on different types of fins have been done by the following researchers, fins with baffles(Yeh et al. 2012), corrugated absorber with fins (Choudhury et al. 1988; Hedayatizadeh et al. 2016), artificial roughness fins (Saini and Verma 2008; Chaube et al. 2006, Packed bed fins (Sharma et al. 1991; Chouksey and Sharma 2016; Karim and Hawlader 2006; Mohammadi and Sabzpooshani 2013). Increasing the number of fins and baffles width causes to reduces the system efficiency (Goldstein and Sparrow, 1976; Ali and Ramadhyani 1992), and also causes turbulence in higher currents (Awad et al. 2011). Fıgure 2.9 shows types of flat absorber fins. The finned plate absorber increases the heat transfer (Pradhapraj et al. 2010).

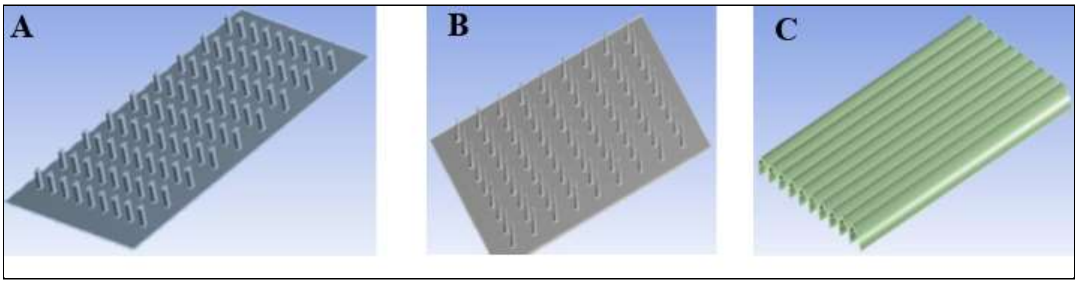


Figure 2.9. An overview of flat absorber fins. **A)** Circular Fins **B)** Tapered Fins **C)** Corrugated Fins

Fins and tubes are used in engineering operations as transportation, heating exchange, and air conditioning (Tahseen et al 2012; Tahseen et al. 2015). Most the industries use heat exchangers for wide temperatures and fin and tube pipes (Kanaris et al. 2009). The use of fins increases the heat transfer area and reducing the air mass leads to a decrease in thermal efficiency.

2.5.2. Type of solar air heaters

The solar air heater is part of the flat solar dryer. This system is often used for hot air ventilation in buildings or for industrial use. Solar Air Heating (SAH) technology is also recommended for heating or preheating the air in commercial areas. The use of SAHs in the desalination process has received more attention (Kabeela et al. 2017). Global energy demand more than doubles by 2050 and more than triple by the end of the century. Many researchers are working on heat-boosting techniques to speed up heat transfer without affecting overall system performance (Kharbade and Shelke 2015). Solar energy has a major role in dryers and space heating. Almost every black surface that is heated by the sun, transfers heat to the air when it is blown on it. Usually, the use of solar energy in commercial and industrial operations and is mostly used in the construction industry to heating space. Solar air collectors are in two types: Unglazed Collectors and Glazed Collectors.

- Unglazed and glazed Collectors

  Unglazed:

These collectors instead of recirculating air, heat the ambient air. They are usually mounted on the wall to absorb solar radiation at a lower sun angle in winter. The outer surface of the solar collector consists of a large number of micro holes that allow the heating layer to be captured and drawn behind the outer panels. The unglazed solar collector is cheaper and easier to handle than the glazed collector (Bandara et al. 2018).

Glazed:

Systems that operate similar to a conventional air furnace and provide heat by circulating air through the collectors. A simple collector can be used for air conditioning by using solar radiation collecting surface to absorb the thermal energy of the sun. Solar air collector consists of a surface as an absorber to capture solar radiation and transfer heat to air through the conduction method. Then heated air is delivered to heating the internal space. These systems are effective to reduce the moisture content of the matter (Mohammad and Mohamed 2013). The transparent cover of dryers causes to pass the solar radiation and reducing heat losses (Duffie and Beckman 1980). The cover should be transparent to provide facilities to pass the short-wave solar radiation (Saxena and El-Sebaii 2015). By using multiple layers of transparent coating and selective glazing causes to reduce top losses. The solar radiation hits the surface of the absorber and converts solar energy to heat. The performance of overhead solar heaters in dryer systems has been analyzed by Aravindh and Sreekumar (2014). Various models of solar air heaters are used around the world. In some solar dryers, the absorber plate is placed under the glazing sheet, to increase the resistance of systems, and one or two glass coatings have been used to reduce convective heat loss. Solar dryers are divided into two categories in terms of the absorber plate: porous and non- porous (Gupta and Garg 1967). Glazed solar collectors (GSC) absorb sunlight more efficiently than unglazed solar collectors and can be used in a variety of weather conditions (Bandara et al. 2018).

- Porous and non-porous collectors
- Porous:

(i) Solar waves are absorbed along the path and penetrate deep.

(ii) Lowest solar radiation losses.

(iii) The pressure drop inside the solar dryer is less than the non-porous type. Improper porosity selection also reduces efficiency. Porous collector increases the solar air heater performance (Kapardar and Sharma 2012).

- Non- Porous:

Type-1

In this model, air flows around the absorber plate, and there is no need for a separate airway. Air is blown over the absorber surface, and leading to increased loss. The type of coating often leads to improved collector performance.

Type-2

In this non-porous model, it is located below the ventilator absorber plate, and a plate is located between the insulation and absorber, also heat losses reaches the minimum rate (Biondi et al. 1988; Loveday 1988).

Type-3

In this model, air flows above and below the absorber plate, and low heat transfer is acccured (Satcunanathan et al. 1973; Garg et al.1985). Turbulence increases the rate of heat transfer. In addition, the proper surface coverage of the absorber plate increases the efficiency of the system. Non-porous heaters include:

1. Normal air heater
2. Corrugated air heater
3. Air heater with fins
4. Double solar air heater
5. V corrugated air heater
6. Two-pass solar air heater.

The disadvantage of a non-porous absorber is that it absorbs all the incoming solar radiation through a thin layer on the screen.

2.5. 3. Literature review in solar air heater

Choosing the right solar dryer depends on the type of product like sludge and how it is designed. Each dryer is able to completely dry the sludge. In most cases, the solids content is less than 85-90%. According to experts, the use of dry sludge with 90% dry matter in furnaces for burning has a higher efficiency than wet sludge and less energy is consumed. In Poland, over the past ten years, 30 solar greenhouses have been built with a mixture of sewage sludge(Bożym and Bok 2017). The role of solar air heaters is to heat the cold air. These systems use renewable energy and are very cost-effective for heating indoor air and for commercial and industrial applications (Ryan 2011). Table 2.6 is a list of SAHs. Solar dryers have different structures depending on the shape, size, and geometry. These dryers are usually covered by an insulating chamber with a transparent cover and no airflow in and out of the system. Polycarbonate is generally preferred in dryers made in our style. The equipment used inside and outside the system is important. In most systems, pumps and fans are used to transfer hot air and solar energy. These systems are more preferred for drying foods with high humidity. In this study, in accordance with similar systems, a pilot solar dryer was made with a scientific and effective design with high accuracy in selecting system components with high thermal conductivity and controllability. In research, there is a problem in heat transfer, and we did our work in this direction to solve the problem. Solar air heaters are also very diverse in terms of construction. Below are some of its structures.

Table 2.6. A collection of field studies on SAH

Author	Notes
(Telkes 1977)	The system is made vertically of a large number of parallel boards. The SAH system is used bilaterally. Air circulates between the slots and is transferred to the structure through ducts.
(Vincent 1980)	The dome-shaped system has a transparent outer cover. Air circulated from one inlet pipe and another outlet pipe in the SAH.
(DeVore and Snow 1999)	The solar dryer is designed for drying wood products. Due to forced air circulation, a chamber with a curved surface is created.
(Stoll 1999)	A container was made of perforated trays for storing food. In that system, PV cells were mounted on the ceiling. In this study, a thermal dehydrator was used to treat food
(Doherty 2008)	This system consists of separate and consecutive partitions where the air is heated in each section. Partitions are made of conductive materials to fully absorb solar radiation energy. 'It solves the problem of mixing fresh air with hot air inside SAH.
(Ryan 2011)	The system consists of a plenum and a solar absorber. The purpose of inventing this system is to create a level of support with the air circulation process, to use an air mechanism including a plenum, a solar absorber, and a reflector.
(Guilin et al. 2009)	In this system, in addition, an electric heater is used to heat the interior space, which is installed above the curved duct. In the absence of solar energy by burning coal, gas, oil is used.
(Strong 2013)	This system is designed with a range of hollow flat closed vessel covered with a blackened metal plate. Reduce electricity, gas, oil, or biomass fuel consumption
(Hao 2013)	This system includes a glass plate, a frame, a wave heating plate, a base, a shaft, and two culverts.
(Dolphin and Finney 2013)	This system consists of a black metal solar collector, a clear glaze, and a sturdy bracket. Solar energy is easily collected in the collector plate. The air is heated through an inlet and hot air is transferred to space using convective heat transfer from the duct.
(Srivastava et al. 2014)	The use of lauric acid as a phase change material (PCM) for storing solar energy has been suggested.
(Coulter, 2014)	For cooling and ventilation for buildings, power plants, and desalination processes, and is designed as an improved heat exchanger for cooling and heating the space through solar energy.

Table 2.6. A collection of field studies on SAH (continiue)

Author	Notes
(Chang et al. 2014)	This system includes an all-glass vacuum tube as a solar collector for fluid circulation, a storage tank, steam outlet control valves, a steam box, and a small water tank. The main purpose of this invention is to supply hot air, steam, and hot water.
(Mohammadi et al.2013)	The thermal efficiency of solar heaters has been investigated using fins and baffles on a single-pass absorber plate.
(A18:A22 al. 2014)	The solar air heater has new glass discharge tubes with a simple composite parabolic concentrate (CPC). Each panel contains a simple CPC and a glass drain pipe with a U-shaped copper tube heat exchanger. The air heats up as it passes through each U-shaped copper tube.
Singh et al. 2015)	The thermal performance of solar heat storage systems and the heat recovery efficiency have been investigated.
(Hedayatizadeh et al. 2016)	In this system interpretive analysis of a solar air heater with a V-corrugated edge / glazed plate and examined for exergy analysis have been investigated.
(Ravi et al. 2016)	The efficiency of the solar heater increases and heat transfer by reducing losses from the collector surface, using insulation have been analyzed and the convection coefficient between the heat and fluid collection surface increased.
Kabeel et al. 2016)	The inspection of flat and corrugated solar panels with a built-in PCM plate to store thermal energy has been investigated.
(Aminu and Yola 2018)	By modifying the geometry of the solar heater system, the problem of low heat capacity and low heat transfer from the absorber to the air can be improved.
(Abdulmunem et al. 2019)	Paraffin wax is suitable for storing latent thermal energy due to phase change material with latent fusion heat and has been used on solar heaters with forced convection. The solar heater with paraffin has a heat storage efficiency of over 50%.
(Rajesh et al. 2019)	Solar heaters are designed to heat the air for drying wet products, fish and grains, including a black body with less heat dissipation. This type of heater is compact and easy to maintain and assemble.
(Mahmood 2020)	In this solar air heater, the thermal efficiency of an unglazed, double-pass perforated absorber with packing wire mesh has been investigated.

- Matrix-type solar air heater

In the matrix type SAH, solar radiation flows on a porous matrix and is absorbed directly. Cold air enters the upper part of the matrix and flows in opposite directions, and heat loss is reduced(Wijeysundera et al. 1982; Lansing et al. 1979). In Table 2.8. some solar air heater structures are shown.

- Honeycomb porous-bed solar air heater

This model is in the shape of a honeycomb and is located between the transparent cover and the matrix absorber plate. Therefore, the convective heat loss at the top of the system is reduced (Lalude and Buchberg 1971).

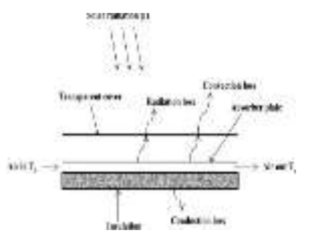
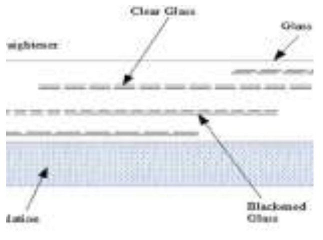
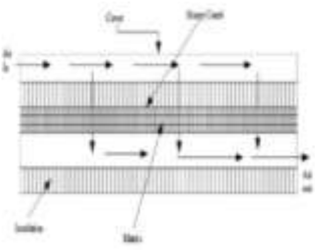
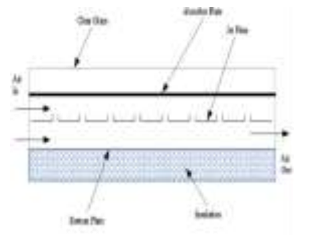
- Overlapped glass plate air heater

This system has parallel overlapping glass plates. The bottom plates are usually black, and air flows between them (Selçuk 1971).

- Jet-plate solar air heater

This type of heater has a transparent coating that is placed between the bottom plate and the absorber plate in the form of a jet plate. This plate has equal holes and the convection heat transfer coefficient is high (Choudhury and Garg 1991).

Table 2.7. Kind of solar air heater structures

Matrix-type (Rajarajeswari et al. 2016)		Overlapped glass plate (Selçuk, 1971)	
Honey comb porous-bed (Lalude et al. 1971)		Jet-plate (Choudhury et al. 1991)	

2.5.4. Advantage and disadvantage of solar air Heater

Solar dryers are one of the newest and most widely used solar systems with high diversity, especially in tropical and subtropical regions. The decision to buy or build a dryer can only be made after careful consideration of the advantages and advantages of different types.

- Advantages of solar air heater:

1. In a solar air heater, air leakage does not cause a problem.
2. Liquid freezing does not occur.
3. Not much pressure is observed inside the solar heater
4. Making an air heater is cheaper and much simpler

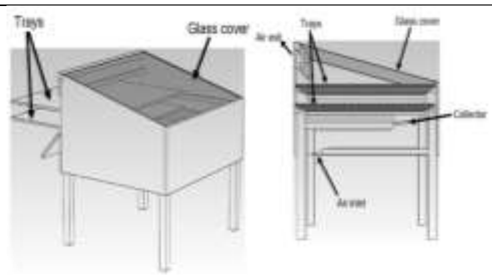
- Disadvantages of solar air heater:

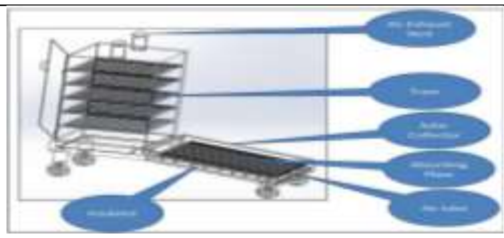
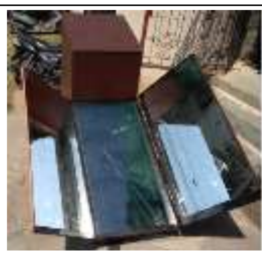
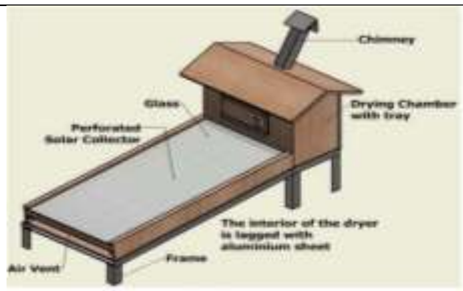
1. Air heaters have poor air heat transfer.
2. Due to low density, a large volume of air is required in the system.
3. Air is not used as a storage material due to its low heat capacity

2.6. Comparison of different solar dryer configurations

Table 2.8 compares the different designs of solar dryer systems for different types of products and has been summarized the performance of each system.

Table 2.8 Overview of different models of the solar dryer

References	Moisture changes	Figure
(Moya and Solana. 2012) pineapple	The components of this system include two walls, wooden floor, collector and a fan. Also, the chamber is painted black. To improve the efficiency hot air injected into the system and a dehumidifier was used.	
(Andreão et al .2017) Mangoes and Tomatoes crops	In this system, a solar collector is used, which is covered by a black aluminum sheet. Air enters the dryer through a grid at the bottom of the system. Tomatoes, with a 15% of moisture content are related to 0.80-0.95 water activity, and mangoes with a 10-15% moisture content are related to 0.45-0.60 water activity.	

(Musembi, 2016) Apples slice	The most important parts of this system are: flexible solar collector, dryer chamber, chimney with a metal absorber plate. In the present study, apple slices with an average radiation of 534.45 watts per square meter reach a humidity of 86% to 12.12% within 9 hours and 20 minutes and a drying efficiency was 17.89%.	
(Eustache, 2017) Kigali and mangoes	The system consists of a solar dryer with a cabinet-shaped drying chamber, a cover and an absorber plate. The absorber plate is painted black. The moisture content of the products is reduced from 60% to 10%.	
(Gupta et al. 2017) Agricultural food crops	The system consists of a glass cover, an aluminum foil painted with black bitumen, a dryer chamber and mirror plates to reflect light. This system protects food well and also reduces contamination.	 
Kilanko et al.) 2019) pepper	The system consists of a rectangular wooden enclosure with a flat glass top. The inside of the chamber is covered with aluminum foil and the collector is made of galvanized sheet. The average system efficiency was 28.4%.	

3. MATERIALS and METHODS

3.1. Type of sludges evaluated

In this study, three different types of sludge with different properties, moisture and production source were studied. Each sludge was obtained by different processes, as treatment sludge from treatment plants, paint sludge from the automotive industry and marble sludge from stone cutting workshops were examined. At the end of this study, a designed solar system, for waste management can be proposed to various industries.

3.1.1. BUSKI west wastewater treatment plant sludge

The refinery is built according to the Bardenpho process. It treats approximately 87,500 m^3 /day of wastewater, and in 2030, it will reach 175 000 m^3/day. In the Sludge Treatment Plant, sludge balancing tank, screens, belt press dewatering equipment, belt type thickener, and sludge stabilization equipment were used for dewatering. The sludge is thickened in the balancing tank and transferred to the belt-press for dehydration. The polymer is added according to the amount of sludge before the thickener. The sludge formed contains 20% solid matter, and the sludge cake is taken to the stabilization unit and stored(buski.gov). Sludge is a by-product and produced during water treatment processes and a significant part is used as fertilizer and soil aeration. Sewage sludge contains nutrients and organic matter that improve the physical properties of soil and crops. Annual sludge dewatering costs are very high. According to Turkish regulations on sewage sludge, it is determined by Directive 86/278 / EEC (1986), which allows the use of treated waste sludge in agricultural lands. It also controls the number of heavy metals and organic matter available. The sludge must drain a large amount of moisture before disposal. Reducing the volume of sludge through landfilling and incineration has led to global environmental concerns (Singh and Agrawal, 2008). The main limitation on sludge disposal is the transmission of the pathogen, which is discussed in most countries. The sludge from the treatment plant contains 20% of dry matter, which is obtained after mechanical dewatering and it is shown in Figure 3. 1 The specifications of the WWTP. sludge is shown in Table 3.1.

Table 3.1. BUSKI west wastewater treatment plant sludge characteristics

Sludge characteristics	Unit	Average Value
Total Dry Matter*	%	23
CaO	%	0
pH		8
Conductivity	(µs/cm)	268
Fluoride (F)	(mg/kg)	641
Sulfate (SO_4)	(mg/kg)	15209
Chloride (Cl)	(mg/kg)	0
Nitrate Nitrogen (NO_3-N)	(mg/kg)	74
Nitrite Nitrogen (NO_2-N)	(mg/kg)	122
Ammonium Nitrogen (NH_4-N)	(mg/kg DS)	1848
Total Khejdahl Nitrogen (TKN)	(mg/kg DS)	8386
Total Nitrogen (TN)	(mg/kg DS)	8494
Silver (Ag)	(mg/kg)	2
Aluminum (Al)	(mg/kg)	9005
Arsenic (As)	(mg/kg)	11
Boron(B)	(mg/kg)	55
Cadmium (Cd)	(mg/kg)	1
Chromium (Cr)	(mg/kg)	185
Copper (Cu)	(mg/kg)	143
Iron (Fe)	(mg/kg)	8857
Manganez (Mn)	(mg/kg)	315
Nickel (Ni)	(mg/kg)	85
Lead (Pb)	(mg/kg)	32
Antimony (Sb)	(mg/kg)	16
Tin (Sn)	(mg/kg)	11
Zinc (Zn)	(mg/kg)	1212
Selenium (Se)	(mg/kg KM)	2
Mercury (Hg)	(mg/kg)	587
Total Phosphorus (TP)	(mg/kg)	17409

Figure 3. 1. waste sludge production from wastewater treatment plant

3.1.2. Paint Sludge

The waste discussed in this study is paint sludge as hazardous waste and produced by automotive factories, which is known by code number 080113 of the European Union, and this waste is not allowed to be buried.

The characteristics of paint sludge are shown in Table 3.2. Burning or combustion methods are used in cement kilns to remove sludge because paint sludge contains a large amount of soluble organic carbon. Paint sludge consists of organic polymers and solvents, which are composed of four main parts: 1) pigments 2) Binder 3) Extender, 4) solvents. In spray booths, water-based and solvent-based paint spraying is performed. The sticky state of the sludge is due to the presence of uncured resins, which makes transportation difficult. Figure 3.2 shows the Turkish Automobile Company paint sludge sample with 56% humidity.

Table 3.2. Paint sludge characteristics from the automotive industry

Sludge characteristics	Water based paint sludge
Total Solids (TS), %	44%
Lead (Pb)	<0.05(mg/L)
Zinc (Zn)	<0.1(mg/L)
Arsenic (As)	<0.05(mg/L)
Mercury (Hg)	<0.001(mg/L)
Selenium (SA) (mg/kg DS.)	<0.01(mg/L)
Nickel (Ni)	<0.05(mg/L)
Sulphate (SO4)	2.52±0.38 (mg/L)
Dissolved organic	1430±28 (mg/L)

Figure 3.2. Paint sludge from automative industry

3.1.3. Marble Sludge

Marble sludge is obtained during the process of cutting and polishing the marble blocks and plates, of which 50% are removed during the production process. Marble sludge is not as hazardous waste and comes from marble factories. The marble sludge morphology is shown in Figure 3.3. Marble dust and sludge have become an economic problem, and even their storage and transportation cause great damage to the environment (Akbulut and Gurer 2003). The marble sludge is stored in both solid and powder form in the organized industrial zone and can be used as cement material, and can also be dried and recycled. In a study, it was observed that 90% of the grain size of marble wastes is below 200 µm, 70% below 100 µm and 40% is below 20 µm (Çelik and Tur 2012). It was determined that 90% of the particles below 200 µm were a mixture of calcium and magnesium (Bilgin and Koç 2016). In Table 3.3 marble sludge charachteristics are shown.

Table 3.3. Marble sludge characteristics

Sludge characteristics	Marble Sludge
Total Solids (TS), %	74%
Magnesium oxide (MgO)	4,47%
Calcium oxide (CaO)	49,07%
Silicon dioxide (SiO_2)	1,69%
Iron (III) oxide (Fe_2O_3)	0.21-1.3%
Aluminum oxide (Al_2O_3)	1.04-1.3%
Carbon dioxide (CO_2)	38.60%

Figure 3.3. marble sludge from marble blocks cutting

3.2. Expeimental study

An experimental design in this research has investigated the place of the study and what kind of devices to be used in this process. For this study, certain solar values and the institution location of the dryer system at the university were selected, and what kind of analyzers used during the study were determined. The study was carried out in Bursa, where Turkey's solar energy values is not high. Bursa city where the research was conducted and located in northwestern of Turkey as the fourth most populous city. This industrial city is mostly dedicated to automotive manufacturing and also this area was chosen because the university is located there and to research system efficiency in an industrialized city with low solar values. It has been tried to built an efficient system in a place with low solar radiation in Turkey. According to the Turkish State Meteorological Service, in Figure 3.4 shows the distribution of solar radiation in Turkey and Bursa.

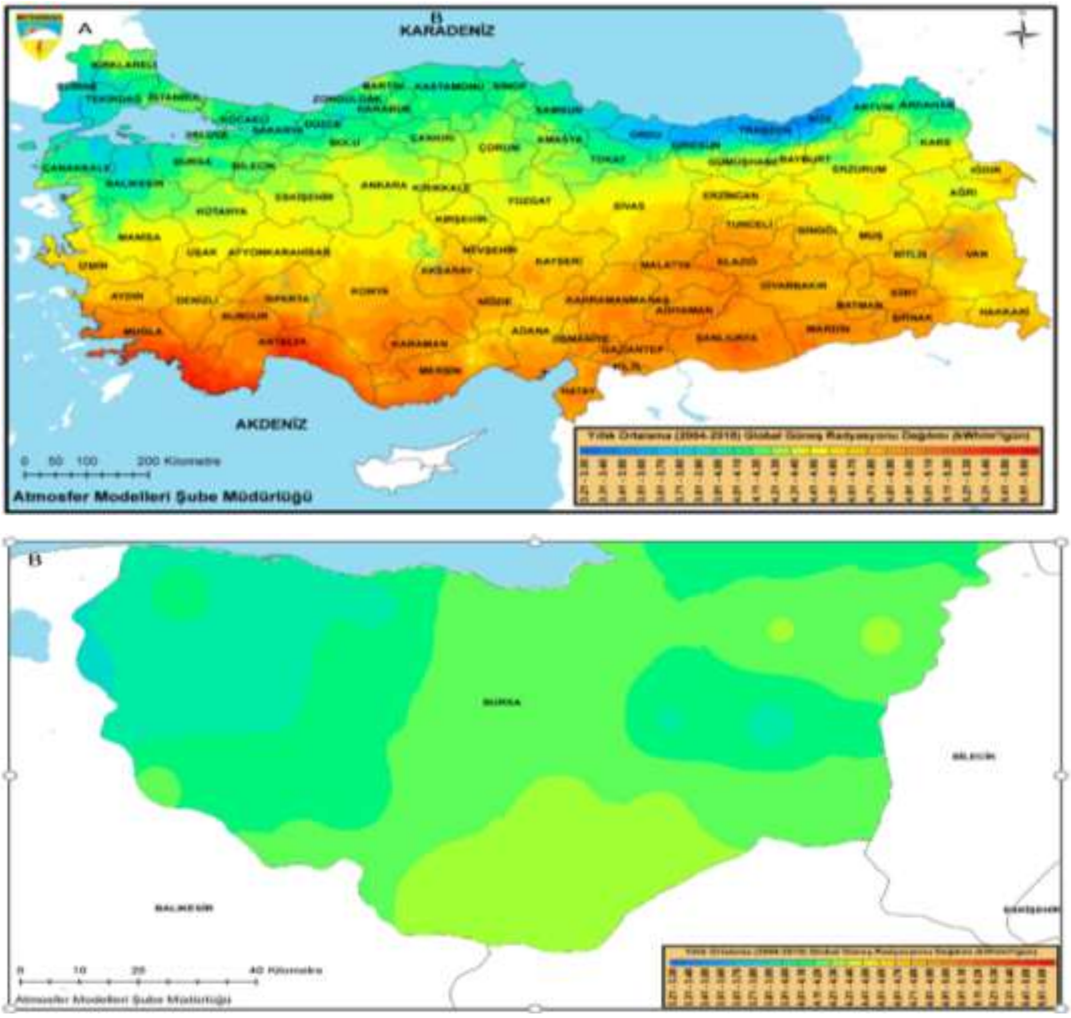


Figure 3.4. Distribution of Solar Radiation in Bursa and Turkey. **A)** Turkey **B)** Bursa

Bursa climate is warm and this city is located 257 meters above sea level. The annual average temperature of Bursa is 15,1 ° C and the average annual relative humidity is 67.4%, also the average solar radiation during the year is 642,7 kWh/m^2 (APPX 1; APPX 2; APPX 3; APPX 4). The highest wind speed is also known in March, and average sunshine hours are shown in Figure 3.5.

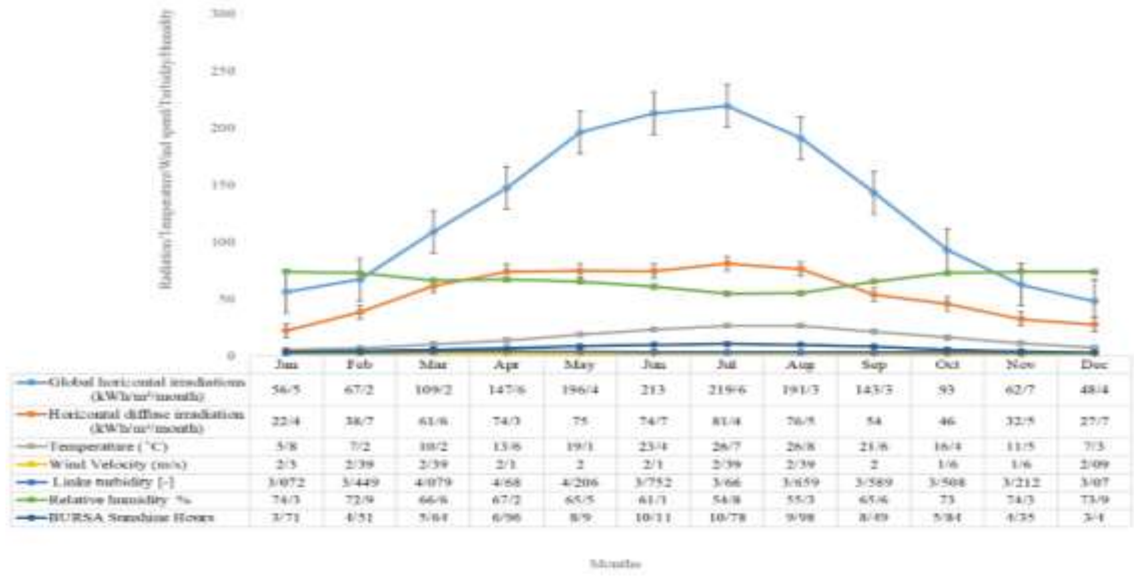


Figure 3.5. Bursa/Uludag university geography location parameters

The minimum sunshine hours in Bursa are 3,4 hours in December and the maximum sunshine hours are 10,78 hours in July. There is a very serious difference between the two values. The highest sunshine hours are in June, July and August, and these months cause more efficiency for dryer. Our system works according to the sunshine hours and the maximum hot air produce from solar dryer during sunshine hours. If we can increase the amount of sludge on a daily basis or to dry sludge in a short time, maybe we can take advantage of additional renewable resources and either use different materials or PV batteries for heat storage, especially in winter, and keep the temperature constant (Sudhakar 2020).

3.3. Design of the solar dryer

The designed solar dryer is based on the triangular shape and because it is more preferred especially for food industries in the world. In the literature review, triangular shaped dryers were considered due to the importance of heat transfer via natural convection (Kamiyo et al. 2014).The first model of the dryer was made according to Figure 3.6 It is a triangular system with a height of 110 cm and a width of 100 cm. The floor length of the system was 190 cm and the length of the triangle chord was 220 cm. The system consists of an aluminum box frame. The back and the bottom of the system are insulated with a 4-cm thickness polyurethane coating. The front and sides of the system are covered with 10cm (Sumer ambalaj brand) polycarbonate. Beneath the polycarbonate are five glass tubes with 180 cm height that are connected to the radiator from above the system. The inside of each tube is filled with 1 kg of melted paraffin. Inside the system, above the intermediate partition, a fan with a speed of 100m^3/h is connected. Inside each glass tubes are placed copper tubes. And at the bottom side of the system, there was a Vaillant VCK pump.

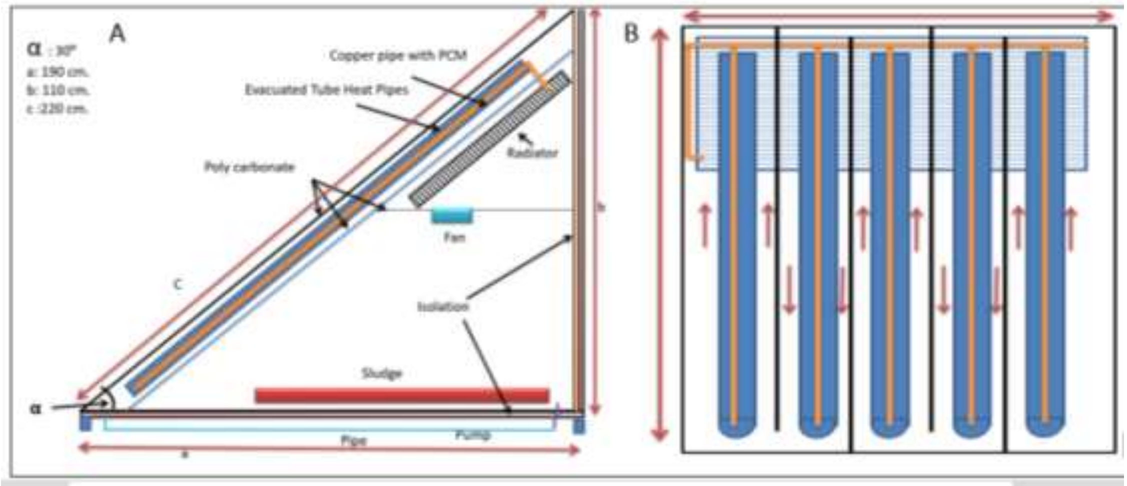


Figure 3.6. An overview of solar dryer structure A) Side view of the solar dryer B) Evacuated glass tubes.

All research in the dryer system was performed in parallel with a similar systems, which was modified according to the passage of time and progress during the research.

3.4. Material selection and methods for drying

Table 3.4 shows all the measuring equipment used in the research. The devices used for TKN testing, TGA for sludge gravimetry, and SEM device for observing sludge after drying are clearly shown. Also, the types of heat and humidity sensors along with the solar analyzer are given in the Table 3.4.

Table 3.4. Analyzing materials used in the study

Device	Description	Picture
Kjeldahl Analyzer	The Kjeldahl system is used to determine nitrogen. The amount of nitrogen is determined during the distillation and titration process.	
SEM	It is a TESCAN VEGA3 device with high and low vacuum tungsten heat dissipation. Electron microscopy has been used to image and evaluate the quality of samples and microstructural properties.	
TGA	TG / DTA is a measuring instrument that combines a vertical TG beam and a horizontal differential equilibrium DTA beam. This method is to detect the reaction reaction of velocity and acceleration degradation in samples.	
Drying Oven	The oven was used to determine the moisture content of the sludge computationally.	
Moisture Analyzer	Sartorius MA150 is an ideal way to determine moisture content in a short time.	
HOBO data logger (RX2100, onset)	This device has 4 outputs, and 4 sensor cables could receive data from different points. The device has the ability to store information for a long time and the datas can be easily transferred to a computer. With this device, heat and humidity datas are collected from different points of system.	
Digital Lazer Infrared manual sensor (WH320)	This non-contact thermometer works with infrared rays and detects the temperature of each point with a laser indicator.	
FLIR E5 Infrared thermal camera	The FLIR E5 is a sensitive and powerful device for thermal imaging. This 10800 (120 x 90) pixel camera with infrared resolution without direct contact easily produces accurate thermal images. Field of view (FOV) 45° 34°, Image frequency 9 Hz, On-board 640 x 480 Digital Camera, High Accuracy Temperature Measurements ±2%, File format: Radiometric jpg, Battery operating time approx 4 hours, Simultaneous storage of IR/Visual/MSX Images, Variable emissivity and reflected temperature parameters for detection accuracy, Ergonomic, lightweight pistol-shaped design.	
CEM (DT 185) solar data logger	This device has an alarm and a low consumption LED indicator. The system also has 32,000 memories that measure the intensity of sunlight. Device properties are: Measuring range -30 to +70 °C, Accuracy ±0.4 °C, Resolution 0.1 °C.	
Comet (S3120)	This device is used to record the temperature and humidity of the environment and the information is stored in electronic memory.	
Balance	A scale was used to determine the rate of change in sludge moisture on an hourly basis.	

When the dryer system is installed, the materials used in the interior and exterior are explained on the Table 3.5 The type of polycarbonate cover and the insulation material used in the back and around it was mentioned. Glass tubes with paraffin content as collector and copper pipes are placed inside the tubes. In addition, a fan is used for air circulation, and a pump is used to move, the air and push it out. Finally, silica gel is used in the system to absorb moisture.

Table 3.5. Material used in pilot plant

Device	Description	Picture
Polyurethane	The main advantages of polyurethane are high insulation, air resistance, reduce odor transmission and prevent energy loss.	
Poly carbonate	Polycarbonate is a lightweight, durable, and scratch-resistant plastic material used in window making, medical equipment, and hard shields and lenses. Hollow polycarbonate is known as multiwall polycarbonate.	
Copper pipe	Copper has high resistance to heat and ultraviolet rays, and also has high thermal conductivity (401W/mK) in heat exchange. It does not deform at high temperatures and has a long life.	
Glass tube	One of the important advantages of a Glass tube is its very simple installation, and in case of breakage or cracking, it can be replaced separately from the system. evacuated tubes with an angle of sunlight perpendicular to the tubes have good performance. The pipes are made up of several rows of glass pipes. The glasses are made of borosilicate, which is resistant to high temperatures.	
Fan	The "mutlusan" brand fan power was 12 W, 220-240V / 50-60 Hz flow and 100 m³ / h speed, also the revolution Speed was 2250 rpm.	
Pump	Vaillant VCK 8825003ET25 (230V, 0.51A) Fan Motor is an electrical combi spare part that provides the transfer of the oxygen amount required for snail-shaped combustion from the outside atmosphere to the inside of the device.	
Sludge tray	The aluminum tray used in this study is designed for a maximum load of 5 kg sludge. The dimensions of the tray are 60 * 40 * 4 cm. The reason for choosing aluminum is the high thermal conductivity of 205(W/m K).	
Silica gel	Silica gel contains cobalt chloride, which changes color and turns pink with the absorption of moisture. Can be reused after warming up and changing colors.	

3.5. Analysis Methods

3.5. 1. TKN Analysis

According to (N-4500) standard method process, 0,2 gr. of sample is placed in the Kjeldahl tubes, then 10 ml of H_2SO_4 (98%) and 0,5 gr of nitrogen catalyst are added. The combustion procedure takes about 5 hours at 400ºC. It is continued to burn until the solution color becomes lighter. In the distillation process, 2% boric acid is used. These solution is titrated until the color turns from green to light pink. The calculation formula of Kjeldahl nitrogen is shown in Eq.3.1.

$$[\text{Consumption}(ml) \times 14 \times 0.1(H_2SO_4 \text{ normality}) \times 1000]/1(\text{Sample gr.}) \quad (3.1)$$

Waste sludge usually contains between 40-80% of nutrients such as nitrogen and phosphorus (Schowanek et al. 2004). According to studies waste sludge usually contains 3.3% nitrogen (Tchobanoglous et al. 2003).

3.5.2. E-coli Analysis

It is a multi-tube method that is inoculated by a series of tubes containing a suitable selective culture medium. The sample is added to the ringer solution and the dilution process is performed by preparing a A-1 medium solution. In this test, an autoclave is used to sterilize the culture medium. The incubator temperature is set at 37 degrees. After 48 hours of incubation of the tube samples, the result is checked according to the standard table. Using specific statistical tables, the probable number (MPN) of bacteria in the tubes is determined from Environmental Protection Agency (SMWW-APHA/EPA Standard Method 9221).

4. RESULTS and DESCUSSION

4.1. Improvement modification on solar dryer

In this study, frequent changes were made to the system structure by using different modifications to increase product quality. The optimum designed system efficiency has increased with the use of appropriate tools such as solar glass collectors as absorbers in the dryer structure, phase change materials to store heat, and silica gel to drain internal moisture. The shortcomings of each stage are also evaluated. Figure 4.1 is an overview of the first shape of system design. In the following figure, three different dimensions of the system are photographed. In the first stage, the two systems were placed parallel to each other. Each system was covered on three sides by a polycarbonate coating. The door of the system opens from the back and there is a small power box for embedding the cables, which controls the fans of the systems, also, the temperature, humidity and fan operation inside the system are displayed on the monitor of the power box monitor.

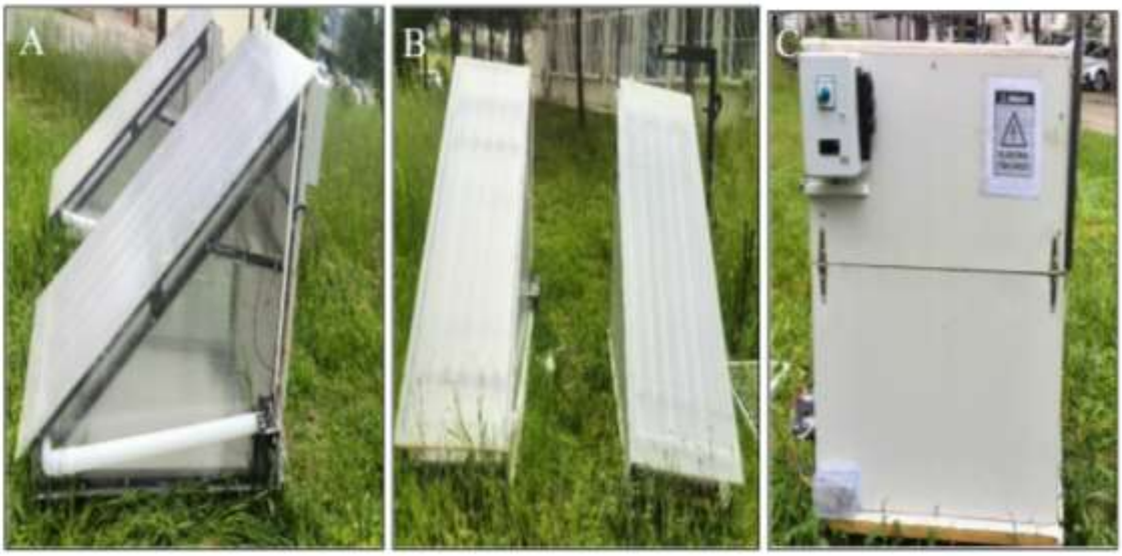


Figure 4.1. Overview of different dimensions of the solar dryer. **A)** Side view of dryer systems **B)** Front view of drying systems **C)** Back view of drying systems

If we want to arrange the dryers back to back in similar studies in the same size in Figure 4.2, we can find the distance between them using the Eq. 4.1, Eq. 4.2 and Eq. 4.3

equations. Dryers placed in this way are generally used for different purposes, especially in the food sector.

$$D = x.\sin\theta / \tan\alpha \qquad (4.1)$$

X = Length of collector

θ = Collector floor angle

h = Collector height

α = Angle of the sun with the ground

D = Distance between two dryers

$$\Psi = 180 - Azimuth\ angle \qquad (4.2)$$

$$D' = \frac{D}{cos\Psi} \qquad (4.3)$$

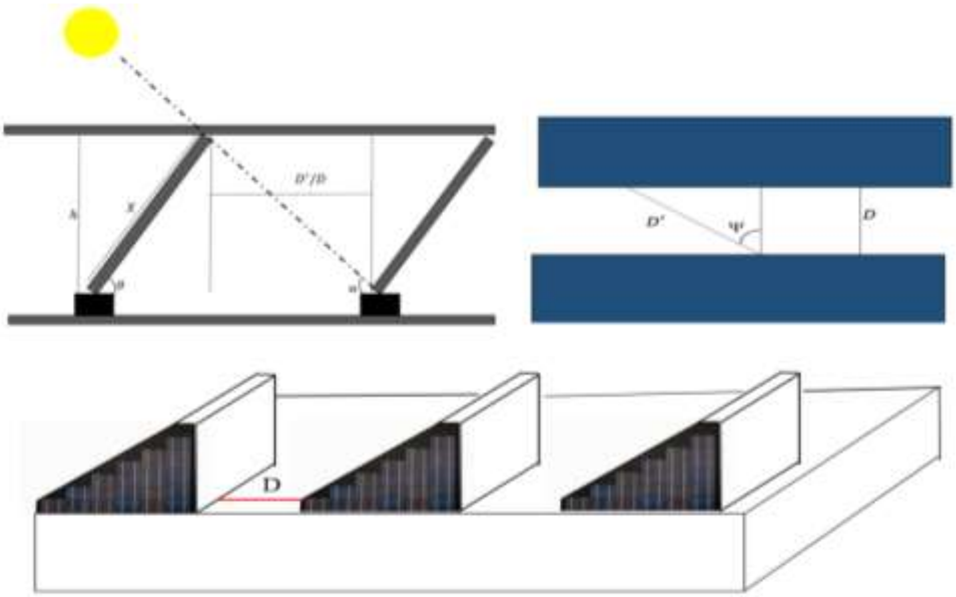


Figure 4.2. Distance between two solar dryers

X = 220 cm

θ = 30°

h = 110 cm

$\alpha = 28.12$

$\Psi = 177.55^{o}$ D = 320cm D'= 270cm

According to the above equation distance between two systems is estimated 320 cm. This model of dryers was previously installed industrially on the roof. In this arrangement, the amount of heat energy accumulation on the roof can be exploited by these systems (Simo Tagne et al. 2017).

In the first stage, the glass tubes are placed between the two-layer polycarbonate coating and all the glass tubes are connected to each other by a radiator. This two-layer coating prevented sufficient sunlight reached to the system. Solar radiation is split into three types when it hit the coating of double layers of polycarbonate. The first part of the waves is reflected by hitting the top layer and is known as incident solar radiation. The second radiation after entering the middle layer is reflected outwards. The last part passes through both layers as transmitted radiation and enters the system. Figure 4.3 shows how solar waves are split due to hits with the system cover.

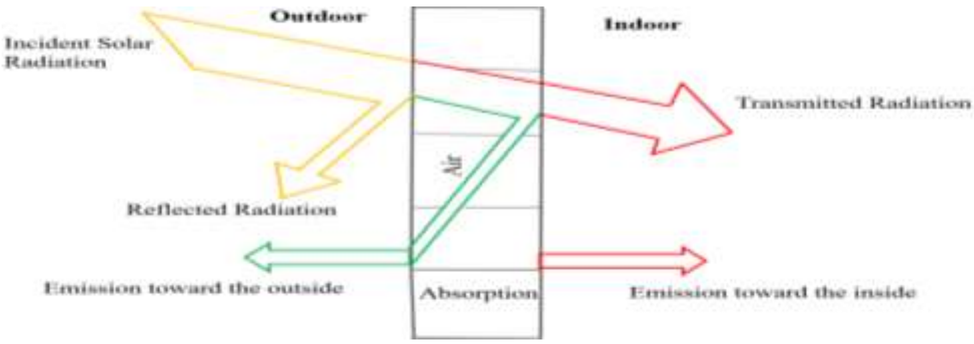


Figure 4.3. The results of solar radiation hits on the double layer polycarbonate coating

4.1.1. The effect of glass tube collector placement on improving dryer performance

At this stage of the study, the two systems were examined in parallel and simultaneously as basic and hybrid systems. In the hybrid system, glass tubes filled with paraffin-wax are used, and placed vertically between the two surfaces of polycarbonate coating with air passage walls. But in the basic system between the two-polycarbonate layer was empty and only the air walls were installed. In addition, in both systems, silica gel was placed inside the white pipe to drain the internal moisture produced during the drying of the sludge. Humid air is sucked from inside the system by a pump and passed through the silica gel and redirected back to the bottom of the system. The system is a closed-loop system and glass tubes have been used as solar collectors. These glass tubes are U- form and vacuumed. The problem with using vacuum tubes is that heat extraction is more difficult (Morrison et al. 2004). In this study, heat extraction has become easier by embedding copper pipes inside the tubes. The glass tubes are dark in color, which increase the absorption of solar waves. The process of heat transfer is improved by embedding a variety of phase change materials inside the tubes. Increasing the number of these tubes expands the absorption surface, improves system efficiency.

4.1. 2. The effect of phase change material on improving system performance

The results show that the addition of PCM inside the tubes leads to an increase in temperature increases and keeps the system at a constant temperature for a long time in the absence of sunlight (Reyes et al. 2014), also drying time reduces. The freezing process of paraffin in tubes occurs with heat loss during the hours when there is no sun. Using phase change materials, it is possible to use solar systems in different seasons of the year. The type of phase change material and its location in the system is important. During this research, necessary studies have been performed on the thermophysical properties of various phase change materials. Melting temperature, density, fusion heat, thermal conductivity, and thermal properties in hot and cold periods were investigated. According to Mofijur et al. (2019) studies based on fusion heat and melting temperature, the graphic of PCMs is compared in Figure 4.4. As shown in the following figure paraffin-wax, salt hydrate, fatty acids, and eutectic mixture have low melting temperatures, but chlorides, fluorides, and carbonates have high melting temperatures. The cost of fatty acids is 2.0 times higher than the cost of paraffin- wax (Yasin et al. 2014; Huang and Wu 2008). Paraffin is the most common non-corrosive phase change material with low thermal conductivity. It has a high molecular weight and is waxy at room temperature. Paraffin-wax can be used in a wide range of temperatures and has a high fusion heat. It is also quite cost-effective and easily accessible (Mofijur et al. 2019; Agrawal and Sarviya, 2016; Krishnan and Sivaraman, 2017).

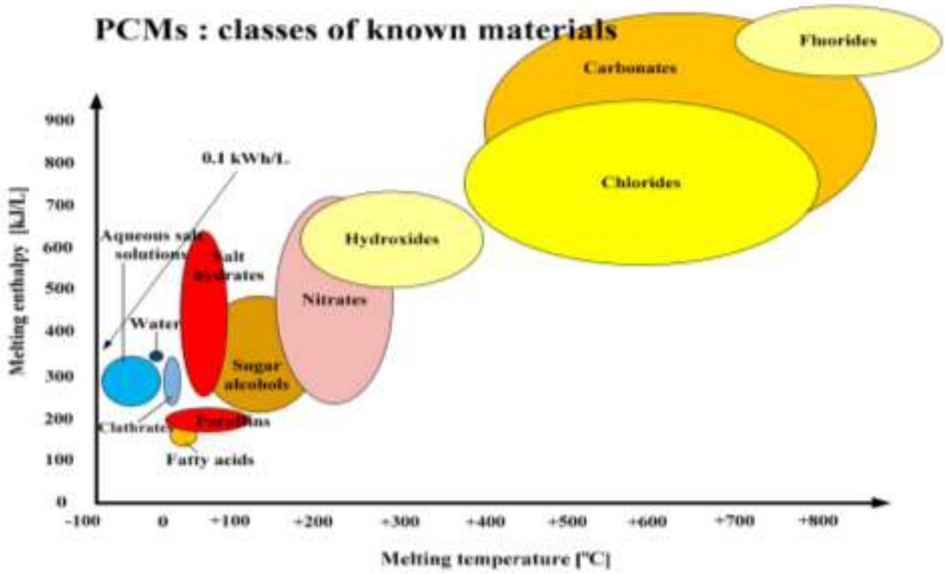


Figure 4.4. Classification of phase change materials according to their melting temperature

The paraffin-wax efficiency has been assessed in solar dryer by Devahastin and Pitaksuriyarat (2006) and Bal et al. (2010). In this study, during the comparison of three different materials for use in this research, three parallel copper pipes were filled with water, empty (air), and melted paraffin, also by installing thermal sensors during a day, temperature changes were examined.

As seen in the Figure 4.5 the temperature of a tube containing paraffin was approximately two degrees higher than the temperature of the water, also the water was preferable to air in terms of heat storage. In this study, paraffin phase change material was preferred for the rest of the study, with the choice of paraffin in all stages except the second stage the air was used.

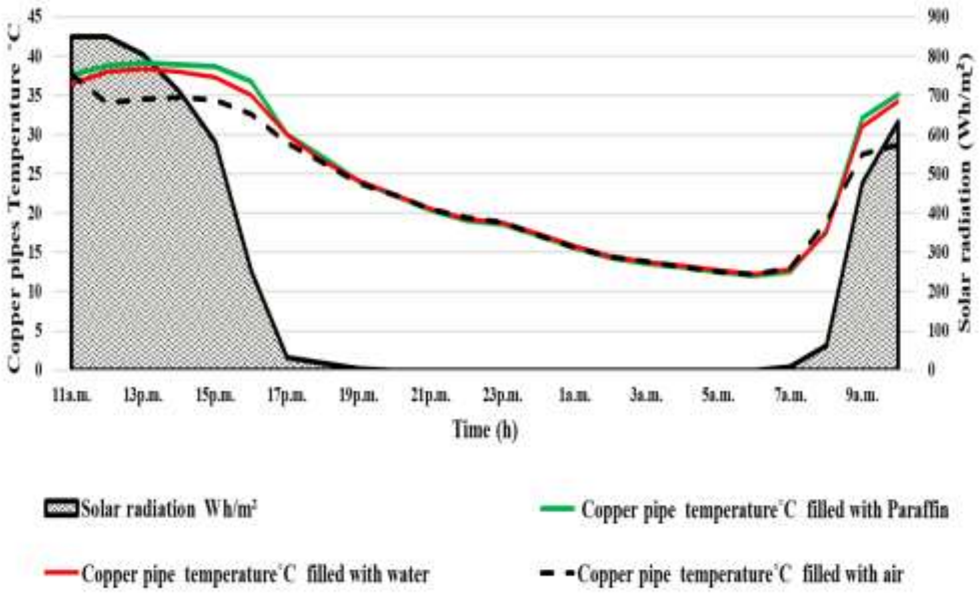


Figure 4.5. Comparison of temperature changes of three different types of materials

The area of copper pipes is 0,471 m^2. In fact, the average amount of energy that reaches on this surface is equal to 104 Wh per 0,471 m^2, also the average temperature difference in a tube containing paraffin is 4% more than water, but this amount is negligible during sunny hours.

4.1. 3. The effect of Silica gel on improving system performance

In this study, silica gel in the form of granules has been selected as a suitable adsorbent due to the high latent heat for moisture absorption. At the bottom of the system, a plastic pipe is connected to the pump on one side and the other side returns to the system. One kilogram of silica gel is embedded inside this pipe. The humid air of the system is transferred to the pipe by the pump and passes through the silica gel. The moisture is removed, and the dry air must be returned to the system. The silica gel was repeatedly drained and dried after absorbing moisture by changing the color from blue to pink, but the amount of silica gel was not enough to moisture removing. According to Chen (2017) silica gel can absorb moisture above 30% of its weight. In this study, one kilogram of silica jel was used for the removal of air humidity in each system, but the maximum moisture absorption was 6 %, per week. Factors affecting the dryer intensity.

4.1.4. The First structure of the dryer

In this section, system performance was repeatedly evaluated in parallel for 1 kg of waste sludge in one day and 5 kg of sludge in one week in both basic and hybrid systems. Figure 4.6 shows the tools used and the operation of both basic and hybrid systems.

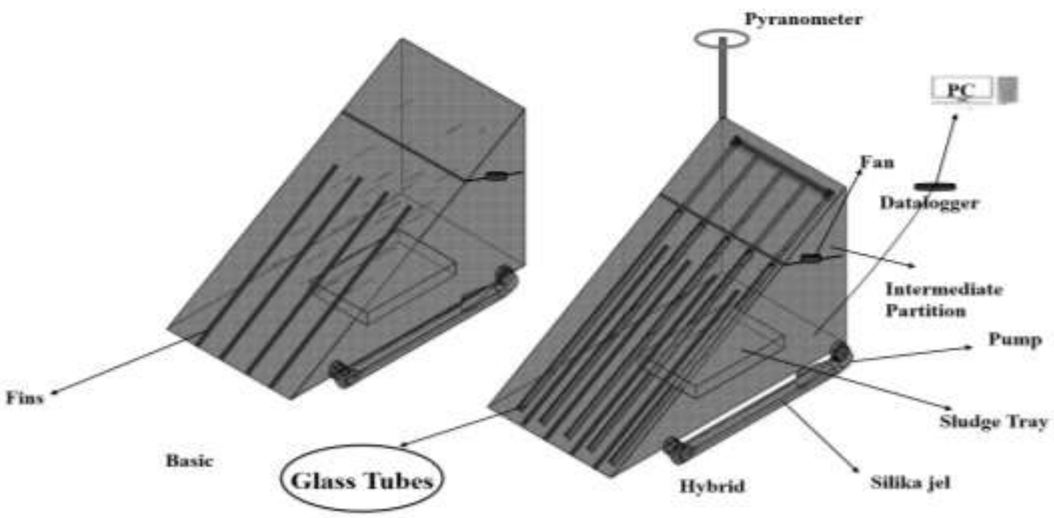


Figure 4.6. Basic and hybrid parallel systems in the first structure

In Figure 4.6 The operation of these two systems was simultaneous and under the same weather conditions. The only difference between the two systems was in the hybrid device of glass tubes containing phase change materials, but in the basic device, these glass tubes were not available. The performance of both dryers was evaluated by examining the drying rate of the sludge.

In Figure 4.7 the system was checked in two stages, one day and one week, several times. During the average results obtained at this stage the hybrid system with a supply of 1435 Wh/m^2 internal cumulative solar radiation, the sludge weight with 80% humidity changes from 1000 gr. to 277 gr. in one day. In this process, the average internal temperature and humidity of the system were 20˚C and 68%. The maximum outside temperature on these days was 16˚ C. Also, the average temperature of sludge was 17˚ C and the average temperature of the inner partition was 19˚C.

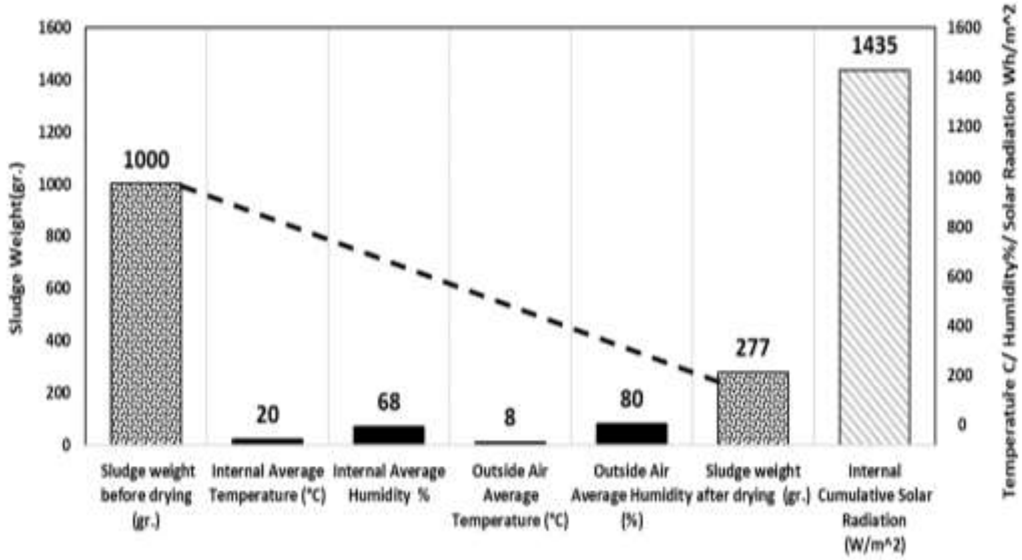


Figure 4.7. 1kg WWTP.sludge drying in 1 day in Hybrid system

In the basic system in Figure 4.8 with the supply of 1435 Wh/m^2 internal cumulative solar radiation, the average internal temperature and humidity were changed to 20˚C and 55% and the weight of sludge is reduced from 1000 gr. to 273 gr.

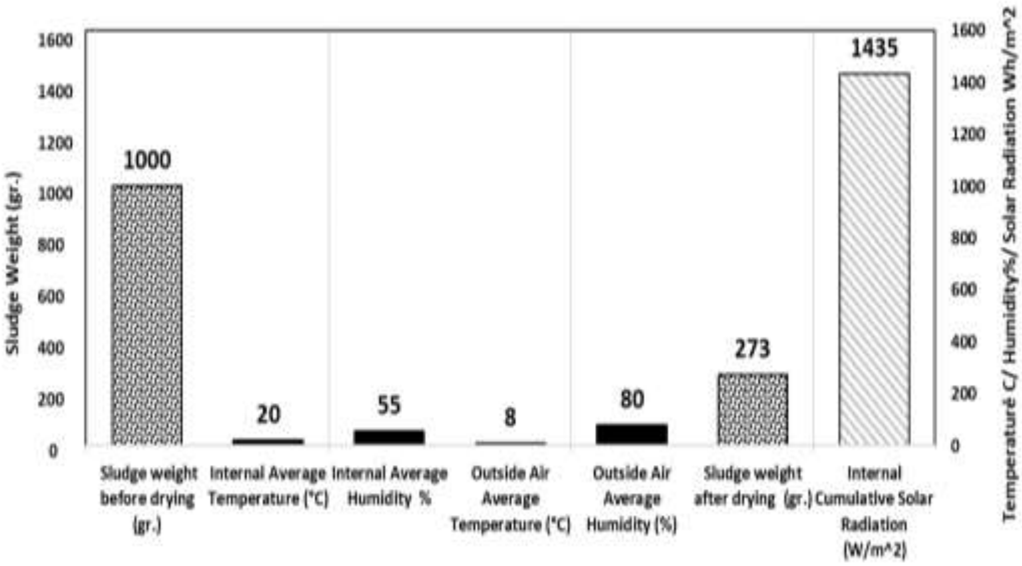


Figure 4.8. 1kg WWTP.sludge. drying in 1 day in Basic system

Unfortunately, the internal temperature of both systems was the same, only the internal humidity in the hibrid system was slightly higher, which resulted in very little change in the weight of the sludge. In the next step, the drying efficiency of the sludge was tested by loading 5 kg of sludge to investigate the penetration of heat into the thicker sludge. During this process, as shown in Figure 4.9 in the hybrid system, by supplying 11878 Wh/m^2 internal cumulative solar radiation, the weight of the sludge was reduced from 5000 gr to 1055 gr during one week. The average internal temperature and internal humidity of the system were 26˚26 ° C and 49%. The maximum outside temperature was 17% Celsius.

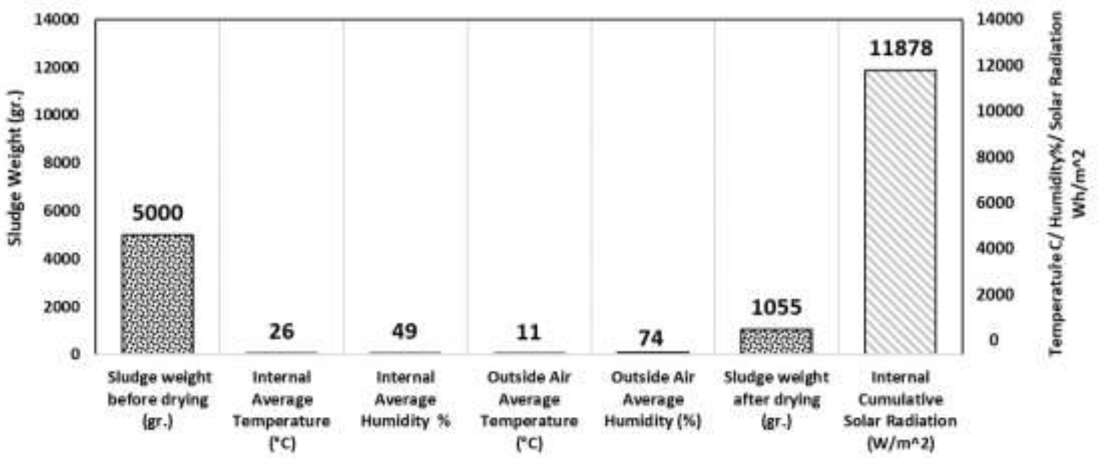


Figure 4.9. 5kg WWTP. sludge drying in 1 week in hybrid system

In Figure 4.10 in the basic system, by supplying 11878 Wh/m^2 internal cumulative solar radiation, the weight of the sludge was reduced from 5000 gr. to 1 059 gr. during one week. The average internal temperature and internal humidity of the system were 24˚C and 55 %. As the amount of sludge increased, no special change in the efficiency of the hybrid variable system was observed. With an increase of two degrees in the internal temperature of the hybrid system, the internal humidity decreased slightly.

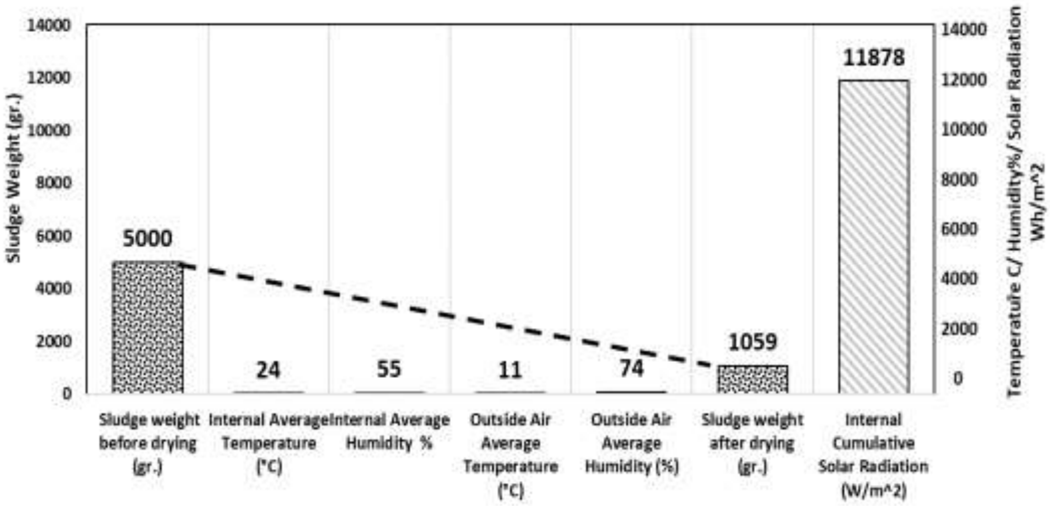


Figure 4.10. 5kg WWTP.Sludge drying in 1 week in basic system

In this system the tubes completely covered the front of the system, and the sludge does not get enough sunlight. So, in the next step, the location of the tubes was changed.
The results of the first structure of the dryer system were evaluated by the Eq.4.4 (Zohuri 2015).

$$Q = \frac{KA(T_{hot}-T_{cold})}{d} \qquad \text{Conduction heat transfer} \qquad (4.4)$$

Q = Conduction heat transfer (W)
K = Thermal conductivity of materials (W/mK)
A = Area (m²)
T_{hot} = Internal temperature (°C)
T_{cold} = External temperature (°C)
d = Thickness of materials (m)

The heat gained by the initial solar dryer per unit time in both basic and hybrid systems are calculated.
As mentioned in the previous sections, the important factors in the drying of sludge is the amount of solar radiation, temperature and humidity of the drying system.
In this research, linear relationships have been formed between the variables in pairs. In the first stage, with the increase of solar radiation intensity, the temperature inside the

system has also increased. According to the results, at the time of loading one kilogram of sludge in both systems at the internal and external temperature of the system, unfortunately, no change was observed. And the conduction heat transfer from poly carbonate in both systems was 253,44 watts. Also, according to the results of loading 5 kg of sludge after one week, the heat transfer content in the hybrid system was 316,8 watts and in the basic system was 274,56 watts. Due to the lack of sufficient heat transfer, improvements were made in the structure of the dryer.

4.1.5. The second structure of the dryer

In the second stage, the radiator and glass tubes were removed from the front of the system, but the two-layer cover remained. At this stage, by removing the silica gel and plastic pipe, the system is released from the closed-loop to an open, and fresh air circulates inside the system. Also Figure 4.11 shows the glass tubes are removed from the upper part of the hybrid system and replaced in the bottom of the device with a low slope on the ground. At this stage, instead of paraffin inside, only air flows in the tubes.

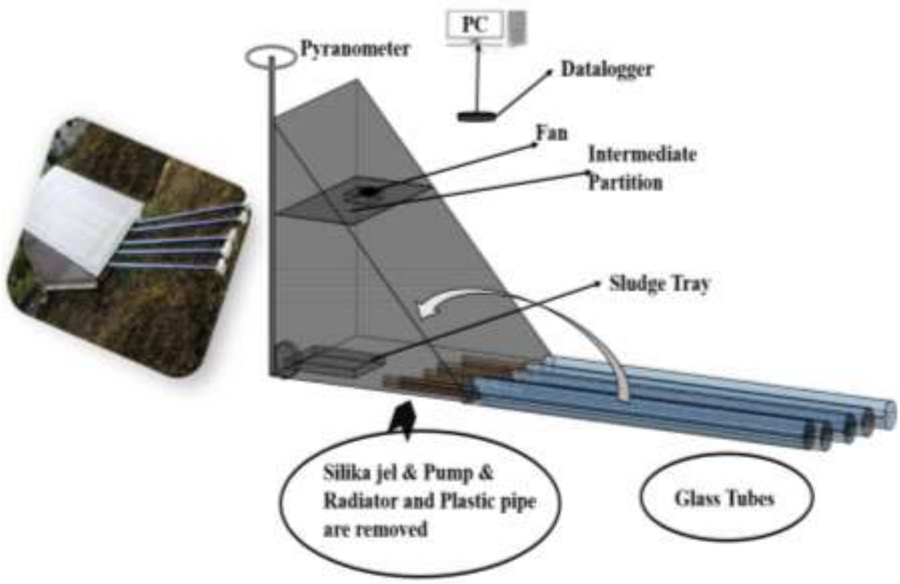


Figure 4.11. Second structure of hybrid solar dryer

In the hybrid system in Figure 4.12 by supplying 3602Wh/m^2 internal cumulative solar radiation for one kilogram of waste sludge, after two days, its weight has been reduced from 1000 gr. to 285 gr.

The average internal temperature and internal humidity of hybrid system were 32˚C and 55%. The outside maximum temperature of the system was 31℃.

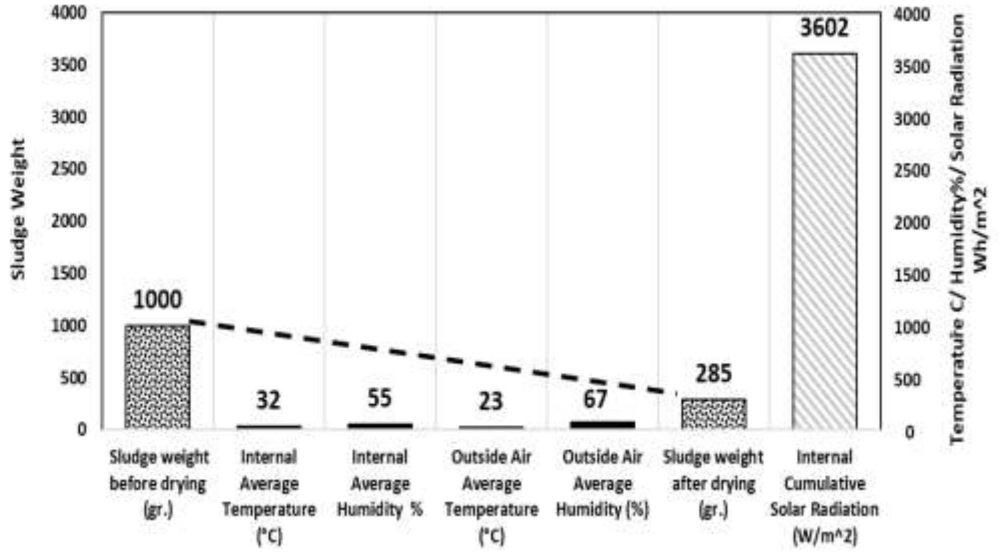


Figure 4.12. 1kg WWTP sludge drying during 2 days in hybrid system

In the case of the basic system in Figure 4.13, by supplying 3 602 Wh/m^2 internal cumulative solar radiation the weight of waste sludge was reduced from 1000 gr. to 290 gr. The average internal temperature and internal humidity of the system were 31˚C and 56%.

At this stage, changes in the system leads to the direct reception of solar energy. Also, the paraffin was removed. Unfortunately, there was no significant change in improving the performance of the hybrid system.

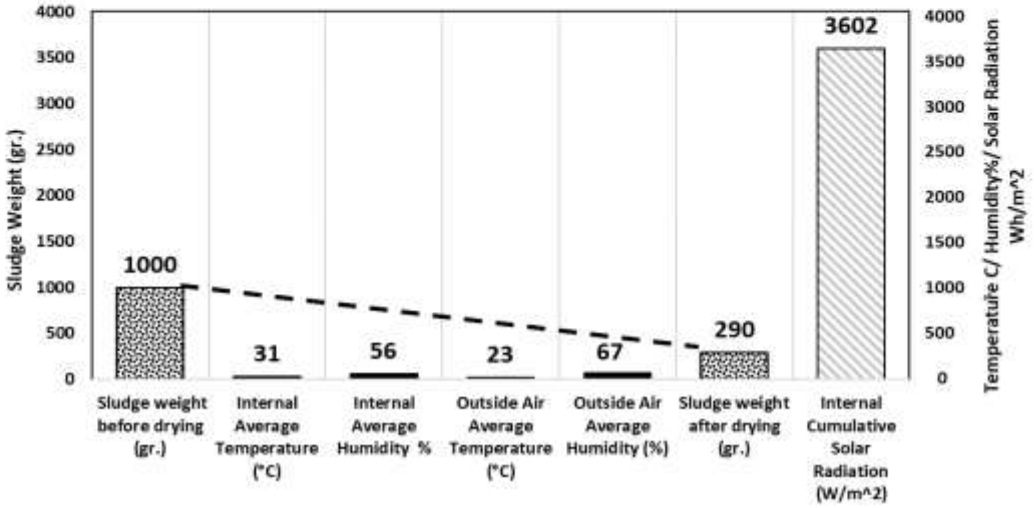


Figure 4.13. 1kg WWTP sludge drying, during 2 days in basic system

In hybrid system hot air was transferred directly to the system. The two-layer coating prevented sunlight from passing through and reaching the product. The improper inclination of the tubes also led to the incomplete receipt of sunlight.

According to the results obtained from the second structure of the drying system, for loading one kilogram of sludge in the hybrid system, the difference between internal and external temperature of the system was 9 ˚C and the content of heat transfer was 190.08 watts and also in basic system with 8 ˚C, internal and external temperature differenc , the heat transfer rate was calculated to be 168.96 watts. In this system, in addition to the modification made, the slope of the collectors was not suitable, and also high energy was lost from the lower part of the system due to the gaps created for the entry of glass tubes into the system.

4.1.6. Third structure of the dryer

In the third improvement in the hybrid system structure, the glass tubes were placed parallel with the system on a metal pedestal vertically in the direction of the system. All tubes were connected to each other and the hot air created inside the tubes was directed into the system by a hose. In Figure 4.14 is shown the third improvement of the dryer.

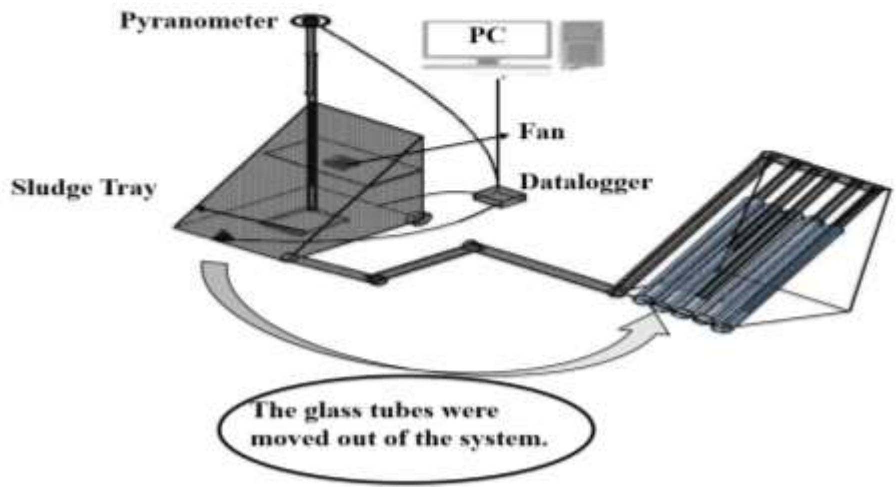


Figure 4.14. Third structure of hybrid solar drying system

The sludge drying rate was evaluated several times daily and weekly. As the thickness of the sludge increases, the drying time of the sludge also increases. After the sludge has dried completely and passing the sludge drying threshold, the sludge absorb moisture from the ambiant. In Figure 4.15 one kilogram of WWTP. sludge receives 1 964 Wh/m^2 of cumulative solar radiation, and the weight of sludge decreases to 270 gr. in one day. In Figure 4.16 shows 5000 gr. of sludge weight changes to 1 054 gr. with 11 741 Wh/m^2 of cumulative solar radiation during a week. Changes in temperature and humidity inside and outside the system are also significant.

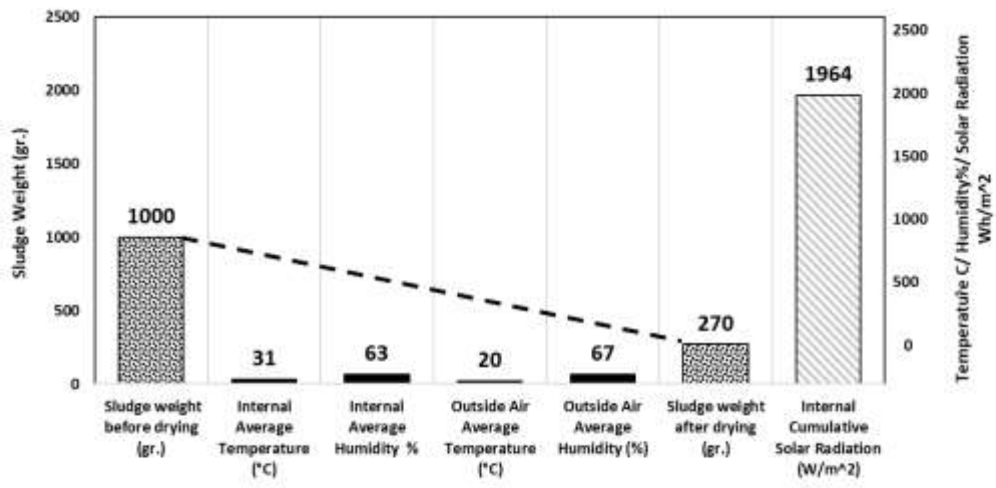


Figure 4.15. 1kg WWTP. sludge drying, during 1 day in hybrid system

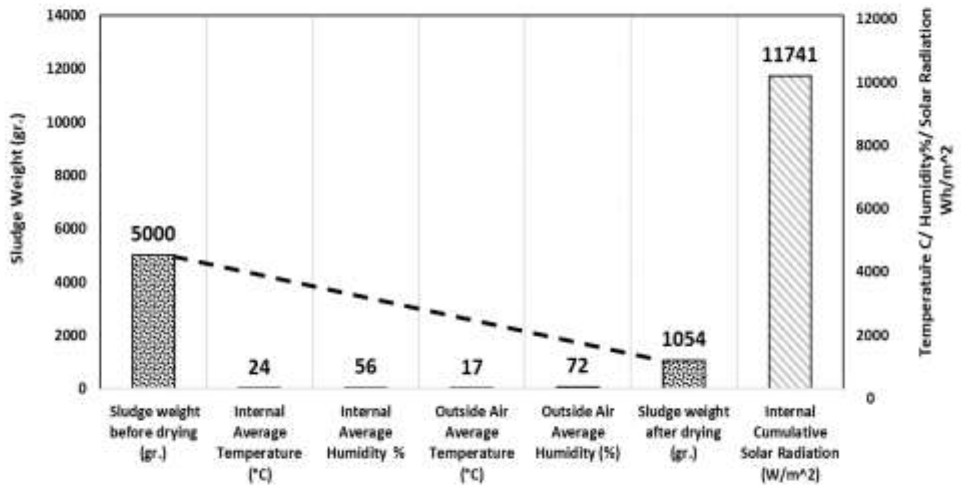


Fig.4.16. 5kg WWTP. sludge drying, during 1 week in hybrid system

In Figure 4.17, the process of reducing the volume of 5 000 gr. of sludge during a week is examined. In the first three evaporation days, increasing trends are shown. From the third to the seventh day, the evaporation rate decreases. In fact, the surface water of the sludge is drained in the first three days, and in the following days, the internal water leaves the sludge due to stronger bonds.

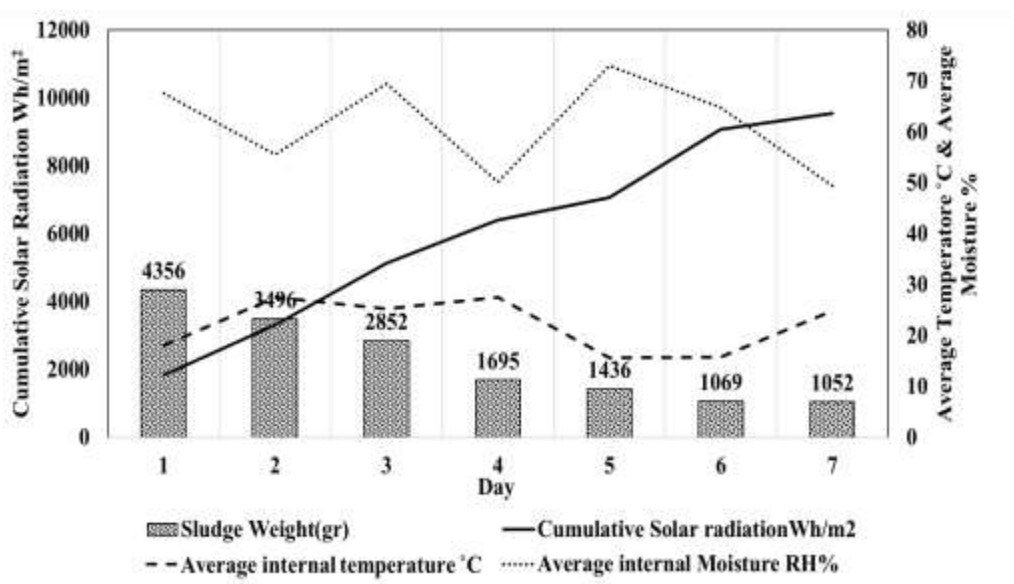


Figure 4.17. Evaluation of the daily drying of 5 kg of waste sludge for a week

In the third stage, due to the inability to properly direct hot air into the system, the necessary efficiency of the system was not achieved. Figure 4.18 shows waste sludge before and after drying.

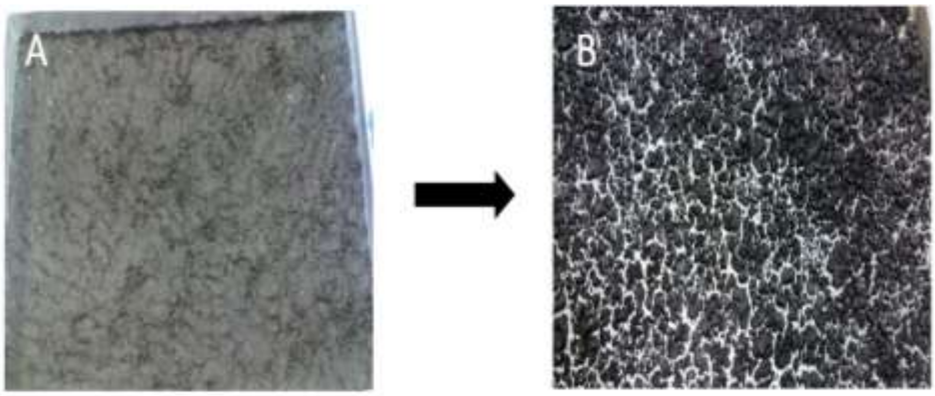


Figure 4.18. Picture of WWTP. sludge before and after drying. **A)** Raw WWTP. sludge **B)** Dried WWTP. sludge

At this structure, the desired result is not achieved because the airflow does not circulate properly in the systems. In the third structure of the dryer system, by loading one kilogram of sludge in the hybrid system, the difference between the internal and external temperature of the system was 11 ˚C and the heat transfer was 232,32 watts and also in the same system by loading 5 kg of sludge for a week with 7 ˚C Indoor and outdoor temperature difference , the amount of heat transfer was calculated to be 147,84 watts. In this system, with the transferring glass tubes out of the system, it was impossible to conduct sufficient heat from the tubes into the system, and the system's efficiency decreased.

4.1.7. The fourth improvements stage of the hybrid dryer system

In the last step, some minor improvements were made to pursue system improvements of the hybrid dryer system. At this stage, the system coverage changed to one layer. Each pipe is filled with 650 gr. of paraffin-wax and 70 cm of the length of copper pipes are entered into the system for better heat transfer from the bottom. Figure 4.19 shows the final structure of the dryer.

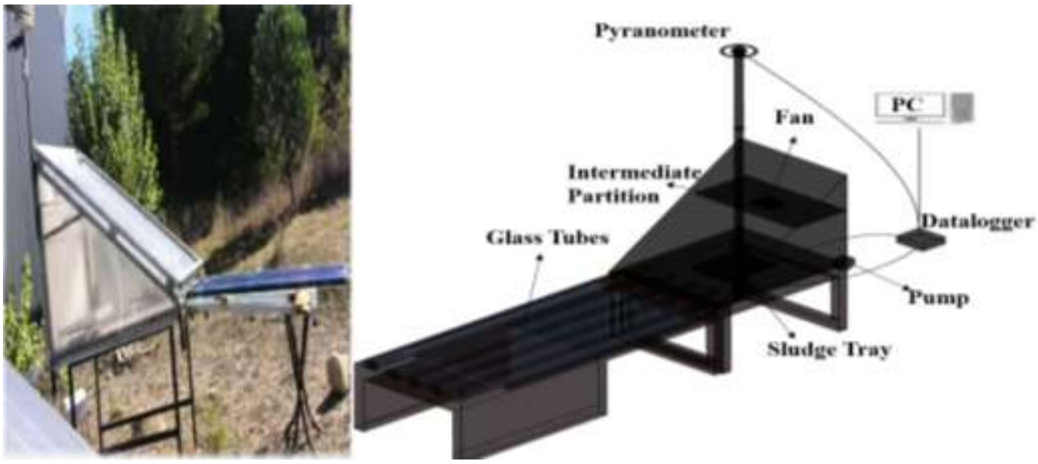


Figure 4.19. The fourth structure of dryer

At this stage of the research, three models of sludge have been used to study. By using a scale inside the system, the amount of evaporated moisture for each sludge per hour was measured. The drying process of one kilogram of each type of sludge with a thickness of 0,5 cm has been investigated. Figure 4.20 shows a view of placing a tray containing sludge inside the system.

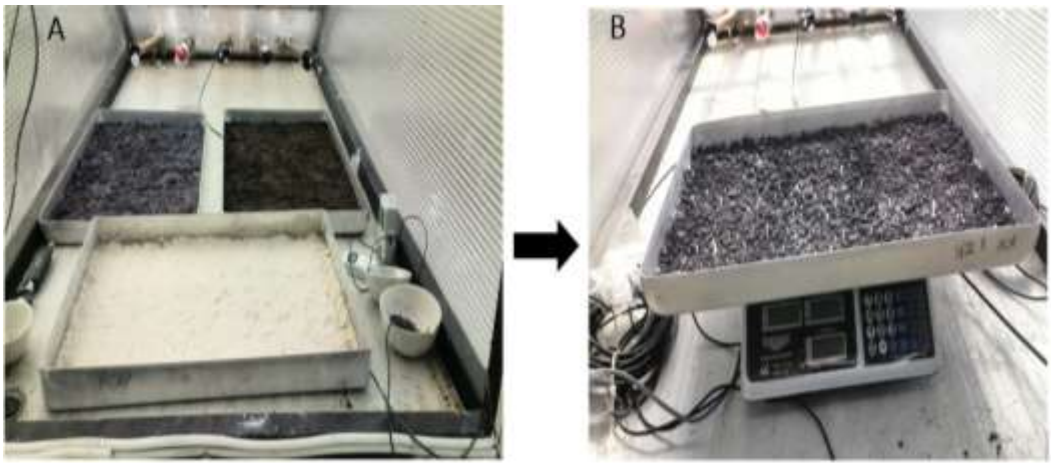


Figure 4.20. Interior view of the drying system. **A)** Three sludge tray loading in the system **B)** WWTP. sludge tray on the scale

- Applying Screws on improving dryer performance

At this section, the efficiency of the system was studied for 6 hours from 10:00 AM to 4:00 PM. In the first step, the effect of scattered standing steel screws on sludge surfaces with high thermal conductivity 50,2 (W/m K) during drying time was investigated. Steel screws improved the drying process by receiving heat from the solar waves and transferring it to the sludge by increasing the cracks on the surface. Due to the high thermal conductivity of the screw and contact with the hot surface of the tray and sludge, the heat transfer process created by solar radiation occurs with high efficiency. Within the system, all three types of heat transfer processes convective, conductive and radiative are achieved. Figure 4.21 shows the morphology of the three sludges and the cracks obtained by spreading the screws on the sludge surface.

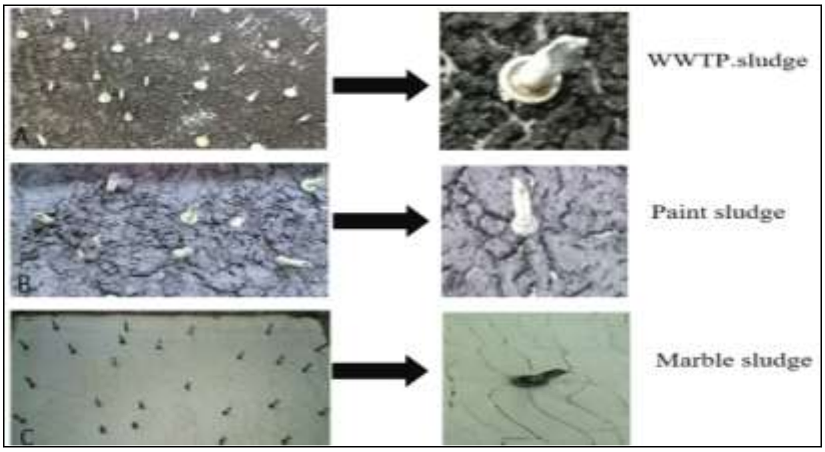


Figure 4.21. Morphology of sludge by spreading screws on the surface after drying. A) WWTP. sludge B) Paint sludge C) Marble sludge

In the figure below, the drying efficiency of WWTP. sludge for 6 hours in the non-screw mode and its changes by adding screws are compared. In both cases, by receiving the same cumulative solar radiation, 1 120 Wh /m², the weight of the waste sludge in Figure 4.22 has decreased from 1000 gr. to 800 gr. without screws and in Figure 4.23 by scattering the screws, the weight of sludge has reached to 782 gr. The average internal temperature and internal humidity in both systems were 17 ˚C and 45, 8%.

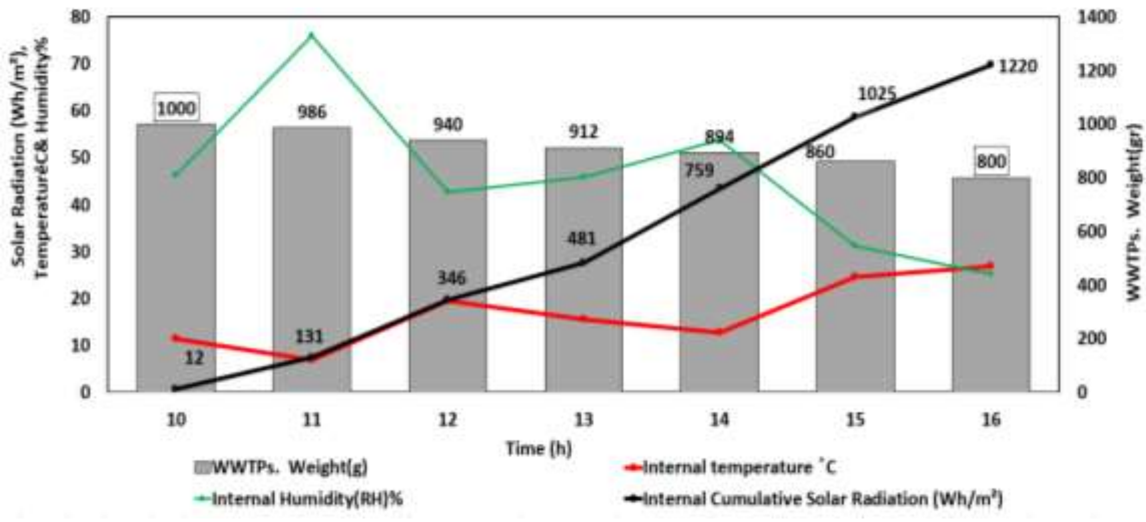


Figure 4.22. WWTP. Sludge drying without screws

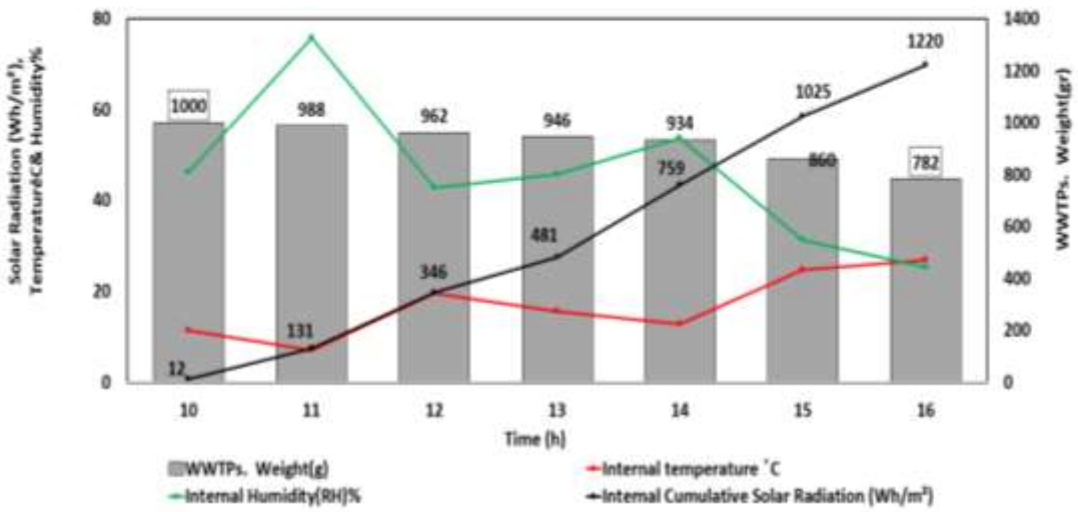


Figure 4.23. WWTP. Sludge drying with screws

In the fourth structure, 329, 472 watts of heat transfer were observed using screws and between indoor and outdoor temperature difference was 8°C.

The weight of paint sludge without adding screws in Figure 4.23 by receiving 1141 Wh / m^2 of cumulative internal solar radiation reduced from 1000 gr. to 824 gr. and by adding screws in Figure 4.24 has reached to 763 gr. The internal temperature and humidity were 19 °C and 41 %.

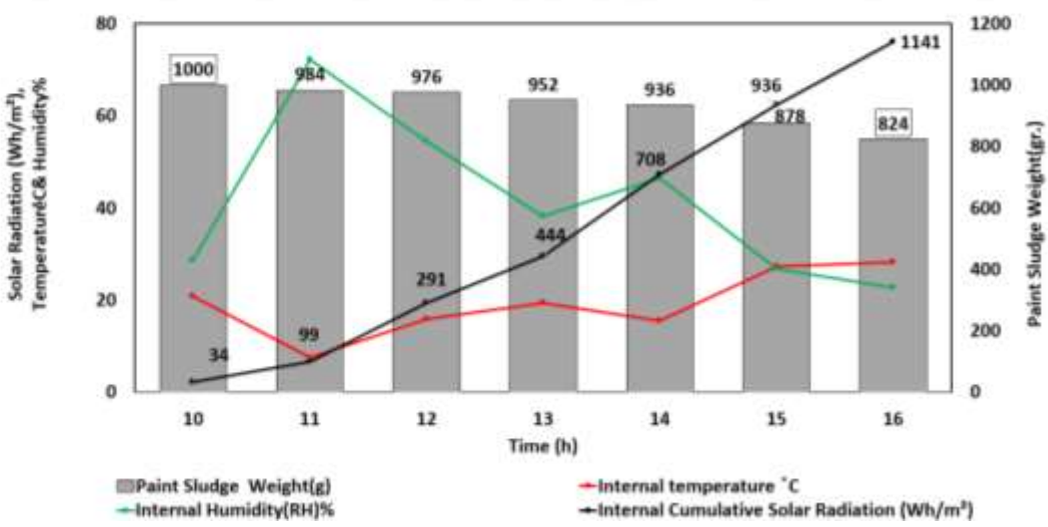


Figure 4.24. Paint Sludge drying without screws

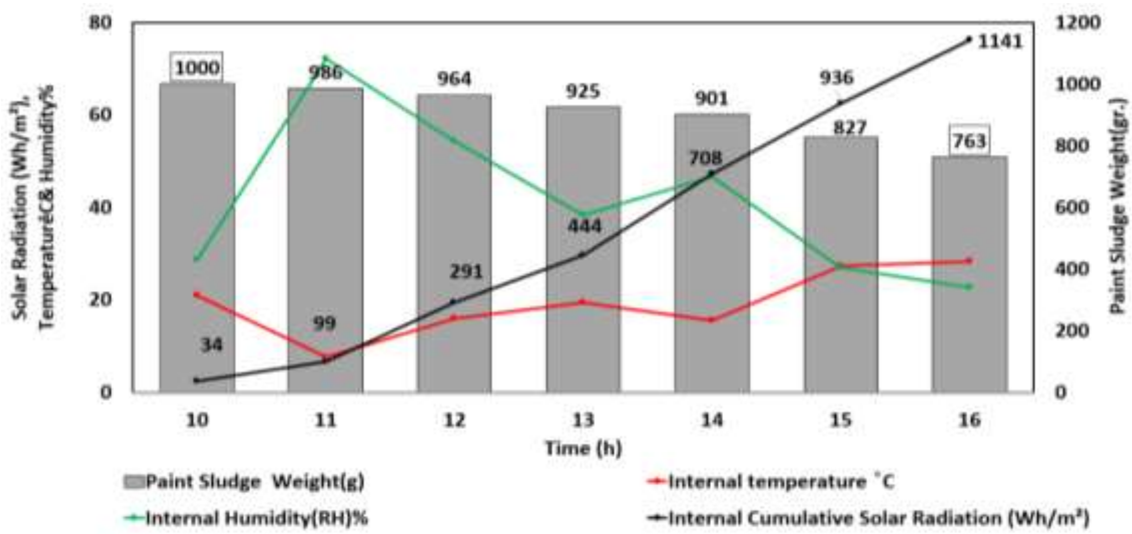


Figure 4.25. Paint Sludge drying with screws

In Figure 4.26 shows that the weight of marble sludge with receiving 1367 Wh / m^2 cumulated internal solar radiation reached from 1000 gr. to 854 gr. without the use of screws and in Figure 4.27 reduced to 810 gr. with addition of screws. Average indoor temperature and humidity were averaged 25 ° C and 45%. At this stage, by using screws in the paint sludge with 9 ˚C as a difference of internal and external temperature of the system, the heat transfer content was observed 388,608 watts.

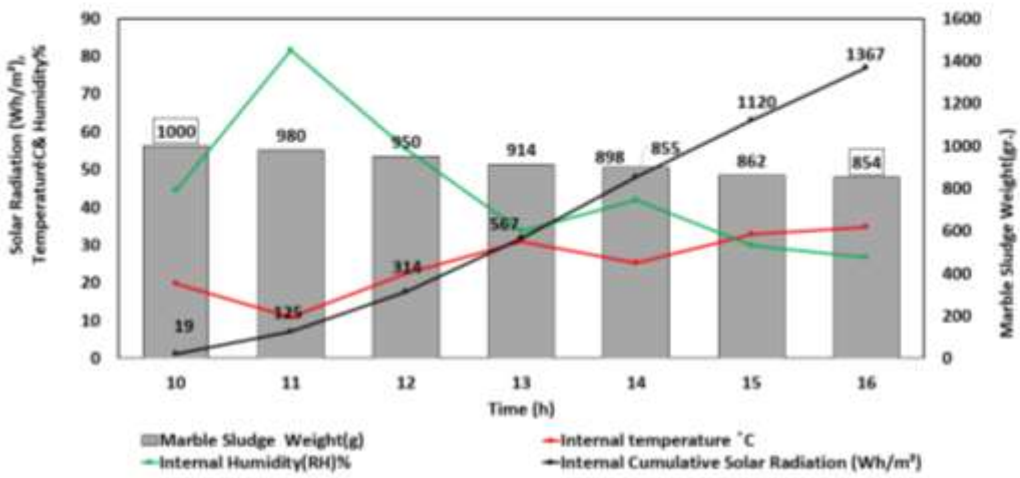


Figure 4.26. Marble Sludge drying without screws

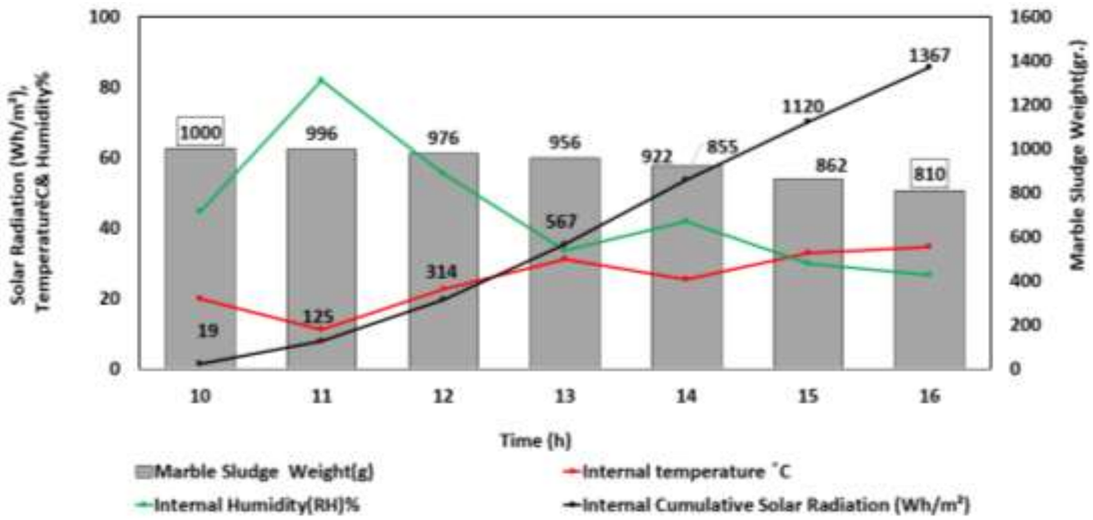


Figure 4.27. Marble Sludge drying with screws

By using screws in marble sludge inside the dryer system with 8 ˚C as a difference of internal and external temperature of the system, the heat transfer was 350 watts.

- Applying screws and black trash bag as an absorber on improving dryer performance

At this stage, to increase the absorption rate of solar energy, the dryer floor was covered with a black trash bag. Various studies have been conducted on the effect of dark color options on the efficiency of solar drying system (Saleh and Badran 2009). Black color used in solar dryers boosted the system efficiency and help to increase the drying performance.

In a similar study by (Food and Agriculture Organization of the United Nations (FAO, 1995), the internal surface of the system was painted black to increase sunlight absorption. In this study, both screws and black floor covering were used. The weight of the WWTP. sludge was changed from 1000 gr. to 754 gr. in Figure 4.28 by receiving the internal cumulative solar radiation of 1064 Wh/m^2. The average internal temperature of the system was 18,6 ° C and the internal humidity of the system was 41,1%. At this stage of the system, the amount of heat transfer with a difference of 10 ˚C between indoor and outdoor temperature, was 413,952 watts.

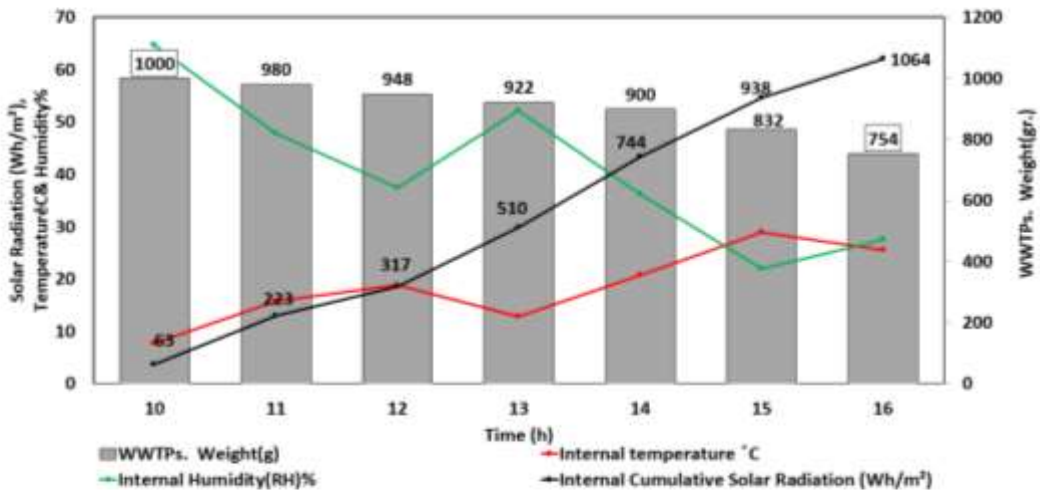


Figure 4.28. WWTP. Sludge drying with screws & Trash bag cover

In Figure 4.29, have been used the screws and black trash bag for covering the system floor. As a result, the weight of the paint sludge reduced by receiving 1103 Wh/m^2 of cumulative intern al solar radiation from 1000 gr. to 740 gr. The internal temperature of the system was 21 ° C and its relative humidity was 37%. The amount of heat transfer with a difference of 12 ˚C between indoor and outdoor temperatures was 506,88 watts.

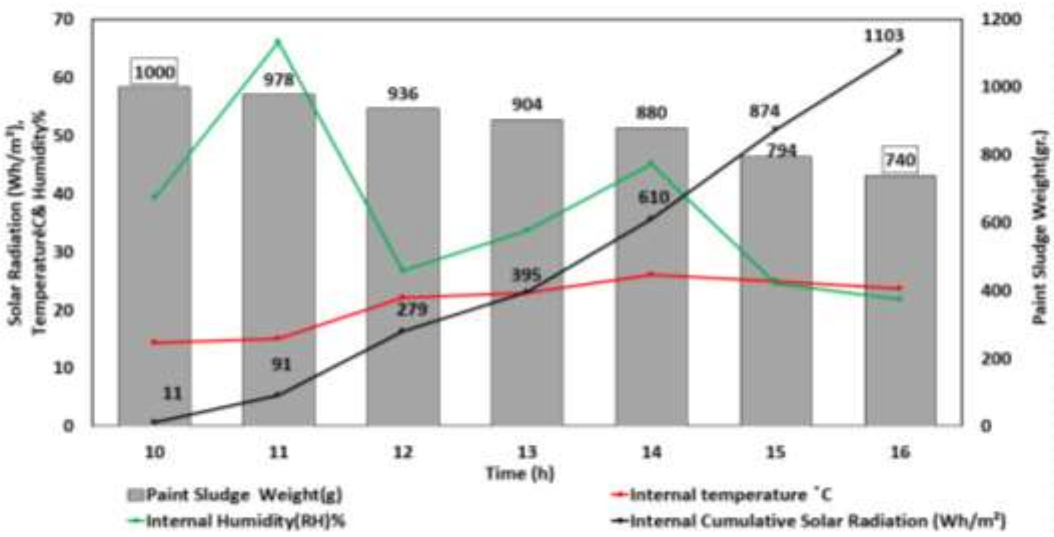


Figure 4.29. Paint Sludge drying with screws & Trash bag cover

In Figure 4.30 the system changes the sludge weight from 1000gr. to 808 gr. by applying screws in the sludge and a black trash bag on the floor of the system, and receiving 1 361 Wh / m^2 of cumulative internal solar radiation. Dryer average temperature was 25 ° C and the internal humidity of the system was 35%, also heat transfer content was 549,12 watts with 13 ˚C temperature differences between inner and out of the system.

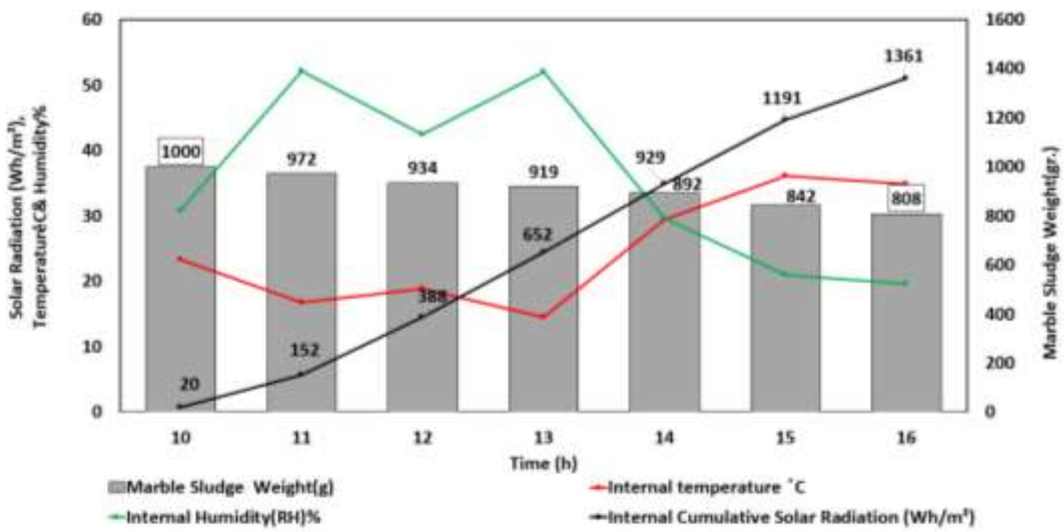


Figure 4.30. Marble Sludge drying with screws & Trash bag cover

- By spreading Screws, black trash bag and reflectors on improving dryer performance

At this stage, all three operation by adding the screws, black trash bag, and aluminum foils are used to reflect the solar waves around the glass tubes. The solar waves are reflected towards the glass tubes and more sunlight is absorbed. Previous Studies have shown that using reflectors in solar dryers increases system efficiency from 40% to 58.5% (Wagner et al. 1980).

Solar radiation is reflected to the paraffin-containing tubes by aluminum foil in the form of mirrors. The radiation trapped in the glass tubes and transfers the heated air into the system. This process continues until the sludge is completely dry. Due to the change in the angle of solar radiation during the day, the amount of energy absorbed and its reflection by reflectors decreases (Ajunwa etal. 2020). In one study, the efficiency of a solar dryer system with a reflector was 10% and without a reflector was 8,5% (Nandakumar et al . 2018) . Figure 4.31 shows how to use aluminum foil as a reflector.

Figure 4.31. View of placing the reflector around the glass tubes

Using the reflector, floor cover and screws, cause to the weight of the WWTP. sludge was reduced from 1000 gr. to 722 gr. by receiving 1 046 Wh / m^2 of cumulative internal solar radiation. The average temperature and humidity of the dryer were 21,6 ° C and 35,9%. In Figure 4.32 is shown the waste sludge drying efficiency was increased from 20% to 28%.

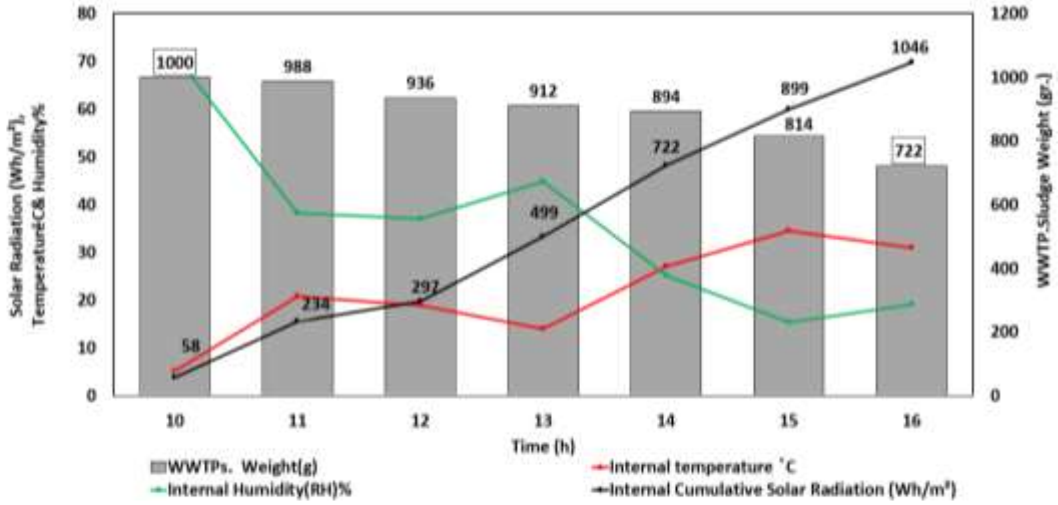


Figure 4.32. WWTP. Sludge drying with screws, Trash bag cover& Reflector

In this structure of the system, the amount of heat transfer with a difference of 10 ˚C between indoor and outdoor temperature, the amount of heat transfer was 422,4 watts. The weight of paint sludge weight is reduced by performing all three stages of improvement in the system by receiving a cumulative internal solar radiation of 1100 Wh/m^2 to 690 gr. Also, the average temperature was 23 ° C and the internal humidity of the system was and 32%. In Figure 4.33 the drying efficiency of sludge increases from 18% to 31%, and also the heat transfer content was 507,30 watts.

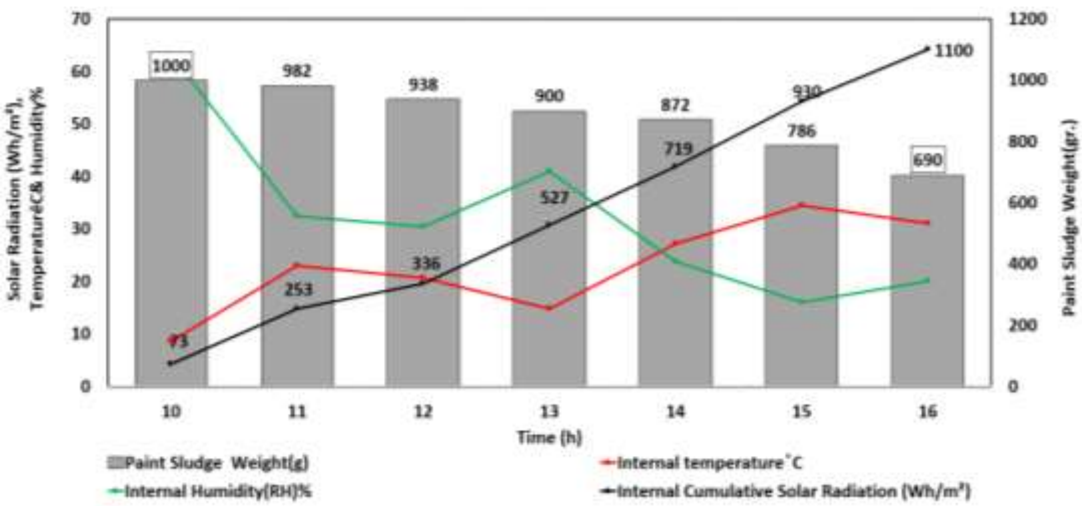


Figure 4.33. Paint Sludge drying with screws, Trash bag cover& Reflector

After improvements the marble sludge weight was reduced to 792 gr. by receiving 1 002 Wh/m^2 internal cumulative solar radiation the average internal temperature was 26℃ and humidity was 50%. As shown in Figure 4.34 the drying efficiency was changed from 15% to 21%.

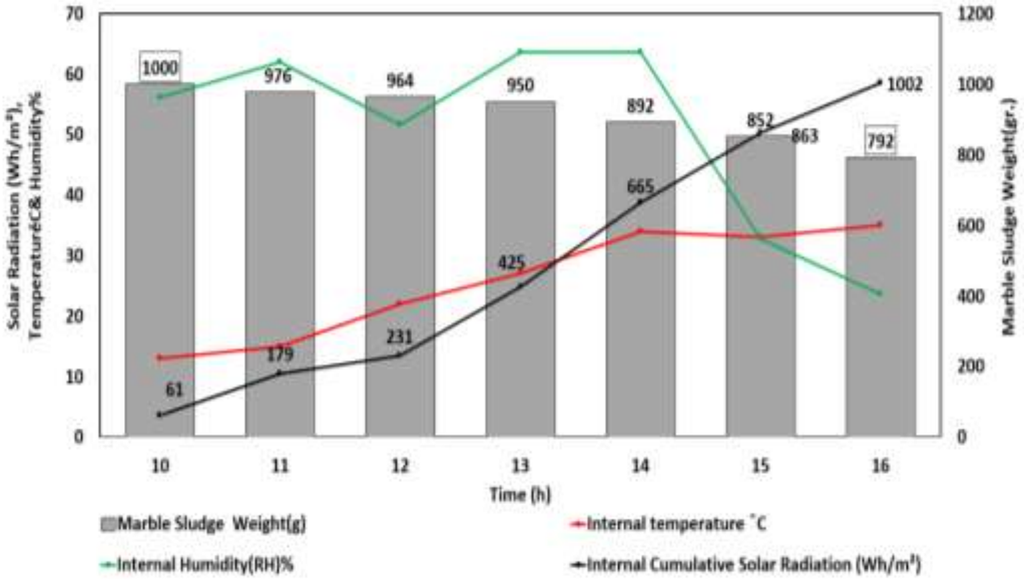


Figure 4.34. Marble Sludge drying with screws, Trash bag cover& Reflector

At each stage, by decreasıng in the intensity of solar radiation during the system upgrade, the efficiency of the dryer increases. The drying efficiency of the system is increased from 6% to 13% for marble sludge. In the last structure of the system, the heat transfer was 620, 928 watts with 15 ˚C temperature differences.

According to the content of the research, increasing the intensity of solar waves inside the system does not lead to an increase in system temperature and a decrease in humidity on a constant basis. In this study, the tools and materials used in the system are as important as solar waves in sludge drying. In fact, the thermal conductivity of all equipment and the duration of heat storage are the particular important.

4.1.8. Statistical analysis of fourth structure system

- Matlab program analysis for sludge drying by moisture and time factors

In this research, the drying behavior of sludge types is investigated by a mathematical model. Three mathematical models are used for statistical analyzing as (Exponential, Logarithmic and Polynomial), also the time and moisture parameters have been used to investigate the sludge drying process. These three mathematical models have been used to explain the drying kinetics. Table 4.1 shows the mathematical equation for each model. Using a MATLAB software version R2018b, drying rate of sludge types and time factors with the theoretical model is presented in Table 4.2. R^2 coefcient is criteria factor to evaluate the accuracy of the methods, also 95% confidence is estimated. The Standard error of the estimate is mentioned by (SEE) and RMSE shows the root mean square error.

Table 4.1. Mathematical Modelling Equation by MATLAB Toolbox

Model	Equation	Reference
Exponential	MR=a*exp(-k*t)	El-Beltagy et al. 2007
Logarithmic	MR = a exp(-kt)+ c	Karathanos, 1999; Mendieta et al. 2016
Polynomial	$MR=1+at+bt^2$	Wang ve Singh 1978

In the case of WWTP. Sludge, paint sludge and marble sludge the polynomial model is well suited due to its higher R^2 values and lower SEE and RMSE values. In MATLAB software, the Cftool plot uses the curve fitting method, which is with the initial set of X and Y. The X value indicates time (h), and the Y value means the moisture ratio, also, a, b, c, are empirical constants in the drying models.

Table 4.2. Statistical parameters models for different sludge drying kinetics

Sludge Type	'Model	Coefcients of determination R^2	RMSE	SEE	
Wastewater treatment plant sludge	Exponential	0.8581	0.01118	0.0006244	a = 0.809 (0.7891, 0.8289) b = -0.01494 (-0.02196, -0.007921)
	Logarithmic	0.8618	0.01233	0.0006082	a = 1.536 (-126.1, 129.1) b = 0.007652 (-0.6426, 0.6579) C= -0.7279 (-128.3, 126.9)
	Polynomial	0.866	0.01086	0.0005899	a = -0.01167 (-0.01694, -0.006391) b= 0.8089 (0.7898, 0.8279)
Paint sludge	Exponential	0.9273	0.03951	0.007806	a = 0.5873 (0.5073, 0.6673) b = -0.1519 (-0.2045, -0.09935)
	Logarithmic	0.9456	0.03822	0.005844	a = 6.875 (-281.6, 295.3) b = 0.00896 (-0.3772, 0.3952) c = -6.305 (-294.8, 282.2)
	Polynomial	0.9459	0.03409	0.005812	a = -0.06024 (-0.0768, -0.04368) b = 0.5698 (0.5101, 0.6296)
Marble sludge	Exponential	0.8191	0.03273	0.005357	a = 0.2835 (0.2174, 0.3496) b = -0.1481 (-0.2372, -0.05898)
	Logarithmic	0.9031	0.02678	0.00287	a = 19.44 (-6505, 6544) b = 0.001577 (-0.5302, 0.5334) c = -19.16 (-6544, 6506)
	Polynomial	0.9041	0.02384	0.002841	a = -0.03092 (-0.0425, -0.01935) b = 0.2817 (0.24, 0.3235)

The polynomial model "second-order " is the most common mathematical language used to express the best accurate relationship nonlinear between the independent variable x and the dependent y, and is often used to explain logical results.

The reason for using this model is the complete mismatch of the data with the linear regression model and its suitabile for a brode range of curvatures. High-grade polynomials are notorious for fluctuations between appropriate exact values. It is difficult to fit linear regression with low error for existing data. When linear regression of all data points is not taken, polynomial regression is used to increase the fit between the data. It can be clearly seen that polynomial regression is better in data fit than linear regression. Also, due to better fit, RMSE polynomial regression is less than linear regression. According to values, the polynomial models were suitable in describing the drying phenomena of sludge.

- Pearson correlation test for cumulative solar radiation and sludge evaporated water

The results of the last stage of system modification were evaluated by Pearson XLSTAT correlation test at the same time as adding screws to the sludge, covering the system floor with a black trash bag, and using a reflector. At this stage, according to the explanations of the previous section, due to the high number of variables R^2, there is a logical relationship between evaporating water and cumulative solar radiation in the WWTP, paint and marble sludges based on the Figure 4.35 satisfactory results have been obtained. Based on the Proximity of the variable R^2 to the "1", is a reasonable relationship between parameters. In all three types of sludge, during pearson analysis in marble sludge, due to less moisture and equal degree of moisture distribution in this model, the moisture is also released from the sludge surface by logical and regular correlation, also R^2 value is more than others. In the case of paint sludge, it has a larger R^2 than waste sludge. This also means that the moisture released from the sludge is more closely related to the amount of cumulative solar radiation. In addition, the drying process takes a period of 6 hours, at the end of which the marble sludge is completely dried and most of the moisture in the paint sludge is evaporated.

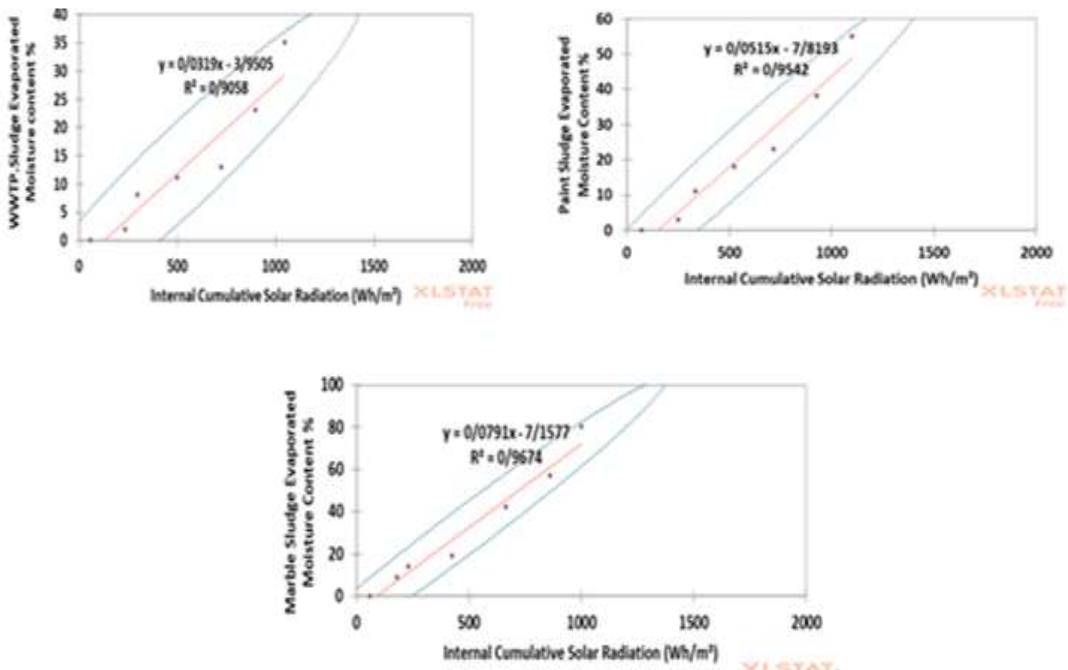


Figure 4.35. pearson analysis of three types of sludge

By evaluating the results in the last modified device in fourth system, the solid matter ratio and volume of the three types of sludge after modification are changed and determined by using the Eq. 4.5

$$V = (\frac{W_s}{\rho_W . s_{sl} . P_s}) \tag{4.5}$$

V = Sludge Volume (m^3 /day)

Ws =Sludge Dry Matter (kg/day)

ρw = Density of Water (1000 kg/m^3)

Ps =Dry Matter Percentage

Waste sludge volume with 20% dry matter is 0.00098 m^3 and increases by 27.7% dry matter to 0.000709 m^3. The difference in volume is (0.00098-0.000709=0.00028m^3) is the amount of water evaporated from 0.24 m^2. There is 0.00028m^3x1000 kg/m^3= 0.28 kg evaporated water.

Paint sludge volume with44% dry matter is 0.009821 m^3 and increases by 63.78% dry matter to 0.000677 m^3. The difference in volume is (0.0009821-0.000677=0.0003051m3) is the amount of water evaporated from 0.24 m^2. There is 0.0003051m^3x1000 kg/m^3= 0.3051 kg evaporated water.

Mable sludge volume with72% dry matter is 0.00982 m^3 and increases by 90.90% dry matter to 0.000777 m^3. The difference in volume is (0.000982-0.000777=0.000205m^3) is the amount of water evaporated from 0.24 m^2. There is 0.000205m^3x1000 kg/m^3= 0.205 kg evaporated water.

The sludge tray area is 0.24 m^2 and the amount of evaporated water is calculated for an area of one meter for each sludge sample separately, which is shown in the table.

Table 4.3. Evaporated water during drying from $1m^2$ of different types of sludge

Type of Sludge	Time(h)	Evaporated water (L/m^2)
Wastewater treatment sludge	6	1.16
Paint sludge	6	1.27
Marble sludge	6	0.9

In general, the rate of evaporation without making any modification and adding screws, collectors, and trash bags, the amount of water evaporated during six hours is more in WWTP. sludge than others and then in paint sludge is more than marble sludge. However, in the latest modification and the addition of screws, reflectors, and trash bags on the floor, during six hours, the amount of water evaporation in the paint sludge was more than other sludge types. During this process, the marble sludge is almost dry due to the smaller volume of water. The lack of resistance between water particles and sludge particles in marble sludge and paint sludge and bound water is less in this type of sludge.

4.2. Ineffective test results

4.2.1. Impact of mixing process on sludge drying

In the research, at each stage, three types of sludge were loaded simultaneously in two separate trays in the system. The sludge contents of one tray are mixed every hour, the other tray was dried without the mixing process. As shown in Figure 4.36 the weight of unmixed WWTP. sludge decreases from 1000 gr. in 8 hours to 328 gr. and mixed sludge weight decreased to 483 gr. According to the Figure 4.37, in the paint sludge, the weight of unmixed sludge is reduced to 474 gr. and mixed reached to 632 gr. The weight of marble sludge according to Figure 4.38 when not mixed during 6 hours was reduced from 1000 gr. to 754 gr. and mixed reached to 775 gr. The rate of evaporation in unmixed sludges were higher.

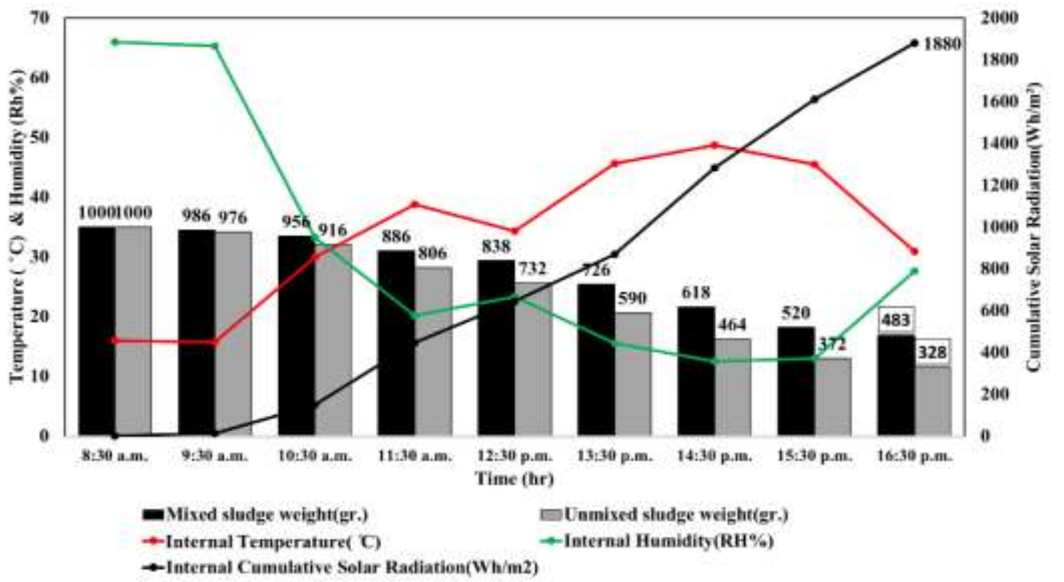


Figure 4.36. WWTP. Sludge drying comparison for mixed & unmixed sludge

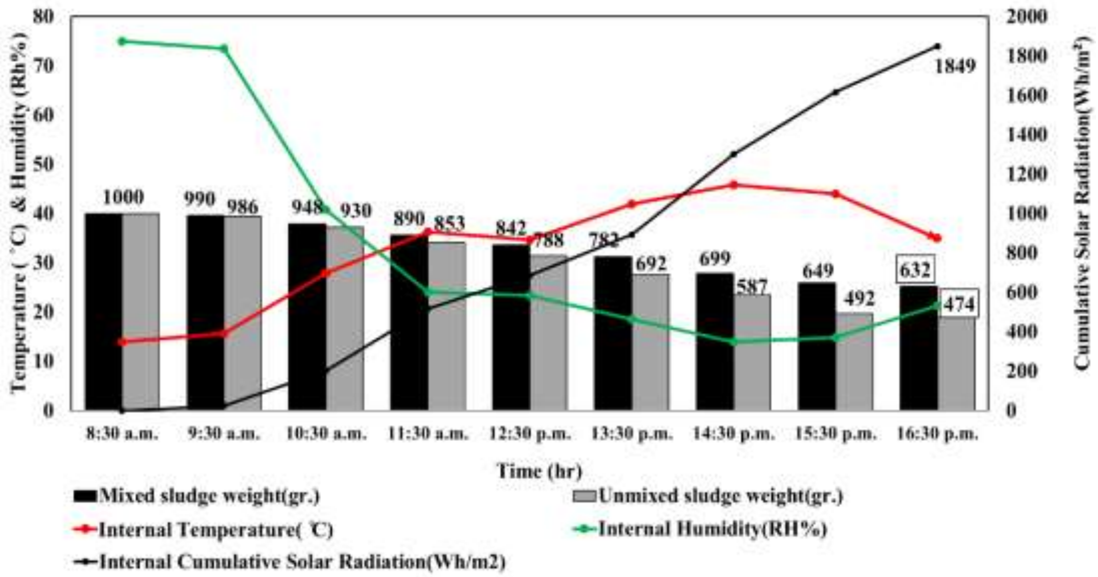


Figure 4.37. Paint Sludge drying comparison for mixed & unmixed sludge

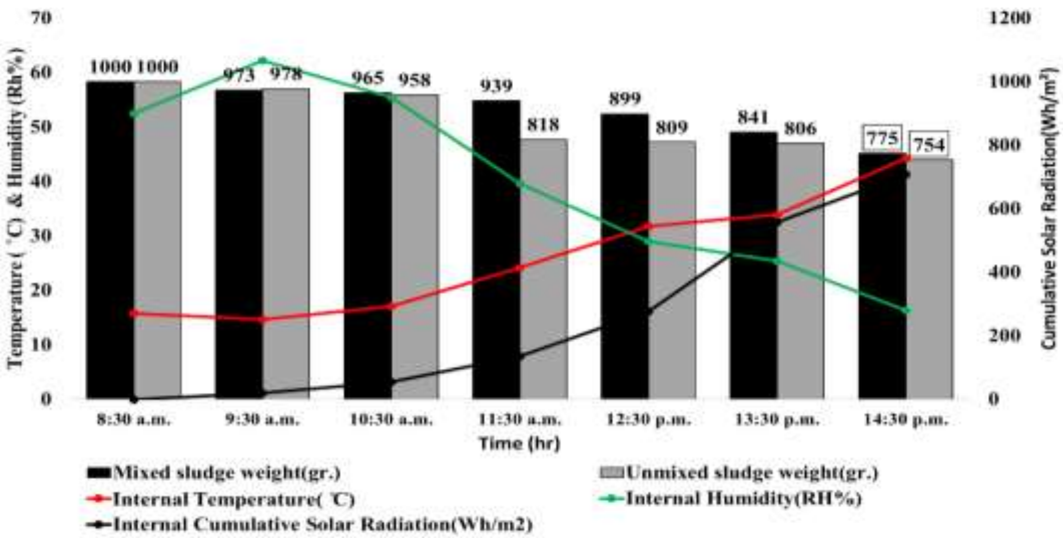


Figure 4.38. Marble Sludge drying comparison for mixed & unmixed sludge

In general, mixing provides an advantage in the sludge drying process (Li et al. 2020), but in this study, due to conduction, the contact of the sludge tray with the surface area is reduced and there is not enough heat transfer from the tray to the sludge and leads to negative effect instead of a positive effect.

Figure 4.39 shows the appearance of three types of sludge after mixing and without mixing.

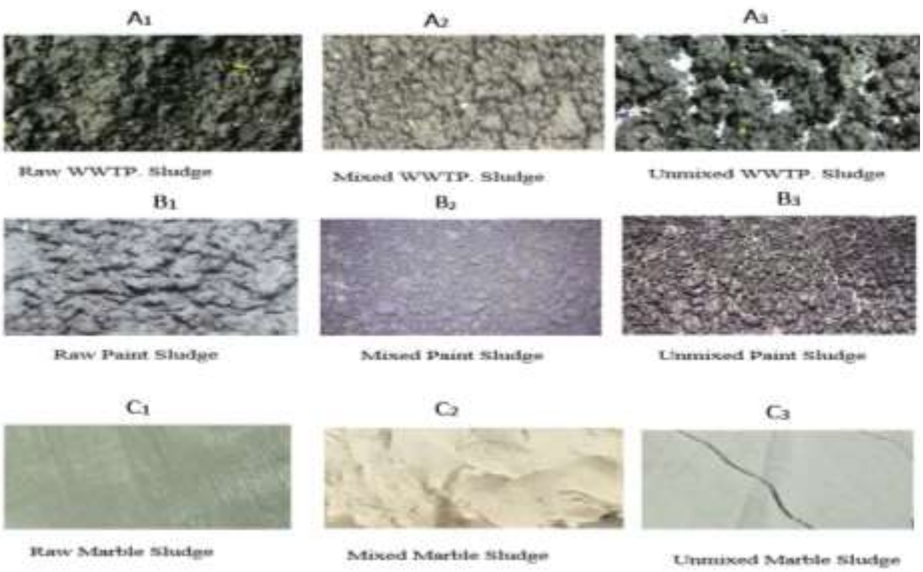


Figure 4.39. View of mixed and unmixed sludge types

4.2.2. Using paraffin under the sludge tray

As mentioned in previous studies, paraffin - wax was used as a phase change material inside glass tubes to increase system efficiency by heating the air and transferring to the system as convection heat. In this section, instead of using paraffin in glass tubes, paraffin was poured into a tray under the tray containing WWTP. sludge, and the sludge was expected to dry faster. Figure 4.40 shows sludge changing appearance by placing it on a tray containing paraffin.

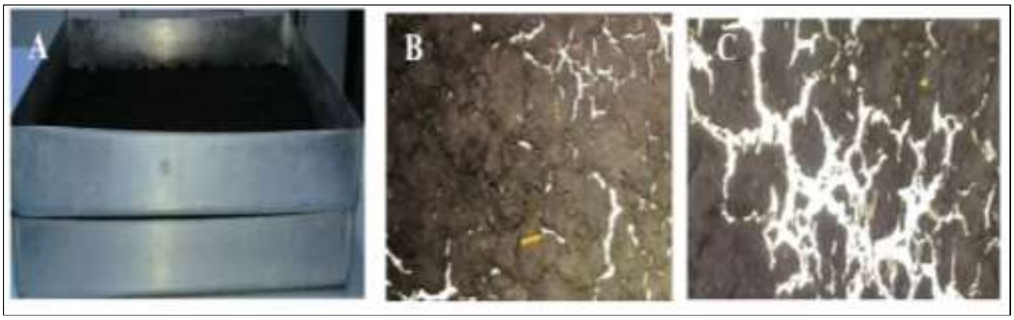


Figure 4.40. Display of WWTP. sludge after placing on a tray containing paraffin. **A)** Place a tray containing paraffin and sludge on top of each other **B)** Sample of dried sludge in the upper tray of paraffin **C)** Sample of dried sludge without paraffin tray

As shown in Figure 4.41, the rate of evaporation is lower in the sludge tray on the paraffin tray. The weight of waste sludge on a tray containing paraffin decrease from 1000 gr. to 732 gr. but if the tray containing paraffin is not used, its weight reaches 570 gr.

According to the results, paraffin receives heat through the environment and the tray during melting to reach the melting point and due to the high thermal conductivity of the aluminum tray reduces the temperature of the tray and this process leads to reduces the drying performance.

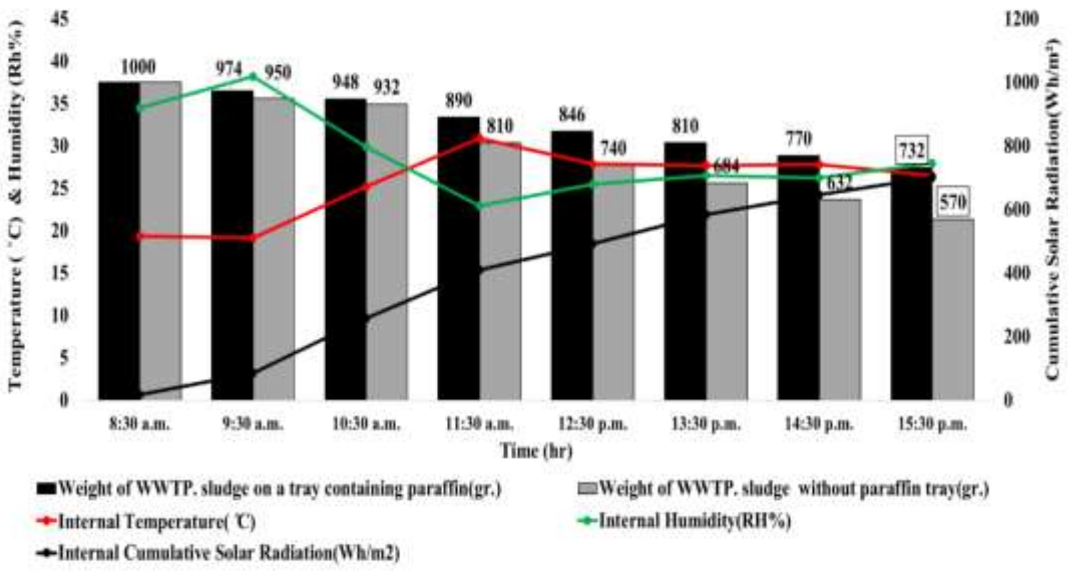


Figure 4.41. WWTP. sludge drying performance when paraffin-wax tray is under the sludge tray

When paraffin melts during the day time, and it absorbs the heat and may not give a good result, but at night it can be reversed and can give the absorbed heat back to the system, and it provides a stable temperature, especially in winter months.

4.2.3. WWTP.sludge and paint sludge mixing together

To speed up the drying process, we mixed one kilogram of two samples of paint sludge and WWTP. sludge and loaded in a separate tray for one day. In addition, one kilogram of two samples of sludge separated was loaded with a mixture tray in the system and the water evaporation process was investigated. Figure 4.42 shows the evaporation process in mixed sludge is less than other samples. When two types of sludge are mixed, a flocke structure and a new surface of the water with the chemical composition may be created, making this structure difficult to evaporate.

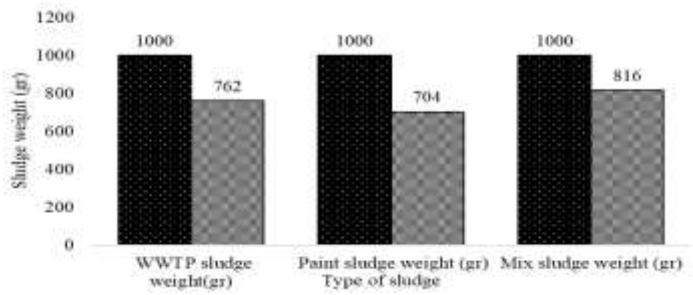


Figure 4.42. WWTP. sludge and paint sludge mixing together

The characteristics of the paint sludge and WWTP.sludge are different and mixing operation does not provide an advantage, also according to the regulations, it is not possible to mix them anyway, and must be disposed of separately. Although the mixed tray was at the end of the system and closest to the pipes, the least drying took place. The air is warmer near the pipes but evaporation is reduced and this is a disadvantage for sludge disposal. When paraffin melts during the day time, it absorbs the heat and may not give a good result, but at night it can be reversed and can give the absorbed heat back to the system, and it provides a stable temperature, especially in winter months, it can be very advantageous and there will be constant heat inside.

4.3. Heat transfer to sludge

To evaluate the energy transfer in the dryer, the system efficiency during the sludge drying is evaluated. To increase the efficiency of the dryer, selecting the structural components of the system are important. The drying of the product depends on simultaneous heat and mass transfer processes (Agrawal and Tiwari 2012). Each part receives solar energy independently as a heat source and heat is transferred through them. The thermal distribution in the drying system is evenly transferred between the system materials from the outside to the inside. In addition to the internal equipment, the external environment around the system is also important and the heat is transferred from outside into the system. Figure 4.43 shows sunlight heats, all the internal and external components of the system, especially the sludge bed, and heat reaches to the sludge through convection, conduction and solar radiation through the components and air. Combining all three heat transfer methods and formulating them mathematically is one of the most important challenges. Figure 4.44 shows temperature changes from outside to inside the system. By blowing hot air on the surface of the sludge, latent heat causes water to evaporate. During the impact of solar waves on the surface of the collector, solar energy is converted into heat and due to the convection process, it enters the dryer chamber and the relative humidity decreases with increasing temperature and vapor pressure (Musembia 2016). The drying process continues until the heat and mass are completely transferred and heat is transmitted according to solar radiation and all components of the system (Ayensu1997; Karim and Hawlader 2004; Lahsasni et al. 2004; El-Sebaii et al. 2002; Sing et al. 2004; Garg and Kumar 1998; Mabrouk and Belghith 1994). The heat transfer process occurs during the temperature difference between the components and the environment. Paraffin-containing glass tubes absorb heat and transfer hot air into the system. The melting point of paraffin is between 58˚Cand 60˚C (Nair et al. 2018). As shown in Figure 4.44, the temperature of copper pipes containing paraffin reaches above 50˚C at noon. The thermal conductivity of copper pipes, aluminum trays, and boxes are high and they transfer heat inside the system. Energy transfer in the system depends on the rate of temperature increase and this process reached until the equilibrium temperature is reached. In the last stage of the evaporation process, the heat transfer is almost constant and the sludge is seen as granular. Sludge in non-adhesive state has a better heat transfer coefficient than adhesive (Bennamoun and Belhamri et al. 2003). Temperature changes of appliances used in the system and air inside and outside the system during the heat transfer process.

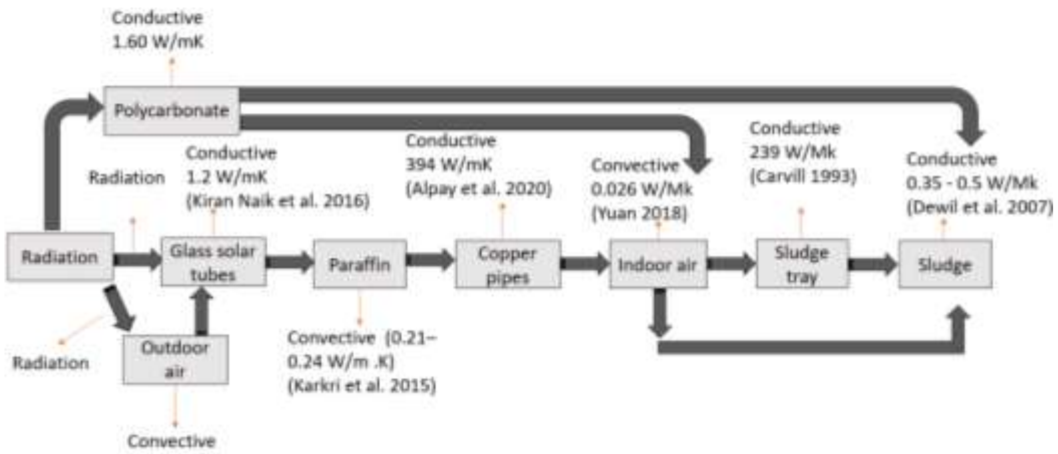


Figure 4.43. Heat transfer route in solar dryer

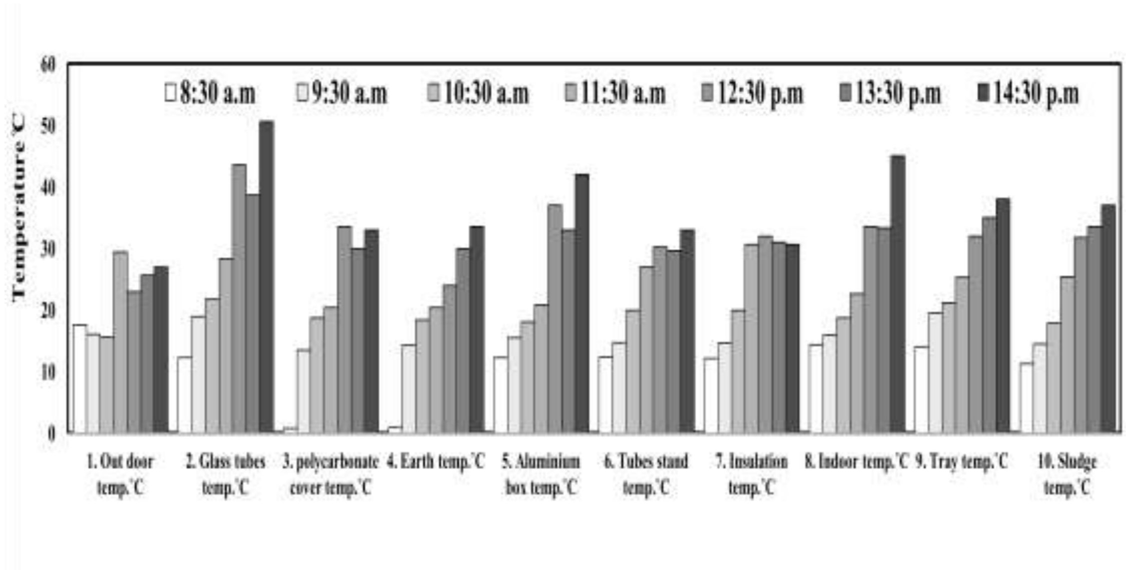


Figure 4.44. Temperature changes of material during drying

Figure 4.45 shows the heat transfer from paraffin through copper pipes into the system, which was photographed by the FLIR thermal camera. By absorbing solar radiation through glass tubes, the paraffin and copper pipes are also heated. The heat from the copper pipes is transferred into the system. The figure below shows a circle on a copper pipes with a temperature of 38,5 ° C, which is red. The end of the pipes is connected to the aluminum box of the system, which is also red due to its high thermal conductivity.

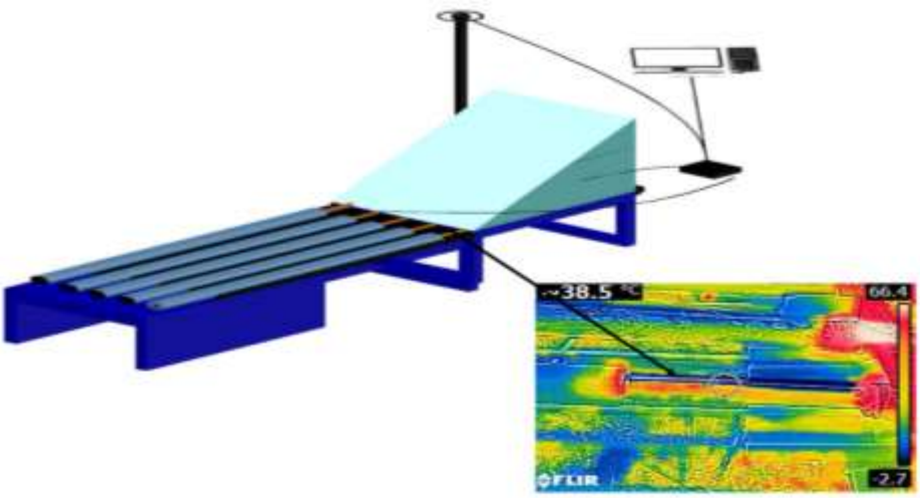


Figure 4.45. Displays the heat transfer of copper pipes to the system

4.4. Time Effect on drying process:

The influence of time was investigated for all three sludge samples under different temperature and solar radiation conditions. In this study, the sludge drying process was evaluated in a short period of 6 hours. The highest percentage of evaporation occurs during the peak hours between 12:00 and 14:00 noon. By doubling the percentage of humidity inside the system, the internal temperature also decreases to one-third of the initial values, and as the time factor triples, the sludge dries completely. As shown in Figure 4.46, by simultaneously loading three samples of sludge in the drying system, the free water inside the paint sludge is released faster than wasee skudge. Also, the temperature of the paint sludge is higher than the two samples of waste and marble sludge. As the solid's concentration increases, free water is more difficult to separate from the sludge and the movement of moisture to the sludge surface is limited. In addition to solar radiation, temperature and air velocity also affect the amount of moisture during the drying process but have less effect than temperature (Golisz et al. 2013). Based on previous studies, the relationship between time and temperature on sludge shrinkage is significant. With increasing temperature, contractile stresses are created in the cell wall of the material along with porosity (Abasi et al. 2009).

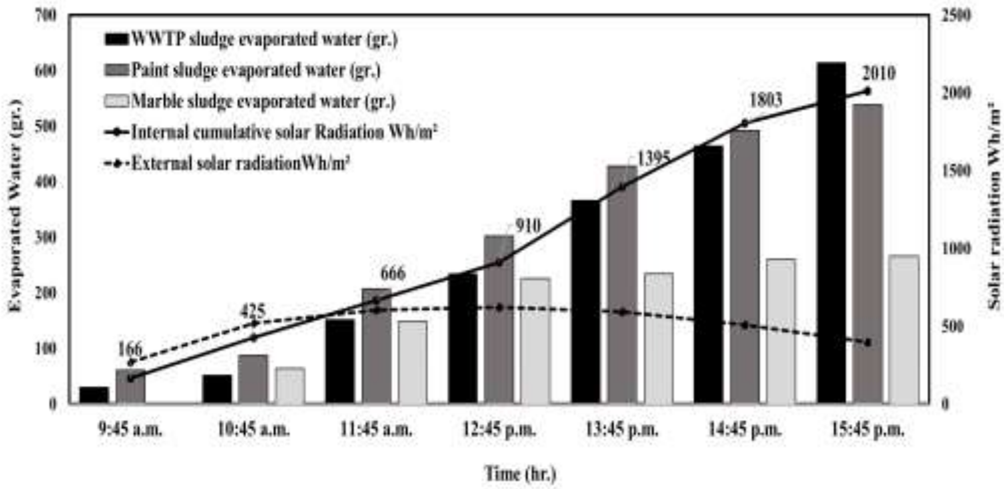


Figure 4.46. Evaluation of Time factor on different sludge drying

4.5. The logical relationship between temperature and moisture during sludge drying process

As the temperature rises, the bound water of the sludge turns into free water and leaves the surface of the sludge (Deng et al. 2009), also the sludge changes from sticky to granular. The moisture content absorption depends on the temperature. As shown in Figure 4.47, there is an inverse relationship between internal and external temperature and humidity. The range of external temperature and humidity varies between (13-32) ˚C and (29-100) and the internal range varies between (14-62)℃ and (10-99). As it is clear, there is a prominent difference between the internal and external temperature of the system and this is a sign of good performance of the drying system. The greatest temperature difference was observed between 9:00 and 15:00 in the afternoon. The temperature and humidity inside the system are based on the same pattern, but the outside space is still fluctuating. Relative humidity increases with decreasing air exchange flow. Proper humidity and relative temperature control of the system is provided by providing proper ventilation. Removal of moisture from the sludge surface occurs during the diffusion phenomenon. Increasing air contact with the sample surface leads to more moisture absorption (Mirzaee et al. 2009).

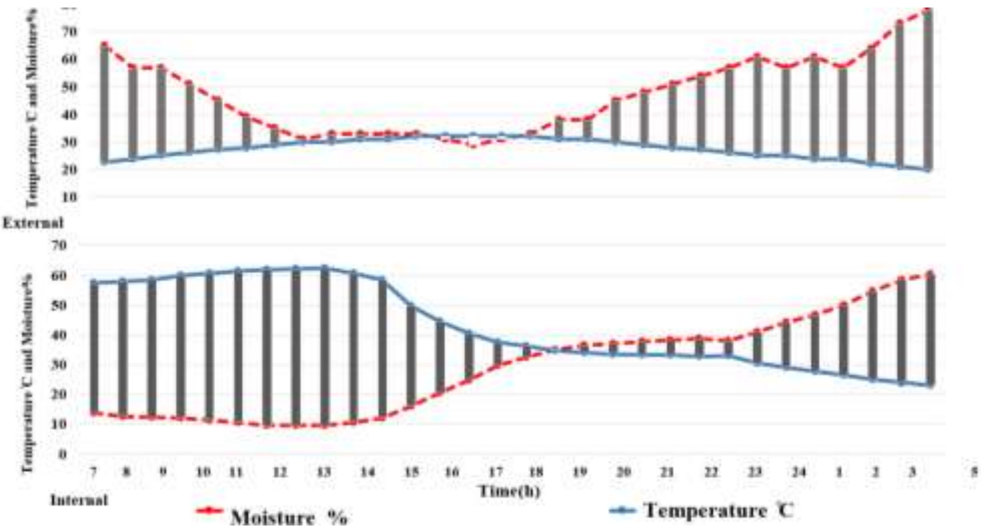


Figure 4.47. Relation between internal and external temperature and moisture.

4.6. TKN Analysis results

The process of thermal drying of waste sludge results was investigated in the release of nitrogen. The mass of nitrogen released is equal to the mass of dissolved nitrogen in the sludge, which leaves the sludge in the form of ammonium evaporation (Horttanainen et al. 2017). Most of the soluble nitrogen according to (N-4500) standard method in Total Kjeldahl nitrogen determined as total ammonia and organic nitrogen. During waste sludge drying, nitrogen is removed and is calculated by soluble nitrogen, total nitrogen, ionized ammonia, and nonionized ammonia. The titration step by sulfuric acid is performed after the distillation process and the boric acid solution plays the role of the receptor in this step. Most of the nitrogen that binds to the cell structure is organic nitrogen. Experiments were made three times and the results were evaluated. Figure 4.48 shos after one day of sludge drying, the amount of ammonia drops from 9000 mg / kg TS to 6800 mg / kg. According to a study by Hortetainenen et al. (2017), total nitrogen in waste sludge contains 81% organic nitrogen, 19% soluble nitrogen, of which 12% is NH_4^+ and 7% is NH_3, NO_x. Results show that there is a logical relationship between temperature and ammonia release.

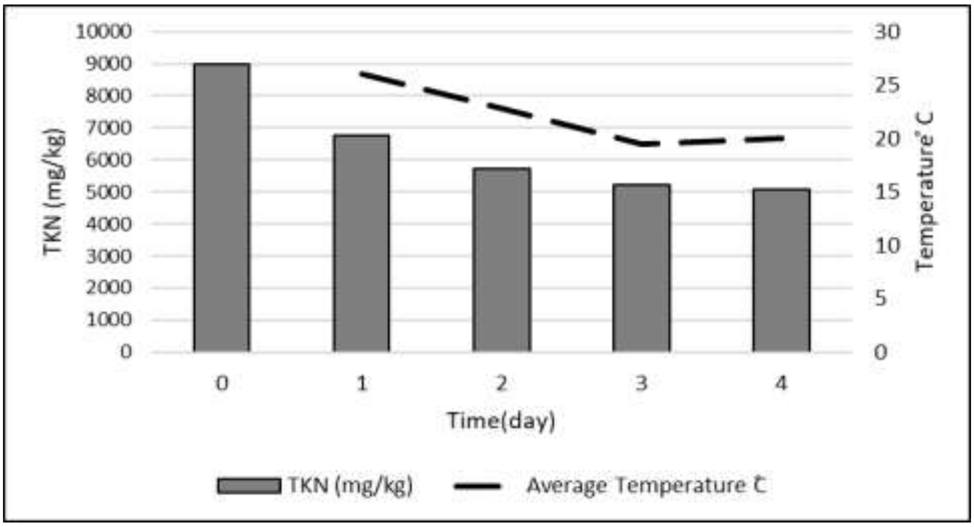


Figure 4.48.TKN reduction after WWTP. sludge solarisation

4.7. E-coli Analysis results

The process of disinfecting sludge with a solar dryer has been studied to reduce the transfer of microorganisms to the environment. The four main pathogens in sludge are: bacteria, viruses, protozoa and helminths. The amount of sludge pathogens depends on its treatment conditions. The main cause of pathogens is due to insoluble solids in the sludge. Escherichia coli (E-coli) is a type of bacteria that is abundant in sewage sludge. Viruses are unable to reproduce in the absence of living host cells and are highly resistant to harsh conditions. Pathogens are inactivated by heat, and heat prevents them from growing. According to studies, pathogens are inactivated if expoed to sun, more than 7 minutes at 70 ° C, 30 minutes at 65 ° C, 2 hours at 60 ° C, 15 hours at 55 ° C and more than 3 days at 50 ° C (Carrington et al. 1998). Pathogens are classified into two groups:

- Group A Treatment Sludge

The number of coliforms in the stool should be less than 1000 per gram of dry matter, salmonella bacteria less than 3 per 4 grams of dry matter, helminth eggs less than 1 in 4 grams, and the intestinal virus should be less than 1 plaque in 4 grams of dry weight.

- Group B Treatment Sludge

The fecal coliforms per gram should be less than 2 million. It is clear that with increasing time, the efficiency of pathogen removal increases. It is not possible to produce sludge without pathogens. According to the US EPA (1989) study, standard sludge produced is in "Class B". At an average daily temperature of 60 °C, the number of pathogens should be reduced by approximately 1 log.

WWTP. sludge is a source of a variety of infectious microorganisms. The population of microorganisms in such systems is reduced by only 2 log10 (Sypuła et al. 2013). The number of pathogens in the sludge depends on the type of wastewater source, treatment plant and environmental factors. In the study conducted by Process Safety and Environmental Protection, the effect of drying on the contamination of wastewater microorganisms has been investigated. Also, (Gontijo et al. 2018), researchers, they mentioned the effect of solar radiation on the reduction of sludge microorganisms. Solar waves, temperature and time affect the activity of microorganisms (Singh et al. 2011). In this study, the EPA method (2006) was used to quantify E-coli. is growed for 48 ± 3 hours at 35°C ± 0.5°C. in an incubator. In this study, E- coli index microorganisms have been investigated in waste sludge. As you can see in Figure 4.49, the amount of E- coli decreases after exposure to sunlight. After 24 hours, the number of microorganisms has decreased by 2 log at an average temperature of 32˚C. Waste sludge is classified based on pathogen density into two levels of class A and B. Due to EPA 503, there are restrictions on the use of waste sludge. According to the European Health Standards Approval, Escherichia- coli concentrations are classified as Class B in West treatment plants. In the research that conducted by (Salihoglu et al. 2007) closed- loop solar drying system sludge pathogen reduction was observed. After the sludge dried, the level of pathogens reaches a minimum and does not pose a threat to environmental health. For the Class A pathogen qualification, with 34˚C sludge temperature after exposure, more than >2312Wh/m^2 the internal cumulative solar radiation 2 log reduction achieved after one day.

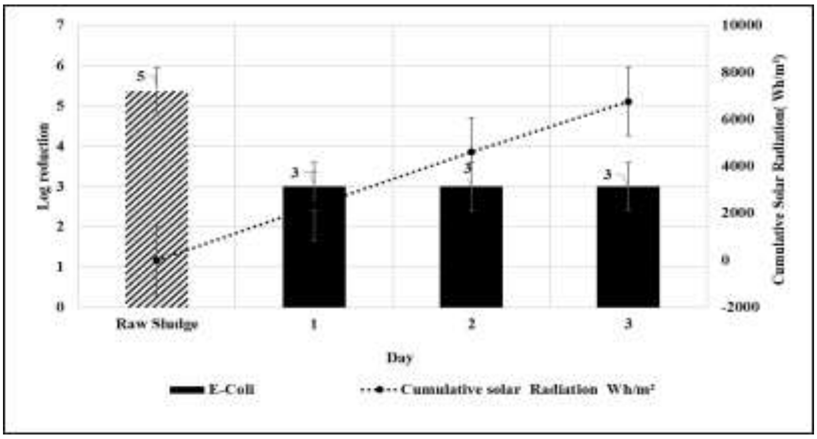


Figure 4.49. E-coli M.O reduction after WWTP. sludge solarisation

The regrowth of microorganisms was examined after drying. Regrowth is defined as an increase in the microbial population following a previous decrease in acceptable numbers. In other experiments, re-growth of E. coli has been observed after the inactivation of the pathogen. Due to temperature disturbances, the bacterial regrowth process after treatment was also observed by keeping the sludge in the dryer after 48 hours at the rate of 1 log reduction.

4.8. WWTP. sludge and paint sludge SEM analysis results

For WWTP. sludge and paint sludge morphology SEM analysis " TESCAN VEGA3 SEM" device was used by 1.01 & 599 magnifications. According to sludge pasty and soft state, it deforms after drying due to cracks and can be clearly seen by SEM device (Skyscan, Belgium). WD also shows the distance between the final pole of the sample and the lens when focusing. The sludge micro-structures after dehydration in both sludges with different moisture content were observed. As you can see in Figure 4.50, holes and pores of different sizes have formed after drying in both samples of sludge, which is more prominent on the surface of the paint sludge. In the adhesive phase of the sludge, only the internal water remains, which is attached to the particles with a stronger bond, so most of these pores are created by the discharge of free water (Manara and Zabaniotou 2012). Marble sludge becouse of smooth surface structure and properties cannot be evaluated by SEM. Dried waste sludge with a moisture content of 11% and paint sludge with a moisture content of 7% have been investigated in this system. Figures 4.50 (A_1 and A_2) with scale of 100 μm and image Fıgure 4.50 (A_3) scale of 50 μm show waste sludge with magnification above 323. The scale of picture Figures 4.49 (B_1) is 200 μm and pictures Figures 4.50 (B_2 and B_3) are 50 μm, scales of paint sludge.

From Figure A_1, and B_1 to A_3 and B_3, the magnification effects on the sludge particles and the water release are clearer. paint sludge particles look more prominent than sewage sludge. Waste sludge structure was the filamentous shape and paint sludge has an amorphous structure and has more surface area due to its chemical structure, also due to the lack of free water in it and porous surface leads to dry in a short time.

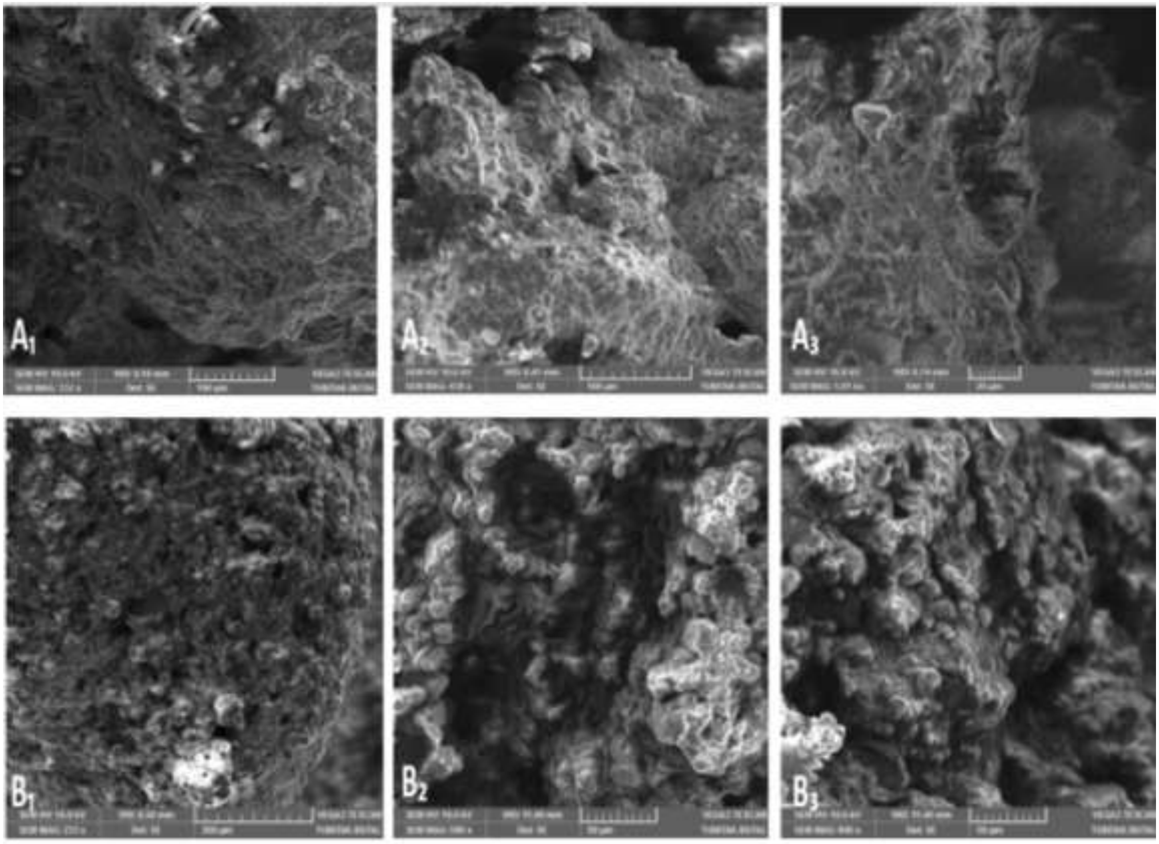


Figure 4.50. SEM pictures. **A_1, A_2,A_3)** WWTP. sludge **B_1,B_2,B_3)** Paint sludge

4.9. WWTP.sludge TGA analysis results

In this study, waste sludge was studied by Thermal-Gravimetry analysis (TGA - SEIKO EXSTAR TG/DTA 6200) to investigate the free water content. The heat flow and mass losses as a function of time and temperature are determined by this method(Karaca et al. 2019); (Müller and Mühlbauer 2012). Figure 4.51 shows the mass change curve of sludge with (TG) and exothermic and endothermic phenomena by (DTA) which characterizes the effect of temperature increase on physical and chemical changes in sludge. TGA curves show thermal degradation in the drying mechanism along with sludge composition changes. The melting points and upper-temperature range is determined by the Thermo-gravimetric analyzer. When the sludge is heated between 0 and 900 ° C, with high thermal stability not much decomposition occurred. The DTA curve at about 502.6C shows an endothermic reaction suitable for sludge decomposition. At 30 ° C, a peak is observed that physically and chemically indicates the removal of water molecules. In the TGA curve up to 534.1 ° C weight loss is seen. The sludge evaporation process is characterized by cracking. Phase change is determined by DTA peaks in the physical (endothermic) process. Figure 4.50 shows the thermal analysis curve. At 21,3–138,9, ℃ Major decrease in endothermic mass, and at 919.1 ° C, minimal weight loss was observed.

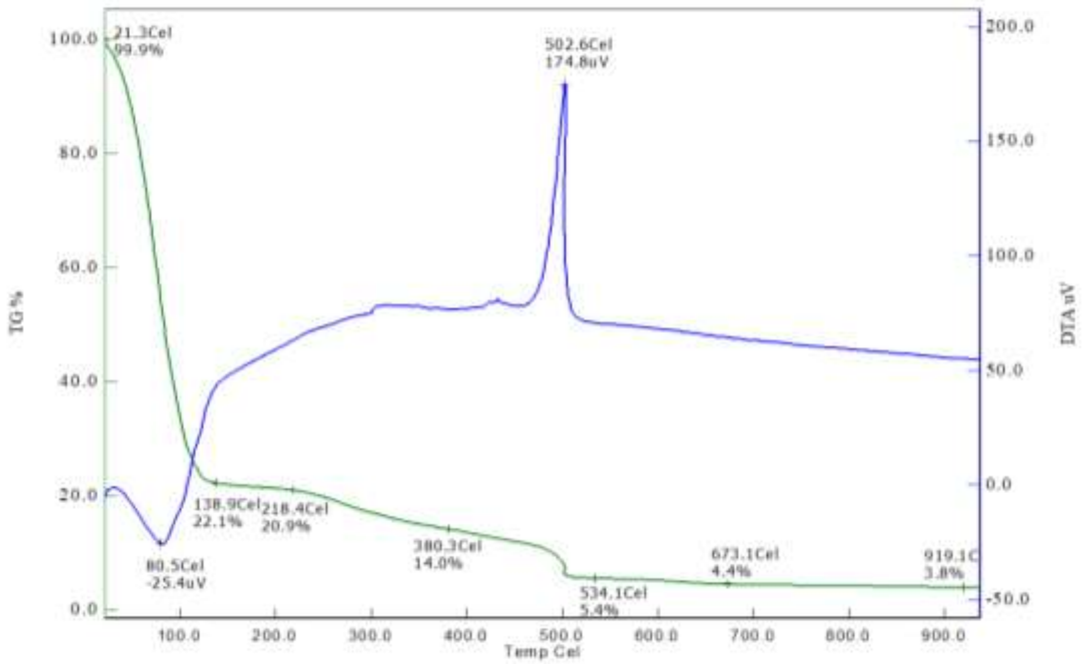


Figure 4.51. WWTP. sludge TGA curve

4.10. Investigation of energy consumption during the drying process of three sludge samples by a moisture analyzer

Solar energy is main sources of various types of energy. The energy consumption of the sludge drying process largely depends on the amount of water in the sludge. The easiest method to absoeb solar energy and convert it to heat is to use solar collectors. Solar devices are technologies for the direct use of solar energy. The amount of solar energy reaching the sludge surface varies according to local climatic conditions, geographical location, and dryer angle. In a study by Saxena and Goel (2013), a vertical collector absorbs about 1000 W/m^2 of sunlight and can increase hot air temperature from 30˚C to 100 ˚C, which can be used to dry agricultural products. The energy collection efficiency of the solar heater is poor due to the low heat transfer coefficient between the absorber plate and the airflow, also the heat transfer rate can be improved by modifying the system, and the same problems have been observed in studies conducted by Chand (2017). Energy is a fundamental factor for the economic growth of any country. The use of solar systems is appropriate for saving conventional fuels and reducing air pollution (Saxena et al. 2015). Solar heaters convert solar radiation into heat and transfer it to sludge. This method improves economic efficiency and reduces the energy consumption of drying systems. Energy consumption is determined by the moisture content of product (Pirasteh et al. 2014).

Each type of sludge contains a certain volume of water and must be dried down to 10% for use in fuel. The energy required for all dryers is between 0,82 and 1,1 kWh/kg of evaporating water(Arjona 2005). In this system, 15 kg of sludge can be easily dried. This system is designed on a small scale and by increasing its dimensions, it can be expanded. This system must be cost-effective to commercialize the project.

In this research, using a moisture analyzer device in a short period, three types of the sludge drying process have been investigated. By Sartorius Moisture Analyzer (MA 150), 0,7 gr. of each sample was dried separately. In the Figure 4.50 comparison of evaporation rate, three types of sludge have been shown. As you can see in the figure below, the water vapor from the drying of the sludge is divided into 4 main parts.

The first type is free water with the largest volume, and evaporates easily during the mechanical drying، because this type of water is not absorbed by sludge particles.

The second part of the water that leaves the surface of the sludge is called interstitial water, which is connected to the sludge particles by capillary force.

The third type of water is the surface water which is joined to the surface of the sludge particles by adsorption force, and the last type is bound water, which is separated by drying.

The free water in the WWTP. sludge evaporated as 50% in the first 7 minutes at consumption of 0,003 kWh energy. Paint sludge free water evaporates at a rate of 54,56% at the same time with consumption of 0,005 kWh. 10% of the water in the marble sludge leaves the sludge surface in the first 1,7 minutes by consuming 0,003 kWh. After the release of free water, the sludge becomes sticky, and in this stage, extracting water from the sludge requires more energy and time.

In the final stage of evaporating, the sludge becomes granular forms. In Figure 4,52 the last step can be seen as white circles in a straight line. The water in this part is known as bound water and is discharged from the sludge with high energy. WWTP. sludge with a moisture content of 79,05% and energy consumption of 0,011 kWh, paint sludge with 60,9% moisture content and energy consumption of 0,009 kWh and marble sludge with a moisture content of 23.1% with consumption of 0,005 kWh completely dried. According to the obtained data, the energy required to dry one kilogram of waste sludge is required 15,714 kWh, paint sludge 12,857 Kwh, and marble sludge 7,1428 kWh of energy.

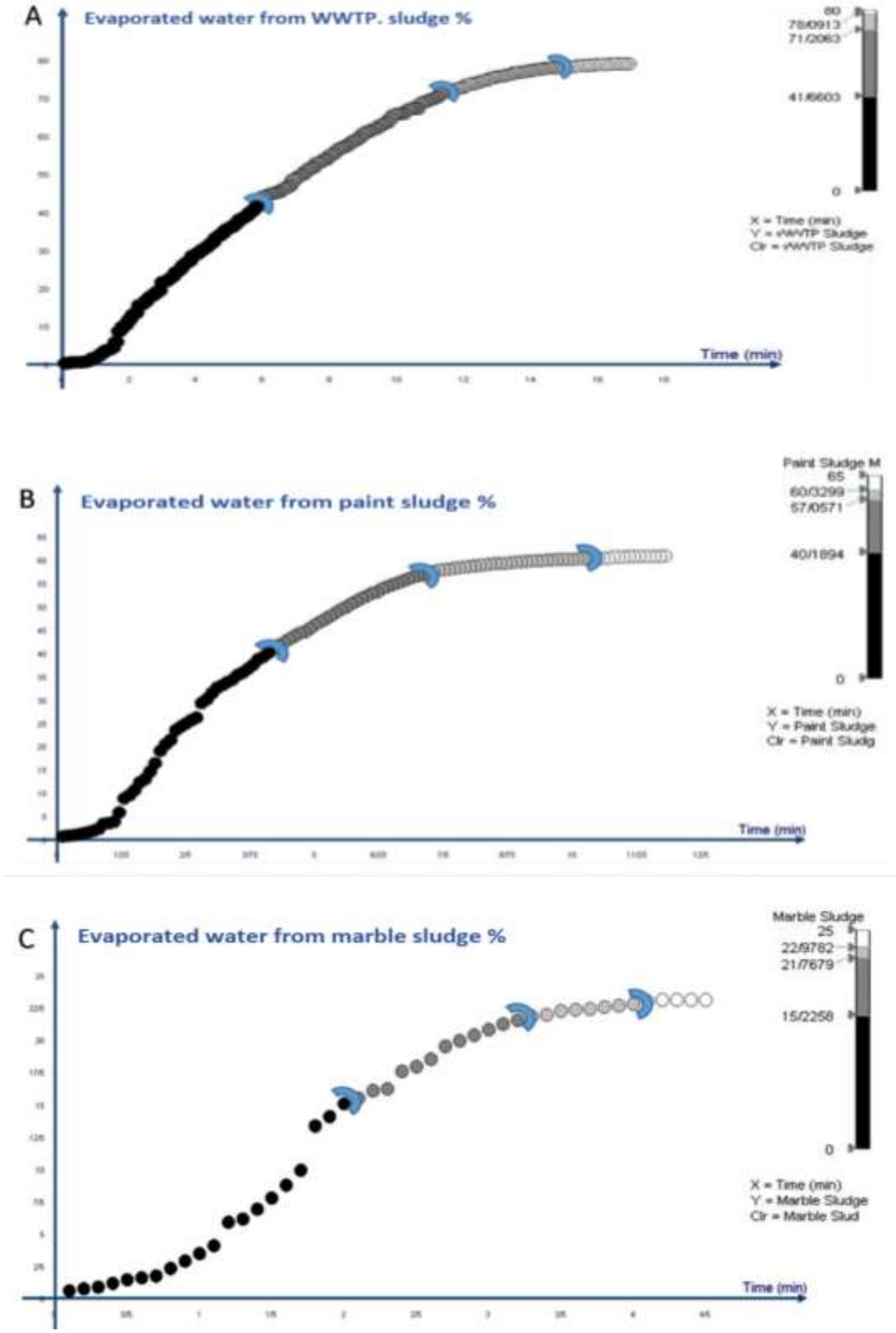


Figure 4.52. Evaluation of three different sludge drying process by moisture analyser, **A)** WWTP. sludge **B)**Paint sludge **C)** Marble sludge

In the absence of a moisture analyzer , the amount of moisture in each sample can be calculated by the following equation.

$$MC = \frac{\mathrm{w} - d}{\mathrm{w}} x100 \qquad \textbf{(4.5)}$$

W=wet sludge weight
D=dried sludge weight
MC= moisture content

4.11. Future Works

Many recommendations are suggested to improve and increase the efficiency of the dryer in the future. This system is not only designed for dewatering sludge, but can also be used for drying food products, as well as disinfecting equipment. In futures researches, more in-depth studies can be done on the release of sludge bound water and the amount and timing of its release in a specific range of solar waves. In addition, by using suitable tools and parts with high thermal conductivity in the system, it increases the internal temperature and accelerates the evaporation process, and by applying various activities, the number of cracks created could be increased. In future studies, geothermal energy can be used simultaneously with solar energy to increase system efficiency. Before building the system, by designing and modeling the 3D of the system to properly estimate the airflow in the interior, and it is possible to prevent gap spaces within the system. In this system, in order to increase the evaporation rate, by installing more fans in different parts, the intensity of airflow can be increased. Also, by using appropriate devices or components, the internal moisture discharge of the system can be improved. In this study, paraffin has been used as a phase change material, but different materials with more latent heat can be used instead of paraffin.

5. CONCLUSION

In this study, by designing a solar dryer and modifying it to improve efficiency during different stages, the effect of environmental and physical factors on the drying of different kinds of sludges was investigated.

In this research, while comparing the types of dryers and the data obtained with previous studies, the heat transfer path on the drying process through numerical studies has been used for the accuracy of the information.

According to the study of mechanical methods, only a very small volume of sludge water evaporates and can not be suggested as a suitable method for dewatering sludge. Active and indirect methods dry more economically and in a shorter time than different dryer types. Drying systems have different types and can be expanded into various shapes. One of our main goals in this study is to get maximum solar energy during sunny hours and to create a constant temperature all day.The results of this study are explained below:

- Dryer modifications include removing glass tubes from the front of the dryer to increase solar energy absorption, also by removing one of the polycarbonate layers caused enough solar radiation to enter the system. Since the moist airflow did not pass through the silicate gel at sufficient pressure and the moisture in the system was not discharged, so the silica gel was removed. Increasing the height of the system from the ground and creating a suitable slope in the orbit improves the dryer performance. Finally, in the last structure of the system, drying is accelerated by spreading the screws on the sludge, for increasing the contact surface. The higher drying temperature reduces the adhesion, but due to the degradation of organic matter, the amount of sludge heating decreases. Increasing the surface area of the sludge during drying increases the drying speed and this can be done by adding steel screws on the sludge and passing the adhesion stage faster. Also use black cover on the floor and reflectors, which increases the reflection of radiation to the glass.
- By comparing different types of phase change materials, paraffin has been suggested in this study due to its cheapness, easy access, and low vapor pressure.

- The distribution of the homogeneous air velocity inside the dryer increases the heat transfer. In all 4 stages, by calculating the conductive heat transfer and comparing the difference between the internal and external temperature, the efficiency of the system was evaluated, and the numerical calculation obtained indicates the increase in the value of Q in each step. The amount of heat transfer in the waste sludge, paint, and marble sludges in the initial stage, are (329, 472 watts), (388,608 watts). and (350 watts), respectively, in the final stage the heat transfer variable are changed to (422,4 watts), (507.30 watts), and (620, 928 watts), which are visible increases.
- In the last stage of the modified system, the efficiency of the dryer without adding new materials in waste sludge, paint, and marble sludge are (20%, 18%, and 6%), but after adding materials related to this stage, its efficiency for each type of sludge changes to (28%, 31%, and 13%) respectively.
- During the different mathematical models in this study, the polynomial model was selected as the optimal model. Due to the fact that the amount of water dispersion in different parts of sludges are not homogeneous and the time spent to get water out of each part is different, so using this model and creating high R^2 values and lower SEE and RMSE cause the better result. Also, by performing Pearson analysis, a linear and significant relationship is obtained between the variable of cumulative solar radiation and the evaporated water for each sludge.
- Using numerical calculations, the amount of water that evaporates during 6 hours was calculated from an area of one m^2. According to the results obtained in the first hours of the evaporation before the waste and paint sludges are dry completely, the amount of water evaporated in paint sludge is more than the waste sludge.
- One of the important parameters in the heat transfer in the system is to pay attention to the choice of materials used in the system. This process is improved by choosing appliances with high thermal conductivity such as copper, and steel.
- waste sludge and paint were examined for morphological changes with different magnifications by SEM device. The holes created in the paint sludge are much clearer and more prominent than the waste sludge, and this is one of the reasons why the free water in paint sludge release faster than waste sludge.

- In addition, through solar drying, in waste sludge ammonia content reduced from 9000 mg/kg TS to 6800 mg/kg by TKN method, and E-coli M.O reduced 2 log after one day.
- The drying process of all types of sludge, in addition to reducing the volume of sludge, also reduces transportation costs, and finally, it is possible to remove the sludge or use it for various agricultural purposes due to its high-water holding capacity.
- According to the study of waste sludge using a TGA device, the effects of temperature on chemical and physical changes of sludge were investigated. A temperature of 502.6 ° C is suitable for sludge decomposition.

In the last step, by using the moisture analyzer, the energy consumed for drying all types of sludge was calculated. The energy spends per kilogram of waste sludge, paint, and marble sludges are 15,714 kWh, 12,857 Kwh, and 7,1428 kWh respectively.

This model is just a small-scale simulation that leads to higher performance for experimental results.

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APPENDIX

APPX 1 Geographical site information (BURSA)

View permissions

PVsyst V7.2.3

Geographical Site	Situation	
BURSA_MN72.SIT	Latitude	40.23 °N
Turkey	Longitude	28.88 °E
	Altitude	90 m
	Time zone	UTC+3

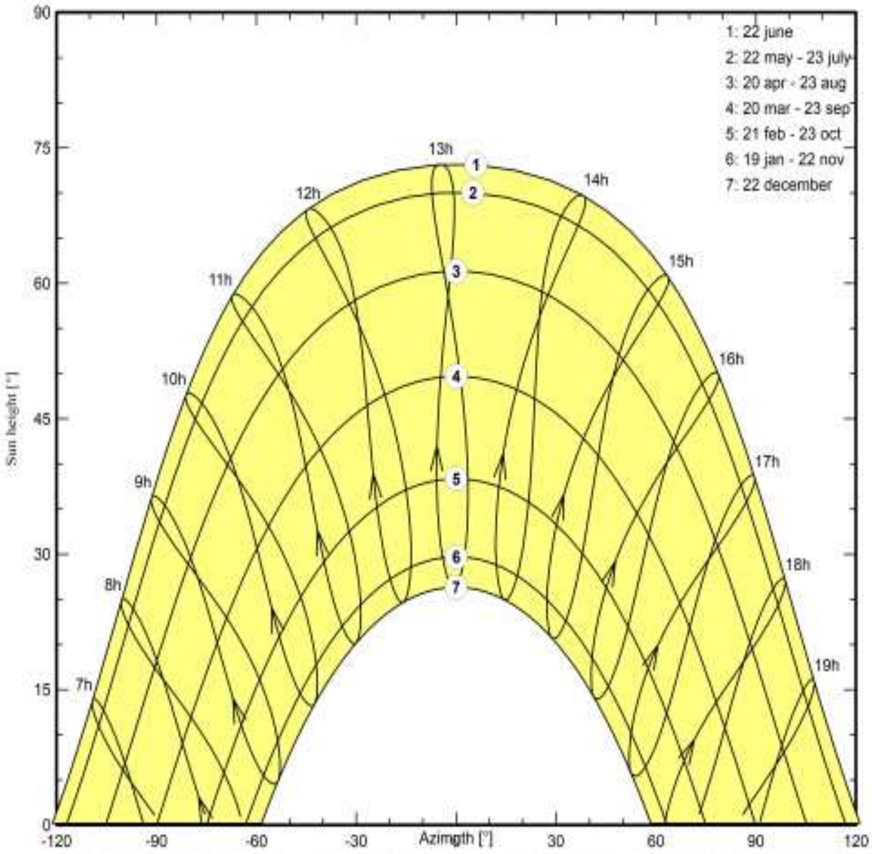
Monthly Meteo Values

Meteonorm 8.0 (2005-2013), Sat=100% (Modified by user)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Horizontal global	56.5	67.2	109.2	147.6	196.4	213.0	219.6	191.3	143.3	93.0	62.7	48.4	1548.1	kWh/m²
Horizontal diffuse	22.4	38.7	61.6	74.3	75.0	74.7	81.4	76.5	54.0	46.0	32.5	27.7	664.7	kWh/m²
Extraterrestrial	131.4	161.8	237.1	289.2	341.6	348.1	351.7	317.4	253.5	199.6	139.8	117.9	2889.1	kWh/m²
Clearness Index	0.430	0.415	0.461	0.510	0.575	0.612	0.624	0.603	0.565	0.466	0.448	0.410	0.536	ratio
Ambient Temper.	5.8	7.2	10.2	13.6	19.1	23.4	26.7	26.8	21.6	16.4	11.5	7.3	15.8	°C
Wind Velocity	2.3	2.4	2.4	2.1	2.0	2.1	2.4	2.4	2.0	1.6	1.6	2.1	2.1	m/s

Monthly Meteo Values

Solar paths at BURSA_MN72.SIT, (Lat. 40.2268° N, long. 28.8777° E, alt. 90 m) - Legal Time



APPX 2 Monthly meteo values in (BURSA)

PVsyst V7.2.3

Meteo

Situation

Latitude	40.18 °N
Longitude	29.07 °E
Altitude	100 m
Time zone	UTC+2

Source file characteristics

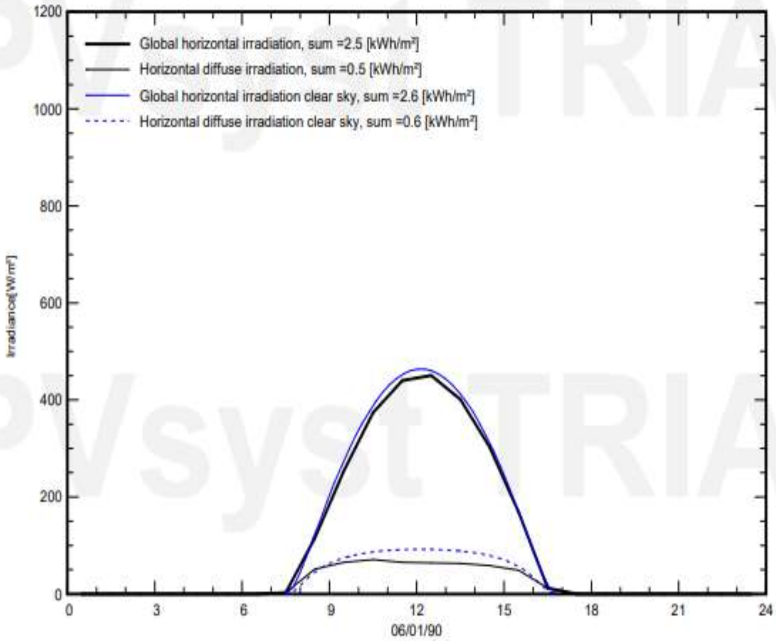
Synthetic Data generation

Source MeteoNorm 8.0 station

Monthly Meteo Values

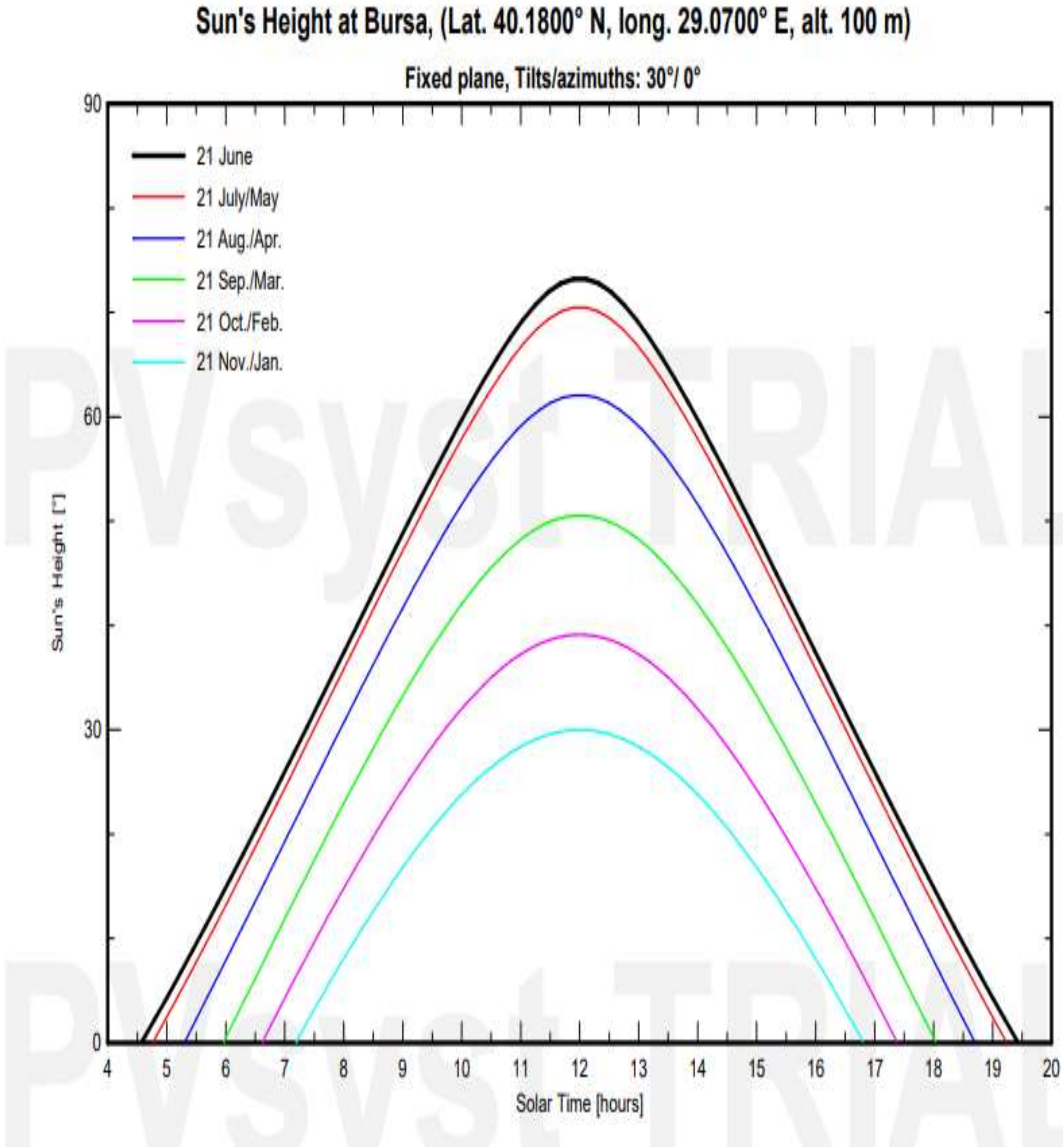
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Horizontal global	47.2	60.1	93.1	135.8	160.3	188.5	193.5	170.5	124.6	80.6	64.4	46.5	1365.1	kWh/m²
Horizontal diffuse	28.6	29.3	58.9	75.1	87.6	85.2	81.7	78.6	56.5	44.6	30.0	21.3	677.4	kWh/m²
Extraterrestrial	131.5	161.8	237.1	289.2	341.6	348.1	351.7	317.4	253.6	199.7	139.9	118.0	2889.7	kWh/m²
Clearness Index	0.359	0.371	0.393	0.470	0.469	0.541	0.550	0.537	0.491	0.404	0.460	0.394	0.472	ratio
Ambient Temper.	5.7	6.5	9.6	13.1	18.5	22.9	25.8	25.5	20.3	16.1	10.3	6.6	15.1	°C
Wind Velocity	2.4	2.4	2.5	2.1	2.0	2.0	2.1	2.1	1.8	1.6	1.5	2.1	2.1	m/s

Meteo for Bursa - Synthetically generated data from monthly values.



APPX 3 Sun's Height at (Bursa)

PVsyst V7.2.3



APPX 4 Clearness index for morning and afternoon hours

PVsyst V7.2.3

Meteo

Situation

Latitude	40.18 °N
Longitude	29.07 °E
Altitude	100 m
Time zone	UTC+2

Source file characteristics

Synthetic Data generation

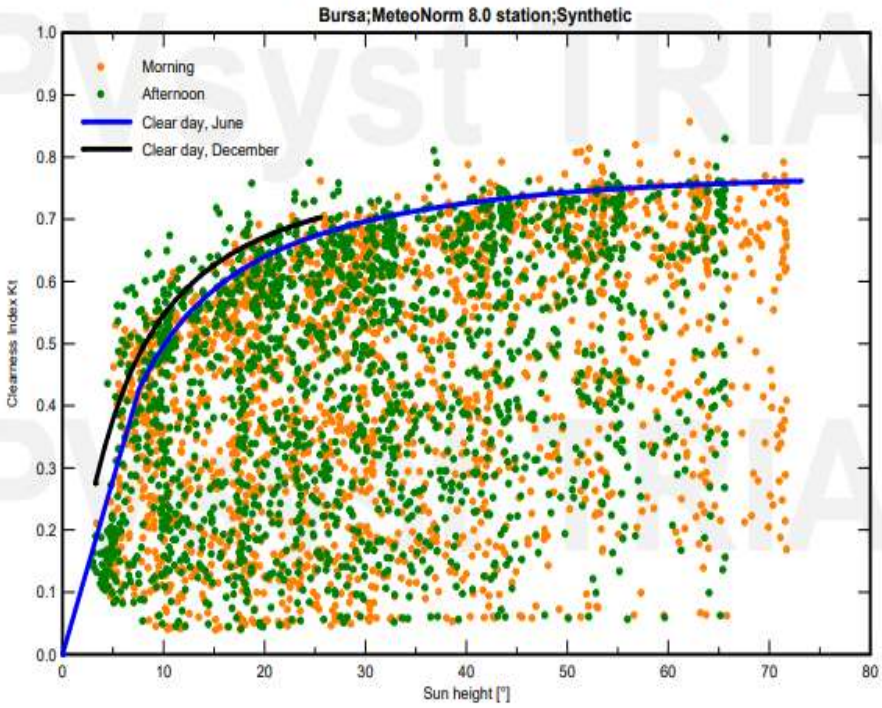
Source MeteoNorm 8.0 station

Monthly Meteo Values

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Horizontal global	47.2	60.1	93.1	135.8	160.3	188.5	193.5	170.5	124.6	80.6	64.4	46.5	1365.1	kWh/m²
Horizontal diffuse	28.6	29.3	58.9	75.1	87.6	85.2	81.7	78.6	56.5	44.6	30.0	21.3	677.4	kWh/m²
Extraterrestrial	131.5	161.8	237.1	289.2	341.6	348.1	351.7	317.4	253.6	199.7	139.9	118.0	2889.7	kWh/m²
Clearness Index	0.359	0.371	0.393	0.470	0.469	0.541	0.550	0.537	0.491	0.404	0.460	0.394	0.472	ratio
Ambient Temper.	5.7	6.5	9.6	13.1	18.5	22.9	25.8	25.5	20.3	16.1	10.3	6.6	15.1	°C
Wind Velocity	2.4	2.4	2.5	2.1	2.0	2.0	2.1	2.1	1.8	1.6	1.5	2.1	2.1	m/s

Clearness Index for morning and afternoon hours

Time shift correction



RESUME

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