ECONOMICAL DESIGN OF COLD-RESISTANT BIOGAS DIGESTERS FOR DEGRADING HOUSEHOLD WASTE IN MOUNTAINOUS AREAS OF DEVELOPING COUNTRIES

BY

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Abstract

ECONOMICAL DESIGN OF COLD-RESISTANT BIOGAS DIGESTERS FOR DEGRADING HOUSEHOLD WASTE IN MOUNTAINOUS AREAS OF DEVELOPING COUNTRIES

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Energy is a basic tool for social and economic development. However, approximately 90% of rural households in low-income countries still rely on unprocessed traditional biomass fuel as the major source of daily energy. These biomass fuels are typically burned indoors, which leads to exposures to high levels of indoor smoke and associated health risks. Sustainable management of household waste is another environmental problem for rural peoples of developing countries. Currently, 90-95% of total generated wastes in most of developing countries is disposed of in open areas and street curbs.

Anaerobic decomposition of waste to produce methane is a cost-effective way of providing energy to rural peoples. Through anaerobic digestion, clean-burning fuel for cooking can be produced from degradation of household organic wastes. Despite being very popular in rural communities, biogas technology poses many challenges in high altitude areas of low-income countries. The methanogenic bacteria responsible for gas production are very sensitive to temperature. Colder temperatures inhibit bacterial activity. Since biogas plants in the mountainous areas do not have heating provisions, they become non-functional or out-of-order during winter months.

The main objective of this study was thus to develop and design a cold-resistant anaerobic digester to improve the fermentation temperature and maintain an efficient biogas production rate. This can alleviate the problem in utilizing biogas technology in rural communities located in the mountainous areas of low-income countries. The second objective was to conduct a life-cycle environmental and economic analysis for the cold-resistant design, compared to a conventional digester design.

To accomplish this, rice husk ash was examined as a locally available insulation material. Rice is one of the major agricultural crops at least in 75 countries of the world, leading to large volumes of rice husk as a readily available waste material. Rice husk ash can be integrated with reactor building materials such as bricks or blocks to enhance the digester performance in cold temperatures.

For this study, rice husk was burned to make rice husk ash (RHA), and soil was obtained from City of Arlington's landfill. The physical and chemical characteristics (pH, bulk density, moisture content and loss on ignition, CHON and S, surface metals analysis, sieve analysis) of soil and RHA were analyzed. Then rice husk ash was combined with soil in three different proportions (10% RHA + 90% soil, 20% RHA + 80% soil, and 30% RHA + 70% soil) to form bricks, which were fired at 500 ^{0}C and 700^{0} C, with burning duration of 4 and 6 hours. So, a total of 12 different types of bricks (3 RHA/soil proportions x 2 firing temperatures x 2 firing times) were tested for compressive strength and water absorption. It was found that the compressive strength of the brick decreases and water absorption increases with an increase in rice husk ash. The 8 bricks with the best compressive strength and water absorption values were then tested for resistance to heat transfer. Resistance to heat transfer increased with increased RHA percent. Leaching test results, determined with the LEAF procedure, showed that concentrations for all metals (primary standard) are lower than the maximum permissible limit on drinking water.

Based on the test results obtained on the different types of brick, a best composition was selected for building reactors. The best composition of brick was 20% RHA and 80% soil with burning temperature of 700^{0}C with 4 hours burning time. Two laboratory-scale brick masonry circular reactors with outside diameter of 2'6" were built, one with the bricks with RHA added and the other one with conventional bricks. Using cow manure (about 12 kilograms), the reactors were operated at a controlled outside temperature of 21^{0}C initially, which was later lowered to 10 ^{0}C. The RHA reactor produced the gas continuously when the temperature dropped gradually from 21 ^{0}C to 12 ^{0}C and stopped after 10 ^{0}C; however, the conventional reactor stopped producing methane after 14 ^{0}C. Compared to the conventional reactor, the reactor with insulation had an average inside temperature about 3.5 ^{0}C degrees higher, started gas formation earlier, peaked earlier and had a higher rate of methane generation. The cumulative volume of methane in RHA reactor was 33% greater than the conventional reactor after 102 days of reactor operation. The likely reason is that the higher temperature helped microorganisms grow faster and degrade the organic matter quickly. So, the RHA seems to be promising insulating material for the use in building the biogas reactor in the temperate areas. Also, microbial analysis of both reactor sludge was done to find out different microbial communities in each reactor during anaerobic treatment of cow dung.

An economic analysis was done to compare the cost and benefit of the cold resistant reactor with the conventional reactor. The cost of both reactor types was calculated based on a data available in a developing country, Nepal, using the present worth method. RHA reactor has a higher benefit-cost ratio (4.3 vs. 3.8) and internal rate of return (80% vs. 71%) for 20 years lifetime. Based on the energy balance results obtained from environmental impact analysis, the net annual energy production of cold resistant reactors is 684 MJ higher than conventional reactors.

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Chapter 1

Introduction

1.1 Background

Energy is universally considered as fundamental input for social and economic development. However, about one-quarter of the world's population (1.6 billion people) have no access to electricity (Mulder et al, 2008). Four out of five people in rural areas of the developing world are without access to electricity, mainly in South Asia and sub-Saharan Africa. Developing Asia and sub-Saharan Africa continue to account, together, for more than 95% of those do not have access to modern energy (IEA, 2012). It is projected that 1 billion people will still be without electricity in 2030 (IEA, 2012).

The provision of affordable and reliable energy service is essential for "sustainable development" (IEA, 2002; Mulder et al., 2008). Per capita, energy consumption is one of the major determiner and an indicator of economic development. Economic development and the per capita energy consumption are interrelated (Katuwal et al., 2009). In developing countries, public access to electricity is mostly influenced by the cost of extending national grid line to the rural areas (Yadoo et al., 2011). So, increasing access to energy for the peoples in the rural community of developing countries has proven to be very expensive and difficult.

Fuelwood has been and still is the major source of energy for the rural peoples. Approximately half the world's population, and the up to 90% of rural households in low income countries (more than 2.4 billion people), still rely on unprocessed traditional biomass fuel as the major source of daily energy. They use firewood, agricultural residues, animal dung and charcoal to meet their daily energy demands for cooking, heating, and lighting (Zahnd and Kimber, 2009; Barnes and Floor, 1996). Around 2.7 billion people in rural areas in low-income countries will likely continue using traditional biomass energy sources until 2030 to meet their energy demand (WEO, 2006).

These biomass fuels are typically burned indoors with limited ventilation in open fires or poorly functioning stoves, which leads to high exposures to indoor smoke and associated health risks, particularly for women and children. Indoor smoke from using fuelwood contains a range of potentially harmful substances, from carcinogens to small particulate matter, all of which can cause damage to the lungs. The long-term exposure to indoor air pollution increases the risk of respiratory and other health problems, such as lung cancer, acute respiratory infections, chronic obstructive pulmonary disease, tuberculosis, and asthma, especially in women and children under the age of 5 years (Bruce et al., 2000; Smith et al., 2004). Moreover, women and young girls have to spend several hours for fetching and collecting heavy fuelwood loads for their daily household uses, which prevents them from participating in other social and educational activities. Indoor air pollution has a high global impact on human morbidity and mortality. Globally indoor smoke accounts for more than 1.6 million deaths per year (more than half of these deaths occur under five years of age) and responsible for 2.7% of the global burden of diseases annually (WHO, 2006). In developing nations with high mortality rates, indoor air pollution ranks fourth in terms of the risk factors that contribute to disease and death (WHO, 2002).

Poverty is one of the main barriers to the adoption of cleaner fuels. Even though the proportion of global energy that is derived from biomass fuel has decreased, there is an evidence that their use is increasing among the poor peoples. In recent years, energy demand has increased sharply due to the fast-economic development and the rise in human living standards. In developed countries, fossil fuel consumption consequently has hastened. As a result, the exploration and development of new, renewable and sustainable energy sources are becoming increasingly important to cope with energy challenges in both developing and developed countries.

The sustainable management of municipal solid waste (MSW) is another environmental problem faced by the world today. Rural peoples of developing countries suffer not only from energy shortages but also from the improper management of the solid waste. Current global MSW generation levels are approximately 1.3 billion tons per year and are expected to increase to approximately 2.2 billion tons per year by 2025, which represents substantial growth in per capita waste generation rates, from 1.2 to 1.42 kg per person per day (World Bank, 2012). Rates of municipal solid waste generation are greatly influenced by economic development, the degree of industrialization, public habits, and local climate. Generally, the higher the economic development and rate of urbanization, the greater the amount of solid waste produced. Per capita income level and urbanization are highly correlated and as disposable incomes and living standards increase, consumption of goods and services correspondingly increases, as does the amount of waste generated. Urban residents produce about twice as much waste as rural residents.

Studies have shown that the average waste collection rates are directly related to income levels. Low-income countries have low collection rates, around 41%, while high-income countries have higher collection rates, averaging 98% (World Bank, 2012). Currently, 90-95% of total generated wastes in most of developing countries are disposed of in open areas, street curbs, etc. and in landfills in developed countries (Pudasaini, 2014). Improving solid waste management, especially in the rapidly growing cities of low-income countries, is becoming a more urgent issue these days. If these wastes are not managed properly, it will lead to the severe deterioration of environmental quality, causing serious threats to human health.

Landfills alleviate many health issues associated with the open dumping of solid waste; however, they pose health and environmental issues of their own. In particular, landfills are sources of methane and carbon dioxide emissions, which are called greenhouse gases (GHGs). Carbon dioxide is the most prevalent greenhouse gas, and methane ranks second. In 2015, methane accounted for about 10% of all U.S. greenhouse gas emissions from anthropogenic sources. Globally, methane accounted about 16% of total greenhouse gas emissions (IPCC, 2014). Over 60% of total methane (CH_4) emissions comes from human activities, such as industry, agriculture, and waste management activities (EPA, 2015). Methane's lifetime in the atmosphere is much shorter than carbon dioxide (CO_2) but it is more efficient at trapping radiation compared to CO_2. The comparative impact of CH_4 on climate change is at least 28 times greater than CO_2 over a 100-year time horizon, and methane can stay in the atmosphere as long as 12 years (EPA / IPCC Report, 2013).

Fortunately, methane from anaerobic decomposition of waste in landfills, as well as anaerobic digesters, can be used as a renewable source of energy, for both developed and developing countries. **In particular, household level biogas digesters could solve the challenges of both renewable energy and sustainable waste management for rural peoples in developing countries.** Burning methane to generate electricity converts the methane to carbon dioxide, which has 28 times lower climate change potential.

1.2 Anaerobic Digestion

Anaerobic digestion (AC) is a biochemical process in which various microorganisms transform high molecular weight complex organic compounds to methane, along with carbon dioxide, water vapor and a few other trace gases such as hydrogen sulfide, hydrogen, nitrogen, and carbon monoxide. Depending upon the source of organic materials used in the AD, biogas contains typically 60-70 % of methane (Ras et al, 2007). Figure 1-1 shows a schematic of the anaerobic digestion process.

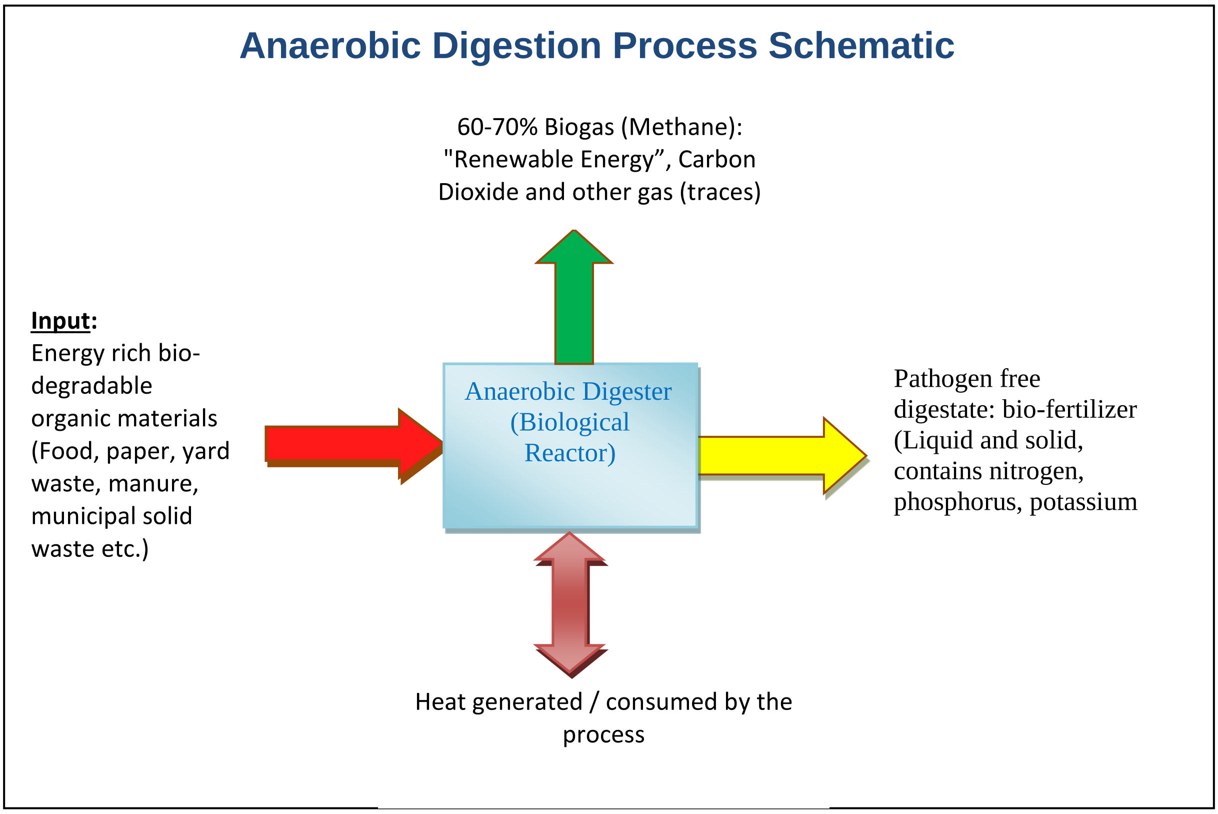


Figure 1- 1 Anaerobic digestion process schematic

The biogas, which is produced from the anaerobic breakdown of organic raw materials and can be used for various energy demands (such as heating, fueling, cooking, and power generation), has been recognized as a viable alternative in solving both energy and environmental issues. Bioenergy accounts for roughly 10% of world total primary energy supply today. Most of this is consumed in developing countries for cooking and heating. About 3.5% of road transportation fuel is provided today by biofuels (IEA, 2015).

The current energy crisis is very acute in rural communities of developing countries, where fuelwood is the major source of daily fuel for cooking and lighting, which ultimately requires cutting of trees. Biomass burning is a major contributor to air pollution and the greenhouse gas effect. Deforestation also leads to a decrease in the fertility of land by soil erosion. Using traditional fuelwood stoves under conditions of limited ventilation leads to high exposures to indoor smoke and associated health risks. Worldwide indoor smoke causes about 21% of lower respiratory infection deaths, 35% of chronic obstructive pulmonary deaths and about 3% of lung cancer deaths. About 64% of these deaths occur in low-income countries, especially in South-East Asia and Africa (WHO, 2009). So indoor air pollution causes a critical public health problem in low-income countries, particularly for women and children.

In developing countries energy poverty is also directly related to gender issues. In rural communities, women and young girls are typically responsible for collecting fuelwood for household uses such as cooking and heating. They have to spend several hours for fetching and collecting heavy fuelwood loads, causing several health problems and restricting them from other important, social, educational activities and income generating activities (Clancy et al., 2002).

Household level small-scale biogas digesters can be a cheap way to provide energy to the rural communities of developing countries. Biogas technology has been developed and widely used over the world because it has a lot of advantages, including reducing the dependence on non-renewable resources, high energy-efficiency, environmental benefits, available and cheap resources to use as feedstock, relatively easy and cheap technology for production, and nutrient-rich digestate as a fertilizer (Zhang, 2012). It has already been proven that this technology is easily implemented, cost-efficient, small-scale, and completely decentralized renewable alternative, which is technically feasible, economically viable and very effective for solving two global environmental problems at once, waste management and renewable energy (Zhang, 2012; SSWM, 2015). Under the right conditions, a biogas plant will yield several benefits for the end-users, including (GTZ, 2007):

- Production of energy for lighting, heat, electricity
- Improved sanitation (reduction of pathogens, worm eggs, and flies)
- Reduction of workload (less firewood collecting)
- Better cooking performance (biogas stoves)
- Environmental benefits (fertilizer substitution, less greenhouse gas emissions)
- Improved indoor air quality (less smoke and harmful particle emissions of a biogas stove compared to wood or dung fuels) (Balasubramaniyam et al., 2008)

Figure 1-2 shows a typical schematic of household level biogas plants.

Figure 1- 2 Typical schematic of household level biogas plants Source: Nepal Biogas Support Programme

Anaerobic digestion of animal wastes and household wastes for production of biogas is a widely studied subject. Properly functioning biogas systems can yield a whole range of benefits for their users. However, in general, studies have been confined to biogas production at mesophilic and thermophilic temperatures. Low temperature has a harmful effect on methanogenesis and can cause decreased gas yields and digester failure when digesters are not properly designed.

Despite being very popular in rural communities, biogas technology poses many challenges in high altitude areas of the low-income countries. A variety of factors affect the rate of digestion and biogas production. The most important factor is temperature. Biogas production is carried out at different temperatures: the temperature range from 45 to 60 °C is referred to as 'thermophilic,' whereas that carried out at a temperature range of 20 to 45 °C is known as 'mesophilic,' and at low temperatures (<20 °C) biogas production is referred to as 'psychrophilic' digestion (Safley et al., 1992). The development of technology to make biogas available as an energy source for cooking and heating in the colder areas of any country during the winter season is a great concern (Balasubramaniyam et al., 2008). The methanogenic bacteria responsible for gas production are very sensitive to temperature. As warm temperatures increase, the bacterial activity also increases up to a point and the rate of gas production increases. Colder temperatures inhibit bacterial activity. Methanogenic bacteria yield the best gas production in the mesophilic temperature range of 35 ^{0}C to 38 ^{0}C (Velsen et al., 1979; Rai, 2004). When temperature decreases 11℃, the production of biogas will falls by 50% (Zhang, 2012). So, the effectiveness of biogas decreases with a decrease in temperature. The biogas plants in the mountainous areas of developing countries do not have heating provisions or automatic temperature control; all of the operational biogas plants in temperate climates have become non-functional or out-of-order, particularly during winter months. The major reason for that failure is climatic conditions (temperature) in these areas.

In the developing country of Nepal, more than 94 % of biogas plants are located in mid-hill and plain areas (BSP, 2004). In communities in the mountainous areas where the temperature falls below 10^{o} C, this technology is not effectively popularized. Only 6% of the total installed biogas plants in Nepal are located in the mountain region of altitude 1600 m and higher. In Nepal, 250,000 household biogas digesters have been installed over the last few decades; however, the potential exists for up to 1.9 million (Gurung et al., 2013). The percent of biogas plants achieved with respect to the estimated potential is stagnant in hilly areas of India such as Jammu and Kashmir because of operational difficulties. India had installed approximately 4.54 million biogas plants by 2012; however, an estimated potential is 12.34 million digesters (Lohan, 2014). The high-altitude states are lagging behind rest of India and have installed only 0.06% of the total plants installed in the country (Lohan, 2014). Although the household digesters have been widely used in rural areas of China, a study showed that Chinese household biogas has an obvious geographical difference in popularization rate (Yang et.al 2012). In cold regions of China, only a small number of household biogas digesters are being used. The household digesters in southern regions work well in all seasons, whereas in northern regions, household digesters may stop anaerobic fermentation process under the extreme weather conditions during winter (Zhang et al. 2016), which limits the application of household digesters in cold areas of China.

Hence for an increased distribution of biogas plants in high altitude regions, further improvements in the design and process efficiency and the development of new technologies for mixing, process monitoring, and process control are essential. Several methods for increasing the digester temperature may be adopted to develop a suitable biogas plant for cold climates, including construction of a digester with hollow insulated bricks for floating-drum plants/fixed dome plants, placing insulation around the digester (such as sawdust, rice husk, foam board, cellulose, mineral wool, fiberglass, straw), enclosing the biogas plant inside a greenhouse, using thermal insulation paint /Plaster of Paris and mixing the input feedstock material with hot water during peak winter months.

1.3 Thesis objectives

One of the most important factors affecting anaerobic degradation of waste to produce biogas is a temperature. The digester temperature not only affects the amount of biogas production but also influences the overall performance of the reactor. The temperature in the digesters especially in winter is likely to be affected by a range of different factors, but primarily by air temperature, the degree of heat exchange between the digester and the outside air, soil temperature, and temperature of inflowing slurry. To find simple ways to maintain higher temperatures during winter, it is important to understand the main driving factors influencing digester temperature and identify ways of keeping the temperature high during the winter.

Previous studies have tested the digester temperature by providing the heating provision inside the reactor. However, one of the most important applications of biogas systems is in rural areas of low-income countries, where clean-burning fuel for cooking can be produced from degradation of household organic wastes. The rural peoples of developing countries do not have access to the alternative source of energy such as electricity because of the high cost of expanding national grid line to the rural areas. Some studies have improved the digester temperature by installing a solar panel on top of the reactor and using hot water while preparing the slurry. However, solar energy is less reliable in the mountainous areas due to harsh weather conditions. Other researchers proposed maintaining the digester temperature by covering the digester with a transparent polyethylene sheet, foam board, circulating hot water pipe around the digester, charcoal coating around the wall, using insulating paint on the wall of the digester, etc.

There are many locally available natural as well as synthetic insulating materials. Very limited studies have been done to increase the digester temperature by using locally available insulating material which is economically cheap and environmentally friendly, such as rice hull ash (RHA), sawdust, and foam boards. Several papers have been published on the performance of different insulation materials; however, there is limited information available on the resistance to heat (R-value) characteristics of RHA blended clay bricks. Generally, a household level biogas plant is a brick/ stone/concrete masonry structure, buried underground. None of the studies have explored the use of construction material that is enhanced with an insulation to build a cold-resistant digester for the cold areas of low-income countries. Therefore, proper insulation measures and a heating system are necessary for such regions with extreme temperature variations, to maintain an appropriate and relatively constant slurry temperature inside the digester.

The overall goal of this study is thus, to develop and design a cold-resistant anaerobic digester to improve the fermentation temperature and maintain an efficient biogas production rate. This can alleviate the problem in utilizing biogas technology in rural communities located in the mountainous areas of low-income countries. Specific objectives are:

1. To investigate and test locally available insulating materials that can be used in the digester to enhance biogas production. Tests will be conducted for thermal resistance (R), compressive strength, water absorption, pH, moisture content, loss on ignition, surface metals (XPS analysis), chemical composition (carbon, hydrogen, oxygen, nitrogen, and sulfur), bulk density, sieve analysis leaching potential (using LEAF procedure).
2. To develop and test a cold-resistant biogas digester design for the use in mountainous areas of developing countries.
3. To conduct a life-cycle environmental and economic analysis for the cold-resistant design, compared to a conventional digester design.

1.4 Dissertation Outline

The remainder of the dissertation is outlined in the following manner:

- The second chapter reviews the literature on greenhouse gas emissions, the composition of municipal solid waste, landfill gasses and factors affecting landfill gas production, degradation phases of organic waste, biogas and its importance, benefits, and types, effect of temperature on the performance of biogas production, and previous studies of increasing biogas production temperature.
- The third chapter describes sample collection, experimental setup, methodologies, and procedure for laboratory tests to address the research objectives.
- The fourth chapter presents, analyzes and discusses experimental results and findings.
- The fifth chapter summarizes the main conclusions of this study and provides some recommendations for future research work.

Chapter 2

Literature Review

2.1 Background

This chapter include background information on greenhouse gases (GHG), sources of GHG emissions, landfills, degradation of wastes and generation of landfill gases, municipal solid wastes and composition, biogas, degradation of waste in anaerobic digesters (AD) and factors affecting performance of AD, importance of biogas in developing countries, global overview of biogas, effect of temperature on performance of digesters, rice husk and other insulating materials.

2.2 Greenhouse Gases

A greenhouse gas (GHG) is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range. When sunlight strikes the Earth's surface, some of it is re-radiated back toward space as infrared radiation. Greenhouse gases are transparent to the short-wave incoming radiation but opaque to outgoing long-wave radiation. As a result, GHGs absorb this outgoing infrared radiation and trap its heat in the atmosphere. There are many chemical compounds in the atmosphere that exhibit the greenhouse properties. Some are naturally occurring, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and water vapor, and some gases are produced by humans and human activities, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3).

GHGs produce a natural warming to sustain life on the Earth. Without greenhouse gases, the average temperature of Earth's surface would be about 15 °C (27 °F) colder than the present average of 14 °C (57 °F) In the past hundred years, however, the average temperature of Earth has risen by 1.5°F, and is projected to rise another 0.5 to 8.6°F over the next hundred years (US EPA, 2015). Even a small change in the average temperature of the Earth can convert to potentially dangerous shifts in climate and weather.

Global warming potential (GWP) is a relative measure of how much heat a greenhouse gas can trap in the atmosphere. GWP measures the amount of heat trapped by a certain mass of a gas over a given period of time, relative to the amount of heat trapped by a similar mass of carbon dioxide (USEPA 2015). Different greenhouse gases have different effects on global warming, which depend on their ability to absorb energy and how long they stay in the atmosphere. The time scale usually used for GWP is 100 years. Policymakers use the values GWP to compare the impacts of emissions and reductions of different gases (US EPA, 2015). Methane (CH_4) has a shorter lifetime but higher energy absorption capacity compared to CO_2, which is reflected in its GWP. The GWP of methane is estimated to be 28-36 over a 100-year period. Nitrous oxide (N_2O) has a GWP 265-298 times that of CO_2 for a 100-year timescale. The high-GWP (thousands or tens of thousands) gases such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), can trap substantially higher heat than CO_2 (US EPA, 2015). In 2015, U.S. greenhouse gas emissions totaled 6,587 million metric tons of carbon dioxide equivalents (US EPA, 2015). Figure 2-1 shows the US methane emissions by source. US landfills and manure management totaled about 28% of overall methane emissions

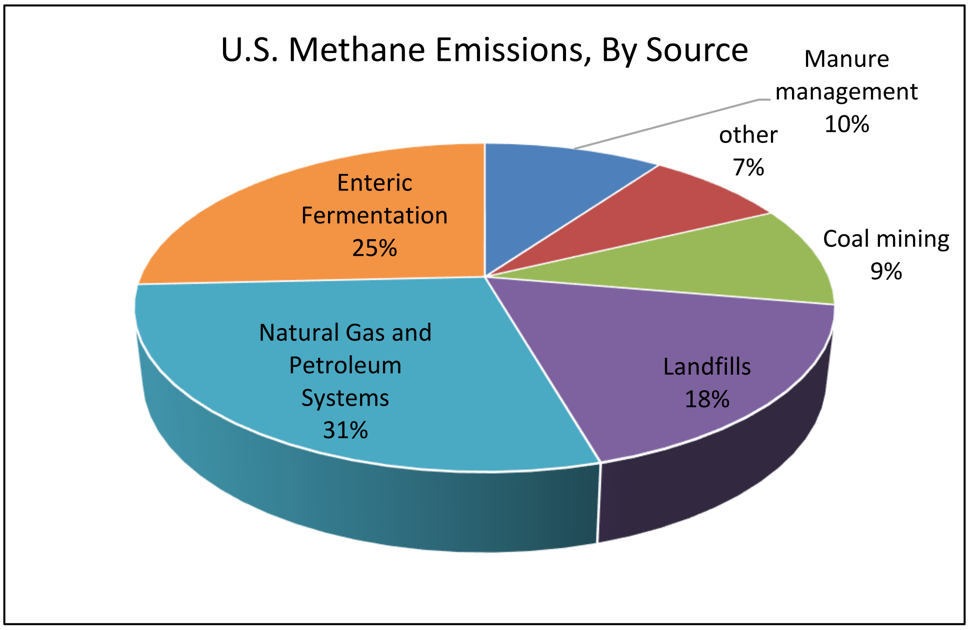


Figure 2- 1 US methane emissions by source (USEPA, 2015)

Globally 60 % of GHG emissions comes from human-related activities. Methane (CH_4) is the second most prevalent greenhouse gas emitted in the United States from human activities. Methane accounts for 16% of the global GHG emissions and 10% of total US GHG emissions. Landfills are the third largest anthropogenic source of US methane emissions, accounting for 18 % in 2015 (US EPA, 2017). Figures 2-2 and 2-3 show the US and global GHG emissions, respectively.

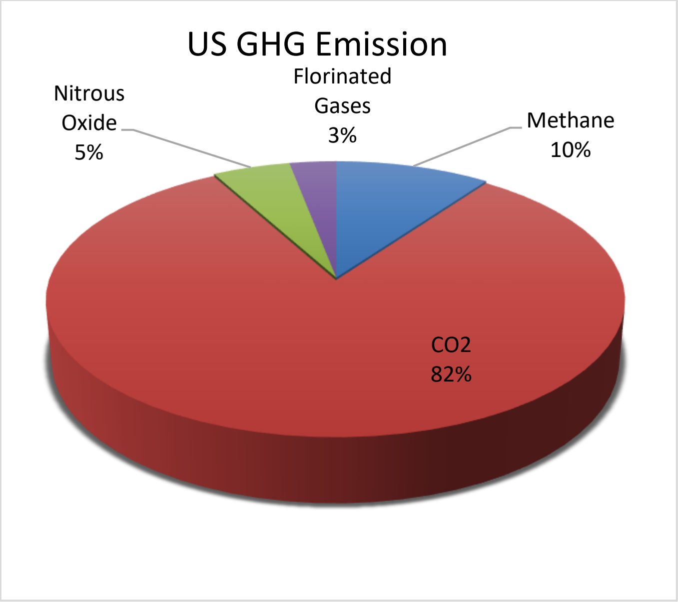


Figure 2- 2 US greenhouse emissions (US EPA, 2015)

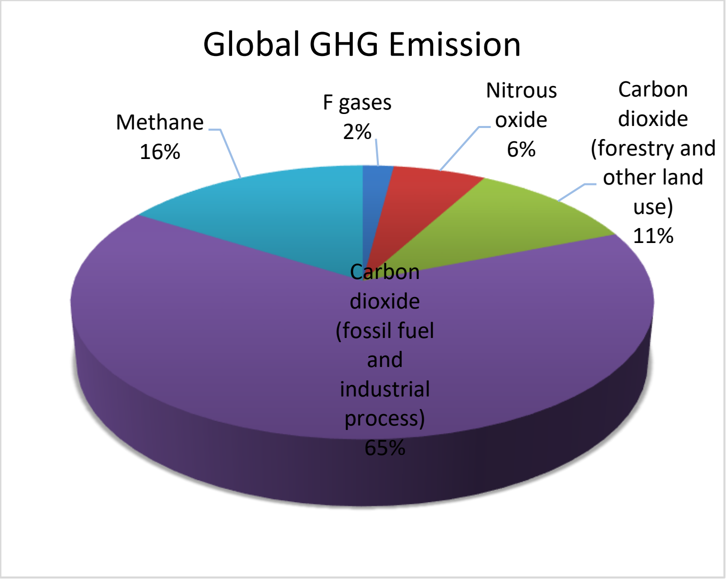


Figure 2- 3 Global greenhouse gas emissions (US EPA, 2015)

2.3 Municipal Solid Waste

Municipal solid waste (MSW), more commonly known as trash or garbage, is waste consisting of everyday items that are discarded by the public, such as product packaging, yard waste, furniture, clothing, plastics, bottles, food waste, newspapers, appliances, glass, metals, and batteries. In other words, MSW is all types of solid waste generated by households and commercial establishments usually collected by local government bodies. According to US EPA (2011), municipal waste does not include industrial wastes, wastes from construction and hazardous wastes.

2.3.1 Composition of municipal solid waste

Total municipal solid waste (MSW) generation in the USA in 2014 was 258 million tons. Figure 2-4 shows the breakdown of MSW generation by the material. Organic materials such as paper and paperboard, yard trimmings and food continue to be the largest components of MSW.

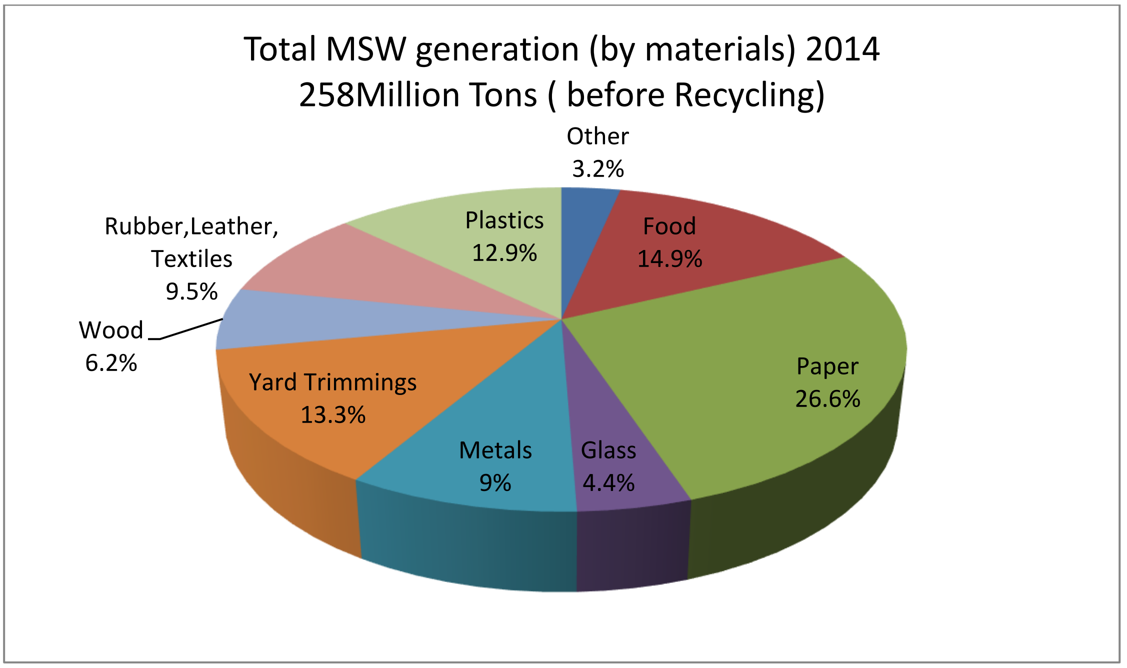


Figure 2- 4 Total MSW generation (by materials) 2014, 258 million tons (before recycling) (EPA, 2016)

In 2014 total MSW recovery (recycling and composting) was over 89 million tons total MSW generation (34.6%), as shown in Fig. 2-5. This provides an annual reduction of more than 181 million metric tons of carbon dioxide equivalent emissions, comparable to the annual GHG emissions from over 38 million passenger vehicles (EPA, 2016).

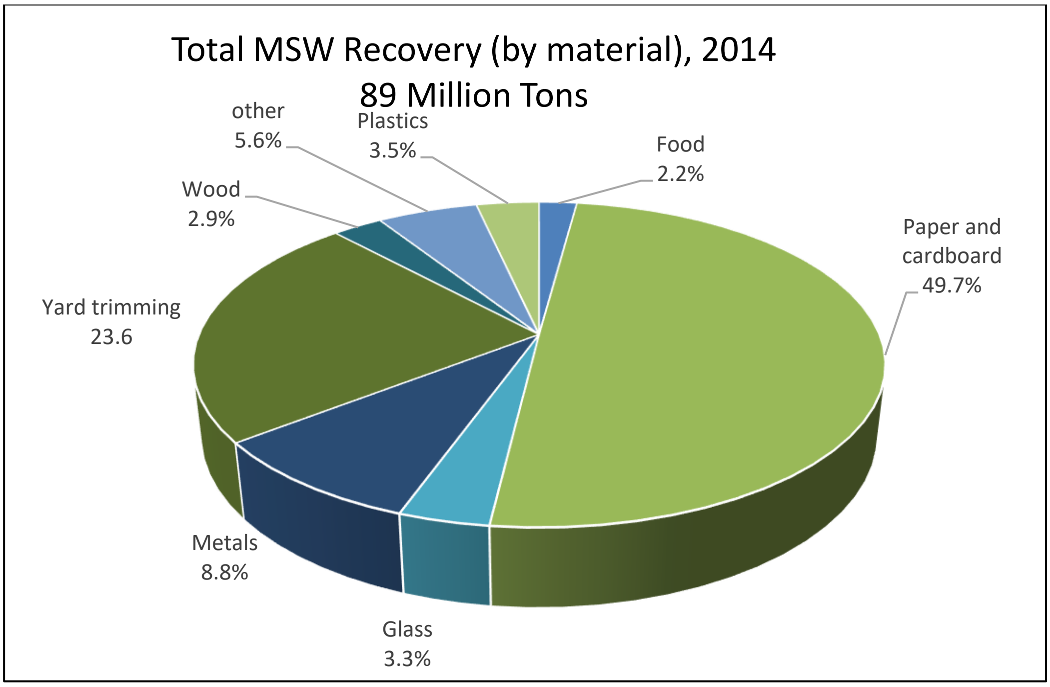


Figure 2- 5 Total MSW recovery (by material) 2014, 89 million tons (EPA, 2016)

In addition, in 2014 over 33 million tons of MSW were combusted with energy recovery and 136 million tons were landfilled (EPA, 2016). Figure 2-6 shows the US MSW recycling rates from 1960-2014 and Table 2-1 shows the generation, recovery, and discards of materials in MSW in 2014.

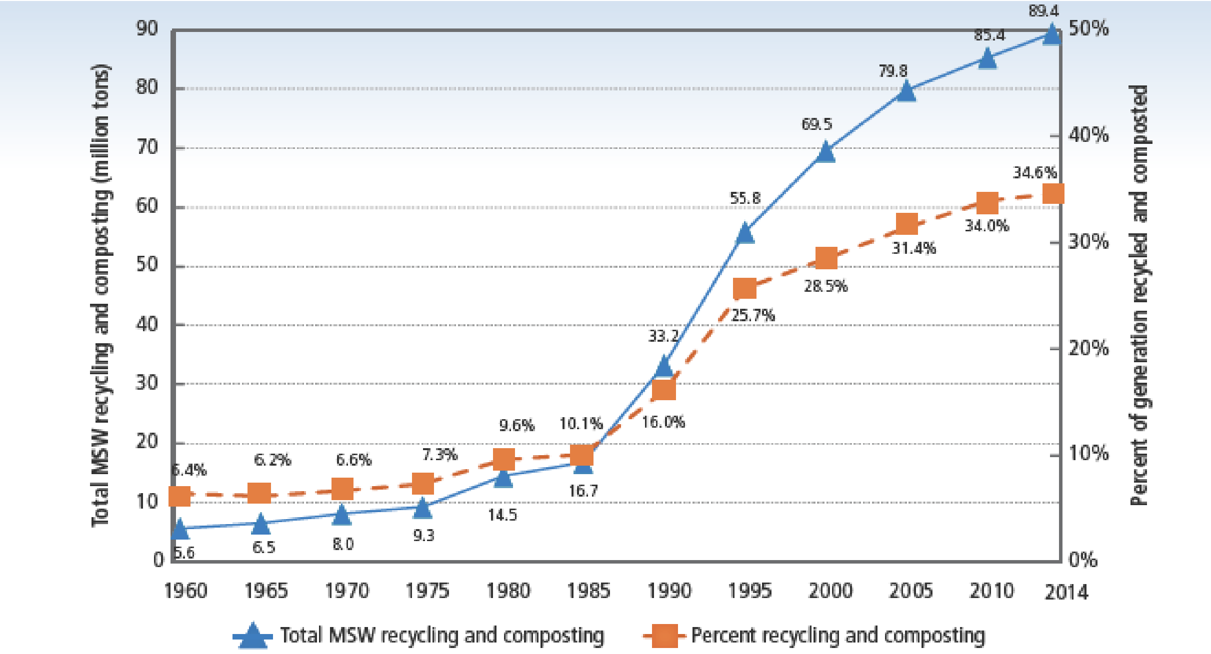


Figure 2- 6 MSW recycling rates, 1960-2014 (EPA, 2016)

Table 2- 1 Generation, Recycling, and Landfilling of Materials in MSW, 2014* (in millions of tons and percent of generation of each material) (EPA, 2016)

Material	**Weight Generated**	**Weight Recycled**	**Weight composted**	**Weight combusted with energy recovery**	**Weight Landfilled**
Durable goods					
Steel	15.52	4.26		1.9	9.36
Aluminum	1.52			0.21	1.31
Other nonferrous metals	2.04	1.36		**0.05**	**0.63**
Glass	2.28			**0.23**	**2.05**
Plastics	12.15	0.91		1.28	9.96
Rubber and leather	7.12	1.44		2.41	3.27
Wood	6.39			1.14	5.25
Textiles	3.96	0.49		1.16	2.31
Other materials	1.67	1.29		0.03	0.35
Total durable goods	**52.65**	**9.75**		**8.41**	**34.49**
Non Durable goods					
Paper and Paperboa**rd**	29.47	14.91		2.85	11.71
Plastics	6.78	0.14		1.31	5.33
Rubber and leather	1.09			0.21	0.88
Textiles	11.95			1.92	7.9
Other materials	2.98	2.13		0.58	2.4
Total nondurable goods	**52.27**	**17.18**		**6.87**	**28.22**
Container and packaging					
Steel	2.17	1.58		0.12	0.47
Aluminum	1.81	0.7		0.22	0.89
Glass	9.2	2.99		1.22	4.99
Paper and paperboard	39.13	29.49		1.89	7.75
Plastics	14.32	2.12		2.39	9.81
Wood	9.73	2.57		1.4	5.76
Other materials	0.31			0.06	0.25
Total container and packaging	**76.67**	**39.45**		**7.3**	**29.92**
Other Wastes					
Food, other	38.4		1.94	7.15	29.31
Yard trimmings	34.5		21.08	2.63	10.79
Miscellaneous inorganic wastes	3.97	Negligible		0.78	3.19
Total other wastes	**76.87**		**23.02**	**10.56**	**43.29**
Total municipal solid waste	**258.46**	**66.38**	**23.02**	**33.14**	**135.92**

2.4 Anaerobic Decomposition of Waste

A landfill is a place to dispose of refuse and other waste material by burying it and covering it over with soil, especially as a method of filling in or extending usable land. Worldwide landfills and open dumps are the most dominant types of solid waste disposal methods (IPCC, 2007). Organic matter contained in the solid waste disposal site (landfill) undergoes biological transformation and produces greenhouse gases under aerobic and anaerobic conditions. Methane, one of the prevalent GHG, is produced from a landfill, depending on the composition and characteristics of the wastes.

2.4.1 Landfills as sources of greenhouse gas emissions

Landfill gas is the byproduct of natural decomposition of municipal solid waste in an anoxic condition. Landfill gas consists of about 50-55% methane (CH_4), about 45-50% carbon dioxide (CO_2), and a small amount other gases. As mentioned already, in the US 18% of total methane emissions comes from landfills (USEPA, 2015). If this amount of CH_4 is not collected from a landfill, it will escape to the atmosphere. The amount of methane generation from the landfills depends on various factors, such as the waste composition, compaction, unit weight, age of the waste, pH, particle size, and initial moisture content and climatic factors such as the annual rainfall and temperature.

2.4.2 Composition of landfill gas

Methane and carbon dioxide are the principal landfill gases and hydrogen sulfide, hydrogen, carbon monoxides are trace gases. Some trace gases which are in small amounts, such as hydrogen sulfide (smells like rotten eggs), can be toxic. The typical composition of landfill gas is given in Table 2-2.

Table 2- 2 Typical Composition of Landfill Gas (Source: Tchobanoglous et al., 1993, EPA 1995)

Component	**Percent (dry volume basis)**
Methane	45-60
Carbon dioxide	40-60
Oxygen	2-5
Sulfides, disulfides, mercaptans, etc.	0.1-1.0
Ammonia	0.1-1.0
Hydrogen	0-0.2
Carbon monoxide	0-0.2
Trace constituents	0.01-0.6

The constituents of landfill gas are discussed in more detail below.

2.4.2.1 Methane

Methane is a colorless and odorless naturally occurring gas. It is flammable and explosive in high concentrations (ATSDR, 2001). Methane can be used as a fuel for ovens, homes, water heaters, kilns, automobiles*,* turbines, and other things (Wikipedia). The familiar smell of natural gas as used in homes is achieved by the addition of an odorant, contains containing tert-butylthiol, as a safety measure. Methane has a boiling point of −161 °C (−257.8 °F) at one-atmosphere pressure (Hensher et al., 2003*).* Methane as a gas it is flammable over a range of concentrations (5.4–17%) in the air at standard pressure.

2.4.2.2 Carbon dioxide

Carbon dioxide is naturally found at small concentrations in the atmosphere (0.03%), which is colorless, odorless, and slightly acidic (ATSDR, 2001). During the initial decomposition of the landfill wastes, the concentration of carbon dioxide is high, which reduces the pH during the initial phase. When the displacement of aerobic reactions by anaerobic reaction starts, the concentration decreases accordingly. Finally, in the methane production phase, carbon dioxide is stabilized (ATSDR, 2001).

2.4.2.3 Oxygen

Oxygen is an odorless, tasteless, and a colorless gaseous chemical element which appears as the third-most abundant element in the universe by mass, after hydrogen and helium. Oxygen comprises approximately 21% of the atmosphere. It is a vital component of the respiration process; without oxygen, most organisms will die within minutes. It is. The concentration of oxygen decreases as the decomposition phases move from aerobic to anaerobic.

2.4.2.4 Sulfides

Sulfides such as hydrogen sulfide, dimethyl sulfide, and mercaptans are naturally-occurring gases that give the landfill gas mixture its rotten-egg smell. Even at very low concentrations, sulfides can cause unpleasant odors (ATSDR, 2001).

2.4.2.5 Ammonia

Ammonia is a colorless gas with a pungent odor. It is lighter than air, its density is 0.589 times that of air. Although ammonia is common in nature and in wide use, ammonia is both caustic and hazardous in its concentrated form and is classified as an extremely hazardous substance in the United States.

2.4.2.6 Hydrogen:

Hydrogen is a colorless, odorless, tasteless, flammable gaseous which is abundant in the earth. Hydrogen gas (dihydrogen or molecular hydrogen) is highly flammable and will burn in air at a very wide range of concentrations between 4% and 75% by volume (Ohta, 2011).

2.4.2.7 Carbon Monoxide

Carbon monoxide is colorless, odorless, and tasteless, but highly toxic gas. In many countries. carbon monoxide is the most common type of fatal air poisoning (Omaye, 2002). It combines with hemoglobin to produce carboxyhemoglobin, which takes the space in hemoglobin that normally carries oxygen but is ineffective for delivering oxygen to bodily tissues. Even a low concentration of 667 ppm may cause up to 50% of the body's hemoglobin to convert to carboxyhemoglobin. (Tikuisis et al., 1992)

2.4.2.8 Trace constituents: NMOCs (non-methane organic compounds)

NMOCs are organic compounds (compounds that contain carbon). Methane is an organic compound but is not considered an NMOC. NMOCs may occur naturally or be formed by synthetic chemical processes. NMOCs most commonly found in landfills include acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis dichloroethylene, dichloromethane, carbonyl sulfide, ethyl-benzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes (ATSDR, 2001).

2.4.3 Factors affecting decomposition of solid waste

Production biogas by degradation of solid waste depends substantially on the composition of the wastes in the landfills or in the anaerobic digester. Some organic waste contains a high amount of nutrients such as sodium, potassium, calcium, and magnesium, which help bacteria live. When such kinds of nutrients are present in the wastes, the production of biogas increases accordingly. However, some wastes contain material that inhibits methane-producing bacteria, such as high salt concentrations or highly toxic substances, causing less gas production.

Generally, municipal solid waste can be categorized as biodegradable and non-biodegradable. Some materials like food, paper, yard, and wood waste, which have high amounts of cellulose and hemicellulose, are decomposable, whereas glass, plastics, metals construction and demolition debris are not easily decomposable and fall into the non- biodegradable category. Food waste decomposes quickly. Table 2-3 describes the laboratory scale decay for the municipal solid waste constituent.

Table 2- 3 Laboratory-Scale Decay for MSW Constituents (Barlaz, 2010)

Component	Average k value (year^{-1})
Office Paper	3.08
Grass	31.13
Branches	1.56
Newspaper	3.45
Corrugated containers	2.05
Food	15.02
Leaves	17.82
Coated paper	12.68

Another important factor that affects decomposition of municipal waste is the presence of oxygen in a landfill or in the anaerobic digester. The more oxygen present, the longer the aerobic Phase I lasts. Only after the oxygen is used up can methanogenic bacteria begin to produce methane. Also, if the deposited waste is loosely buried or frequently disturbed, more oxygen is available, and aerobic bacteria live longer and produce carbon dioxide and water for longer periods. Alternatively, if the waste is more compacted, aerobic bacteria are replaced by anaerobic bacteria in Phase III and methane production will begin earlier.

The presence of a certain amount of moisture in the waste accelerates gas production, up to a point. The moisture content in the waste encourages bacterial growth and helps to transport nutrients. According to Rees (1980), maximum methane production has been obtained at the moisture content of 60-80%. If the water content is too high, however, gas transport is blocked, lowering methane production.

As warm temperatures increase, the bacterial activity also increases up to a point, causing the rate of gas production to increase. Colder temperatures inhibit bacterial activity. Generally, bacterial activity drops off dramatically if the temperature is below 50° Fahrenheit (F). The bacterial activity releases heat, stabilizing the temperature of a landfill between 77° F and 113° F, although temperatures up to 158° F have been noted. Higher temperatures also promote volatilization and chemical reactions. In general, emissions of NMOCs double with every 18° F increase in temperature (ATSDR, 2001; EPA, 1993).

2.5 Biogas

Biogas is a combustible gas used as cooking gas in agricultural communities produced by anaerobic fermentation of different form of organic-rich substrates and is mainly composed of methane and carbon dioxide. Solids remaining after the fermentation process is completed are rich in nutrients and used as organic fertilizer.

Biogas production by anaerobic digestion is popular for treating biodegradable waste because valuable fuel can be produced while destroying disease-causing pathogens and reducing the volume of disposed waste products.

The methane in biogas burns more cleanly than coal and produces more energy with less emissions of carbon dioxide. The capturing of methane and use as an energy source is an important role in waste management, which reduces greenhouse gas emissions. Figure 2-7 shows s typical schematic of the fixed dome household level biogas digester and the digestion processes inside the reactor.

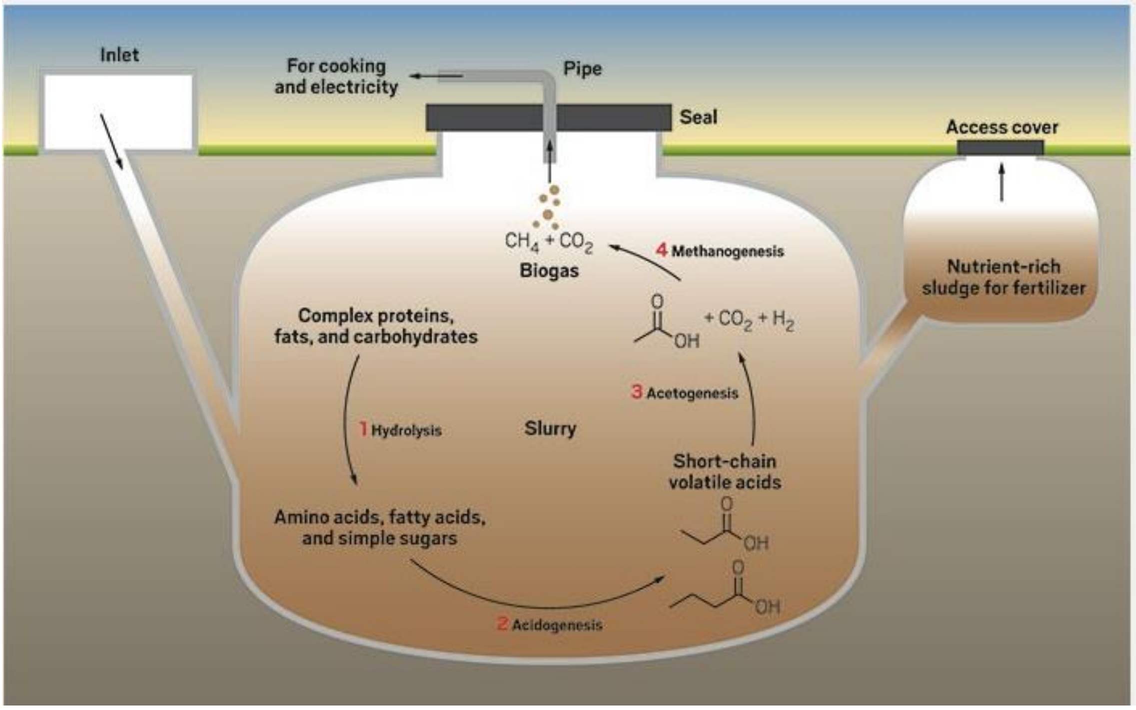


Figure 2- 7 Schematic of fixed dome biogas digester (Google.com)

The biogas is the end product of the anaerobic digester and a mixture of predominantly methane and carbon dioxide. The following table 2-4 shows the typical component and the characteristics of the biogas.

Table 2- 4 Typical Components and Characteristics of Biogas (Deublein, 2008; and GTZ 1999)

Composition/ Characteristics	**Value**
Methane (CH_4)	50-70 %
Carbon dioxide (CO_2)	30-40 %
Hydrogen sulfide (H_2S)	0-5000 mg/m^3
Ammonia (NH_3)	0-0.05
Humidity (H_2O)	2% (20^0C)-7% (40^0 C)
Energy content	20-25 MJ/m^3
Ignition temperature	650-750^0 C
Density	1.2 kg/m3
Critical pressure	75-89 bar

2.5.1 Phases of anaerobic degradation of organic wastes in a biogas digester

Anaerobic digestion is a series of complex and interconnected biological processes that are carried out by different species of microorganisms in the absence of the oxygen. After the solid waste fed into the anaerobic reactor, the conversion of solid waste to methane and carbon dioxide takes place by several microorganisms and by a series of chemical reactions (aerobic and anaerobic). Generally, decomposition of organic waste in anaerobic digester takes places in four phases and the composition of gases produced changes in each of the phases (US EPA, 2015). In case of the landfill, the older waste in one area might be in a different phase of decomposition than the waste which has been deposited recently in another area of the same landfill (ATSDR, 2001).

The process of converting organic waste to methane and carbon dioxide can be expressed by following equation 2-1 (Cooper et al., 1992).

$$C_aH_bO_cN_dS_e + ((4a\text{-}b\text{-}2c+3d\text{-}2e)/4)\_H_20 \xrightarrow{\text{Bacteria}} \qquad 2\text{-}1$$

$$((4a\text{-}b\text{-}2c+3d\text{-}2e)/8)\ CO2 + ((4a\text{-}b\text{-}2c+3d\text{-}2e/8))\ CH_4 + dNH_3 + H_2S$$

.

The degradation of organic waste occurs in four Phases/ stages: hydrolysis acidogenesis, acetogenesis, and methanogenesis.

2.5.1.1 Hydrolysis (Phase I, Aerobic or Lag phase)

This is the first step in the most fermentation processes. The participating bacteria cannot directly process the organic substrate. The substrate particularly has organic material consisting of proteins, carbohydrates, and lipids, which must first be broken down into soluble polymers or monomers, like amino acids, sugars and fatty acids (Gujer and Zehnder, 1983). This process is called hydrolysis (polymer breakdown). The process (hydrolysis) is usually the rate-limiting step in the process of anaerobic digestion of particulate organic substrates (Zeeman and Sanders, 2001). This is because the bacteria responsible for the liquefaction of complex compounds are operating at a very slow rate at this step, compared to the following steps, and are also highly dependent on digester conditions, such as availability of substrate, bacterial population density in the inoculum used, temperature and pH (Evans, 2001). Aerobic bacteria break down the long chain of complex carbohydrates, proteins, and lipids that form the content of the organic waste. While breaking down the substrate aerobic bacteria consume oxygen and mainly produce carbon dioxide as a by-product. The aerobic phase continues until available oxygen is depleted. Phase I decomposition can last for days or months, depending on the amount of oxygen present in the waste (ATSDR, 2001).

2.5.1.2 Acidogenesis (Phase II, Transition phase)

Anaerobic decomposition starts after all the available oxygen in the waste has been used up. In the second step, acidogenic bacteria transform the products of the first reaction into short chain volatile acids, ketones, alcohols, hydrogen, and carbon dioxide. The principal products of this step are propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), acetic acid (CH_3COOH), formic acid ($HCOOH$), lactic acid ($C_3H_6O_3$), ethanol (C_2H_5OH) and methanol (CH_3OH), among others. The digester becomes highly acidic in this phase. When moisture present in the digester mixes with acid formed in the first phase, nitrogen and phosphorus are consumed by certain species of bacteria; then carbon dioxide and hydrogen are produced. Hydrogen, carbon dioxide and acetic acid will skip the acetogenesis stage and be utilized directly by the methanogenic bacteria in the final stage. Three typical acidogenesis reactions where glucose is converted to ethanol, propionate and acetic acid, respectively, are represented by equations 2-2, 2-3 (Ostrem, 2004) and 2-4 (Bilitewski et al., 1997).

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \qquad (2\text{-}2)$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \qquad (2\text{-}3)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \qquad (2\text{-}4)$$

Figures 2-8 and 2-9 show degradation of pyruvic acid and acetic acid through the butyric acid pathway

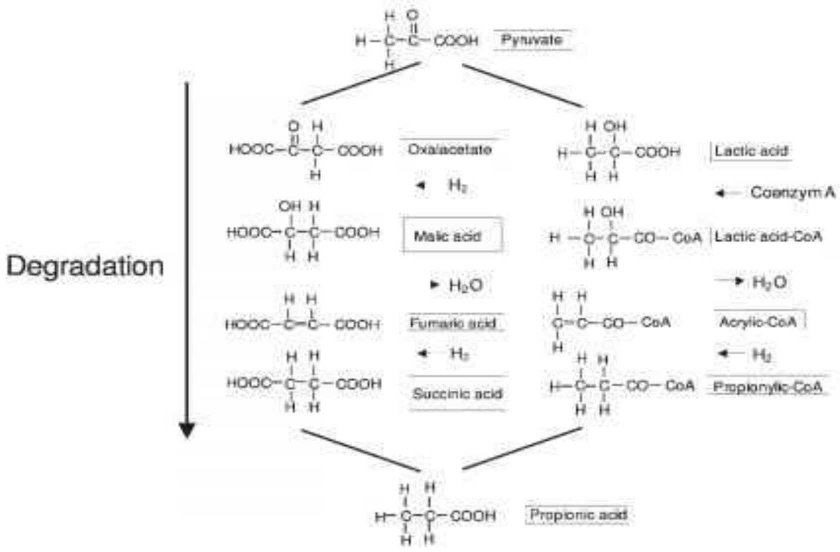


Figure 2- 8 Degradation of pyruvate acid (Free energy planet, biogas from waste, 2015)

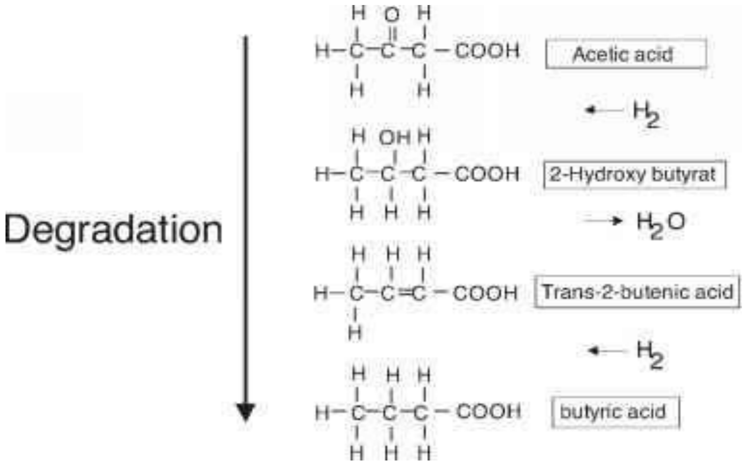


Figure 2- 9 Degradation of acetic acid via butyric acid pathway

(Free energy planet, biogas from waste, 2015)

2.5.1.3 Acetogenesis (Phase III, accelerated methane production phase)

In the third stage (acetogenesis phase), the rest of the acidogenesis products, i.e. the propionic acid, butyric acid, and alcohols, are converted by acetogenic bacteria into acetic acid (CH_3COOH)/acetate (CH_3COO^-), hydrogen and carbon dioxide. In this process the pH becomes more neutral, so the methane-forming bacteria start to produce methane. Methanogenic bacteria can consume carbon dioxide and acetate (a compound that was created by the acid forming bacteria). In this phase, methane and acid-producing bacteria have a symbiotic, mutually beneficial relationship (Barlaz et al., 1990; Rees, 1980). The final products of the acetogenesis process (acetate, H_2, and CO_2) are precursors of methane formation (Metcalf and Eddy, 2003). During the third stage, propionate (equation 2-5), butyric acid (equation 2-6), ethanol (equation 2-7) and glucose (equation 2-8) among others are converted to acetate (Ostrem, 2004).

Propionate → acetate

$$CH_3CH_2COO^- + 3H_2O \rightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \quad (2\text{-}5)$$

Butyrate → acetate

$$CH_3CH_2CH_2COO^- + 2H_2O \rightarrow 2CH_3COO^- + H^+ + 2H_2 \quad (2\text{-}6)$$

Ethanol → acetate

$$CH_3CH_2OH + H_2O \rightarrow CH_3COO^- + H^+ + 2H_2 \quad (2\text{-}7)$$

Glucose to acetate

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (2\text{-}8)$$

2.5.1.4 Methanogenesis (Phase IV decelerated methane production phase)

The fourth step methanogenesis is carried out by a group of microorganisms known as methanogens (strict anaerobes). Microorganisms responsible for methane production are classified as archaea. Many of the methanogenic bacteria found in anaerobic digesters are similar to those found in the stomachs of ruminant animals and inorganic sediments taken from ponds, lakes, and rivers. There are two groups of microorganisms that produce methane. One group, termed acetoclastic methanogens, splits the acetate to methane and carbon dioxide; the other group, called hydrogen utilizing methanogens, use hydrogen as the electron donor and CO_2 as an electron acceptor to produce methane (Metcalf and Eddy, 2003). Bacteria named acetogens are also able to oxidize hydrogen and form acetic acid, but the acetic acid is converted to methane, so the impact of this reaction is very small. The following equations 2-9 and 2-10 are the two main ways of methane production by methanogenic bacteria.

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2\text{-}9)$$

$$4CO_2 + H_2 \rightarrow CH_4 + 2H_2O \quad (2\text{-}10)$$

The composition and production rates of biogas are relatively constant in this phase. The biogas contains approximately 50% to 55% methane by volume, 45% to 50% carbon dioxide, and 2% to 5% other gases such as sulfides (EPA 2015). In this phase, the biogas is produced at a stable rate. Gas production duration in this phase depends upon the type and amount of the substrate (organic waste) fed to the reactor. The pH of this phase is similar to the third phase (Barlaz et al., 1990; Tchobanoglous et al., 1993).

About 72% of methane formation in anaerobic digestion is derived from acetate formation (Figure 2-10).

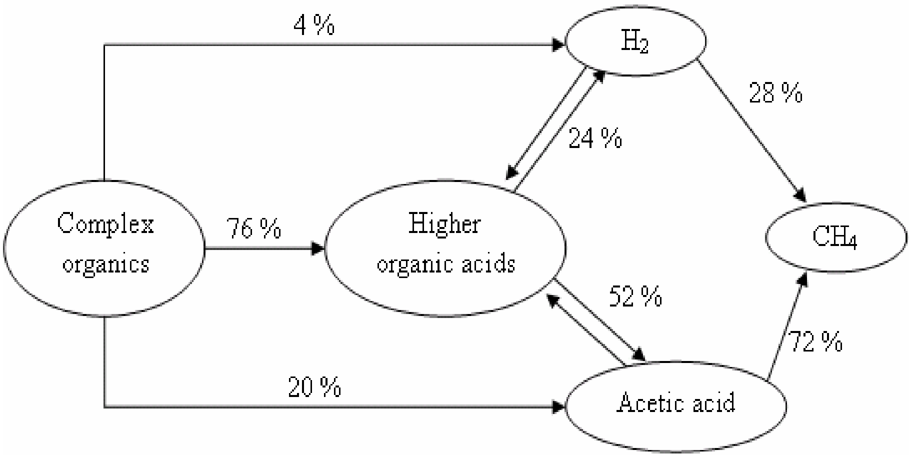


Figure 2- 10 Carbon and hydrogen flow in the anaerobic process (the given percentage values are based on COD) (Metcalf and Eddy, 2003)

Table 2-5 shows the reactions that are carried out by methanogens during the anaerobic digestion process.

Table 2- 5 Reactions Carried out by Methanogens (Demirel et al., 2008)

Hydrogen	$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$
Acetate	$CH_3COOH \rightarrow CH_4 + CO_2$
Formate	$4HCOOH \rightarrow CH_4 + CO_2 + 2H_2O$
Methanol	$4CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O$
Carbon monoxide	$4CO + 2H_2O \rightarrow CH_4 + 3H_2CO_3$
Trimethylamine	$4(CH_3)3N + 6H_2O \rightarrow 9CH_4 + 3CO_2 + 4NH_3$
Dimethylamine	$2(CH_3)2NH + 2H_2O \rightarrow 3CH_4 + CO_2 + 2NH_3$
Methylamine	$4(CH_3) NH_2 + 2H_2O \rightarrow 3CH_4 + CO_2 + 4NH_3$
Methyl mercaptans	$2(CH_3)2S + 3H_2O \rightarrow 3CH_4 + CO_2 + H_2S$
Metals	$4Me0 + 8H+ + CO_2 \rightarrow 4Me++ + CH_4 + 2H_2O$

Figures 2-11 and 2-12 show the flowchart and phases of anaerobic degradation of organic waste respectively.

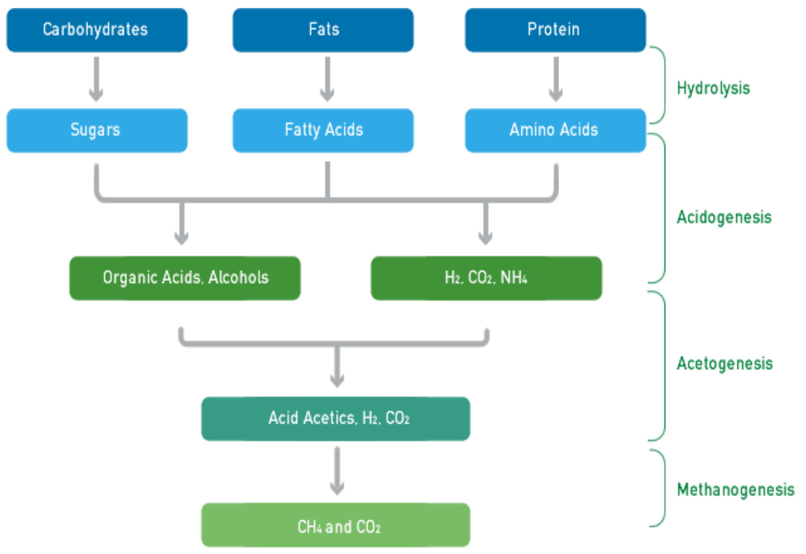


Figure 2- 11 Flow chart of anaerobic digestion

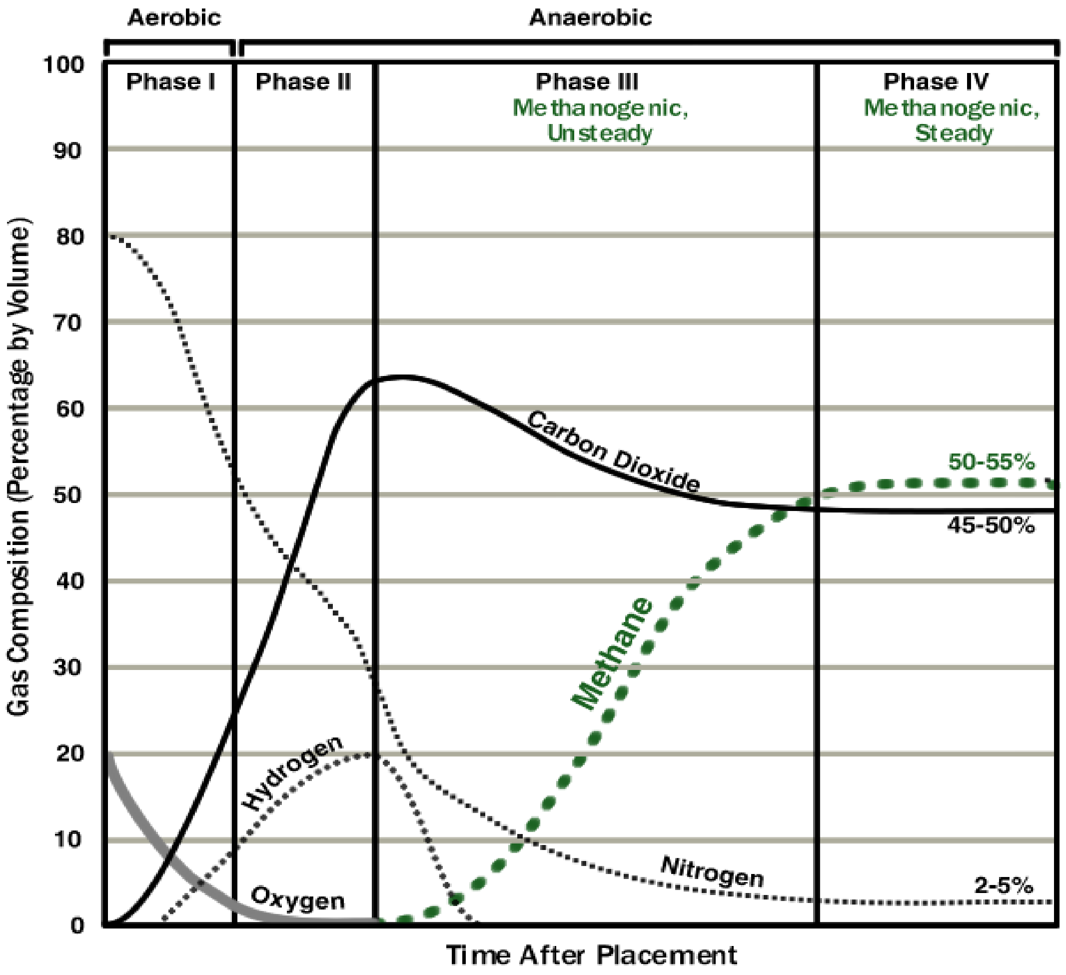


Figure 2- 12 Degradation phases of organic waste (EPA, 1997)

2.5.2 Factors affecting anaerobic digestion (Biogas Production)

Biological processes take place during anaerobic digestion are influenced largely by the conditions inside and outside of the bioreactor. In order to maintain favorable conditions for bacterial activity and to optimize reactor performance (methane production), which is the ultimate goal, some parameters need to be taken care of. These parameters, if not monitored, can cause instability in the digestion process and lower the potential biogas yield. The following are some of the factors that affect methane production.

2.5.2.1 Temperature

Temperature is one of the major parameters that affects the methane production process. According to the temperature at which they live, bacteria are generally divided into two groups, mesophilic ($30^{o}C$ to $35^{o}C$) and thermophilic ($50^{o}C$ to $60^{o}C$). Since most of the methanogens are mesophilic, the mesophilic AD is the most widely used (Deublein and Steinhauser, 2011). In a mesophilic digester, maximum conversion is considered to occur at 35℃. When temperature decreases 11℃, the production of biogas will fall by 50% (Zhang, 2012). In general, bacterial growth rates double for each 10°C rise in temperature over a temperature range.

2.5.2.2 Composition of Substrate

The amount of methane production depends greatly on the substrate composition, along with its particle size and degradability. Methane production can be estimated as follows (equation 2-11).

$$Q_{wastei} = q_{waste\ i} * M_{\cdot waste\ i} * f_{TS} * f_{oTS} * 0.75 \qquad (2\text{-}11)$$

Where

Q_{wastei} =Gas production rate (volume/day) for waste $_i$

q_{wastei} = Maximum specific yield of biogas for waste $_i$ (maximum biogas produced per total organic solid, vol/mass)

$M_{\cdot wastei}$ = waste feed rates for waste $_i$ (mass /day)

f_{TS} = fraction of the waste by weight that is solids

f_{oTS} = fraction of the waste by weight that is organic (volatile)

0.75 = factor to account for practical biogas yield

The smaller the waste particle size, the more surface area is exposed to bacteria, and the faster methane will be produced. Shredding the waste can increase the rate of methane production, particularly for wastes with a high content of structural materials (e.g. cellulose, lignin), which make it difficult for microbes to access and degrade the substrate. The yield for substrates can be increased by up to 20% by shredding (Deublein and Steinhauser, 2008). Table 2-6 shows the extent of decomposition of different wastes and their bio-methane yield.

Table 2- 6 Extent of Waste Decomposition and Methane Yield (Eleazer et al., 1997)

Waste	Methane Yield (ml of CH_4/dry gram of waste)	Extent of decomposition (percent)
Food	300.7	84.1
Grass	144	94.3
Leaves	30.6	28.3
Office paper	217.92	54.6
Old newsprint	74.33	31.1
MSW	92	58.4

2.5.2.3 Retention time

In an anaerobic digester, there are two types of retentions times, solids retention time and hydraulic retention time. Solids retention time (SRT) refers to the average time spent by the bacteria (solids) in the bioreactor. Hydraulic retention time is defined as the average amount of time liquid waste stays inside the reactor. If SRT is too low, there will be chances of organism washout, damaging the process. Alternatively, if it is too long, the system becomes food limited. SRT is same as HRT when there is no solids recycle (Vesilind, 1998). A longer SRT stabilizes the overall process, lowers the amount of effluent produced, and also increases biogas production (Rittmann & McCarty, 2001). Generally, SRT higher than 20 days is needed (Metcalf and Eddy, 2003). High SRT has higher organic load removal capacity, reduced digester volume, and greater shock loads resistance and microorganism acclimation to toxic compounds. High SRT can be achieved either by increasing the digester volume or by increasing the bacterial population (Gerardi, 2003).

2.5.2.4 pH

Anaerobic processes are extremely sensitive to pH changes. A neutral pH value is highly preferred. If the pH drops below 6.8, the methanogenic activity is inhibited, and pH values below 6.2 are toxic. Generally, acidogens prefer pH 5.5-6.5; methanogens prefer 7.8-8.2. If both species coexist, the preferred pH range is 6.8-7.5 (Khanal, 2008). When acidogens and methanogenic bacteria have reached equilibrium, the pH will naturally stabilize around 6.8 to 7.2. The introduction of too much organic raw material can cause the excess formation of acid and the methanogenic bacteria will not be able to digest the acid quickly. The addition of sodium hydroxide can raise the pH value. If the pH grows too high (not enough acid), means the fermentation process will slow until the digestive process forms enough acidic carbon dioxide to restore.

2.5.2.5 Moisture content

Moisture content is also an important factor in the rate of waste degradation. It has many functions in the degradation process: it dissolves metabolite sand influences enzyme and nutrient transport to microorganisms and the accessibility of bacteria to substrate surfaces. Many studies have confirmed that methane generation rate increases as substrate moisture content increases, up to a point (Barlaz et al., 1990; Filipkowska et al., 2004; Chan et al., 2002; Mehta et al.2002, Wreford et al., 2000). If the moisture content is too high, transport of gases such as methane is inhibited, which negatively impacts gas production.

According to Filipkowska et al. (2004), the minimal water content in wastes, at which fermentation starts, is about 25%, and optimal moisture for efficient landfill stabilization ranged from 60 to 70%. Results also confirmed that waste moisture that is too high inhibits the fermentation process.

2.5.1.6 Organic Loading Rate

OLR is defined as the amount of biochemical oxygen demand (BOD) or chemical oxygen demand (COD) applied to the reactor volume per day (Tchobanoglous et al., 2003). Organic loading rate is related to hydraulic retention time by the following equation (2-12).

$$OLR = (Q) *(Cvs)/ \text{Volume of reactor} \qquad (2\text{-}12)$$

Where OLR = Organic loading rate

Q = volumetric flow rate (m^3/d)

C_{VS} = concentration volatile solids (kg VS/m^3)

$V_{reactor}$ = reactor volume (m^3)

HRT = hydraulic retention time.

For high-rate anaerobic digestion, the recommended organic loading is 1.6- 4.8 kg $VSS/(m^3*d)$ (Rittmann & McCarty, 2001). If the organic loading rate in the digester is too high, the two methanogenesis pathways can be inhibited, resulting in the formation of volatile fatty acids in the reactor.

2.5.2.7 Mixing

Mixing is another very important parameter that affects the performance of the digester. Mixing increases the rate kinetics of anaerobic digestion, accelerating the overall biological conversion process. Mixing allows uniform heating of the reactor and can be done mechanically through motorized impellers or turbines within the reactor or pneumatically by injecting gas (in anaerobic digestion, methane, and carbon dioxide gas) via spargers at the bottom of the reactor (Tchobanoglous et al., 2003).

2.5.2.8 Concentration of toxic substances

The microbial community could be disturbed if some toxic substances are introduced into the reactor, in addition to pH and temperature considerations. Obviously, oxygen has to be kept out of the bioreactor (in its molecular form O_2). The presence of a toxic substance does not mean that the process cannot operate. Some toxic compounds inhibit anaerobic methanogenic reaction rates, but with a diverse microbial population and low enough loading, the process can be sustained. Acclimatization to toxic concentrations is also possible. Some toxic and inhibitory compounds are ammonia, calcium magnesium, metals, sodium chlorides, sulfate.

2.5.2.9 Nutrients

Microbes need nutrient to grow. The AD process runs best with C/N ratio between 15:1 and 30:1 (optimally 20:1). If waste does not meet the requirement, a nutrient imbalance occurs so additional adjustment is needed. Crop residues or leaves which contain high carbon can be added to improve the digester performance.

2.5.3 Importance of Biogas in Developing Countries

Energy poverty is one of the greatest challenges these days, especially for developing countries. Globally over 2.6 billion people (38% of global population) are without clean cooking facilities (IEA, 2015). A sustainable renewable source of energy is needed to substitute for biomass sources that do not burn cleanly, such as cow dung cakes, fuelwood etc. The importance of biogas for the less developed countries is discussed below.

2.5.3.1 Indoor Air Pollution

About half the world’s population and up to 90% of rural households in developing countries still rely on unprocessed biomass fuels such as wood, dung cakes, crop residues (World Resources Institute, 1998). Because of their involvement in cooking, women’s exposure is much higher than men’s (Behera et al., 1988). Especially young children are often with their mom, carried on their mothers’ backs while cooking, and thus spending many hours breathing in indoor smoke (Albalak, 1997). Indoor air pollution is a critical public health problem in developing countries. Particulate matter released by the burning of wood, coal, animal dung cakes, hay is a primary public health concern because of its ability to affect the upper airways of the respiratory system (Mihelcic et al., 2009).

Figure 2-13 (a) & (b) shows the traditional cooking stove and Figure 2-13 (c) shows the biogas stove with clean energy (Nepal). Using traditional fuelwood stove under conditions of limited ventilation leads to high exposures to indoor smoke and largely associated health risks, particularly for women and children. Indoor smoke from using fuelwood contains a range of potentially harmful substances, from carcinogens to small particulate matter, all of which cause damage to the lungs. Worldwide the Indoor smoke causes about 21% of lower respiratory infection deaths, 35% of chronic obstructive pulmonary deaths and about 3% of lung cancer deaths. About 64% of these deaths occur in low-income countries, especially in South-East Asia and Africa (WHO, 2009).

Figure 2- 13 (a) & (b) Using traditional fuelwood in Nepal (c) Using biogas for cooking in Nepal

(Source: Google.com)

2.5.3.2 Deforestation Caused by Fuel Wood Use

Agricultural expansion and mechanization, the growth of grazing operations, mining, and fuel collection are the main causes of deforestation worldwide (Douglas & Simula, 2010). Deforestation is a very big problem in developing countries. Most of the rural areas of those countries depend on fuel-wood for cooking and lighting, which ultimately requires cutting of trees. Deforestation also leads to a decrease in the fertility of land by soil erosion. Household anaerobic digestion addresses unsustainable deforestation by providing an alternative cooking fuel, biogas, instead of traditional cooking fuel such as firewood. After the successful introduction of household biogas in Nepal (one of the developing countries), wood fuel consumption was observed to decrease by 53%, with each household saving about 250 kg of firewood per month, or 3 tons of firewood per year (Katuwal & Bohara, 2009). Figure 2-14 shows a year supply of fuelwood for a single family.

Figure 2- 14 A year supply of firewood for a family in Nepal (google.com)

2.5.3.3 Empowerment of Women

In developing countries energy poverty is also directly related to gender issues. In rural communities, women and young girls are typically responsible for collecting fuelwood for household uses such as cooking and heating. They have to spend several hours for fetching and collecting heavy fuelwood loads, causing several health problems and restricting them from other important productive, social and educational activities (Clancy et al., 2002). Studies have reported that women can save 3 hours per day because of the reduction in time used for collecting fuelwood, reduced time for cooking meals and cleaning cooking utensils (BSP 2005). Moreover, burning of traditional biomass fuels such as firewood, coal and dung cakes, causes emission of harmful gases, associated with health issues ranging from mild respiratory illnesses to lung cancer, with infants, children, and pregnant women being the most affected (Ezzati, 2005).

As mentioned above, women and girls do most of the cooking and therefore are more exposure to indoor rural air pollution in comparison with men. 40- 45% of the Chronic Obstructive Pulmonary Disease experienced by women in developing countries is caused by indoor air pollution by the use of biomass as cooking fuel (Mihelcic et al., 2009). To promote gender equity and empower women is one of the Millennium Development Goals (MDG's). Anaerobic digestion technology can empower women by saving their time so they can be involved in social and educational activities. Figure 2-15 shows the collection of firewood for an energy source in a rural area of Nepal.

Figure 2- 15 Women collecting firewood in Nepal (Source: Google.com)

2.5.3.4 Energy production /Mitigation of methane

An anaerobic decomposition of household waste is a cheap way of obtaining energy in rural areas. Using household waste, clean-burning cooking fuel can be produced, which can replace traditional biomass or fossil fuel consumption. Since rural peoples in developing countries depend on agriculture, every household has at least one head of cow/buffalo for milk and manure. The anaerobic decomposition of waste products, human excreta, and cattle manure is a cheap way of obtaining energy and also at the same time handling household waste products (Gautam et al., 2007). Dung cakes, crop residues, firewood, and charcoal are all locally-producible fuel sources. LPG and natural gas require transportation; by the time it reaches consumers in rural areas, the fuel cost will be several times more than its original price. Electricity is often not reliable in such developing countries and does not come from sustainable sources. So, in such countries, biogas, an eco-friendly substitute for energy, is very important and essential

The biogas plants of sizes 4, 6 and 8 cubic meters mitigate about 3, 4 and 5 tons of carbon dioxide per biogas plant per year in rural areas (Shrestha et al., 2003). A biogas plant of the size of 6 cubic meters can displace three tons of fuelwood, which is the equivalent of 38 liters of kerosene annually and reduces 4.9 tons of carbon dioxide equivalents per year (Devkota, 2007). So small-scale household size biogas plants help to reduce methane emissions to the atmosphere.

2.5.3.5 Treatment of human/animal waste and uses of digestate as fertilizer

Runoff of animal and human waste into streams and other water bodies adversely affects the surface water quality. Also, waste runoff creates contamination problems for communities living downstream. Sanitation hygiene of the household increases with the installation of toilet-attached biogas plants. According to Sasse (1988), an effluent from one kilogram of digested dung can yield up to an extra 0.5 kg nitrogen compared to fresh manure, and also an estimated N: P: K content in the effluent is 2.7:1.9:2.2, respectively. By a utilizing household level biogas plant, the volume of waste going to the open dump can be reduced from the individual level. Digestate waste which is very rich in nutrients can be used as fertilizer which replaces artificial or chemical fertilizer. So small-scale household biogas is very important for treating the human and animal wastes, improving sanitation hygiene and utilization of bio-slurry as fertilizer. Figures 2-16 (a) & (b) show unmanaged waste and nutrient-rich fertilizer, respectively.

(a) (b)

Figure 2- 16 (a.) Unmanaged waste (Bagmati river, Nepal) (b.) Use of nutrient-rich fertilizer in the farm in Nepal (Source: google.com)

2.5.4 Biogas around the world (Source: World Bioenergy Association, 2015**)**

2.5.4.1 Experience with domestic biogas technology in developing countries

The implementation of biogas plants has taken place in countries where governments have been involved in the subsidy, planning, design, construction, operation and maintenance of biogas plants around the world. Several countries in Asia, especially China and India, are the largest biogas countries, having effectively popularized the biogas technology. China has the highest number of household biogas plants installed in rural areas. According to the World Bio Energy Association, 26.5 million biogas plants had been installed by 2007, whose biogas yield reached 10.5 billion m^3 (equivalent to more than 100 million tons of standard coal) (Chen et al., 2010). China and India added 2.8 million and 150,000 biogas plants respectively in 2011, arriving at the cumulative numbers of 42.8 million and 4.5 million units installed of all sizes. According to Gautam et al. (2007), it is estimated that more than 111,000 biogas plants have been installed in Nepal. The Netherlands Development Organization SNV (Stichting Nederlandse Vrijwilligers) supports national programs for domestic biogas plants for households in developing countries, including countries in Asia such as Nepal, Vietnam, Bangladesh, Bhutan, Cambodia, Lao PDR, Pakistan and Indonesia; and countries in Africa such as Rwanda, Senegal, Burkina Faso, Ethiopia, Tanzania, Uganda, Kenya, Benin and Cameroon. SNV installed more than 475,000 plants in the first half of 2012. Financial support was provided by several national and international organizations.

2.5.4.2 The United States

The U.S. has more than 2,200 sites producing biogas: 239 anaerobic digesters on farms, 1241 anaerobic digesters at wastewater treatment plants (860 currently use the biogas they produce) and 636 landfill gas projects. In comparison, Europe has over 10,000 currently operating digesters; some communities are fossil fuel free because of biogas they produce (ABC, 2014).

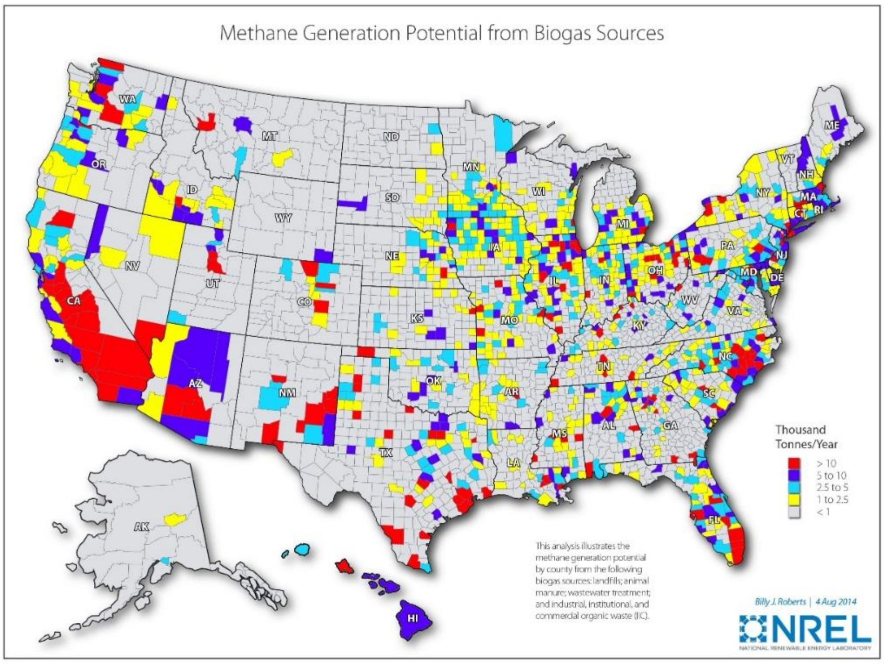
In 2011, there were about 180 operational biogas recovery systems on American commercial livestock farms, which produced enough electricity to power the equivalent of 47,000 homes (EPA, 2010). The AgSTAR program of EPA reported in 2010, about 8,000 U.S. farms could support biogas systems providing about 1,600 megawatts of energy, reducing 1.8 million metric tons of methane emissions, which is the equivalent of taking 6.5 million cars off the road.

The US methane potential from landfill waste, animal manure, wastewater, and industrial, institutional, and commercial organic is estimated at about 7.9 million tons per year, which is equivalent to about 420 billion cubic feet or 431 trillion Btu (NREL 2013). Table 2-7 shows the estimated methane generation potential of selected sources in the United States.

Table 2- 7 Methane Generation Potential in the United States (NREL. 2013)

Source	Methane Potential (tons/yr)
Wastewater	2,339,339
Landfills*	2,454,974
Animal manure	1,905,253
IIC organic waste	1,157,883
Total	**7,857,449**

The following map (Figure 2-17) illustrates the methane generation potential by county from the following biogas sources such as landfills; animal manure; wastewater treatment; and industrial, institutional, and commercial organic waste (NREL, 2014).



Methane Generation Potential from Biogas Sources

This analysis illustrates the methane generation potential by county from the following biogas sources: landfills; animal manure; wastewater treatment; and industrial, institutional, and commercial organic waste (IIC).

Billy J. Roberts | 4 Aug 2014

Figure 2- 17 Estimated methane generation potential for select biogas sources by county (NREL, 2014)

2.5.4.3 Europe

The biogas sectors are usually linked with agriculture in the European Union countries. In Germany, Denmark, Austria, and Sweden, agricultural biogas plants are the most developed; in the countries like Portugal, Greece and some Eastern European countries, biogas technology is currently under development (Holm-Nielsen et al., 2009). In 2010 the European Union produced 21.1 billion m³ of biogas, corresponding to 12.7 billion m³ of biomethane (WBA, 2013).

2.5.4.4 Germany: Industrial scale

One of the reasons that Germany has succeeded in developing biogas plants is government subsidy programs. Since the Renewable Energy Sources Act (REEG) was enacted in 2000, application of biogas technology has significantly increased in Germany (Weiland, 2003). Germany is Europe's biggest biogas producer and is leading the market in biogas technology. The total electricity produced by biogas in 2012 was 20 TWh, which is equal to the supply of 5.7 million houses with electricity. In Germany biogas provides more than 3% of the whole electricity consumption (WBA 2013). About 95%

of all biogas plants are at farms and the other 5% are large centralized plants, using animal manure from a group of suppliers (Weiland, 2003).

2.5.4.5 Sweden: World leader in the use of biogas for transport (source: WBA Factsheet, 2013)

Sweden is a world leader in upgrading biogas and using it for transport. Sweden has many ‘biogas vehicles’, including private cars, buses, and even a biogas train. At the end of 2012, there were nearly 44,000 gas vehicles, representing a 14% increase over 2011. At the same time, the number of upgrading plants has also increased.

2.5.4.6 China (Leader in small-scale household biogas plants)

As of 2013, China had about 42 million small-scale biogas plants in operation, generating biogas for households for cooking, lighting, etc. About 60,000 small, medium and large-scale biogas plants were installed for industrial purposes. Total biogas generated in 2010 is estimated at 15 billion cubic meters, which is equivalent to 9 billion cubic meters biomethane (WBA, 2013).

2.5.5 Benefits of Bio-Gas

Biogas plants provide several benefits at the household, local, national and international levels. These benefits can be classified according to their impact on energy security, employment, environment, and poverty.

2.5.5.1 Environmental benefits

Biogas is a complete and mature technology. Anaerobic digestion reduces the volume of the wastes going to the landfills and problems associated with their disposal. Biogas production using household waste results in reduced contamination of groundwater, surface water, and other resources. In the anaerobic digestion process, harmful pathogens can be destroyed completely. Nutrient-rich by-products (effluent) from biogas digesters can serve as high-quality organic fertilizer, displacing import of synthetic nitrogenous fertilizers.

2.5.5.2 Impact on the greenhouse effect

Production of sustainable biogas plant can significantly reduce greenhouse gas emissions. Annually, worldwide 30 million tons of methane emissions are generated from the different animal waste management systems like solid storage, anaerobic lagoon, liquid/slurry storage, and pastures. These emissions could be cut in half through anaerobic treatment (WBA, 2013). It is estimated that through anaerobic treatment of animal waste and energy use, about 1324 million tons of CH_4 emissions can be avoided worldwide per year (Cassada et al., 1990).

2.5.5.3 Economic and social benefits

Increased employment: promoting the production of biogas from household organic wastes helps to create permanent jobs in local and regional development.

Sustainable energy resources: the development of biogas plant represents an important step away from dependence on fossil fuels, at the same time contributing to the development of a sustainable energy supply and enhanced energy security in the long-term.

Decentralized energy generation: Biogas technology can be established locally, using local materials and local human resources without import of raw any materials.

Sustainable waste management: Utilizing organic wastes reduces the number of wastes that must be taken care of in another way, for example by combustion or transport to landfills.

2.5.6 Types of biogas plants

The reactor is the place where any substrate is digested. The classification of reactors is based on the mixing of fluid (substrate and sludge) in the reactor (Stalin, 2007). We will discuss here only the completely stirred, non-stirred and batch reactor. In addition to these reactors, many combinations of these reactors and additions are available; however, these reactors are not feasible in the targeted countries, because of its complexity and high financial and human capital input

There are various types of systems. Concerning the feed method, mainly two different forms can be distinguished:

- Batch plants
- Continuous plants

- CSTR (Completely mixed tank reactor system)
- Plug flow

Batch plants: These plants are filled and then emptied completely after a fixed retention time. There is no inflow or outflow. Each design and each fermentation material is suitable for batch filling, but batch plants require high labor input. As a major disadvantage, their gas-output is not steady in time. So, it is impossible to align gas production with gas demand at household level. Figure 2-18 shows the batch reactor system.

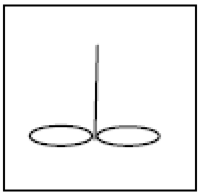


Figure 2- 18 Batch Reactor

Continuous plants: These are fed continuously. The CSTR and plug flow systems are characterized by automatic overflow when new material is filled in. Therefore, the substrate must be fluid and homogeneous. Continuous plants are suitable for rural households, as the necessary work fits well into the daily routine. Gas production is constant. A CSTR system is characterized by a continuous feeding rate and a complete mixture of bacteria and substrate and at constant loading rate, a constant gas production rate is achieved in time. Figure 2-19 shows the completely stirred reactor system.

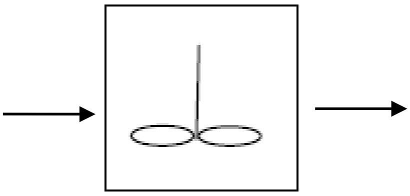


Figure 2- 19 CSTR system

Plug Flow Reactor: The plug flow system is continuously fed, and the feed passes through the reactor in horizontal direction and concentration reduces from left to right. Figure 2-20 shows the plug flow type reactor.

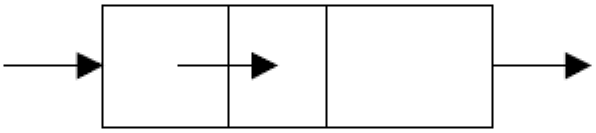


Figure 2- 20 Plug Flow System

There are several types of biogas plant according to their design and uses such as Fixed Dome Biogas Plants, Floating Drum Plants, Low-Cost Polyethylene Tube Digesters, Balloon Plants, Horizontal Plants, Earth-Pit Plants, and Ferro-Cement Plants. In developing countries, the most popular digesters in operation are the fixed dome digesters; in addition, the floating dome digester and bag digester are found in many developing countries.

The following are four basic types of biogas plants that are mostly used all over the world.

2.5.6.1 Fixed dome type biogas plant

The fixed dome digester is the most popular digester; its archetype was developed in China. The digester comes in various types, notably the Chinese fixed dome, Janata model and Janata II model Deen Bandhu and CAMARTEC (Balasubramaniyam et al., 2008)

In a fixed dome digester, the gas holder and the digester are combined (Saleh, 2015). Gas is stored in the upper part of the digester. The pressure inside the digester varies as the amount of gas collected. A fixed dome digester is usually constructed of masonry and built below the ground level, protecting it from physical damage, saving space and providing insulation, which makes it suitable for cold regions (GTZ / GIZ, 1999). Advantages of this type of digesters are: the digesters have no moving parts, no steel is needed, no rusting occurs and hence a long life of the plant (20 years or more) can be expected (GTZ / GIZ, 1999). It can be built by using locally available materials and hence its construction costs are low. The disadvantages are that special sealants are required, and high technical skills are needed for construction; otherwise, plants may not be gas-tight (porosity and cracks), which causes complication of gas use (GTZ / GIZ, 1999). Figure 2-21 shows the typical fixed dome biogas reactors used in a biogas plant.

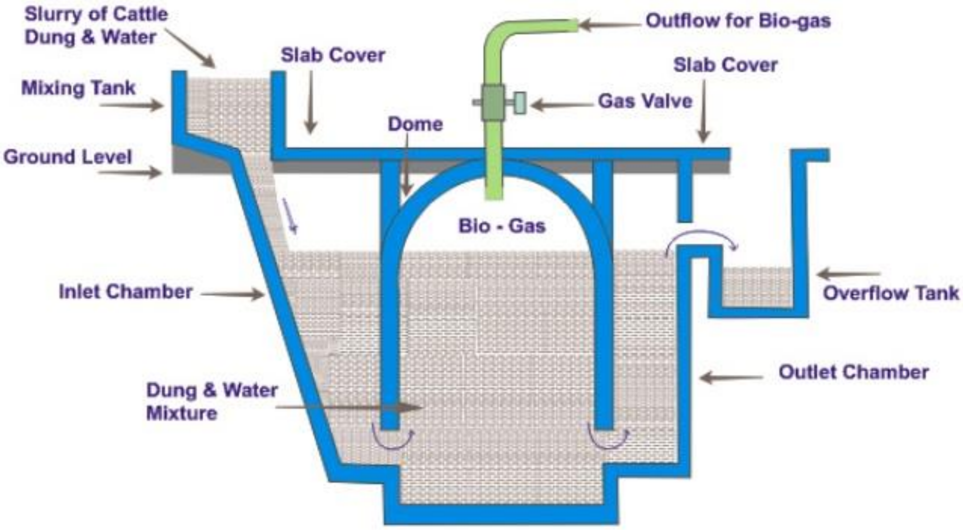


Figure 2- 21 Fixed dome type biogas plant (Biogas Technology, 2011)

2.5.6.2 Floating gas holder type biogas plant.

A floating gas holder type biogas plant consists of an underground brick masonry digester connected with an inlet and outlet, covered by a floating steel gas holder. Depending upon accumulation and discharge of gas, the gasholder moves up and down. This type of construction is expensive compared to the fixed dome type biogas plant; therefore, its use is usually restricted to large-scale sewage treatment plants. When the pressure in the holder rises accordingly, the generated gas is let out through the gas supply pipe. Alternatively, when the pressure is decreased, the holder lowers to stop the supply of the biogas. Floating-drum digesters are easy to operate and easy to maintain in terms of gas tightness by removing rust and repainting regularly (GTZ / GIZ, 1999). The design life of this type of digester is 5-15 years (Laurel, 2011). Figure 2-22 shows the floating dome type biogas digester.

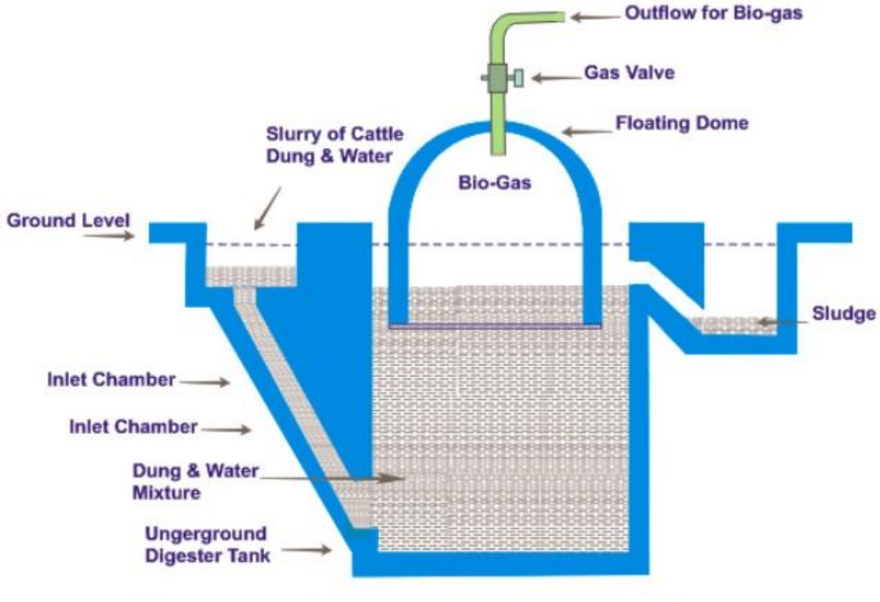


Figure 2- 22 Floating dome type biogas plant (Biogas Technology, 2011)

2.5.6.3 Fixed dome with expansion chamber type biogas plant:

The shape of this type of biogas plant has a curved bottom and hemispherical top which are joined at their bases without a cylindrical portion in between (Saleh, 2015). Displaced slurry following digestion moves to the outlet displacement chamber, as there is no displacement space on the inlet side. An inlet pipe connects the mixing tank with the digester as shown in Figure 2-23. This type of biogas plant is very cheap compared with the other two types of biogas plants (Saleh, 2015).

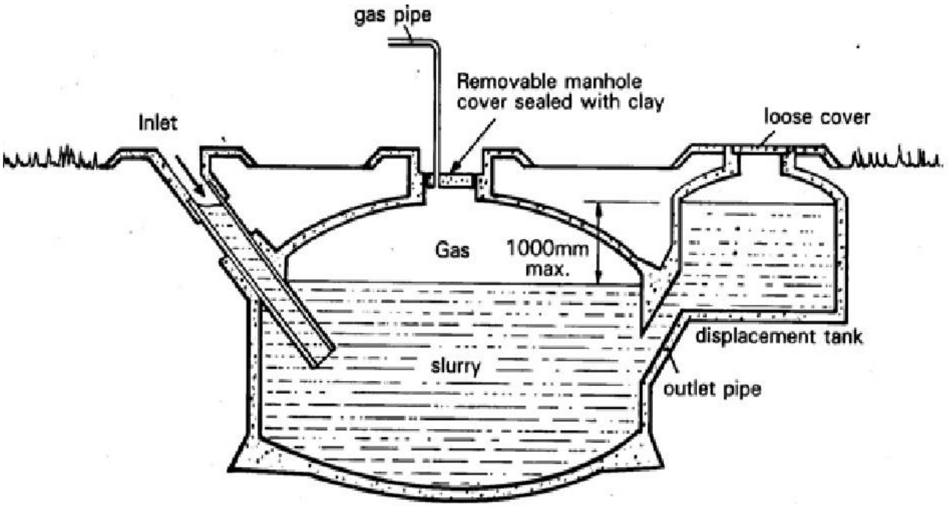


Figure 2- 23 Fixed dome with expansion chamber type biogas plant (Biogas Technology, 2011)

2.5.6.4 Bag digester

A bag digester also referred to as a balloon plant, is a plug-flow type reactor. This digester consists of a plastic or rubber bag combining the gas holder and digester. In the upper part, gas is collected and manure in the lower part; the inlet and outlet are attached to the skin of the bag. The pressure of the gas is adjustable by placing the weight on the balloons such as laying stones on the bag. Safety valves are required if the gas pressure exceeds a limit that the balloon can withstand, which can cause the damage to the skin. A gas pump should be installed if the higher pressure is required. According to GTZ (1999), these bags have a limited lifespan of 3-5 years. It is not advisable to use the bag digester in hilly areas, as it is affected by the ambient temperatures. The main advantages of this reactor types are; low costs, simple technology, uncomplicated cleaning. The disadvantages are; very short lifespan, very susceptible to physical damage, difficult to insulate. Bags are very difficult to repair. Since the bags could withstand the pressure of the gas as well as the material has to be weather and UV resistant. So, it needs high-quality plastic/PVC. Figure 2-24 shows a bag digester.

Figure 2- 24 Bag digester (ttps://upload.wikimedia.org)

2.6 Rice Husk

Rice husk is an agricultural byproduct obtained from the outer covering of rice grains during the milling process. According to Food and Agriculture Organization (FAO) rice market monitor report 2010, the annual production of rice is approximately 697.9 million tonnes (465.4 million tonnes, milled rice basis). On average 20% of the rice paddy is a husk, giving an annual total production of 140 million tonnes. The global market for rice hull ash stood at US$ 1.06 Billion and is expected to grow at a CAGR (compound annual growth rate) of 5% in terms of value to reach US$ 1.64 Billion by 2025 (Transparency Market Research 2018).

The husk is a unique residue with high silica content. Rice is one of the major agricultural crops at least in 75 countries of the world. Rice is one of the largest readily available biomass resources, which covers 1% of earth's land surface worldwide (Rice Husk Ash Market Study, 2003). Production of rice husk is highly dominated by Asian nations, where rice is the primary food crop grown during the rainy season. Following figure 2-25 shows world most rice producing countries.

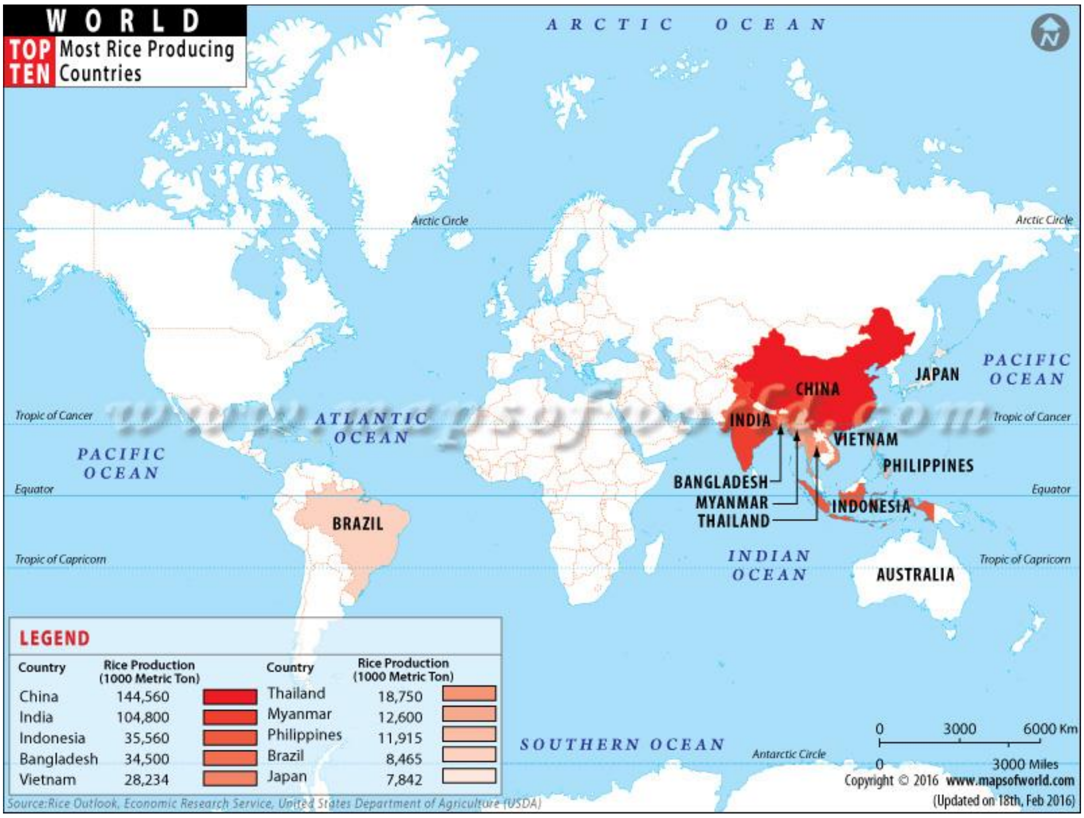


Figure 2- 25 Top ten rice producing countries in the world

Source (www.mapofworld.com, 2016)

Rice husk contains about 75 % organic volatile matter; the balance 25 % of the weight of this husk is converted into ash during the firing process and is known as rice husk ash (Ruhul et al., 2013). In a developing nation, Bangladesh, about 2.5 million tonnes of rice husk ash is produced annually (Ruhul et al., 2013). This huge amount of rice husk ash is disposed of in nearby rivers of rice mills, causing changes in the bed level of the river, which is one of the main reasons for river flooding. Similarly, in some countries, rice husk is disposed of on agricultural land, where the silica content of husk will highly deteriorate the fertility of the soil.

Rice Hull Ash (RHA) is a general term describing all types of ash produced from burning rice husks. In practice, the type of ash varies considerably according to the burning technique. The silica in RHA comes in different forms and can have different physical/chemical properties (specifically thermal conductivity), based on the temperature at which the husks were burned and time of combustion. At 550°C – 800°C amorphous ash is formed and at temperatures greater than this, crystalline ash is formed (Rice Husk Ash Market Study, 2003).

Rice hull ash has been applied as an amendment in many materials. RHA contains roughly 95% silica, is highly porous and lightweight, absorbent, and possesses insulating properties which are beneficial for industrial applications (Rice Husk Ash Market Study, 2003). Many literatures have highlighted different uses of RHA; however, two main uses have been identified: as an insulator in the steel industry and as a pozzolan in the cement industry.

Advantages of rice husk as insulating material include:

- Highly resistant to moisture penetration and fungal decomposition.
- Does not flame or smolder very easily.
- Does not transfer heat very well, smell or emit gases, and is not corrosive with respect to aluminum, copper or steel.
- Can be used very economically to insulate the wall, floor and roof cavities.
- Can be used to produce silicate blocks.
- 20% of ordinary portland cement can be replaced for RHA, the strength of concrete achieved equivalent values to the OPC control mixture.

Figure 2-26 shows the unground rice husk.

Figure 2- 26 Rice Husk (Source: Dreamstimes.com)

A brick is a block made of clay that is burnt in a kiln. It is one of the primary building materials known to humans. Bricks are composed of inorganic non-metallic material and are widely used as building components all over the world. In many countries around the world, Initiatives have been taken to develop low-cost building bricks using rice husk ash. Research has also involved developing bricks with reduced weight and increased thermal insulation ability.

The need for locally manufactured building materials has been emphasized in many countries of the world because of their easy availability and low cost (More et al., 2014). Bricks are one of the longest lasting and strongest building materials, made from locally available sources, used throughout history. Turning rice husk ash to brick can offer multiple benefits such as: Converting the hazardous RHA into bricks and preventing it from deteriorating the environment, as well as reduces the usage of bricks made from the topsoil. In India over 300 million tons of clay are removed from agriculture lands per year to make clay bricks (Mohan et al., 2012).

Ordinary building bricks are made of a mixture of clay, which is subjected to various processes, differing according to the nature of the material, the method of manufacture and the character of the finished product. Considering modern green building, the number of inner pores in building bricks is a critical factor. Lightweight bricks are usually manufactured in the factories by adding some combustible additives as a foaming agent while controlling the appropriate number of pores, particle size, and firing temperature. Generally, to produce lightweight bricks, plastic has been applied as an additive. However, previous studies show that the plasticized lightweight bricks resulted in an excessive amount of pores and decreased compressive strength because of it low apparent density and high water absorption (Veiseh et al., 2003).

Many researchers have studied various properties of bricks made using rice husk ash in different proportions with clay, cement and fly ash. A lightweight brick sintered at 1100 ◦C with less than 15% rice husk by weight was found to have the highest compressive strength, which met the building brick code requirement (100 kgf/cm^2) (Chiang et al., 2009). The compressive strength of brick is decreased with an increase in the rice husk ash content. According to Watile et al. (2015), the best composition of brick is 2% rice husk ash by weight. The 2% rice husk ash by weight obtained 6.59 Mpa of compressive strength and 14.0% water absorption. It was concluded that Increasing percentage of rice hull ash decrease the compressive strength, with high porosity resulting in low dry density. The maximum proportion of RHA was observed as 30% RHA and 70% clay, as the bricks exhibited high compressive strength and low brick weight (Mohan, 2012). When the percent of RHA was increased up to 40%, the strength gradually decreased; beyond 40% RHA, the compressive strength decreased rapidly.

Many researchers have studied how to produce lightweight insulated brick for building low-cost houses; however, there is limited information available on mixing RHA and clay to make insulated lightweight bricks for digesters, to increase the fermentation temperature in mountainous areas.

2.7 Insulation

Thermal insulation is the reduction of heat transfer (i.e. the transfer of thermal energy between objects of differing temperature) between objects in thermal contact or in range of radiative influence. Thermal conductivity relates heat flowing through a sample to the temperature of the sample on opposite sides. Thermal resistance is the ability of a material to resist heat flow. Materials with a higher thermal resistance are more apt to remain at the same temperature when exposed to a change in temperature. Concrete structures have been shown to incur significant damage during fires. If an insulative additive can be included in a concrete structure, it could greatly improve the resistivity of the material. The structure would be more able to resist the change in temperature due to a fire condition. This is improved heat resistance.

The insulating capability of a material is measured as this inverse of thermal conductivity (k). Low thermal conductivity is equivalent to high insulating capability (resistance value).

Thermal conductivity *k* is measured in watt-per-meter per kelvin ($W \cdot m^{-1} \cdot K^{-1}$). The rate of heat transfer, measured in Watts, has been found to be (at least to an approximation) proportional to;

- the difference of temperature, measured in Kelvin;
- the area of the surface for heat to go through, measured in m^2;
- the inverse of the thickness of the material, measured in meters.

Insulation is defined as a material or combinations of materials which retards the flow of heat energy by performing one or more of the following functions: Source www.PDHonline.org.

- Conserve energy by reducing heat loss or gain.
- Control surface temperatures for personnel protection and comfort.
- Facilitate temperature control of processes.
- Prevent vapour flow and water condensation on cold surfaces.
- Increase operating efficiency of heating/ventilating/cooling, plumbing, steam, process and power systems found in commercial and industrial installations.

- Prevent or reduce damage to equipment from exposure to fire or corrosive atmospheres.

The temperature range within which the term **"thermal insulation"** will apply is from -75°C to 815°C.

Thermal conductivity (λ) in steady state is given by the formula (2-13).

$$\lambda = \frac{qxd}{T1-T2} \quad \text{W/mK} \qquad (2\text{-}13)$$

where q = the quantity of heat passing through a unit area of the sample in unit time (W/m^2)

d = Distance between two sides of the sample (m)

T1 = temperature on the warmer side of the sample (K)

T2 = temperature on the colder side of the sample (K)

The quantity of transferred heat q is given by equation 2-14:

$$q = \frac{Q}{A} \quad (\text{W/m}^2) \qquad (2\text{-}14)$$

where Q = the quantity of heat passing through a base area of the sample (W)

A = base area of the sample (m^2)

2.7.1 Methods of measuring thermal conductivity and measuring devices

There are several possibilities/techniques to measure thermal conductivity. Each of them is suitable for a limited range of materials, depending on the thermal properties and the medium temperature. In general, there are two basic techniques of measurement:

Steady-state technique: This technique performs a measurement when material that is analyzed is in complete equilibrium. This makes the process of signals analysis very easy and implies constant signals. The disadvantage is that it generally takes a long time to reach the required equilibrium.

Non-steady state technique: This technique performs a measurement during the process of heating up so that the measurements can be made relatively quickly.

A variety of methods and instruments can be used to determine thermal conductivity. Instruments that use the steady-state conditions described in the Fourier equation are primarily suitable for analyzing materials with low or average thermal conductivities at moderate temperatures. Instruments based on dynamic (transient) methods, such as the hot-wire or flash diffusivity methods, are used to characterize materials with a high thermal conductivity and/or for measurements at high temperatures.

Heat Flow Meters. For this process, a square sample with a well-defined thickness (usually 30 cm in length and width and 10 cm thick) is inserted between two plates, and a fixed temperature gradient is established. The heat flow through the sample is measured with calibrated heat flow sensors that are in contact with the sample at the plate interface. The thermal conductivity is determined by measuring the thickness. This technique is used to analyze materials with low or average thermal conductivities at moderate temperatures. Figure 2-27 shows a modern heat flow meter.

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Figure 2- 27 Heat flow meter (the NETZSCH HFM 436 Lambda) (Source: labwrench.com)

This method can successfully test materials with thermal conductivities between 0.005 and 0.5 W/m.K and is typically used to determine the thermal conductivities and k-factors of fiberglass insulation or insulation boards. Advantages of this method include easy handling, accurate test results, and fast measurements. The main disadvantages are that it has a limited temperature and measurement range.

Guarded Heat Flow Meters. For larger samples that require a higher measurement range, guarded heat flow meters can be used. The measurement principle is nearly the same as with regular heat flow meters, but the test section is surrounded by a guard heater, resulting in higher measurement temperatures. Additionally, higher thermal conductivities can be measured with this method.

Guarded hot plate. A solid sample of material is placed between two plates. One plate is heated and the other is cooled or heated to a lesser extent. The temperature of the plates is monitored until they are constant. Using the steady-state temperatures, the power input into the hot plate, the temperature gradient and the thickness of the two samples, the thermal conductivity can be determined according to the Fourier equation. The advantages of guarded hot plates compared to the heat flow meters are their temperature range (-180 to 650 ^{0} C) and measuring range (up to 2 W/mK) (www.ceramicindustry.com). Moreover, this technique is an absolute measurement technique.

Figure 2-28 shows the schematic of a guarded hot plate.

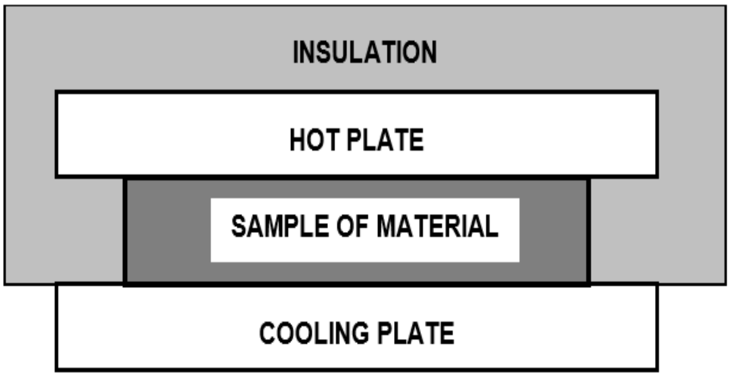


Figure 2- 28 The schematic structure of a guarded-hot-plate apparatus.

Hot-wire method: In this method, a heated wire is inserted in a sample. The heat flows out radially from the wire into the sample and the temperature change in the wire is recorded. The plot of the wire temperature and logarithm of time is used to calculate thermal conductivity if density and capacity are known. Since this is an intrusive measure, it cannot be used for solids; it works well for foams, fluids and melted plastics. Figure 2-29 shows a schematic of a hot wire apparatus.

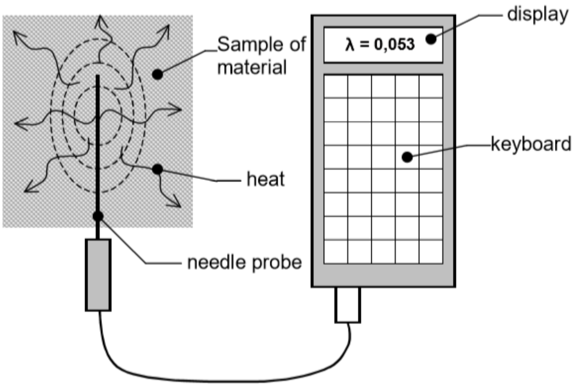


Figure 2- 29 Schematic of hot wire apparatus ISOMET

Table 2-8 shows the thermal conductivity of selected building materials.

Table 2- 8 The thermal conductivity of selected building materials (at 20 °C) (Source: virtual math.org)

Material	Thermal conductivity (W/m.K)
Air (dry and quiet)	0.023
Mineral or glass wool	0.04 – 0.08
Particleboard	0.1 – 0.13
Lightweight concrete	0.11 – 0.25
Timber (pine)	0.14
Water	0.6
Brick	0.65 – 0.80
Glass	0.6 – 1.38
Concrete	1.2 –1.75
Limestone	1.5
Granite	2.8
Steel	43-58
Aluminum and light alloys	125 – 200
Copper	386
Wood wool slab (500kg/m^3)	0.1
Cellular glass	0.038-0.050
Expanded polystyrene	0.030-0.038
Expanded polystyrene slab (25 kg/m^3)	0.035
Extruded polystyrene	0.029-0.039
Glass mineral wool	0.031-0.044
Mineral quilt (12 kg/m^3)	0.04
Mineral wool slab (25 kg/m^3)	0.035
Phenolic foam	0.021-0.024
Polyisocyanurate	0.022 –0.028
Polyurethane	0.022-0.028
Rigid polyurethane	0.022-0.028
Rock mineral wool	0.034 –0.04
Fiber board (25 kg/m^3)	0.06

2.7.2 Types of insulating material

These days there are plenty of common insulation materials available on the market. Each of these insulation materials has its own advantages and disadvantages. As a result, when choosing an insulation material, we should be aware of which material would work the best in a particular place or situation. There are many things to be considered such as resistance to heat (R-value), price, environmental impact, and flammability.

2.7.2.1 Fiberglass

Fiberglass is the most common insulation used in these days. Fiberglass is one of the excellent non-flammable insulation materials, with R-values ranging from R-2.9 to R-3.8 per inch (Home addition plus.com). Since fiberglass is made from finely woven silicon, glass powder and tiny shards of glass are formed. The main downside of fiberglass is the danger of handling it; proper safety equipment needs to be used so that fiberglass installation can be performed without incident. This a cheap insulation; however, installation requires safety precautions.

2.7.2.2 Mineral wool

Mineral wool refers to several different types of insulation, such as glass wool, which is fiberglass manufactured from recycled glass; rock wool, which is a type of insulation made from basalt; and slag wool, which is produced from the slag from steel mills. In the US, most of the mineral wool is slag wool. Mineral wool does not have additives to make it fire resistant. To use in the situation where extreme heat is present, it should be used in conjunction with other fire-resistant forms of insulation. Mineral wool has a resistance to heat (R-value) ranging from R-2.8 to R-3.5 (Thermaxxjacket.com). Like fiberglass, it is also used throughout a house in sidewalls, attics, floors, crawl spaces, cathedral ceilings, and basements

2.7.2.3 Cellulose

Cellulose is made from recycled cardboard, paper, and other similar materials and comes in loose form. Cellulose insulation is one of the eco-friendliest forms of insulation. It has a resistance to heat value (R-value) between R-3.1 and R-3.7 (Thermaxxjacket.com). Recent studies on cellulose have shown that it might be an excellent product for minimizing fire damage. Because of the compactness of the material, cellulose contains next to no oxygen within it. Without oxygen within the material, this helps to minimize the amount of damage that a fire can cause.

However, there are certain downsides to this material as well, such as the allergies that some people may have to newspaper dust. Even though finding individuals skilled in using this type of insulation is relatively hard compared to other insulation, cellulose is a cheap and effective means of insulating.

2.7.2.4 Polyurethane Foam

Polyurethane foams are an excellent form of insulation. Nowadays, polyurethane foams use non-chlorofluorocarbons (CFC) as a blowing agent, which helps to decrease the amount of damage to the ozone layer. These foams are relatively light, weighing approximately two pounds per cubic foot (2 lb/ft^3) and has R-value of approximately 6.3 per inch of thickness (Thermaxxjacket.com). The low-density foams (which have R-3.6 per inch of thickness) can be sprayed into areas that have no insulation. Another important advantage of polyurethane foam insulation is that it is fire resistant.

2.7.2.5 Polystyrene

Polystyrene is a waterproof thermoplastic foam which is an excellent sound and temperature insulation material. It is available in two types, expanded (EPS) and extruded (XEPS), also known as Styrofoam. The two types differ in performance and cost. The XEPS is costlier and has an R-value of R-5.5, EPS is cheaper and has R-4 (Thermaxxjacket.com). This insulation has a uniquely smooth surface, which no other type of insulation possesses. The foam is flammable and needs to be coated with a fireproofing chemical.

2.7.2.6 Rice Husk Ash

RHA is highly resistant to moisture penetration and fungal decomposition. It does not flame or smolder very easily. RHA does not transfer heat very well, smell or emit gases, and it is not corrosive with respect to aluminum, copper or steel. It can be used very economically to insulate the wall, floor and roof cavities. Clay bricks or cement blocks can be produced by molding RHA with clay or cement. Thermal resistance tests on whole rice hulls indicate R-values greater than 3.0 per inch. Rice hull has a thermal conductivity of about 0.0359 W/(m.°C) (Oliver, 2000). The thermal conductivity of rice hull ash is reported to be 0.062 W./m.K (Juliano, 1985).

2.7.2.7 Natural fibers

Some natural fibers such as cotton, sheep's wool, straw, and hemp are used as insulation materials. Cotton insulation consists of 85% recycled cotton and 15% plastic fibers that have been treated flame retardant and insect/rodent repellent. Because of its recycled content, cotton fiber product uses minimal energy to manufacture.

2.7.3 Insulation Summary Tables

Tables 2-9 to 2-20 provide the more detailed information on different types of insulation materials.

Table 2- 9 R-value, Advantages, Disadvantages, and Cost of Rice Hulls/Rice Husk Ash (RHA)

RHA R-value: 3.0 /inch

Advantages/Disadvantages	**Cost**
Pros: • Reuses a waste material • Highly resistant to moisture penetration and fungal decomposition • Does not smell or emit gases • Is not corrosive with respect to aluminum, copper or steel. • Silicate blocks can be produced from rice hull ash. • 20% of Ordinary Portland Cement can be replaced by RHA; the strength of concrete with RHA achieved equivalent values to the OPC control mixture. • RHA is finer than cement, having a very small particle size of 25 microns, so that it fills the interstices in between the cement in the aggregate. • Does not flame or smolder very easily • Cold-resistant **Cons:** • Flame retarding and, at ordinary temperatures, self-extinguishing. A lighted match tossed onto a pile of rice husks will generally burn out without producing a self-sustaining flame in the husks. It poses fire hazards. Source: Habeeb et al, 2010; Wikipedia; Natural building blog. (2018) Mohan el.al ,2012	- Prices ranging from \$2 - \$20 per ton - Average trucking fee of \$1.45 per mile, 24 ton, 53' trailer.

Table 2- 10 R-value, Advantages, Disadvantages, and Cost of Fiber Glass

Fiber Glass R-value: 2.9 to 3.8 /inch

Advantages/Disadvantages	**Cost**
Pros: • Poses no fire hazard • Lifetime is 10-25 yrs if the fiberglass stays dry • Installation is easy: sheet is placed on the wall • Does not absorb water. • Requires no additional fire-retardant chemical treatments • Can resist cold but not suitable for extreme cold. **Cons:** • When it is disturbed, fiberglass insulation releases particulates into the air, which may be inhaled by those installing or removing it. • Small particles that come into contact with skin can lodge in pores and cause itchiness, rashes, and irritation. • When inhaled, particles can cause coughing, nosebleeds, and other respiratory ailments. • Very fine airborne particles are capable of becoming deeply lodged in the lungs and are believed by many to cause cancer and other serious afflictions. • Loses heat quickly in the extreme cold. • Looses R-value over its lifetime. Source: Thermafiber, Inc. (an Owens Corning company); Home advisor (2018) International Association of certified home inspector (2018)	Around $0.40 per sq. ft. for regular sheet (material cost) Blown in fiberglass: $495-$1075 per 1000 sq ft. (should blow through machine)

Table 2- 11 R-value, Advantages, Disadvantages, and Cost of Cellulose

Cellulose R-value: Open Cell - 3.5/inch; Closed Cell – 6 to 7/inch

Advantages/Disadvantages	Cost
Pros: • Natural plant-based insulator • Can be produced from recycled newspapers • Is not believed to pose any serious health risks • Lifetime is more than 80 years • Does not lose heat in extreme cold; cold-resistant • Spray foam (open and closed cell) does not lose R-value over its lifetime **Cons:** • Naturally flammable – needs a barrier with fire rating, like drywall. However, most closed cell spray foams come with a fire retardant. • Installation is not easy: should be sprayed by professional. Sources: International association of certified home inspector. (2018) Diffen home improvement (2018)	The cost to install blown-in cellulose is $0.82 - $1.34 per square foot.

Table 2- 12 Advantages and Disadvantages of Sugarcane Fiber/ Bagasse Ash (SBA)

Advantages/Disadvantages	Cost
Pros: • Reuses a waste material • Light-weight, • Cold-resistant • Has thermal stability till 650°C. • Provides more insulation compared to commercially available fly ash bricks • Compressive strength 30-50 kg/cm^2 • Water absorption 8-12%, whereas regular clay brick absorbs 20-25% **Cons:** • 20% bagasse ash-blended concrete seems to be the optimal limit Sources: Rahul et al, 2014; Mukherjee, 2014	

Table 2- 13 R-value, Advantages, Disadvantages, and Cost of Mineral Wool (Therma Fiber) Insulation

Mineral Wool R-Value: 3.1/inch

Advantages/Disadvantages	Cost
Pros: • Minimum 70% recycled content • Is manufactured in a preformed thickness, eliminating variable thickness problems and inconsistencies in R-value • Is an inert product and is compatible with other building materials. • Naturally fire resistant and noncombustible; does not require a thermal barrier • Does not contain CFC or HCFC blowing agents • Cold-resistant **Cons:** • Mineral wool insulation has little odor. Since other insulating material do not have odor problem. Sources: Thermafiber Inc. (an Owens Corning company,2018) Homewyse (home design and construction professionals,2018)	$900-1700 Per 1000 sq ft (material, transportation, and labor)

Mineral wool insulation (also called rock or slag wool insulation), is made from rock, blast furnace slag, and other raw materials which are melted and spun into fibers to resemble the texture of wool. Mineral wool comes in batts, rolls or loose-fill forms. Like fiberglass, it is also used throughout a house in sidewalls, attics, floors, crawl spaces, cathedral ceilings, and basements.

Table 2- 14 R-value, Advantages, Disadvantages, and Cost of Polyurethane Foam

Polyurethane Foam R-Value: 6.3/inch for high density, for low-density foams 3.6/ inch

Advantages/Disadvantages	Cost
Pros: • Highest thermal resistance, effective in a wide range of temperatures • High strength-to-weight ratio • Resists mildew and fungus • Cold-resistant. • Relatively light, weighing approximately two pounds per cubic foot (2 lb/ft^3) • Low-density type of insulation is fire resistant. • Low-density foams that can be sprayed into areas that have no insulation. **Cons:** Not eco-friendly. polyurethane foams use non-chlorofluorocarbon (CFC) gas for use as a blowing agent. However, it is made of plastics, chances of exposing to the environment is high for low-density foam. Sources: Thermaxx LLC. (2018) Icynene, Canadian spray foam insulation manufacturer (2018)	**-** Cost for the light density product can be $0.44 to $0.65 per board foot. - Closed-cell insulation product can cost roughly $0.70 to $1 per board foot.

Table 2- 15 R-value, Advantages, Disadvantages, and Cost of Polystyrene

Polystyrene R value: 4.0 (expanded, or EPS) - 5.5 /inch (extruded, or XEPS)

Advantages /Disadvantages	Cost
Pros: • Waterproof • Cold-resistant **Cons:** • The type with the higher R-value (extruded, XEPS) costs more. • The foam is flammable and needs to be coated with a fireproofing chemical called Hexabromocyclododecane (HBCD). Sources: Thermaxx llc (2018) Menards home improvement co. (2018)	- $ 30 (2" x 4' x 8' R-10 Extruded Polystyrene Insulation) -$20 (1" x 4' x 8' R-5 Extruded Polystyrene Insulation)

Table 2- 16 R-value, Advantages, Disadvantages, and Cost of Glass Wool*

Glass Wool R-value: 2.9 to 3.8 per inch

Advantages/Disadvantages	**Cost**
Pros: • Suitable for applications ranging from -195°C to +230°C; Cold-resistant • Is chemically inert; does not cause or accelerate corrosion • Lightweight • Is inorganic; does not encourage the growth of fungi and vermin; rot-proof • Odorless • Moisture content less than 2% and water absorption less than 2% • Easy to cut and install. **Cons:** N/A Sources: National industrial CO. Chennai Tamil Nadu, India, (2018) Common equity housing limited, (2018)	**-** Around $0.40 per square foot (same as fiberglass)

Glass wool is an insulating material made from fibers of glass arranged using a binder into a texture similar to wool. The process traps many small pockets of air between the glass, and these small air pockets result in high thermal insulation properties.

Table 2- 17 Advantages and Disadvantages of Plaster of Paris*

Advantages /Disadvantages	**Cost**
Pros: • Lightweight • Durable • Fire-resistant • Does not shrink while setting. Therefore, it does not develop cracks in heating or setting. • Forms a thick surface to resist normal knocks after drying. • Mixes up easily with water and is easy to spread and level. • Has good adhesion onto fibrous materials. • Has no appreciable chemical action on paint and does not cause alkali attack. • Plaster of Paris gives a decorative interior finish. Its gypsum content provides it a lot of shine and smoothness. • Can easily be molded into any shape. **Cons:** • Is not suitable for the exterior finish as it is slightly soluble in water • Is more expensive than cement or cement lime plaster • Cannot be used in moist conditions • Skilled labor is required for precise application and thus labor cost for applying plaster of Paris is high. Source: Rajendran, 2013; Wikipedia, Plaster-of-Paris-pop	

Plaster of Paris (1:2:2): A base (either lime or gypsum) is mixed with sand, water, often a fiber (known as a binder), and a little plaster of Paris (to speed drying) in a lime-based plaster.

Table 2- 18 Advantages, Disadvantages, and Cost of Thermal Insulating Paint

Advantages/Disadvantages	Cost
Pros: • Thermally reflective coatings block heat radiation, dissipate heat rapidly. • These products reduce the work (heat loading) that "resistance insulation" such a fiberglass, foam, and rock wool have to do. • Ceramic paint additives are non-toxic, fire-resistant, cold-resistant & environmentally friendly (no volatile organic compound emission, non-toxic). Can use on interior or exterior. • Hard ceramics provide long-lasting durability. **Cons:** N/A Sources: HY-tech thermal solutions (2018)	Price variance as per manufacturer, \$27 to \$59/gal

Table 2- 19 R-Value, Advantages and Disadvantages of Saw Dust

Saw dust R value: 1 to 2 per inch

Advantages/Disadvantages	Cost
Pros: • Has been shown to control temperature fluctuations in bioreactors • Studies have shown that biogas yield after insulation was much higher than biogas yield before insulation. • Cold-resistant • Cost-effective **Cons:** • Wood dust is known as a human carcinogen • Certain woods and their dust contain toxins that can produce severe allergic reactions • Flammable Source: Mukumba et al., 2015	

Table 2- 20 Advantages and Disadvantages of Aerogel

Advantages/Disadvantages	**Cost**
Pros • One, in particular, Pyrogel XT, one of the most efficient industrial insulations in the world • Its required thicknesses are 50% – 80% less than other insulation materials • Cold-resistant **Cons:** • A little more expensive than some of the other insulation materials Sources: Thermaxx LLC. (2018)	**-**

2.8 Effect of temperature on biogas production in the temperate areas

Millions of simple biogas digesters have been constructed to produce biogas, mainly for cooking and lighting in China, India, Vietnam, Bangladesh, Tibet and Pakistan (Bruun et al., 2014). As of 2013, China has installed over 40 million household digesters. SNV, a non-profit Netherland international development organization, has helped to install more than 600,000 small-scale digesters in countries like Nepal, Vietnam, and Laos by 2014. The household level biogas digesters are not heated and are buried in the soil to maintain as constant a temperature as possible. However, recent studies have shown that digesters do not produce enough gas to meet households' energy requirements during winter in the mountainous regions.

Most of the biogas plants are populated in the mid or low hill area where the temperature is favorable for the microbes to produce methane. In the developing of country Nepal, 94 % of biogas plants are located in plain and low hill areas of elevation less than 1600 meters from the mean sea level. Figure 2-30 shows biogas plants installed in different regions in Nepal.

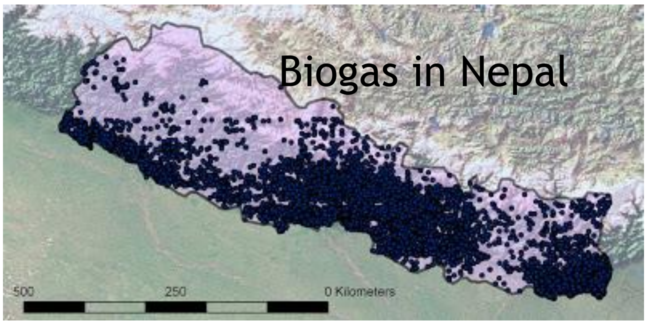


Figure 2- 30 Installation of biogas plants by region in Nepal (BSP,2004)

(57 % in Tarai (plain), 37 % in Hills and 6 % in Mountain)

Globally, there are many poor communities located close to mountains. The peoples of those areas do not have access to the electricity and the cost of imported cooking gas will be several times higher than its original price by the time it reaches to the rural area because of the transportation difficulties. So, they must rely on fuel "firewood". Figure 2-31 shows the Sirubari Village community located close to a mountain in Nepal.

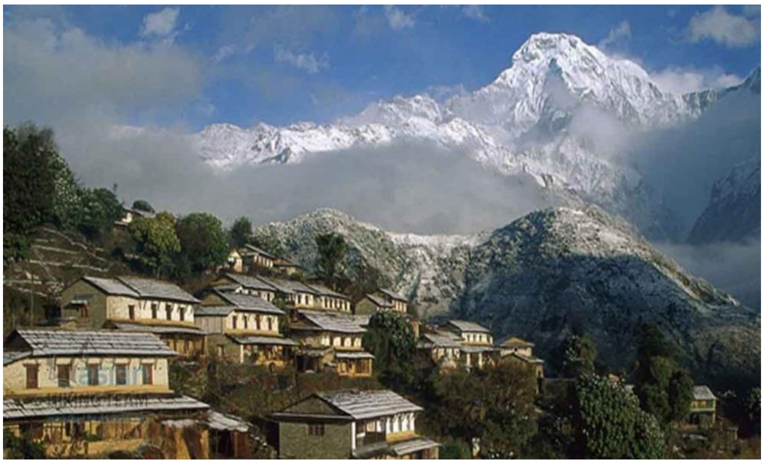


Figure 2- 31 Community located close to the mountain (Sirubari Village, Nepal) Source: google.com

From the microbiological perspective, the anaerobic decomposition process is affected by many factors, such as ambient temperature, retention time, pH level, nitrogen inhibition and C/N ratio. Temperature is the most important one that may dominate the biogas production in a digester (El-Mashad et al., 2004). Many researchers are engaged in studies on bio-methanation, but very little work has been done regarding the production of biogas at psychrophilic temperatures**.**

In nature biogas production can be taken place over a wide range of temperatures from 0 - 97 ^{0} C (Kashyap et al., 2003 and Zeeman et al., 1988). Anaerobic fermentation can take place at any temperature between 8 ^{0}C and 60^{0}C, which can be divided into three temperature ranges: The thermophilic temperature range between 45 ^{0}C and 60 ^{0}C, the mesophilic temperature range between 20^{0}C and 45 ^{0}C, and the psychrophilic temperature range lies lower than 20 ^{0}C (Kocar et al., 2007; Kashyap et al., 2003). Household biogas digesters mainly operate under the mesophilic and thermophilic temperature range. There are limited knowledge and a lack of experience concerning psychrophilic digestion, but lower temperatures need a longer HRT to achieve a similar gas production (Zeeman, 1991). In winter season the temperature falls below 20^0 C due to harsh ambient conditions in cold areas, in such cases, the biogas production rate of a digester will decrease drastically or even stop. Moreover, in some severely cold regions such as communities close to mountains, biogas digesters will not work at all, as the slurry temperature falls below zero. The following figure 2-32 shows graphs characteristic of the three temperature regimes. It is noted that the higher growth rate of the methanogenic bacteria was found to be in the thermophile range, therefore many modern biogas plants run at temperatures contained in this range (Dobre et.al 2013).

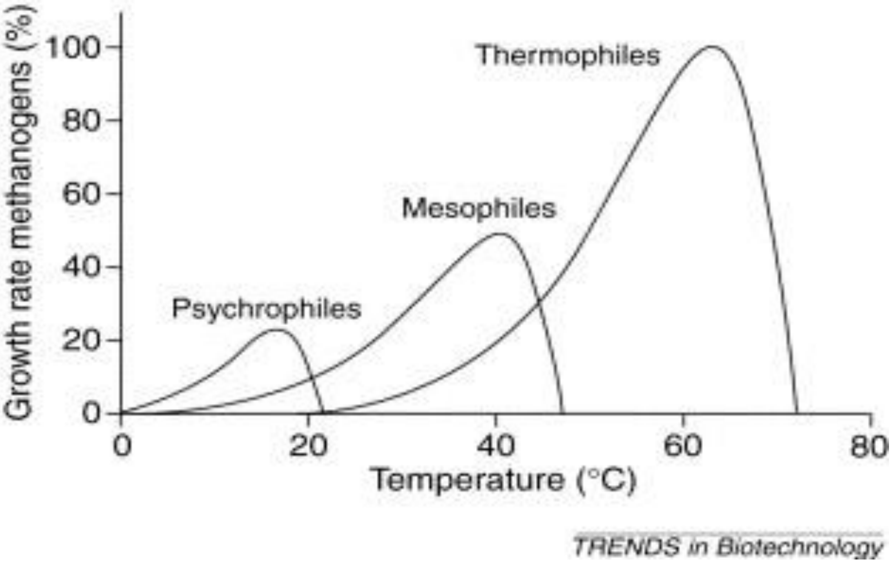


Figure 2- 32 The growth rate of methanogenic bacteria for three temperature range (Google.com)

Researchers have suggested that the temperature fluctuations should not exceed 2–3 ^{0}C per hour. If the temperature inside the digester fluctuations exceeds 5 ^{0}C in a short period of time, biogas yield will decrease significantly (Zhang et al. 2011). Temperature fluctuations also highly dependent on the quality and quantity of waste used, geometry of the digester, wall and floor thickness of the biogas digester and ambient temperatures of that location (Mukumba 2015).

To prevent heat loss of a digester in winter, different measures can be taken such as adding insulating materials on the outer wall (composites made of glass wool, sawdust, and plaster of Paris, black cloth coated with pitch, glass wool), building the digester under the ground of proper buildings or in a greenhouse, building the digester wall using insulated bricks and employing a fire pit surrounding the digester, installation of solar panels, using electricity or other renewable energy sources as heating measures to achieve digester heating. Different methods and techniques have been applied by the different researchers to increase the digester temperature in the low-temperature areas. The temperature effect on biogas production has been included in many kinetic models of biogas production as well (*e.g.* Chen and Hashimoto, 1978; Gavala et al., 2003; Ma et al., 2013).

In a comparative study of a conventional and solar-assisted greenhouse coupled biogas plant done (Sodha et al., 1987), it was concluded that the temperature of the slurry could be raised from 20 ^{0}C (in the conventional plant) to nearly 35 ^{0}C. Zhang (2016) proposed a hybrid system in which solar and biogas energy can be used in the fixed dome digester to improve the gas production during the winter season in northern China. With the installation of greenhouse and use of hot water to feed the digester, the maximum temperature increased from 9.3 to 20.8 ^{0}C, which was favorable to microbial activities, thereby resulting in the continuous production of biogas under the harsh climatic conditions. (Lohan et.al, 2012).

Integrating solar energy into a biogas as a solar greenhouse assisted mode and solar heating mode are seems capable of increasing the psychrophilic temperature to maintain the fermentation temperature at the mesophilic range to improve the biogas production. However, each mode has its own shortcoming.For solar greenhouse assisted mode there is an additional cost of building the greenhouse which results in a great increase in the initial capital investment on the biogas fermentation system. While for solar heating mode the fermentation temperature could be kept at proper level during the sunshine, the fermentation temperature significantly decreases in the night time.That means strong fluctuation occurs in the digester temperature which adversely affects the microorganism. Also in the

Himalayan range, very less sunshine occurs during the winter month. The solar system itself is not the effective way to provide heat.

The biogas production rate and the total production of biogas are increased by heating the biomass, also called hot charging. Since in the rural community there is no electricity available, biomass is heated with circulating water which is heated in a boiler with a fraction of the gas being produced (Sommer et al,2008). But using the fraction of gas for heating the biomass will reduce the amount of gases available for the household.

Also, hot charging is not very practical at a long retention time. The influent needs to be 60 degrees higher to counteract 1-degree heat loss of the digester per day (Buysman,2009).The temperature of the water needs to be almost 100 °C to heat up the influent to 60 °C (assuming the substrate is 20°C) if the ratio of waste and water mix is 1:1.Such a high temperature would affect the microorganisms which are acclimatized to the psychrophilic temperatures in the digester negatively. So hot charging can be done if the digester is very well insulated and might be feasible to overcome a smaller heat loss per day (Anand and Singh 1993).

Other researchers also pointed out that covering the biogas plant with a transparent polyethylene sheet was possible to obtain a substantial increase in gas yield on a typical winter day (Tiwari, 1986; Bansal, 1988). But the UV resistant plastic cover will not resistance to a higher temperature more than 50 ^{0}C. It will become brittle and reduced the transparency over the time (Sodha et.al 1989). Night soil under psychrophilic conditions (below 20 ^{0}C) can produce methane with the addition of temperature-adopted inoculums (Maher et al., (1994). Application of sawdust minimized heat loss from the slurry to soil through the floor because of its low thermal conductivity of 0.08 W/m.K (Mukumba et al., 2015). However, the sawdust degrades over the time. Solar insulation paint outside the rectors was also suggested but some of the paint cannot apply in the humid condition.

Building a greenhouse on top of digester can provide sufficient energy to heat the digester for an Indian floating-dome digester (Tiwari et al. 1986). However, the greenhouse increased the temperature during the daytime but was only able to maintain an acceptable nighttime temperature when insulation was used in the construction. Greenhouse heating of a bag digester increased the slurry temperature in South America (Perrygault et al., 2012). Charcoal coating on the digester wall has been proposed as a simple form of insulation, which can increase the temperature by 3 °C and gas production by 7%–15% during the winter, but rain and percolating water erode the charcoal insulation

(Gebremedhin et.al., 2005). Paddy husk placed on top of the digester can also help in maintaining the digester temperature during winter (Subramanian, 1977). However, while raining chances of washing out the husk will be more. Herrero, 2007 found that the combination of a solar canopy, hot charging, and the thin plastic digester increases the digester temperature to 10 °C compared to 0°C ambient but requirement of additional setup building and buying the material would add the upfront cost of the digester.

Some researchers have studied about the shape and type of reactor which is less affected by the temperature variation. Plug flow (tubular) reactors have been found to be less influenced by the temperature than the India Janta model because of their ability to separate acidogenesis and methanogenesis longitudinally down the reactor, which allows the reactor to behave as a two-phase system (Anjan,1988). A Chinese fixed dome digester was found to have better insulation properties compared to the Indian type fixed dome digester model (Hamad et al., 1981). Comparison of various geometries for digesters done by Wu et.al 2006, found that the cylindrical digester design had lower heat loss than did shapes that were rectangular, rectangular with arched top, or cylindrical with a conical bottom.

Over 40 million digesters are currently in use in developing countries (Brunn et al., 2014). Three types of digesters are standard in these countries: bag digesters, floating-drum digesters, and fixed-dome digesters. However, most of the household level digesters in developing countries are the fixed dome digester type. These small digesters have simple designs to keep construction, operation and maintenance costs low. About 77% of biogas digesters in Northern Vietnam and 100% of those in Central Vietnam are dome digesters made of bricks (Cu et al, 2012). These simple biogas digesters are generally buried underground to achieve a more stable internal temperature, which is very important especially in subtropical climates with relatively cold winters (Kossmann et al., 1997).

Different methods have been studied and suggested to apply in biogas digester to increase the fermentation process. However, none of the studies have integrated locally available insulating materials with reactor building material such as bricks or blocks to enhance the performance of biogas digester by increasing fermentation temperature. For most of the previous studies, there is a requirement of building an additional setup, which will increase the capital cost, which peoples in the rural community cannot afford. Since this study aims at rural communities in developing countries, a requirement is that the solutions be both affordable and possible to construct with locally available skills and materials. Moreover, some practices are not actually feasible for the rural mountainous areas, such solar-assisted system. For the current study, locally available insulation materials will be explored, tested and used for building the biogas reactor, so the people in the rural community will be benefitted and able to use the bioreactor for degrading their own household waste to produce the clean-burning fuel for their daily household uses.

2.9 Research Objectives

Even though household level biogas digesters are buried in the ground, low temperatures may restrict biogas production in the winter in subtropical areas, especially in mountainous areas (Cu et al., 2012). This makes biogas a less reliable energy source for the peoples in those areas and can be the reason for a farmer to choose another form of energy source (Bruun et al., 2014). Therefore, proper insulation measures and a heating system are essential for the regions with extreme temperature variations, to maintain a relatively constant slurry temperature inside the biogas digester.

The objectives of the present study are, therefore:

1 To investigate and test locally available insulating materials that can be used in the digester to enhance biogas production. Tests will be conducted for thermal resistance (R), compressive strength, water absorption, pH, moisture content, loss on ignition, surface metals (XPS analysis), chemical composition (carbon, hydrogen, oxygen, nitrogen, and sulfur), bulk density, sieve analysis and leaching potential (Using LEAF procedure).

2 To develop and test a cold-resistant biogas digester design for the use in mountainous areas of developing countries.

3 To conduct a life-cycle environmental and economic analysis for the cold-resistant design, compared to a conventional digester design.

Chapter 3

Methodology

3.1 Introduction

The first objective of this study was to select locally available insulating material and conduct laboratory testing of material properties. The laboratory testing includes CHONS (carbon, hydrogen, nitrogen, oxygen, and sulfur) analysis, surface metals, pH, moisture content, loss on ignition, particle size, and the bulk density of the material itself (soil and rice hull ash). Then the physical properties of rice hull ash and soil mixed bricks were measured, such as compressive strength, water absorption and resistance to heat transfer (R-value).

The second objective was then to build a laboratory scale reactor using the best insulating material and run a batch test using animal waste in a temperature-controlled room and measure the methane production.

The third objective was to conduct a life-cycle environmental and economic analysis for the cold-resistant reactor design, compared to a conventional digester design. The following Figure 3-1 shows a summary of the process.

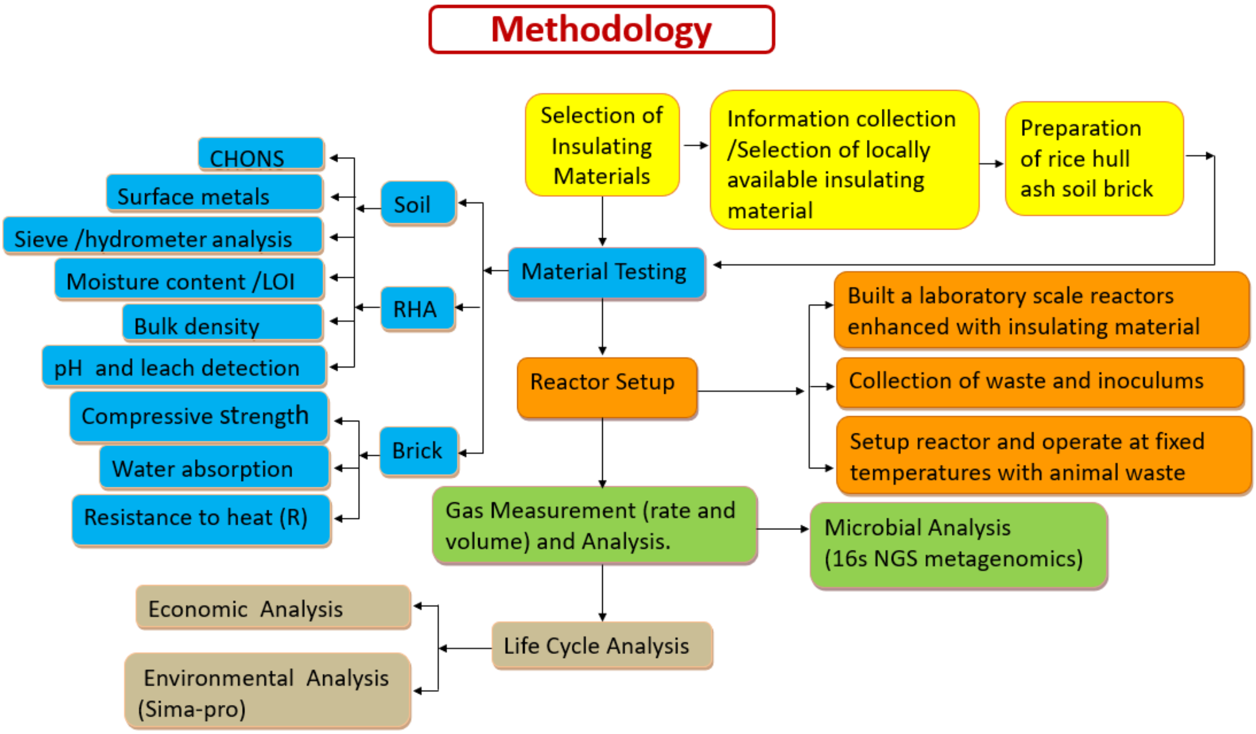


Figure 3- 1 Schematic of the study procedure

3.2 Selection and Preparation of Insulating Materials

3.2.1 Selection of Insulating Material.

Information on locally available insulating material, natural as well as synthetic, such as rice hulls, sugarcane bagasse, glass fiber, and different types of foam boards, was collected from journal articles as well as online sources. Their properties, usage durability, environmental effects, and resistance to heat value (if available) were compared and analyzed. Depending on the properties, one of the best insulating material, rice hull was selected for laboratory testing. Using rice hull, rice hull ash was prepared. The rice hull ash was combined with soil to make bricks, as described in the following sections. The information on different types of insulation materials were presented in Tables 2-9 to 2-20 in Ch. 2.

3.2.2 Collection of Raw Insulating Materials

About 340 pounds of an un-ground rice hull was bought from Golden Ridge Rice Mill, LLC Wynne, Arkansas. Figures 3-2 shows the unground rice hulls.

Figure 3- 2 Unground rice hulls

3.2.3 Rice husk charcoal preparation

Rice hulls (or rice husks) are the hard-protecting coverings of grains of rice. In addition to protecting rice during the growing season, rice hulls can be used as building material, fertilizer, insulation material, or fuel. First of all, the following equipment needed for making rice hull ash was collected:

- Rice Hulls
- Tinder
- Half barrel
- Charcoal hood and chimney
- Kindle, lighter fluid and lighter.
- Cinder blocks
- Water hose and fire extinguisher

Charcoal hood preparation**:** An 8 to 6-inch 30 gauge galvanized reducer was drilled with ½ -inch diameter holes in an inch apart. The reducer was connected to a 6“-diameter duct pipe to make the charcoal hood. A full barrel was cut in half by using a jig-saw to make a half barrel. Figure 3-3 shows the charcoal hood and a half barrel.

Figure 3- 3 Charcoal hood (left) and a half barrel (right)

Burning of rice husk: Personnel conducting burning first completed required hot works training conducted by the University of Texas at Arlington Environmental Health and Safety employees. The burning work was done at the University of Texas at Arlington Research Institute (UTARI). As per the safety requirement, the burning should be done at least 30 meters away from any building. A level spot (south-west side of the lot) was picked that can be scorched and has access to water. Cinder blocks of 8”x8”x16” and 8”x8”x8” inches were put around the barrel to guard the fire and to prevent the spread of heat, as shown in Figures 3-4 and 3-5. About 250 meters of water hose was connected to the water outlet and a fire extinguisher was set ready in case of fire.

Figure 3- 4 Firing the Kindle

Kindle was put in the bottom of the barrel and lighted. Then the charcoal hood was dropped over the burning kindle. The draft from the chimney caused the kindle to burn furiously. Rice hull was put around the hood, not in the middle. As much rice hull was added as possible, sloping up towards the chimney. The hulls in contact with the hood begin to char, consuming the oxygen. As the burn zone worked its way out, the inner layer had no more oxygen was not able to continue burning. As long as the oxygen was available, the husk kept burning. The rice husk should be burned at a temperature of 400-500 ^{0}C to turn into charcoal. There should not be any unburned pockets of rice hulls inside the barrel. For the complete burning of rice hull to charcoal, one batch required about 4-6 hours of burning time.

Figure 3- 5 Burning of rice husk

After most hulls charred, the hood was pulled out. The hulls were allowed to cool down for 20 minutes and then water was sprayed to the charcoal/ embers, so it would not burn further and turn into ash. The resulting volume of the rice husk was shrunk by about one-third of its initial volume, meaning that it was now 2/3 of its original volume. Figure 3-6 shows the rice husk charcoal after burning rice husk at 400-500 ^{0}C for 4 hours.

Figure 3- 6 Rice husk charcoal after burning (a), spraying water (b)

3.2.4 Soil collection and preparation

Soil are compounds of silica and alumina. Calcareous soils have calcium carbonate and will burn to a yellow or cream color. Non-calcareous typically contain feldspar and iron oxides and will burn to a brown, pink or red, depending on the amount of iron oxide.

Soil used for brick manufacturing should have the following properties:

- Plastic when mixed with water,
- Have enough tensile strength to keep its shape,
- Soil particles must fuse together.

For this study, soil was collected from the City of Arlington Landfill. The city's landfill has fresh piles of soil to use as landfill cover. Since the soil collected for this study was not used for the landfill cover, it was not contaminated with any of the landfill gases and other harmful substances. The soil was collected by using a shovel and bucket. Figure 3-7 shows the collection of soil from the landfill.

Figure 3- 7 Collecting the soil from the City of Arlington Landfill

The lumps of the soil were first spread on the floor in the lab and dried at least five days to remove the inherent moisture, as shown in Figure 3-8. In the meantime, the unwanted foreign particles like leaves, stones, large aggregates or other substances were removed.

Figure 3- 8 Drying the soil to remove moisture

The dried soil was crushed into a fine powder using the pulverizing machine, as shown in Figure 3-9 below.

Figure 3- 9 Pulverizing soil into fine particles

3.3 Test of insulating materials

Two materials, soil and rice husk charcoal, were used for making the bricks. So, various physical and chemical properties of those materials were tested in the civil engineering lab at the university as well as another certified lab outside the university. The following tests were conducted for the rice hulls ash and soil.

3.3.1 Moisture content

Moisture content test was conducted for both materials, rice husk ash (RHA) and the soil by using an oven drying method ASTM D-2216-90. Duplicate samples were tested for both materials. 20 grams samples of soil and 10 grams samples of RHA were used for testing. First, four crucibles were cleaned and dried in the drying oven for an hour at 108 ^{0}C and allowed cool for 30 minutes. Then the crucibles were cleaned using the alcohol and let dry for another 5 minutes. After the crucibles were completely dried, the empty crucibles were weighted (W_C). Then the samples (RHA and soil) with crucible were weighted (WS_{wet}). Figure 3-10 shows the samples being weighed.

Figure 3- 10 Soil (left) and Rice husk ash (right) samples being weighed

The measured samples were then dried at 108^{o}C in the drying oven for 24 hours to determine the moisture loss. Figure 3-11 shows samples being dried in the oven for the determination of moisture content. Figure 3-12 shows the samples before and after drying in the oven for 24 hours at 108^{0}C. After 24 hours, the crucibles with samples were taken out from the drying oven and put in the desiccator, allowed to cool, and reweighed (WS_{Dry}) The percent loss was determined on both a wet weight and dry weight basis, using the Equations 3-1 and 3-2, respectively.

Figure 3- 11 Samples in the drying oven for moisture content test

Figure 3- 12 Samples before (left) and after 24 hours drying in an oven at 108^{0}C (right)

Figure 1-1

$$Moisture\ content\ (wet\ basis) = \frac{Weight\ of\ the\ sample(WS\ wet) - Weight\ of\ the\ sample\ (WS\ dry)}{Weight\ of\ the\ sample(WS\ wet)}\ X100\% \tag{3-1}$$

$$Moisture\ content\ (Dry\ basis) = \frac{Weight\ of\ the\ sample(WS\ wet) - Weight\ of\ the\ sample\ (WS\ dry)}{Weight\ of\ the\ sample(WS\ dry)}\ X100\% \tag{3-2}$$

3.3.2 Loss on ignition

Loss on ignition (LOI) is one of the most widely used methods for measuring organic matter content in soils. a sample of 0.2 gram to 20 grams is recommended for the testing. For this study, 10 grams of RHA sample and 20 grams of soil samples were used. First, the crucibles were cleaned and dried for an hour in the drying oven at 108 ^{0}C and allowed to cool for 30 minutes. Then the crucibles were wiped using alcohol and allowed to dry for another 5 minutes. The empty crucibles were weighed (W_C); the dry crucible with the sample was weighed and the readings were noted. The crucibles with samples were kept in the drying oven at 108^{0}C for 24 hours. This temperature was enough to evaporate the moisture from the samples but not volatilize the organic matter. After 24 hours the crucibles with samples were taken out from the drying oven and put in the desiccator, allowed to cool, and reweighed (W_S). Then the crucibles with the dry sample were put into the muffle furnace (sentry 2.0) for burning, as shown in Figure 3-13 below.

Figure 3- 13 Samples in the muffle furnace

The temperature in the furnace was programmed to increase at a rate of 500 ^{0}C per hour. When the temperature reached 650^{0} C, that temperature was held for 1 ½ hour. Next, the crucibles were extracted using tongs and put into an aluminum foil pan for at least 5 minutes to cool initially, before being placed in a desiccator to fully cool. Figure 3-14 shows the samples after burning at 650 ^{0} C for 1 ½ hour.

Figure 3- 14 Sample after 1 ½ hour burning in the furnace at 650^{0} C

After the crucibles with the ash were fully cooled, they were reweighed (W_A). Loss on ignition was calculated by using Equation 3-3.

$$Loss\ on\ ignition = \frac{(WS)-(WA)}{(WS)-(WC)} X100\% \qquad 3\text{-}3$$

Where W_S= Weight of the crucible with sample after 24 hours drying oven at 108^0C

W_A= Weight of the crucible with ash

W_C= Weight of the empty and dry crucible

3.3.3 pH

pH is the measure of the hydrogen ion concentration of a solution (potential of Hydrogen). pH measurement reveals if a solution is acidic or alkaline (also base or basic). Solutions with a high concentration of hydrogen ions have a low pH and solutions with a low concentration of H+ ions have a high pH. The pH of the two materials used for this study (soil and rice husk ash) were measured. For pH measurement of samples, 2 grams of each sample (rice husk ash and soil) were weighed and mixed with the 20 ml of water in a beaker. Using a stirrer and magnet, the samples were stirred for 20 minutes. Then they were allowed to settle for 15 minutes. The pH was then measured by using HQ40d Portable pH Hach meter and IntelliCAL™ probes. The pH meter was calibrated before the measurement by using the Hach standard solutions. The pH of both samples with duplicates was measured and the readings were averaged. Figure 3-15 shows the pH measurement of the samples.

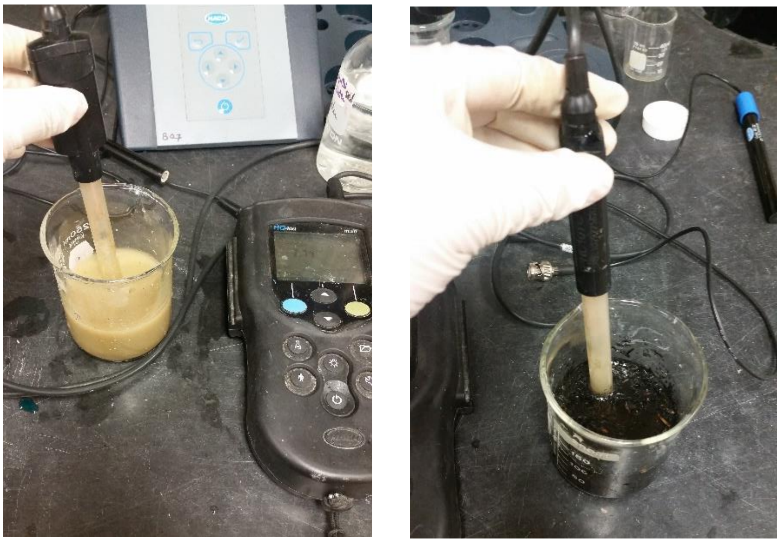


Figure 3- 15 pH measurement of samples

3.3.4 Surface Metals

ESCA (Electron Spectroscopy for Chemical Analysis), also known as XPS (X-ray Photoelectron Spectroscopy), is the energy analysis of photoelectrons generated at the sample surface by x-ray irradiation. The photoelectron spectrum includes characteristic peaks for all elements (except H and He), which can be used to identify the elements qualitatively and quantitatively.

One gram of each sample was weighed, labeled and sent to Innovatech Labs, LLC Plymouth, Minnesota for surface metal analysis. The surface chemistry and composition of two powder samples were evaluated using Electron Spectroscopy for Chemical Analysis (ESCA). The ESCA data show varying concentrations of aluminum (Al), carbon (C), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), nitrogen (N), sodium (Na), oxygen (O) and silicon (Si) in the samples that were tested. The atomic concentration summary, the carbon chemistry, and the binding energies of the metals detected in the powder samples were provided by the lab. Figure 3-16 shows the samples in vials for sending to the lab for surface metal analysis.

Figure 3- 16 Samples for surface metal analysis.

3.3.5 Leach test using Leaching Environment Assessment Framework (LEAF) procedure

When a liquid comes into contact with a solid, through the process of chemical and physical interactions leaching can occur and chemical species such as organics and metals can be released into the aqueous phase. The released species will become mobile in the environment.

For this study, the USEPA SW8 1315 semi-dynamic tank leaching test was conducted for the rice hull ash mixed soil bricks. This method aims to determine the rate of mass transport from either monolithic material such as concrete materials, bricks, tiles, or compacted granular materials such as soils, sediments, fly ash, as a function of time using deionized water as the leaching solution. Figure 3-17 shows the schematic of the USEPA SW8 1315 semi-dynamic tank leaching test.

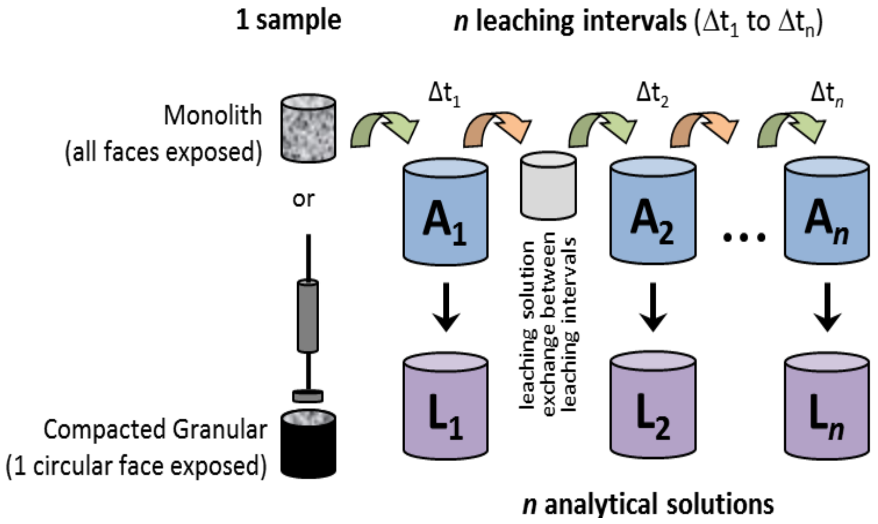


Figure 3- 17 Semi-dynamic tank leaching test (EPA, 2017; www.vanderbilt.edu)

For this study, a rectangular size brick specimen was used as the monolithic sample. The vessel and sample dimensions were chosen in such a way that the sample was fully immersed in the leaching solution. Two 5-gallon plastic pails of 14” height and 11” diameter were used, one for the sample and one for the blank. A plastic holder was prepared by using 6 “diameter high-density polyethylene (HDPE) pipe. A clean leaching vessel was filled with the required volume of reagent water (DI water was used as reagent water for this study) based on an L/A (liquid-surface area ratio) of 9 ± 1 mL/cm^2. Surface area of the sample was 851.2 cm^2, so 7.8 liters of reagent water were used. Samples were contacted with reagent water at a specified liquid-surface-area ratio (L/A). At nine specified time-intervals, the sample was transferred to fresh reagent water as per USEPA 1315. The mass of the sample and the holder was measured and recorded. Figure 3-18 shows the sample and the sample holder.

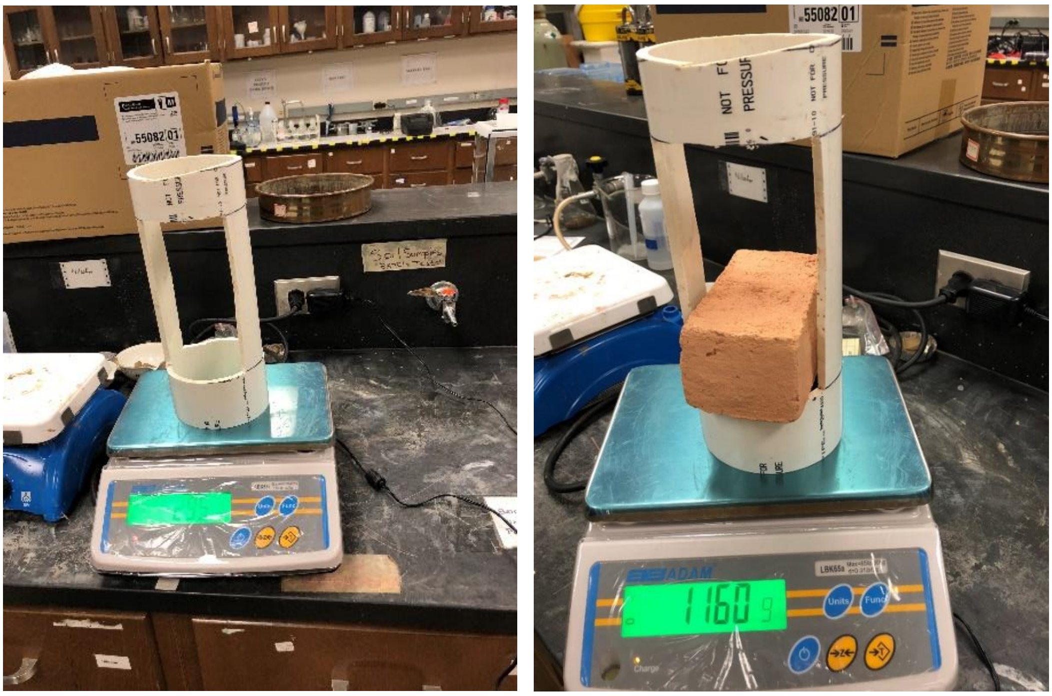


Figure 3- 18 Measurement of the sample holder and the sample

The samples were placed into the holder and the specimen and holder were carefully placed into the leaching vessel. The sample was placed very gently and centered so that the scouring of the solid could be minimized. A monolithic sample (brick) was submerged in the eluate such that at least 98% of the entire sample surface area was exposed to eluent. Figure 3-19 shows the sample with the holder placed into the leaching vessel.

Figure 3- 19 Sample with the holder placed into the leaching vessel.

The leaching vessel was covered with an airtight lid placed at room temperature until the end of the leaching interval, as shown in Figure 3-20. At the end of each leaching interval, the sample with the holder was removed, the liquid from the surface was freely drained for about 20 sec. and the mass of sample was recorded to monitor the amount of eluent absorbed into the brick sample at the end of each leaching interval. Then the sample was placed into the clean leaching vessel with the new eluent. The same process was repeated for the nine interval times.

Figure 3- 20 Leaching vessel

The eluate pH, conductivity, and total dissolved solids were measured within 15 minutes after removing the samples and recorded for each time interval. The pH was measured by using the HQ40d Portable pH Hach and the conductivity and total dissolved solid were measured by using Oakton PCTS 50 conductivity meter. Figure 3-21 shows the pH and conductivity meter.

Figure 3- 21 Conductivity and pH meter

About 140 ml of eluate samples were removed from the leaching vessel and filtered by using a 0.45-μm membrane filter then preserved for the chemical analysis. All the subsequent eluate during the nine intervals was collected. For heavy metal analysis, all the filtrate eluate was acidified by using 2.5% of 63% nitric acid. About 15 ml of each nitrified sample was sent to the geo-science lab for heavy metal using ICPMS (Inductively Coupled Plasma Mass Spectrometry). An ICPMS is a highly-sensitive analytical technique that measures elemental concentrations. The concentrations of following heavy metals at microgram per liter were measured: Silver (Ag) Aluminum (Al Arsenic (As)) Barium (Ba) Beryllium (Be) Cadmium (Cd) Cobalt (Co) Chromium (Cr) Copper (Cu) Manganese (Mn) Molybdenum (Mo) Nickel (Ni) Lead (Pb) Selenium (Se) Thorium (Th). Figure 3-22 shows the samples filtered and prepared for chemical analysis.

Figure 3- 22 Eluate filter and samples prepared for heavy metal analysis

The concentrations of eluate were plotted as a function of time, as a mean interval flux, and as a cumulative release as a function of time.

The interval mass released was calculated for each leaching interval as follows:

$$M_{ti} = \frac{C_i \text{ x } V_i}{A} \qquad 3\text{-}4$$

M_{ti} = mass released during the current leaching interval, i (mg/m^2)

C_i = constituent concentration in the eluate for interval, i (mg/L)

V_i = eluate volume in interval, i (L)

A = specimen external geometric surface area exposed to the eluent (m^2)

The flux of a constituent of potential concern (COPC) in an interval was plotted as a function of the generalized mean of the square root of cumulative leaching time (t). Generalized mean leaching time was calculated using the following equation 3-5

$$t_{imean} = \left(\frac{\sqrt{t_i}+\sqrt{t_{i-1}}}{2}\right)^2 \qquad 3\text{-}5$$

The flux across the exposed surface of the sample can be calculated by using the following equation 3-6

$$F_i = \frac{M_i}{t_i - t_{i-1}} \qquad 3\text{-}6$$

Where

F_i = flux for interval, i (mg/m^2·s)

M_i = mass released during the current leaching interval, i (mg/m^2)

t_i = cumulative time at the end of the current leaching interval, i (s)

t_{i-1} = cumulative time at the end of the previous leaching interval, i-1 (s)

3.3.6 Chemical Composition (CHON and S)

One gram of each sample, soil and rice hull ash, were weighed, put into vials and labeled. The vials then sent to the Intertek Pharmaceutical Services Whitehouse, New Jersey for the analysis of chemical composition. The two powdered samples were analyzed for Carbon (C), Hydrogen (H), Nitrogen (N), Oxygen (O) and Sulphur (S). A summary table of the analytical report was provided by the lab service. Figure 3-23 shows the samples for CHON and S analysis.

Figure 3- 23 Samples for CHON and S analysis

3.3.7 Bulk density:

Bulk density is defined as the mass per unit volume (including voids) of particulate matter. The bulk density depends on how the material is loaded into the container. For this study, loose bulk density was determined for soil and rice husk ash using ASTM E1109-86 method. Bulk density is not an absolute material property, as is the density of individual particles of a material. The bulk density can be of two types, compacted and uncompacted. For example, the bulk density of material placed loosely in a container will be less than that of material tamped into a container. Also, some materials placed loosely in a container will settle with time due to their own weight; thus, their bulk density will increase. To determine bulk density of the materials used for this study (soil and the rice husk ash), a 1000 ml (known volume) Pyrex glass beaker was used. The beaker was cleaned using soapy water and dried. The dry empty glass beaker was weighed (C), as shown Figure 3-24.

Figure 3- 24 weight of empty beaker

The sample was placed in the container and filled level with the 1000 ml line then weighed (W). Figure 3-25 shows the container with the sample.

Figure 3- 25 Beaker with sample soil (left) and rice hull ash (right)

Bulk density was calculated from the weight of the contents and volume of the container by using Equation 3-7.

$$Bulk\ density(\rho) = \frac{Weight\ of\ container\ with\ sample\ (W) - Weight\ of\ empty\ container\ (C)}{Volume\ of\ Contanier\ (V)}\ (\text{kg/m}^3) \quad 3\text{-}7$$

Where 1 m^3 = 1000 L

3.3.8 Sieve analysis

A sieve analysis is a practice or procedure used to assess the particle size distribution (also called gradation) of granular material. The size distribution is often of critical importance to the way the material performs in use. For this study ASTM D 422 - Standard Test Method was conducted for particle-size analysis of soils. The sieve analysis was performed to determine the distribution of the coarser, larger-sized particles. The distribution of different grain sizes affects the engineering properties of soil. Grain size analysis provides the grain size distribution, and it is required in classifying the soil. For this study, the particle size analysis test was performed to determine the percentage of different grain sizes contained within the soil and rice hull ash samples.

A set of sieves (Numbers 8, 16, 30, 50, 100, 200) was obtained and cleaned by using a brush, making sure all the dust and other particles were removed from sieves as well as from the bottom pan. Figure 3-26 shows the set of sieves used for this study.

Figure 3- 26 Different sizes of sieves

Each sieve and bottom pan were weighed. Soil and rice hull ash samples were weighed (W) as shown in Figure 3-27. For this study, 500 grams of soil sample and 200 grams of rice husk ash sample were used. Mass of the soil was chosen based on the sieve analysis test manual in which it was suggested to use at least 500 grams of the soil sample. However, for RHA, 200 grams of samples were taken for the analysis because of the light weight; 500 grams samples did not fit in the sieve.

Figure 3- 27 Empty sieve (Left) and sample (right)

Sieves were assembled in an ascending order, such the finest sieve was placed on the bottom, followed by increasing coarser sieves, with the coarsest on top (#8 sieve at the top and #200 sieve at the bottom). The pan was placed below the #200 sieve. The soil sample was poured into the top sieve carefully, as shown in Figure 3-28, and the lid was placed over it so that the stack could be easily secured to the shaker.

Figure 3- 28 Pouring the sample, soil (left) and rice hull ash (right) into top sieve

A stack of sieves was placed in the mechanical shaker, with the bottom pan resting on the cradle platform, and the top of the stack was secured with the sieve hold-down bar. The mechanical shaker was turned on and the stack shaken for 10 minutes. Figure 3-29 shows a stack of sieves placed on the mechanical shaker.

Figure 3- 29 Series of the sieve on a mechanical shaker

The machine was stopped when the timer had expired. The set of sieves was removed from the mechanical shaker. Each sieve with its retained sample was weighed (S) and the weight recorded, as shown in Figure 3-30. The percentage of the original dry weight that was retained on each individual sieve and in the bottom pan was calculated.

Figure 3- 30 Sieves with the retained sample

The following equations (3-8, 3-9, 3-10) were used to calculate the weight and percentage of sample retained in each category, and percent finer.

$$Weight\ of\ sample\ retained\ (R) =\ weight\ of\ sieve\ with\ retained\ sample\ (S) - Empty\ weight\ of\ the\ sieve\ (W) \qquad 3\text{-}8$$

$$Percent\ sample\ retained\ in\ each\ sieveor\ pan\ = \frac{Weight\ of\ sample\ retained\ in\ each\ sieve\ or\ pan\ (R)}{weight\ of\ total\ mas\ retained} x100\% \qquad 3\text{-}9$$

$$Percent\ passing\ (finer) = percent\ entered\ - percent\ retained\ in\ an\ individual\ sieve \qquad 3\text{-}10$$

3.3.8.1 Calculation of Coefficient of Curvature and Coefficient of Uniformity

Determining the Coefficient of Uniformity (Cu) and Coefficient of Curvature (Cc) only has meaning when classifying coarse-grained soils having more than 50% of material larger than No. 200 sieve with less than 5% fines. So, the samples for the current study falls in the above category. There would be no reason to determine these coefficients for fine-grained soils (i.e. soil, silt, and peat). The Cc and Cu are calculated by using the following equations 3-11 and 3-12.

Coefficient of uniformity (C_U) = D_{60}/D_{10} 3-11

Coefficient of Curvature/Gradation = $(D_{30})^2/ D_{60}xD_{10}$ 3-12

Where,

D_{30} = Diameter for which 30% of particle are finer

D_{60} = Diameter for which 60% of particle are finer

D_{10} = Diameter for which 10% of particle are finer

3.4 Making soil bricks with rice hull charcoal

Bricks were prepared using three different proportions of soil and rice hull ash. One set of soil only (0% rice hull ash) was also prepared. For each composition, about 14-16 bricks were made. The proportions of the bricks were chosen based on the previous studies (Mohan et al., 2012; Ganesan et al., 2007; More et al., 2014) done on the rice husk ash and soil mixed bricks. The proportions of mixtures were:

- 10% rice husk ash + 90% soil.
- 20 % rice husk ash + 80 % soil.
- 30 % rice husk ash + 70% soil.
- 0 % rice husk ash + 100% soil.

3.4.1 Wooden mold preparation for making bricks

The wooden mold for making the bricks of size 8.0 "x 3.5"x 2.5" was prepared by using wooden planks and nails, as shown in Figure 3-31 below. A rectangular wooden base plank (2.5 ft X4 ft) was also prepared on which to set the wet bricks. A wooden box on the top and the bottom opening was made so that the filling the soil and releasing would be easier. All edges were nailed tight to prevent the soil from leaking through. Multiple molds were prepared so that it would be easier to use side-by-side in one unit as well as to handle when filled with soil.

Figure 3- 31 Preparation of wooden mold for making brick

3.4.2 Weighing and mixing samples (soil and rice hull charcoal)

Rice hull charcoal prepared by burning unground rice hulls and pulverized soil powder, as shown in Figure 3-32, were used to make the bricks for this study.

Figure 3- 32 Soil and rice hulls charcoal

The required amount of the rice hull charcoal and the soil was measured by using a measuring container and put into the mixing tub, as shown in Figure 3-33 below. All ingredients (dry) were mixed thoroughly in mixing tub by using a brick trowel. Figure 3-34 shows the mixing of the dry samples. Water was added slowly until the mix had the consistency of dough, retaining its shape when formed but still be soft enough to use in molds. The mold was left for about 15 minutes soaking in water and covered in plastic to prevent drying. Figure 3-35 shows the mixed dough ready to make brick.

Figure 3- 33 Measuring the dry samples

Figure 3- 34 Manually mixing soil and RHA (left); adding water to the sample (right)

Figure 3- 35 Soil dough for making the bricks

3.4.3 Making bricks

The wooden mold was lubricated with water before filling with mixes so that dough would not stick on it and could be pulled out without destroying the shape of the bricks. Coarse-grained soil was sprayed on the wooden board as shown in Figure 3-36 below so that the soil would not stick to the board, damaging the shape of brick when taking it out.

Figure 3- 36 Dry coarse-grained soil sprayed on wooden board

Then mixed dough (soil and RHA) was packed into the mold manually. The packing was done slowly and tamped by hand so that there would not be any unpacked space left inside the mold. After filling up to the top, the excess was trimmed along the top edge and leveled on top with a finishing trowel. Figure 3-37 shows the packing of soil mix (left) and trimming the edges (right).

Figure 3- 37 Packing dough into a mold (left) leveling the edge (right)

The mold was then carefully removed by sliding up, leaving the wet brick on a wooden board, which was stored for drying as shown in Figure 3-38. If the brick was too wet and soft, it was left to sit for a few hours before putting it out in the sun.

Figure 3- 38 Prepared bricks of different compositions

3.4.4 Sun Drying of bricks

The bricks were dried by placing them on a wooden board in the sun for 5 days (about 8 hours a day). The bricks were turned as each side dried white in color. The bricks were kept out of the rain. Figure 3-39 shows the bricks drying on the sun. Most of the 0% rice hull ash bricks, which were made of soil only, were broken while drying in sun. Figure 3-40 shows the broken bricks. Sun-dried bricks were then transferred to the lab for firing in a muffle furnace at different temperatures.

Figure 3- 39 Bricks drying in the sun

Figure 3- 40 Broken 0% RHA bricks

3.4.5 Firing bricks in a muffle furnace

Firing the soil bricks can provide high compressive strength. For this study, the bricks were fired in an electric muffle furnace, Paragon, Sentry-2. Sun drying was carried out before the firing stage, When the moisture content of the soil was high to prevent the swelling or bloating of the samples at high temperature, caused by the expansion of entrapped water. After drying in the sun, the brick loses most of the water added to the soil during the preparation phase. Each specimen was marked and weighed before firing in the electric furnace. The furnace was programmed to increase the temperature at the rate of 500°C per hour. When the temperature inside the furnace reached the required temperature, it was programmed to hold for the required amount of firing time that the bricks were going to be burned. Here firing time means the time to be maintained after the corresponding firing temperature was set. The rate of the firing process is very important, as it attains the final properties of the product. Rapid firing causes the bloating of soil due to the formation of an impermeable vitrified outer skin, preventing the loss of gases such as water vapor and CO_2 from the interior of the soil. Therefore, the furnace temperature was gradually increased from 0°C to the firing temperature of each treatment. When the temperature first starts increasing until it reaches 105 °C, it will help to evaporate moisture. The temperature then increased to a firing temperature of 500 ^{0}C or 700^{0}C, which was held for about 4-6 hours. The bricks fired at 700ºC turned reddish because of the oxidation of ferrous silicate. Having completed the firing process, the hot specimen was allowed to cool down, as the temperature of the furnace was gradually decreased.

Having the furnace turned off, the specimen was allowed to stay about four hours in the furnace and then removed. Figure 3-41 shows brick firing in a muffle furnace.

Figure 3- 41 Firing bricks in the muffle furnace

For each composition, four sets of brick were prepared as follows.

- 1st set was burned at 500^0 C with burning time of four hours (9 bricks).
- 2nd set was burned at 500^0 C with burning time of six hours (11 bricks).
- 3rd set was burned at 700^0 C with burning time of four hours (11 bricks).
- 4th set was burned at 700^0 C with burning time of six hours (10 bricks).

The firing temperatures and firing duration were chosen based the previous studies (Watile et al., 2015; Sutas et al., 2013; Rahman et al., 1987; Ganesan et al., 2007; More et al., 2014) done on the rice husk ash and soil mixed bricks to test physical and chemical properties. The 10% bricks were marked as 1, 20% bricks were marked as 2, and 30% bricks were marked as 3. The temperature and time were marked as 5, 4; 5, 6; 7, 4 and 7, 6. The first numbers 5 and 7 are firing temperature 500^{0}C and 700^{0}C. The second number denotes the firing time, such as 4 and 6 hours. Figure 3-42 shows the same proportion of brick (30%) fired at different temperature and times. Figure 3-43 shows the different proportions of bricks burned at the same temperature and time.

Figure 3- 42 The same proportion of brick fired at different temperatures and times

Figure 3- 43 Bricks with different mixing proportions after burning at 700 ^{0} C for 4 and 6 hours

3.5 Physical tests on the bricks

3.5.1 Compressive strength test:

The compressive strength of the samples prepared was determined by using Compression Testing Machine (400KIP Tensile Compression Machine). A software called Horizon and VMC was used to provide the load to the samples and monitor the reading. The VMC software is an accessory to the Horizon software package. It aids in the control, calibration, and troubleshooting of the controller. The VMC software runs side-by-side with Horizon whenever a machine with the new controller is connected. Figure 3-44 shows the compression tensile machine.

Figure 3- 44 400 KIP Tensile Compression Machine

The Proterm, a wired handheld device which allows for control of the machine, was used to perform crosshead positioning and monitoring of the machine status. Proterm can only be used in conjunction with the Horizon software. Figure 3-45 shows Proterm, a computer running horizon and VMC software (left) and crosshead controller (right).

Figure 3- 45 Proterm, computer running software (left) and cross-head controller (right)

For this study, four samples (one for each firing temperature and time) of each proportion (10%, 20%, and 30%) were tested. A circular plate of diameter greater than the brick length was placed under the cross-head to put the sample on. After placing the sample on a plate, the cross-head was released down by using the controller and stopped just before it touched the sample. The cross-head should be positioned close to the specimen before running the test. It should not touch the sample but should be close. Figure 3-46 shows the sample placed in between the plate and the crosshead.

Figure 3- 46 The specimen in between plate and cross head

Using the Horizon software, a program was set up to provide the load slowly to the specimen. The load was given to the sample at the rate of 1000 pounds per minute. The pump and position of the load were zeroed on the handheld Proterm each time before running the test. While running the test, the live data was viewed on the screen of the handheld Proterm as well as on the computer screen. The Horizon software plotted the live curve of a given load versus the distance. Depending upon the load given and the type of sample, the testing time varied. The plotted curve, as well as the data, gave the ultimate and break-point load, its distance and time that it occurred for the specimen. Figure 3-47 shows a live graph of the load given to the sample versus distance plotted by Horizon software.

Force 2,723 lbf
Position 0.51 in
Time 168 sec
Position Rate 0.07 in/min

Figure 3- 47 The live graph plotted by the software, force versus distance

When the ultimate load was reached, the machine gradually lowered the load that was provided and stopped after 40% of the maximum load was reached. However, the testing process could have been stopped at any time during the testing. Figure 3-48 shows a sample after the ultimate load had been reached.

Figure 3- 48 Sample after the ultimate load was reached

After the machine stopped, the cross-head was moved up by using the cross-head controller and the broken specimen was removed from the plate.

The compression strength of the brick was calculated by using equation 3-13.

$$Ultimate\ stress = \frac{Ultimate\ force\ (lbf)}{Area\ of\ Specimen\ (Sq.inch)} \qquad 3\text{-}\ 13$$

3.5.2 Water absorption test

The water absorption of the soil and rice hull ash mixed brick samples was determined by 24-hour cold water immersion test. A brick with water absorption of less than 7% provides better resistance to damage by freezing. The degree of compactness of bricks can be obtained by the water absorption test, as water is absorbed by pores in bricks. The water absorption by bricks increases with an increase in pores. For this study, two samples of each composition were tested, and the results were averaged.

For the test, 72-quart clear storage boxes were used. The boxes were filled three-quarters full of water. First, each fired brick was weighed (W1); then the bricks were placed into the box as shown in Figure 3-49 below.

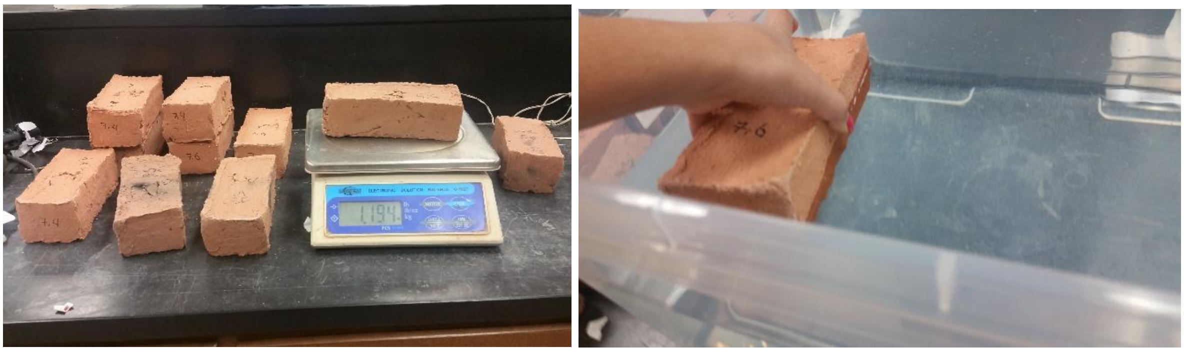


Figure 3- 49 Fired bricks being weighed (left), immersed in water (right)

The bricks were immersed completely in clean water (about 1 ½ feet of water) and kept at room temperature (74 ^{0} F) for 24 hours. Figure 3-50 shows the specimens immersed in water.

Figure 3- 50 Specimens immersed in water for 24 hours

After 24 hours, the specimens were removed from the water and kept for a couple of minutes to drain out drops of water that were on the surfaces of the bricks, as shown in Figure 3-51 below.

Figure 3- 51 Specimen removed from the water bath

Any traces of water were wiped away with a damp cotton cloth and the specimen was weighed after it had been removed from water (W2). Figure 3-52 shows the samples which were cleaned and reweighed (wet).

Figure 3- 52 Specimen cleaned (left) and reweighed (right)

The difference in the weight of the brick samples (dry and wet) was calculated by using the following Equation 3-14, which gives the water absorption of the brick.

$$Percentage\ of\ water = \frac{Wet\ weight\ of\ sample\ (W2) - Dry\ weight\ of\ sample (W1)}{Dry\ weight\ of\ sample\ (W1)} \qquad 3\text{-}14$$

3.5.3 Thermal conductivity:

Thermal conductivity (k) is the time rate of steady-state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area (Ctherm.com). The SI unit for k-value is watt per kelvin meter (W/ (K·m)). The R-value is a measure of thermal resistance, the ratio of the temperature difference across an insulator and the heat flux (heat transfer per unit area per unit time) through it under uniform conditions. The SI unit for R-value is kelvin square meters per watt (K·m^2/W).

Thermal resistance (R-value) is the temperature difference, at steady state, between two defined surfaces of a material or construction that induces a unit heat flow rate through a unit area, K·m^2/W. Thermal resistance can be determined (using equation 3-15) by dividing the thickness by the thermal conductivity of the specimen.

$$R = \frac{L}{K} \qquad 3\text{-}15$$

Where R= Resistance to heat value (K·m^2/W)

L – Thickness of the specimen (m)

K = thermal conductivity (W/K.m)

The thermal resistance of the specimen was tested using the ASTM C518 hot box method at Dynalene Inc., Whitehall, Pennsylvania.

3.5.3.1 Sample preparation for resistance to heat value measurement.

Rice hull charcoal prepared by burning unground rice hulls and pulverized soil powdered was used to make the square block for this study. A 6-inches square block of height 2.5 inches was prepared. The mold for making the square sample was made by using wooden planks. Square bricks of soil with rice hull charcoal in different proportions (10% and 20%) by volume were prepared.

The required amount of the rice hull charcoal and the soil were measured and mixed thoroughly in a mixing tub. Water was added slowly until the mix had the consistency of dough. The mold was lubricated with water before filling with mixes, and coarse-grained soil was sprayed on the wooden board so that the soil would not stick to the board, damaging the shape of the cylindrical sample while being taking out. Then soil and RHA mix were packed into the mold manually. After filling up to the top, the excess was trimmed along the top edge and leveled on top. The cylindrical mold was removed carefully by sliding up, leaving the wet square brick sample on a wooden board.

Figure 3-53 shows the square brick samples for thermal conductivity measurement.

Figure 3- 53 The sample for thermal conductivity measurement.

The samples were dried in the sun for 5 days; then they were burned in an electric muffle furnace at 500 and 700 ºC for four and six hours.

Compressive strength and water absorption tests were conducted for all sample compositions. The results of those tests were considered to narrow down the number of thermal resistance tests to be conducted, to save costs. All of the compositions with compressive strength of more than 3.5 MPa (minimum building brick compressive strength) and water absorption of less than 20 % (for 24 hours water immersion test) were tested. Four samples of 10 % rice husk ash and three samples of 20% rice husk ash were prepared and sent to the laboratory for testing the resistance to heat value (R). In addition to this, one sample of 0% rice husk ash (100 % soil) was tested to compare heat resistance value with bricks made by rice husk ash mixed soil. To make a proper composition for soil brick, the soil should have some silt and sand particles as well. Table 3-1 shows the different compositions and sets of samples prepared for resistance to heat value test.

Table 3- 1 Sample types, firing temperatures and times for R-value testing

Sample	500 ^{0}c		700 ^{0}c	
10%	4 hrs.	6 hrs.	4 hrs.	6 hrs.
20%	4 hrs.		4 hrs.	6 hrs.
0%				6 hrs.

3.6 Biogas Reactor Building and Operation

After all the laboratory tests on the different compositions of rice husk ash and soil mixed brick, a best composition was selected for building reactors. Two laboratory-scale brick and cement mortar circular reactors were built, one with the insulating material and one without insulating material. The dimensions of the reactors were chosen based on the biogas construction manual of Alternative Biogas Promotion Center, Nepal by comparing the digester depth and inside radius of the smallest size of 2 cubic meters system. The radius was reduced in the same ratio (radius to depth) as 2 cubic meter, but the height of the reactor was made a little taller the reactor capacity needed to be greater so that it would be easier to compare with the 6 m^3 capacity, and there was no more space in the temperature control room to increase the reactor diameter. The wall thickness, concreting thickness, the thickness of plaster and punning were chosen based on the manual. Dimensions are shown in Fig. 3-54.

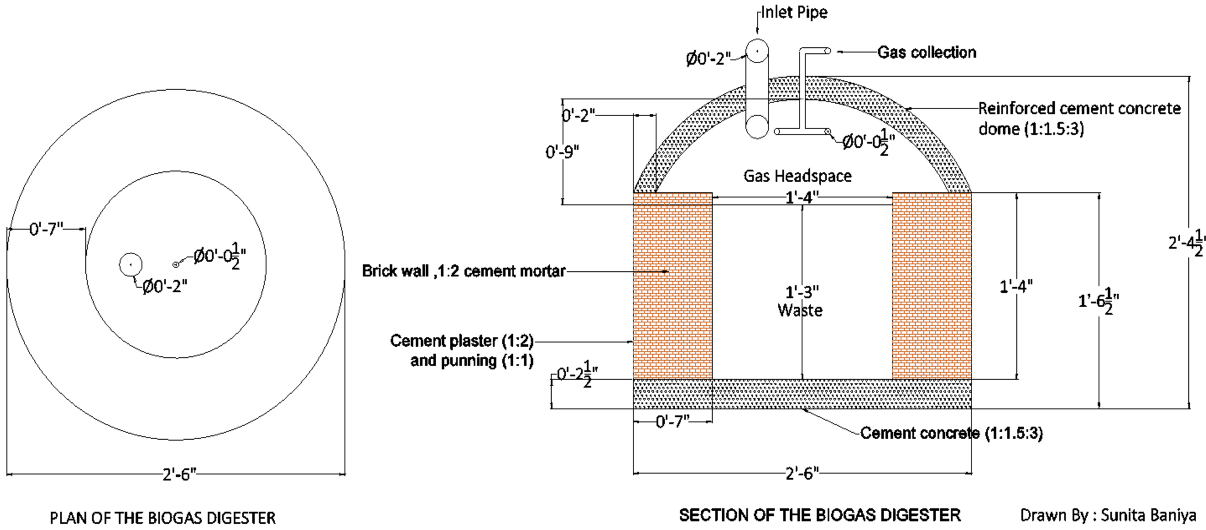


Figure 3- 54 Plan and cross-section of the biogas reactors

On top of the dome and at the center, a ½ inch diameter galvanized iron (GI) nipple with GI Tee for gas collection was installed, which later was connected to a gas collection bag using a reducer and Tygon tube. A 2” diameter high-density polyethylene pipe was attached on the side of the dome to use for the waste inlet/outlet. During the reactor operation, the pressure, humidity, and temperature sensor was deployed through the inlet opening to monitor the gas pressure inside the reactor. For both reactors waste was filled up to a height of 15” above the bottom, leaving about 9“above the waste as gas headspace.

3.6.1 Making bricks for building reactor

The mold and the bricks were prepared by using the same procedure described in Section 3-4 above. The soil and RHA mixed bricks of size 6”x3.5”x 2.5” (Length x Breadth x Height) were prepared using the wooden mold. The results obtained from the compression strength, water absorption and resistance to heat value (R-Value) tests, were utilized for selection of best brick composition to build the reactors. Based on the results obtained from the three major tests on bricks, the 20 % RHA brick (20% rice husk ash + 80 % soil) burned at 700 ^{0}C with 4 hours burning duration gave the best result among other combinations. Thus, that composition of brick was selected for building the reactor. About 200 bricks, 100 with 20 % RHA and 100 using only soil were prepared. The bricks were sundried and burned in the furnace at 700 ^{0}C with the firing time of 4 hours. Because of the larger number of bricks to be burned, bricks were taken outside UTA lab for burning in a larger sized furnace.

3.6.2 Making bottom slab

For building the reactor, the bottom slab and gas collection dome were prepared outside the lab and transported to the lab. For casting the bottom slab, first, a 31-gauge galvanized steel roll was selected for formwork. A galvanized steel sheet of 94 inches long was cut using a metal cutter to provide the frame/shape of the circular slab. The two ends were taped together, and sheet diameter was measured. Store-bought 9-Gauge galvanized tension wire and steel binding wire were used to make the wire mesh for the reinforcement work. The 9-gauge Galvanized tension wire was cut into pieces with different lengths (28 inches to 8 inches) to put inside the slab concreting to can give the maximum strength. The metal rods were placed about 1-1 ½ inches apart (longer at the center and reduced length to the sides) inside the circular galvanized sheet form. The rods were placed from both sides and tied together using steel binding wire. The rods were lifted about ¾ inched from the bottom by using small-sized stones, so the rods were positioned at the center of the slab. A thick plastic was placed on the floor before pouring the concrete mix. Figure 3-55 shows the preparation wire mesh for making the slab.

Figure 3- 55 Preparation of wire mesh for concreting

Quikrete concrete mix of 4000 PSI average compressive strength was used for making the slab and the dome of the reactor. Quikrete is a blend of strength blend of Portland cement, sand and gravel or stone that meets the ASTM C387 requirements for compressive strength. This is a structural concrete mix and gains 4000 PSI strength in 28 days and has normal setting time. The required amount of concrete mix was poured into a plastic container. Water was added gradually and mixed thoroughly by using a shovel to make a uniform concrete mix. Figure 3-56 shows the premixed concrete and preparation of concrete slurry.

Figure 3- 56 Preparation of concrete mix

Then the slurry was poured into the circular frame and tamped with a metal rod for proper compaction by avoiding any formation of voids in the concrete as shown in Figure 3-57. The concrete was poured about 2 ½ inches thick. The top of the concrete surface was leveled by using the leveling tool. While placing the concrete, special care must be taken to prevent small holes that can expose the steel reinforcement, which will cause corrosion. There are holes formed in the slab; these should be filled with a plaster layer.

Figure 3- 57 Pouring and leveling of concrete

The concrete was left for setting/hardening about 24 hours. Immediately following completion of the concreting work, the circular slabs were sprinkled with water 2 to 4 times a day for 14 days, which is known as curing. The curing reduces the loss of mixing water from the surface of the concrete and accelerates the hardening process (quora.com). Also stacking of water on top of the concrete helps to reduce the evaporation of water out of the concrete and thus gets rid of shrinkage and cracks. Curing should be performed by spraying and stacking water for at least 7 days. Figure 3-58 shows the curing of the concrete.

Figure 3- 58 Curing of concrete

When the concrete gained its full strength in about 28 days, the GI sheet frames were removed. Figure 3-59 shows the circular slab which is ready for building the reactor.

Figure 3- 59 Circular slab for building reactors.

3.6.3 Building Gas Holder (Dome)

The dome shape gas holder was also prepared outside the lab. The gas holder was attached on top of the reactor for gas collection. The reinforced cement concrete dome was constructed using Quikrete concrete mix and mild, steel wire and binding wire.

Two 18-inches diameter rubber planters were used as a form to support the reinforcement and to give dome shape concrete work. The planter was put upside down and lumps of moist soil were placed and tamped on sides of the planter to give the mild slope for the dome. A thick plastic layer was placed over the planter. Figure 3-60 shows the planters used for making the dome-shaped holder.

Figure 3- 60 Planter to use as a frame for casting dome-shaped gas holder

Small sized stones were put at the bottom to lift the wire mesh so that galvanized wire will be laid at the middle of the slab. At the bottom, a 2 ½ inch high, 31-gauge GI sheet was put around the planter bottom so that the concrete would not flow downside and to keep the circular and smooth shape. Store-bought 9-Gauge galvanized tension wire and steel binding wire were used to prepare the wire mesh for the reinforcement. The circular rings were prepared and bound together as shown in Figure 3-61.

Figure 3- 61 Preparation of wire mesh for concreting dome

The concrete mix was prepared by adding the required amount of water to the mix as per the instruction. The required amount of concrete mix and water for one batch was added to the mixing container and mixed thoroughly by using a shovel and trowel until the mix became slurry. Then the concrete slurry was poured on top of the plastic and wire mesh. The concrete mix was tamped into the frame for proper compaction that eliminates the possibility of void formation in the concrete. For making the dome, the slurry should be a little thicker so that it will not flow down the slope. The concrete was poured about 2 inches thick. The top of the concrete surface was leveled by using the leveling tool and the concrete was left to set for 24 hours, as shown in Figure 3-62.

Figure 3- 62 Concreting of the gas holder

Two concrete domes of two inches thick were constructed with an outer diameter of 23 inches and height 8 inches at the center. Special care was taken regarding the thickness of the gas holder (dome) while casting, the thickness near the outer edge should be greater than the thickness at the center. On top of the dome, at the center, a ½ inch diameter galvanized iron (GI) nipple for the gas collection was installed, which later was connected to a gas collection bag using a reducer and Tygon tube. Also, one 2” diameter HDPE pipe (4 inches long) was inserted on the side of the dome to leave a hole for waste inlet/outlet. During the reactor operation, the inlet opening was used to deploy the pressure, temperature and humidity measurement instrument (Kestrel Drop D3 wireless less data logger).

After the concreting work completed, curing was done by sprinkling water 2 to 4 times a day for 14 days. The curing decreases moisture evaporation out of the concrete throughout hardening and thus get rid of shrinkage and cracks.

3.6.4 Building the reactor wall

The bottom slab and the gas holder for the gas collection was prepared outside the lab and transported to the lab. However, the reactor was assembled inside the temperature-controlled room in the lab. The reason was that moving brick masonry reactors from one location to another would cause damage to the brick wall. The reactor wall was built using bricks and the mortar mix.

3.6.4.1 Mortar preparation

For this study, store-bought Sakrete S type mortar mix of Compressive Strength >1,800 PSI, which meets property requirements of ASTM C1714 and ASTM C270, was used. Pre-mixed mortar is a combination of cement, sand and hydrated lime which is blended together in the proper proportions to make a Type S mortar.

Cement mortar paste was prepared by mixing the mortar mix and water in the proper ratio. A bag of premixed mortar was poured into the plastic tub. The water was added gradually to make the desired consistency (smooth plastic-like consistency). For each 60-pound bag, 1.5 -2 gallons of water was added. The mixture was mixed manually for 7 to 10 minutes in the plastic tub using the trowel. The mortar was mixed in such a way that no dry powder was left in the mix. Figure 3-63 shows the preparation of mortar for a brick masonry wall.

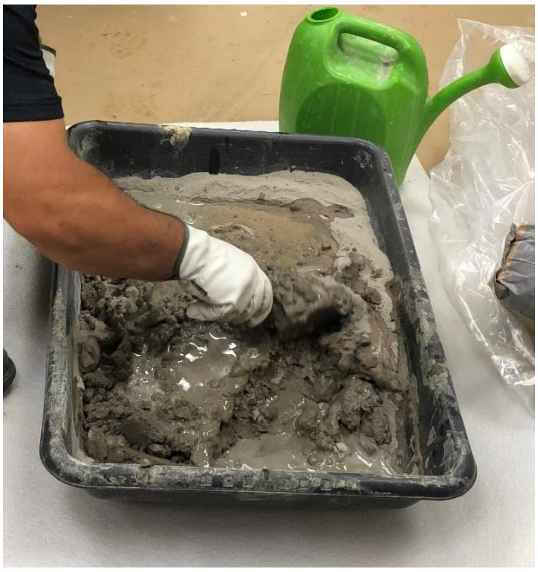


Figure 3- 63 Preparation of mortar

3.6.4.2 Building wall

The bottom slab which was constructed outside the lab was transferred to the lab and placed on the floor where the reactors were going to be built. The slabs were placed in such a way that some space was left on all four sides to fill the earth to simulate the underground digester. After deciding the radius of the digester, a circle was drawn marking the inner circumference of the round wall.

The bricks were immersed in clean water for 15-30 minutes for proper soaking as shown in Figure 3-64, so that they would not absorb water from the mortar, which is needed for setting properly.

Figure 3- 64 Immersion of bricks in water before laying the wall

Scratching and chiseling were done on the surface of the slab where the brick wall was going to be built by using a sharp metal rod. Water was sprayed onto the surface to make it wet so that new mortar would bond with the concrete surface. A thick layer of mortar about 1-inch was placed at the base of the round wall. The first brick layer was placed in a circle with the help of the lines marked with the marker. The brick wall was constructed from one direction only, either clockwise or anticlockwise. The face of the brick wall was maintained inside while constructing the wall. The row of bricks was positioned on their sides so that a 2.5" high, 6" wide base was made. It was essential that the first row be placed on a firm, untouched and leveled surface. The joint should be opposite in the next layer. So, 6 rows of bricks were placed for each reactor. While laying bricks, it was ensured that the space (joints) between them was filled with mortar and properly compacted. The thickness of the mortar joint was at least be 10 mm. It was also ensured that the mortar joints in two adjacent brick layers never fell in a vertical line. Figure 3-65 (a) and (b) shows the completed brick wall and laying brick in layers, respectively.

Figure 3- 65 Completed wall (a) and laying the brick in layers (b)

3.6.4.3 Plastering the wall and gas holder (inside and outside)

After the construction of the round-wall reached the correct height, the inside and outside surface of the wall was plastered with a smooth layer of cement mortar prepared by mortar mix and water of the desired consistency. The entire surface of the wall (inside and outside) of the reactor and inside surface of concrete gasholder was covered with a smooth layer of plaster. The surface for plastering was cleaned before starting the plastering work. After cleaning, scrubbing and scratching (chiseling) was done. The surface was wet by spraying water and 10 mm thick plastering was applied using with a plastering trowel. The following figure 3-66 shows the cement plaster work on the reactor wall.

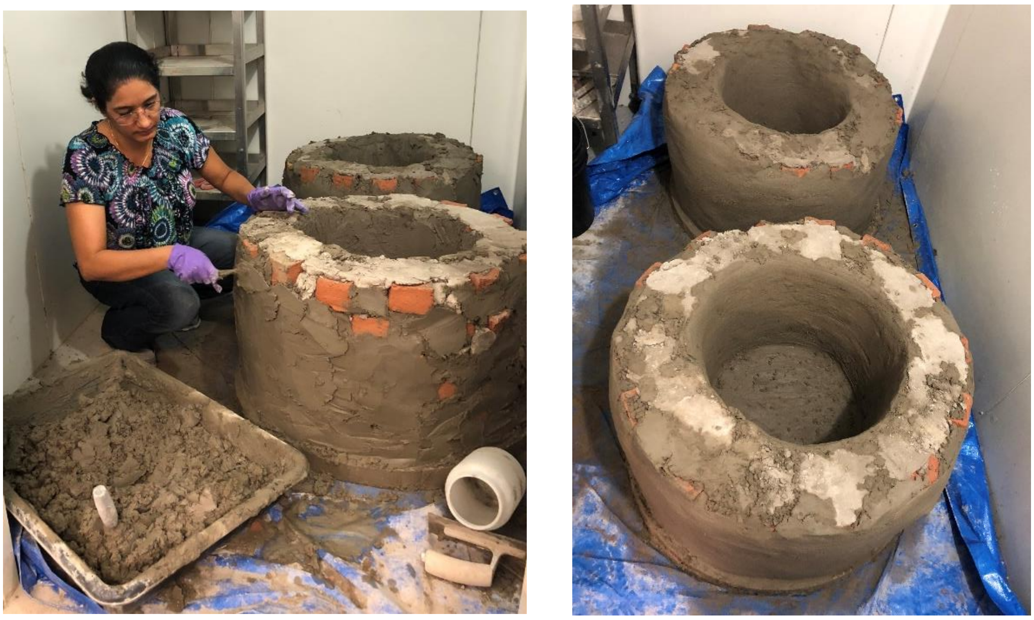


Figure 3- 66 Plaster work Inside and outside the reactor wall

The plaster was cured for 7 days by spraying water at least 2 times a day. A plaster coat was well set before applying the next layer.

3.6.4.4 Cement punning inside the reactor and gas holder

A store-bought Quikrete hydraulic water- stop cement was applied to the reactor inside to prevent leakage. This is a rapid setting, high-strength repair material designed to plug leaks instantly in concrete and masonry surfaces as well as to block running water. Quick setting cement can set in 3-5 minutes. The hydraulic water stop cement was mixed with the water to make a thick paste and applied on the top of the plastered surface inside the reactor using a paintbrush. Cement paste was applied 3-5 mm thick and also powder cement was sprayed on top of the wet surface to soak water and dry quickly. Figure 3-67 shows the water stop cement that used to prevent leakage from the reactor. Figure 3-68 shows the cement punning done inside the reactor using the water stop cement.

Figure 3- 67 Hydraulic water stop cement

Figure 3- 68 Cement punning inside the reactor.

The performance of the biogas digester is highly dependent on the gas tightness of the dome. One-inch thick plaster and 3-5 mm thick water stop cement punning was applied to the inside surface of the dome as shown in Figure 3-69, which helped to cover holes if any and prevent gas leakage from the gas holder.

Figure 3- 69 Plastering and cement flushing inside the dome.

3.6.4.5 Check for the water leak

Water tightness in the rector is also one of the most important factors for the performance of the reactor. If the water seeps away from the reactor, then there will not be enough water for the microorganisms to function properly. After 2 days of punning, both reactors were checked for water leaks. For this, the water was filled inside the reactors up to the height where the waste was expected to be filled. The water was kept inside for 4 hours and the system was checked for leaks. No water was found to be leaking from surroundings or from the bottom. The water surface level was not decreased at all, which means both reactors were watertight. Now it was all right to attach the gas holder on the top of the reactor. Figure 3-70 shows the leakage check on the reactors.

Figure 3- 70 Leakage check on the reactors

3.6.4.6 Deployment of temperature sensors inside the reactors

One of the goals of this study was to test the insulation capacity of the rice husk ash which was mixed with the soil while making the bricks. So, the temperature of the reactor inside and outside needed to be recorded. For recording temperature, temperature loggers were set and deployed inside the reactor. For each reactor 4 HOBO ONSET MX, 2201 temperature loggers were attached at four different places. Plastic hangers were attached on the inside wall by using the epoxy glue. The temperature loggers were tied with the plastic hanger by using zip ties. Two sensors were attached 3 inches above the bottom (opposite wall) and two were attached 9 inches above the bottom for both reactors. All 8 sensors recorded the temperature every 12 hours. Figure 3-71 shows the attachment of temperature sensors inside the reactor for continuous monitoring of temperature.

Figure 3- 71 Attachment of temperature sensors inside the reactors

3.6.4.7 Attachment of gasholder on top of wall

When the plaster and punning on the round wall of the digester was complete, the gas holder was then attached on the top of the reactor wall. The final diameter (after plaster and cement punning was completed) of the inside and outside wall was 30 and 15 inches, respectively. The outside diameter of the precast gas holder was 23 inches. The gas holder rested at around the center of the 6 inches thick round wall. A ½ inch galvanized iron Tee was connected with the ½ nipple (which was attached for gas outlet) inside so that the gas can enter from the two sides of the pipe to the outlet.

The top surface of the wall was cleaned and wet. Then 1-inch thick cement mortar was applied around the wall as shown in Figure 3-72. The precast gas holder (dome) was placed on the top of the brick masonry wall.

Figure 3- 72 Placing mortar on top of the wall

Thick mortar paste was applied at the joint and outside part of the wall as shown in Figure 3-73, so that no void space was left in between the reactor wall and gas holder. The gas holder should rest perfectly on top of the wall. Otherwise, there will be great chances of leaking gas during the reactor operation.

Figure 3- 73 Attached the gas holder with the circular reactor

3.6.4.8 Cement punning and flex seal paint on the outside part of the gas holder

For the effective functioning of the biogas digester, gas tightness of the gas-holder is very important. If the gas holder is not made perfectly gas-tight, the gas from the gas-holder escapes through the minute pores. For this, first, the surface of the gas holder was cleaned by scrubbing with an iron brush and water was sprayed to make the surface wet. Quick-setting cement was mixed with the water to make a thick paste. About 3-5 mm thick cement paste was applied on the top of gas holder using a paintbrush and let dry for few hours. Figure 3-74 shows the water stop cement paste applied on the gas holder.

Figure 3- 74 Water stop cement paste applied outside the gas holder

After the first coat of cement punning, a store-bought Flex Seal paint was sprayed over the surface thoroughly and let dry for a couple of days. Flex Seal is a liquid rubber coating spray that turns into a durable waterproof barrier; sprayed out as liquid, it seeps into cracks/holes and dries to a rubberized coating. Flex Seal seals out water, air, and moisture, preventing rust and corrosion. The paint was applied manually by spraying over the cemented surface thoroughly without leaving any space. This paint clogs the minute pores in the plastered surface.

After the application of this spray paint on the top of the gas holder, the room was kept open for proper air circulation, so the spray dried faster, and smells went away. Two coats of spray were applied. Since this spray seals out the air as well, the main reason for its application to the reactor is to prevent gas leakage from the gas holder. Figure 3-75 shows the Flex Seal paint applied to the outside surface of the gas holder.

(a) (b)

Figure 3- 75 Flex seal paint (a) Application of paint to the gas holder (b)

After the Flex Seal paint was completely dried, the second coat of the cement flushing (3-5 mm thick was done over it to make gas holder even more airtight. Figure 3-76 shows the second coat of cement flushing applied to the dome.

Figure 3- 76 Application of second coat of cement punning

3.6.4.9 Deployment of pressure sensors.

The monitoring of the gas pressure inside the reactor is very important. If the gas with high pressure occurred inside, that might damage the whole system. However, this is very rare case in the actual condition in rural communities. The peoples in a rural community use gas for cooking everyday meals. Accumulation of gas inside with significant high pressure will not take place. Because of the lack of availability of other energy sources, they never have enough biogas for their daily household usage.

Pressure, humidity and temperature sensors Kestrel Drop D3 were used to monitor the air pressure inside both reactors. These loggers were deployed through the inlet pipe. For each reactor, one pressure data logger was attached on the lid to a 2-inch diameter polyethylene pipe. The Kestrel drop was attached by nylon string and dropped in such a way that the logger would not touch the waste inside the reactor. It was dropped up to 5 inches down from the top of the pipe. The temperature and pressure logger continuously recorded the air pressure and temperature inside both reactors. Figure 3-77 shows the pressure sensor deployed through the inlet of the reactors.

Figure 3- 77 Deployment of pressure sensor through the inlet

3.6.4.10 Preparation of wooden box to keep the reactors

A wooden box was used to fill earth surrounding the reactor. In the rural communities of the low-income countries, the digester is buried under the ground. To simulate this, the reactors were kept inside the wooden box and the dirt was filed. Two wooden boxes of size 3 feet x 3 feet with height 2 feet were prepared by using ½ “thick plywood and nails as shown in Figure 3-78.

Figure 3- 78 Preparation of the plywood box to keep the reactor

The box was kept in such a way that there was some space left on each side to fill the dirt to provide the insulation for the reactors. The dry soil was filled surrounding the reactor wall. For proper insulation during the cold season, compacted earth or any other material is required to fill over the gas holder as well. For this study, the raw rice husk was filled above the gas holder to help insulate the reactor as shown in Figure 3-79. In an actual field, the backside of the round wall should be filled with properly compacted back-fill. If this is not done, the pressure of earth can lead to cracks in the round-wall.

Figure 3- 79 Earth filling outside the reactor

3.6.4.11 Soil moisture and temperature sensors

The Pro-check Decagon temperature and moisture sensors were inserted into the soil which was filled surrounding the reactor to monitor the temperature of the outer surface of the reactor wall. Four sensors were placed for each reactor at different heights. The sensors were placed in such a way that the inside temperature loggers and outside temperature sensor were located at the same level. The difference in temperature between the reactor’s wall outside and inside depends on the insulating capacity of the materials used to build the reactor. Figure 3-80 shows the soil moisture and temperature sensor.

Figure 3- 80 Temperature and soil moisture sensors (Pro Check Decagon)

3.6.5 Waste collection

For the current study, animal waste, specifically cow dung, was used as feedstock for both reactors. The waste collected from an outdoor loafing shed near Weatherford, Texas. The dung had been stored on-site in static piles for approximately one week prior to being collected for this study. Also, some fresh dung was mixed. The cow dung was collected on the same day that reactor operation was started. Peoples in rural communities use mainly animal waste for household level biogas plants. For this study, leftover food waste could have been used too, but food waste generates acid easily and the pH must be controlled by adding base solution. Opening reactors to add base will have chances of losing the gases that formed inside the reactors and introducing oxygen, which would affect the fermentation process inside the reactor. Also, in rural communities the leftover food, yard waste, etc. will be feed to the animals and animal dung will be used to feed the biogas reactor. Figure 3-81 shows the outdoor farm where the animal waste was collected.

Figure 3- 81 Cow dung collected from outdoor loafing shed

After the waste collected from the loafing shed, the tree leaves, small stem of trees and plant, soil lumps, stones if any were removed from the waste manually as shown in Figure 3-82.

Figure 3- 82 Removing the unwanted material from the waste.

3.6.6 Reactor Setup and Operation

The amount of required waste mass was weighed, and the calculated volume of tap water was added to make sure that the waste was near the saturation limit. For the current study, 12 kilograms of animal waste was used for each reactor. Figure 3-83 shows the weighing of the waste to feed the reactor.

Figure 3- 83 Weighting the required amount of waste

To ensure good microbial contact and faster start-up, the required amount of water was added to make waste to water ratio 90%. If the water is not sufficient, it will affect the acclimatization of micro-organisms to the waste composition in the reactor, which results in a longer lag period. According to Deublein and Steinhauser (2008), 75-90% of water is recommended with 10-25% dry matter.

About 10 liters of water was added to the waste to fill each reactor. Then the waste and water mixture was stirred manually by using a metal rod. The water and waste mix (slurry) was fed to the reactors through a 2-inch diameter inlet pipe which was installed on the side of the gas holder while building gas holder by using a funnel, as shown in Figure 3-84. The reactor was filled up to 15 inches from the inside bottom and the empty space of about 9 inches in the gas holder was reserved for gas headspace.

Figure 3- 84 Mixing and feeding waste to the reactor

The gas outlet was connected to the gas collection bag. The ½ “diameter nipple from the gas outlet was connected to the Tygon tube with ½ “elbow and ½ “ to ¾ “ reducer. All the fittings, Tygon tubes, two-way valves, and connections were leak checked before use. The transparent sealant was applied as necessary and dried for 6-8 hours. Figures 3-85 shows the fittings and Tygon tubes used for this experiment.

Figure 3- 85 Fittings and Tygon tubes

Six-layered aluminized gas sample collection bags with a storage volume of 22 L (Cali 5-Bond Bag, Calibrated Instruments, Inc.) were used to collect the biogas generated from the reactors. As shown in Figure 3-86, gas sampling bags were installed for each reactor to collect the gas produced from the reactors.

Figure 3- 86 Gas sample collection bag.

Both the reactors were operated in a temperature-controlled room. For about 10 days during the lag period, the reactors were left at room temperature at around 22 ^{0}c. After the methanogenic phase started, the reactors were operated at a fixed psychrophilic temperature (20^{0}C) to see how the insulation worked to maintain the temperature inside the reactors.

3.6.7 Temperature and Pressure Measurement

The inside temperature of the reactor was measured by using Hobo temperature loggers which were attached to the reactor wall. The loggers were set to record the temperature every 12 hours. The loggers continuously monitored and recorded the data. The Hobo apps were used to extract the data. Figure 3-87 shows the graph export form the Hobo software.

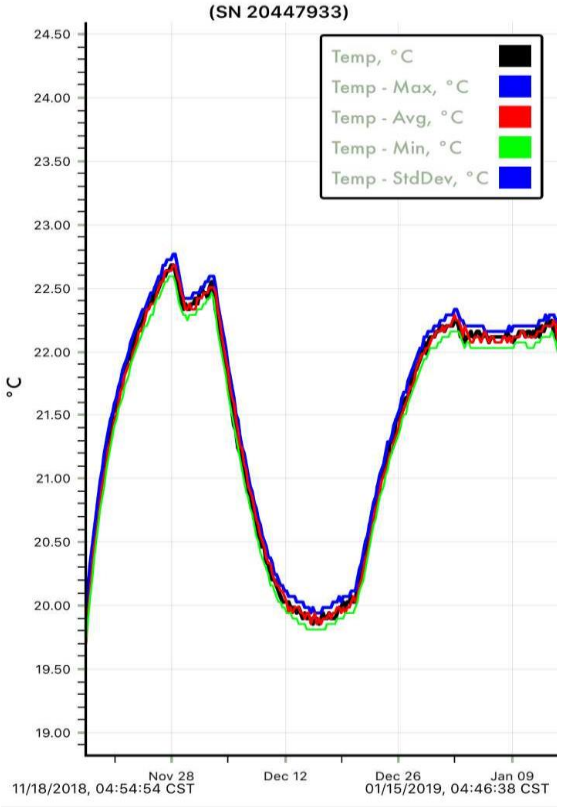
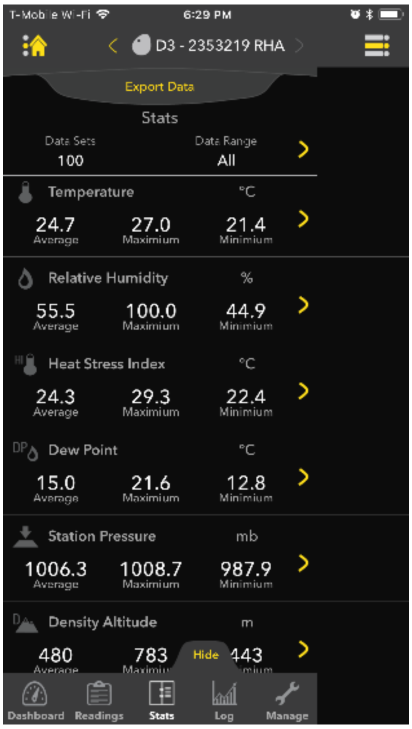


Figure 3- 87 Graph from the temperature logger.

The temperature of the outside wall was measured regularly by using the Pro-check Decagon temperature and moisture sensors. Figure 3-88 shows the monitoring of the temperature. Data from the four sensors were averaged.

Figure 3- 88 Measuring the soil temperature outside the reactor wall.

The pressure of the gas inside the reactors was monitored by using the Kestrel drop. The pressure logger continually records the data. The Kestrel app was used to extract the data from the logger as shown in Figure 3-89. The temperature and pressure were monitored throughout the reactor operation.



Data Sets: 100
Data Range: All

	Unit	Average	Maximium	Minimium
Temperature	°C	24.7	27.0	21.4
Relative Humidity	%	55.5	100.0	44.9
Heat Stress Index	°C	24.3	29.3	22.4
Dew Point	°C	15.0	21.6	12.8
Station Pressure	mb	1006.3	1008.7	987.9
Density Altitude	m	480	783	443

Figure 3- 89 Data obtained in Kestrel apps

3.6.8 Gas composition and volume measurement

Gas generated from each reactor was collected in a gas bag and measured on a regular basis. The composition of biogas produced (% methane, (CH_4), % carbon dioxide (CO_2), % oxygen (O_2), and percentage of other gasses) was measured by using LANDTEC GEM 5000 (with infrared gas analyzer), as shown in Figure 3-90.

13:25 - 01/22/19 Baro: 29.20 "Hg

Channel	Adjusted	Initial	Previous	Units
CH_4		58.7	0.0	%
CO_2		39.9	0.1	%
O_2		0.5	20.5	%
H_2S		0	0	ppm
CO		2	1	ppm
Bal		1.0	79.4	%
Static P			-0.01	"H_2O
Diff P			0.006	"H_2O
Temp.			0.0	°F
Flow			0.0	SCFM
Power			0.0	e3BTU/h

Figure 3- 90 Gas composition measurement instrument Landtec GEM 5000

The amount of gas production was measured by pumping gas out of the collection bag through a standard SKC 44*R Universal Sample Pump connected to a Calibrator (Mesa Labs Bios Defender, flow instrument), to obtain a minute by minute gas pumping rate. A stopwatch was used to measure the time of gas flow. Figure 3-91 shows the gas composition and volume measuring instruments.

Figure 3- 91 Volume measurement instruments, Calibrator & SKC Sampler

3.7 Microbial Analysis

Microbial analysis was conducted on six samples, two from each reactor (insulated and non-insulated) and two fresh samples. Samples from each reactor and fresh samples were duplicates. Samples were stored at -20 ^{0}C, thawed, and then homogenized prior to DNA extraction. The Life Sciences Core Facility at the University of Texas at Arlington performed the microbial analysis. Metagenomics 16srRNA PCR analysis was done on the samples to find out the presence of different microbial communities in each reactor during anaerobic treatment of animal waste.

The DNA extraction was done using DNeasy PowerSoil Kit CatNo. Cat No./ID: 12888-50. This kit is mainly used for the samples containing high humic acid such as compost, sediment, and manure. Sample was liquefied with the addition of 2 m sterile water, and vortexed with 2 BBs (BBs are used to help disrupt the samples). The power bead tube contains the buffer that will help to disburse the soil particles, begin to dissolve and protect nucleic acid from degradation. Gentle vortexing mixes the components with power bead tube and begins to disperse the samples in buffer. 250 µl of homogenized sample supernatant was harvested and DNA extraction performed as outlined in the DNeasy PowerSoil Kit protocol with the exception that following heating, the samples were disrupted with a Tissuelyser II (30 seconds at 30 hz) instead of using the Vortex adapter, and silica column loading and washing was performed using the vacuum manifold protocol adaptation. Final homogenate was captured on a single silica column and eluted with 50 µl of solution C6.

Nano Drop spectrophotometer was used to measure the DNA concentration after extracting the DNA. All samples were spectrophotometrically quantified with 260/280 ratio. The DNA amplification by Polymerase Chain Reaction (PCR) quantitation was done using Applied Biosystems Veriti thermocycler. PCR can amplify few copies or even Nano levels of nucleic acid (DNA) in a sample to several orders of magnitude and it can produce millions copies of DNA. Figure shows 3-92 shows the thermocycler used for PCR.

Figure 3- 92 Biosystems Veriti thermocycler

Six forward primers (515F) and six reverse primers (806R) were used for PCR. The Agarose gel which contains ethidium bromide (EtBr) buffer during electrophoresis. The 1kb Promega DNA ladder was used to compare the size of DNA after gel electrophoresis. Next gen 300PE (300 bp paired end) amplicon sequencing was performed using sequencing reaction kit.

3.8 Life cycle Analysis

3.8.1 Economic Analysis

For economic analysis, building cost was calculated using the present worth method. The cost of materials, labor, and transportation was calculated based on a data available in a developing country, Nepal. The reactor size for this analysis was taken as 6 cubic meters, which is the more general size of household biogas plants for a medium size family with at least two farm animals. The cost of locally-available insulating materials, preparation of bricks as well as other reactor materials collection were included in the economic analysis. The capital cost, overhead cost, and maintenance cost and any subsidy provided by the government of Nepal was also included in the economic analysis of cold resistant design and was compared with the conventional reactor design for the same size of the biogas system installed in the same location. The location of the reactor is taken in the mountain region of elevation more than 1600 m from the mean sea level. According to the Alternative Energy Promotion Center Nepal (AEPC, 2018), around 0.3 million biogas plants have been already installed all around Nepal via a common initiative of the Government of Nepal, development partners and partner agencies. Figure 3-93 and 3-94 show components of fixed dome biogas plants and sections and dimensions of the plant components, respectively.

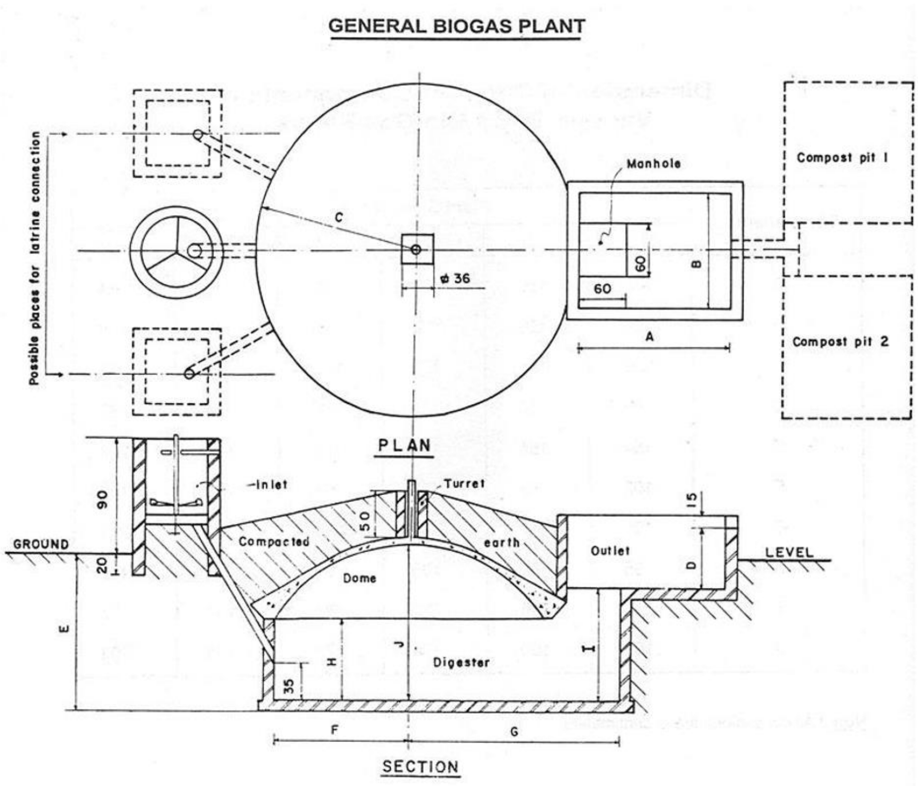
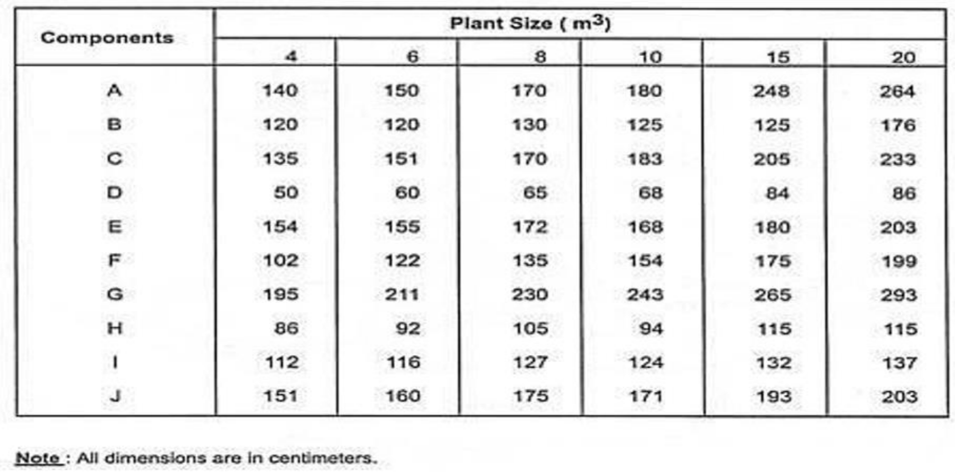


Figure 3- 93 General biogas plants plan and section



Components	Plant Size (m³)					
	4	6	8	10	15	20
A	140	150	170	180	248	264
B	120	120	130	125	125	176
C	135	151	170	183	205	233
D	50	60	65	68	84	86
E	154	155	172	168	180	203
F	102	122	135	154	175	199
G	195	211	230	243	265	293
H	86	92	105	94	115	115
I	112	116	127	124	132	137
J	151	160	175	171	193	203

Note : All dimensions are in centimeters.

Figure 3- 94 Components sizes (dimensions)

3.8.2 Cost of the biogas plant

For the current economic analysis, a 6 cubic meter size of the biogas plant installed in mountain districts of Nepal is considered. Table 3-2 shows the detailed cost estimate of the conventional and cold resistant biogas system. The required materials, appliances needed skilled, and unskilled labor and financial value was taken from Nepal Biogas Promotion Association (NBPA) approved domestic biogas quotation for fiscal year 2018-2019. The rate is derived from the actual quotes for the mountain region. The maintenance cost of the system is considered as 1% of the capital cost. The local price of rice husk was obtained as per interviews with the local rice mill owner and local women group members. The required materials, and appliances needed skilled and unskilled labor, etc. for building 6 cubic meter capacity biogas system in the mountain district of Nepal was taken from the biogas support programme (BSP), Nepal Alternative Energy Promotion Center (AEPC) Nepal, Government of Nepal Norms, bBiogas construction manuals related research and articles, etc . Financial value was taken from Nepal Biogas Promotion Association (NBPA) approved domestic biogas quotation for fiscal year 2018-2019. The rate is derived from the actual quotes for the mountain region. The maintenance cost of the system is considered as 1% of the capital cost. The local price of rice husk was obtained as per interviews with the local rRice mill owner and local women group members.

Table 3- 2 Cost estimate of 6 m^3 biogas plant (Conventional and Cold-resistant)

SN	Item	Unit	Quantity	Unit Rate in NRS.	Conventional	Cold Resistant
A	***Construction Materials***				**59,750**	**56,950**
1	Stones/Bricks	Pc	1400	18	25,200	
2	RHA mixed clay brick (80% Clay+ 20 % RHA) (including buying rice husk, RHA preparation etc)	Pc	1400	16		22,400
3	Sand	bag	70	180	12,600	12,600
4	Gravel 1x2	bag	35	160	5600	5600
5	Iron rod	kg	15	110	1650	1650
6	Cement (Brick Masonary)	bag	14	1050	14,700	14,700
B	***Unskilled Labour***	Day	30	1200	**36000**	**36000**
C	***Multilayer pipe and fittings***				**3012**	**3012**
1	GI nipple, ½ " Ø for connecting main gas pipe and main gas valve (6" or 15 cm long	Pc	1	99	99	99
2	½ " Ø GI pipe (20" or 50 cm long)	Pc	1	198	198	198
3	½ " Ø GI Elbow	Pc	2	77	154	154
4	½ " Ø 1216_yellow color (C1216(max length)	Meter	12	121	1452	1452
5	½ " Ø Male Straight Union (Brass)	Pc	1	151	151	151
6	½ " Ø Female Tee (F5-T1216*1/2 F1215 IIA	Pc	1	330	330	330
7	½ " Ø GI Tee	Pc	1	99	99	99
9	½ " Ø Four way Tee (Cross Tee)	Pc	0	193	0	0
10	½ " Ø GI Nipple(2" or 5 cm Loong)	Pc	1	44	44	44
11	Teflon Tape	Pc	1	23	23	23
12	½ " Ø Female Elbow L1216x1/2F)	Pc	1	231	231	231
13	½ " Ø Wall Plated Female Elbow (WPL1216x1/2F)	Pc	1	231	231	231
2	**Appliances and Accessories**				**11,384**	**11,384**
1	Mixture	Set	1	3084	3084	3084
2	Inlet pipe	Meter	4	303	1212	1212
3	Emulsion paint	Liter	1	374	374	374
4	Dome Gas pipe	Pc	1	1727	1727	1727
5	Main Gas Valve	Pc	1	762	762	762
6	Water drain	Pc	1	395	395	395
7	Gas Tap (For stove and pressure meter	Pc	2	702	1404	1404
8	Nylon hose pipe(For stove and pressure Meter)	Meter	2	58	116	116
9	Pressure Meter	Pc	1	631	631	631
10	Stove (Angel frame or CI frame)	Pc	1	1679	1679	1679
3	**Other Direct Cost**				**13,020**	**13,020**
	Skilled labor				7500	7500
	Fees and charges, Sales and quality assurance documentation, Warranty etc.				5520	5520
	Total Capital cost for a plant with multilayer fittings				**123,166**	**120,366**
4	**Maintenance (1% of the total capital cost)**				**1232**	**1204**
	Grand Total Nepalese Rupees				**124,398**	**121,570**
	Grand Total US Dollars				**1131**	**1105**
5	Subsidy per plant per household for domestic biogas plant, in mountain district				**35,000**	**35,000**
	Total cost after the government subsidy				**89,398**	**86,570**
	Total Cost (after Subsidy) US Dollar @ $1 =110 Nepalese Rupees)				**813**	**787**

The comparison of the RHA mixed brick with the traditional soil brick considered the costs of materials purchase, burning (husk to make rice husk charcoal) and transportation. Since RHA + Soil mixed brick is 12% lighter than the soil (only) brick, there is saving (approximately 12%) associated with the transportation of the RHA bricks. Moreover, the density of soil is more than 6 times higher than the RHA, thereby savings on the transportation of raw rice husk as well. The rice husk can be obtained free to very minimal cost (about 5 rupees per kilogram) from the local rice mills. So considering all costs, RHA mixed brick is cheaper than the conventional brick for building the reactors. The capital cost of the 6 m^3 biogas plant (traditional and cold resistant) in the mountainous region of Nepal is Nrs. 124,398 (USD 1131) and 121,570 (USD 1105), respectively.The government subsidy of Nrs 35,000 per plant per household is provided by the government of Nepal for domestic biogas plant of 6 m^3 or above for mountainous region. Additional 10% subsidy is provided to targeted beneficiary groups. “Targeted beneficiary groups” refers to “women-led households with dependent children, earthquake victims from earthquake-affected districts, endangered indigenous community identified by Government of Nepal and Dalit” (Government of Nepal, 2016). After the government subsidy, the total cost of the biogas plant is Nrs. 89,398 (US $ 813) and 86,570 (US$ 787), respectively, for conventional and cold resistant digester.

3.8.3 Benefits of biogas plants in rural areas

There are several benefits of the biogas plant in the rural areas of developing countries which are explained below. For the current economic analysis, the four major forms of the benefit are used.

3.8.3.1 Gender Benefit of Biogas

The installation of household-level biogas systems in the mountainous areas of low-income countries has provided a direct benefit to the women and young girls by reducing the labor required to collect fuelwood, as well as reducing the danger to personal safety. Less fuelwood has to be collected, which results in saved labor. Studies have reported that using biogas, rural women have been able to save 3 hours per day. Using biogas reduced the time used for collecting fuelwood, chopping it into smaller sizes, and cooking meals. When burning biogas, no soot particles deposit on the surfaces of utensils, which requires less cleaning time and less water consumption. However, for the biogas plant, additional time is needed for fetching water and mixing dung with water. So overall 180 minutes of time is saved per day per plant. The unskilled labor cost (400 per day) was determined based on the interview with local community member of Gorkha district, Nepal. Table 3-3 shows the financial benefit of saving women hours by using the biogas.

Table 3- 3 Value of time saved using biogas plant.

Items	Amount	Source
Time saved per household/day	3 hrs	BSP-Nepal, 2005
Approximately total time saved per plant per year	3*365 = 1095 Woman hours per year	BSP-Nepal, 2005
Approximate total savings	1095 hrs *Nrs. 400 per day/8 hrs per day = Nrs 54,750 per year	Gautam et al., 2007 Interview with locals
With 1 US$ = @ NRs 110, the total savings	$ 497 per year	As per current exchange rate

3.8.3.2 Reduction in Firewood Consumption

The installation of biogas plants has helped protect forests. Using the 6 cubic meter capacity biogas plant can save 3 tons of fuelwood per plant per year. Since there are different sizes of biogas plants, it can be assumed that an average 2 tons of fuelwood is saved annually. This means that there is a nationwide savings of more than 600,000 tons of fuelwood per annum. Table 3-4 shows the financial benefit of fuelwood savings for a 6 m^3 biogas system.

Table 3- 4 Financial benefits from fuelwood savings

Particulars	Average	Source
Total annual saving Fuelwood (tons/HH/year)	3.00	BSP-Nepal, 2005 Gautam et al., 2007
Cost of fuelwood (NRs) per ton	6000	Interview with local community members
Annual financial saving	NRS 18,000	
With 1 US$ = @ NRs 110, the total savings	$163	

3.8.3.3 Benefit from the reduced use of kerosene

Kerosene is widely used in rural communities of Nepal for cooking and lighting. Due to the installation of biogas plants, the use of kerosene has been reduced by almost 20.8 million liters per annum in Nepal nationally, which decreases expenditures as well as increases safety for the households. The petroleum product is imported using hard earned foreign currency. The actual price of kerosene in Nepal varies considerably from cities to mountainous areas. As per the current 2018/2019 rate of the kerosene in Nepalese rupees is 95 per liter in the city and approximately 135 rupees per liter in mountainous areas. So, the reduced use of kerosene due to 300,000 biogas plants, has saved approximately NRs. 1980 million (US$ 18 million) per annum as per the current foreign exchange rate.

The estimated annual savings per plant associated with expenditures for kerosene are presented in Table 3-5.

Table 3- 5 Financial benefits of reduced use of kerosene

Items	Amount	Sources
Kerosene saving (liters per HH per day)	0.19	East Consult, 2004
Total annual Saving (Liters / plant / year)	69.35	
Unit rate of the Kerosene (NRs/Liter)	135	List Nepal .com /petrol prices
Total annual financial saving (NRs/plant)	9362	
With 1 US$ = @ NRs 110, the total savings	$85	

3.8.3.4 Reduced use of chemical Fertilizers

Reduced use of chemical fertilizers Since people in the rural households depend on agriculture, they began to use more chemical fertilizers to grow crops. After the introduction of biogas, the high nutrient content bio-slurry reduced the need for chemical fertilizers. The use of chemical fertilizers in the rural communities declines when farmers have a biogas system. According to the East Consult (2004), an average annual savings of 39 kg nitrogen, 19 kg phosphorous and 39 kg potash was estimated per household (HH) using slurry as manure in the farms.

According the World Bank Implementation and Completion report (2012), a 6 m^3 biogas plant produces enough biofertilizer to reduce urea consumption approximately 56 kg. The cost of urea is varies widely due to different transportation costs. The cost of urea in the mountainous areas is highly dependent on the local transportation cost. The average cost of chemical fertilizer (urea) is Nrs. 25 per kg in the hill district (Panta, 2018).

Including the local transportation, the price of urea is $38 per kg in the mountainous area. Table 3-6 shows the estimated annual savings due to the reduced use of chemical fertilizer.

Table 3- 6 Financial benefits of reduced use of chemical fertilizer

Items	Amount	Source
Chemical fertilizer avoided, kg/plant /year	56.35	BSP Nepal, 2005; Gautam et al., 2007
Cost of urea/ kg	38	Panta, 2018
Approximate total savings	2141.3	
US Dollars @ $1=110 NRS	19	

3.8.3.5 Reduced use of agricultural residues

After the installation of a biogas plant, there is a significant reduction of use of agricultural residues used as cooking fuel. Studies have found that the average estimated decrease in the use of agricultural residue is about 2.7 kg per HH per day per biogas system. The main economic benefit from the reduction is the organic value these residues have, which can be ploughed back into the soil. The benefit from this is difficult to quantify in dollars or rupees, however, and thus will not be included in this analysis.

3.8.3.6 Reduced use of dung

Before the installation of a biogas plant, dung was dried and dung cakes were used as household fuel for cooking and heating. So, similar changes have been observed in the use of dung cakes as agricultural residues. In a biogas system, dung is used as feedstock for the reactor. The average reduction of dried dung is about 0.7 kg per HH per day per system (BSP-N, 2005). The reduced use of dried dung leads to a reduction in the burning of dung cake for production of gas and the conversion of dung cake into bio-slurry, which ultimately preserves the forest resources and restores organic matter to the soil and improves the soil condition and agricultural output. These impacts are difficult to quantify financially, however, and thus will not be included in the economic analysis.

3.8.3.7 Environmental Benefits

At the local level, biogas helps to improve the indoor quality by employing- biogas stoves in place of traditional wood stoves, which reduces the health impact related to indoor air pollution. Also, installation of toilets attached to biogas systems helps to improve the sanitary condition of rural homes due to the better management and disposal of human waste (night soil), as well as animal waste.

At the national level, biogas systems help to reduce deforestation and soil erosion. Using composted slurry as a soil amendment improves the fertility of the land, which reduces the pressure to expand the agricultural land by clearing the forest, the main cause of deforestation in low-income countries.

Nepal is one of the countries in Asia which produces rice as the main crop. Using rice husk to make bricks for building reactors helps to utilize this agricultural by-product, which instead is dumped to the land and deteriorates the soil properties. Moreover, using rice husk as an insulation for the reactor helps to reduce the use of other sources of energy to increase the temperature of the slurry inside the reactor. For building a 6 m^3 biogas plant, 168 kilograms of rice husk can be utilized.

As a mentioned above, the national average annual reduction of fuelwood per HH is 2 tons. According to the IUCN (1995), it is assumed that 32.7 metric tons of fuelwood is harvested per hectare per year (Dutta et al., 1997). About 1350 fully grown trees can be grown in one hectare. For this study, the comparison is made for a 6 m^3 biogas system. So, a 6 m^3 biogas unit can save 3 tons of fuelwood, 0.09 hectares forest area, which is equivalent to saving 124 fully grown trees.

The household biogas helps to reduce greenhouse gas emissions by displacing the consumption of fuelwood. Each biogas plants of size 6 m^3 mitigates about 4 tons of carbon dioxide equivalent per year in rural areas (Shrestha et al., 2003). In a national average (Nepal), the available carbon reduction per year per system from the displacement of fuelwood, agricultural wastes, dung cakes, and kerosene is nearly 4.6 tons of carbon equivalent. So nationwide total greenhouse gas reduction from 0.3 million plants is 1.38 million tons CO_2 equivalents annually.

The financial value of environmental benefits, however, is difficult to quantify and will not be included in the economic analysis.

3.8.3.8 Summary of benefits

Table 3-7 summarizes the benefits of biogas plants.

Table 3- 7 Summary of benefits

Particulars	**Saving per 6 m^3 system**	**Total average annual saving (300,000 units)**	**Remarks**	**Source**
Fuelwood (tons / year)	3.0 2 (average)	600,000	Since all plants are not 6 m^3, and not in the same region, Average saving is 2 tons per plant	BSP-Nepal, (2005), Gautam et al. (2007)
Kerosene (liters /year)	69.4	20,805,000		East Consult (2004)
Wo(men) time (hour)	1095.0	328,500,000		BSP-Nepal (2005)
Bio-fertilizer produced (tons /year)	1.7	510,000	Replaces chemical fertilizer	BSP-Nepal (2004); Panta (2018)
Reduced use of dung (Kg/year)	255.0	76,500,000	0.7 kg/day/system	East Consult (2004)
Reduced use of agriculture residue	985.5	295,650,000	2.7 kg/system/day	East Consult (2004)
Equivalent forest area protection (Ha)	0.060	18,000		Dutta et al. (1997)
Number of trees saved	124	24,768,000	1 Ha grows 1,350 fully grown trees*	Dutta et al. (1997)
Rice husk utilization (kg)	168.0	50,400,000		
Carbon dioxide equivalent saving (tons)	4.0	1,380,000	Average emission is 4.6 tons CO_2-e/year	Shrestha et al. (2003)

3.8.3.9 Cost-benefit analysis and internal rate of return (IRR)

For the current study, the biogas of 6 m^3 capacity in the mountain region of developing country Nepal is considered for the cost-benefit analysis. The service life of the biogas plant was assumed to be 20 years (BSP-Nepal, 2005). All the capital cost was assumed to be expended in the first year. The annual operation and maintenance costs and all the benefit were assumed to be constant over the 20 years of life span. Economic factors or shadow values are taken from the related articles, researches and tariff rate published by the Department of Customs, Government of Nepal. Economic analysis is concerned with the true value a project holds for the society as a whole. The economic analysis of both representative 6 m^3 biogas system was undertaken to assess the benefits to society of the use of biogas system, which compares the benefits and costs to the whole economy. In contrast, financial analysis compares benefits and direct costs to the enterprise, uses market prices to check the balance of investment and the sustainability of a project. In other words, the economic analysis compares direct as well as indirect costs and benefits from the social point of view, whereas financial analysis compares the direct costs and benefits from the investors' point of view. For the current study, the financial values are converted to economic values by using the economic factor or shadow value.

All costs and benefits have been assessed at values prevailing at the time of current study. For the benefit-cost analysis, an interest rate 18 % was assumed, which is the current general rate provided from the bank to the consumers in Nepal. For the cost-benefit analysis and rate of return analysis, four major form of benefits (which can be converted to monetory value) were considered, including firewood, cooking time savings, savings in use of chemical fertilizers and reduced use of kerosene. Since the cost of buying firewood is included, the time saving related to the firewood collection is not included. The other benefits which cannot be converted to the monetory values such as carbon dioxide equivalent saving ,forest area protection, numbers of tree saved, reduced use of agriculture residue are not included for calculating benefit-cost ratio and IRR. In mountainous areas it is assumed that for about 6 months (180 days), the temperatures fall below the 20 ^{0}C. During that time (50% of the year), it was assumed that cold resistant reactor produced 30 % more biogas than the conventional reactor.

Table 3-8 shows the costs and benefits (financial and economic) of the 6 m^3 biogas system in mountain district of Nepal.

Table 3- 8 Cost-benefit breakdown of 6 m^3 biogas system in mountain district of Nepal (Nepalese rupees)

Cost/ benefit Break down	**Financial Value**		**Economic Factor or Shadow value**	**Economic Value**		**Source**
	Conventional Digester	**Cold resistant Digester**		**Conventional Digester**	**Cold resistant Digester**	
Cement (Brick Masonry)	14,700	14,700	0.7	10,290	10,290	World Bank / BSP Nepal (2012)
Materials	45,050	42,250	0.9	40,545	38,025	World Bank / BSP Nepal (2012)
Unskilled Labor	36,000	36,000	0.8	27,000	27,000	AEPC (2018)
Skilled Labor	7500	7500	0.8	6000	6000	World Bank / BSP Nepal (2012)
Appliances	14,396	14,396	0.9	12,956	12,956	World Bank / BSP Nepal (2012)
Fees and charges	5520	5520	1.0	5520	5520	World Bank / BSP Nepal (2012)
Maintenance	1232	1204	0.8	924	903	AEPC (2018)
Total Capital Costs (Nepalese rupees)	**124,398**	**121,570**		**103,235**	**100,694**	
Capital Costs After Subsidy	**88,398**	**85,570**		**67,235**	**64,694**	
Benefit						
Reduced use of kerosene (RHA reactor produce 30% more gas about 50 % of the time)	9362	10,766.3	1	9362	10,766.3	BSP-Nepal (2005)
Reduced use of fuelwood (RHA reactor produce 30% more gas about 50 % of the time)	18,000	20,700	1	18000	20,700	World Bank / BSP Nepal (2012)
Time saved using biogas	26,158	26158	0.75	19618.5	19,618.5	BSP-Nepal (2005)
Chemical fertilizers avoided	2,141.3	2462.5	0.7	1498.9	1723.7	World Bank / BSP Nepal (2012)
Total Annual benefits	**55,661.3**	**60,086.8**		**48479.4**	**52,808.5**	

Cost-benefit Ratio is calculated by using the present worth method and using the following equations 3-16 and 3-17:

$$\text{Cost-benefit ratio} = \frac{Present\ worth\ of\ Benefit}{Present\ worth\ of\ the\ Cost} \qquad 3\text{-}16$$

$$= \frac{(\ Annual\ Benefit)*\frac{p}{A}(i,n)-(Annual\ mainatainance)*\frac{P}{A}(i,n)}{Total\ Capital\ Cost} \qquad 3\text{-}17$$

The summary table of benefit-cost ratio and internal rate of return (IRR) is presented below in Table 3-9. The benefit-cost ratio and internal rate of return are calculated using both financial as well as economic values. For both cases, the benefit-cost ratio of cold resistant digester is slightly greater than the conventional digester. Similarly, the internal rate of return (IRR), which is defined as the interest rate when present worth of cost is equal to the present worth of benefit, is also calculated. For IRR the return period is considered for 20 years. The calculated internal rate of return is 6% and 9% greater for the cold resistant digester then the conventional digester using financial and economic values, respectively. However, both digesters have high rates of return, between 62% and 80%. Benefit-cost ratio is greater than one for both designs using financial as well as economic values.

Table 3- 9 Summary of B/C and IRR

Benefit-cost ratio and internal rate of return	Financial (Rupees)		Economic (Rupees)	
	Conventional Digester	Cold resistant	Conventional Digester	Cold resistant
Net Annual Benefit	54,430	58883	47,556	51906
Present Worth of benefit	291,346	315184	254,551	277836
Total Capital Costs	88,398	85570	67,235	64694
Benefit cost ratio	3.30	3.68	3.8	4.3
Rate of return (IRR) 20 year	62%	69%	71%	80%

3.8.4 Environmental Analysis

For this study, the life cycle analysis of the materials used for the cold resistant reactor design and conventional reactor design were analyzed and compared using life cycle analysis software SimaPro.

3.8.4.1 Life cycle Assessment.

A life-cycle assessment (LCA) is a concept and methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the whole life cycle of a product, process, or activity (U.S. EPA, 1993). An LCA is a comprehensive method for assessing a range environmental impacts associated with all the stages of a product's life “cradle-to-grave,” from raw material acquisition through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Figure 3-95 shows the all stages of products life cycle. Figure 3-96 shows the life cycle assessment framework.

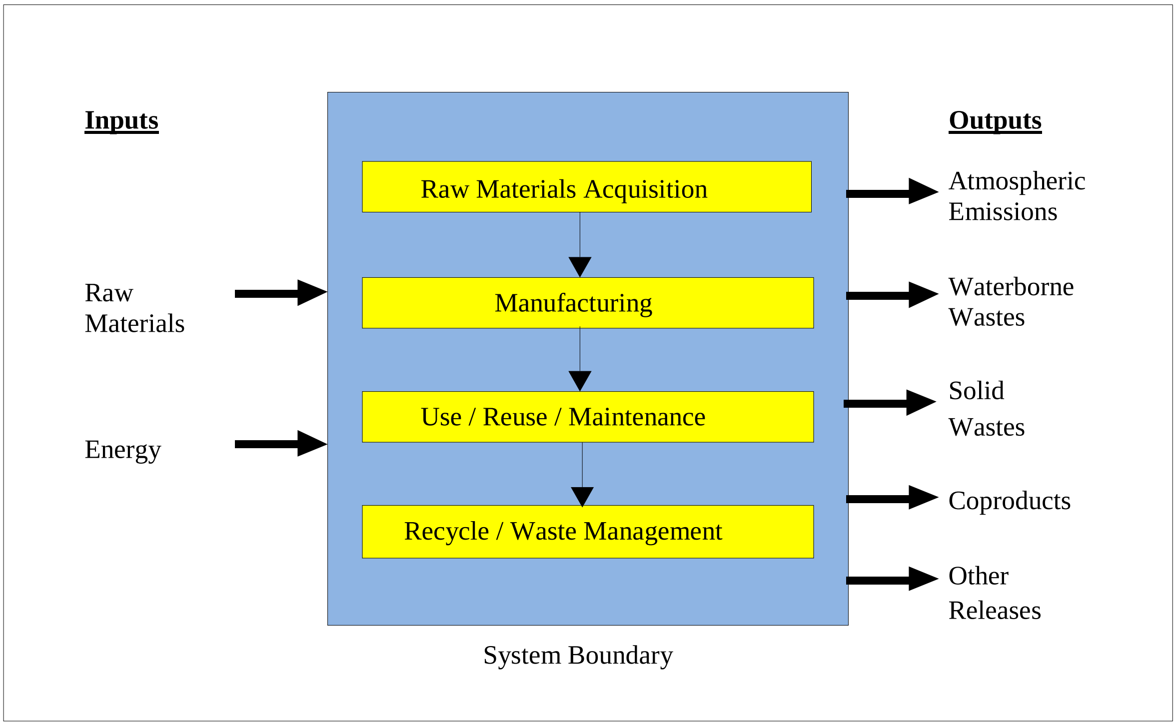


Figure 3- 95 Life Cycle Stages (Source: EPA, 1993)

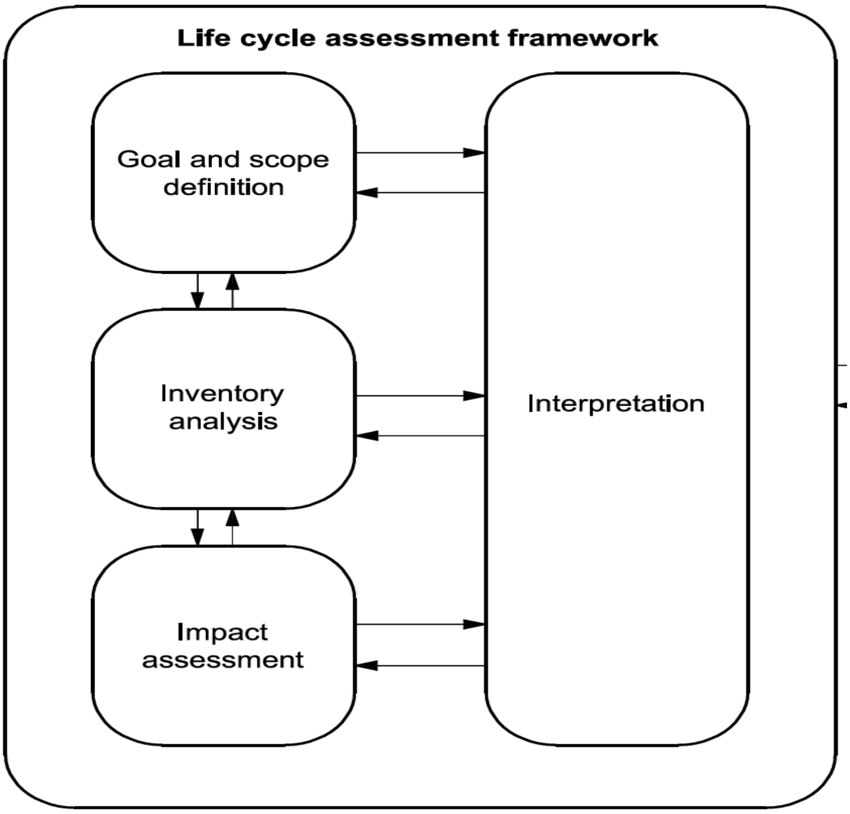


Figure 3- 96 LCA Framework (ISO 14040, 2006)

The LCA is used for:

- Identifying opportunities to improve environmental performance of the product at various points in their life cycle
- Informing the decision -makers in industry, governmental or non-governmental organizations (e.g. strategic planning, priority setting, product or process design or redesign)
- Marketing (e.g. environmental claims, eco-labeling, or environmental product declarations).

For the current study, the life cycle impact assessment (LCIA) calculation of the materials used to build the reactors was made using Life Cycle Assessment (LCA) software, SimaPro version 8.5.2.0, IMPACT 2002+ method. The following key database libraries within SimaPro were applied for this LCA study.

- Agri-footprint version 2.0,
- European Life Cycle Database (ELCD) version 3.1,
- The EU27 and DK input-output (IO) database,
- The U.S. Life Cycle Inventory (USLCI) (the data protocol is based on ISO 14048).

3.8.4.2 Goal and scope of the project

The aim of this study is to evaluate the environmental impacts of the cold resistance biogas digester and the conventional digester using the mid-point and endpoint approaches in LCA methodology.

System boundaries

The careful selection of system boundaries has a big impact on LCA (Lundin et al., 2000). In this study, four reactor building materials were used for analysis. The system boundaries include the raw material acquisition such as soil and rice husk, and manufacturing/construction (making brick, building reactor) phases. Maintenance during the use phase of the reactor is not included because there is very minimal maintenance required for the fixed dome digesters, which are buried underground. Only gas tightness and replacement of gas pipe might be required, which does not have much environmental impact. Reuse/landfilling is not applicable for the scenario in rural communities of low-income countries and thus is not included.

The spatial boundaries for the current study is assumed to be 30 kilometers, based on the distance that materials need to be transported to build the reactors.

3.8.4.3 Inventory

The data to input into the SimaPro software were obtained from the Nepal Biogas Promotion Association, Government of Nepal (approved biogas quote of 2018/2019). The mass of materials such as cement, steel, and soil required for building a 6 m^3 biogas system in the mountainous region of Nepal were taken directly from the quotation. The rice husk mass was calculated based on RHA mixed brick used for the current study. Four major materials categories, including cement, steel, soil and rice husk, were taken into consideration in the product assembly phase. The water used for the process is generally not treated in the water treatment plant. So, the water and other minor consumable materials such as office supplies, aggregate, tools, and fittings, were neglected.

The material category input for the cement, steel and rice husk was market data, which includes transportation. The input for the soil was the transformation data category. Transformation data does not include transportation. The transportation from the material available location to the consumers was not considered separately for cement, steel and rice husk, since a reasonable assumption for the transportation was already made in SimaPro by using market data. The soil for making bricks is assumed to be locally available within a 30 km distance. Brick is generally manufactured locally. Since there are about 3 tons of soil required, the transportation of the material was rounded off at 100-ton kilometers (tkms).

Table 3-10 shows the reactor material, energy, and transportation SimaPro categories. Since the current study is particularly focused on remote areas of developing countries, categories in SimaPro were selected as {GLO} global and {RoW} rest of the world (as opposed to US or European Union). Allocation default categories were chosen. An equal amount of rice husk is included for both reactor types (cold resistant and conventional). Whether it is used for making brick or not, rice husk is produced as a by-product during the crop production in the developing countries. If rice husk from the rice milling is not used for making bricks, it is usually open burned and disposed of in an open area. In the Sima-pro material categories and processes, however, open burning of rice husk is not provided as an option, so this could not be included in the environmental analysis.

Moreover, less soil is used for cold -resistant reactor than the conventional reactor because it contains 20% rice husk ash (by volume). So cold resistant reactor requires less energy for burning brick than the conventional reactor. Energy input for the burning of bricks is described in more detail in a later section.

Table 3- 10 Reactor material, energy, and transportation SimaPro categories

Reactor building Material/Energy/ Transportation	**SimaPro Material Category**	**Unit**	**Cold Resistant Reactor**	**Conventional Reactor**
Steel	Steel, unalloyed {GLO}| market for | Alloc Def, U	kg	15	15
Rice Husk	Rice husk, from dry milling, raw, at plant/CN Mass	kg	168	168
Cement	Portland cement (CEM I), CEMBUREAU technology mix, CEMBUREAU production mix, at plant, EN 197-1 RER S	kg	700	700
Soil	Clay {RoW}| clay pit operation | Alloc Def, U	kg	2323	2800
Transportation	Transport, freight, light commercial vehicle {GLO}| market for | Alloc Def, U	tkm	100	100
Burning of bricks	Heat, central or small-scale, other than natural gas {RoW}| heat production, mixed logs, at furnace 30kW | Alloc Def, U	MJ	354	417

3.8.4.4 Impact assessment

Life Cycle Impact (LCI) results are grouped into midpoint categories (characterization) and then allocated to end-point categories (damage) using equivalent units of reference such as CO_2 equivalents (eq). Midpoint categories are problem-oriented and endpoint categories are damage-oriented. Simapro IMPACT 2002+ method links 15 midpoint categories to four damage categories, which are listed in Table 3-11 and Table 3-12, respectively.

Table 3- 11 Characterization/midpoint impact category

S.N	**Impact/ Midpoint category**	**Unit**	**Damage/Endpoint category**
1	Carcinogens	kg C_2H_3Cl eq	Human health
2	Non-carcinogens	kg C_2H_3Cl eq	Human health
3	Respiratory inorganics	kg PM2.5 eq	Human health
4	Ionizing radiation	Bq C-14 eq	Human health
5	Ozone layer depletion	kg CFC-11 eq	Human health
6	Respiratory organics	kg C_2H_4 eq	Human health
7	Aquatic ecotoxicity	kg TEG water	Ecosystem quality
8	Terrestrial ecotoxicity	kg TEG soil	Ecosystem quality
9	Terrestrial acid/nutrification	kg SO_2 eq	Ecosystem quality
10	Land occupation	m^2org.arable	Ecosystem quality
11	Aquatic acidification	kg SO_2 eq	Ecosystem quality
12	Aquatic eutrophication	kg PO_4 P-lim	Ecosystem quality
13	Global warming	kg CO_2 eq	Climate change
14	Non-renewable energy	MJ primary	Resources
15	Mineral extraction	MJ surplus	Resources

Table 3- 12 Damage/Endpoint impact categories

Damage category	Unit
Human health	DALY
Ecosystem quality	PDF*m^2*yr
Climate change	kg CO_2 eq
Resources	MJ primary

3.8.4.5 Heat energy input and output calculation

The fuelwood for burning the bricks (soil only and soil and rice husk ash mixed) to the temperature of 700 ^{0}C was considered as mixed logs in a furnace of 30-kilowatt capacity. The heat energy required to fire the brick (RHA and soil) from the normal room temperature to the required firing temperature of 700 ^{0}C was calculated by using Equation 3-17. The heat content, *Q*, of an object depends upon its specific heat, *c*, and its mass, *m*.

Heat transfer = (mass)(specific heat)(temperature change)

$$Q = mc\Delta T \qquad \text{Equation 3-17}$$

Q = heat content in Joules

c = specific heat, J/g °C

T = temperature

ΔT = change in temperature

For the current study, the specific heat of soil was taken as 800 J/kg ^{0}C (Engineering tool box.com) and for rice husk is 0.98 kJ/kg^{0}k (transtutor.com). The room temperature (T1) is 25 ^{0}C and firing temperature (T2) is 700 ^{0}C.

The heat energy output from the biogas reactor in the form of the biogas (50-70% methane) was converted to megajoules per year. Assuming the lifetime of the reactor is 20 years, total energy input of each reactor will be divided by 20 to find the annual energy input. The energy out from the cold resistant reactor and the conventional reactor through the 70 days of the reactor operation at the same temperature will be converted to 6 m^3 capacity reactor for the energy input and output comparison.

Chapter 4

Results and Discussion

In this chapter, the results obtained from experiments conducted for the reactor building materials (soil, rice hull ash and brick), laboratory scale reactors, as well as the economic and environmental analysis, are presented to evaluate the effect of integrating insulating materials with the reactor building materials on the overall performance of the anaerobic reactor.

4.1 Physical Properties of Soil and Rice Husk Ash

Two materials, soil and rice husk ash, were used for making the bricks. So, various physical and chemical properties of those materials were tested in the civil engineering lab at the university as well as a certified lab outside the university. The following are the results obtained from the different tests conducted for the materials.

4.1.1 Experimental results on moisture content and loss on ignition (LOI)

Table 4-1 shows the average moisture contents of each sample based wet weight and dry weight. The rice husk ash has greater LOI than soil. This is due to the fact that the rice husk ash has more organic matter, which volatilizes while burning at high temperature. The soil has less organic matter and more inorganic matter.

Table 4- 1 Experimental result on moisture content and on loss on ignition

Sample	Average Moisture Content (WW)	Average Moisture Content (DW)	Average LOI (%)	Moisture Content
Soil	4.79	5.03	5.74	18-20 (Fresh Soil, Haseeb, 2017)
RHA	12.99	14.93	67.24	8.5 (Theeba et al., 2012)

4.1.2 pH and bulk density:

Table 4-2 shows the tabulated value of pH and bulk density of two powdered samples. The pH of the soil is 7.07, which is considered neutral, and rice husk ash is 8.05, which is alkaline. Most soil is considered alkaline; soils typically have a pH range between 7 and 8.5. Our soil sample pH was at the low end of that range. The pH of the rice husk charcoal in previous studies has been found to be 8.9-9.5. (Theeba et al., 2012; Cheng et al., 2012). Our pH of 8.05 was somewhat below that range.

Table 4- 2 pH and bulk density of soil and rice husk ash

Sample	pH	Bulk Density kg/m^3
Soil	7.07	1375
RHA	8.05	204

The typical bulk density of the soil is between 1100 and 1300 kg/m^3 (United States Department of Agriculture, 2019; agriinfo.in, 2019). our value of 1375 kg/m^3 is slightly higher than that range. Ganesan et al. (2008) found the bulk density of rice husk ash burned in a furnace at a temperature of more than 650 ^{0}C to be 400 kg/m^3, which is higher than our value of 204. However, all these properties of RHA are affected by the burning time and temperature of the rice husk. For the current study, the rice husk was burned in an open space at the temperature of 400-500 ^{0}C. So, the bulk density obtained in the current study is lower than the data presented above.

4.1.3 Sieve analysis

Tables 4-3 and 4-4 present data obtained from the sieve analysis of soil and RHA samples, respectively. According to Unified Soil Classification, the soil is considered coarse-grained soil if more than 50 % is retained on or above No. 200 (0.075 mm) sieve and less than 5 % is finer (passing No. 200 sieve). For soil samples, 95.1% was retained on or above the No. 200 sieve, with 4.9% passing through. For the RHA samples, 99.5 % was retained on or above the No. 200 sieve, with only 0.5 % passing through. So, for both samples, more than 50% is larger than 0.075 mm and less than 5% is smaller than 0.075 mm. Thus, both samples fall into the coarse-grained soil category. The soil used here is not typical clay, which have particle size < 2 µm. This means that what is being called “soil” here is coarse-grained soil. This will be discussed in more detail in the following section.

Table 4- 3 Sieve analysis on soil sample

Sieve No	Size (mm)	% Retained	% Passing
8	2.360	0.99	99.01
16	1.160	12.43	86.58
30	0.600	29.59	56.99
50	0.300	19.72	37.27
100	0.150	24.27	13.00
200	0.075	8.09	4.91
Bottom Pan		4.91	0.00
	Total	100.00	

Table 4- 4 Sieve analysis of RHA sample

Sieve No	Size (mm)	% Retained	% Passing
8	2.360	14.07	85.93
16	1.160	18.09	67.84
30	0.600	41.21	26.63
50	0.300	20.10	6.53
100	0.150	5.03	1.51
200	0.075	1.01	0.50
Bottom Pan		0.50	0.00
	Total	100.00	

Figure 4-1 and 4-2 show the percent passing of the samples through the different sizes of sieve versus the size of the sieve. The percent passing through the largest sieve (No.8) is 99.01% for soil and 85.93% for RHA.

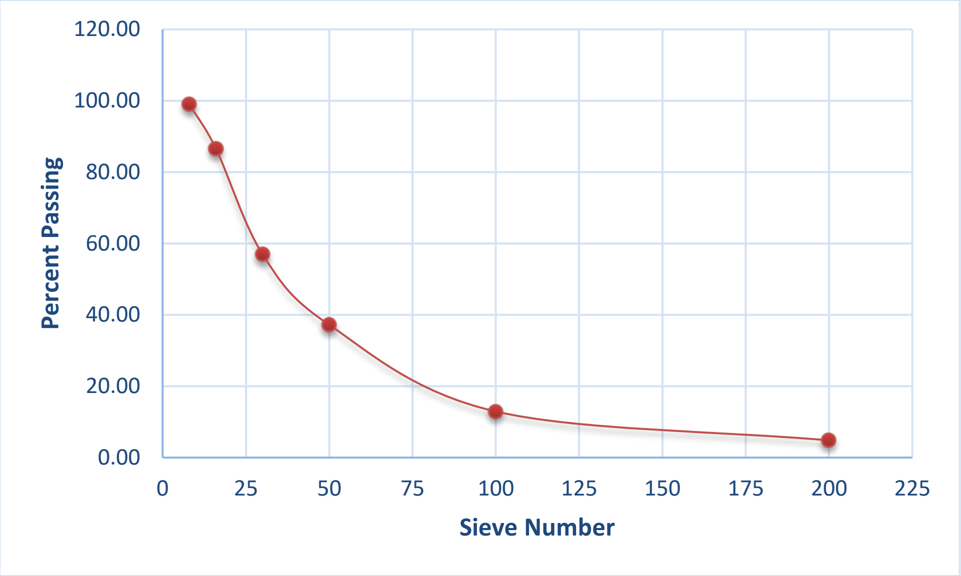


Figure 4- 1 Particle Size Distribution for Soil

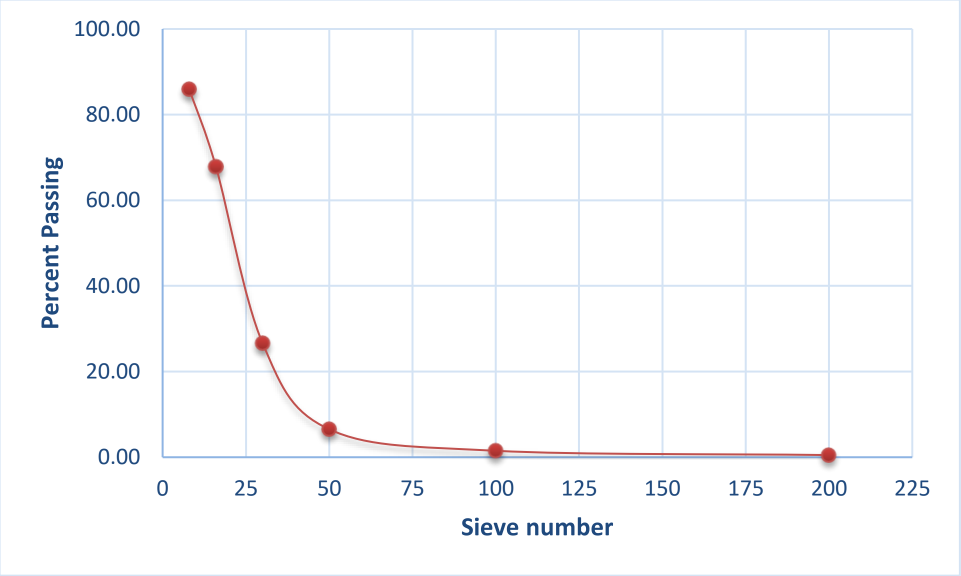


Figure 4- 2 Particle Size Distribution for Rice Husk Ash

4.1.3.1 The coefficient of uniformity and coefficient of curvature

Figures 4-3 and 4-4 show the percent finer versus sieve size in log scale for both samples. These figures were used for determining C_u and C_c, according to the equations given in Ch. 3. Resulting values for Cu and Cc are provided in Table 4-5. According to the Hazen Uniformity coefficient, if the C_U is less than 5, the soil is uniform in particle size, which means the particles falls within a narrow range. Well-graded soils have uniformity coefficient greater than 10 and have a continuous, wide range of particle sizes. A well-graded soil contains a wide range of sizes, varying from Sieve 4 to sieve 20. According to the C_u obtained (≤5), the soil and RHA samples fall in uniform sizes. The effective diameter /size of the samples, D_{10} for Soil is 0.13 mm and RHA is 0.38 mm.

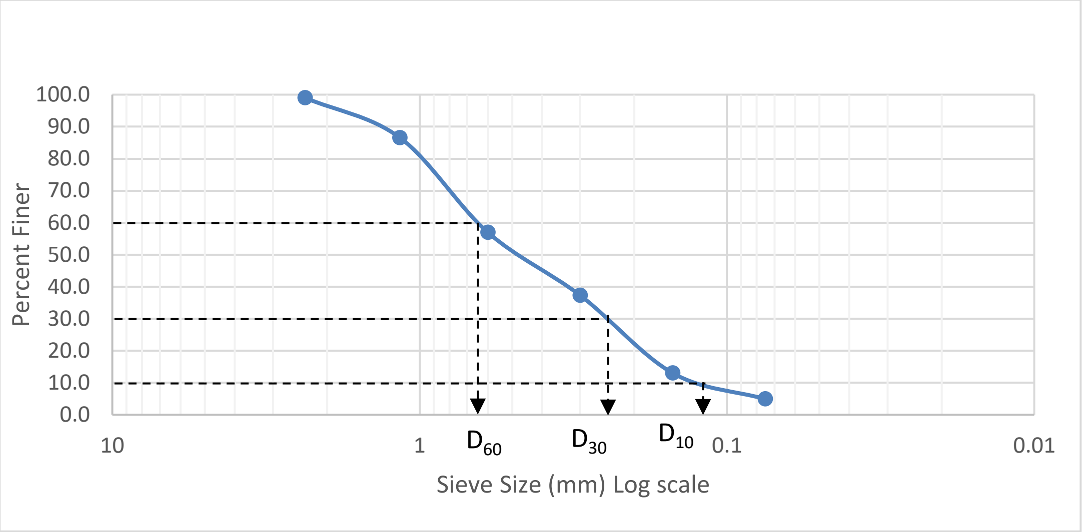


Figure 4- 3 Percent finer versus sieve size in log scale for C_U and C_C of Soil

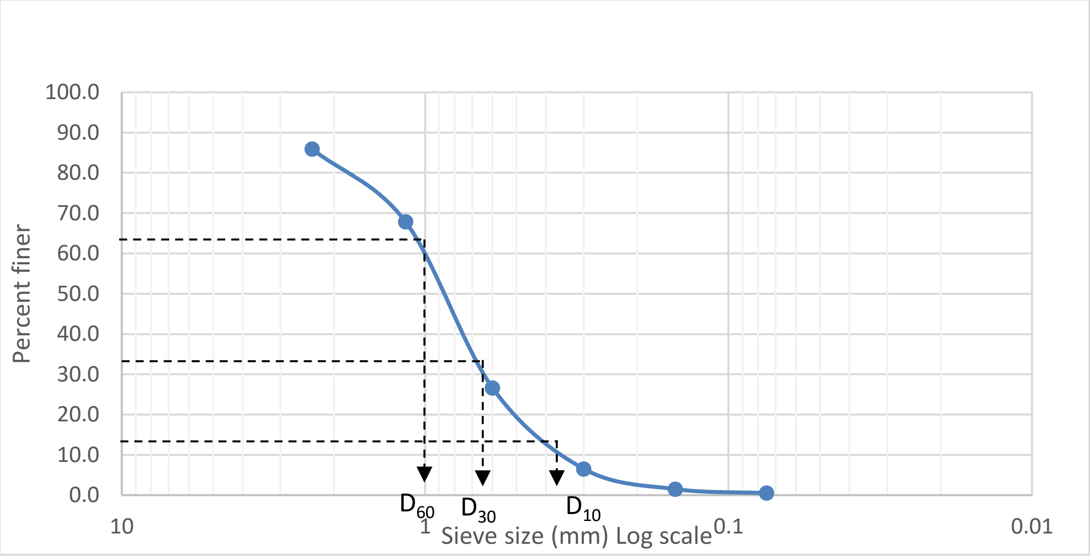


Figure 4- 4 Percent finer versus sieve size in log scale for C_u and C_c of RHA

Table 4- 5 The coefficient of Uniformity (C_{U}) and Coefficient of Curvature (C_C)

Sample	Coefficient of Uniformity	Coefficient of Curvature
Soil	5	0.739
RHA	2.63	1.11

According to ASTM D2487-11 standard practice for classification of soil (Unified Soil classification system), soil with more than 50% retained in No. 200 sieve and less than 5% fines, with $C_U < 6$ and/or $C_C < 1$ or $C_C > 3$, is classified as coarse-grained soil with group name as poorly graded sand (SP). However, the soil used for this study has 4.9% fines, smaller than 0.075 mm size, which is at the borderline (close to 5%) that exhibits both characteristics of fine-grained and coarse-grained soil. For making brick, about 50 % sand and 50 % silt + soil is required; otherwise, the brick will fall apart. According to ESCA results shown in Table 4-6 below, the soil sample exhibits 16.6% silica, which is the second highest composition after oxygen. The chemical composition of sand is primarily SiO_2, or silica oxide. A good building brick material should contain about 50% to 60% silica, which prevents cracking, shrinking and warping of raw bricks. The presence of this constituent imparts uniform shape to the bricks (www.civileblog.com). So, the soil used for this study was ideal to make the bricks; there was no need to add sand while making bricks.

Note: Even though the soil used for making brick falls in the coarse-grained soil category, not the fine-grained soil, the bricks are called here “Conventional and RHA” brick. Sample notations are “Soil” and “RHA.”

4.2 Chemical Properties

4.2.1 Test Results of Surface Metals and Chemical Composition (CHON and S) Analysis

Table 4-6 summarizes the average atomic surface concentration of chemical samples evaluated using Electron Spectroscopy for Chemical Analysis (ESCA) and chemical composition (CHONS) analysis of two powder samples provided by the lab services.

Table 4- 6 ESCA and CHONS atomic concentration summary (atomic percent)

Surface Metals (ESCA) and CHONS Results for Both Samples												
Component	[Al]	[C]	[Ca]	[Fe]	[K]	[Mg]	[N]	[Na]	[O]	[Si]	[H]	[S]
Soil												
ESCA (Atomic %)	8.3	8.4	1.1	0.8	0.5	0.8	ND	0.3	62.6	17	-	-
CHONS (Composition %)	-	1.04	-	-	-	-	<0.05	-	7.76	-	0.5	<0.1
Previous study (Watile et al., 2015)	-	4.59	-	-	-	-	-	-	42.4	-	-	-
RHA												
ESCA (Atomic %)	ND	57.9	0.7	ND	0.6	ND	1.8	0.3	30.8	7.9	-	-
CHONS (Composition %)	-	36.84	-	-	-	-	0.29	-	24.6		3.3	<0.1
Previous studies (Theeba et al., 2012; Watile et al., 2015)	-	41-78	0.1	-	-	-	-	-	18.3-37		3.5	0.3

According to the ESCA results, for the soil sample, the major constituents were oxygen, silica, carbon, and aluminum, in that order. Other constituents were 1% or less, and nitrogen was not detected. This agrees with the CHONS analysis of soil, in which oxygen composition is highest, followed by carbon.

According to the ESCA results, the major constituents of rice husk ash were carbon, oxygen, and silica, in that order. Carbon and oxygen had the highest percent in the CHONS analysis as well. Other constituents in the ESCA analysis were 2% or less, and aluminum and iron were not detected. The results from the surface metal analysis are helpful in knowing what might leach into the soil or water, and thus what chemicals should be evaluated during the LEAF test.

The typical composition of soil and RHA from the previous studies are also presented in Table 4-6. The composition of the soil depends greatly on the source from which it is obtained. If the soil, for example, obtained was formed by the decomposition or sedimentation of organic matter, it will have high carbon content. However, in the case of rice husk ash, hydrogen, oxygen and sulfur content are mostly the same as previous studies, but the carbon percentage may vary based on the burning temperature.

4.2.2 LEAF test results for rice husk ash mixed brick

Table 4-7 presents the maximum concentrations of heavy metals measured for the semi-dynamic tank leaching test performed on rice hull ash mixed soil bricks. The results show that concentrations for all metals are lower than the maximum permissible limit on drinking water (primary and secondary standard) except for the aluminum. For aluminum, the measured concentration of 6.07 mg/L exceeded the secondary standard of 0.05 to 0.2 mg/l. The secondary standard means these contaminants are not health threatening. The secondary maximum contaminant levels are established as guidelines to assist public water systems in managing their drinking water for aesthetic considerations, such as taste, color, and odor.

Aluminum especially colored the water. Federal regulations do not require monitoring or treating of secondary contaminants in water. Thus, the results show that heavy metals are not leached at high concentration that is threatening to human health and the environment. Also, from the ESCA result, it can be said that the aluminum is leaching from the soil, not from the RHA. For making bricks, people use locally available soil, which might not have the same properties as the soil used for the present study.

Table 4- 7 LEAF Test Results

Element	Measured Concentration (mg/L)	Maximum Permissible in Drinking Water (mg/L)	
		Primary Drinking Water Standard	Secondary Drinking Water Standard
Silver (Ag)	0.00159		0.1
Aluminum (Al)	6.07		0.05 to 0.2
Arsenic (As)	0.00142	0.01	
Barium (Ba)	0.0331	2	
Beryllium (Be)	0.000478	0.004	
Cadmium (Cd)	0.000365	0.005	
Cobalt (Co)	0.000516	No EPA enforced limit on nickel levels in water	
Chromium (Cr)	0.0594	0.1	
Copper (Cu)	0.012	1.3	
Manganese (Mn)	0.00181		0.05
Molybdenum (Mo)	0.324	0.04 (Health advisory limit but not regulated)	
Nickel (Ni)	0.00293	No EPA enforced limit on nickel levels in water	
Lead (Pb)	0.000761	0.015	
Selenium (Se)	0.00048	0.05	
Thorium (Th)	0.000338	No EPA enforced limit on nickel levels in water	
Thallium (Tl)	0.000285	0.002	
Uranium (U)	0.000324	0.03	
Vanadium (V)	0.0795	No EPA enforced limit on nickel levels in water	
Zinc (Zn)	0.0241		5

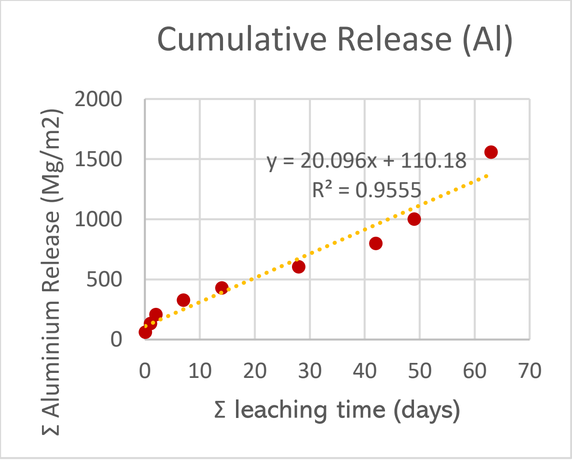
pH and conductivity were also measured as part of the LEAF test, as shown in Table 4-8. The pH of the eluate increased from first to the ninth interval. However, the contaminants leaching per unit time interval decreasing during the final interval. The pH increased from 7.18 to 10.65 in one day (between T01 to T02), but it increased only from 11.25 to 11.40 in 14 days (between T08 to T09), which means that the impurity in the eluate was decreasing. An initial increase in the pH was likely because the RHA is alkaline and soil has neutral pH. Conductivity increased from T01 to T09, which meant the contaminant leaching was increasing over time. However, the interval duration during the initial day was

2 hours, 1 day and then increases to 5,7 and 14 days. So, contaminants leaching per day is lower in the final interval than the initial intervals.

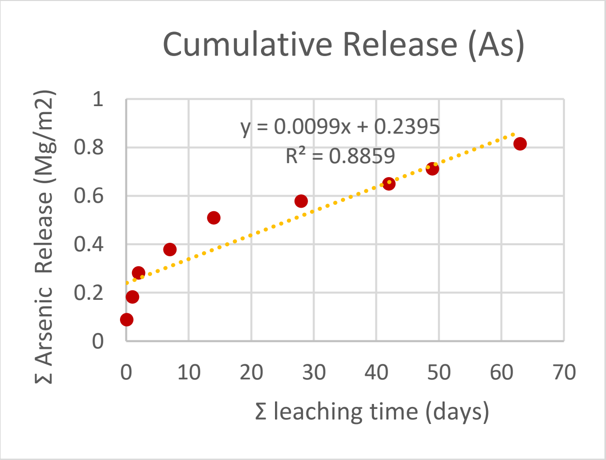
Table 4- 8 pH and Conductivity based on interval duration

Interval Label	Interval Duration (Days)	pH	Conductivity (mS/cm)
T01	0.08	7.18	0.261
T02	0.96	10.65	0.218
T03	0.96	10.77	0.233
T04	5	11.16	0.425
T05	7	10.50	0.481
T06	14	10.50	0.572
T07	14	10.62	0.534
T08	7	11.25	0.376
T09	14	11.40	0.530

Since all the measured concentrations for primary drinking water standards are below the limit. There is no health threatening. However, three major metals, which are toxic, can have health impact (skin, lung, kidney) causes cancer due to long term exposure, were selected to plot the cumulative release. Additionally, aluminum concentration is higher than the EPA drinking water standard. Even if it is categorized as secondary standards, aluminum also selected for the calculation of cumulative release. The cumulative release of four metals are presented in Figures 4-5 (a, b, c, and d).



(a)



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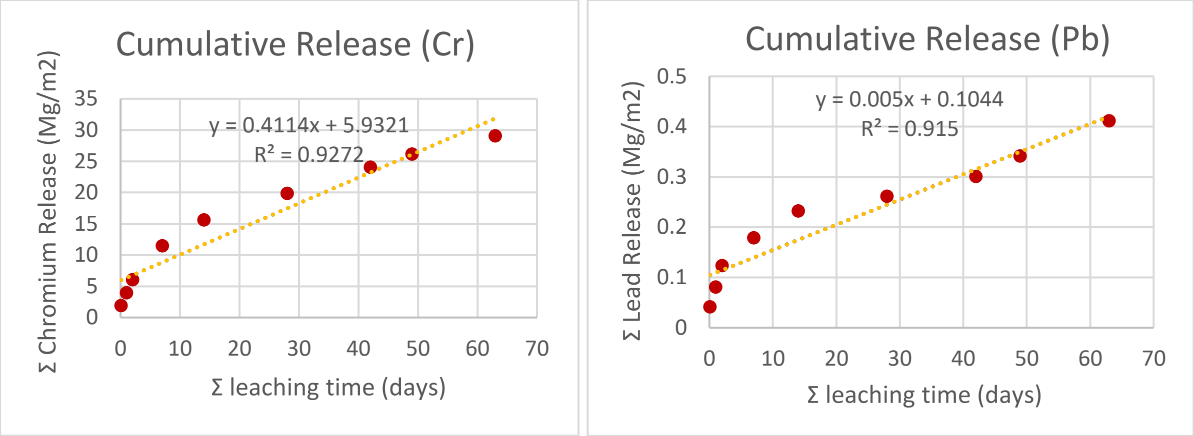


(c) (d)

Figure 4- 5 Cumulative release of Aluminum, Arsenic, Chromium, and Lead

Table 4-9 shows the cumulative releases in mg/m^2 and maximum mean interval fluxes in mg/m^2·s for aluminum arsenic, chromium and lead through 63 days of leaching.

Table 4- 9 Cumulative release and maximum mean interval flux of four metals.

Metals	Aluminum	Arsenic	Chromium	Lead
Cumulative release (mg/m^2)	1560	0.81	29.06	0.41
Mean interval flux mg/m^2. s	9.05 E-04	1.187E-06	2.582E-05	5E-07

4.3 Physical Tests on the Bricks

4.3.1 Compressive Strength Test:

The values for the compressive strength of any building material are essential for construction purposes to ensure stability in a structure. Table 4-10 and Figure 4-6 present the compressive strength test results. The highest compressive strength was obtained on the brick with 10% RHA burned at 700^0 C for 4 hours (8.9 MPa), followed by 10% RHA burned at 700^0 C for 6 hours (8.3 MPa). The compressive strengths of the various proportions (RHA and soil) bricks varied with the amount of rice husk ash added, burning time and temperature. As shown in Figure 4-6, for all the temperature and burning durations, the compressive strength of the bricks with 10 % rice husk ash was the highest, followed by 20 % and 30% RHA. Compressive strength test results reveal that the higher the percentage RHA, the lower the compressive strength. The accuracy of the 400 KIP tensile compression machine used for compressive strength test was ± 0.1%. So, the data provided in the table can be varied by ± 0.1 %. For example, the uncertainty in the strenght of the 20% RHA brick cured at 700°C for 6 hours would thus be 0.0038MPa. The differences between the ultimate stress values in the table are larger than the uncertainty values, meaning tha the differences are significant.

Table 4- 10 Compressive strength test results

Composition	Temp/Time	Ultimate stress (kg/cm^2)	Ultimate stress (MPa)
10% RHA, by volume (1.67 % by weight)	500,4 hrs	41.30	4.04
	500,6 hrs	53.88	5.27
	700,4 hrs	90.42	8.84
	700,6hrs	85.16	8.33
20% RHA, by volume (3.71 % by weight)	500,4hrs	39.48	3.86
	500,6hrs	34.40	3.36
	700,4hrs	62.56	6.12
	700,6hrs	38.89	3.80
30% RHA, by volume (6.36 % by weight)	500,4hrs	31.24	3.06
	500,6hrs	29.05	2.84
	700,4hrs	31.10	3.04
	700,6hrs	28.29	2.77

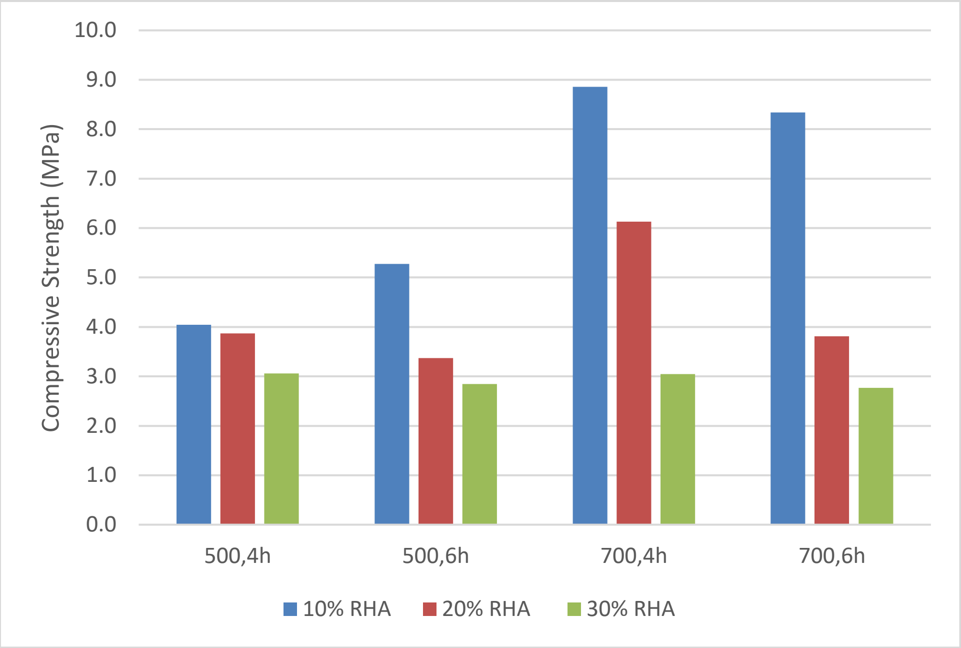


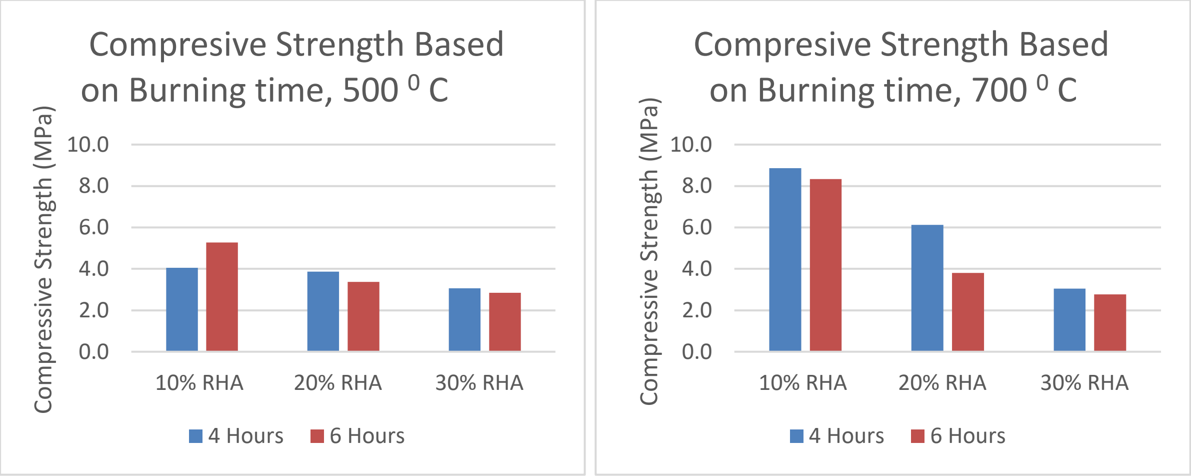
Figure 4- 6 The compressive strength of bricks based on the percent RHA

Mohan et al. (2012), found compressive strengths for bricks of 10%, 20%, and 30% RHA (by volume) to be 42-46 kg/cm^2, 40-45 kg/cm^2, and 37-40 kg/cm^2, respectively. Thus increasing % RHA decreased compressive strength, although the decreases were not as dramatic as those observed in this study. Le et al. (2014), however, reported that the addition of RHA with high-performance fine-grained concrete increased the compressive strength regardless of ages of bricks. For common building brick, the minimum compressive strength required is 35 kg/cm^2, for second class brick the minimum is 70 kg/cm^2 and for first class, the minimum is 105 kg/cm^2 (Indian Standard - 1077, 2007).

For the current study, 1.67 % RHA, by weight (10% by volume) gave 4.04 to 8.33 MPa compressive strength, while 3.71 % by weight (20% by volume) RHA composition gave 3.36 to 6.12 MPa. Watile et al. (2015) and Sutas et al. (2012) found bricks containing 2% (by weight) of RHA to have compressive strengths of 6.59 and 6.20 MPa, respectively. Hence, the compressive strengths results obtained from the current study are comparable with previous studies.

Based on the burning temperature and duration, the compressive strength varies as shown in Figure 4-7 (a) and (b). The bricks burned for 4 hours have the higher compressive strength than burning time of 6 hours for both burning temperatures, except for 10%, 500 ^{0}C, where 6 hours bricks have higher compressive strength than 4 hours bricks. This is likely because soil and RHA were not mixed homogeneously while making the bricks; also, while burning, the samples might have been in the middle of other bricks so that it would not burn completely on all sides.

The brick burning at high temperature will harden the brick and increase the bulk density as well as compressive strength up to 850 ⁰ C. So, for this study the bricks burned at 700 ⁰C had higher compressive strength than the bricks burned at 500 ⁰C. However, temperatures higher than 850 °C start volatilizing the rice husk ash out of the brick. The void space increases the porosity, with the effect of decreasing the bulk densities and compressive strength (Sutas et al., 2012).



(a) (b)

Figure 4- 7 Compressive Strength Based on the firing time and temperature

4.3.2 Water absorption test results

The water absorption of the soil and rice hull ash mixed brick samples was determined by 24-hour cold water immersion test. The water absorption of bricks increases with an increase in pores. The strength of bricks will be comparatively low if the water absorption capacity is greater. A brick with water absorption of less than 7% provides better resistance to damage by freezing. Table 4-11 and Figure 4-8 show water absorption of bricks with different proportions of RHA and soil. The water absorption capacity of the rice husk mixed soil bricks is highly affected by rice husk ash addition, brick burning time, and temperature. The digital scale used to weigh the brick has the accuracy of 0.0003 gram/gram.So the error in the water absorption percentage of the samples provided in Table 4-11 is ±

0.033%. Since the differences between the water absorption values for the different bricks are larger than 0.033%, the differences are significant.

As shown in Figure 4-8, the results reveal that water absorption increased with increased rice husk ash addition. Generally, the water absorption increased from around 16% to 24% when the rice husk ash increased from 10 to 30% by volume. A 100% soil brick (no RHA) was also tested; the lowest water absorption (14.18%) was obtained for the 100% soil brick. Adding more RHA means more organic matter which volatilizes after burning at high temperature, resulting in more void space in the sample brick.

Table 4- 11 Water absorption results on Brick

Composition	Temp/Time	Water absorption %
10% RHA by volume (1.67 % by weight)	500 ^{0}C,4hrs	16.73
	500 ^{0}C,6hrs	18.54
	700 ^{0}C,4hrs	15.89
	700 ^{0}C,6hrs	16.62
20% RHA by volume (3.71 %by weight)	500 ^{0}C,4hrs	19.37
	500 ^{0}C,6hrs	18.29
	700 ^{0}C,4hrs	17.77
	700 ^{0}C,6hrs	17.94
30% RHA by volume (6.36 % by weight)	500 ^{0}C,4hrs	23.84
	500 ^{0}C,6hrs	24.39
	700 ^{0}C,4hrs	21.91
	700 ^{0}C,6hrs	22.65
0% RHA (100% soil)	700 ^{0}C,4hrs	14.18

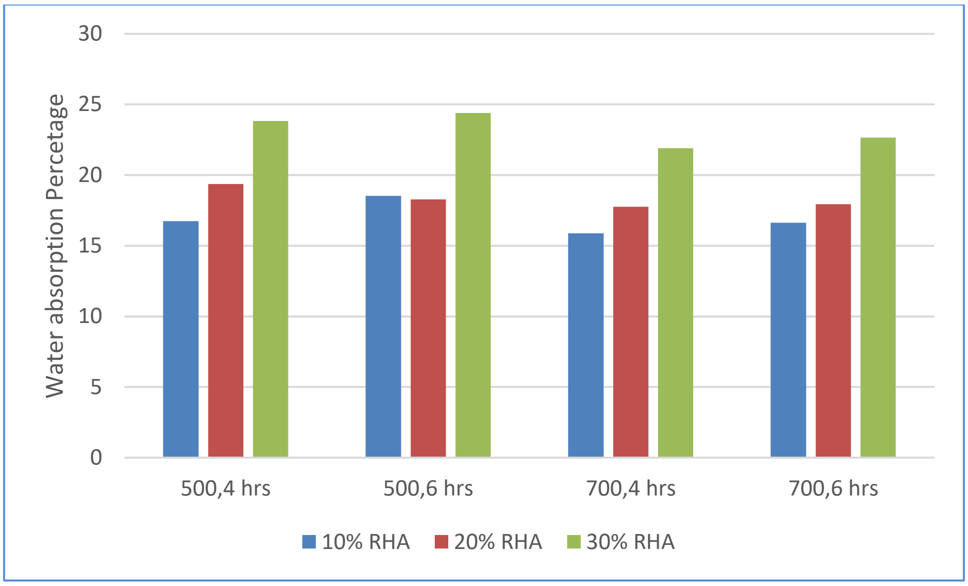
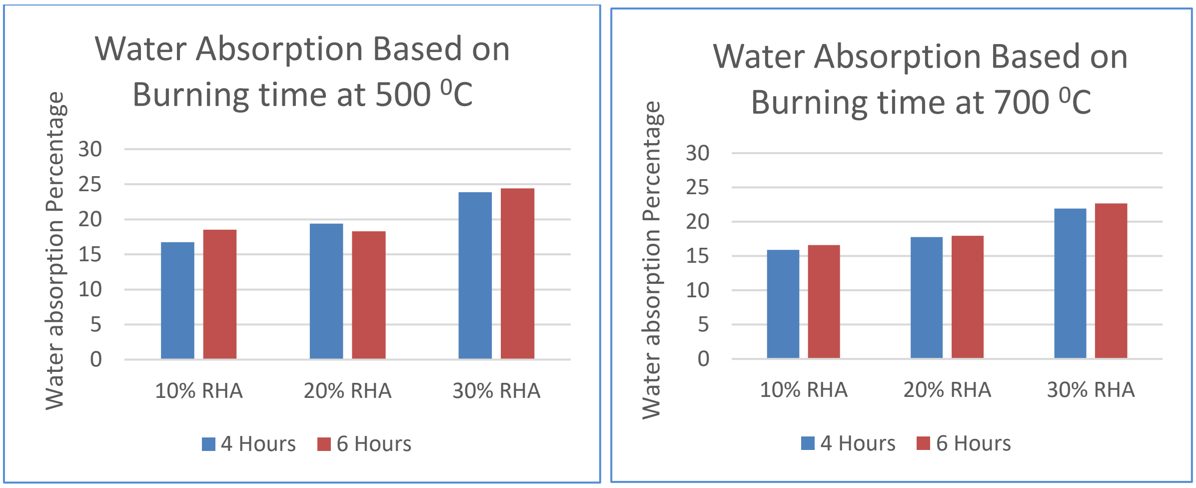


Figure 4- 8 Water absorption percentage based on percent RHA addition

Water absorption capacity (by weight) of bricks should be <20% for first class brick, <22% for second class brick and <25% for third class (Quora.com). The results reveal that 30% RHA bricks had water absorption capacity >20% and thus did not meet the criteria of good quality brick.

Watile et al. (2015) and Sutas et al. (2012) measured water absorption percent of 14.0 and 15.2 for bricks containing 2% rice husk ash (by weight). Mohan et al. (2012) observed the lowest water absorption of 15% for 10% RHA (by volume) mixed soil brick. Rahman (1987) obtained water absorption of 16.18% for 5% RHA (by volume) mixed soil brick. The results obtained from the current study are comparable with the previous studies.

Figures 4-9 (a) and (b) show the water absorption based on the firing temperature. Water absorption percentage decreases with an increase in firing temperature; water absorption of bricks burned at 500 ^{0}C is higher than water absorption of bricks burned at 700^{0}C for both burning duration (4 and 6 hours). Also, the water absorption increases with an increase in the firing duration for the same temperature, except for the 20 % RHA samples of 500 ^{o} C, where six hours water absorption was lower than the 4 hours. Higher burning temperature and duration volatilize the organic compound (mainly rice husk ash), leaving voids inside the brick. Increased porosity increases water absorption capacity.



(a) (b)

Figure 4- 9 Water Absorption Based on the firing time and temperature

4.3.3 Resistance to Heat Value

The results obtained from compressive strength and water absorption tests were considered to narrow down the number of thermal resistance tests to be conducted, to save costs. Seven sample compositions with compressive strength >3.5 MPa (minimum building brick compressive strength) and water absorption <20 % were tested. In addition, one sample of 0% rice husk ash (100 % soil) was also tested to compare heat resistance value with bricks made by adding rice husk ash.

The results obtained from the lab were normalized to per two inches thickness for a fair comparison of the results to each other. The heat resistance test result obtained from Dynalene lab is presented in Table 4-12 and Figure 4-10. The accuracy of the machines used for resistance to heat transfer test (using ASTM C518 method) was ± 5% per one-inch thick sample. For the current study, resistance to heat transfer value was calculated per two-inches thick. So, the data provided in Table 4-12 has an uncertainty of ± 10 %.

The highest resistance to heat value (0.86) was obtained on the composition 20 % RHA burned at 700 ^{0}C for 4 hours. The lowest R-value was obtained on the 100% soil brick (0% RHA). As shown in Figure 4-10, all 20% RHA brick samples, for the same firing time and temperature, had R-values higher than the 10% RHA samples. The results thus reveal that resistance to heat (R-value) increases with increase in RHA percent in the brick, as expected. The higher the R-value, the greater the insulating effectiveness.

For the 20% RHA bricks, the uncertainty in the R values is larger than the differences between the values. For example, the uncertainty of 0.09 is larger than the difference between the 0.86 and 0.85 values, which is only 0.01. Thus, the 0.85 and 0.86 values cannot truly be distinguished from each other because of the large uncertainty. So, for the current study, the best brick was chosen based on water absorption and compressive strength tests.

Table 4- 12 Results of R-Value obtained from the lab

Composition	**Temp/Time**	**R-value ($F.Ft^2/Btu$)**	**Thickness (Inch)**	**R-value / 2 Inches ($F.Ft^2/Btu$)**
10% RHA	500, 4h	0.75	2.14	0.7 ± 0.07
	500, 6h	0.7	2.14	0.65 ± 0.07
	700, 4h	0.93	2.26	0.82 ± 0.08
	700, 6h	0.7	2.17	0.65 ± 0.07
20% RHA	500, 4h	0.84	2.16	0.78 ± 0.08
	700, 4h	0.94	2.19	0.86 ± 0.09
	700, 6h	0.93	2.19	0.85 ± 0.09
0% RHA	700, 4h	0.64	2.03	0.63 ± 0.06

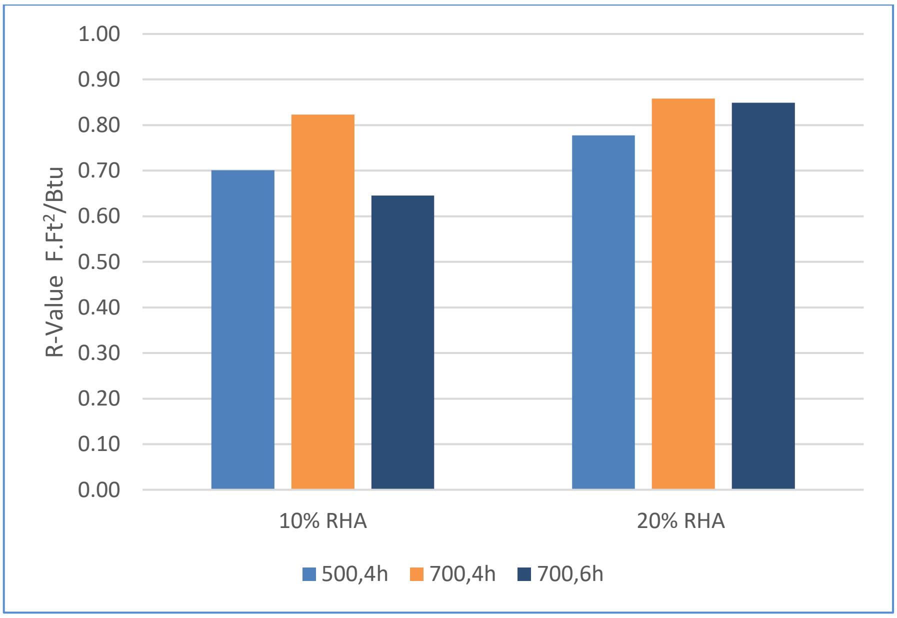


Figure 4- 10 R-Value based on percent RHA

R-value is also affected by the firing temperature and time, as shown in Figure 4-11. For the 4-hour firing time, the R-Values are higher on the samples burned at 700^{0}C than at 500^{0}C. However, for the same burned at 700^{0}C, increasing the firing time from 4-6 hours lowered the R-value, especially for the 10% RHA bricks.

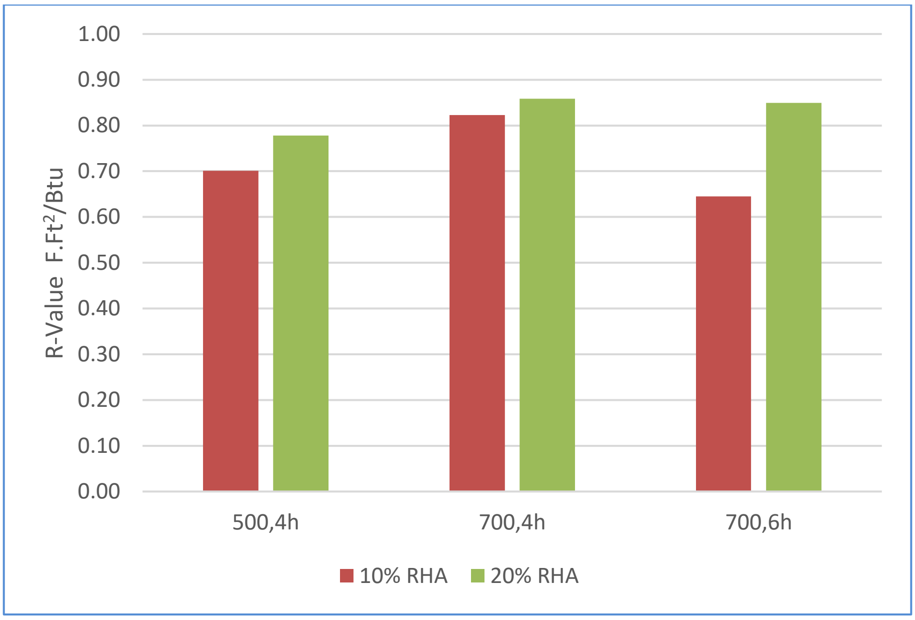


Figure 4- 11 R-Value based on firing temperature and time

4.4 Biogas Reactor Building and Operation

4.4.1 Reactor Temperature

Figure 4-12 shows the temperature variation inside the reactors in comparison to the temperature measured outside the reactors and the control room set temperature. For the first 60 days, the temperature of the room was kept at either 20^{0}C or 21^{0}C to allow the microorganisms a chance to flourish at a hospitable temperature. After that, the temperature was gradually reduced to see how low the temperature could go with continued gas production. Throughout the 116 days of reactor operation, the temperature inside the reactor RHA is higher than the temperature inside the conventional reactor. It is likely because the rice husk ash added to the brick provided the thermal insulation to the reactor. The maximum temperature difference between the reactor with RHA bricks and the outside temperature was 3.56^{0}C on day 32, the day when methane peaked in the RHA reactor. The maximum temperature difference between the reactor with conventional bricks and the outside temperature was 1.34^0 C on day 74.

Around day 81 of the reactor operation, there were some problems on the temperature controller in the controlled room (it was not working properly). Due to the servicing, there were some fluctuations in the constant temperature. During that time the inside temperature of the conventional reactor was observed to be lower than the outside temperature. The temperature loggers used for monitoring the inside temperature have ±0.5°C (±0.9°F) accuracy.

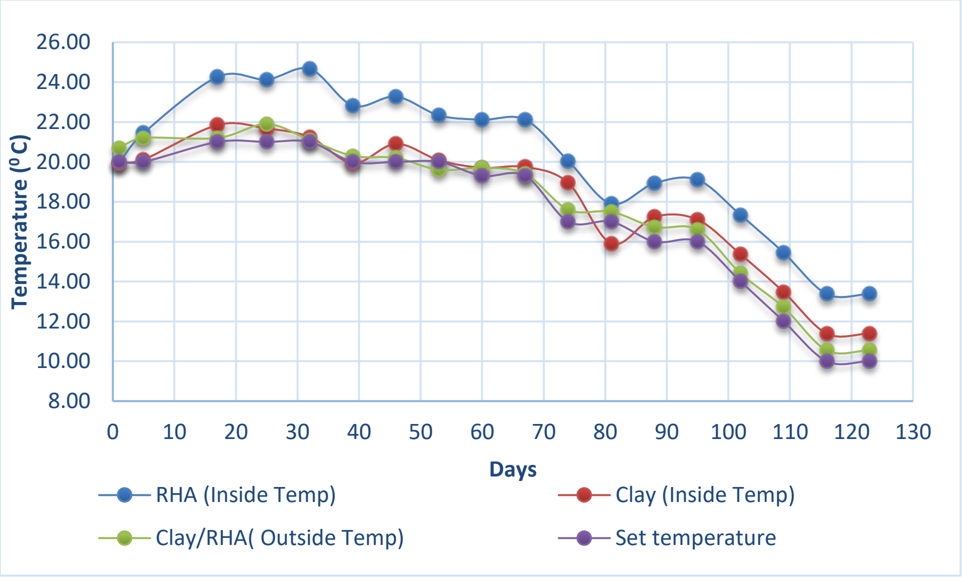


Figure 4- 12 Comparison of temperature variation in reactor with RHA bricks and reactor with conventional bricks

4.4.2 Reactor Pressure

Maintaining high pressures in a biogas reactor can be very challenging. As gas is generated, it exerts pressure and displaces the slurry upward into an expansion chamber in the fixed dome household biogas plant. When the gas is removed, the slurry flows back into the reactor. If the pressure inside the reactor increases too high, it could damage the structure. So, the gas from the biogas system is used daily for household purposes so that no gas accumulates inside the reactor with high pressure. The pressure can be used to transport the biogas through pipes.

For the current study, the reactor pressure was monitored continuously by using the Kestrel Drop pressure logger. The outlet gas pipe from the biogas reactors was connected to the gas sampling bag. When the gas formation started, the biogas collected in the sampling bags. However, the gas pressure inside the reactor was monitored to prevent the danger of exploding gas, if the pressure increased extremely high. Since the gas was collected in the bag, there was no risk of high-pressure build-up inside the reactor. Throughout the reactor operation, the pressure inside the reactors was observed to be low, between 980 to 1015 millibars, as shown in Figure 4-13.

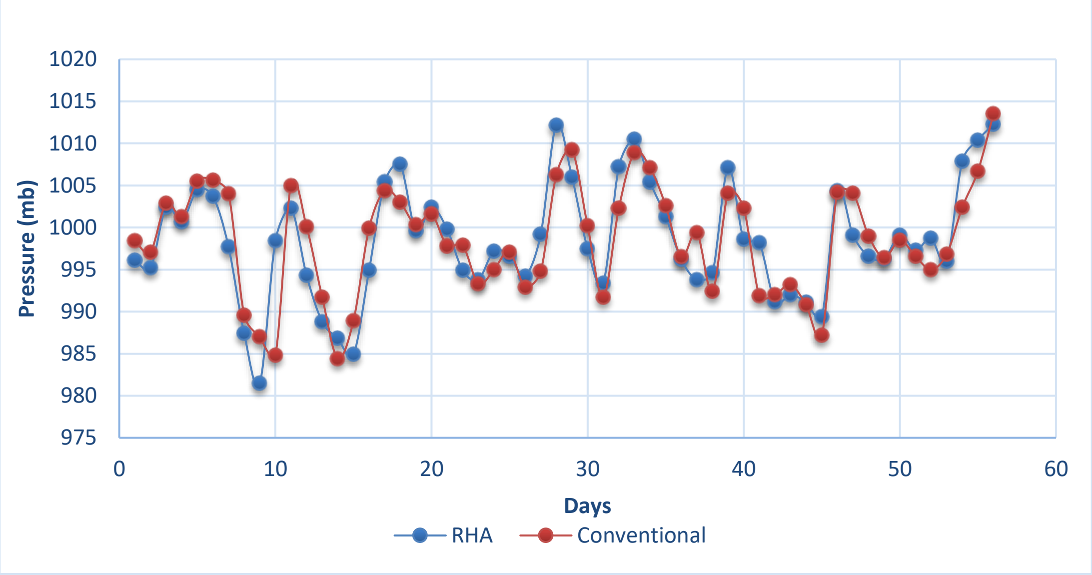


Figure 4- 13 Station pressure inside the reactors

4.4.3 Gas composition

Figures 4-14 and 4-15 show composition of gases generated from the RHA (cold resistant) reactor and conventional reactor, respectively, for the first 116 days of operation. Both reactors generally behave similarly. The reactor with RHA insulation produced gas continuously throughout to day 116; however, the conventional reactor ceased after day 102. It is likely due to the low temperature inside the reactor that microbes were inhibited. The percentage of oxygen drops quickly, leading to anaerobic conditions inside the digester. Other gases, initially mostly nitrogen in air, decreases quickly when the acetogenesis phase starts. Other gases increases again after Day 50, likely due to production of hydrogen and water vapor during the acidogenesis and methanogenesis phases, respectively. Other gases can also include trace gases such as sulfides, disulfides, mercaptans, and ammonia generated from decomposition of organic compounds containing sulfur and nitrogen under anaerobic conditions, as well as carbon monoxide.

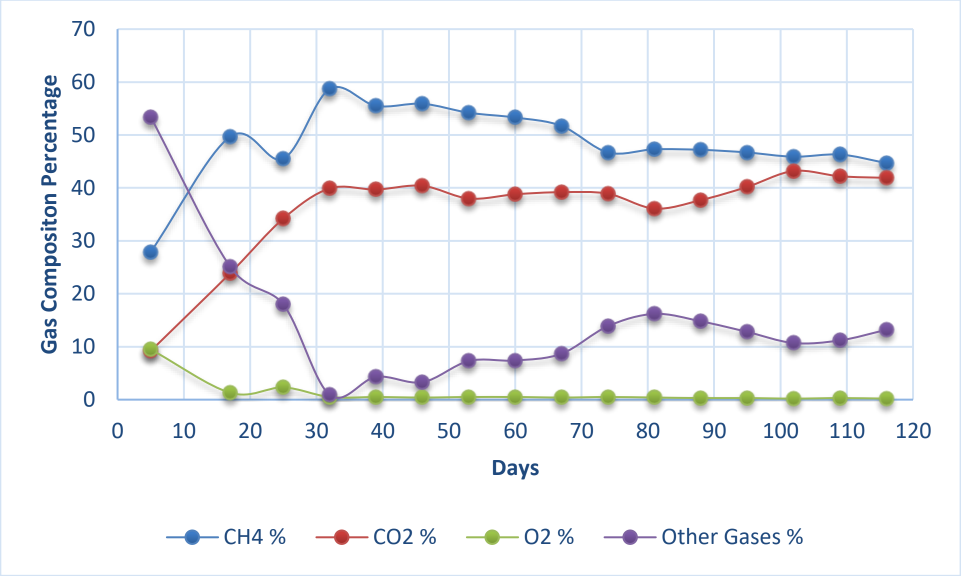


Figure 4- 14 The composition of gases in the RHA reactor

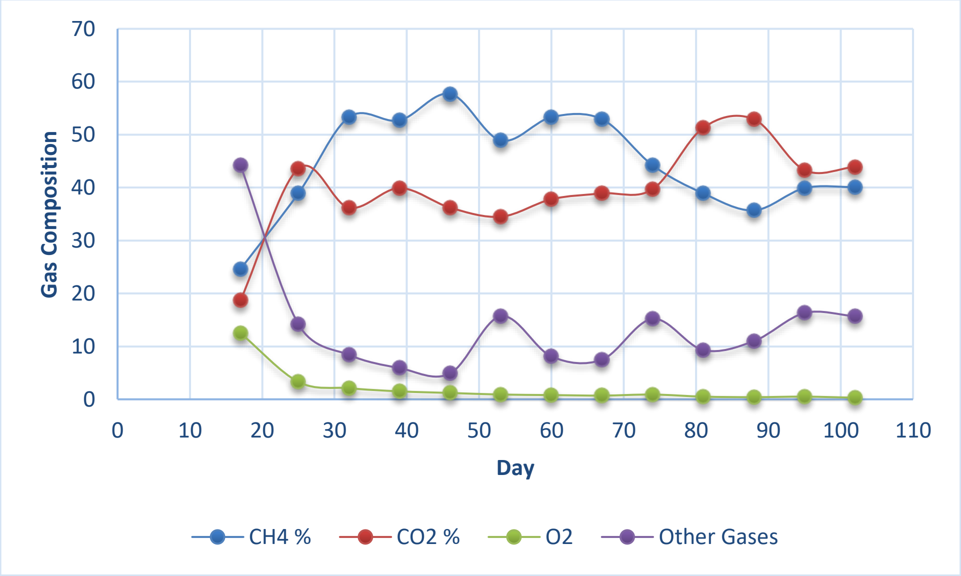


Figure 4- 15 The composition of gases in the conventional reactor

At the very beginning, it took some time for both reactors to generate some gas. Gas measurement started when gas initially accumulated in the gas bag. The RHA reactor has a shorter lag period (5 days) than the conventional reactor (17 days), likely because the RHA reactor has a higher inside temperature than the conventional reactor. So, the microbes have more favorable temperature which leads to faster acclimation and population increase.

For most anaerobic reactors, carbon dioxide concentrations are initially higher than methane concentrations, since carbon dioxide is produced during the acidogenesis phase and methane is not produced until the later methanogenesis phase. However, since cow dung was used as an inoculum as well as the feedstock, the methane percentage was higher initially than carbon dioxide. Due to the rumen in the animal body, acetogenesis and methanogenesis phase occurred simultaneously, or methane production started faster. Moreover, the waste was collected from the waste pile on the same day as the reactor operation and mixed with water then poured into the reactor. So, there were likely anaerobic pockets remaining in the cow manure, and anaerobic reactions were going on at the bottom of the waste. Thus, the methane production percentage was higher initially. For both reactors, the percentage of carbon dioxide and methane increases rapidly during the initial phase of biogas production and then stabilizes.

Figure 4-16 shows the percentage of methane over time for both reactors (RHA and conventional). Both reactors were continuously producing methane; however, for the conventional reactor, the methane production ceased after 102 days, while the reactor with RHA insulation continuously produced methane through day 116 and then ceased after that. The maximum methane percent was 58.7% (day 32) for the RHA reactor and 57.7% (day 46) for the conventional reactor. The conventional reactor peaked 14 days after the RHA reactor peaked. The peak methane percentages for RHA was slightly higher than that for conventional. For both reactors, methane stabilized at 40-50%.

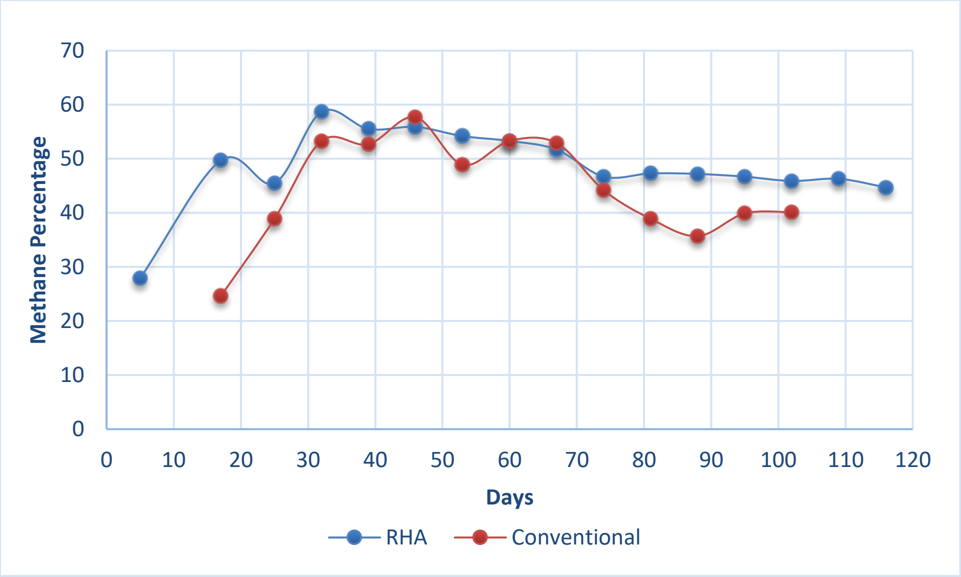


Figure 4- 16 Methane percentage RHA versus conventional reactor

Due to the increase in temperature in the RHA reactor, the methane production started earlier, peaked earlier and a slightly higher percentage of methane was observed compared to the conventional reactor. Table 4-13 shows the initial lag phase for both reactors, maximum methane production and days of occurrence for both reactors.

Table 4- 13 Methane data comparison for RHA and conventional reactors

Reactor	Initial lag phase	Maximum CH_4 %	Day of occurrence of maximum
RHA	5	58.7	32
Conventional	17	57.7	46

4.5 Cumulative Volume and Rate of Methane Generation

Figure 4-17 compares cumulative methane generation (liters/kg) over time for RHA and conventional reactors. Conventional reactor has a longer lag time than RHA. Both reactors have the same amount and type of feedstock; however, the reactor temperature was higher for the RHA reactor because of the insulating properties of RHA. The reactor with RHA insulation produced 33% more methane by day 102 than the conventional reactor. At the end of reactor operation (day 116), the RHA reactor produced 9.8 liters methane per kilogram of waste and conventional reactor (day 102) produced 6.2 liters methane per kilogram of waste.

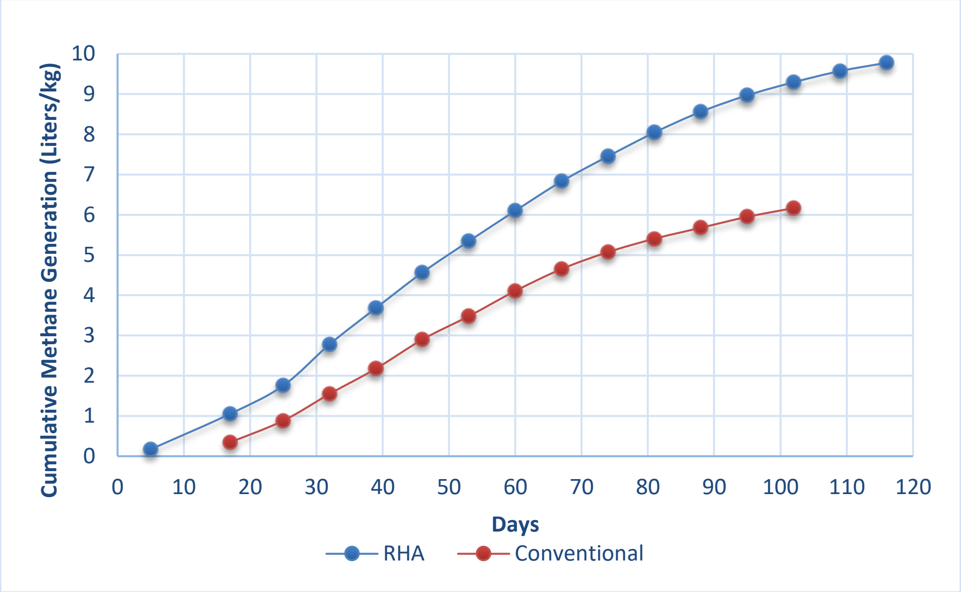


Figure 4- 17 Cumulative methane generation through 81 days of reactor operation

Figure 4-18 shows the rate of methane production (ml/kg waste/day) versus time for the RHA (cold resistant) reactor. Initially, the control room temperature was set for 20^{0}C then increased to 21^{0}C. The temperature inside the reactor increased from 21.52^{0}C (day 5) to 24.66^{0}C (day 32). The methane percentage increased as the inside temperature increase. The maximum difference between the reactor inside temperature and the control room temperature (3.66^{0}C) occurred at 32 days, the same day which the maximum methane percentage as well as the maximum rate of methane production (147 ml/kg/day) was obtained. Increasing the temperature increases microbial activities, which also increases methane production. The RHA reactor produced the gas continuously when the controlled room temperature dropped gradually from 21 ^{0}C to 12 ^{0}C and ceased after 10 ^{0}C. Due to the insulation,the cold resistant reactor had inside temperature around 14 ^{0}C even when the room temperature was set at 10 ^{0}C.

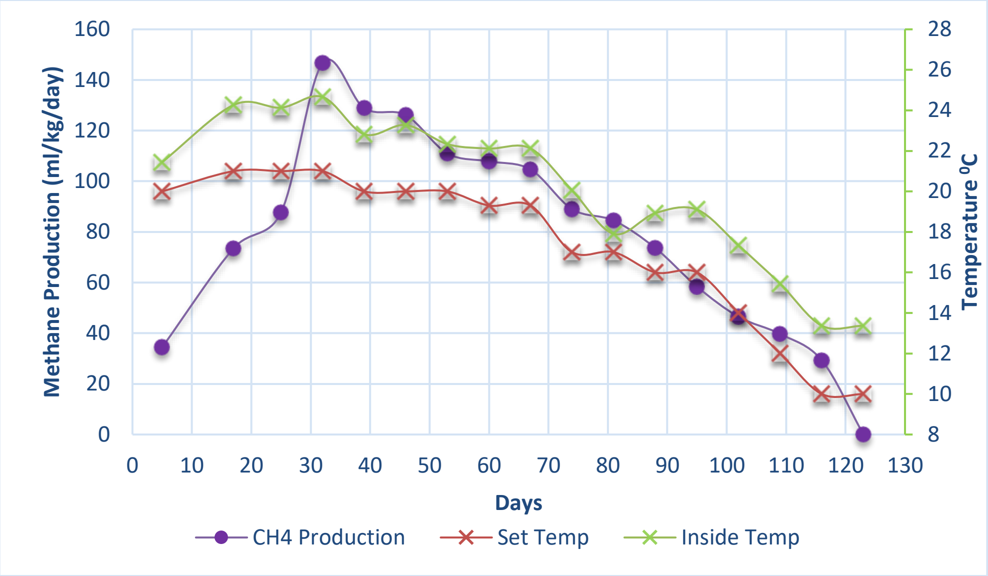


Figure 4- 18 Temperature and methane production rate vs. time in RHA reactor

Similarly, Figure 4-19, shows the rate of methane production and temperature variation vs. time for the conventional reactor. Initially, the temperature was set for 20 ^{0}C then increased to 21 ^{0}C. The temperature inside the reactor increased from 20 to 21.85 ^{0}C (day 17); however, methane production did not start until day 17. The maximum methane production rate (103 ml/kg/day) was observed on day 46, when the methane percentage peaked and the temperature was 20.9 ^{0} C. The conventional reactor produced gas continuously when the controlled room set temperature dropped gradually from 21 ^{0}C to 16 ^{0}C and ceased after 14 ^{0}C.

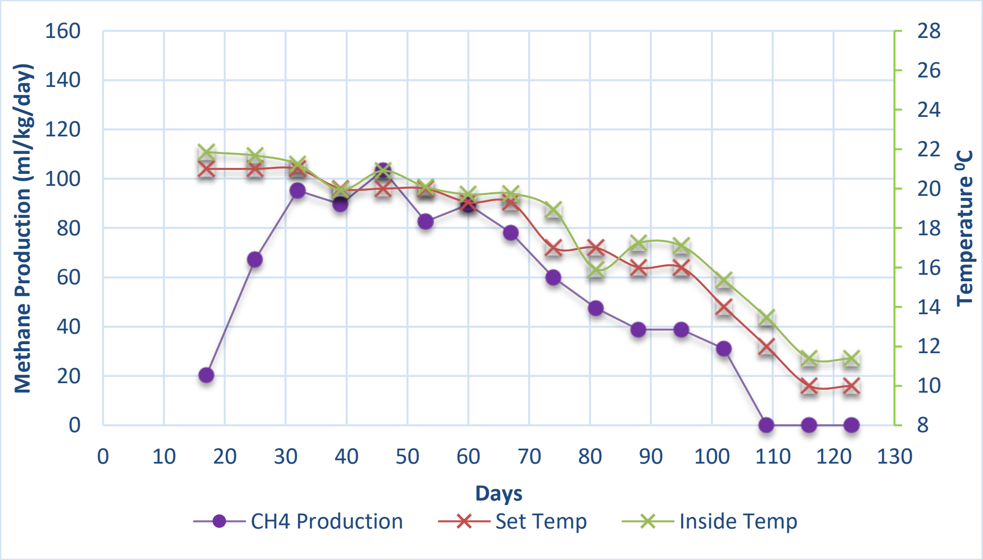


Figure 4- 19 Temperature and methane production rate vs. time in the conventional reactor

Figure 4-20 directly compares the methane generation rate (ml/kg/day) vs. time for RHA and conventional reactors. The RHA reactor has the highest rate of methane generation throughout the time period, as well as a higher peak rate, likely due to a higher reactor temperature which becomes a favorable condition for microbes to degrade organic wastes. Methane production stopped after day 102 for conventional reactor and after day 116 for RHA reactor.

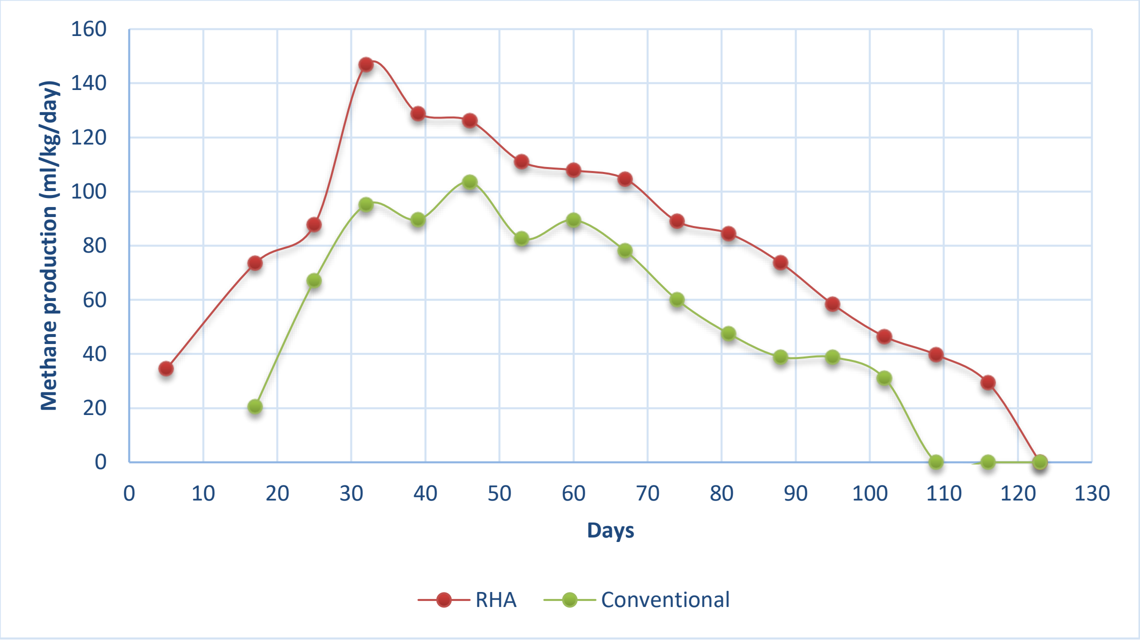


Figure 4- 20 Methane production rate for both reactors

Table 4-14 compares the maximum methane generation rate and day on which it occurred for the RHA and conventional reactors. Due to the higher temperature, the RHA peak rate was higher and occurred sooner, compared to the conventional reactor.

Table 4- 14 Maximum CH_4 Generation rate (ml/kg/day

Reactor	**Maximum CH_4 generation rate (ml/kg/day)**	**Days of occurrence**
RHA	147	32
Conventional	103	46

4.6 Life Cycle Analysis

4.6.1 Economic Analysis

Biogas systems provide multiple benefits at the household, local, national and global levels. The key benefits are related to time-savings for the women and young girls, environment, health, reduced deforestation, avoided chemical fertilizer, availability of bio-fertilizer, etc. The monetary values of some of these benefits are not quantifiable. However, the financial and economic analysis of the costs and benefits that are quantifiable clearly demonstrate the value of biogas systems.

The benefit-cost ratio of conventional and cold resistant design is 3.3 and 3.68 (using financial value) and 3.8 and 4.3 (using economic value), respectively. Since this ratio is more than one for both designs, the project is acceptable. The Financial Internal Rate of Return (FIRR) for an average size (6-m^3) biogas system is estimated at 62 percent for the conventional design and 69 percent for the cold resistance design. The Economic Internal Rate of Return (EIRR) is estimated at 71 percent for conventional design and 80 percent for the cold resistant design. The benefit-cost ratio, FIRR, and EIRR are very sensitive and highly dependent on the price of fuelwood, which is estimated to be NRs 6.0 /kg in the mountains, and the rate of the local labor. The prices of fuelwood, kerosene and chemical fertilizer vary based on location as well as time of the year. The provided government subsidy helps to reduce the burden for the farmer. Without this support for the biogas system, it is likely that the Nepalese farmer would not have sufficient incentive to adopt the biogas system. It is certain that with this programme, the dissemination of biogas in Nepal has risen.

Based on the results obtained from all the calculations, the total capital cost, benefit-cost ratio, as well as internal rate of return, the cold resistant design is better than the conventional reactor design. The capital cost is slightly less, and benefit-cost ratio and internal rate of return are slightly higher for the cold resistant design than the conventional design. Even if there is very little difference in cost, the cold resistant design helps to insulate the slurry inside the reactor, which enhances the biogas production in cold areas and increases the overall reactor performance. Moreover, using the raw rice husk for making brick helps to reduce the agricultural by-product, which ultimately reduces the volume of waste going to the landfill/open dumps.

4.6.2 Environmental Analysis

In this section, the life cycle environmental impact assessment of the material used for building the cold-resistant reactor and conventional reactor are presented. Figure 4-21 and 4-22 show the RHA (cold-resistant) and conventional reactor elements' impact in the 15 mid-point characterization categories. For the environmental analysis of the cold resistant and conventional reactor, rice husk ash is considered for both reactors. Whether rice husk is used for making brick or not, it is produced as a by-product during the crop production. The rice husk produced from the rice milling is usually open burned. For the current study, more soil is used for conventional reactor than the RHA reactor. Since RHA is considered for both reactors, the midpoint impacts are very similar to each other.

For both reactors, each element contributes to all 15 categories. The highest contributor to most of the categories were rice husk, cement, and transportation. Cement and transportation have the highest contribution to ozone layer depletion. Rice husk has greater land occupation hence caused greater impacts on the ecosystem. Steel, cement, and transportation contributed to the mineral extraction and nonrenewable energy categories.

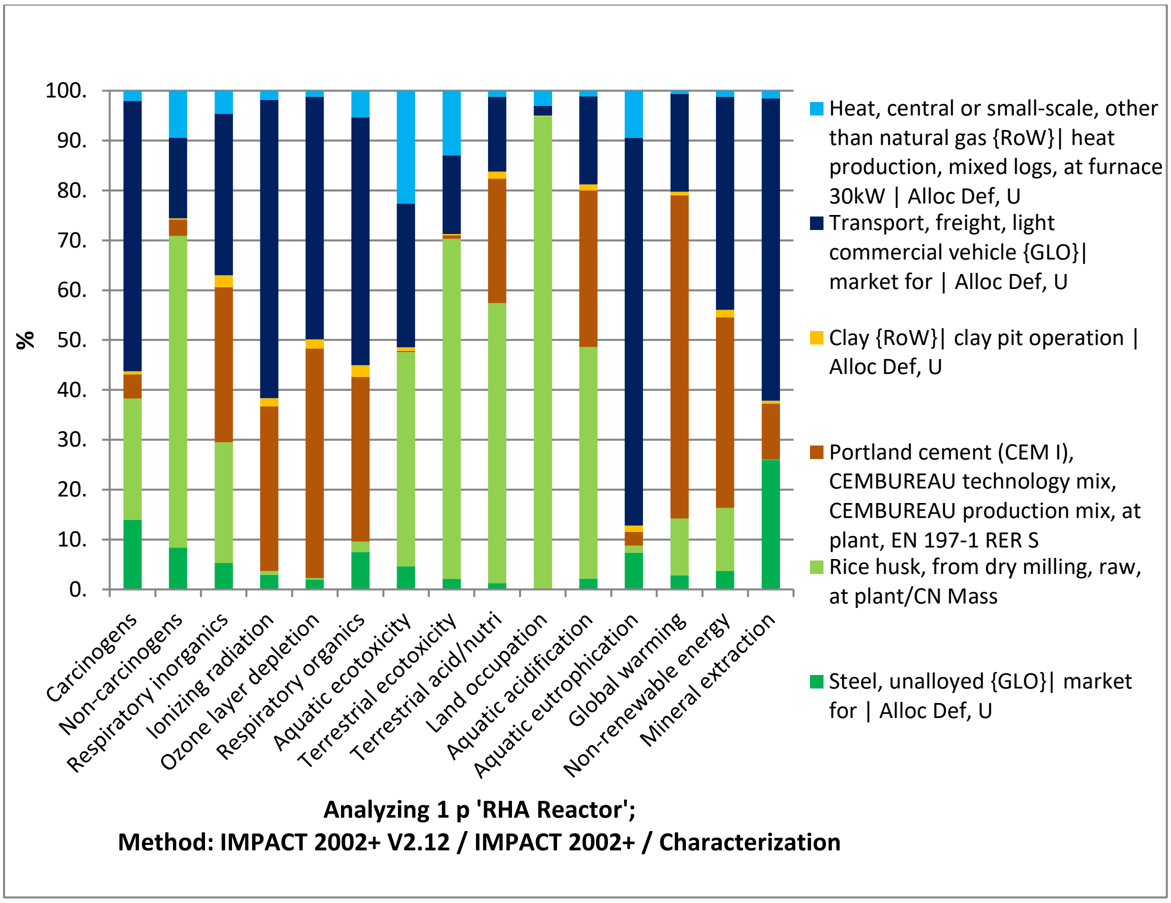


Figure 4- 21 Characterization Categories for Cold Resistant Reactor

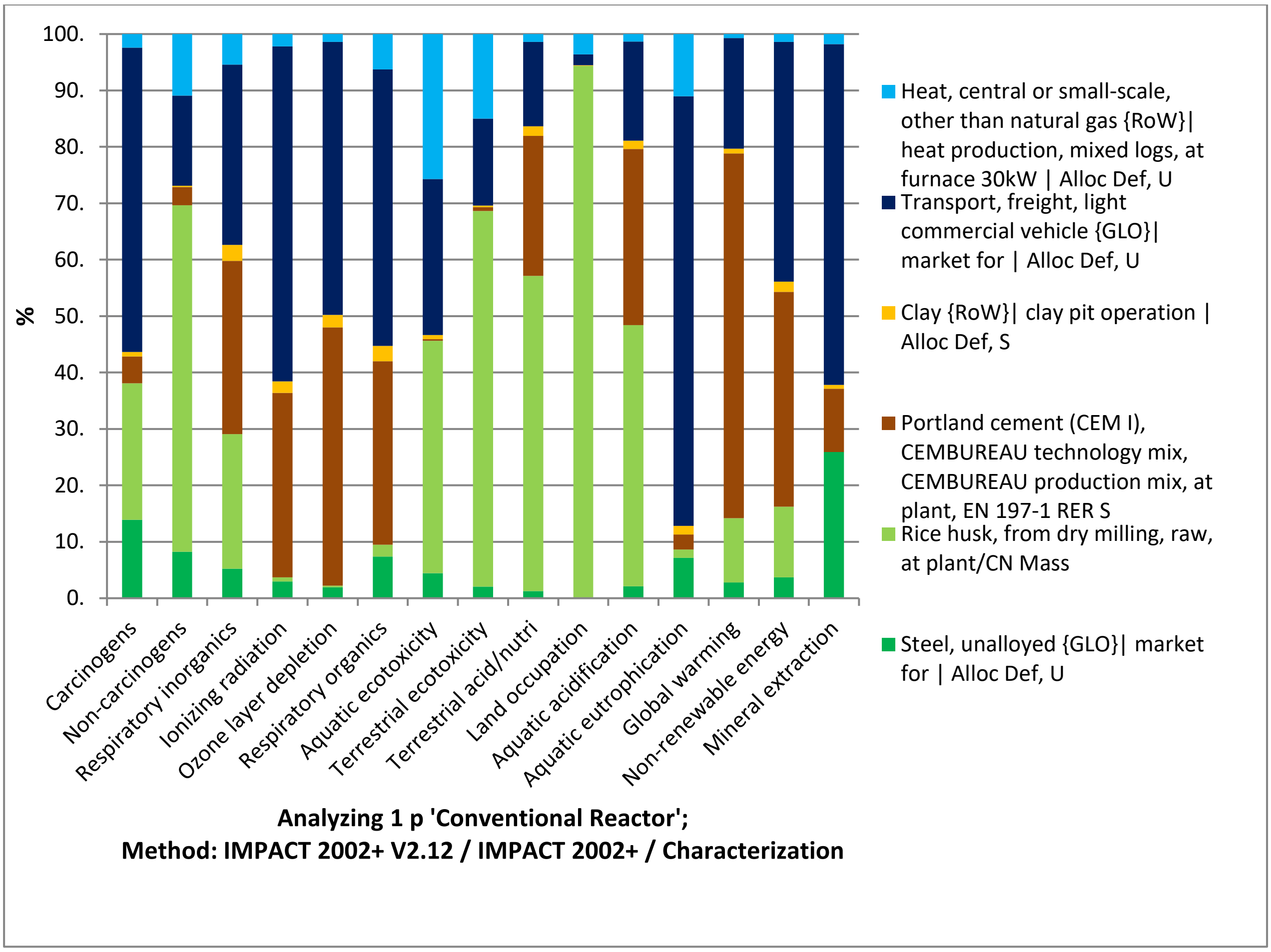


Figure 4- 22 Characterization Categories for Conventional Reactor

Four endpoint calories of damage assessment – human health, ecosystem quality, climate change, and resources – were analyzed for both reactors. Figure 4-23 and 4-24 show the endpoint (damage) assessment of the RHA and conventional reactor. The endpoint damage assessment of both reactors revealed that transportation, rice husk, and cement contributed mostly to human health. Rice husk contributed the most to ecosystem quality. Also, Portland cement is the most significant contributor to climate change. Transportation and cement had the largest effect on resources.

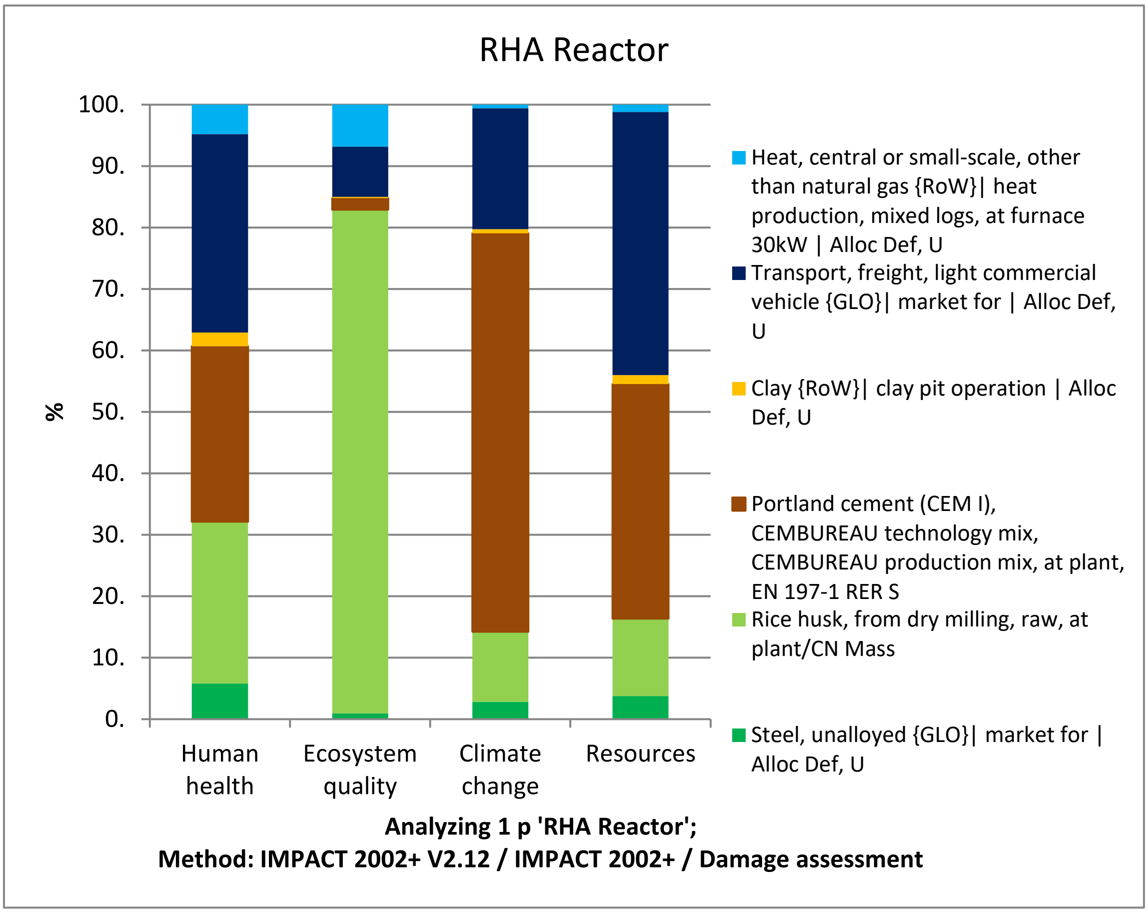


Figure 4- 23 Endpoint damage categories for RHA reactor

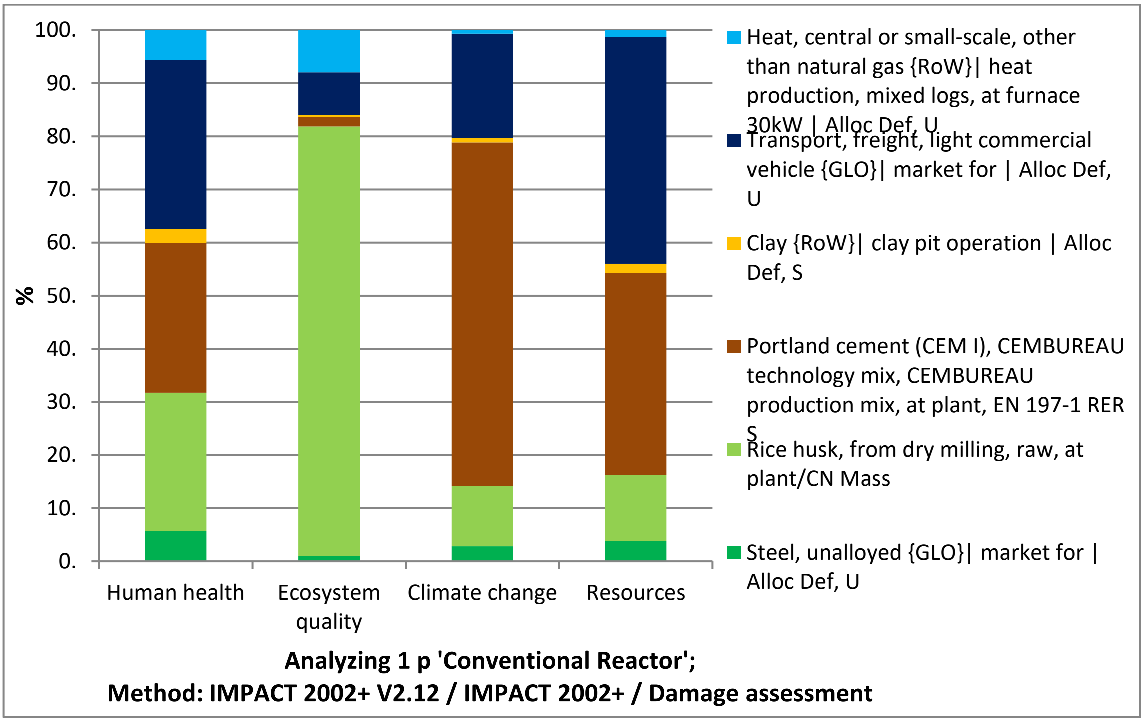


Figure 4- 24 Endpoint Damage Categories for a conventional reactor

For all the damage categories, the conventional reactor has a slightly greater impact than the RHA reactor. It is likely because it includes more soil than the RHA reactor. More soil used means more energy for raw materials acquisition, transportation (since conventional brick is heavier than the RHA brick), burning, etc. Table 4-15 shows the endpoint damage assessment of RHA and the conventional reactor.

Table 4- 15 Damage Category for the reactors

Damage category	**Unit**	**RHA Reactor**	**Conventional Reactor**
Human health	DALY	0.0006	0.0006
Ecosystem quality	PDF*m^2*yr	532	539
Climate change	kg CO_2-eq	965	967
Resources	MJ primary	7109	7147

Normalization is the calculation of the magnitude of the category indicator results relative to some reference information. The aim of normalization is to understand better the relative magnitude for each indicator of the product system under study (ISO 14044, 2006). For the Damage Assessment Normalization results as shown in Figure 4-25, the most impacted areas were Climate Change, Human Health, and Resources, respectively. The least impacted was Ecosystem Quality for both types of reactors. The conventional reactor has slightly higher normalized values than the RHA rector.

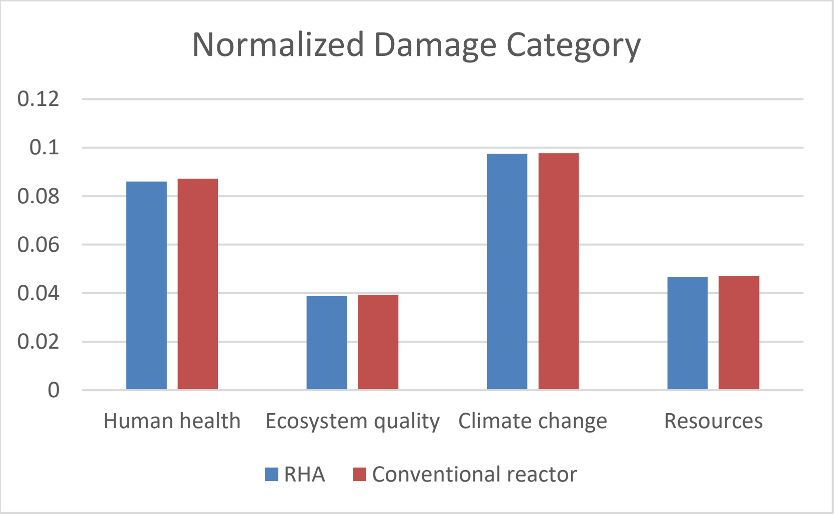


Figure 4- 25 Damage assessment normalization

Figures 4-26 and 4-27 show the Single Score results and damage category network for the RHA reactor, respectively. Portland cement has the greatest overall impact, followed by transportation and rice husk, at about equal impact.

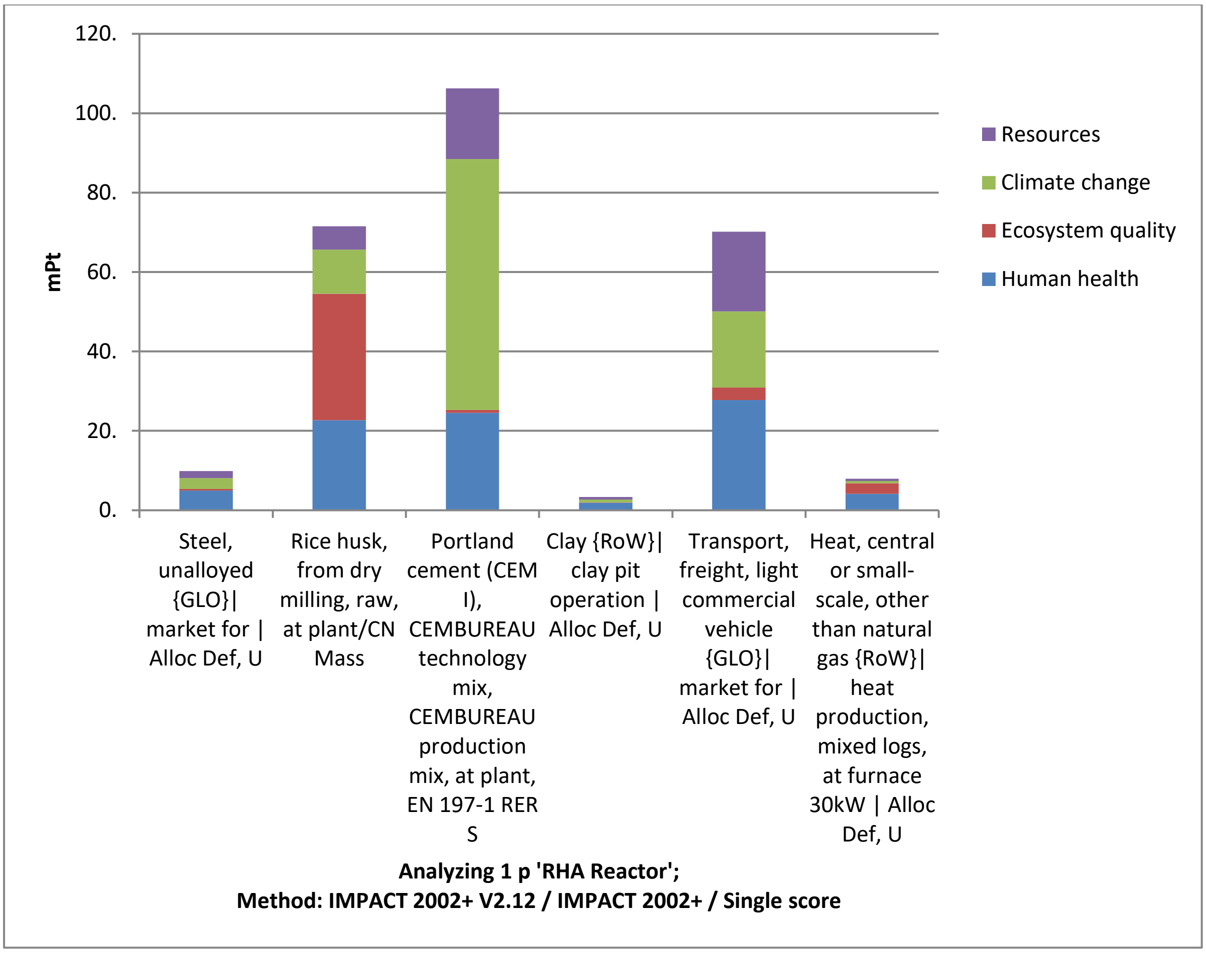


Figure 4- 26 Single score damage assessment on RHA reactor

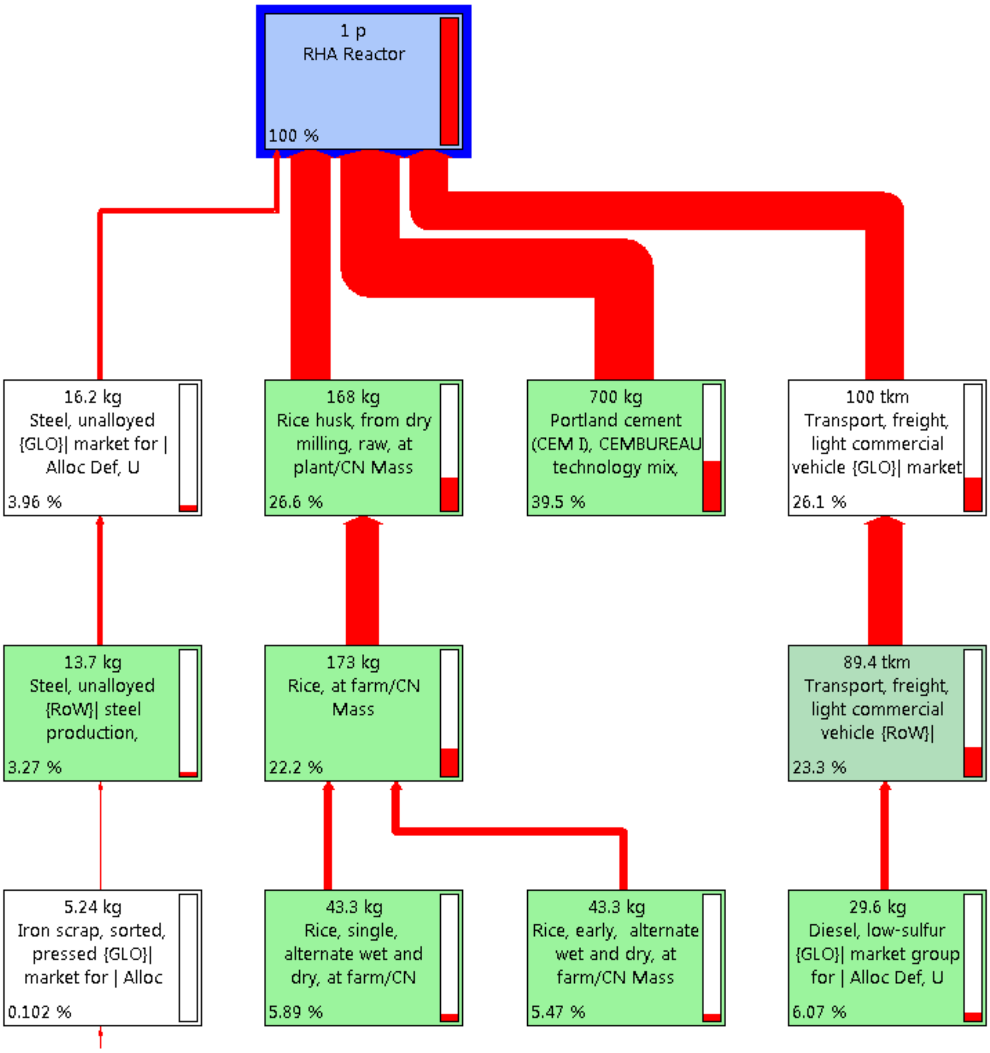


Figure 4- 27 Network – Single Score RHA reactor at 5% cutoff (Sima-Pro Software)

Similarly, Figures 4-28 and 4-29 show the Single Score results and damage category network for the conventional reactor, respectively. Portland cement has the greatest overall impact, followed by transportation and rice husk.

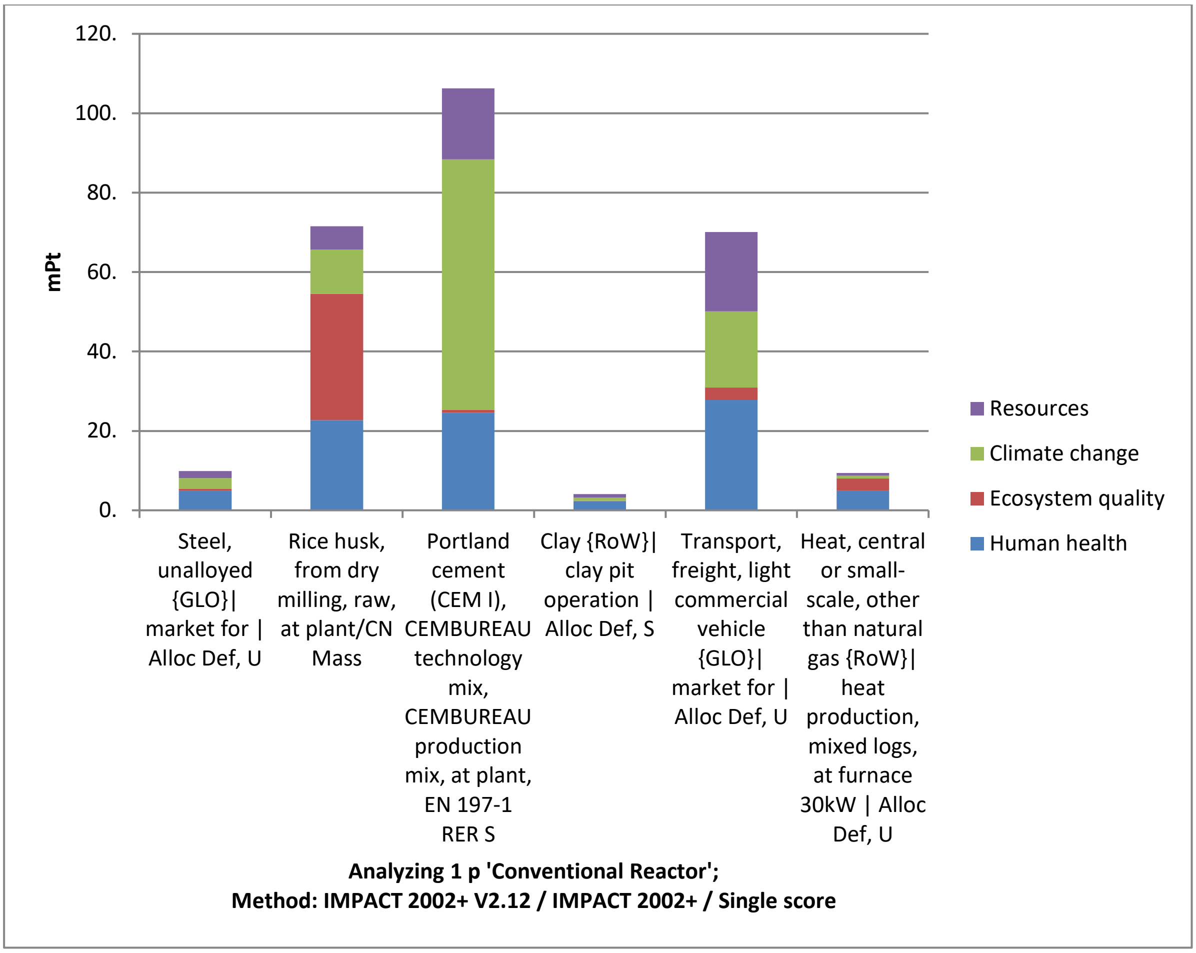


Figure 4- 28 Single score damage assessment on conventional reactor

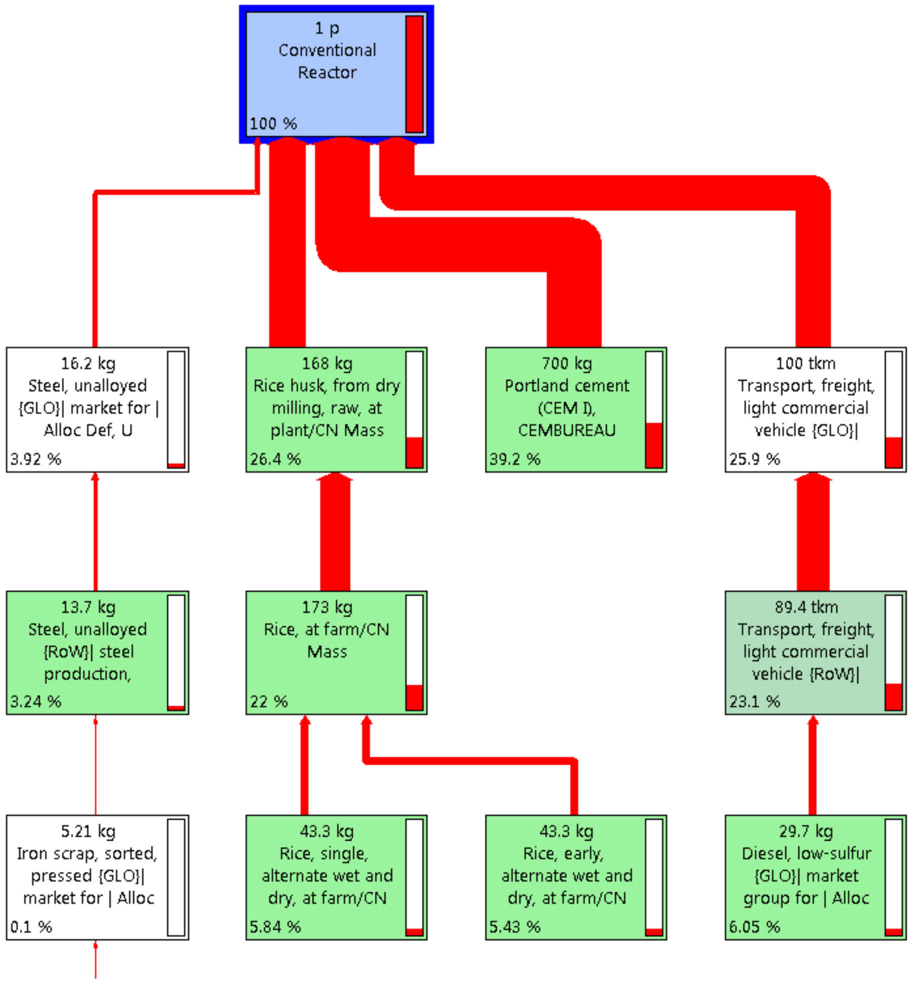


Figure 4- 29 Network – Single Score conventional reactor at 4% cutoff (Sima-Pro Software)

4.6.2.1 Comparison of energy consumption and production

Comparison of resources used throughout the process versus energy production from both types of the reactor was calculated. One kg of waste can produce up to 0.05 m^3 of biogas and one cubic meter biogas produces approximately 6 kWh energy (Balasubramaniyam et.al, 2008). A case study in Hainan Province, China, found that a 6 m^3 anaerobic digester has an annual net energy output of 3.5 million kilo calorie when operated at a mesophilic temperature range (Bi, 2007).

The biogas produced through the 70 days of reactor operation from the current reactor is scaled to the 6 m^3 reactor. According to the biogas digester construction manual, a six m^3 reactor has approximately 4.29 m^3 sludge (waste + water) capacity. So, the average mass of the waste which stays inside the reactor throughout the reactor operation is 2000 kilograms.

Table 4-16 shows the energy consumption and energy production from both types of reactor. The energy consumption of RHA reactors is slightly lower (2 MJ) than the conventional reactor, but energy production is 682 MJ higher than the conventional reactor. So based on the energy balance, RHA reactor is comparatively better than the conventional reactor.

Table 4- 16 Energy consumption and production

Items	RHA	Conventional
Energy utilized (MJ Primary) 20 years life	7109	7147
Energy utilized per year (MJ)	355	357
Biogas production in 6 m^3 reactor per year (liter)	143,136	107,257
Energy Produce (MJ/Year) (@Biogas energy content: 6kWh/M^3)	2720	2038
Total energy production (20 years)	54,392	40,758
Net Energy Production per year	2365	1681

4.7 Microbial Analysis Results

Table 4-17 summarizes the microbial communities present in the samples. The most dominant phyla were Bacteroidetes, Firmicutes, Fibrobactor, Spirochaetes, Tenericutes, and Proteobacteria; Euryarchaeota were also present. Similarly, Li et al. (2013) found the dominant phyla in anaerobic digesters with sewage sludge to be Bacteroidetes, Firmicutes, and Proteobacteria ().

Bacteroidetes (42% of microorganisms measured) includes hydrolytic bacteria (Metcalf and Eddy, 2004). Those bacteria help to break down long chain monomers to short soluble monomers. Bacteroidetes are well known to be associated with a high rate of hydrolysis and volatile fatty acid fermentation, which occurs in anaerobic digesters (Vanwonterghem et al., 2014).

According to Deublein and Steinhauser (2008) and Metcalf and Eddy (2004), **Firmicutes** (32% of microorganisms measured) contain hydrolytic, acidogenic and acetogenic bacteria. Garcia-peña et al. (2011) reported that most members of the Firmicutes phylum are volatile fatty acid-degrading bacteria, which often exist in both activated sludge systems and anaerobic digesters. Firmicutes help to convert short chain monomers to volatile fatty acids and to acetic acid.

Proteobacteria (2.2% of microorganisms measured) are important microbes in the anaerobic digestion process, because most of the Proteobacteria a contain hydrolytic and acidogenic bacteria.

Proteobacteria helps to breakdown the long chain molecules to short soluble monomers, as well as convert short chain monomers to volatile fatty acid such as lactic propionic and butyric acid. Proteobacteria are very important in the anaerobic digestion process and are well-known glucose, propionate, butyrate, and acetate-utilizing microbes (Ariesyady et al., 2007).

Euryarchaeota, a phylum of **Archaea** (0.44% of measured microorganisms), includes classes of methanogens which help to produce methane or convert acetic acid, carbon dioxide and hydrogen to methane.

Overall, bacteria comprised 99.3-99.7% of the samples and Archaea comprised 0.27-0.65%. Studies have shown that even the lower percentages of methane-forming bacteria present in the samples are able to generate methane up to 60-70% (Smith et.al, 2014).

Table 4- 17 Percentage of Microbial Communities in Samples

Kingdom	Phylum	Class	Cold Resistant Reactor	Conventional Reactor	Fresh Sample	Functions
Bacteria	Bacteroidetes	Bacteroidia	41.8	49.9	47.9	Hydrolytic
Bacteria	Firmicutes	Clostridia	32.6	30.1	21.8	Hydrolytic; Acidogenic Acetogenic
Bacteria	Fibrobacteres	TG3	5.1	3.1	2.7	
Bacteria	Spirochaetes	Spirochaetes	3.0	4.3	3.2	
Bacteria	Tenericutes	Mollicutes	2.4	1.1	1.4	
Bacteria	Proteobacteria	Betaproteobacteria	2.2	1.6	3.5	Hydrolytic; Acidogenic
Bacteria	Spirochaetes	Leptospirae	2.1	0.6	1.6	
Bacteria	Verrucomicrobia	Opitutae	1.5	0.5	1.3	
Bacteria	WWE1	Cloacamonae	1.1	0.3	0.7	
Bacteria	Verrucomicrobia	Pedosphaerae	1.0	0.9	1.3	
Archaea	Euryarchaeota	Methanomicrobia	0.4	0.27	0.22	Methanogens
Archaea	Euryarchaeota	Methanobacteria	0.04	0.10	0.02	Methanogens

Figure 4-30 compares archaea percentages in both reactors and fresh sample. Based on the archaea contained in each sample, RHA rector had highest percentage of the methane-forming bacteria, followed by the fresh sample and conventional reactor. That is the reason the RHA reactor started gas formation earlier, peaked earlier and had a higher rate of methane generation. Due to insulation the temperature inside the reactor was higher, and microbes acclimated faster and increased in population.

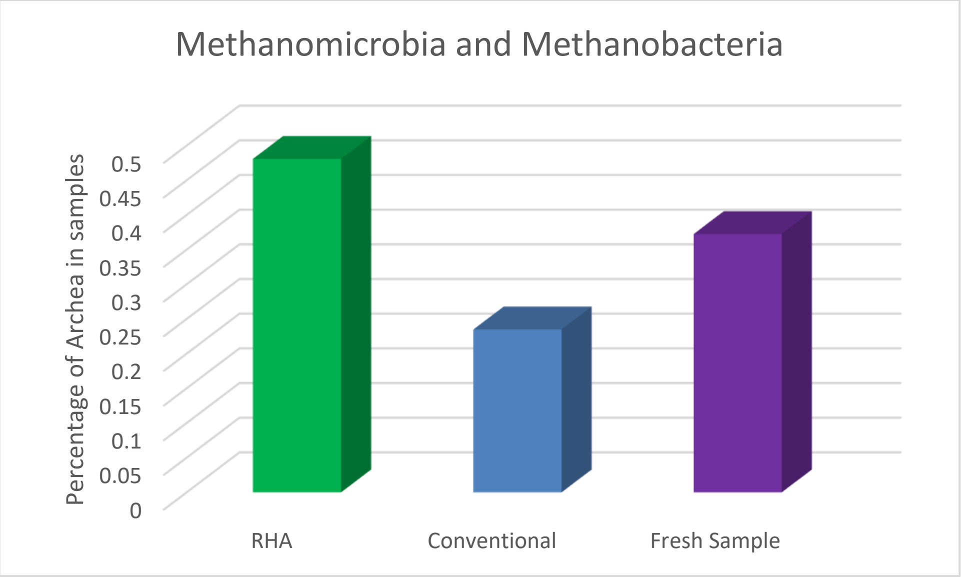


Figure 4- 30 Methane-forming bacteria in the samples

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

The results obtained from the current study can be summarized as follows:

1. The highest compressive strengths and lowest water absorption were obtained for bricks with 10% brick RHA, followed by 20% and 30%. The compressive strength of the brick decreases, and water absorption increases with increase in rice husk ash addition.
2. Firing time and temperature also affect the compressive strength and water absorption of the brick. Compressive strength increased and water absorption decreased with an increase in firing temperature. Increased firing duration sometimes increased and sometimes decreased compressive strength and water absorption, depending on the RHA composition.
3. Resistance to heat transfer increased with increased RHA percent and an increase in firing temperature. The 20% RHA mixed bricks had a higher R-value than the 10% bricks.
4. For both reactors (insulated and non-insulated), the reactor with insulation started gas formation earlier, peaked earlier and had a higher rate of methane generation as well as a larger cumulative volume of methane (33% greater after 102 days). The likely reason is that the insulation keeps the inside temperature higher in the reactor with the insulating material, which helped microbes grow faster and degrade the organic matter quickly.
5. After the gas formation started, the RHA reactor continuously produced gas even when the controlled room temperature (set temperature) was reduced gradually from 21 to 12 ^{0} C and ceased after 10^0 C; however, conventional reactor ceased after 14 ^{0}C.
6. According to the economic analysis, RHA reactor has a higher benefit-cost ratio (4.3 vs. 3.8) and internal rate of return (80% vs. 71%) for 20 years lifetime.
7. Based on the environmental impact analysis using computer software Sima-Pro, net annual energy production of RHA reactors is 684 MJ higher than the conventional reactor. So based on the energy balance, RHA reactor is comparatively better than the conventional reactor.

5.2 Recommendations for future studies

Based on the results obtained from the present study, the following recommendations are made for future study.

1. Performance of reactors can be investigated by using different types of waste such as paper, yard waste, food waste or a combination of all three waste with cow dung as an inoculum.
2. In this study, the experiments were conducted at a cold temperature, so further study on the effect of insulation on reactor performance can be done at warmer temperatures such as 30^0C, 35^0C, and 40^0C.
3. Reactor performance can be investigated by using bricks made of RHA and cement (instead of soil). Cement brick has a higher compressive strength than conventional bricks so more RHA can be added, resulting more improvement in insulation.
4. Further study can be done using the finer rice husk ash for making RHA brick rather than the coarse rice husk ash (charcoal).
5. For the current study, bricks were burned for 4 hours and 6 hours. So, the burning duration can be varied such as 8 hours 10, hours, 12 hours that can provide more combinations of samples.

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