Addis Ababa University

Addis Ababa institute of Technology

School of Mechanical and Industrial Engineering

Experimental Investigation of Solid-Liquid Separator and Solar Tunnel Dryer for a Biogas Digestate

A Thesis Submitted to the School of Graduate Studies of Addis Ababa Institute of Technology, Addis Ababa University in partial fulfillment for the Degree of Master of Science in Mechanical Engineering (Thermal Engineering Stream)

By: Tesfamichael Awoke

Advisor: Dr.-Ing. Wondwossen Bogale

June, 2023

Addis Ababa, Ethiopia.

Addis Ababa University

Addis Ababa Institute of Technology

School of Graduate Studies

School of Mechanical and Industrial Engineering

Experimental Investigation of Solid-Liquid Separator and Solar Tunnel Dryer for a Biogas Digestate

By

Tesfamichael Awoke

Approved by the Board of Examiners:

Dr. Wondwossen Bogale Advisor Name	Signature	19/10/2023 Date
Dr. Yilma Tadese Internal Examiner	Signature	19/10/2023 Date
Dr. Kamil Dino External Examiner	Signature	19/10/2023 Date
Dr. Araya Abera School Dean	Signature	23/10/2023 Date
Dr. Sosina Mengistu Associate Director for PG Program	Signature	Date

Director of Postgraduate Program

Addis Ababa University

Addis Ababa Institute of Technology

i

Declaration

I hereby declare that the work which is being presented in this thesis entitled Experimental Investigation of Solid-Liquid Separator and Solar Tunnel Dryer for a Biogas Digestate is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

Tesfamichael Awoke — 19/10/2023 Date

This is to certify that the above declaration made by the candidate is correct to the best of my Knowledge.

Dr. -Ing. Wondwossen Bogale (Advisor) — 19/10/2023 Date

Acknowledgments

Above all, I would like to provide thanks to the Almighty God for the blessings and gifts of time, hope and endurance throughout this research schedule. First and foremost, I would like to thank my advisor Dr.-Ing. Wondwossen Bogale for his offers of helpful and constructive comments, providing the required materials, guiding and encouraging me in all moments of this research work. All the comments, advice and heartful support in both ideally and materially during manufacturing and experimentation time greatly helped me to come up with good and comprehensive result of this thesis. I would like to thank also Dr. Abdulkadir A., Dr. Kamil D., Dr. Yilma T. for their kindness, positive and precious comments and suggestions during this thesis proposal and progress defenses. I am also thankful to Addis Ababa institute of Technology and Mechanical Manufacturing Workshop Assistants; Mr. Hayredin, Mr. Israel, Mr. Anteneh and others for their assisting during the manufacturing and experimenting of this thesis. Finally, I would like to thank my friend and classmate Mr. Biruk H. for his time to assist me during the manufacturing and experimentation time of this research work.

Abstract

Through the 20th century, higher energy demand, fossil fuel depletion, environmental pollution problems and waste management requirements led the development of biogas production technology. However, the biogas plant's slurry/digestate, causes significant environmental issues since it pollutes the soil, water, and air through the release of phosphate and nitrate gases. With the use of mechanical and thermal treatments, digested biogas waste is suitable for use as fertilizer or a soil amendment. In order to use biogas digestate as fertilizer, to minimize environmental pollution and to store and transport it securely and conveniently; liquid components must first be separated mechanically by presses (solid-liquid separator) and then thermally by vaporization (dryer). This study examines the fundamental design of the screw type solid-liquid separator and solar tunnel dryer, manufacturing and laboratory investigations, as well as characterize both the solid and the liquid portions' suitability from the mechanical and thermal parameters such as the portions' final moisture content. By using both the separator and dryer, the moisture content (the liquid fraction) of the fresh biogas digestate is able to reduce from 75% to 5% (from 75% to 40% using the separator and from 40% to 5% using the solar dryer). The separator has a capacity of separating 7.5m^3 of digestate at 8 hours and the dryer has the capacity to dry 2m^3 of digestate at a drying time of 3 days, 7-8 hr. per day at the experimentation site Addis Ababa, 8.9806° N, 38.7578° E. Both the separator and dryer has a cost of approximately 35,000 ETB.

Key words: Biogas, Digestate, Organic fertilizer, Solar dryer, Moisture content

Table of Contents

Table of figures

List of tables

Nomenclature

.

W	Mass of product, kg
C_{p}	Specific heat of water, $\mathrm{kJkg^{-1}C^{-1}}$
C_{a}	Specific heat of air, kJkg.$^{-1}$ $\mathrm{C^{-1}}$
T_{d}	Drying temperature, .$°\mathrm{C}$
T_{a}	Ambient temperature, .$°\mathrm{C}$
T_{e}	Temperature of moist air at chimney outlet, .$°\mathrm{C}$
M_{w}	Mass of water to be removed during drying, kg
m_{w}	Mass of water to be removed per hour, $\mathrm{kgh^{-1}}$
λ	Latent heat of vaporization, $\mathrm{kJkgkg^{-1}}$
m_{f}	Final moisture content, %
m_{i}	Initial moisture content, %
t_{d}	Assumed drying time, h
Q	Total energy required, kJ
Q_{t}	Energy required per hour, kJh.$^{-1}$
Q_{a}	Rate of air required, $\mathrm{m^3}$s.$^{-1}$
Q_{c}	Rate of air flow in chimney, $\mathrm{m^3s^{-1}}$
r	Radius of dryer (m)
L	Length of dryer (m)
Rh_{am}	Ambient relative humidity, %
t_{d}	Drying period, h
I	Incident solar radiation, $\mathrm{MJh^{-1}m^{-2}}$
η	Dryer efficiency
ρ_{a}	Density of air at ambient temperature, $\mathrm{kgm^{-3}}$
D_{a}	Density of exit air, kg $\mathrm{m^{-3}}$
D_{i}	Produced draft

Chapter One: Introduction

1.1. Background

Through the 20th century, higher energy demand, fossil fuel depletion and waste management requirements led the development of biogas production technology in China, Germany, and the US (International Renewable Energy Agency, 2018). To assist ensure the energy and waste management availabilities, biodigesters have been deployed at the household and community levels (Global Conference on Energy Efficiency, 2022). Organic waste, such as municipal solid waste from landfills, livestock waste (manure) from farms or dairies, food waste, wastewater, or plant waste, is digested anaerobically to produce biogas (food and water watch, 2016).

According to research conducted in East Africa, households having access to biogas have benefits such as easier cooking, less time spent gathering fuelwood, and a decrease in the prevalence of respiratory health issues. Additionally, utilizing digestate as fertilizer with pretreatment could increase agricultural output.(Clemens et al., 2018) In anaerobic digesters, which are confined environments without oxygen, waste is broken down by microorganisms into digestate and biogas (Environmental and Energy Study Institute EESI, 2017; World Biogas Association, 2021).

Because of the emissions of CH_4 gas, NH_3 gas, and CO_2, the biogas digestate, the final byproduct of the biogas plant, causes major environmental problems by polluting the soil, water, and air. Digesters for animal waste with no mechanical treatments can cause air pollution, methane leaks, and nutrient leaching from digestate (C Romio, 2021).

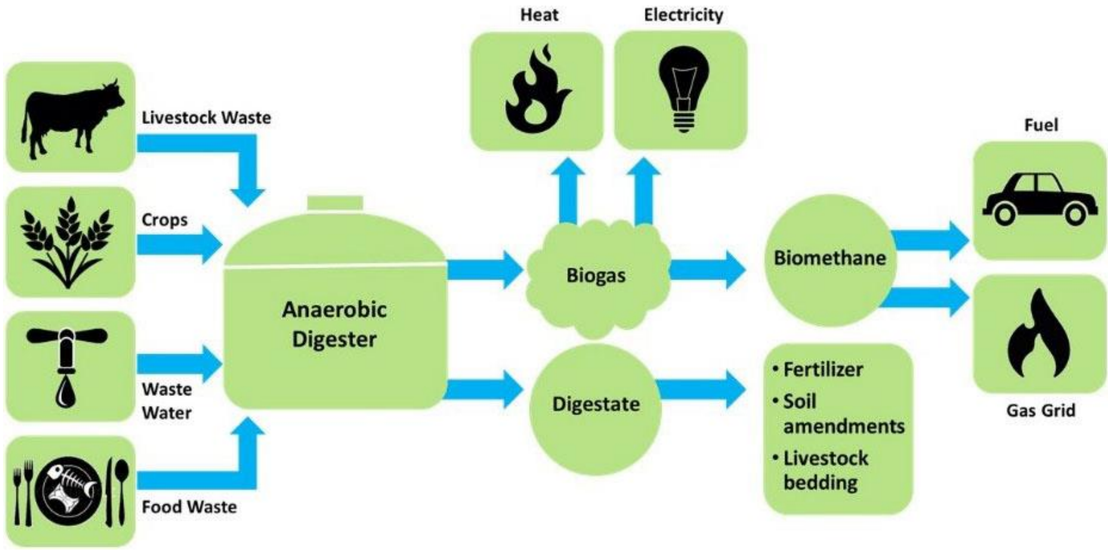


Figure 1: Biogas anaerobic digestion processes

When given mechanical and thermal treatments, digested biogas waste is suitable for use as fertilizer or a soil amendment (Taha M. A. Razek; et al, 2018). Digestate can be separated into liquid and solid parts, for improving its potential for additional processing and increase the usefulness as a fertilizer (Akor et al., 2020). In order to use biogas digestate as fertilizer and to store and transport it securely and conveniently, liquid components must first be separated mechanically from the digestate using presses, and then thermally using vaporization.

Solid-liquid separation equipment which uses the screw for conveying and pressing has the following characteristics: continuously-feed, continuously-discharge, high dehydration rate, compact structure, small footprint, simple installation, low maintenance cost, and the ability to be outfitted with washing accessories.

After separation, drying a solid component removes large amounts of moisture from the solid substance. The process of drying is typically the last in a sequence of steps, and the finished product from a dryer is frequently prepared for packaging. Prior to putting the material through a heated drier, it is advisable to minimize the liquid content as much as is practical. Drying is a relative phrase that simply denotes a decrease in liquid content from a starting point to a satisfactory ending point.

1.2. Problem Statement

Biogas plants always have enough storage capacity for the slurry (digestate) up to a 6-month period. However storing the digestate always generates problems as ammonia, carbon dioxide, and phosphorus oxide are emitted during storage. It is known that digestate has excellent fertilizing property which can keep the nutrient cycle of agricultural plants and increase the fundamental constituents of agricultural lands such as phosphorus, nitrogen and potassium. But a direct use of fresh biogas digestate is forbidden due to firstly, digestate has multiple fertilizer elements and on agricultural lands, using all fertilizer kinds at the same time is not appropriate and secondly, if fresh digestate without mechanical and thermal pretreatments is used in agricultural lands the timely unneeded fertilizing elements are forced to emit to the atmosphere. therefore alternative methods for digestate treatment in particular nitrogen, phosphorus and potassium separation are still needed as a first step. During mechanical separation of digestate into a solid and liquid fractions, nitrogen goes with the liquid portion and whereas phosphorus and potassium are with the solid portion. And further it is still a problem after separation to store the separated portions for long period of time.

Generally solid-liquid separators cannot exceed 65% total solid content (TS); so to get a long-lasting commercial product, water content of the dewatered must be reduced with the suitable drying processes. And still most solid-liquid separation and drying processes requires electricity to derive fan , pump, and motors, which is problematic due to higher consumption of energy and unavailability of electricity in rural area biogas which primary purpose is for heating only. Therefore, it is necessary to design digestate separating and drying systems without the use of electricity for the mechanical and thermal treatments of bio-slurry or digestate to be used as an organic fertilizer.

1.3. Research Objectives

1.3.1. General Objective

The general objective of the research is to design, manufacture and experimentally investigate solid-liquid separator and solar dryer for a biogas digestate.

1.3.2. Specific Objectives

The specific objectives of the research include

- To design solid-liquid separator of the biogas digestate and model and analyze the screw.
- To design solar dryer for the solid portion of the separated digestate and model and analyze the drying chamber.
- To select available materials and manufacture both the solid-liquid separator and the solar dryer in the laboratory.
- To test both the separator and the dryer with sample digestate, describing the drying time and temperatures and characterize the sample digestate from mechanical and thermal treatments side.

1.4. Scope of the Study

The scope of this research is mathematical designing, modeling and Simulation of screw and drying chamber using Solidworks and Ansys softwares, laboratory manufacturing of both the separator and dryer and conducting experimentations with a sample biogas digestate. The manufactured separator and dryer equipment have the capacity to provide a treated organic fertilizer for $8m^3$ biogas plant with total of three days. The two equipment have reduce the moisture content of fresh digestate from 75% to 5 % in common.

1.5. Structure of the research

This thesis report has six chapters in the following logical order. The first chapter is introduction which clearly states about background of biogas plants and organic fertilizer, problem statement and research objectives, the second chapter is literature review which is composed of theoretical backgrounds, types, previous related research works and their gaps about the separator and dryer; the third chapter is methodology which states the methods of data collection and analysis, flowchart of processes, and the important equations which can be used later; the fourth chapter is the design analysis which consists subtopics of detail design of parts and assembly of screw separator and solar dryer; the fifth chapter is results and discussion and under this chapter the simulation result contours, calculated and record tables, manufacturing processes and cost analysis with clear explanations, comparisons are stated, and the last chapter, chapter six is about conclusions and recommendations.

Chapter Two: Literature Review

2.1 Theoretical background

Every living plant cell contains phosphorus (P), which is essential for plant growth. It participates in the processing of sugars and starches, photosynthesis, energy transport, and other vital plant processes. The resource phosphorus (P) is scarce but crucial. P can be recovered from waste but it cannot be replaced. The circular economy and the 4Rs (reduction, recovery, reuse, and recycling) can make p recovery more sustainable[Anna et al., 2020].

During solid-liquid separation of a biogas digestate, nitrogen, one of the most important nutrients in the digested residue, bind to the separated liquid fraction, which makes it an excellent N-fertilizer concentrate. Phosphorus and potassium typically bind to a separated solid fraction(C Romio, 2021). Nitrogen is an essential macronutrient for plant function and is a key component of amino acids, which form the building blocks of plant proteins and enzymes.

Because N is mostly contained in the liquid fraction, S/L by press screw does not allow for a significant amount of N from digestate to go through solid fraction (Fulvia Tambone et al., 2017). There is a widespread belief that the liquid fraction of digestate acts as an effective fertilizer due to its high N and other nutrient contents and that the solid fraction of digestate can act as an organic amendment because it contains high amounts of DM and organic matter (P and K).(Fulvia Tambone et al., 2017). Due to its high ammonia concentration, the liquid portion of digestate has been suggested as an useful mineral fertilizer (nitrogen fertilizer) replacement (Riva, C. et al, 2016). Modern food production is heavily dependent on industrially manufactured mineral fertilizers. The Haber-Bosch process fixes most of the nitrogen used in agriculture and accounts for 1-2% of the world’s total energy consumption and 3-5% of the world's natural gas consumption. By replacing mineral fertilizers with organic fertilizer, digestate can considerably reduce emissions.

SLS separates digestate into multiple streams with varying characteristics, most commonly divided into two streams known as the liquid and solid fractions. The liquid fraction has reduced total solids (TS) compared to the unseparated digestate, is more easily transported via pumps, and reduces NH_3 emissions when land applied due to a rapid infiltration (Guilayn et al., 2019). The solid fraction has increased TS and nutrient density that can reduce overall farm hauling costs if managed effectively (Husfeldt et al., 2012).

In addition, studies have reported that SLS systems can reduce GHG emissions related to digestate management by 20% when compared to a system with no processing (Aguirre-Villegas et al., 2014).

2.1.1 Biogas Technology

Biogas technology provides multi-purpose importance such as delivering useful heat, generating methane gas, which used for electricity generation, combination of both heat and electricity, specially, biogas's byproduct, digestate can be used for landfilling at the farms of agriculture in an alternative way to mineral fertilizer. The input substrate for the biogas can be liquid or solid animal dung, waste water, and organic wastes from industries such as wastes from brewery industries are all used raw materials for biogas production in a biogas digester.

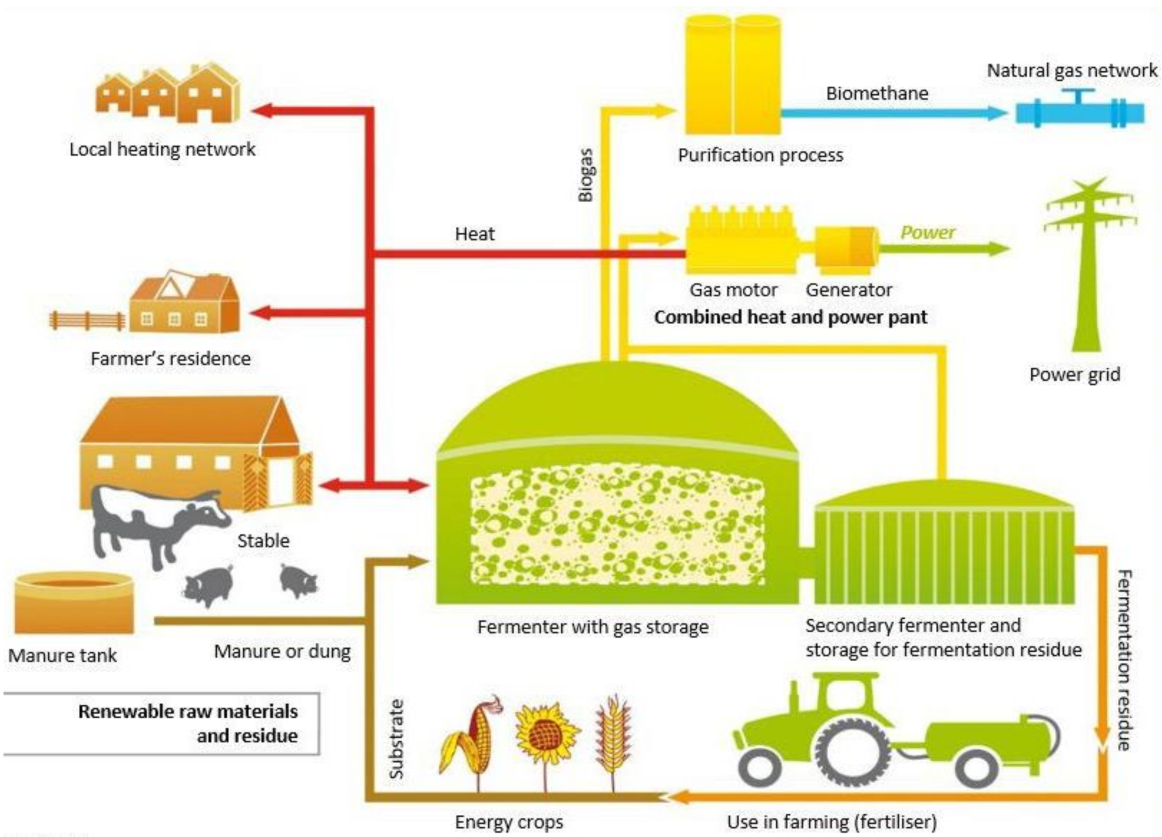


Figure 2: How anaerobic digestion biogas/biomethane plant works (Clean energy wire, 2021)

Large amounts of digestate are left over after anaerobic digestion, in addition to the creation of biogas. Generally speaking, the digestate is rich with nutrients for plants and it can be used as an organic fertilizer. Digestate's soil amendment capabilities stops the structural degradation of agricultural soils. However, the use of digestate in agricultural operations is constrained by strict rules. As a result, digestate storage and transportation are required. Still, digestate's mass and volume rise due to its high water content, making storage and transportation hard. Additionally, a high moisture content raises the possibility of microbial growth, which might result in decays of compositions of digestate during the course of storage (European Biogas Association (EBA), 2020). Therefore, dewatering and drying of digestate is considered as a necessary treatment, because

- Separator and dryer are used for lowering the material's mass and volume, noticeably transportation costs too.
- Drying enhances storability.
- Compared to fresh digestate, NH_3 emissions from dried digestate are significantly lower.
- For enhanced marketability, the dried digestate might be pelletized.

2.1.2 Status of Biogas Technology in Ethiopia

Even if Ethiopia is the leading country in Africa with the number of cattle,(Lars Kamer, 2022) it's energy system is dominated by biomass energy (Amigun, B. et al., 2012). When managed and used appropriately, animal waste collected at the home level has the ability to provide enough biogas energy to cover any energy shortfalls in households, thereby reducing the need for wood fuels (Eshete, G. et al, 2006).

The market-driven installation of 18000 high-quality biogas plants and its provision of clean energy to homes for lighting and cooking and the promotion of the use of bio-slurry or biogas digestate as organic fertilizer has supported by SNV. SNV has been working with the existing private companies of Ethiopia to manufacture and supply biogas appliances/ accessories and promoting the use of bio-slurry as a high value organic fertilizer and this builds on the successful installation of 8161 biogas plants from 2009 to 2013.

2.1.3 Digestate as an organic fertilizer; importance ,constituents and characteristics

Microorganisms are the main parts for AD process, which results in biogas and two renewable energy sources that may be used to generate power, heat, and fuel. Digestate, a byproduct of biogas plants, contains nutrients that can be applied to the ground as fertilizer (Europian Biogas Association (EBA), 2022). The volume of the digestate is always between 90 and 95 percent of what was fed into the digester and is made up of leftover indigestible material and dead microorganisms the digestate will still contain all of the nitrogen, phosphorus and potassium that were present in the feedstock. When compared with raw slurry, digestate's the nutrients are more readily available and are simpler for plants to utilize the nutrients. The nutrition of the animals affect the precise make-up of digestate, however, the following are some normal nutritional values.

- 2.2 - 4.2 kg/ton of N
- 0.2 - 1.5 kg/ton of P
- 1.3 - 5.2 kg/ton of K (Biogas info, 2022)

The use of digestate as a soil fertilizer and/or improver has many agricultural benefits, and research on its suitability for application to land has just recently begun to examine the environmental concerns connected with its use. Digestate can be applied to the soil after mechanical separation to obtain a solid fibrous material (solid digestate, SD) which can then be spread directly on the field, composted, or dried for temporary storage and transportation (Roberta Pastorelli et al., 2021).

Organic fertilizers that offer an appealing replacement to frequently used mineral fertilizers and they have the potential to fundamentally change the agriculture sector in developing countries. In a number of sectors digestate has excellent fertilizing abilities and can be used instead of mineral fertilizer for agriculture because it contains all the micronutrients necessary for farming lands including nitrogen, phosphorous and potassium. Digestate can also be used to complete the nutrient cycle and reuse these important minerals (Biogas info, 2022; Europian Biogas Association (EBA), 2022).

Mechanical de-watering technologies are usually applied in order to increase the dry matter content of digestate. However, the output still has considerable amounts of water, so that after mechanical separation the percentage of the solid fraction is at most 35% (Sutherland, K. S., 2015). Evaporation can be used to concentrate digestate or boost the amount of dry solids. By using thermal energy (heat), evaporation raises the concentration of nutrients and solids while releasing moisture from the digestate (NEO Energy, 2015). But high temperatures of thermal drying will release ammonia to the atmosphere. This can be avoided by lowering the drying temperature and time (HRS Heat Exchangers, 2010). The dried digestate is used as an organic fertilizer. The dried product can easily be stored for a long time and has a suitable particle flowability for applications using conventional farm fertilization machinery, as well.(Riva, C. et al, 2016) Furthermore, the NH_3 emissions from dried digestate with a higher dry matter content are lower compared with those from moist digestate (Fulvia Tambone et al., 2017).

All organic materials can release powerful GHGs such as methane and nitrous oxide if they are left in contact with the atmosphere.

2.2 Solid Liquid Separation techniques

A first step in the design of a separation system is to choose the most appropriate technology from filtration, sedimentation, or a combination of these two methods. In general, sedimentation techniques are cheaper than those involving filtration; the use of gravity settling would be considered first, particularly where large, continuous liquid flows are involved.

2.2.1 Density separation processes

2.2.1.1 Pneumatic flotation

A nozzle or the hollow shaft of the mixer itself is used to draw air into the liquid, which is subsequently distributed into tiny bubbles in the rotor/stator system and mixed with the suspension in a very turbulent flow. The froth needs to have the ability to rise up under calm conditions following turbulent dispersion and mixing. Flotation columns can range in height from 5 to 15 meters, with a maximum diameter of 4 meters. Here, the countercurrent is fueled with gas and suspension. As a result, selectivity is increased as compared to mechanical flotation devices (Fuerstenau, M., 2007).

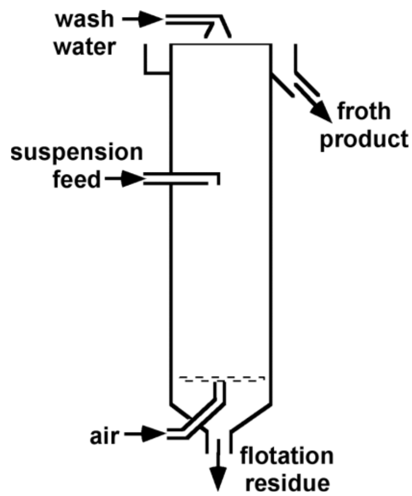


Figure 3: Pneumatic flotation apparatus (Fuerstenau, M., 2007)

2.2.1.2 Hydro cyclone

Here, tangential injection under pressure rather than the rotation of a solid bowl is used to accelerate the suspension that needs to be separated. The tangential intake forces the liquid on spiral circular routes into the cylindrical/conical process room. As a result, particles up to a particular cut size are discharging as a concentrate via the underflow apex orifice, settling outwards through the apparent potential vortex, splitting at the solid wall of the cylinder. The main portion of the liquid and the smaller particles are extracted through a cylindrical tube that is positioned in the middle of the top and extends a short distance into the cyclone as the smaller particles follow the streamlines (Anlauf, H., 2007).

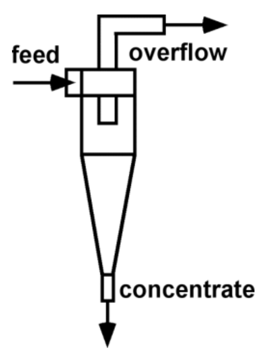


Figure 4: Hydro cyclone(Anlauf, H., 2007)

2.2.2 Filtration

2.2.2.1 A worm screen centrifuge

It is also possible to combine continuous filter centrifuges with an internal machine component that thickens the slurry first through pure sedimentation. For press filtering of suspensions that are creating compressible filter cakes, hydraulic or mechanical pressure may be used. In the rather uncommon scenario of discontinuous piston and tube presses, maximum filtration pressures of about 10 MPa are used, depending on the flow resistance of the originating filter cakes. For discontinuous frame, chamber, and diaphragm presses, pressures of up to 2 MPa are utilized. For continuous screw and belt presses, comparatively low pressures of about 0.1 MPa are used. The discontinuous filter press is one of the most often used filter equipment for solid-liquid separation of moderately challenging mixtures to filter (Sutherland, K. S., 2015).

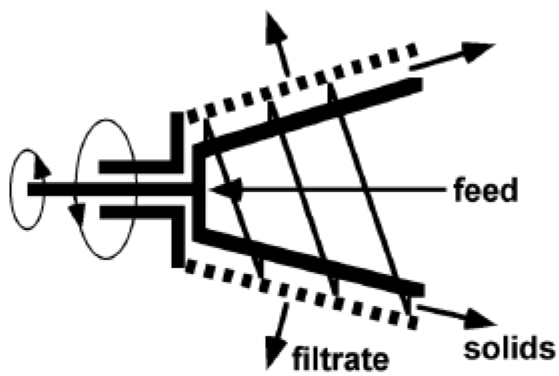


Figure 5: Worm screen centrifuge (Sutherland, K. S., 2015)

2.2.2.2 Screw press

A transport and press screw that is slowly moving in a sieve basket receives the suspension that needs to be separated. Metallic wedge wire screens are employed as the filter media. Conical sieve basket diameter and the space between screw blades decrease when moving in one direction. As a result, the solids are crushed and the volume that is available to them gradually decreases. The filtrate passes through the filter medium, enters the screw press's housing, and is then directed away from it. The sieve basket releases the squeezed and dewatered solids to the press channel's terminus. To prevent pore clogging, the screen must be cleaned periodically from the outside using a powerful water spray (Lyko, H., 2016).

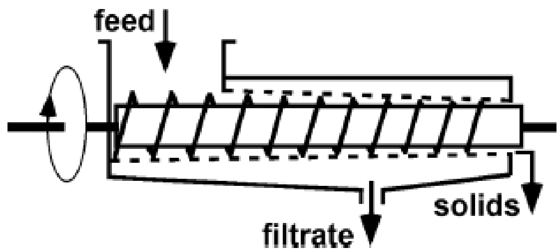


Figure 6: Screw press (Lyko, H., 2016)

The screw press is common technology for digestate separation; it is effective mechanical separation method. Different feedstocks can be accommodated by altering separation efficiency, for instance by changing the screen size. A screw press may reach about 40% dry matter content of the separated solid fraction, depending on the feedstock material (C Romio, 2021).

2.3 Theoretical framework of solar dryer for the solid portion of digestate

The solar dryer is a device which uses solar energy for drying. There are several processes by which heat can be transferred to a substance like conduction, convention and radiation. Various types of solar dryers have been developed as an alternative to open-air sun drying and other conventional drying methods. These include cabinet type solar dryer suitable for small scale use, roof integrated solar heating systems and solar dryer based on flat plate collectors. Solar heated air can suitably be used for space heating during winter in cold regions and can meet process heat requirement in industries. There are different type solar dryer used for drying application worldwide.

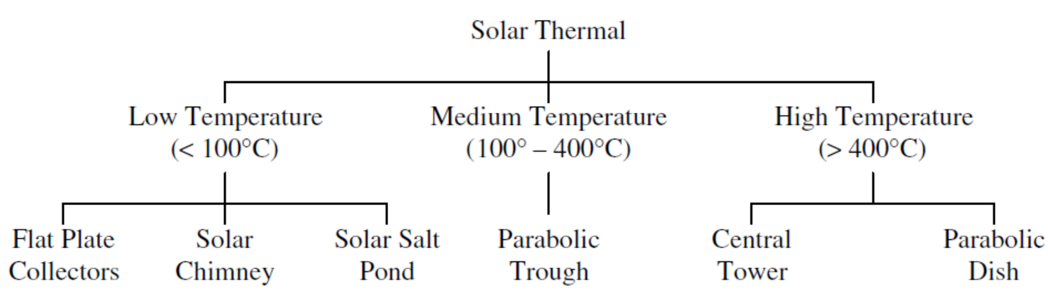


Figure 7: Categorization of solar thermal technologies according to temperature (Muruganantham et al., 2021)

2.4 Methods of drying

There are three fundamental ways to dry things out.

1. Open-air drying and solar drying.
2. Atmospheric drying, including batch (kiln, tower and cabinet dryers) and continuous (tunnel, belt, belt-trough, fluidized bed, explosion puff, foam-mat, spray, drum and microwave).
3. Sub-atmospheric dehydration (vacuum shelf/belt/drum and freeze dryers).

The last method uses either fuel or electricity, whereas the first two rely on solar energy for drying. The choice of fuel mainly dependent on ones capacity to invest higher initial costs and continuous buying of fuel costs. Therefore, the choice of drying method depends on the type of the product, availability and cost of the dryer, energy source and consumption, cost of dehydration and the final quality of the dried product (Sagar and Kumar, 2010).

2.4.1 Open-air drying

The oldest method of drying, sun drying (open-air drying), is still used in many regions of the world today. People have utilized open-air drying for thousands of years since it is the most affordable source of heat (Salunkhe et al., 1991) and requires no equipment. Dust, rain, and gloomy weather are the main obstacles to sun drying. It needs a continuous follow up throughout the drying period to protect domestic animals, and to remove the produce when the weather becomes too windy, dusty, or rainy. The dried product is often of poor quality as a result of dirt (Bala and Janjai, 2009) Furthermore, it requires much land compared to solar drying (ITDG, 2004).

2.4.2 Solar drying

Recent efforts to improve open-air drying have led to solar drying. Hence, solar drying is said to be an elaboration of sun drying and is an efficient system of utilizing solar energy (Zaman and Bala, 1989; Bala and Janjai, 2009). Under solar drying complete drying is possible due to higher drying temperatures (Bala and Janjai, 2009).

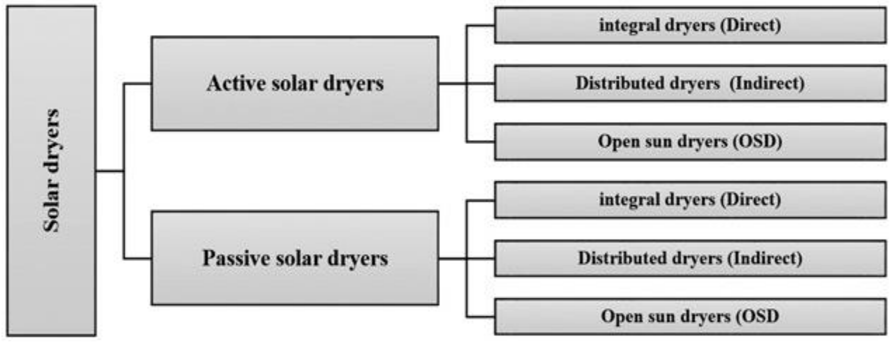


Figure 8: Classification of solar drying systems

2.4.3 Mechanized drying

Open-air drying has been mostly supplanted by automated drying in industrialized areas. In this process, incoming air is heated by boilers and sent through at a high speed to speed up the drying of the produce. Compared to open-air and solar drying, mechanical drying utilizes far less area and produces goods that are often of higher quality. When compared to solar heating, it typically allows for improved drying rate control and continuous drying. However, the apparatus is expensive and needs a large amount of fuel or electricity to run.

2.5 Principles of drying

The moisture level of a biogas digestate ranges from 65% to 85%. In a solar tunnel dryer of the natural convection variety, the air inside the dryer is naturally heated by the phenomenon known as the greenhouse effect. The drying process is accelerated by hot air flow, and the movement of an air mass around a product involves complex thermal processes. Sahin and Dincer (2002) assert that air velocity and drying air temperature have an impact on the extent of transfer of heat and moisture elimination. Air velocity in a natural convection dryer is influenced by the draft created by the temperature difference. As hot air passes over produce, a little pressure difference occurs. This pressure difference is what causes moisture to move from the produce's inner core to its outer layer. As moisture starts to evaporate, the relative humidity rises and the evaporated moisture is carried away by the air (Van Arsdel and Copley 1963)..

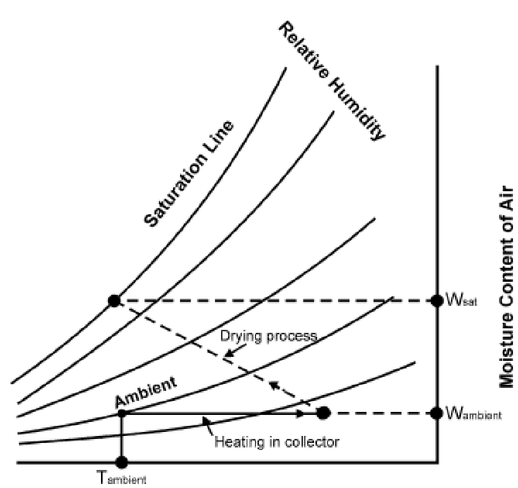


Figure 9: Drying processes on psychometric chart (Simo-Tagne, 2021)

The reasons why solar tunnel dryer is better than other types of dryer for biogas digestate are listed below.

1. The construction is straightforward, and humidity and temperature control are simple.
2. Large-scale material loading and unloading is simple.
3. A more affordable model for industrial-scale commodity drying.
4. Moderate design based on particular requirements.
5. Local craftsmen can create the system using less expensive materials that are readily available.
6. It is simple to dry any industrial or agricultural product with free moisture.
7. This is a novel idea for the widespread integration of solar energy.

Chapter Three: Methodology

3.1. Experimentation Site and System description

A manual/motor operated screw press solid liquid separator and natural convection solar tunnel drying system have been designed and developed for separating and drying biogas digestate. The data of both the separator and the dryer has been used at Addis Ababa institute of Technology, thermal engineering experimenting site ($8.9806°$ N, $38.7578°$ E) for the separating and drying of digestate's moisture content from 40% moisture content to 5% moisture content. The solar tunnel dryer is consisted of a hemicylindrical metallic frame structure covered with UV stabilized semi-transparent plastic sheet of $30\mu m$ thickness. The product to be dried is put into a continuous tray in thin layers. A chimneys were placed at the outlet part of the tunnel, the shape of the chimney is a divergent or conical structure to make a pressure difference for the air movement. The air gets heated and owing to density difference moves upward through the product and picked up moisture and finally passed out through chimney.

3.2. Data Collection and Analysis Methods

The data which have been incorporated in this research were both primary and secondary data of biogas digestate, solar radiation, constant parameters of the manufacturing materials, the working fluid (air), selected fixed property standard materials (such as bearings) etc. The secondary data were elemental constituents of both the fresh digestate and the portions after separation and drying, biological and chemical properties of artificial (mineral) fertilizer and its constraints. The primary data were all the measured and calculated parametric values such as recording temperatures, recording time, volume flow rate (mass flow rate), percentages of moisture contents of both the solid and liquid as well as the fresh digestate, mass values of inlet and outlet portions of the screw press separator etc. The excel sheet format recorded values of temperatures at different points of the dryer, are then analyzed using matlab software.

3.3. Experimental procedure

The digestate separating and drying experiments of this study has been carried out in the laboratory which the separator has the options to use both manual operating and using electrical motor driver unit (motor) and the drying air is using a natural convection air circulation system. A digestate with a specific volume has been used for experimentation in the laboratory. To increase the dry matter (DM) content, the solid and liquid fractions of the digestate have been separated using a press screw separator first and after separation, both portions are considered as nutrient rich organic fertilizers and the dewatered solid digestate has been set up for drying experimentation under the solar dryer.

A laboratory scale screw press separator and solar tunnel dryer are used for the trials. Solar intensity, temperatures at different points of the dryer; at the inlet, at the middle points of the three segments, at the center points of the left side insulator, the right side insulator, the bottom insulator, temperature at the outlet (chimney) and ambient temperature were measured with fixed time intervals. Temperatures were recorded using different temperature measuring instruments. Thermocouple with data acquisition device and infrared thermometer were used to record the temperatures at different points such as at the inlet, at different points of the drying chamber, chimney, south wall, north wall and bottom insulators.

Finally, the dried solid digestate characterization parameters and suitability to use it as a fertilizer has been analyzed. The equation previously employed by other researchers examining digestate, digestate fractions, and slurries was utilized to measure separation efficiency (% SF and% LF, fresh weight -FW).

Figure 10: Temperature measuring instruments used

(a) Infrared thermometer (b) thermocouple (c) glass thermometer

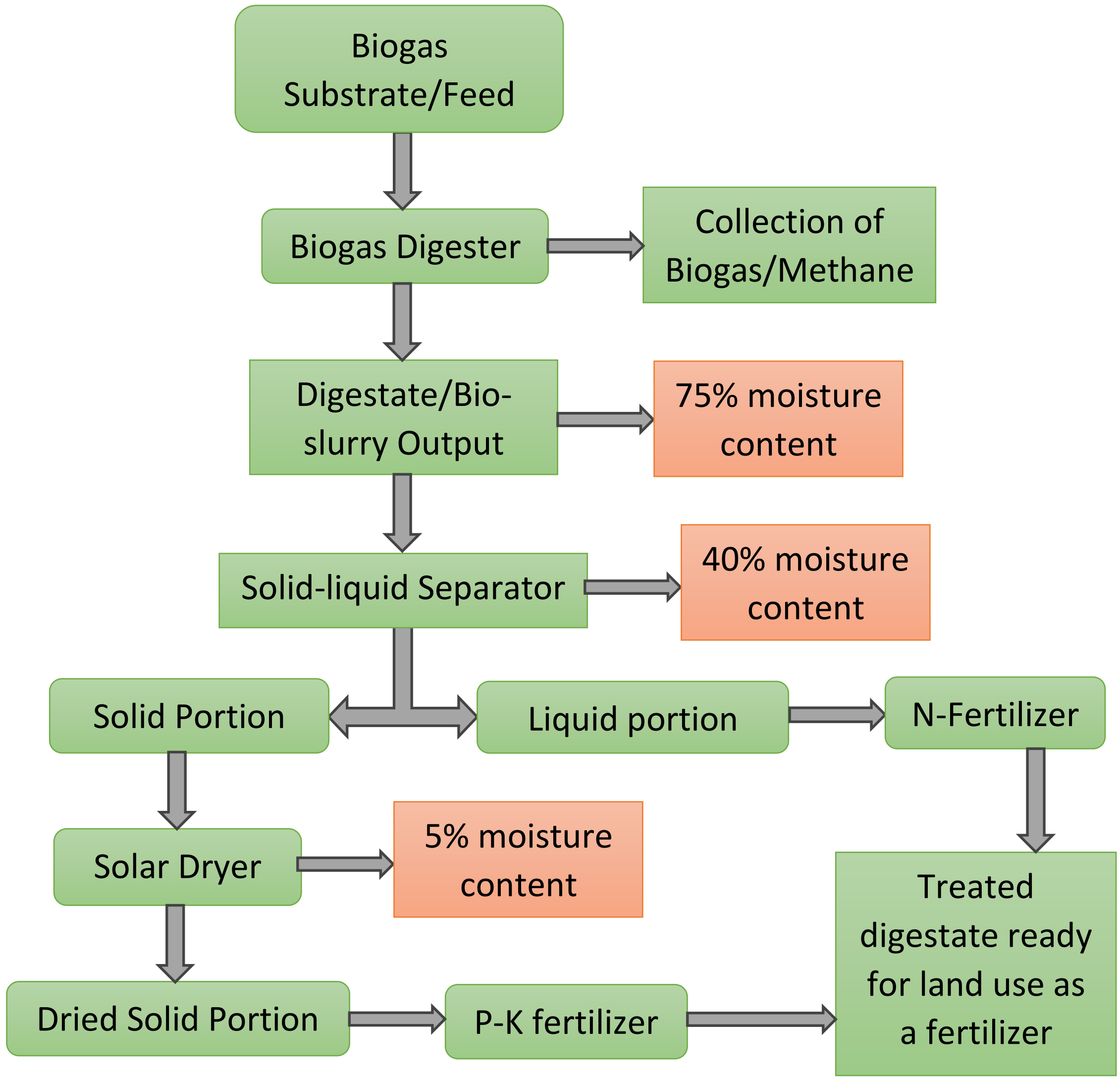


Figure 11: Flowchart of sludge /digestate treatment processes

3.4. Equations commonly used in the Design Analysis

Stress is the force applied per unit area.

$$\sigma = \frac{F}{A} \dots\dots\dots \; 1$$

Where, σ *is stress*

F is force in N

A is area in mm^2

Torque is twisting effect of the force.

$T = F * R$……….. 2

Where, T is torque in N.m

F is Force in N

R is radius (perpendicular to force) in mm

Moment is the magnitude of a turning effect produced by force acting at a distance, expressed as the product of the force and the distance from its line of action to a given point.

$M = F * D$………..3

Where, M is Moment in Nm

F is Force in N

D is distance in m

Polar Moment of Inertia is a quantity used to predict an object's ability to resist torsion, in objects (or segments of objects) with an invariant circular cross section and no significant warping or out-of-plane deformation.

Hollow cylinder

$J_{Z=\pi(D^4-d^4)}$ ……….. 4

Solid cylinder

$J_Z = \frac{\pi d^4}{32}$………. 5

Where, J_Z is polar moment of ineria

d is internal diameter in mm

D is outer diameter in mm

R is the radius in mm

Rating Life

is defined as the life of a group of apparently identical ball or roller bearings, in number of revolutions or hours, rotating at a given speed, so that 90% of the bearings will complete or exceed before any indication of failure occur.

$L = \left(\frac{c}{w}\right) * 10^6\ revolutions, C = W\left(\frac{L}{1000000}\right)^{1/k}$………6

Where, L is rating life

C is basic dynamic load rating

W is equivalent dynamic load and

K = 3 for ball bearing and

= 10/3 for roller bearing

Equivalent twisting moment is the sum of bending moment and torque

$T_e = (M_b^2+T^2)^{1/2}$ …… *7*

Where, T_e is equivalent twisting moment Nm

M_b is bending moment Nm

T is twisting torque in Nm

Whale's correction factor is the combined effect of direct share and curvature correction

KW =4C -1 / 4C-4 + 0.615 / C……. *8*

Length on RHS

L = n *(t + d) …….. *9*

Where, L is length of RHS in mm

N is no of holes

The driving force of the loaded screw conveyor

$P = P_H + P_N + P_{st}$ …….. *10*

$P_H = \dot{m}.L. \lambda.g / 3600$ *(kilowatt)* …….. *11*

L= length

$\dot{m}$= mass flow rate of the material

λ= friction coefficient

g = acceleration due to gravity

λ = Progress resistance coefficient has a value between 2 to 4.

PN = D.L / 20 (Kilowatt) …….. *12*

Where,

D is the screw diameter (m).

L is the screw conveyor's length (m).

$PST = \dot{m}tHg / 3600$……. 13

H can be considered negative for descending screws and positive for ascending screws.

Capacity of screw conveyor

$Q = 15\pi D^2\ PN\eta\rho H$……. 14

Where,

D = screw diameter
P = pitch of screw
N = rpm of screw
η = loading efficiency
ρ = density of material
C = factor of inclination of screw

The air temperature, T at any point inside the drying chamber

$$T = \frac{S}{2(U_L+h)} \dots\dots\ 15$$

$$h = \frac{1}{(1/h_{c,b-a})+(1/h_{r,p-b})} \dots\dots\ 16$$

The absorbed solar radiation is

$$S = G_t(\tau\alpha) \dots\dots\ 17$$

Collector efficiency factor, F' for air collectors, given by

$$F' = \frac{1/U_L}{(1/U_L)+(1/h)} = \frac{h}{h+U_L} \dots\dots\ 18$$

$$A_c = WL$$

$$T_o = T_i + \frac{1}{U_L}[S - U_L(T_i - T_a)]\left[1 - exp\ \left(-\frac{A_c U_L F'}{\dot{m}c_p}\right)\right] \dots\dots\ 19$$

$$Q_u = A_c F_R[S - U_L(T_i - T_a)]\ \dots\dots\ 20$$

The Nusselt, Rayleigh, and Prandtl numbers to design solar collector are given by

$$N = \frac{hL}{k}\ \dots\dots\ 21$$

$$Ra = \frac{g\beta'\Delta T L^3}{\nu\alpha} \dots\dots 22$$

$$Pr = \frac{\nu}{\alpha} \quad \ldots \ldots . \quad 23$$

The relationship between the Nusselt number and Rayleigh number for tilt angles β from 0 to 75° as

$$Nu = 1 + 1.44\left[1 - \frac{1708(\sin\ 1.8\beta)^{1.6}}{Racos\ \beta}\right]\left[1 - \frac{1708}{Racos\ \beta}\right]^{+} + \left[\left(\frac{Racos\ \beta}{5830}\right)^{1/3} - 1\right]^{+} \ldots \ldots 24$$

From fluid mechanics the hydraulic diameter of the air channel is given by

$$D \quad = 4\left(\frac{\text{Flow cross-sectional area}}{\text{Wetted perimeter}}\right) = 4\left(\frac{Ws}{2W}\right) = 2s \ldots \ldots . 25$$

The Reynolds number is given by

$$Re \quad = \frac{\rho VD}{\mu} = \frac{\dot{m}D}{A\mu} \quad \ldots \ldots \quad 26$$

$T_{m,\text{ air}}$, the following properties of air can be obtained

$$\begin{aligned} \mu &= 2.051 \times 10^{-5}\ \text{kg/m} - \text{s} \\ k &= 0.029\ \text{W/m} - \text{K} \\ c_p &= 1008\ \text{J/kg} - \text{K} \end{aligned}$$

For this single-glass-cover system

$$U_t = \left(\frac{1}{h_{c,p-c}+h_{r,p-c}} + \frac{1}{h_w+h_{r,c-a}}\right)^{-1} \ldots \ldots 27$$

The radiation coefficient from the plate to the cover hr, p-c is

$$h_{r,p-c} = \frac{\sigma(T_p^2+T_c^2)(T_p-T_c)}{\frac{1}{\varepsilon_p}+\frac{1}{\varepsilon_c}-1} \ldots \ldots 28$$

The radiation coefficient for the cover to the air $h_{r,c-a}$ is given as

$$h_{r,c-a} = \varepsilon_c\sigma(T_c^2 + T_s^2)(T_c + T_s) \ldots \ldots . 29$$

The equation for the cover glass temperature is

$$T_c = T_p - \frac{U_t(T_p-T_a)}{h_{c,p-c}+h_{r,p-c}} \ldots \ldots 30$$

The overall loss coefficient U_L is

$U_L = U_t + U_b + U_e$ … …. *31*

The edge loss coefficient, based on the collector area A_c, is

$U_e = \frac{(UA)_{edge}}{A_c}$ … …. *32*

The back loss coefficient U_b is approximately

$U_b = \frac{1}{R_4} = \frac{k}{L}$ … …. *33*

The mean air temperature, $T_{m,\text{ air}}$

$4\left(T_{m,\,air}\right)^3 = \left(T_p + T_b\right)\left(T_p^2 + T_b^2\right)$ … …. *34*

Where, T_p is absorber plate temperature

T_b is back plate temperature

Chapter Four: Design Analysis

4.1 General assumption and initialization

From 8 m^3 digester biogas plant around 7.5 m^3 digestate is ready to be separated and dried. The replaced time of a biogas substrate and digestate is from 60 days to 90 days. From 7.5 m^3 of a biogas digestate 75% of the digestate is liquid portion and the remaining 25% is solid portion.

Solid portion/matter, $SM = \frac{25xQ}{100}$

$SM = \frac{25x7.5m^3}{100}$ = 2.8 m^3

Liquid portion/matter, $LP = \frac{75xQ}{100}$

$$SM = \frac{75x7.5m^3}{100} = 4.2 \text{ m}^3$$

The replaced time of biogas digestate is 3 months, September 15, December 15, March 15, June 15. The screw separator should be derived below 100N as to make it derived by human being manually. The working force/effort can be taken by the average human hand force limits of 150N to 200N. For a continuous work, the design force / effort is 100N.

The overall load that has to pushed forward is the sum of weight of digestate and weight of screw.

$$W_{Tot} = W_{digestate} + W_{screw}$$

$$W_{digestate} = m_{digestate} x g$$

$$m_{digestate} = \rho x V$$

Size of screw is selected by welding and shearing strengths,

d = 80mm, r = 40mm

D = 200mm, R = 100mm

L = 730mm

Therefore, the volume of the screw to be used as a conveyor is

$$V = l\pi\left(\frac{R^2}{2} - r^2\right) = 0.73mx\pi x\left(\frac{0.1^2}{2} - 0.04^2\right) = 0.007797m^3$$

$$m_{digestate} = 7850\,{}^{kg}/_{m^3}\ x\ 0.007797m^3 = 61.2kg$$

$$W_{digestate} = m_{digestate}xg = 61.2kg\ x\ 9.81\,{}^{m}/_{s^2} = 600.4N$$

$$m_{screw} = m_{screw\,shaft} + m_{blades}$$

Based on diameter and density of mild steel,

The shaft is circular galvanized mild steel pipe with Do=0.3m and Di=0.25m

$$m_{screw} = 3kg$$

$$W_{screw} = m_{screw}xg = 3kgx9.81\,{}^{m}/_{s^2}$$

$$W_{screw} = 29.43N$$

$$W_{Tot} = W_{digestate} + W_{screw}$$

$$W_{Tot} = 600.4N + 29.43N = 629.83N$$

4.2 Design of Screw Press Solid-Liquid Separator

4.2.1 Design of the rotating shaft

The shaft on which the screw material is winding around is designed based on the following assumptions:

Blades of the screw is made from mild steel with a yield stress 250MPa

Density of shaft material is 7850 kg/m^3.

Pitch of screw (p) 146 mm.

Length (L) = 0.73m

Factor of safety FS is 2.5

4.2.2 Size of screw press

The capacity of the conveyor

$Q = 15\pi D^2\ PN\eta\rho H = 15 \times 0.114 \times 0.286 \times 8 \times 0.1 \times 1000 \times 1 = 1.2$ tonne/hr

$$\begin{aligned} Q &= 15\pi D^2\ Sn\Psi\rho C \\ &= 15 \times 0.114 \times 0.286 \times 8 \times 0.1 \times 1000 \times 1 \\ &= 0.02 \text{ tonne } /\mathrm{hr} \end{aligned}$$

friction factor: friction factor of the material on through, 0.1 for non- abrasive, free flowing materials.

Screw pitch: (S)

Commonly the screw pitch is taken equal to the diameter of the screw D. however; it may range from $0.75 - 1.0$ times the diameter of the screw.

Loading efficiency : (Ψ)

The value of loading efficiency should be taken large for materials which are free owing and non-abrasive, while for materials which are not free owing and, or, are abrasive in nature, the value should be taken low:

$=0.12$ to 0.15 for abrasive material.

$=0.25$ for mildly abrasive material.

$=0.1$ for non- abrasive, free flowing materials.

4.2.3 Power required for driving the screw

The equations for the power required for driving the screw are adapted from the article design of solid liquid separation equipment. (Sutherland, K. S., 2015)

$$\begin{aligned} N &= \frac{QL}{367}[\ W + \sin\beta]\frac{1}{\eta} \\ &= 1000 \times 2.6/367[4 \pm 0.0174] \\ N &= 0.05\mathrm{KW} \end{aligned}$$

1 Torque on screw shaft, M,

$$\begin{aligned} M &= 975, \frac{N}{n} \\ &= 975 \times 0.4883/8 \\ &= 315.4 \text{ Nm} \end{aligned}$$

2 Load propulsion speed

$$V = \frac{sn}{60}, \text{m/s}$$
$$= 0.285 \times 8/60$$
$$= 0.0381 \text{ m/s}$$

a. Inclination factor: (C)

The inclination factor C is determined by the angle of screw conveyor with the horizontal. Approximate values may be obtained from the following table

Table 1: Value of Inclination Factor C

$\boldsymbol{\beta}$, deg.	0	5	10	15	20
C	1.0	0.9	0.8	0.7	0.65

N = power in kw

L = length of conveyor, mH = Lsin β

w = material factor

= 2.5 for coal, rock salt

= 4.0 for fine dry clay, foundry sand, cement, sulfur, ash, etc.

η = efficiency of gear reducer.

μ = friction factor of the material on trough, 0.1

4.2.4 Design of Screen/Sieve drum

L=735mm=0.735m

D=208mm=0.208m

V=$\pi r^2 h$= π(0.104)2(0.735)= 0.024975m3=24.98L

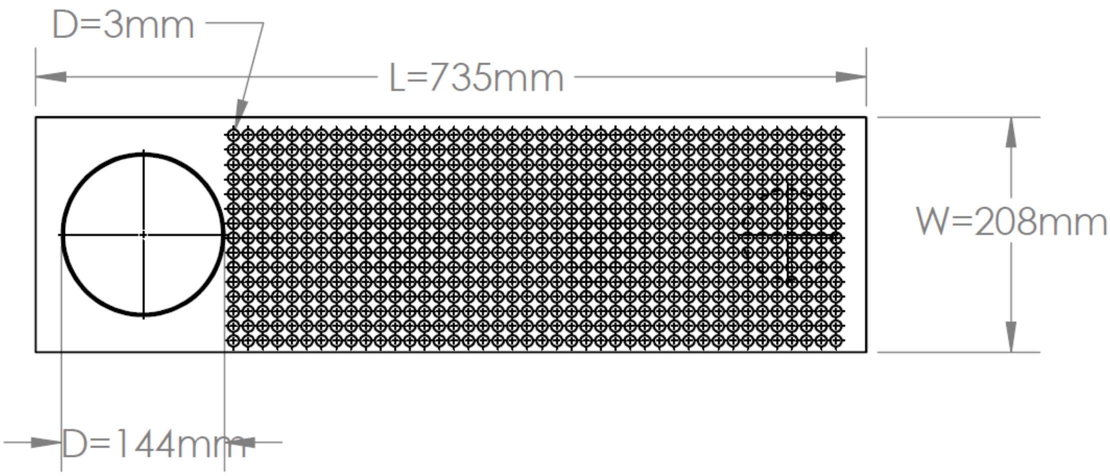


Figure 12: Dimensions of the Screen drum

At full load for 7.5m^3 digestate, the total number of times the reservoir can hold is 7.5/0.024975=300

Screen hole/Sieve parameter

3mm diameter hole with approximately 4mm gap between a consecutive holes which cover ¼ of the total circumference of the drum for the length of 560mm.

The total circumference the sieve holes cover

C_{sh} =1/4*C_T

Where C_{sh} is the circumference of screen hole

C_T is the total circumference of the screen drum

CT=2 π r=2 π(0.104)=0.65312m

C_{sh} =1/4*0.65312=0.1633m

Ash=L_{sh}* C_{sh} =0.56m*0.1633m=0.09145m^2

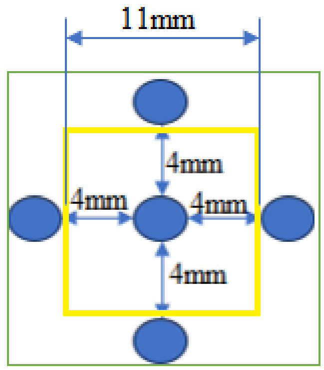


Figure 13: Single screen hole surrounding dimensions

From the figure above it is shown that one screen hole covers 11mm x 11mm =121mm^2 =0.000121m^2 area

The approximate number of screen holes are the product of horizontal number of holes and vertical number of holes; 42x15=630

4.2.5 Bearing selection

Rolling bearings come in a wide variety of types, shapes and dimensions. The most important factor to consider in bearing selection is a bearing that will enable the machine or part in which it is installed to satisfactorily perform as expected. Shaft assemblies generally require two bearings to support and locate the shaft both radially and axially relative to the stationary housing. These two bearings are called the fixed and floating bearings.

Axial thrust on screw, p

$$\mathrm{P} = \mathrm{qL}\mu, \mathrm{kgf}$$
$$= 652.91 \times 1 \times 0.6$$
$$= 391.74\mathrm{kgf}$$
$$\mathrm{Fa} = 3273 \text{ N}$$

Equivalent load:

$$\begin{aligned} \mathrm{P} &= \mathrm{xFr} + \mathrm{yFa} \\ \mathrm{P} &= \mathrm{yFa} \\ &= 1.45 \times 3273 \\ &= 4245 \text{ N} \end{aligned}$$

Loading calculation:

$$\begin{aligned} L_{10} &= (C/P) \\ L_{10} &= 20000 \\ 200000 &= (C/4245)^{10/3} \times 10^6/60/25 \\ &= 64.61 \\ C &= 2.77 \times 4825 \\ &= 133.63\text{KN} < 200\text{KN} \text{ so that Design is Safe.} \end{aligned}$$

As per ISO 32218 Std. Taper Roller Bearing is selected

4.2.6 Design of screen drum cover

From the dimensions of the screen drum and screw shaft

The screen drum cover has a 200mm diameter and 735mm height.

It is made from 2mm thickness mild steel sheet metal using a continuous arc welding.

4.2.7 Design of Separator stands

Stands is made from 40 x 40mm RHS materials connected with arc welding. From the dimension of the cover drum, it has a length, width and height of 540mm, 195mm, 150mm respectively.

4.3 Design of Solar Dryer

Specifications and analysis of the solar collector

The solar collector's entire surface area is 200 x 80 cm in both length and width, which have the capacity to dry the solid portion of the 7.5m^3 biogas digestate in 24 hours. A 1.15mm thick sheet metal is installed as an absorbing surface area to convert radiation waves into heat energy. In order to reduce reflection losses from the collector to the surroundings, the absorber is painted black. A transparent thick plastic cover with a thickness of 30 μm is fastened to the collector box's top edges. The transmission coefficient for the transparent cover is 0.16 W/m^{2}K. The width and length of the cover are 200 and 80 cm, respectively. Wooden material insulation with smooth edges is fixed at the bottom and the sides of the collector. Back and side insulations has a heat transfer coefficient of 0.036 W/m^2 K. Rectangular hollow shafts (RHS) are used to create body frames since they are easier to shape and lower in weigh.

4.3.1 Thermal Analysis of Drying Chamber

$h_{r,p-b} =$ radiation heat transfer coefficient from absorber plate to back plate,

An energy balance on the air stream volume (sxlx δx) gives

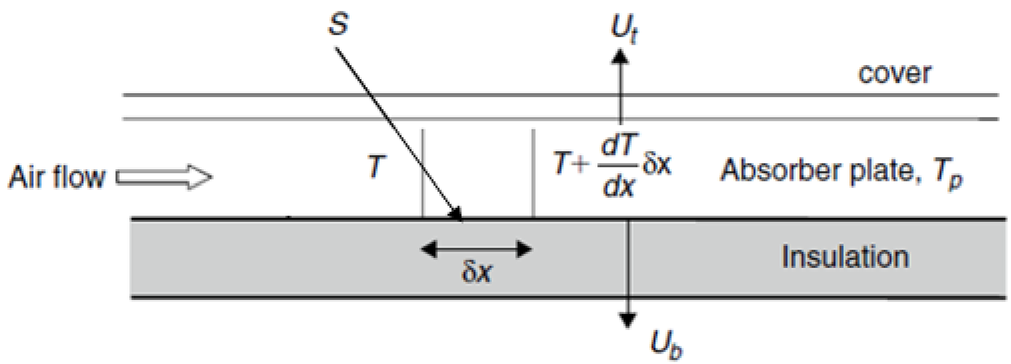


Figure 14: Thermal analysis of the drying chamber

The solar tunnel dryer has a single glass cover with the following specifications:

Design of solar tunnel dryer

Table 2: Assumptions and conditions to design solar tunnel dryer

Items	Condition or assumptions	References
Location	Addis Ababa $(9° \ 0'\text{N}, 38° \ 45'\text{E})$	www.mapsofworld.com
Product	Solid portion of biogas digestate	This is my product to be dried.
Loading rate (M) in each batch	10 kg	Loading capacity of the manufactured solar dryer.
Initial moisture content (m_j)	40%	Experimental measurement result of the initial moisture content of the solid portion.

Final moisture content (m_f)	5%	Experimental measurement result of the final moisture content of the solid portion.
Ambient relative humidity (Rh_{am})	25\% (Average for April, May-June)	www.globalsolarradiation.com
Drying period (T_{d})	8 h	The drying time that I measure during solar drying experiment.
Incident solar radiation (I)	$5.83\mathrm{kWhm}^{-2}$	www.globalsolarradiation.com
Dryer efficiency (η)	30%	Calculated result using eq.20, eq. 40 & eq.41
Thickness of plastic sheet	$30\mu m$ (UV stabilized)	Thickness of the plastic sheet information from the market.
Density of air at ambient (kgm^{-3})	1.204 kg/m³	The dry air density can be calculated as ρ = P/(R×T) with R = 287.058 J/(kg·K) , at 101325 Pa and 20 °C = 293.15 K , we get: ρ = 101325 / (287.058 × 293.15) = 1.204 kg/m³
Height of chimney (H)	0.70 m	Measuring result of the chimney of the solar drier.

The mass of water to be removed during drying, M_w kg

$$M_w = \frac{m_i - m_r}{100 - m_r} \times W \ldots\ldots\ldots\ldots\ldots \quad 35$$

Mass of water removed per hour m_m kg h^{-1}

$$m_w = \frac{M_w}{t_d} \ldots\ldots\ldots\ldots\ldots \quad 36$$

Total energy required Q kJ

$$Q = WC_p(T_d - T_a) + (M_w \lambda) \ldots\ldots\ldots\ldots \quad 37$$

Drying area

$$\text{Area} = \frac{Q}{(I \times \eta \times 0.68)} \ldots\ldots\ldots\ldots \quad 38$$

Area of chimney

$$A = \frac{Q.}{V \times K} \ldots\ldots\ldots\ldots \quad 39$$

Energy utilized for drying

Energy utilized is the amount of energy used for drying ,is the sum of energy required for raising the temperature of the digestate to the boiling point of water, plus the energy required to vaporize the major part of the water in the digestate. Therefore, the amount energy utilized can be obtained from the following Eq. [3] [10],[11].

$$E_u = m_i C_{pi}(T_b - T_o) + H_{fg}(m_d - m_i) + (m_d - m_i)C_{pw}(T_b - T_o) \quad \ldots\ldots\ldots \quad 40$$

Heat loss from bare plate, cover, bottom and sides enclosure

Heat energy is lost from the bare plate, cover, bottom and sides enclosures of the dryer through convection and radiation heat transfer modes and computed by using Eq. [4], [12], [13].

$$\dot{q}_{loss} = \left[hA(T - T_\infty) + \varepsilon\sigma A\left(T^4 - {T_\infty}^4\right)\right] \quad \ldots\ldots\ldots \quad 41$$

Chapter Five: Result an discussion

5.1 Results from calculations, laboratory measurements, and ANSYS simulations

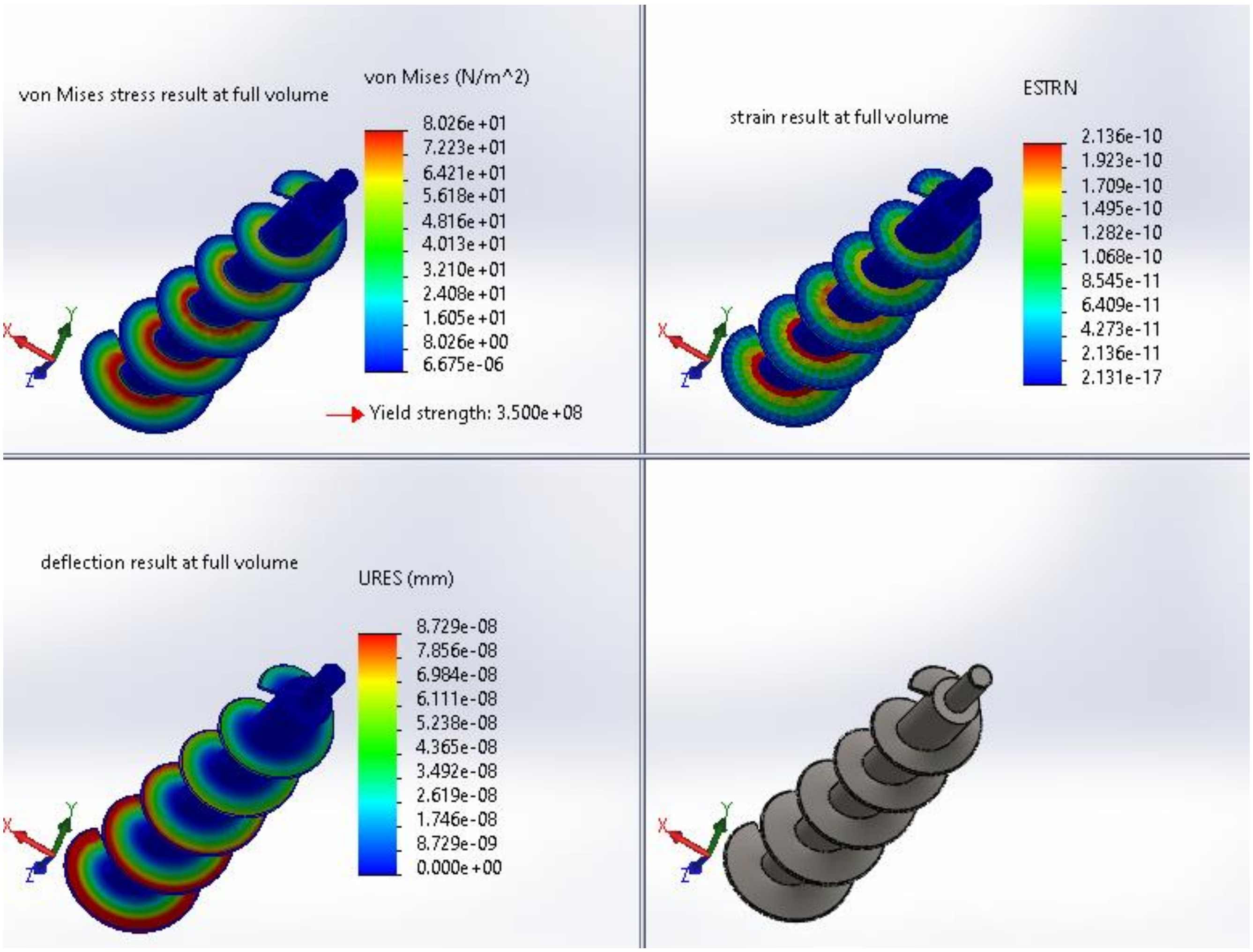


Figure 15: Simulation of screw conveyor

As the screw is the fundamental part (it has multipurpose such as conveying and pressing) of the solid liquid separator, it is important to simulate it to understand and optimize to safe condition. Therefore, from the screw simulation shown above the Stresses, strain and deflections under a full load condition is simulated and in all conditions the screw conveyor is safe.

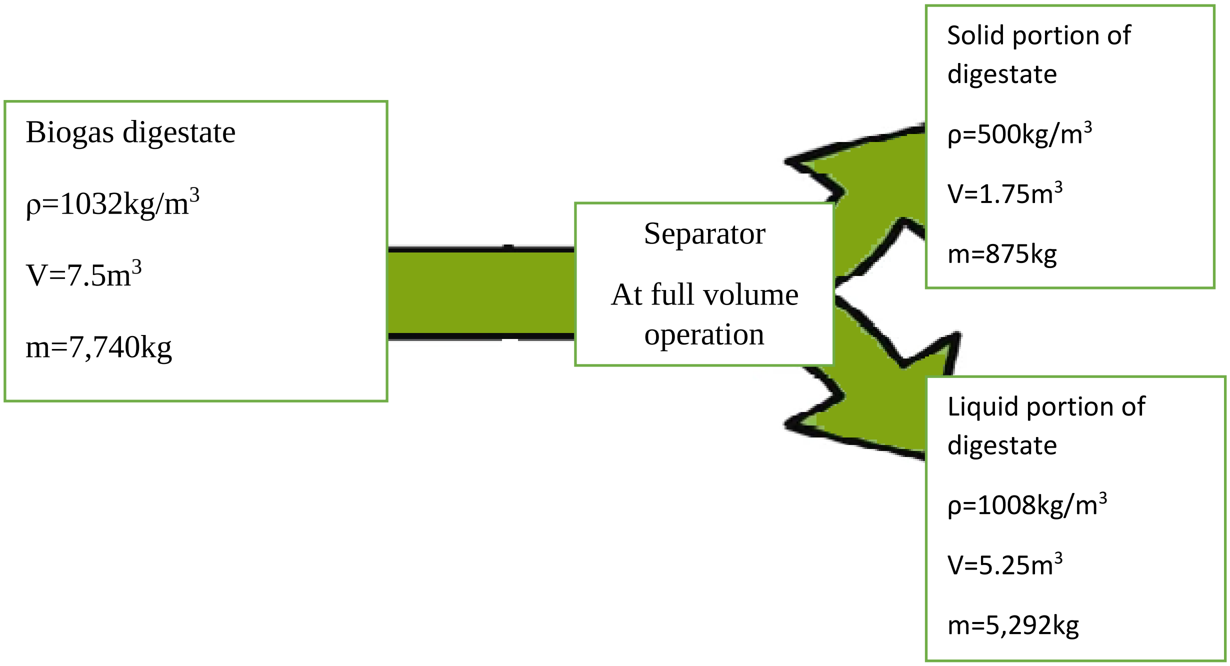


Figure 16: Parametric values at the inlet and outlet of the separator

Table 3: Solid-liquid separator laboratory recordings

a. Theoretical values using equations

Trials	Inlet digestate parameters			Liquid portion discharge parameters			Solid portion discharge parameters		
	V_i (L)	m_i (kg)	x_i (%)	V_l (L)	m_l(kg)	SM(%)	V_S(m3)	m_S(kg)	x_S(%)
1 (1/4)	6.24	6.44	75	4.68	4.72	7	1.56	0.78	55
2 (1/2)	12.49	12.89	75	9.37	9.45	11	3.13	1.57	50
3 (2/3)	16.65	17.18	75	12.49	12.59	16	4.17	2.09	45
4 (Full)	24.98	25.78	75	18.74	18.89	20	6.25	3.13	40

The inlet digestate parameters, V_i and m_i are calculated by dividing full drum capacity (24.98L & 25.78kg) with quarter, half, two-thirds and full values. The liquid portion discharge parameters are calculated as a percentage (75% which is the theoretical liquid percentage of the biogas digestate) values of the inlet parametric values and the solid portion discharge parameters are the differences of the inlet digestate parameters and the liquid portion discharge parameters.

b. Recorded values

Trials	Inlet digestate parameters			Liquid portion discharge parameters		Solid portion discharge parameters		Efficiency
	V_i (L)	m_i (kg)	x_i (%)	V_l (L)	m_l(kg)	V_S(m3)	m_S(kg)	η
1 (1/4)	6.24	6.44	75	0.75	0.76	5.49	2.75	16
2 (1/2)	12.49	12.89	75	1.78	1.79	10.74	5.37	19
3 (2/3)	16.65	17.18	75	2.87	2.9	13.78	6.89	23
4 (Full)	24.98	25.78	75	5.62	5.67	19.36	9.68	30

The efficiency is calculated using the

$$\eta = \frac{experimental\ value}{Theoretical\ value} x100\%$$

For trial 1, $\eta_1 = \frac{0.75L}{4.68L} x100\%$ = 16%

For trial 2, $\eta_2 = \frac{1.78L}{9.37L} x100\%$ = 19%

For trial 1, $\eta_3 = \frac{2.87L}{12.49L} x100\%$ = 23%

For trial 2, $\eta_4 = \frac{5.62L}{18.74L} x100\%$ = 30%

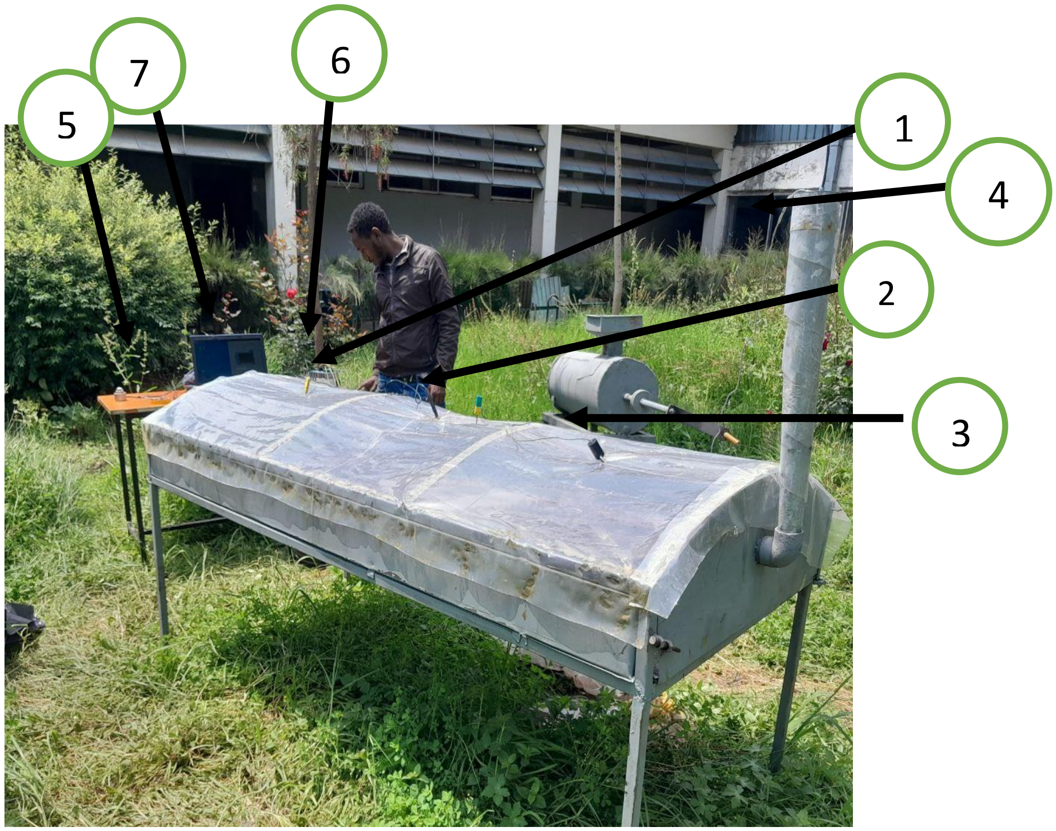


Figure 17: Image shown experimental setup during data collection

1. Point 1 (inlet side) of the drying chamber
2. Point 2 (middle point or end of collector area) of the drying chamber
3. Point 3 of the drying chamber (place of drying material)
4. Chimney (outlet vent)
5. Pyranometer
6. Data logger
7. PC to store data

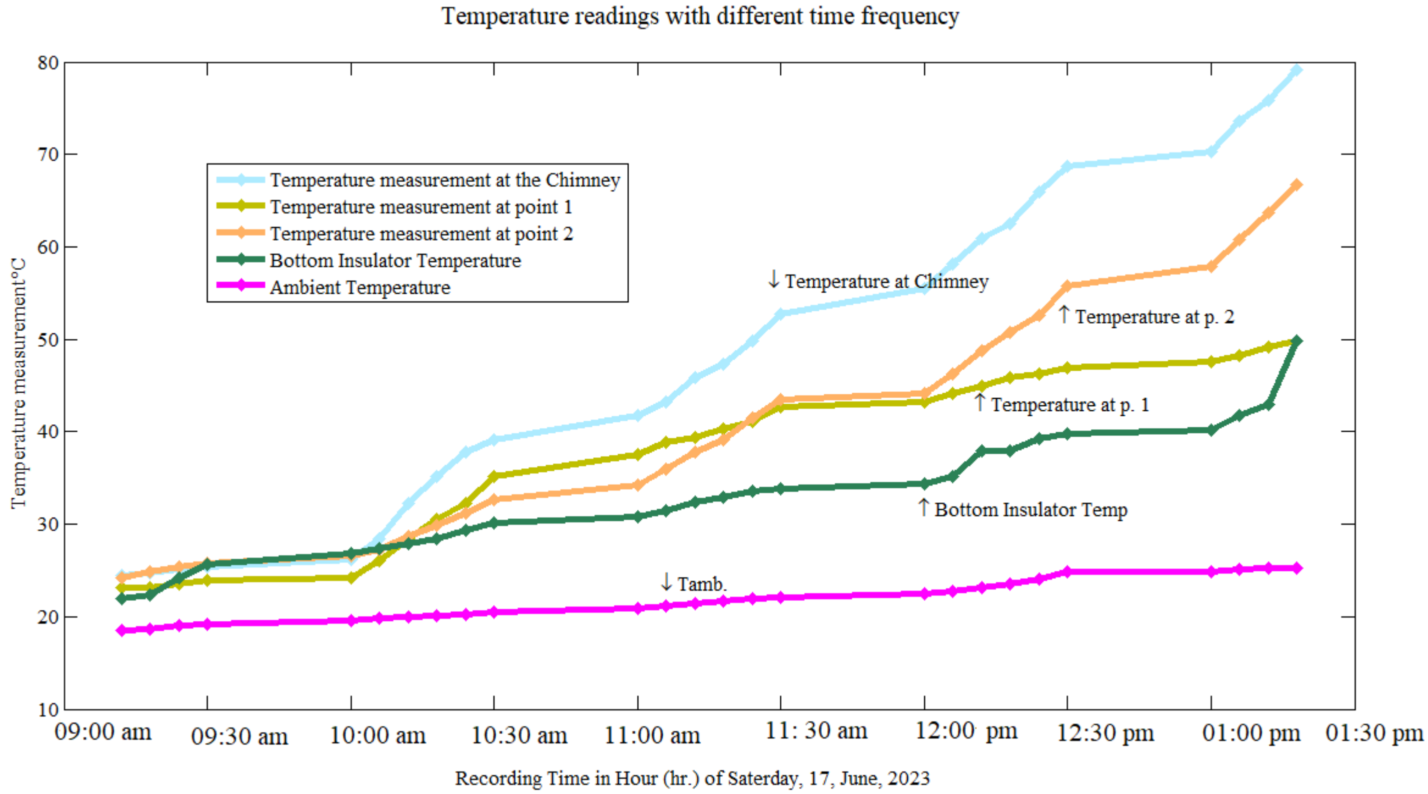


Figure 18: No load air temperature readings

From the graph shown above, the temperature readings at region two is the highest specially as the recording time increases. It is clearly visible that the temperature readings of region two is higher than region 1 (the inlet) with no load condition. These temperature readings are recorded values using mercury thermometer and verified using thermocouple thermometers with datalogger.

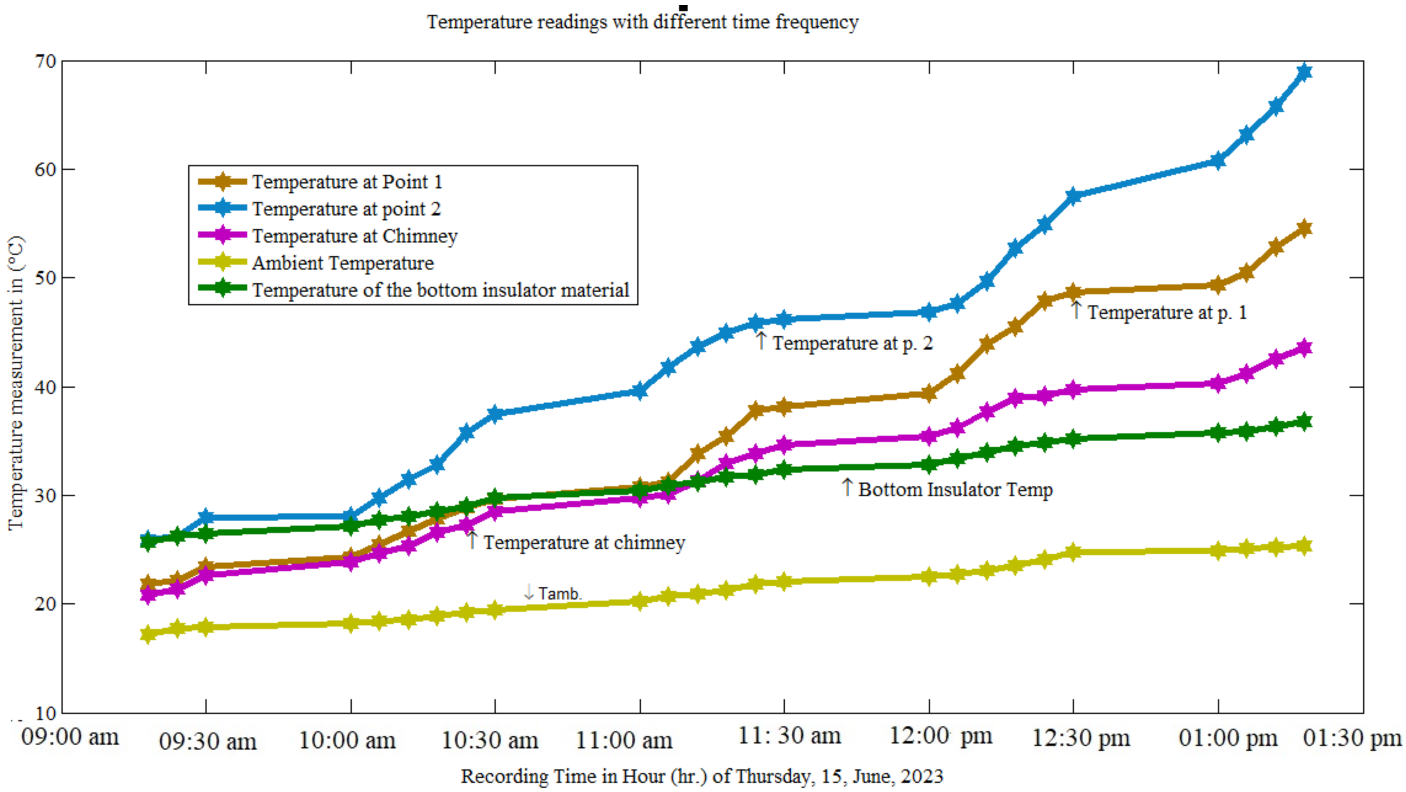


Figure 19: Air temperature readings

The temperature readings of the surface of the solar collector at region 2 (the middle region) and at region 3 (the place at which the drying substance, solid portion of digestate) have highest values, because these are the surface temperature measurements using infrared thermometer. Surface temperature of middle point of region 3 is higher because it is under no load condition, i.e. the tray has no digestate substance. The North and South sides of the drying chamber are insulators made from wood materials. The surface temperatures of these insulators have recorded and it is a minimum temperature value. However, it is increasing slightly with the increment of recording hour. Therefore, it is recommended that the insulator has to be a thick material made from better insulator materials.

Validation of the results

Researches carried out by Claudia and Joachim "Drying Characteristics of Biogas Digestate in a Hybrid Waste-Heat/Solar Dryer" were quite similar with this research. The investigations were carried out in a pilot hybrid waste-heat/solar dryer, developed by the University of Hohenheim in cooperation with the company Thermo-System. The dryer was located at a farm in Baden-Württemberg, Germany ($49°14'30''$N, $9°38'23''$E, 340 m a.s.l.). The dryer is a solar greenhouse dryer with a drying area 480 m^2, and was modified to use, beside solar energy, waste-heat from the combined heat and power unit (CHP) as well, and the exhaust gas from the micro turbine.

The waste-heat from the CHP is launched via water-air heat exchangers, which are installed in the headspace of the dryer. The exhaust gas from the micro turbine was mixed with ambient air and injected into the drying hall at the front side. The drying hall was built in a greenhouse style with a transparent polyethylene air bubble foil with a transmission coefficient (τ) of 0.82 . During the drying process, the digestate was mixed automatically with a rotary cultivator up to twelve times per day to avoid casehardening of the digestate surface.

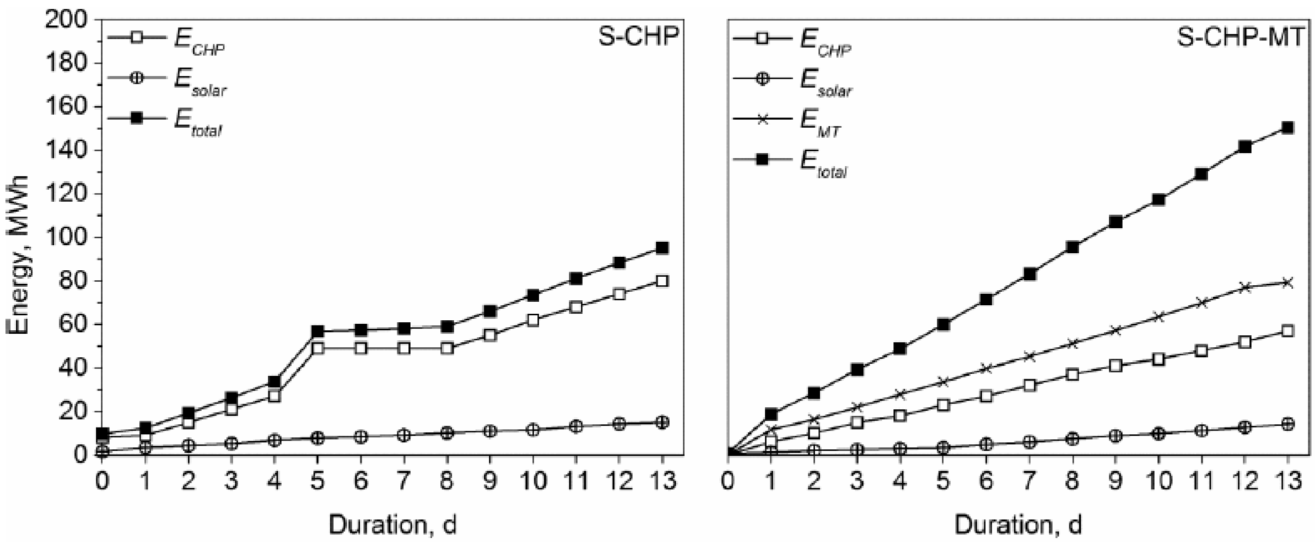


Figure 20: Cumulative energy input Biogas Digestate in a Hybrid Waste-Heat/Solar Dryer

(Adapted from Claudia and Joachim "Drying Characteristics of Biogas Digestate in a Hybrid Waste-Heat/Solar Dryer")

Table 4: Solar tunnel dryer size and moisture removal calculation result

Parameter	Value
Initial humidity ratio, w_i	$0.0018 kgH_2O/kg$ dry air
Initial enthalpy, h_i,,	34.5 kJ/kgdry air
Equilibrium relative humidity, RH_f	51%

Final enthalpy, h_f	65.5 kJ/kg dry air
Final humidity ratio, w_f	$0.014 kgH_2O$/kg dry air
Mass of water to be evaporated, m_w	79.33 kg
Average drying rate, m_{dr}	$3.967 kgH_2O/hr$
Air flow rate, m_a	325.1 kg dry air /hr
Volumetric airflow rate, V_a	$270.94\ m^3/hr$
Total useful energy, E	201.562MJ
Solar collector area, A_c	$1.8\ m^2$
Vent area, A_v	$0.0376\ m^2$

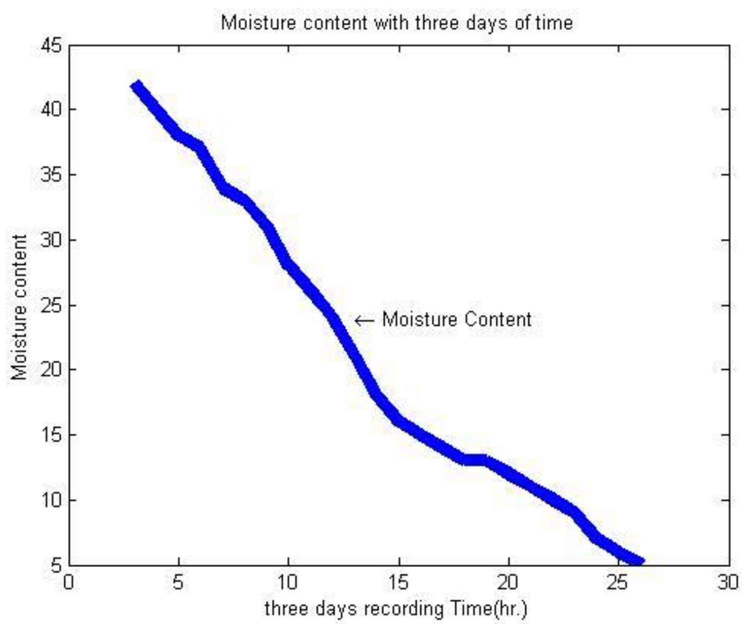


Figure 21: Graphs of effectiveness parameters (moisture content) of solar tunnel dryer

The graph shown above indicates the moisture removal of the dryer. The dryer has a maximum efficiency of 32% and 24 hours drying time (3 days, 8hr per day) is required to decrease the moisture content of the solid portion of the digestate from 42% to 5%.

The solar tunnel dryer was designed as per the procedure mentioned above, and its dimensions are given in Table below .

Table 5: Dimensions of solar tunnel dryer

Drying area	0.98 m^2
Width of dryer	1m
Length of dryer	2.00 m
Width of north wall	20 cm
Length of north wall	2 m
Number of chimney	1
Height of chimney	0.40 m
Diameter of chimney	0.20 m

5.2 Manufacturing processes

Table 6: Laboratory manufacturing processes of the separator

No	Parts	Material selected	Manufacturing processes	Equipment's/tools used
1	Screw	1.15mm mild steel sheet metal for the blade and 40mm diameter	Making 200mm diameter circles of sheet metal; drilling at the center with 40mm diameter, cut at the one edge of all the round sheet metals, and then	Scriber, measuring tape, hacksaw, drilling machine, Centre punch.

		soldi shaft for the rotating shaft	welding the edges and stretching on the shaft.	
2	Screen drum	1.15mm mild steel sheet metal	Cutting of sheet metal 55cm x 78cm and sieve making by drilling with 3mm drill bit at the center half and 15cm each side and cutting of round holes at opposite sides for intake and discharge hopper. Finally, rolling and continuous welding.	Lathe machine Scriber
3	Screen drum cover	3mm thickness mild steel sheet metal	Cutting 1m x 1m 3mm thickness sheet metal, making round holes at center for liquid discharge, and at the two opposite ends for the feed hopper and solid portion discharge. And welding the hoppers.	Welding machine
4	Front and rear covers	3mm thickness mild steel sheet metal	Making 35cm diameter round sheet metal and drilling at the centers at 50mm for the bearings and the rotating shaft Then fastening with the screen drum cover with screws.	Drilling machine Center punch
5	Separator stands and surrounding supporting frames	40mm x 40mm with thickness of 1.5mm RHS	Cutting at 54cm length and 20cm width for the frame and 15cm for the stands	Lathe machine Scriber

6	AC motor, pulley and belt	Selection of ac motor, pulley and belt		Scriber, measuring tape, hacksaw, drilling machine, Centre punch.
7	Bearings	Selection	Hard fit	

5.3 Cost and financial analysis

No	Item	Specification	Quantity	Price	Total price
1	Sheet plate	1000 X 8000 X 1.5mm	1	7000	7000
2	Shaft (round bar)	Ø30 X L=240mm	1	1500	1500
3	threaded shaft and nuts	threaded shaft Ø24*330mm	4	500	2000
		nut Ø 24mm X 20mm	8	8	64
4	Shaft material	Ø40, H 50cm	1	180	180
6	Handle	Ø100	1	700	700
7	Pulley and belt	Spring Pitch 4, no of helix 16	1	1800	1800
8	RHS	300 X 140 X 50mm	2	2500	5000
9	Rubber sheet board	520X55X18	1	300	300
Total Price			19000		

5.4 Manufacturing costs

No	Machine	Hour	Price/ hour	Total(birr)
1	Cutting	1hr	50	300

2	Welding	3hr	100	300
3	Drilling	2hr	50	1000
4	Assembly	3hr	80	2400
5	Milling	1hr	50	500
6	Turning	2hr	100	2000
7	Painting	1hr	50	500
Total		7000		

Table 4.4: Manufacturing cost

The total expense which is required for making this machine is 35,000 Birr.

Chapter Six: Conclusion and recommendation

6.1 Conclusion

Due to several reasons such as cost inflation of mineral fertilizer, environmental pollution of storing the digestate, illegal use of land filling fresh digestate, high transportation cost, applying mechanical and thermal treatments to biogas digestate / bio-slurry is a best alternative for agricultural usage. Based on the listed comparing criteria, this research has focused on screw type solid-liquid separator and solar tunnel dryer as a pretreatment mechanism for bio slurry to be used as a valuable organic fertilizer.

6.2 Recommendation

From the values which have been got during experimentation, calculation and simulation, it is recommended that screw conveyor solid liquid separator and solar tunnel dryer has to be used for a biogas digestate mechanical and thermal treatment mechanisms to get a best alternative organic fertilizer and to remove environmental pollution. From these results, it is recommended that the insulator materials of the two south and north walls as well as the bottom surface has to be a good insulator material to increase the efficiency and decrease overall heat loss coefficient.

Reference

Akor et al. (2020). Thermo-kinetic Study of Residual Solid Digestate from Anaerobic Digestion.

Amigun, B. et al. (2012). Anaerobic Biogas Generation for Rural Area Energy Provision in Africa.

Anlauf, H. (2007). Recent development in centrifuge technology. Separation and Purification Technology.

Barampouti et al. (2020). Title: Exploring technological alternatives of nutrient recovery from digestate as a secondary resource.

Biogas info. (2022). The digestate.

C Romio. (2021). Digestate post-treatment for a better utilization of a biogas plant digestate's fertilizer value.

Clean energy wire. (2021). Bioenergy—The troubled pillar of the Energiewende.

Clemens et al. (2018). Africa Biogas Partnership Program: A review of clean cooking implementation through market development in East Africa. Energy for Sustainable Development.

Environmental and Energy Study Institute EESI. (2017). Biogas: Converting Waste to Energy.

Eshete, G. et al. (2006). Feasibility Study of a National Biogas Programme on Domestic Biogas. Addis Ababa, Ethiopia.

European Biogas Association (EBA). (2020). Analysis of European regulation on digestate (definition and use) and proposals for improvements.

Europian Biogas Association (EBA). (2022). Digestate factsheet.

food and water watch. (2016). Hard to digest: greenwashing manure into renewable energy.

Fuerstenau, M. (2007). Froth Flotation – A Century of Innovation.

Fulvia Tambone et al. (2017). Solid and liquid fractionation of digestate: Mass balance, chemical characterization, and agronomic and environmental value.

Global Conference on Energy Efficiency. (2022). Outlook for biogas and biomethane: Prospects for organic growth.

Havukainen et al. (2021a). Environmental performance of dewatered sewage sludge digestate utilization based on life cycle assessment.

International Renewable Energy Agency. (2018). Biogas for road vehicles: Technology brief.

Lars Kamer. (2022). Countries with the largest cattle population in Africa.

Liu et al. (2019a). Air impingement drying of digestate.

Lu & Xu. (2021). Post-treatment of food waste digestate towards land application: A review.

Lyko, H. (2016). Membrane technology: Innovative separation techniques for many fields of application.

Müller. (2011). Life cycle assessment of biogas digestate processing technologies.

Muruganantham et al. (2021). Performance analysis of a tubular solar dryer for drying Mexican mint (Plectranthus amboinicus)—An experimental approach.

NEO Energy. (2015). Anaerobic Digestate—Food Waste pH adjusted with Sulfuric acid amount.

Peng et al. (2021b). Char derived from food waste based solid digestate for phosphate adsorption.

Peng et al. (2019b). Digestate management for high-solid anaerobic digestion of organic wastes: A review.

Riva, C. et al. (2016). Short-term experiments in using digestate products as substitutes for mineral (N) fertilizer: Agronomic performance, odours, and ammonia emission impacts.

Roberta Pastorelli et al. (2021). Recycling Biogas Digestate from Energy Crops: Effects on Soil Properties and Crop Productivity.

Rowe et al. (2015). Environmental assessment of digestate treatment technologies using LCA methodology.

Simo-Tagne. (2021). Thermal, economic, and environmental analysis of a novel solar dryer for firewood in various temperate and tropical climates.

Sutherland, K. S. (2015). Solid/Liquid Separation Equipment.

Taha M. A. Razek et al. (2018). Utilization of poultry manure in biogas production as an alternative to liquiefied petroleum gas.

Teng et al. (2019c). Digestate Evaporation Treatment in Biogas Plants: A Techno-economic Assessment.

World Biogas Association. (2021). Global Potential of Biogas.

Zheng et al. (2016). Enhancement of digestates dewaterability by CTAB combined with CFA pretreatment.

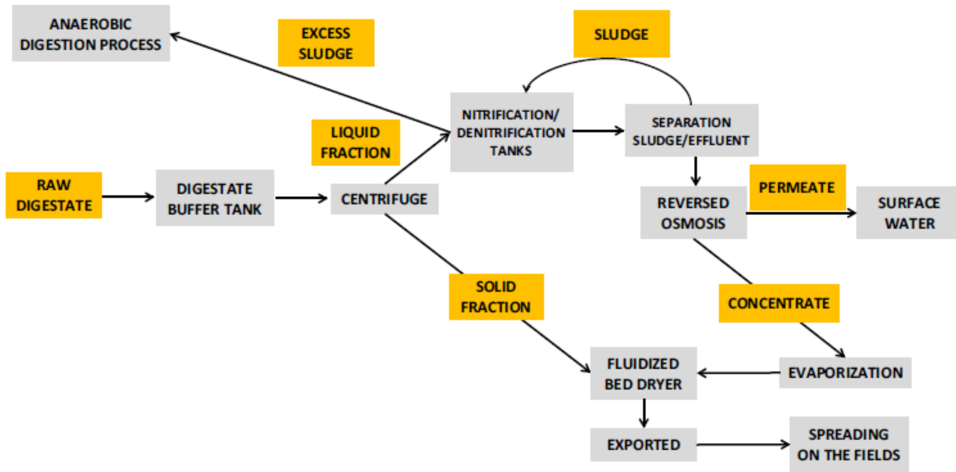
Appendices

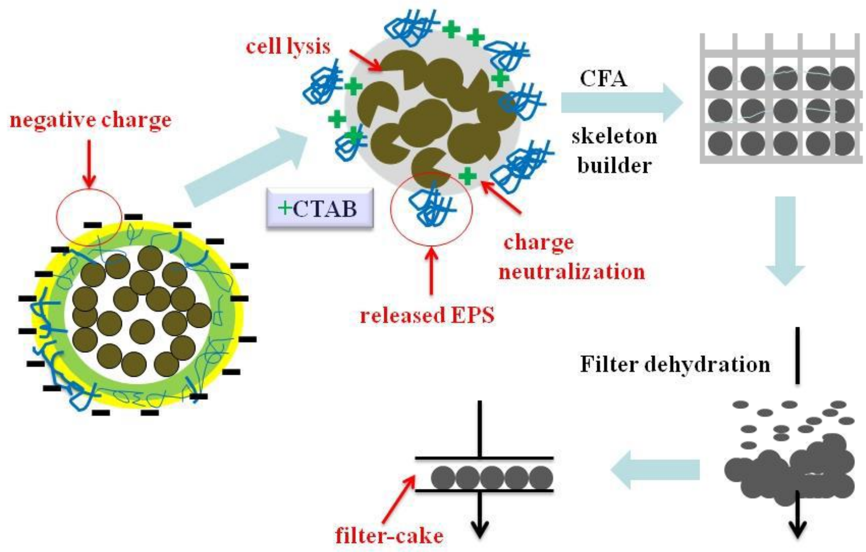
1. Summary of literature review

Digestate dewatering and drying literature review summary

Table 7: Digestate dewatering and drying literature review summary table

1	Title: Environmental assessment of digestate treatment technologies using LCA methodology(2015)
	Authors: Rowe et al. 6 May 2015
	Schematic drawing:

	 *Figure 22: Biological treatment, reverse osmosis and drying (RO&D)*
	Summary: It should be emphasized that additional study is necessary to learn more about whether it is appropriate to develop these methods further. The first issue that needs to be addressed is the creation of dynamic models in order to comprehend how the processes that make up the life cycle structure behave in relation to time. For instance, the features of the incoming digestate are linked to a critical temporal aspect of the system's operation: the amounts of raw materials utilized during the treatment operations. Gap Finding: The drying mechanism applied here is using electricity. It is not indicated for drying mechanisms using other renewable energy sources.
2	Title: Enhancement of digestates dewaterability by CTAB combined with CFA pretreatment(2016)
	Authors: Zheng et al. 30 January 2016
	Schematic drawing:

	 *Figure 23: illustration of the enhanced digestate dewatering process pretreatment by CTAB combined CFA*
	Summary: When taken together, CTAB and CFA can help digestate dewater more easily. The SRF value and WC of the four digestates under study were dramatically reduced when CTAB and CFA were combined during conditioning. The best dewatering conditions for the St-digestate, PM-digestate, CD-digestate, and KW-digestate were 50% and 100%, 30% and 100%, 20% and 100%, and 50% and 100%, respectively. Gap Finding: for solid – liquid separation a method of cell lysis is used, which leads high energy to break the binding bonds.
3	Title: Exploring technological alternatives of nutrient recovery from digestate as a secondary resource(Barampouti et al., 2020)
	Authors: Barampouti et al. 1 July 2020
	Schematic drawing:

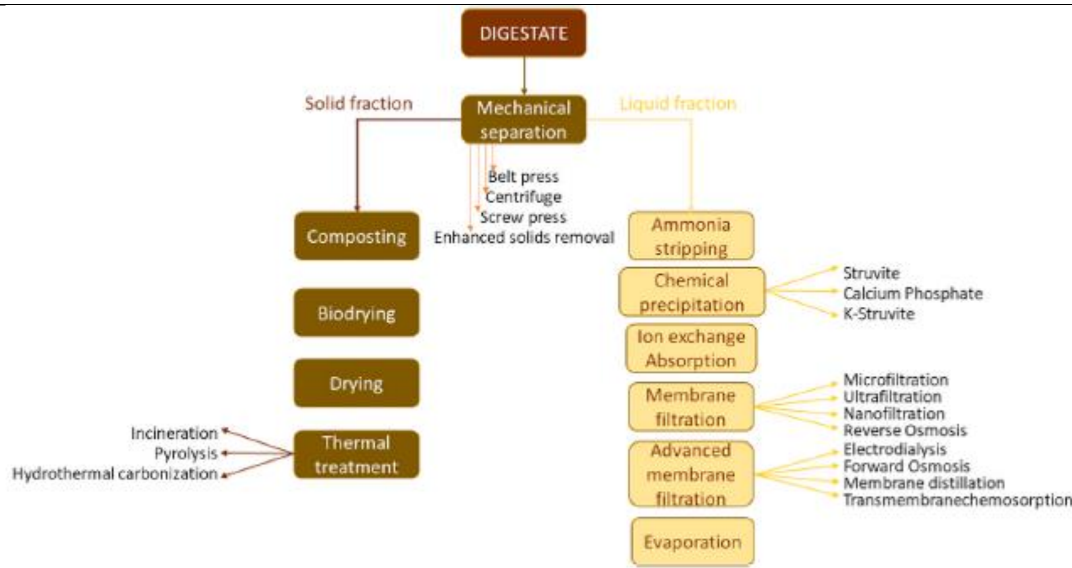
<table>
<tr><td></td><td>


Figure 24: Schematic overview of techniques available for the recovery of nutrients.
</td></tr>
<tr><td></td><td>Summary: Thermal drying results in a 98% dry matter digestate-based stream that is odorless and ammonia-free. The waste heat from the anaerobic digestion process often covers the high energy requirements of this operation. Palletizing finished goods may enhance their fertilizing qualities, lower their shipping costs, and simplify land application techniques. Tests on binders like lime and starch have produced pellets with enhanced mechanical characteristics. Numerous applications, such as those for agriculture, landscaping, or particular cultivars (like mushrooms), have been suggested.
Gap Finding: The mechanical separation used in this research is only using electrical energy, which is high costly and unavailable in rural area biogas plants which primary purpose is heating.</td></tr>
<tr><td>4</td><td>Title: Char derived from food waste based solid digestate for phosphate adsorption(2021b)</td></tr>
<tr><td></td><td>Authors: Peng et al. 10 March 2021</td></tr>
<tr><td></td><td>Schematic drawing:</td></tr>
</table>

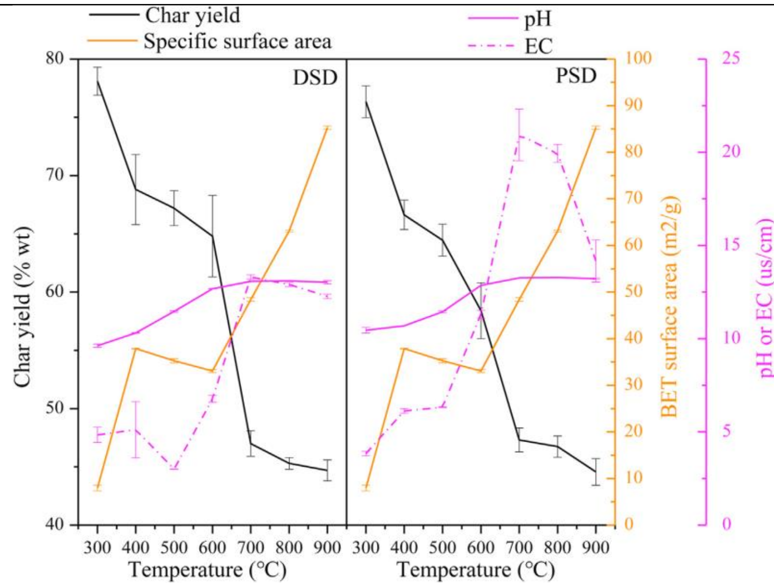
<table>
<tr><td></td><td>

Figure 25: Changes of char yield, surface area, pH and EC with pyrolysis temperature.</td></tr>
<tr><td></td><td>Summary: The natural resource of phosphorus is running out, hence recovering it from waste streams is beneficial. Based on results from investigations of digestate char, phosphate adsorption tests under various settings (pH correction, ash removal, and L/S ratio), and the characterization of char from two types of dried digested food waste (DSD and PSD) pyrolyzing at 300 - 9000C.
Gap Finding: the environmental pollution due to the combustion of digestate char is not indicated, which is highly problematic for the whole globe.</td></tr>
<tr><td>5</td><td>Title: Post-treatment of food waste digestate towards land application: A review(Lu & Xu, 2021)</td></tr>
<tr><td></td><td>Authors: Lu, Xu, 3 April 2021</td></tr>
<tr><td></td><td>Schematic drawing:</td></tr>
</table>

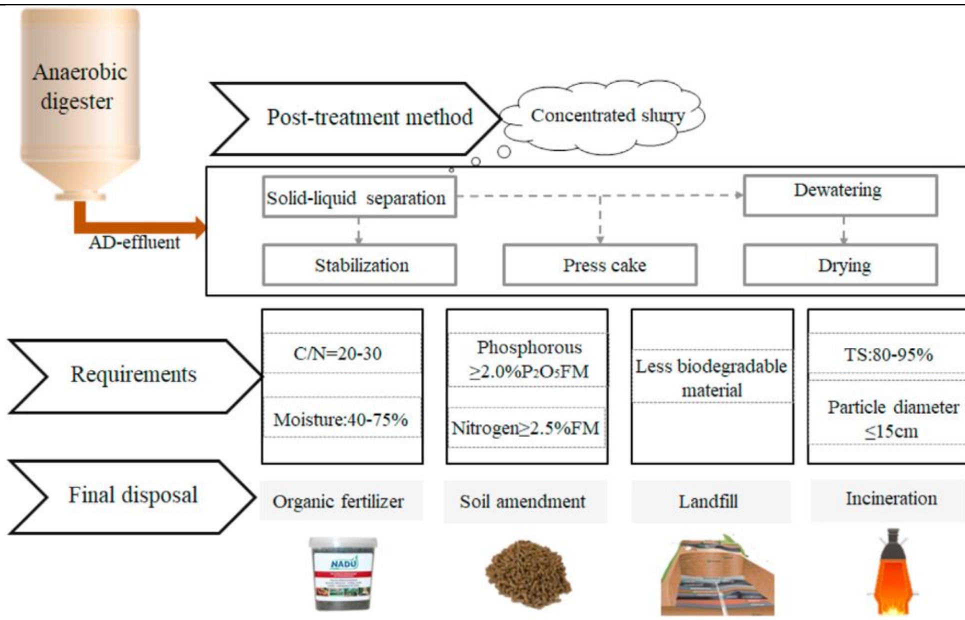
<table>
<tr><td></td><td>

Figure 26: Various disposal methods and pretreatment requirements of AD-effluent.</td></tr>
<tr><td></td><td>Summary: the necessity of treating digestate to reduce environmental harm as well as the potential for recycling and utilizing food waste digestate for land use based on its properties use of food waste digestate in agriculture is more cost-effective and environmentally sustainable because it contains significantly fewer heavy metals than sewage sludge and manures
Gap Finding: the drying mechanism is not briefly discussed, which cannot be applicable in the rural areas where there is not electricity.</td></tr>
<tr><td>6</td><td>Title: Life cycle assessment of biogas digestate processing technologies(Müller, 2011)</td></tr>
<tr><td></td><td>Authors: Rehl, Müller, 18 August 2011</td></tr>
</table>

Schematic drawing:

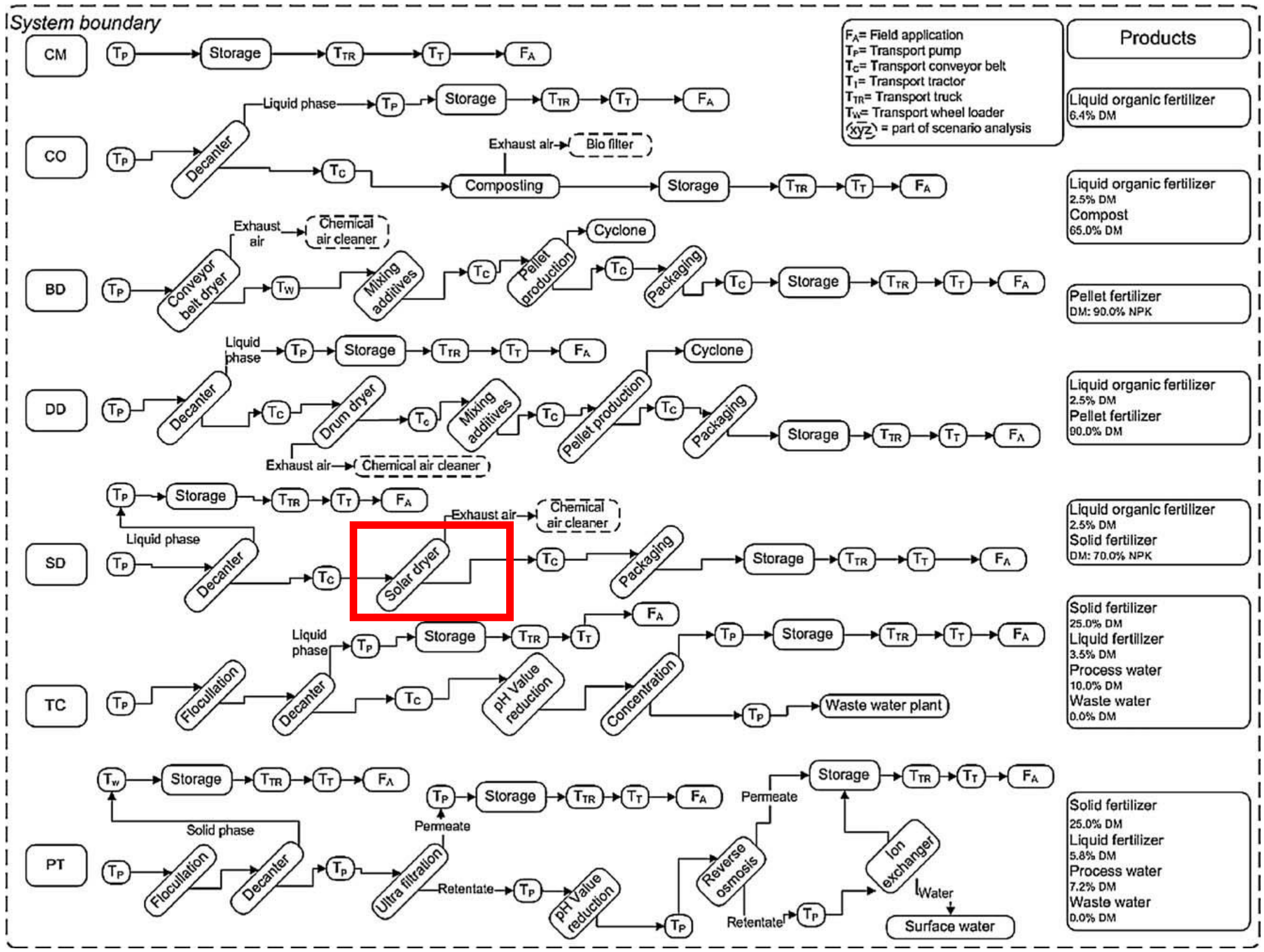
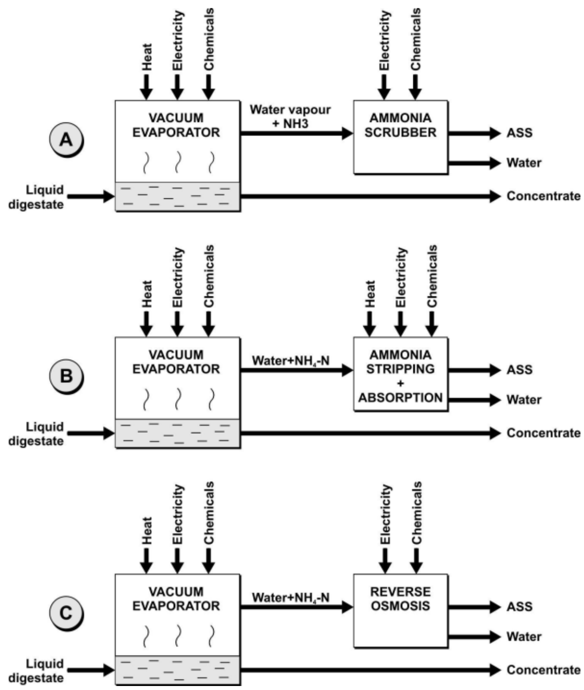


Figure 27: System boundary, mass flow and final products for the treatment options conventional digestate management (CM), composting (CO), belt drying (BD), drum drying (DD), solar drying (SD), thermal concentration (TC) and physical–chemical treatment (PT).

Summary: quantifying the life cycle environmental profile of seven treatment options for biogas digestate from ‘cradle to grave’. Belt drying of non-separated digestate was the treatment requiring the most primary energy and showed the highest global warming potential and acidification potential, whereas solar drying of separated digestate was the best option. In general, solar drying, composting and physical/chemical treatment were most suitable to reduce resource use and environmental impacts. In a sensitivity analysis, treatment, storage, regional transportation and field application were identified to be life cycle stages with the greatest potential for improvement.

	Gap Finding: the mechanisms and affecting parameters during drying using solar power is not stated, which is a focused area concerning environmental pollution.
7	Title: Digestate Evaporation Treatment in Biogas Plants: A Techno-economic Assessment(2019c)
	Authors:Teng et al., 31 July 2019
	Schematic Drawing  *Figure 28: Evaporation systems for the liquid digestate treatment. ASS = Ammonium sulphate solution*
	Gap Finding: the input power for the drying device is not associated with solar power, which is the most widely available renewable energy.
8	Title: Air impingement drying of digestate(2019a)
	Authors: Liu, et al., 22 March 2019
	Schematic drawing:

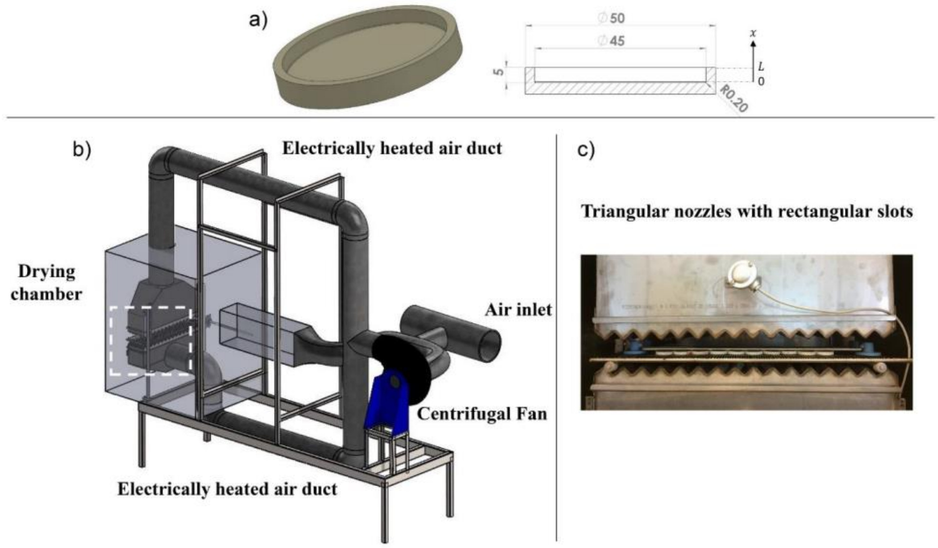
	 *Figure 29: Shape and dimensions of the plates. Dimensions are given in mm b) Schematic diagram of the air impingement dryer c) Zoom on air jets setup*
	Summary: An important stage for composting over a lengthy period of time or for long-distance transportation is drying the digestate. In order to solve this problem, an air impingement drier prototype was developed; its goal was to lower the moisture content from 80% to 20% in wet basis (w/w) in order to prevent the sticky effect. Since there haven't been many research looking at digestate drying, the paper's innovative components include its product's nature as well as the modeling of drying kinetics used to identify key variables for drying process improvement. When drying digestate by air impingement, temperatures of 40°C and 70°C were used, respectively, for six air velocities (1, 5, 7, 13, 17 and 19 m s-1). Gap Finding: the biogas in off-grid area, it is not discussed how the centrifugal pump and fan can be operated.
9	Title: A review on performance evaluation of solar dryer and its material for drying agricultural products[18]
10	Title: Digestate management for high-solid anaerobic digestion of organic wastes: A review(2019b)
	Authors: Peng et al., 21 November 2019
	Schematic drawing:

	 *Figure 30: Two options for the integration of high solid anaerobic digestion (HSAD) with invertebrate cultivation*
	Summary: When the use of digestate for agricultural application is limited due to nutrient surplus and low market acceptance, digestate management for anaerobic digestion (AD) plants is turning into a bottleneck of the sustainability of AD plants. High solid anaerobic digestion (HSAD) can produce superior digestive quality and treatment than a traditional low-solid system. The energy consumption of digestate management in high solid anaerobic digestion (HSAD) can be significantly impacted by the rheological behavior of the digestate. The solid digestate can then be further treated based on the integrated solutions to improve the energy efficiency or nutrients recovery after post-conditioning that is guided by rheological characteristics. This study also assessed the environmental implications of certain of those integrated systems' fundamental components.
11	Title: Drying of biogas digestate: A review with a focus on available drying techniques, drying kinetics, and gaseous emission behavior
	Authors: Razieh Salamat et al., 03 Jul 2020
	Schematic drawing:

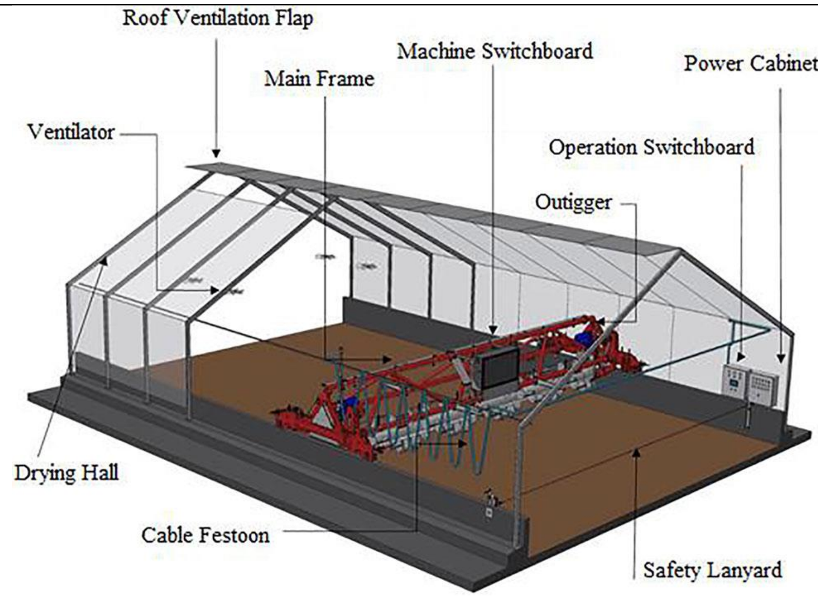
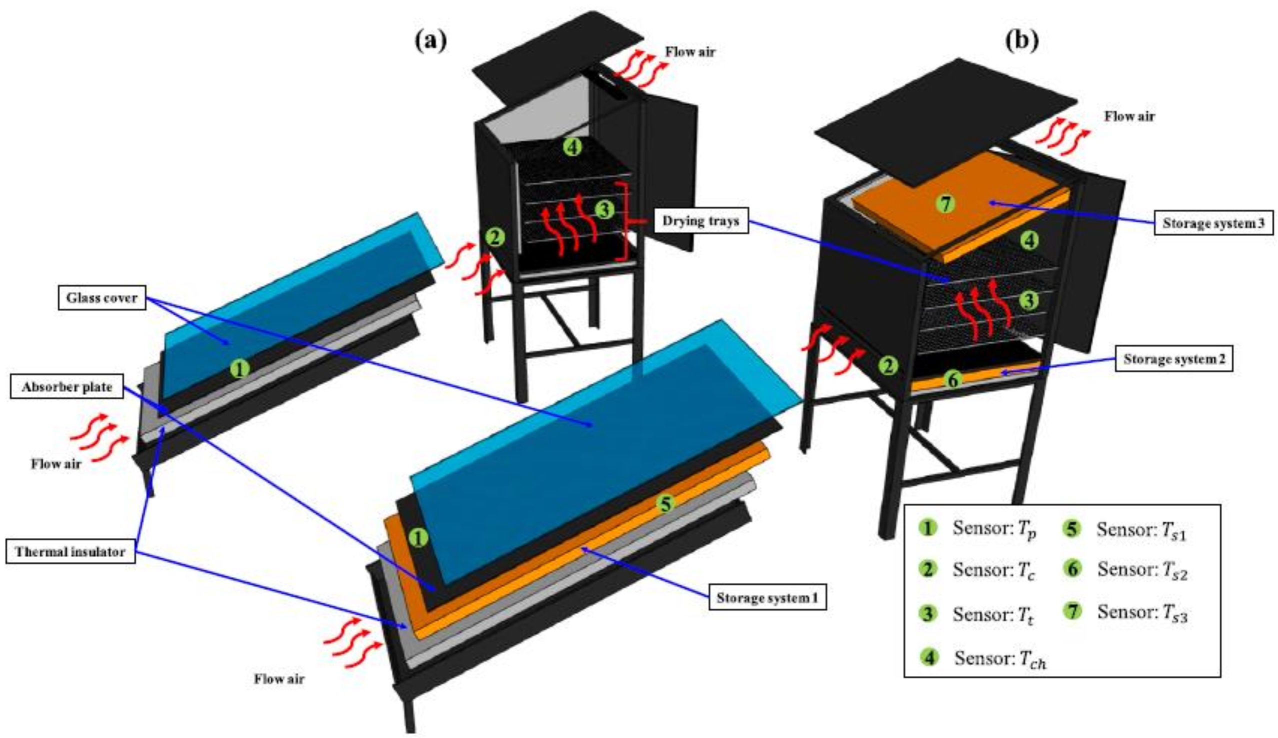


Figure 31: Proposed plant layout without CST system and with CST system (including dashed line)

Summary: Currently, digestate and sludge are dried using convective dryers, conductive dryers, radiative dryers, hybrid dryers, and superheated stream dryers. However, because drying processes are among the most energy-intensive unit operations, designing effective drying procedures is crucial. Due to two factors, this is more important in regards to digestate and sludge. First off, due to their unique properties, drying such materials is not always easy. Due to their high moisture content, sewage sludge and digestate have a tendency to adhere to dryer surfaces, which presents certain challenges for material flow in continuous drying systems. On the other hand, in environments with low moisture content, these materials are vulnerable to caking. Back-mixing or additives can help to a great extent handle this issue. Additionally, the combined impact of additives and operational factors may differ from each factor's individual impact. Additionally, depending on the initial feedstock, digestates behave differently during the process. Therefore, it is important to precisely assess the drying behavior of digestate under various drying conditions. In addition to raising environmental issues, drying-related pollutants significantly reduce the nutritional value of the digestate. Ammonia volatilization was primarily the subject of research among gaseous emissions, and as a result, it is well-researched in the literature. Nitrogen scrubbers can efficiently prevent the harmful environmental effects of ammonia emission, but from a nutritional standpoint, nitrogen retention is more intriguing.

12	Title: Experimental evaluation of an indirect type solar dryer for agricultural use in rural communities: Relative humidity comparative study under winter season in tropical climate with sensible heat storage material[13]
	Authors: Qui˜nones et al. 15 May 2021
	Schematic drawing:  Figure 32: Schematic diagram of solar dryers (a) conventional solar dryer, (b) ITSD-TSS
	Summary: Limestone and beach sand, two sensible heat sources from the Mexican State of Yucatan, were evaluated experimentally after being added to an indirect type solar dryer with thermal storage systems (ITSD-TSS). Under various environmental conditions, a comparison with a traditional solar dryer was also done. According to the test's results, which were conducted in highly cloudy conditions, the absorber plate's highest temperature readings were 79.3°C for beach sand and 86.8°C for limestone. The greatest humidity values obtained with limestone were found to be 88.75% for sensor 1, 86.61% for sensor 2, and 94.14% for sensor 3, whereas beach sand produced values of 89.88%, 89.9%, and 91.79% for sensors 1, 2, and 3, respectively.
14	Title: Drying technologies for foods: Fundamentals and Applications[16]
	Authors: Prabhat et al., 22 February 2021
	Schematic drawing:

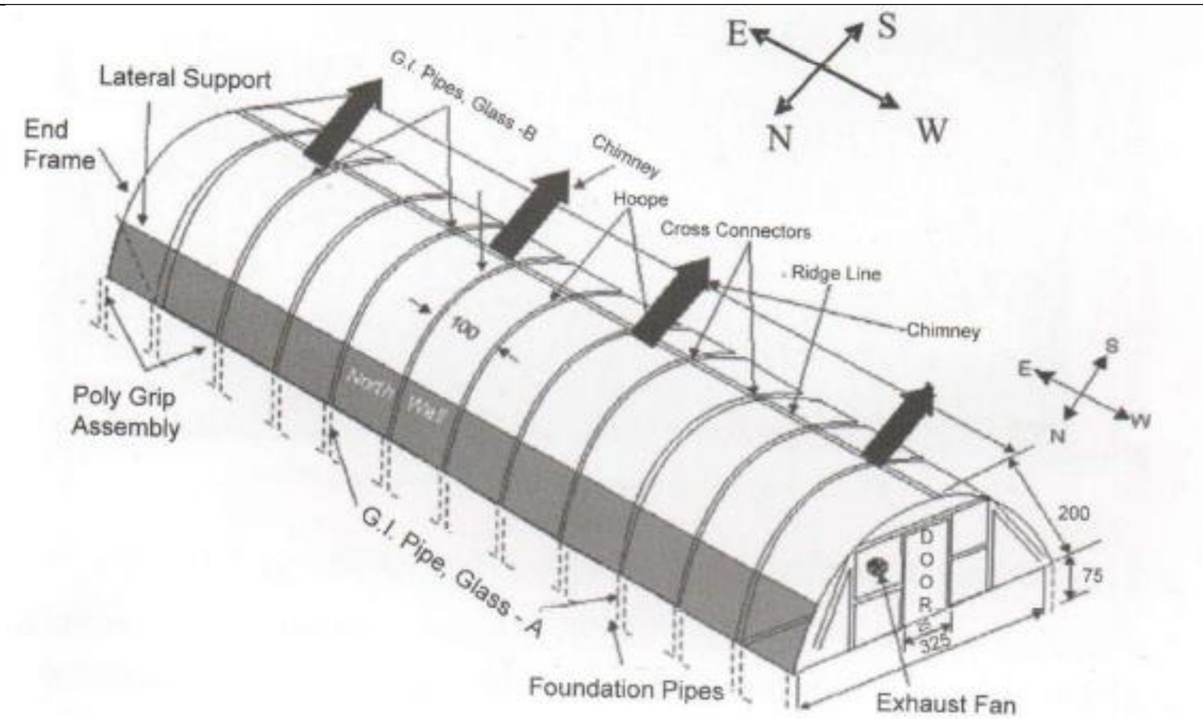
<table>
<tr><td></td><td>


Figure 33: Natural convection solar tunnel dryer
</td></tr>
<tr><td></td><td>Summary: When compared to other dryer designs, the solar tunnel dryer is easier to assemble, less expensive, and more effective in drying huge quantities of industrial and agricultural materials. The tunnel dryer is made of a hemi-cylindrical metallic frame construction that is wrapped in a 200 micron thick UV-stabilized semi-transparent polythene sheet. In order to absorb the sunlight entering the tunnel, the floor and other items inside the tunnel dryer are typically painted black. Long wave thermal radiation is emitted by the items in the tunnel dryer and is trapped inside the tunnel by the metallic frame structure's opaque cover. The sun's energy is trapped inside the tunnel, which boosts air temperature and hastens the evaporation of moisture from products stored there. Fig. below shows a schematic representation of a developed natural convection solar tunnel dryer. Through both natural and induced convection currents, the moist air can be evacuated. By adjusting the exhaust fan(s)' air flow rate, the microclimate inside the tunnel dryer may be managed.</td></tr>
<tr><td>15</td><td>Title: Environmental performance of dewatered sewage sludge digestate utilization based on life cycle assessment(2021a)</td></tr>
<tr><td></td><td>Authors: Havukainen et al., 7 November 2021</td></tr>
</table>

Schematic drawing:

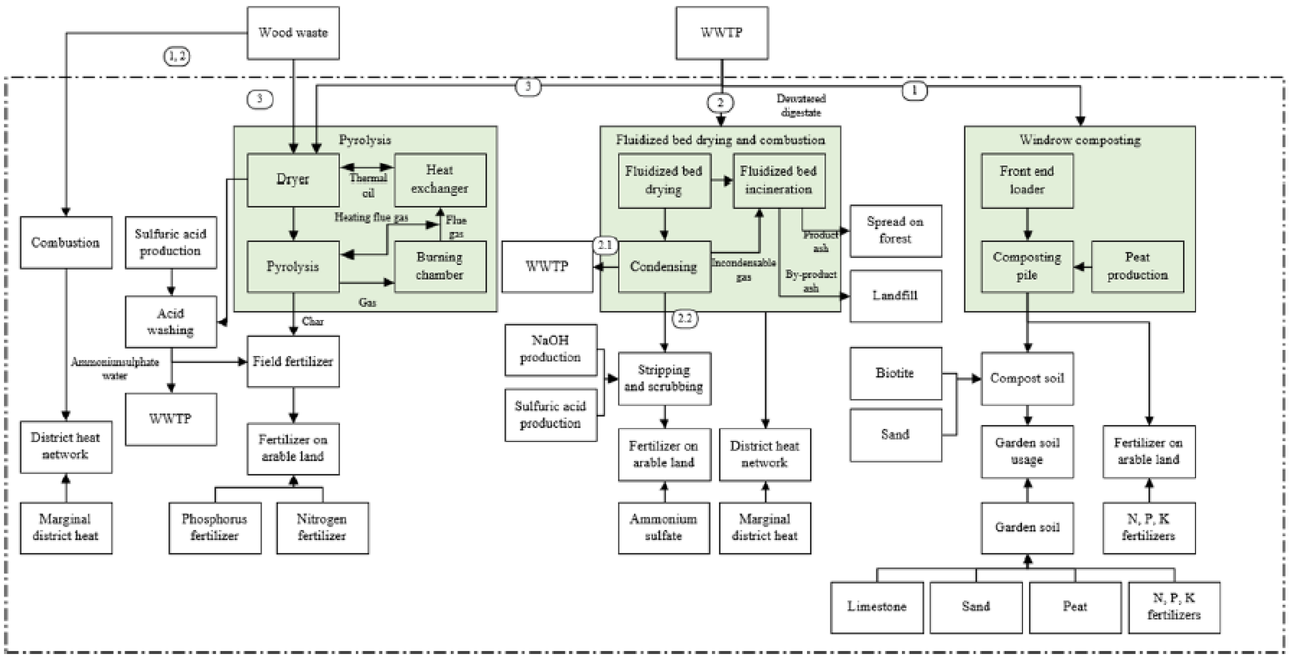


Figure 34: System boundary of sewage sludge digestate treatment

Summary: According to the study's findings, dewatered sewage sludge combustion or composting outperformed pyrolysis in terms of environmental performance in a Finnish setting. When there is a chance to use the leftover compost, composting can be feasible. The amount of the sludge is greatly reduced after combustion, and the ash that is produced can be used as a nutrient-rich fertilizer. Overall, transportation emissions were not as significant as sludge treatment processes themselves (with the exception of effect categories related to toxicity). When it comes to composting, the accompanying air emissions and impacts from peat usage have a substantial impact on a number of categories, but they also result in large emission reductions when gardening soil that contains peat is replaced. In the combustion scenario, the additional emissions from recovering nitrogen from the condensate completely outweighed the advantages of replacing fertilizer production, which suggests that nitrogen recovery efficiency should increase while process chemistry requirements should decrease.

Laboratory recordings of solar tunnel dryer

Table 8: Recording table with no load condition

t(sec)	Ts using infrared and mercury thermometers(^{0}C)				T_i(^{0}C) /Tamb	To(^{0}C) Chimney T^0	Insulator temperatures		
	T_1(^{0}C)	T_{2i}(^{0}C)	T_{2m}(^{0}C)	T_3(^{0}C)			T_B(^{0}C)	T_S(^{0}C)	T_N(^{0}C)
3:20	24.5	25.0	23.1	25.0	18.5	24.2	21.9	22.3	21.5
3:30	24.7	25.1	23.2	25.3	18.7	24.9	22.4	23.8	22.9
3:40	25.1	25.7	23.5	25.9	19.0	25.4	24.2	24.9	23.4
3:50	25.4	26.3	23.9	26.8	19.2	25.8	25.7	25.3	24.3
4:00	26.2	27.5	24.2	34.8	19.6	26.6	26.9	26.8	27.8
4:10	28.4	32.6	26.1	42.1	19.8	27.2	27.4	27.2	28.1
4:20	32.3	37.8	28.4	53.7	20.0	28.7	27.9	28.1	29.4
4:30	35.2	42.3	30.5	62.7	20.1	29.9	28.4	28.6	30.2
4:40	37.8	47.9	32.2	70.4	20.3	31.2	29.3	29.2	31.5
4:50	39.1	50.7	35.1	76.3	20.5	32.7	30.1	30.3	32.8
5:00	41.7	52.1	37.6	81.7	20.9	34.3	30.8	31.9	33.4
5:10	43.2	54.7	38.8	87.4	21.1	35.9	31.5	32.4	34.2
5:20	45.9	56.3	39.4	92.5	21.4	37.8	32.4	33.9	35.3
5:30	47.3	58.8	40.3	97.9	21.7	39.1	32.9	34.9	36.1
5:40	49.8	62.9	41.1	101.8	21.9	41.5	33.6	35.6	37.4
5:50	52.7	65.3	42.7	104.5	22.1	43.5	33.8	36.3	38.9
6:00	55.5	68.9	43.2	106.8	22.5	44.1	34.4	37.4	39.7
6:10	58.2	71.5	44.1	108.5	22.7	46.3	35.2	38.3	39.9
6:20	60.9	77.3	44.9	109.2	23.1	48.7	37.9	39.7	40.2
6:30	62.5	85.8	45.8	110.1	23.5	50.7	38.0	40.8	40.8
6:40	65.9	91.9	46.2	112.7	24.1	52.6	39.3	41.5	41.7
6:50	68.7	98.5	46.9	113.1	24.8	55.7	39.8	42.3	42.5
7:00	70.3	104.3	47.6	114.5	24.9	57.9	40.2	43.7	43.7
7:10	73.6	109.6	48.3	116.9	25.1	60.8	41.7	44.5	44.2
7:20	75.9	114.6	49.1	118.3	25.2	63.7	42.9	45.9	44.9
7:30	79.1	119.2	49.8	123.9	25.3	66.7	49.8	49.9	45.1

Table 9: Recording table with a condition of inlet mass (mi=1.9639kg) and outlet mass (mo=1.6154kg)

t(hr)	Ts using infrared and mercury thermometers(^{0}C)				T_i(^{0}C) /Tamb	To(^{0}C) /Tchimney	Insulator temperatures		
	T_{1m}(^{0}C)	T_{2i}(^{0}C)	T_{2m}(^{0}C)	T_3(^{0}C)			T_B(^{0}C)	T_S(^{0}C)	T_N(^{0}C)
3:30	21.8	27.3	25.9	29.1	17.2	20.8	25.7	24.7	24.1
3:40	22.2	30.2	26.3	31.7	17.7	21.4	26.2	25.2	24.9
3:50	23.4	32.9	27.9	34.2	17.9	22.6	26.5	25.9	25.4
4:00	24.3	34.5	28.1	37.7	18.2	23.9	27.1	26.4	26.3
4:10	25.5	35.9	29.8	42.6	18.4	24.7	27.7	27.3	27.8
4:20	26.7	37.1	31.4	48.2	18.5	25.3	28.1	27.8	28.1
4:30	27.8	39.3	32.8	54.1	18.9	26.6	28.5	28.5	29.4
4:40	28.9	42.2	35.7	61.5	19.2	27.3	29.0	29.4	30.2
4:50	29.6	45.1	37.4	68.1	19.5	28.5	29.8	30.9	31.5
5:00	30.8	47.4	39.6	74.9	20.3	29.7	30.4	32.3	32.8
5:10	31.2	49.5	41.8	80.1	20.7	30.1	31.1	34.6	33.4
5:20	33.8	51.3	43.7	86.4	20.9	31.3	31.8	35.4	34.2
5:30	35.4	53.4	44.9	92.9	21.3	32.9	32.7	36.8	35.3
5:40	38.8	56.8	45.8	97.4	21.8	33.8	33.1	37.9	36.1
5:50	40.1	58.6	46.2	102.8	22.1	34.6	33.9	38.7	37.4
6:00	43.4	60.3	46.9	106.7	22.5	35.4	34.8	39.1	38.9
6:10	45.2	62.2	47.6	108.5	22.7	36.2	35.8	39.7	39.7
6:20	47.9	64.1	49.7	109.2	23.1	37.7	36.3	41.3	39.9
6:30	49.5	65.1	52.7	110.1	23.5	38.9	37.5	41.9	40.2
6:40	51.9	66.5	54.9	112.7	24.1	39.2	38.4	42.3	40.8
6:50	53.7	67.3	57.5	113.1	24.8	39.7	39.2	43.5	41.7
7:00	56.3	68.4	60.8	114.5	24.9	40.3	40.1	44.2	42.5
7:10	58.5	68.9	63.1	115.3	25.1	41.2	42.5	46.3	43.7
7:20	60.8	69.5	65.7	116.7	25.2	42.5	43.3	48.8	44.2
7:30	62.6	70.3	68.9	118.6	25.3	43.6	44.8	49.5	44.9


2271.4

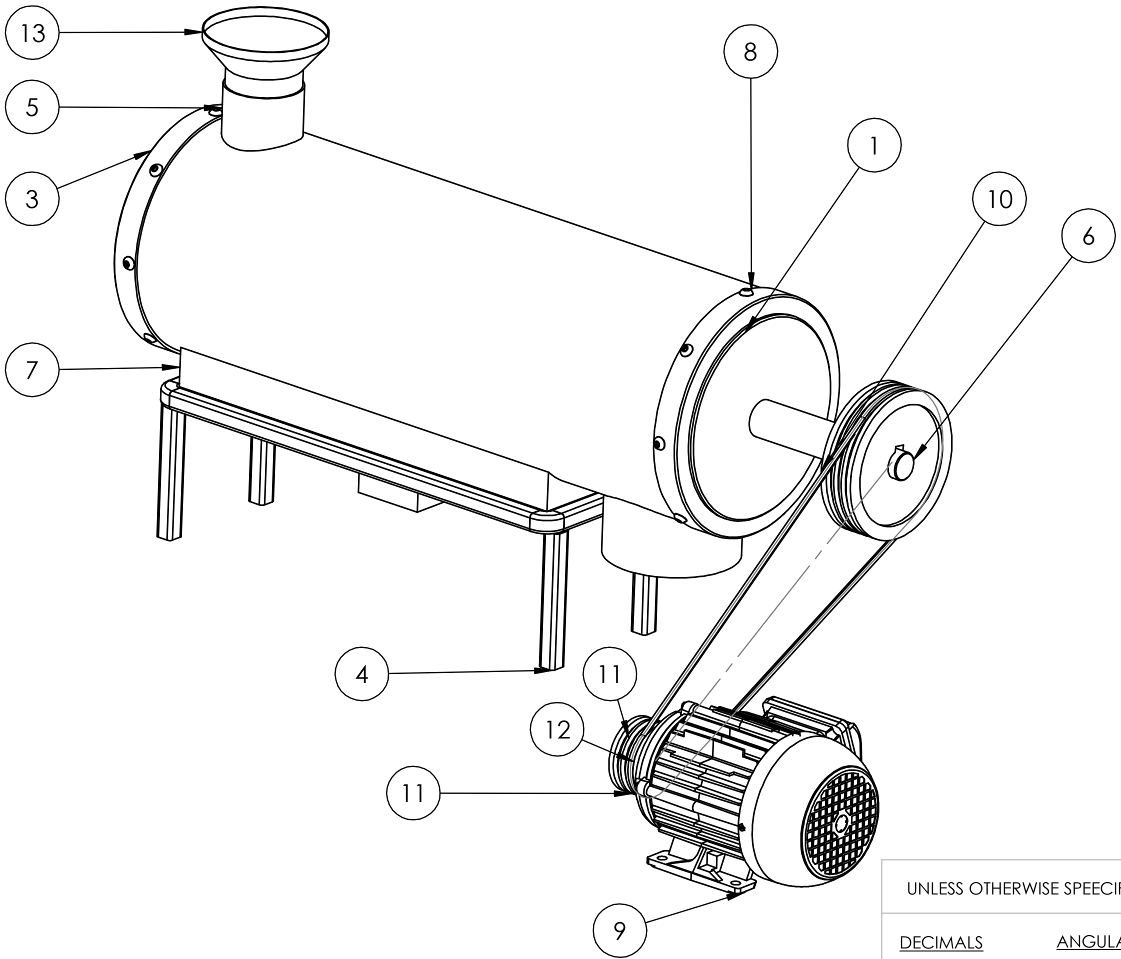

60.0


72.7.

NOTE -

1-INTERPRET DRAWING PER ANSI B4.21978(R2004)
2-MATERIAL_1020
3-SURFACES TEXTURES 3.5- 4.2MICROMETERS RA = 0.004MM
CUTOFF 0.008MM
4-CONTINUOUS WELDS

QUANTITY =1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Back _Case_008	1	1
2	Deep Groove ball bearing_6804	2	2
3	Front _Case_007	3	1
4	leg_008	4	1
5	Screening_Drum_002	5	1
6	Screw _Conveyer_001	6	1
7	Top_Screening_Drum_003+002	7	1
8	B18.3.4M - 8 x 1.25 x 16 SBHCS --C	8	16
9	Motor Leg	9	1
10	pull 01	10	1
11	Pull 02	11	1
12	Belt one	12	1
13	Hooper	13	1

UNLESS OTHERWISE SPEECIFIED	DESIGNED	Tesfamichael A.	30/07/2014
DECIMALS ANGULAR	CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014
.X+/-.0 .XX +/-.00 .XXX +/-.112mm	APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014

ADDIS ABABA UNIVERSITY (AAU)

AAiT

SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)

ASSEM-SCREW PRESS SOLID LIQUID SEPARATE -001

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	DCFT003-1020	A	1

NOTE -

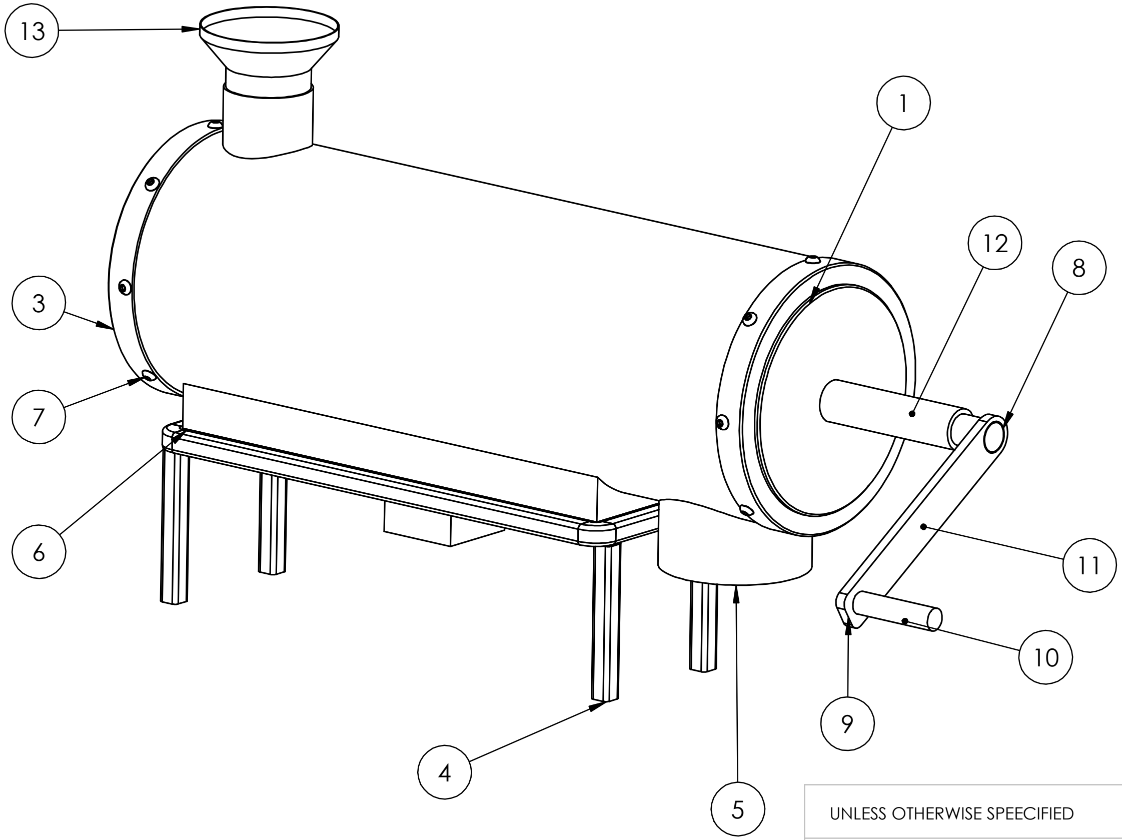
1-INTERPRET DRAWING PER ANSI B4.21978(R2004)

2-MATERIAL_1020

3-SURFACES TEXTURES 3.5- 4.2MICROMETERS RA = 0.004MM
CUTOFF 0.008MM

4-CONTINUOUS WELDS

QUANTITY =1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Back _Case_008		1
2	Deep Groove ball bearing_6804		2
3	Front _Case_007		1
4	leg_008		1
5	Screening_Drum_002		1
6	Top_Screening_Drum_003+002		1
7	B18.3.4M - 8 x 1.25 x 16 SBHCS --C		16
8	shaft pin		1
9	pin		1
10	Handle		1
11	lever		1
12	Screw _Conveyer_001		1
13	Hooper		1

UNLESS OTHERWISE SPEECIFIED	DESIGNED	Tesfamichael A.	30/07/2014	ADDIS ABABA UNIVERSITY (AAU)
DECIMALS ANGULAR	CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	AAiT
.X+/-.0 .XX +/-.00 .XXX +/-.112mm	APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)

ASSEM-SCREW PRESS SOLID LIQUID SEPARATE -002

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	DCFT002-1020	A	1

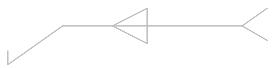
NOTE -

1-INTERPRET DRAWING PER ANSI B4.21978(R2004)

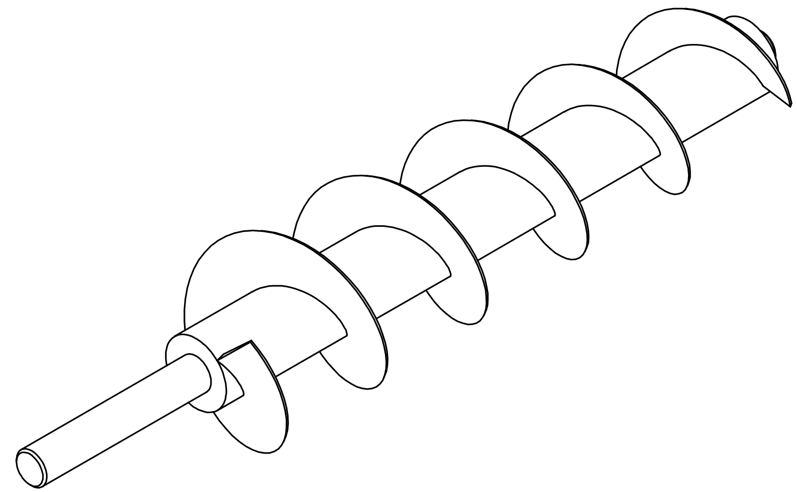
2-MATERIAL_1020

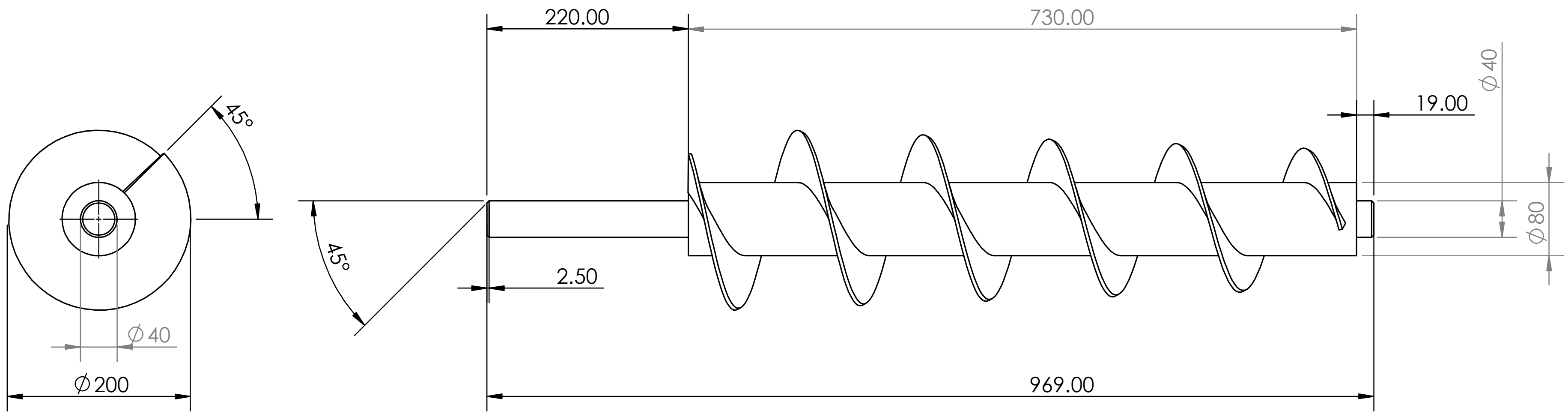
3-SURFACES TEXTURES 3.5- 4.2MICROMETERS RA = 0.004MM
CUTOFF 0.008MM

4-CONTINUOUS WELDS



QUANTITY =1





UNLESS OTHERWISE SPEECIFIED	DESIGNED	Tesfamichael A.	30/07/2014	ADDIS ABABA UNIVERSITY (AAU)
DECIMALS ANGULAR	CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	AAiT
.X+/-.0 .XX +/-.00 .XXX +/-.112mm	APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)

SCREW _CONVEYER_001

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	SC001-1020	A	1

NOTE -

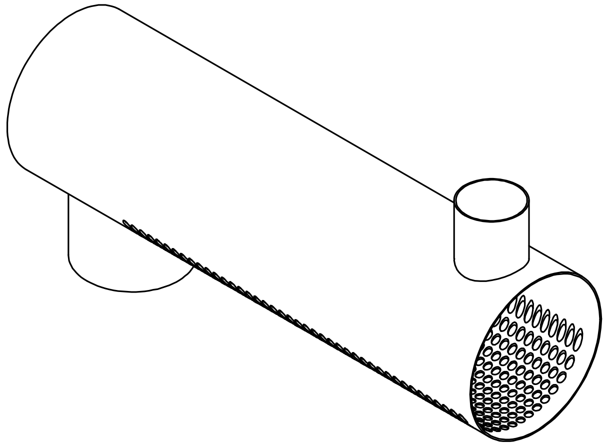
1-INTERPRET DRAWING PER ANSI B4.21978(R2004)

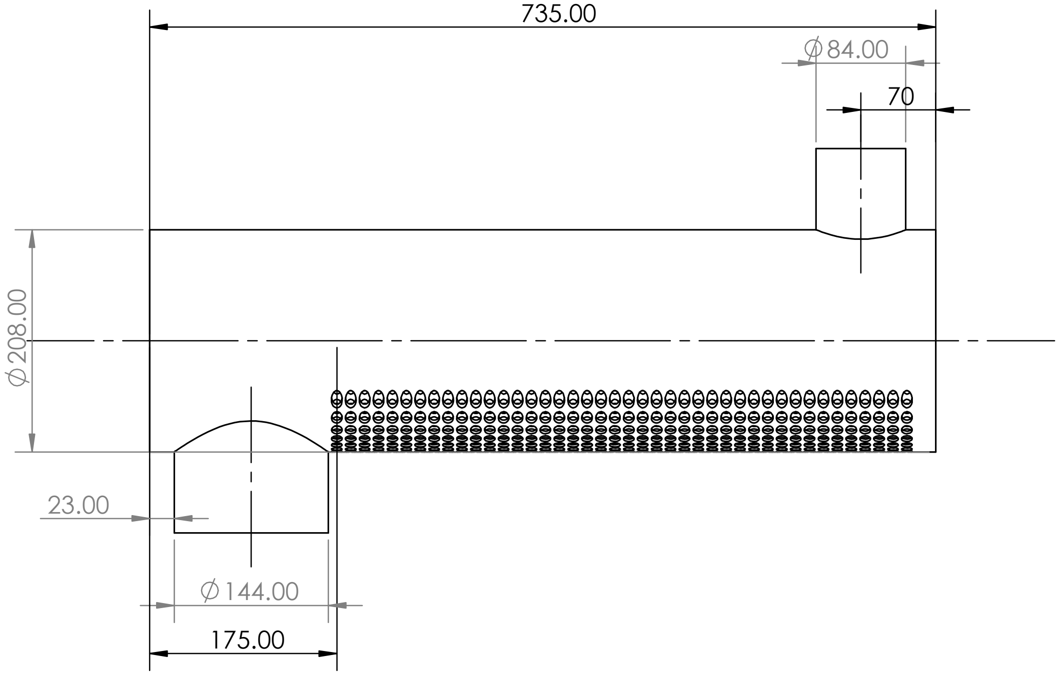
2-MATERIAL_1020

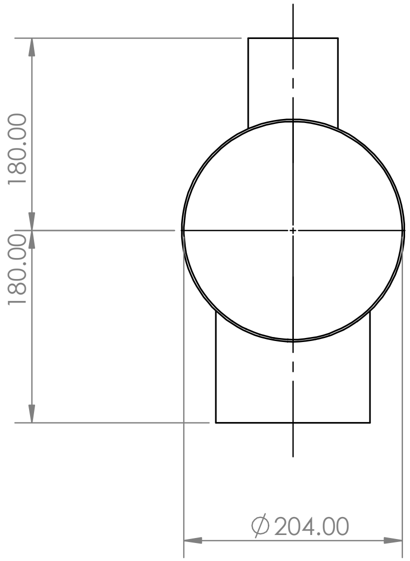
3-SURFACES TEXTURES 3.5- 4.2MICROMETERS RA = 0.004MM
CUTOFF 0.008MM

4-CONTINUOUS WELDS

QUANTITY =1







UNLESS OTHERWISE SPEECIFIED	DESIGNED	Tesfamichael A.	30/07/2014	ADDIS ABABA UNIVERSITY (AAU)
DECIMALS ANGULAR	CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	AAiT
.X+/-.0 .XX +/-.00 .XXX +/-.112mm	APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)

SCREENING_DRUM_002

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	SD002-1020	A	1

NOTE -

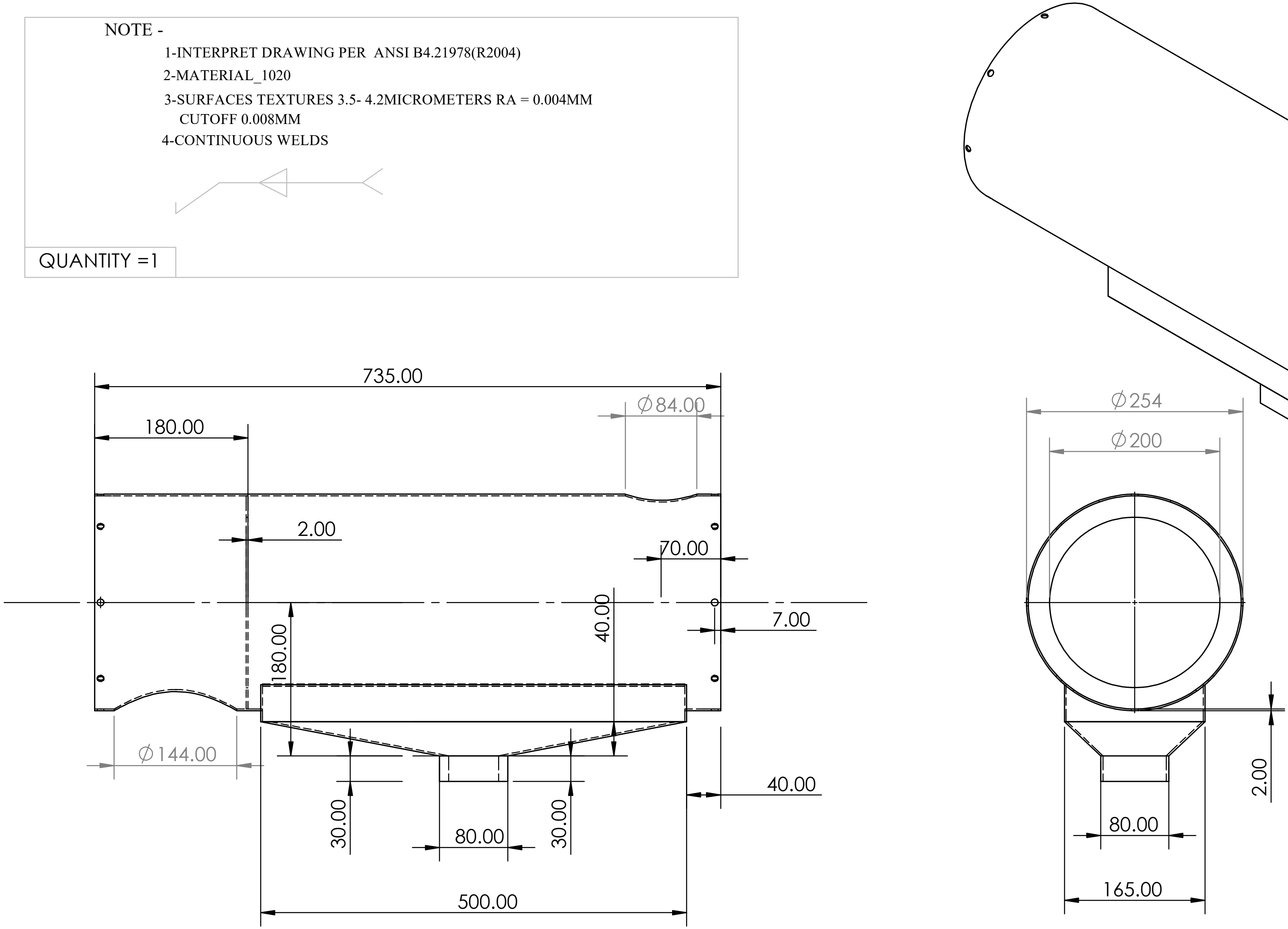
1-INTERPRET DRAWING PER ANSI B4.21978(R2004)

2-MATERIAL_1020

3-SURFACES TEXTURES 3.5- 4.2MICROMETERS RA = 0.004MM
CUTOFF 0.008MM

4-CONTINUOUS WELDS

QUANTITY =1



UNLESS OTHERWISE SPEECIFIED	DESIGNED	Tesfamichael A.	30/07/2014	ADDIS ABABA UNIVERSITY (AAU)
DECIMALS ANGULAR	CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	AAiT
.X+/-.0 .XX +/-.00 .XXX +/-.112mm	APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)

TOP_SCREENING_DRUM_003+002

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	TSD003-1020	A	1

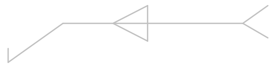
NOTE -

1-INTERPRET DRAWING PER ANSI B4.21978(R2004)

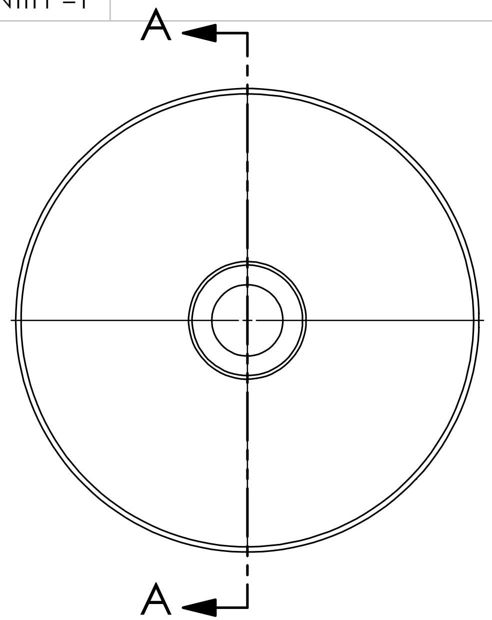
2-MATERIAL_1020

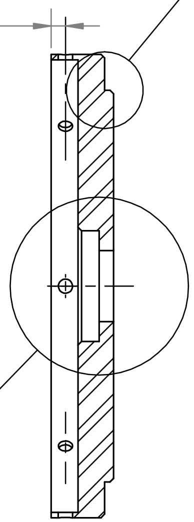
3-SURFACES TEXTURES 3.5- 4.2MICROMETERS RA = 0.004MM
CUTOFF 0.008MM

4-CONTINUOUS WELDS



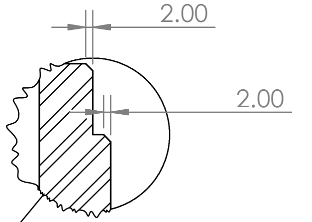
QUANTITY =1





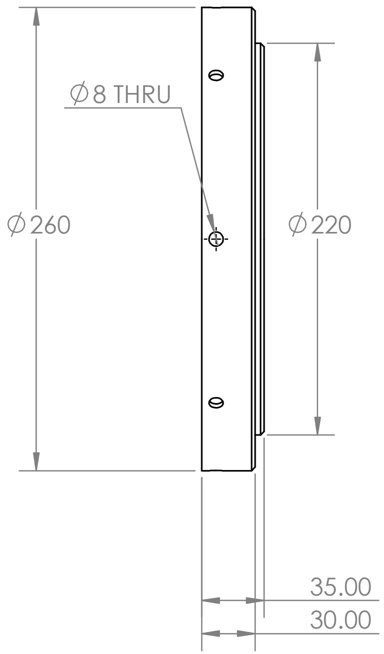
SECTION A-A

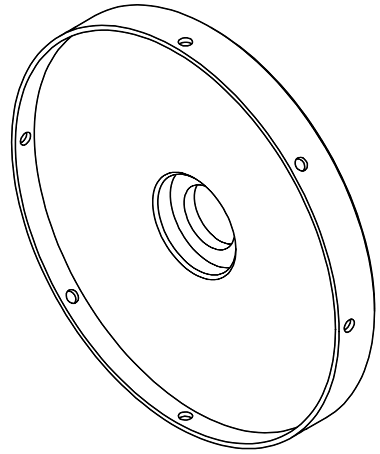
SCALE 1 : 3

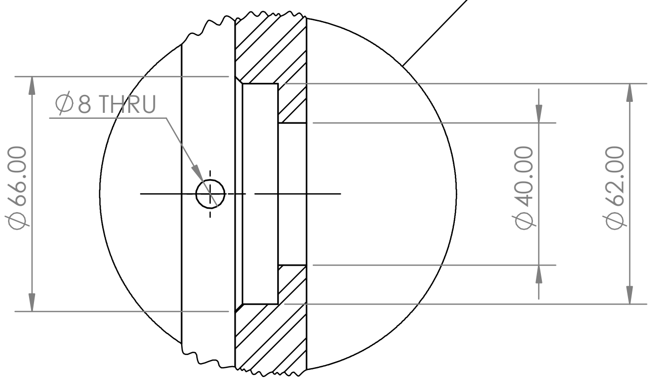


DETAIL C

SCALE 2 : 3







DETAIL B

SCALE 2 : 3

UNLESS OTHERWISE SPEECIFIED	DESIGNED	Tesfamichael A.	30/07/2014	ADDIS ABABA UNIVERSITY (AAU)
DECIMALS ANGULAR	CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	AAiT
.X+/-.0 .XX +/-.00 .XXX +/-.112mm	APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)

BACK _CASE_008

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	BC008-1020	A	1

NOTE -

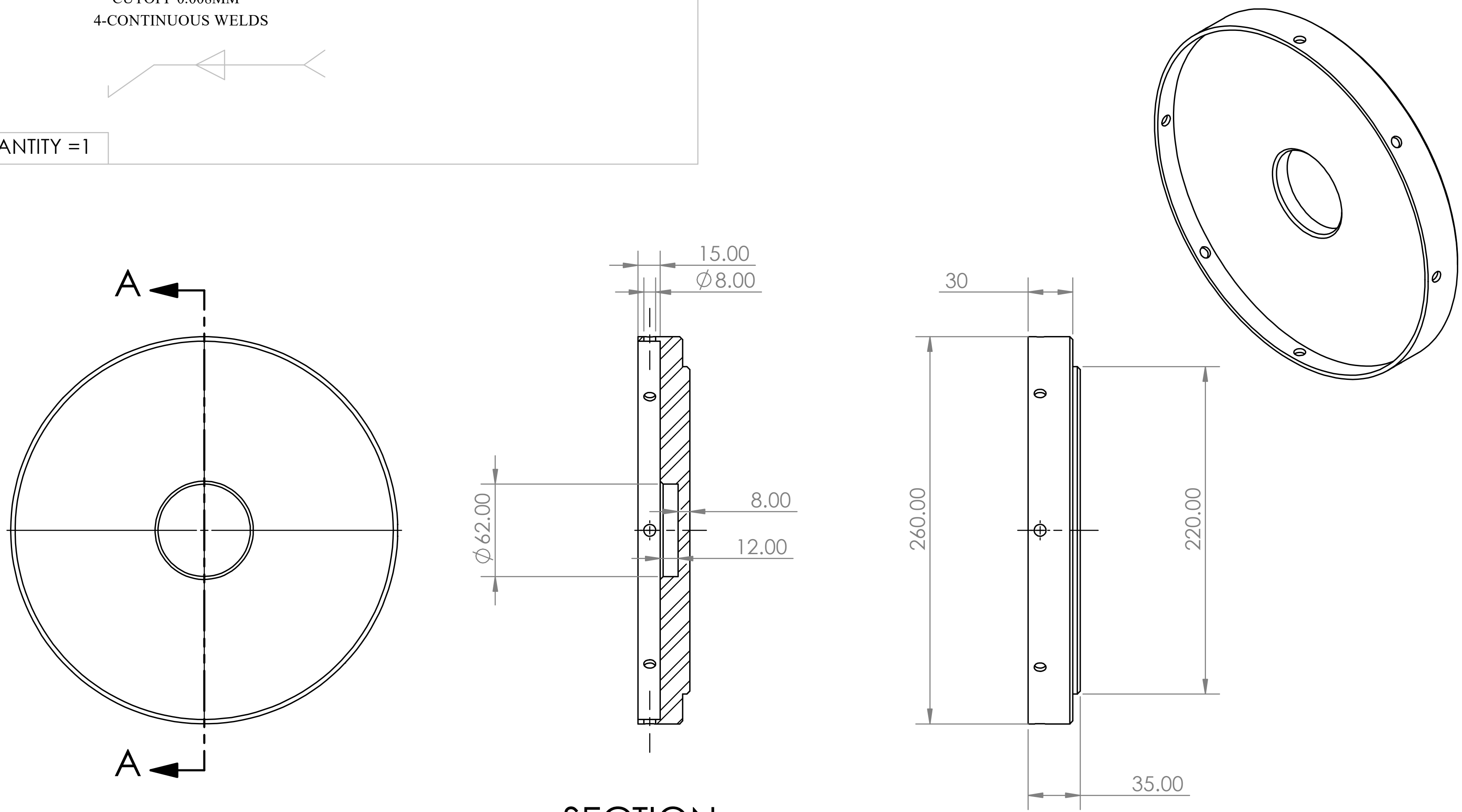
1-INTERPRET DRAWING PER ANSI B4.21978(R2004)

2-MATERIAL_1020

3-SURFACES TEXTURES 3.5- 4.2MICROMETERS RA = 0.004MM
CUTOFF 0.008MM

4-CONTINUOUS WELDS

QUANTITY =1



SECTION A-A

SCALE 1 : 3

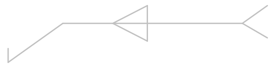
UNLESS OTHERWISE SPEECIFIED	DESIGNED	Tesfamichael A.	30/07/2014	**ADDIS ABABA UNIVERSITY (AAU)**
DECIMALS / ANGULAR	CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	**AAiT**
.X+/-.0 .XX +/-.00 .XXX +/-.112mm	APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	**SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)**

FRONT _CASE_007

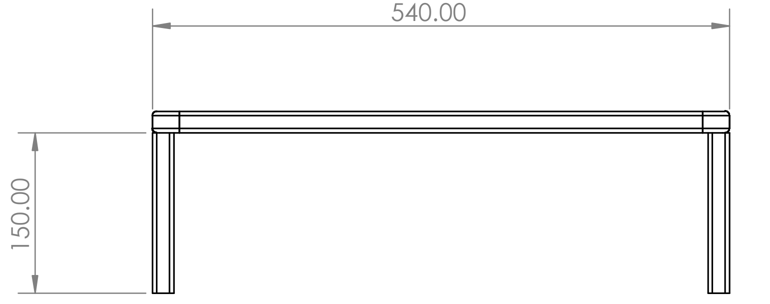
FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	FC007-1020	A	1

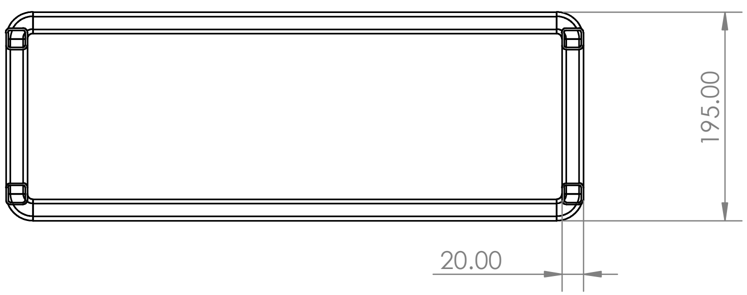
NOTE -

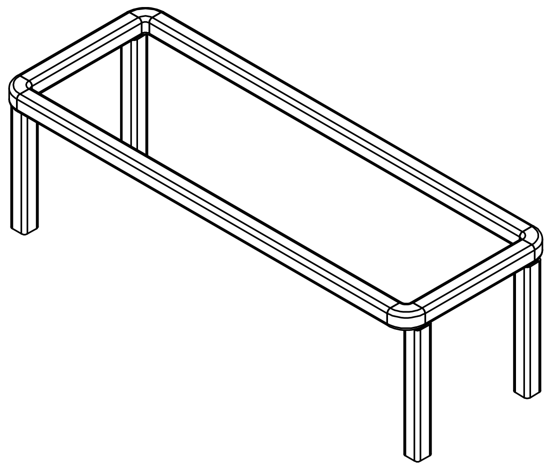
1-INTERPRET DRAWING PER ANSI B4.21978(R2004)
2-MATERIAL_1020
3-SURFACES TEXTURES 3.5- 4.2MICROMETERS RA = 0.004MM
CUTOFF 0.008MM
4-CONTINUOUS WELDS



QUANTITY =1

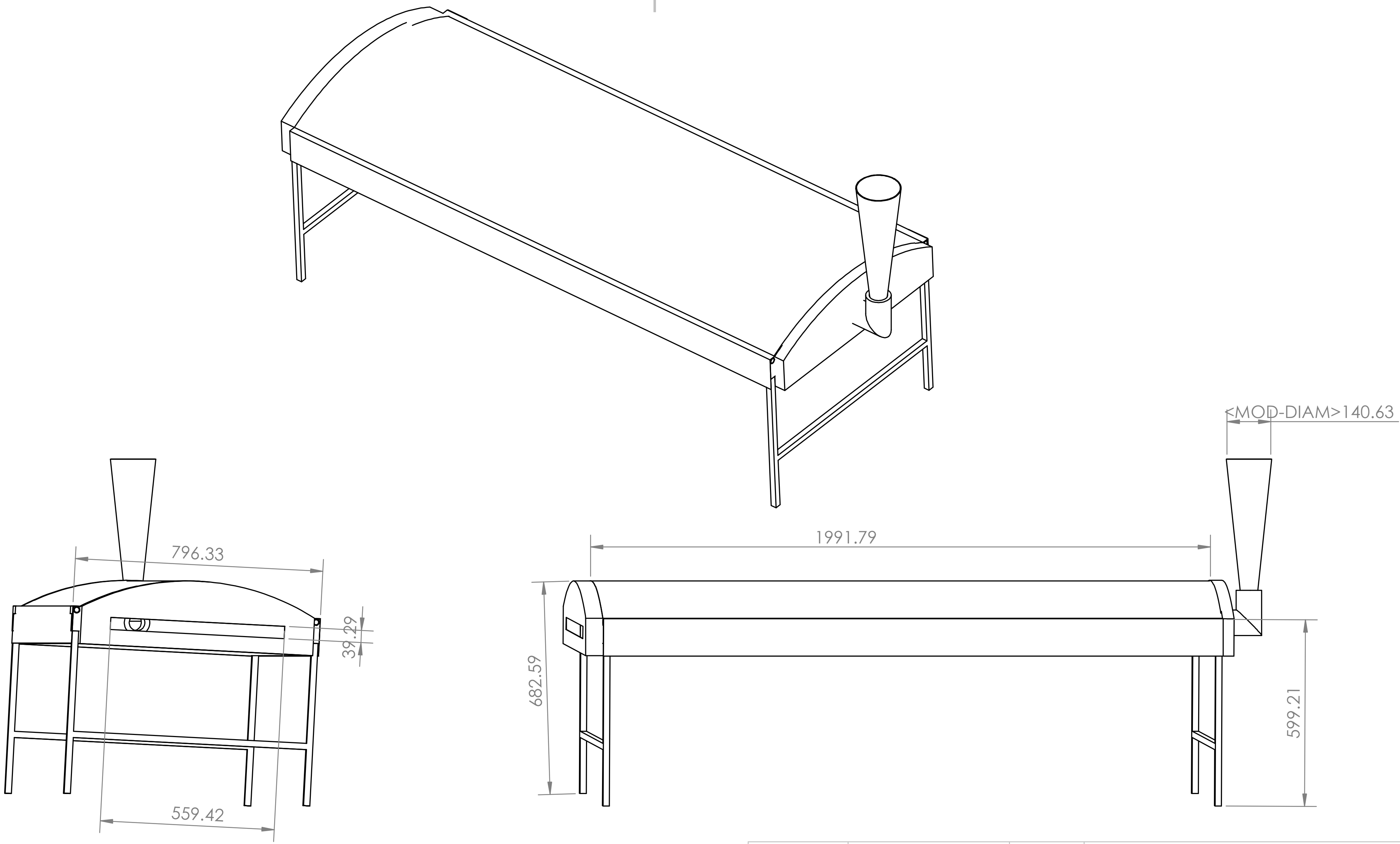






UNLESS OTHERWISE SPEECIFIED	DESIGNED	Tesfamichael A.	30/07/2014	ADDIS ABABA UNIVERSITY (AAU) AAiT SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)
DECIMALS ANGULAR	CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	
.X+/-.0 .XX +/-.00 .XXX +/-.112mm	APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	
	LUG_008			

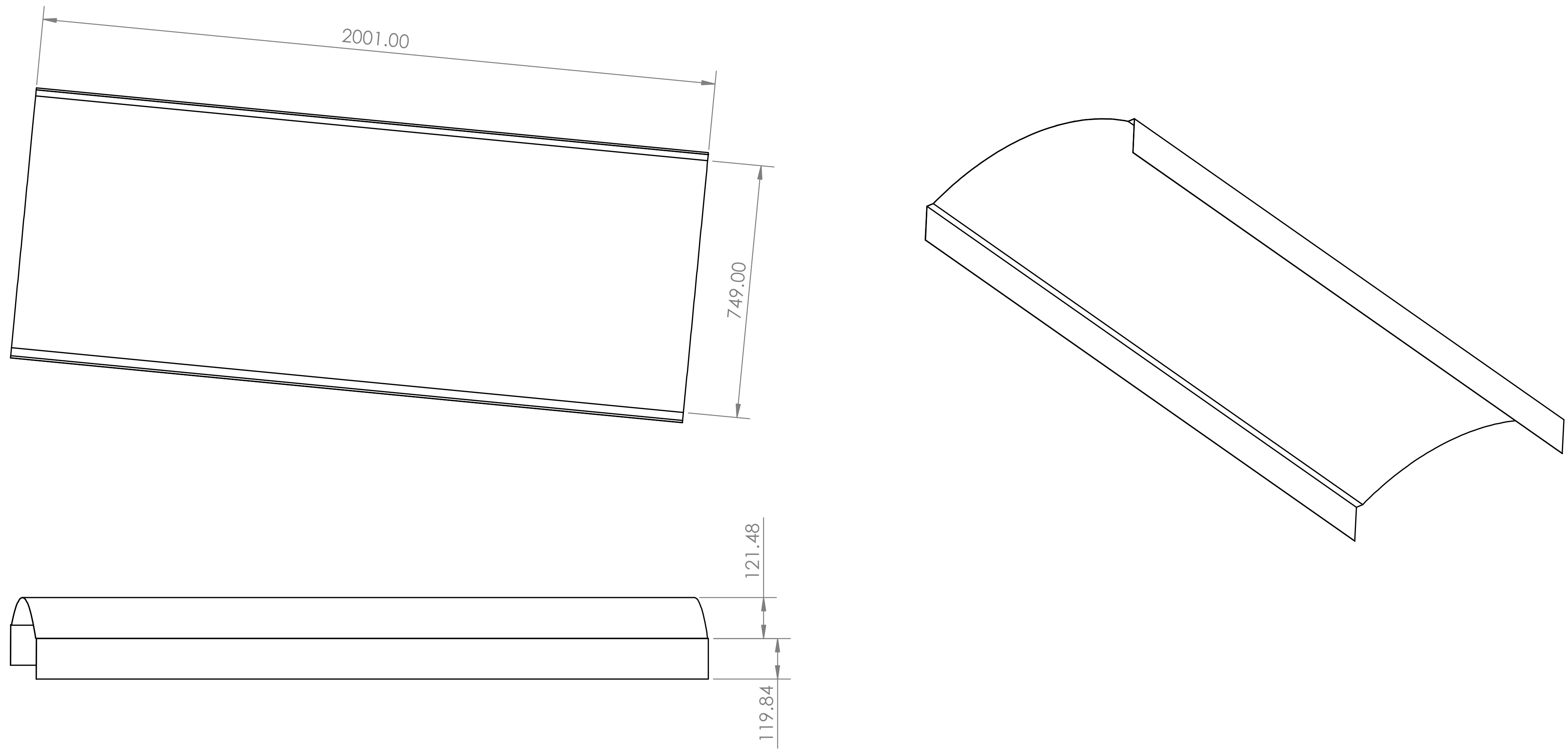
FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	L008-1020	A	1



DESIGNED	Tesfamichael A.	30/07/2014	**ADDIS ABABA UNIVERSITY (AAU)**
CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	**AAiT** **SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)**
APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	

SOLAR_TUNNEL_DRYER

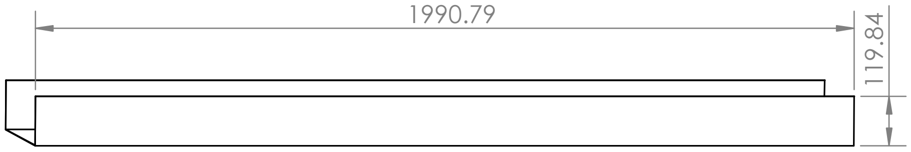
FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	TSD003-1020	A	1

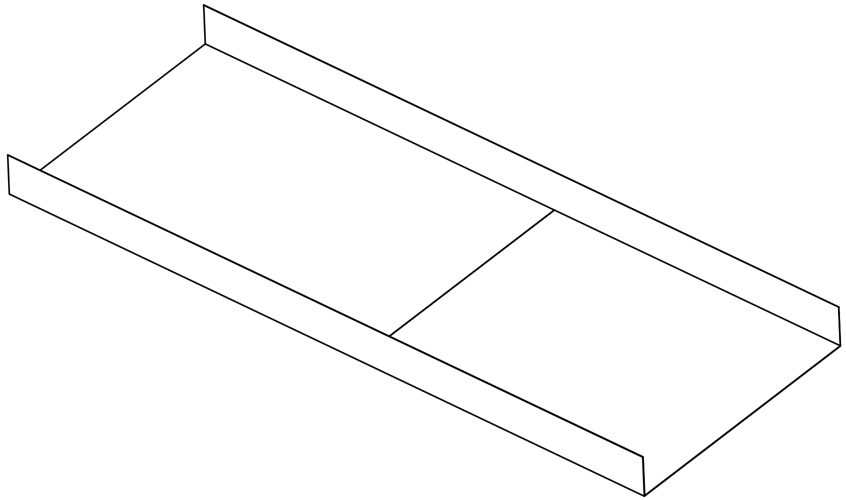


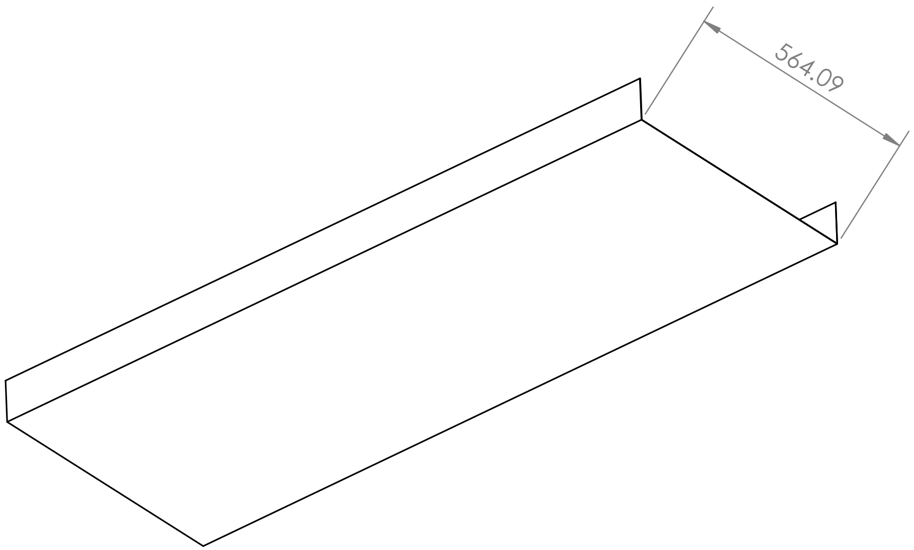
DESIGNED	Tesfamichael A.	30/07/2014	**ADDIS ABABA UNIVERSITY (AAU)**
CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	**AAiT**
APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	**SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)**

PLASTIC/GLASS_COVER

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	TSD003-1020	A	1



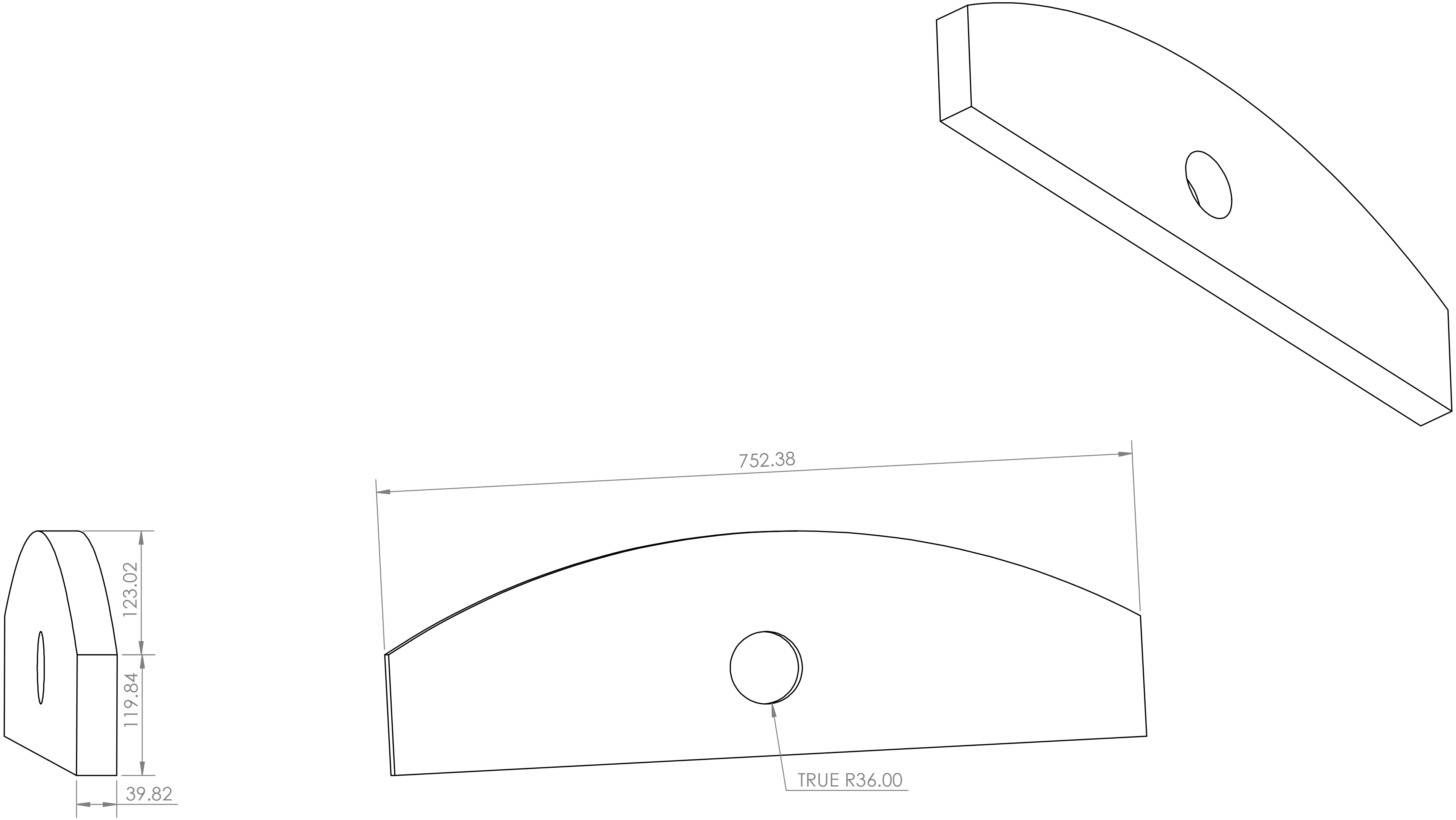




DESIGNED	Tesfamichael A.	30/07/2014	**ADDIS ABABA UNIVERSITY (AAU)**
CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	**AAiT**
APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	**SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)**

SOLAR_COLLECTOR

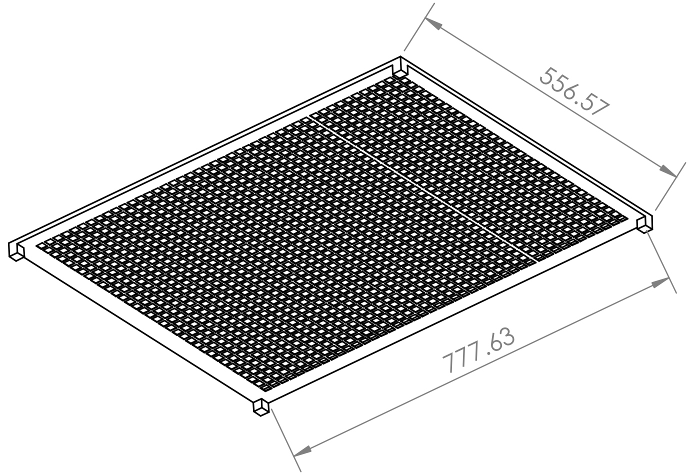
FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	TSD003-1020	A	1

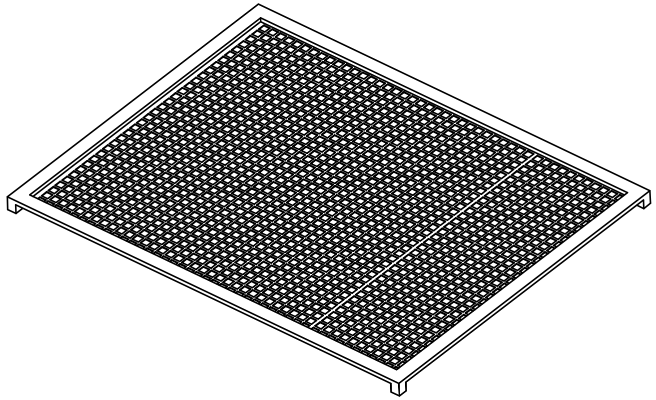


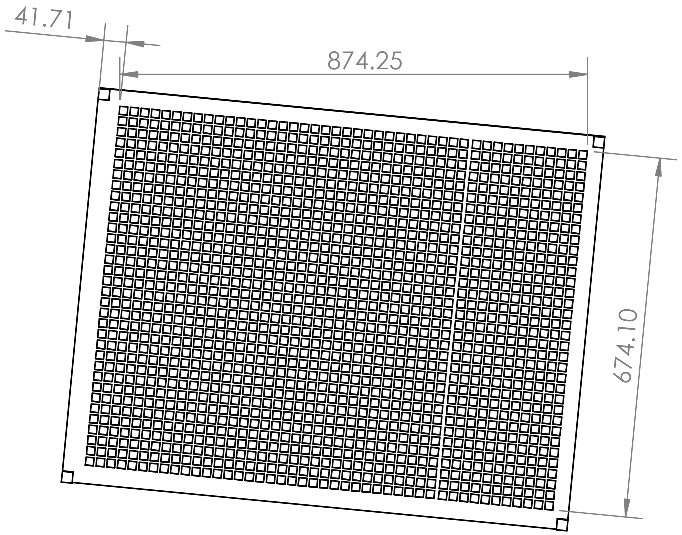
DESIGNED	Tesfamichael A.	30/07/2014	**ADDIS ABABA UNIVERSITY (AAU)**
CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	**AAiT**
APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	**SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)**

CHAMBER_OUTLET_COVER

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	TSD003-1020	A	1



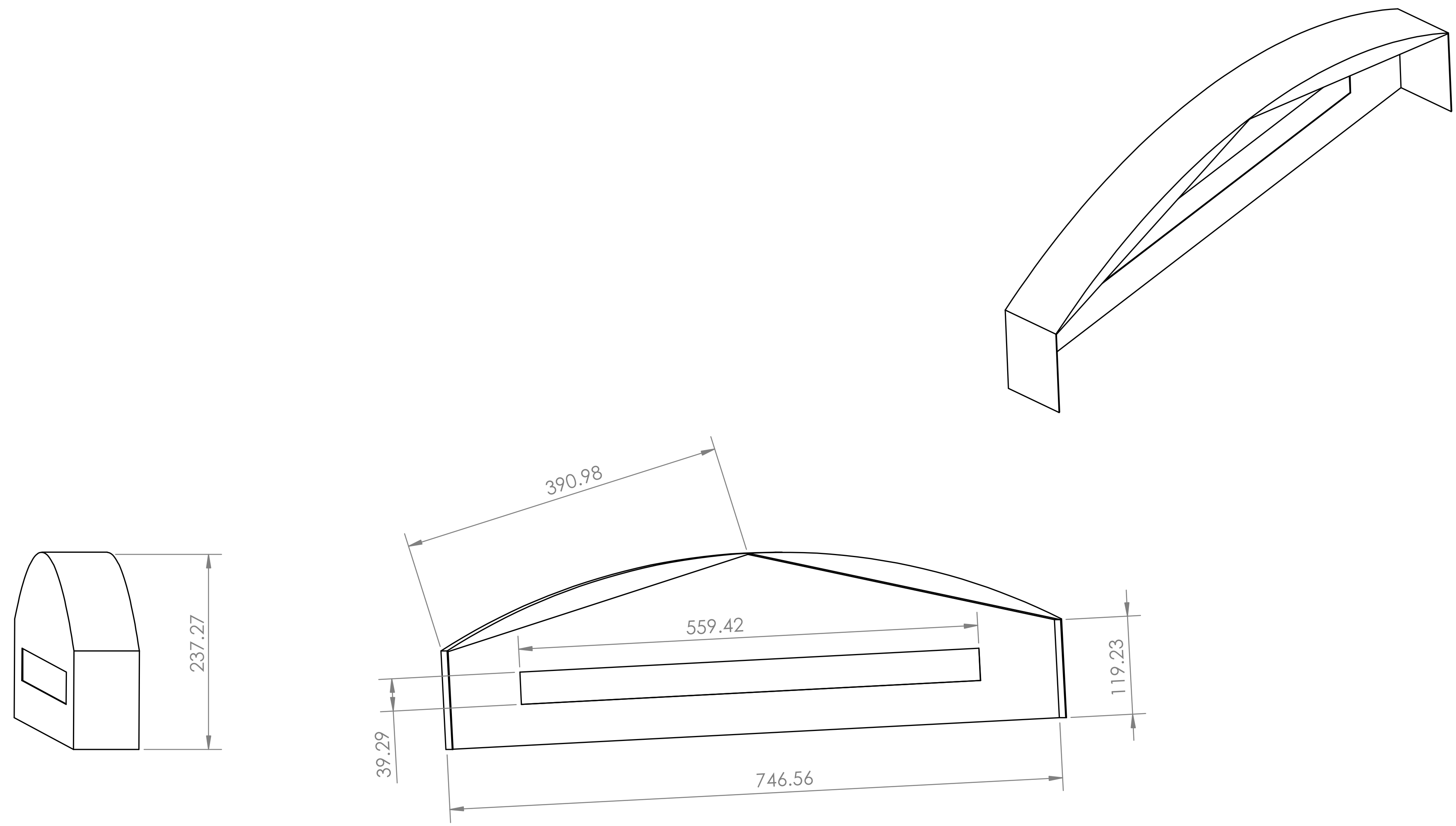




DESIGNED	Tesfamichael A.	30/07/2014	**ADDIS ABABA UNIVERSITY (AAU)** **AAiT** **SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)**
CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	
APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	

DRYING_TRAY

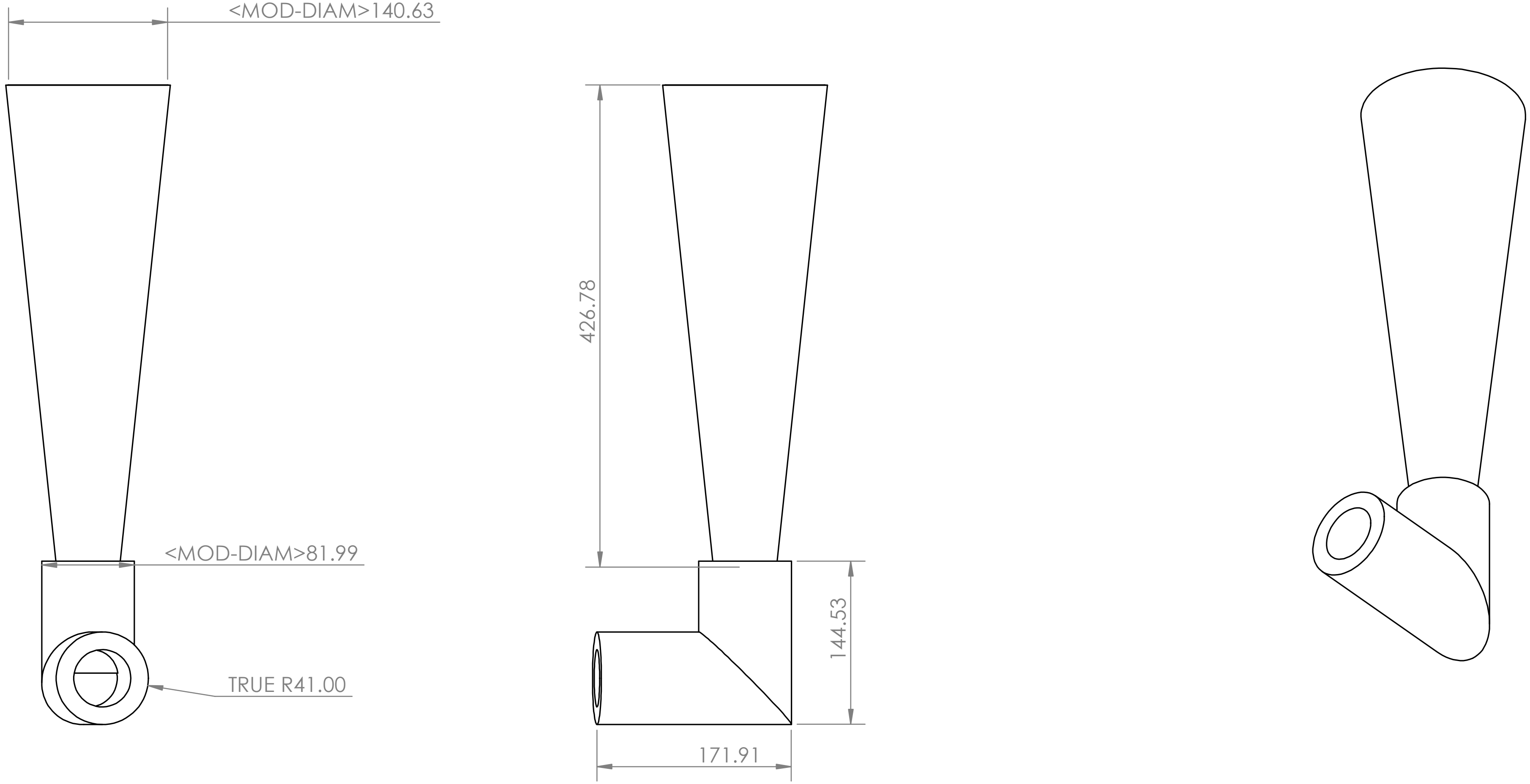
FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	TSD003-1020	A	1



DESIGNED	Tesfamichael A.	30/07/2014	ADDIS ABABA UNIVERSITY (AAU) AAiT SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)
CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	
APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	

CHAMBER_INLET_COVER

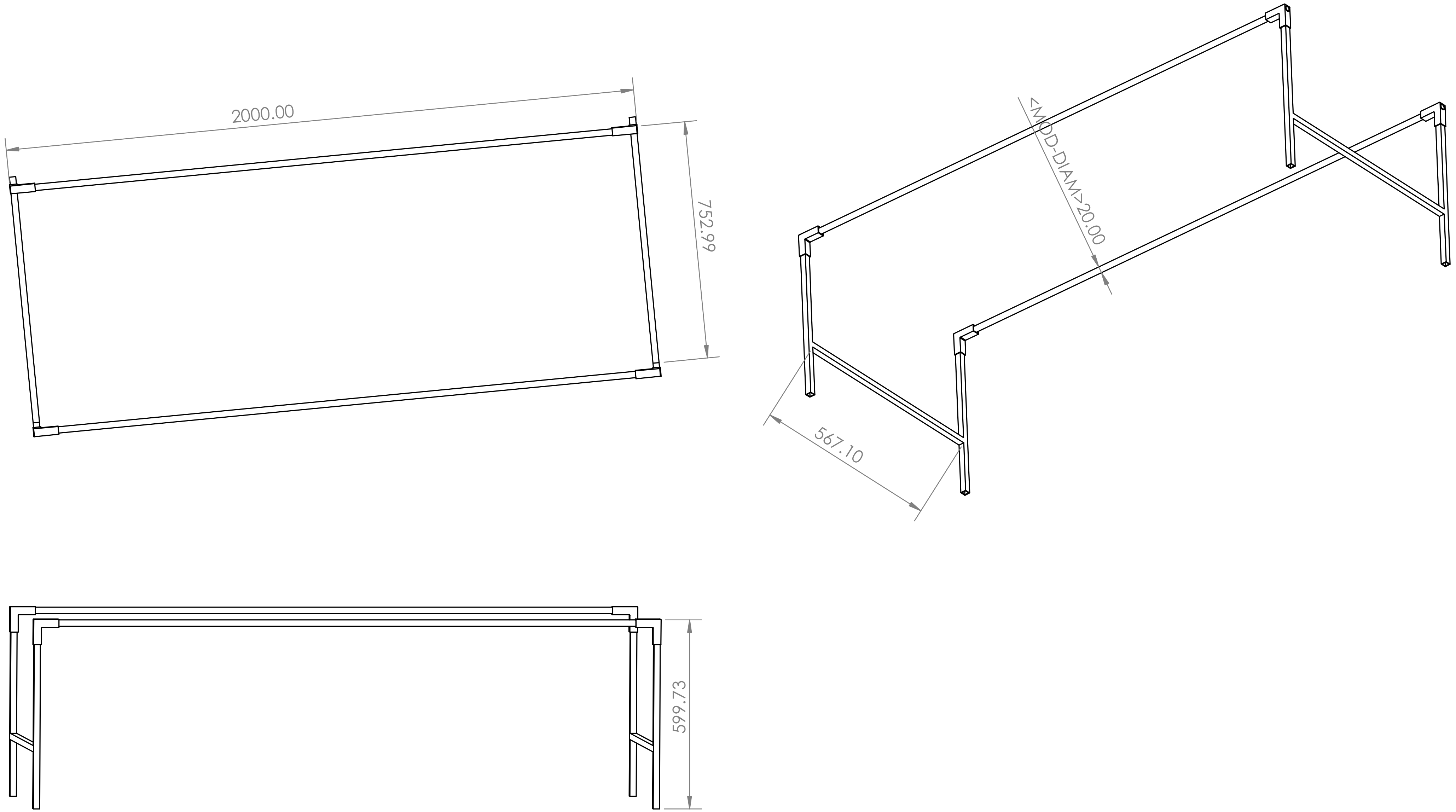
FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	TSD003-1020	A	1



DESIGNED	Tesfamichael A.	30/07/2014	**ADDIS ABABA UNIVERSITY (AAU)** **AAiT** **SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)**
CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	
APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	

CHIMNEY

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	TSD003-1020	A	1



DESIGNED	Tesfamichael A.	30/07/2014	ADDIS ABABA UNIVERSITY (AAU) **AAiT** SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING (SMIE)
CHECKED	Dr.-Ing. Wondwossen B.	30/07/2014	
APPROVED	Dr.-Ing. Wondwossen B.	30/07/2014	

DRYER_STANDS

FORMAT	SCALE	UNITS	DRAW-NO	REVISION	PAGE
A	1:1	mm	TSD003-1020	A	1