Thesis for the Degree of Doctor of Philosophy

Industrial Bioprocess Developments for Biogas and Ethanol Production

Karthik Rajendran
Abstract

Current biofuels face a noteworthy misfortune on commercialization because of its economic comparison with low-cost fuel from the oil reserves. To compete with gasoline as a fuel, the biofuels need to be economically feasible and demonstrated on a large-scale. Biogas and ethanol have a great potential as commercial biofuels, even though it has difficulties, for example, high-capital investment, absence of demonstrated innovations, and availability of raw materials and so forth. This thesis focuses on different application-driven bioprocess developments for improving the techno-economic feasibility of the biogas and ethanol industries.

The biogas industry was studied from three different perspectives:

1) **Modeling** approach in which a Process Simulation Model (PSM) model was developed for predicting the biogas productions, as exploiting new substrates is vital for a biogas industry growth. The PSM model was created using Aspen Plus® which includes 46 reactions of different phases in the Anaerobic Digestion (AD) processes. It also contains certain important process parameters, thermodynamics, rate-kinetics, and inhibitions involved in the AD processes. PSM was a library model for the AD processes, which was validated against the laboratory and industrial data. The validation showed that the PSM predicted the biogas production about 5% in excess, which could ease the biogas industry to predict biogas from new substrates.

2) **Simulation** approach to study the imperative components affecting the profitability of the plant. For this purpose, a local municipality plant was studied under distinct situations. The choice of upgrading method, capacity, cost of waste and its processing, number of digesters used, etc. were exploited. The results showed that the collection and transportation fee, landfilling fee, and the reduced operation of a plant were the main considerations in influencing its profitability. Moreover, it was identified that for bigger cities the decentralization strategy could beat the expense of collection and transportation of waste, and the plant could obtain a 17.8% return on investment.

3) **Rethinking digester technology** in which the cost of the digester was significantly lessened using a cutting-edge textile, which was principally intended for developing countries. The digester cost played an important role in consuming biogas for different applications. The textile digester was tested on a laboratory scale, followed by field tests in different countries including India, Indonesia, and Brazil. Textile digesters cost one-tenth of the conventional digesters, and the payback was more or less between 1–3 years, when replacing the Liquefied Petroleum Gas (LPG) and kerosene as a cooking fuel for households.

When it comes to ethanol, the first generation ethanol production using grains was financially possible with a payback of about 13 years. Nonetheless, with the fluctuation of the oil prices, the ethanol industries need to look for alternative sources of revenues. Different retrofits were considered, including the effect of thin-stillage/whole-stillage to ethanol and biomass, in addition to the integration of the first and second generation ethanol production. The results revealed that 4% additional ethanol could be obtained when the thin-stillage was converted into ethanol and fungal biomass, while the payback was reduced to 11.5 years. The integration of the first and second generation ethanol production revealed that it has a positive influence on the overall economics of the process with a payback of 10.5 years. This could help the ethanol industries to consider a revamp for a better environmental, economic, and energy efficient process.

**Keywords:** biogas, ethanol, process design, techno-economic analysis, simulation, modeling
As a kid growing up in a country with a population of more than one billion, I have seen what happens when it is announced on television that there will be a hike in the price of petrol the next day. Everybody runs to the nearest petrol filling station to fill their gas tanks to save some money. This incident has always been in my mind, specifically, to provide fuel at a “cheaper price.” I took that as a challenge to work on as a thesis during my bachelors program, i.e., hydrogen from algae. Then, I realized that what I had discovered was not close to reality, and I realized that I needed more concrete knowledge. This motivated me to continue higher education in one of the developed countries through which I could learn the latest technology. One such place was the University of Borås in Sweden. There, the Bioprocess Design course, which I can say is still a unique course, fascinated me and led me towards Borås.

During that time, I met Professor Mohammad Taherzadeh and had a discussion on starting laboratory work on biofuels. He suggested that I pursue a thesis on biogas from waste textiles. I remember having to handle about 16 reactors during that time, and it was a huge task. A co-worker and I worked hard to make that project successful. But the first question in my mind was not yet answered. During this period, I also realized that research was something for which I had developed a passion during these years. The first thing that makes one a good researcher is to ask questions wherever and whenever possible. Research is nothing but answering questions and supporting those answers with evidence from the experiments.

Then, after my master’s program, I started a project work on biogas, but the challenge was different. I was asked to design a digester using a textile material, which could be portable, easy to operate, and cost-effective. Well, in hindsight, it was still challenging. I reviewed the existing literature on what had been done thus far, and then gave my suggestions as to how it could be novel. This work was published as a review article in Paper III. Based on that, a digester was designed; however, there were some practical challenges, in the form of adapting to temperatures, especially in Sweden. Acclimatizing the thermophilic or the mesophilic inoculums to the psychrophilic conditions was not easy; as a result, there were some failures. Then, I decided to try from scratch the good old theory of anaerobic digestion, i.e., from the rumen of the cow and using synthetic substrates. Both of my experiments were successful, and I could produce biogas using a textile digester. Based on the results, I did an economic analysis for developing countries, replacing the LPG and kerosene as fuel sources. I could foresee that biogas was not only environmentally friendly but also economically attractive (Paper IV).
At this point, I realized that the heart of any process to be successful was based on its economic returns. I wanted to study more about the biogas process industry and its economics. The source of funding for my Ph.D. studies was also for such a project; I could utilize those resources to exploit my hunger for knowledge on the bioprocess design with a focus on economics. The main challenge in studying the complete process industry was that one requires an adequate knowledge on simulation. Given my background, which is mainly in Biotechnology and not Chemical Engineering, I had to get my basics right. It was challenging however, the software I had learnt during my master’s program, i.e., SuperPro program had provided such a platform. To study an industrial process and its economics, it was necessary to build a model, which reflects reality. To study the complete biogas process, a digester model was built first. I tested this model in comparison with different experimental data (Paper I). The continuation of this work led to a process design for the complete biogas industry, and I studied the different factors that affect the profitability of the biogas plant or for that matter any process industry (Paper II).

To continue with my Ph.D. studies, I also got funding for a project to study an ethanol industry, based on some developments that our group proposed for the largest ethanol plant in Sweden. The experiences from the two process design works on biogas and its economics helped me to do the simulations with ease. However, the challenge here was the total number of unit operations used. Compared to the biogas industry, the ethanol industry has a large number of unit operations; thus, getting the simulation to work with the mass and energy balance was challenging. In the first work, I worked with some retrofitting solutions for the first generation ethanol industry (Paper V), and it was followed by the alternatives and suggestions proposed from our colleagues in the laboratory (Paper VI).

During this tenure of my Ph.D. studies, I also got the opportunity to work as a teaching assistant, where I taught the SuperPro designer to masters’ students and had a chance to supervise some masters’ theses, which molded me to the next level of my career. At every point of time, I think about learning, getting inspired and giving inspiration, and I’ll continue to do so. Still, I haven’t succeeded in my first objective; however, I have learnt the methods and steps to achieve my goal. I knew that my journey to be successful in this objective is neither too far nor near, but this thirst and search will continue forever.

Karthik Rajendran
I dedicate this thesis to my new born, priceless princess, Advikaa!
List of Publications

This thesis is mainly based on the results presented in the following articles:


Statement of Contributions

Karthik Rajendran’s contributions to each of the above publications are:

**Paper I:** Responsible for the idea, part of the simulation, data analyses, statistics, writing of the manuscript, and its revision

**Paper II:** Responsible for the idea, experimental design, economic evaluation, writing of the manuscript, and its revision

**Paper III:** Responsible for all the literature survey, data collection, writing of the manuscript, and its revision

**Paper IV:** Responsible for all the experimental work, data analyses, economic evaluation, writing of the manuscript, and its revision

**Paper V:** Responsible for the idea, part of the simulation, economic evaluation, data analyses, writing of the manuscript, and its revision

**Paper VI:** Responsible for the simulation, data analyses, writing of the manuscript, and its revision
List of Publications Not Included in This Thesis

Articles:


Book Chapters:


Acknowledgements

The route to a Ph.D. is not a freeway, but the speed-bumps and the pull-overs made it special. However, lots of mixed emotions have been felt by taking this route, some of them turned the hurdles into highlights. I take this opportunity to thank everyone who helped me to achieve this goal.

The Godfather: Professor Mohammad Taherzadeh, who gave me invaluable insights not only in research but also beyond. The speed of light was a little slow, compared to your lightning quick replies. Every time I sent you an email, waiting to check the time you opened and replied back. That was an awesome experience that I enjoyed throughout this journey. A good mentor is one, who tells you where to see but not what to see, and you have been a top flight. You have been planting the seeds in my mind for the last six years, and I believe that at least a few of them have started to sprout.

The second-eye: My co-supervisor Karimi and examiner Kim, you both have helped me with your suggestions and encouraging words. Especially, Karimi, with whom, until today, my contact has been through e-mail and he managed it effectively.

A beautiful mind: The teachers who made the basement strong for my research building, Peter, Magnus, and Elizabeth. Your extraordinary and simplified teaching methodologies have made my fundamentals sound.

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The meaning of life: My parents, and sisters Vino, Thavasi, and Niti. You have sailed with me to this point of my life. Thank you all; you are wonderful human beings to stand by me.

Life of Pi: As pi can never end, so too is the love and affection I have received from my wife Aparnnaa. Thanks for being in my life. Tweety-pie Advikaa, I’m waiting to see you soon.
### Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>Anaerobic Digestion</td>
</tr>
<tr>
<td>ADM1</td>
<td>Anaerobic Digestion Model No.1</td>
</tr>
<tr>
<td>AMPTS</td>
<td>Automatic Methane Potential Testing System</td>
</tr>
<tr>
<td>APC</td>
<td>Annual Processing Capacity</td>
</tr>
<tr>
<td>BFD</td>
<td>Block Flow Diagram</td>
</tr>
<tr>
<td>CBG</td>
<td>Compressed Biogas</td>
</tr>
<tr>
<td>CCP</td>
<td>Cumulative Cash Position</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>COOAB</td>
<td>Carbon Dioxide Absorption by Amine</td>
</tr>
<tr>
<td>CSTR</td>
<td>Continuous Stirred Tank Reactor</td>
</tr>
<tr>
<td>DDGS</td>
<td>Dried Distillers Grains With Soluble</td>
</tr>
<tr>
<td>GC</td>
<td>Gas Chromatography</td>
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<tr>
<td>HPLC</td>
<td>High Performance Liquid Chromatography</td>
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<tr>
<td>HRT</td>
<td>Hydraulic Retention Time</td>
</tr>
<tr>
<td>IRR</td>
<td>Internal Rate of Return</td>
</tr>
<tr>
<td>LCFA</td>
<td>Long Chain Fatty Acids</td>
</tr>
<tr>
<td>MEA</td>
<td>Mono-Ethanol Amine</td>
</tr>
<tr>
<td>MMSP</td>
<td>Minimum Methane Selling Price</td>
</tr>
<tr>
<td>NFDS</td>
<td>Non-Fermentable Dissolved Solids</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>OFMSW</td>
<td>Organic Fraction of Municipal Solid Waste</td>
</tr>
<tr>
<td>OLR</td>
<td>Organic Loading Rate</td>
</tr>
<tr>
<td>P&amp;ID</td>
<td>Process and Instrumentation Diagram</td>
</tr>
<tr>
<td>PBP</td>
<td>Payback Period</td>
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<tr>
<td>PFD</td>
<td>Process Flow Diagram</td>
</tr>
<tr>
<td>TS</td>
<td>Total Solids</td>
</tr>
<tr>
<td>VFA</td>
<td>Volatile Fatty Acids</td>
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<tr>
<td>VS</td>
<td>Volatile Solids</td>
</tr>
<tr>
<td>WWTP</td>
<td>Waste Water Treatment Plant</td>
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References
1 Introduction

Fossils are the leftovers of animals and plants, which undergo natural anaerobic decomposition, and it takes millions of years to form fossil fuels. Today, more than 84% of the world energy demand is met by fossil fuel reserves. Let us consider the balance between the rate of formation of fossils and its utilization. It is rather easy to say that the utilization of fossils exceeds the rate of its formation, which is due to factors such as growth in population, and developments in science and technology. This trend raises the question about sustainability of energy for the future. It is estimated that petroleum, natural gas, and coal reserves will be depleted within a span of 200 years [1].

Harvesting energy in an ecological and environmental manner is the only way to answer the question of sustainability. Since the 1970s oil crisis, different forms of energy extraction have been studied including solar, wind, hydrothermal, geothermal, and biomass. Most of the green energies available today are heavily subsidized, which will raise a problem in the future regarding its economic acceptance and mass production levels. In addition, most of the technologies could not be proven both technically and economically as equivalent to energy production from petroleum and coal reserves. Even if some technologies were proven, for instance, ethanol or biodiesel for food/energy crops, the next plea arises regarding the conflict of food and fuel. For a change to happen, efforts are required from various stakeholders including policy makers, government, research, industries, and the public.

Forms of biofuels include ethanol, biodiesel, biogas, hydrogen, butanol, etc. The focus of this thesis was given to ethanol and biogas. The important reason behind this choice was that ethanol has a well-established industrial setup, while the industrial acceptance for biogas has started recently. Ethanol is mostly produced from corn, grains, and sugarcane, and it is mainly used in the transportation sector. On the other hand, biogas is now seen as a technology, not just to produce energy but also as a method to manage waste. Recent focus on biogas includes the exploitation of new substrates, optimization, etc. This thesis tries to address certain important issues concerning the techno-economic feasibility for the biogas and ethanol industries.
1.1 Aim

The aim of this thesis was to address some of the problems in the biogas and ethanol industries toward the betterment of profitability and efficiency of the process. This work can be fragmented into:

1. To develop a model for the AD processes, which can be used in studying the overall process design and profitability of an industrial biogas plant (*Papers I and II*).

2. To study the existing digester technologies and develop a cost-effective digester technology applicable on different scales (*Papers III and IV*).

3. To check the possibility of retrofitting an existing ethanol plant and seeing its behavioral changes on the techno-economic perspective. In addition, the possibility of integrating the first and second generation ethanol production was studied (*Papers V and VI*).

1.2 Outline of the thesis

This thesis was divided into eight main chapters and addressed as:

- *Chapter 1* – Synopsis to the thesis and motivation behind, including the goals.
- *Chapter 2* – Reviews the biogas and ethanol technologies, and how it could be a realistic energy source from the biofuel sector. In addition, current problems in the industries were also highlighted.
- *Chapter 3* – This chapter focuses on the need for a model for the AD processes, which could shape the biogas industry to exploit new substrates with ease. Previously available models are emphasized, with an elaboration on the new model proposed including its validations from different case studies (*Paper I*).
- *Chapter 4* – Presents the important factors affecting the profitability of an industrial biogas plant working on MSW. The focus was given towards the process design and economic considerations (*Paper II*).
- *Chapter 5* – Introduces the need for a cost-effective technology in biogas, which should be affordable across different countries. In addition, a summary is presented on the existing technologies. Furthermore, the new concept of a textile reactor was
introduced with studies on different scales, including its commercial acceptance (*Papers III and IV*).

- **Chapter 6** – This chapter focuses on the first generation ethanol production and its improvement based on an industrial process, which use grains. In addition, the integration of the first and second generation ethanol production was also exploited. The main focus was on the process design aspects to replicate the industrial scenario (*Papers V and VI*).

- **Chapter 7 & 8** – Provide the final remarks on conclusions and further improvements for this thesis.

1.3 **Social and ethical reflections**

Every research and finding has an objective i.e., to bring a betterment to humanity. The likes and passions motivate one to drive on different roads, and my motivation was always toward bioprocess and in that way, I’m really happy to follow my passion. But, what is my passion going to give to this humanity? What have I done? Did I improve the quality of a human life here? The answer is yes! Let’s consider the textile digester, where the current discussion on the business model is that we will have agents, traders, and laborers, who will be responsible at the ground level. This stimulates a lot of business and employment opportunities directly and indirectly for several people. This project not only improves the economic situation but also the environment. It was mentioned that most villages and rural areas still use firewood for cooking, which leads to health hazards. Nonetheless, when using some kind of technology, which is cost effective and which improves the standard of living, it is a positive reflection on the environment. Also, when I consider certain industrial projects, where you improve the energy efficiency of the ethanol company by 2.5%, you could consider that the saved energy could light up some homes. The social reflections are that a provision for a better society, the ways to teach about the importance of using our environment efficiently and not just dumping the waste, brings awareness to the public on the importance of source separation. Life is about sustainability and what we can give to our future generations. And I believe I will carry a message about sustainability to the future generations.
2 Biogas and Ethanol – A Realistic Energy Source

2.1 Biomass – a source of energy

The need to meet the energy demand has left the choice of exploiting different sources of energy. Biomass is one of the leading contenders as it annually accounts for 20–50 billion tons in dry weight [2]. Some of the important reasons as to why using biomass for energy could be interesting are its abundance, environmentally friendly, renewable and replenishing source, diversified raw materials choice. Producing energy from biomass is not a new concept, as more than 2 billion people use it as a primary fuel source for cooking. Although the direct combustion is hazardous for health, producing or converting it into energy in a controlled way solves this issue. It is not always that all the biomass is directly converted into energy; on the contrary, in certain scenarios, it is converted into its intermediators such as biofuels.

Biomass could be converted into energy or its carriers by three different routes: (1) Thermo-chemical conversion – in which the biomass is converted into charcoal, oil, and heat by processes such as combustion, pyrolysis, and gasification [3]. (2) Biochemical conversion – where biomass is converted into products such as methane or alcohol using biochemical methods either by anaerobic digestion or fermentation [4]. (3) Chemical conversion – where the addition of chemicals is used to extract fuel from the biomass, for instance, the transesterification process in the production of biodiesel [5]. Figure 2.1 shows the different routes of processing biomass and its products.

Biomass is a diversified source, which could be fragmented as:

(1) Agricultural and forestry biomass – This includes leaves, stalks, branches from the plants and forests. It also includes the wastes from wood and agricultural industries during its production and processing.

(2) Animal waste – The animal waste includes the wastes from livestock operation such as cattle farms and slaughter houses. The dung from the cattle farms could be converted as dung cake or biogas, while slaughter house wastes can be the left overs as well the dead animals, which could be combusted.
(3) Municipal waste – Municipal waste includes the garbage from households, human excreta, sewage, and effluents.

(4) Marine biomass – This includes biomass from water such as seaweeds, water hyacinth, and algae, which could be converted into biodiesel, biogas, and other fuels [6].

(5) Energy plantation – Energy plantation specifically refers to the growth of biomass, which could be harvested in a short time for a specific purpose of biofuel production. Some of the energy crops include jatropha, soybean, castor seeds, and silage. However, the use of energy crops raises the debate on the use of arable land for the production of food or for energy production [5, 7].

![Figure 2.1 Different routes of energy production from biomass](image)

2.2 Food vs. Fuel

The increase in biofuels production over the years has used raw materials such as corn, sugarcane, or vegetable oil, which were once primarily used as a source of food. What this trend does is that there is a shift in using arable lands for cultivating food/energy crops for the
production of biofuels instead of its primary purpose i.e., food [8]. This drift is due to the fact that the cost of these energy/food crops for biofuels increases, which is evident from the increase in the corn price in the United States over the last few years. This, in turn, increases the inflation on the other agricultural products as the usage of land for other purposes becomes reduced. With the biofuels that use energy crops, the question is raised as to whether the land should be used for cultivating food crops or for use in energy production.

This raises a conflict in the developing countries with issues related to sustainability. For instance, Sweden produces an excess of grains, which are used as a source of ethanol production, while in several other countries the requirement of grains for food is high [9]. If the grains are mainly consumed for ethanol production, this increases the deficit in the availability, which increases the price of grains, resulting in consumers having to pay more money for food. This debate is ongoing, and only the future will provide answers to this dilemma.

2.3 Biogas – a multi-diversified fuel

Overview

Biogas is a mixture of predominantly methane and carbon dioxide produced as a result of AD of organics. The production of biogas is a four-step process, where the complex materials such as carbohydrates, proteins, and fats are first converted into their short-chain molecules such as sugars, amino acids, and fatty acids in the hydrolysis phase. Next, these short-chain molecules are converted into short chain fatty acids such as propionic acid, butyric acid, iso-butyric acid, valeric acid, iso-valeric acid, and caproic acid. In the third phase, i.e., the acetogenesis phase, these short chain fatty acids are converted into acetate and hydrogen, and finally in the methanogenesis phase, they are further converted into methane and carbon dioxide [10]. Figure 2.2 shows the schematic diagram of the different phases in the anaerobic digestion.

In the biogas production, the substrates are usually reduced in size and stored in a vessel, before they enter the actual digestion process. During the AD process, the substrates are converted into two fractions, comprising a liquid fraction and a gas fraction. The gas fraction contains methane, carbon dioxide, and other traces, while the liquid fraction contains the undigested materials and the excess nutrients. Mostly, this fraction, which is rich in nitrogen,
Phosphorus, and potassium, could be used as a fertilizer. The fertilizer acts as a valuable byproduct, which could improve the overall economics of the process, especially in countries where the cost of fuel is less or the need for fertilizer is high. For instance, in Indonesia, the palm oil plantations require a high quantity of fertilizer to grow the trees than the biogas itself.

Diverse applications

The energy density of methane is about 55 MJ/kg, which can be used for different purposes including cooking, heating, electricity, and fuel. Table 2.1 shows the typical energy density of different fuels, which are used today. Most of the biofuels are primarily used in the transportation sector and is produced only in industries. For instance, biodiesel or bioethanol are mainly used in the transportation sectors and are mainly produced only on an industrial scale. With regard to the biogas, it can be produced and applied starting from a household to the industries. Biogas is a diverse fuel, which can be used for different applications, including

![Figure 2.2 Schematics of the biogas production process (Paper IV)](image-url)
cooking at the household level; it can be converted into electricity using generators or fuel cells or micro-turbines, producing heat using combined heat and power (CHP) systems, and finally, as a vehicle fuel when upgraded [10].

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Energy density (MJ/kg)</th>
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<td>Landfill gas</td>
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<tr>
<td>Biogas from AD</td>
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<td>Methane</td>
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<td>Diesel</td>
<td>45.6</td>
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<tr>
<td>Ethanol</td>
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</table>

2.4 Ethanol – a transportation fuel

Overview

The oil crisis in the 1970s led to the search of alternative sources of fuel for transportation, which has increased the ethanol production. Since then, bioethanol has become one of the most important biofuels, and it is blended with up to 95% gasoline depending on the geographical location and the engine used in the vehicle. Currently, ethanol is produced from simple sugar and starchy materials such as sugarcane, corn, sugar-beet, and grains [11]. Ethanol, with a molecular formula of C₂H₅OH, has advantages, compared to gasoline including higher octane number, broader flammability limits, high flame speed, and higher heat of vaporization. This advantages result in higher efficiency, burning time, and short compression ratio in the engines. Nonetheless, there are certain disadvantages including corrosion, lower vapor pressure, and energy density [12].

The ethanol production processes shall be distinguished as preprocessing, fermentation, and down-stream processing. During the preprocessing step, the objective is to release the sugars from the substrate, which is easy for the yeast to convert into ethanol during fermentation. Post-fermentation, the mash contains ethanol and undigested solids. The ethanol is upgraded using the distillation unit procedures, while the solids contain a lot of organics, which could be a byproduct as an animal feed [13]. The byproducts are essential for the economic sustainability of the process, as the revenue only from the ethanol would not help an ethanol plant to have a positive economic situation.
Transportation fuel

Ethanol is predominantly used in the transportation sector as an additive to the gasoline, with the common blending with an upper limit of up to 10%. Some countries that have mandated 5% or greater concentrations of ethanol in the gasoline include Sweden, India, Jamaica, Canada, Finland, Thailand, Philippines, Paraguay, Romania, and Ireland. Up to 10% blending means that an engine modification is not required. However, for higher concentrations of ethanol, specially designed engines should be used. Currently, different ethanol blends are available such as E85, E95, E100, mainly due to the modifications in the combustion engines. Previously, the Brazilian ethanol was cheaper due to the abundance of the raw materials; however, in recent years, Brazil has imported ethanol from the US [14]. The important reason to consider ethanol as a transportation fuel is due to its higher octane number, and in higher blends of ethanol i.e., E85, 15% gasoline was added to provide ignition during the cold weather.

2.5 Problems with biogas and ethanol industrialization

Both biogas and ethanol have made a significant progress on industrialization, markets, and registered its presence as a biofuel in reality. Nonetheless, there are certain issues that should be addressed, and the solutions have to be modified according to the problems on a case to case basis. Some of the important issues that need to be addressed are:

- **Biogas** – For biogas processes, the problems include the exploitation of certain new substrates, designing an energy and economically efficient process, bringing down the investment and production costs, addressing the issue of the separation of organics mainly in the MSW. Moreover, the current need is the affordability of the technology to all people. Due to the heavy investment, biogas technology is a problem for many developing countries, even though it is much needed.

- **Ethanol** – The need for lignocellulosic ethanol production is increasing; however, it still does not match with the industrial requirements to proceed with a full scale production due to the fact that the cost of the first generation ethanol production is cheaper. On the other hand, the existing first generation processes could also be
improved with additional byproducts, which could make it even more economically
attractive.

This thesis was developed with a focus to solve some of the problems on the industrial
scale, with a priority on the techno-economic perspective.
Models are the representations of the real life processes, which require computational powers to build. With the advancement of computers, it makes the complicated process calculations faster. The important application of the model is to help to troubleshoot real life process, which can help to resolve a problem in the process industry. In addition, they can also be used in analysis, be a tool for decision making about new alternatives, check what-if scenarios, as well as to test the agility and reliability and furthermore, help in finding opportunities to reduce the operating cost.

3.1 Models of anaerobic digestion

Andrews et al. (1968 – 1974)

The first model for the AD processes was built by Andrews and colleagues in the late 1960s, and this model was based on the Monod kinetics. The original model was a mathematical model, which was presented for both batch and continuous systems. The significant feature about this model was the use of an inhibition function to relate the concentration of a substrate and the specific growth rate of the microorganism. However, this was a generalized model for the microorganism, irrespective of the AD process [15]. The inhibition function is given by the following equation:

\[
\mu = \frac{\mu^*}{1 + \frac{K_s}{S} + \frac{S}{K_i}}
\]

\(\mu\) - specific growth rate
\(\mu^*\) - Maximum specific growth rate in the absence of inhibition time
\(S\) – Limiting substrate concentration
\(K_s\) – Saturation constant
\(K_i\) – Inhibition constant

Based on the generalized model, a specific model was developed for the continuous AD processes. This model contains the equations for the interactions between the gas, liquid, and biological phase. Inhibition expression for the organism growth rate from the mathematical
model was considered to be the key step. In addition, the VFA production was considered as the rate-limiting step [16-18]. This model was further modified as an extended model, with the inclusion of an expression for the death of the microorganism due to the toxic compounds and the experimental verification of the physical-chemical relationships, buffering the effects from the solid phase. As a result of this simulation, the toxic overloading could be studied, in addition to the other process parameters such as VFA, pH, etc. [18].

McCarty et al. (1969 & 1975)

McCarty and colleagues developed the AD model based on the kinetics of utilization of important VFA and was also based on the Monod kinetics. According to the model, the kinetic coefficients were calculated based on the substrate utilization in the form of free energy. The digester was fed with different VFAs at different concentrations, temperatures, and hydraulic retention times (HRT). Here, the microbial growth was related to the free energy available, which was formed as a result of the biochemical transformations of the substrate. The free energy was calculated in the form of the chemical oxygen demand (COD), and it is related to the methane formation [19]. The relationship between the solids retention time or the inverse of specific growth rate and the effluent VFA concentration is given by:

\[
(SRT)^{-1} = \mu = \frac{a \times k \times s}{K_s + s} - b
\]

\(SRT\) - Sludge retention time  
\(\mu\) - Specific growth rate  
\(a\) - Growth yield coefficient  
\(b\) - Microorganism decay coefficient  
\(s\) - Waste concentration in the reactor  
\(K_s\) - Half velocity coefficient  
\(k\) - Maximum rate of waste utilization

The kinetic model was further developed as a BIOTREAT model with the computational program FORTRAN, which includes the stoichiometric reactions for the microbial growth, VFAs, and a custom reaction for unknown organics. This model combined stoichiometry, thermodynamics, and kinetics. However, it was a general model for waste water treatment, which includes sludge, nitrification, anaerobic treatment, aerobic treatment, etc. [20].
**Angelidaki et al. (1993 – 2002)**

The other group that also worked on the modeling of the AD process was the one led by Angelidaki. In 1993, she formulated a mathematical model that included 12 chemical compounds as well as ammonia inhibition, pH, temperature, and enzymatic hydrolysis [21]. Further, this model was developed as a comprehensive model, which included more details from the previous model such as phosphate, more chemical compounds, VFA, and long chain fatty acids (LCFA). It also included the co-digestion of different substrates, and it was verified with an industrial biogas plant operating on manure, waste water, and lipids [22].

Later, the International Water Association formed a task group in 1997 to develop a generalized AD model. This model was called the anaerobic digestion model no.1 (ADM1), which implemented differential equations to solve the complexity of the AD process. This model included the extracellular hydrolysis, carbohydrates, proteins, lipids, VFA, LCFA, and separate methanogenesis phase. In addition, the chemical engineering aspects such as ion association and dissociation, and gas-liquid transfer were also accounted for, leading to one of the best available models for the AD process until today [23-25].

**Other Models**

Some of the other models, which were developed for the AD process, are described below. The common methodologies include kinetics, mathematics modeling using differential equations, statistical model, regression model, numerical methods, integration, and algebraic equations [26-29]. Furthermore, there were software program approaches that included software such as Bio Win, SIBMA, and programming languages such as FORTRAN [30-32]. The flow patterns or the chemical engineering aspects were generally considered using COMSOL, and open FOAM, using the computational fluid dynamics approach. Other approaches included artificial neural networks, which use fuzzy logic [33-35]. Although the approaches were different, the basic assumptions for most of the models developed were based on the ADM1.
Applications and modifications of ADM1

ADM1 from the International Water Association was a very strong model for the AD processes. This model was incorporated in several studies for different purposes including the application of ADM1 and customizing ADM1 for their respective purposes. For instance, Antonopoulou et al. [36] modified the ADM1 to fit fermentative hydrogen production as ADM1 did not account for metabolic products such as lactic acid and ethanol, which are formed as intermediates [36]. Similarly, in another instance, ADM1 was compared to the Gompertz [37] Model for hydrogen production, and the former model could predict the COD, cumulative hydrogen production, and VFA. Although the fit was high in the latter model, it shows that ADM1 model had a strong basic consideration and could predict the parameters with less input than the other models [37].

The ADM1 model was modified for specific substrates to improve the precision of the model. Some of the studies that modified the model included substrates such as agricultural residues, pig manure, and glycerin co-digested [38, 39]. In other cases, the ADM1 was used to study the effect of the two-stage AD process, which examines the experimental work and the modified model of the agricultural wastes [40, 41]. Other applications of the ADM1 include the prediction of the AD process using waste water, sludge, and grease waste [42-44].

Another interesting application of the ADM1 is the waste characterization studies performed by Girault et al. [45]. In that study, a procedure for the degradation kinetics was developed for the characterization of the available COD as carbohydrates, proteins, and lipids. In addition, other parameters such as the substrate to inoculum ratio were also examined. The results showed that the variation in the COD for the substrate characterization, and its effect in the biogas production was temporary [45].

3.2 Process simulation model

Most of the previous available models were built on mathematical models or complicated equations, which did not consider the process parameters such as the loading rate, retention time, total solids, etc. These parameters play a pivotal role in the biogas formation. For modeling an AD process, the combination of thermodynamics, kinetics, and process
parameters were never attempted before, which shows the significance of the process simulation model (PSM).

This model was comprised of two different sets of reactions: set (a) contains the equations for the hydrolysis phase in the AD process and set (b) contains the kinetics equations for the remaining three phases of the AD processes i.e., acidogenesis, acetogenesis, and methanogenesis. In total, about 46 reactions were added to the model, which contains kinetics, pH, ammonia inhibition, volume, total solids, loading rate, and retention time. Figure 3.1 shows the block diagram of the PSM, which contains the reaction set (a) and (b) with the calculator blocks. Compared to the previous available models, this model is unique, in considering the process parameters such as the total solids, loading rate, and volume and retention time. These process parameters are used as input information in the form of carbohydrates, protein, fats, and water content to the model. These inputs pass through the reaction set (a), where the amount of monomers released during the hydrolysis step is determined. In reaction set (b), ten different blocks are used, which are comprised of different equations for the different phases of the AD (Paper I).

![Figure 3.1 Block diagram of the process simulation model](image-url)
Depending on the released monomers from the hydrolysis phase, the respective block equation with the kinetics will be activated. For instance, the protein mixture goes through the amino acids block, where the amino acids will be converted into short chain fatty acids. Finally, all the intermediary components will pass through the methanogenesis block, where the amount of methane formation is estimated. The reaction set (b) contains a FORTRAN program for each block, which calculates the product formation for each individual reaction. The model was developed based on the ADM 1 and its kinetic parameters were obtained from [23, 46]. Power law was used to calculate the reaction rate, specific growth rate, and ammonia inhibition (Paper I).

### 3.3 Validations

The developed model was validated against experimental data to check for its robustness and reliability. A total of seven different case studies were considered for validation using different substrates, loading rate, size of the digester, and retention times. A wide variety of scales were considered, ranging from laboratory scale to industrial plants, which could prove the credibility of the model. The results of the validations from the model for different datasets were in the range between +11.9% to -12.4%. Table 3.1 shows the different cases and the simulation results from the model. A statistical analysis was performed to check if there was any difference between the results, and it was showed that the P-value was greater than 0.05, meaning that there was no significant difference between the experimental results and the results from the model, which considered the different datasets (Paper I).

In addition, a sensitivity analysis was performed to check the detailed behavior of the model. The sensitivity analysis was performed for two important factors i.e., the extent of the reaction in reaction set (a) and a variation in the composition of the substrate. A regression plot and confidence interval were calculated to identify the durability of the model. On average, about 5.3% higher value was expected from the model due to the sensitivity analysis, while the average regression value was greater than 0.9383 showing the model to be fit, when altered for the important parameters. Using such computational power could help the biogas industry to exploit new substrates and study the substrates based on the respective scenarios (Paper I).
Table 3.1 Validation of the PSM with different studies

<table>
<thead>
<tr>
<th>Volume</th>
<th>HRT (days)</th>
<th>Loading rate</th>
<th>Substrate</th>
<th>Experimental results</th>
<th>Simulation results</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 L</td>
<td>15</td>
<td>0.33 L day⁻¹</td>
<td>Cow manure</td>
<td>353.5 L kg⁻¹ vs day⁻¹</td>
<td>365.83 L kg⁻¹ vs day⁻¹</td>
<td>3.4</td>
</tr>
<tr>
<td>5 L</td>
<td>21</td>
<td>3.0 g VS L⁻¹ day⁻¹</td>
<td>MSW</td>
<td>0.54 m³ CH₄ kg⁻¹ vs day⁻¹</td>
<td>0.473 m³ CH₄ kg⁻¹ vs day⁻¹</td>
<td>-12.4</td>
</tr>
<tr>
<td>5 L</td>
<td>21</td>
<td>3.0 g VS L⁻¹ day⁻¹</td>
<td>70% MSW and 30% citrus waste</td>
<td>0.555 m³ CH₄ kg⁻¹ vs day⁻¹</td>
<td>0.537 m³ CH₄ kg⁻¹ vs day⁻¹</td>
<td>-3.2</td>
</tr>
<tr>
<td>30 L</td>
<td>8</td>
<td>230.4 g VS day⁻¹</td>
<td>Pig manure</td>
<td>0.269 m³ kg⁻¹ vs</td>
<td>0.268 m³ kg⁻¹ vs</td>
<td>0.3</td>
</tr>
<tr>
<td>600 L</td>
<td>25</td>
<td>2.0 g VS L⁻¹ day⁻¹</td>
<td>MSW</td>
<td>401 L kg⁻¹ removed</td>
<td>448.76 L kg⁻¹ removed</td>
<td>11.9</td>
</tr>
<tr>
<td>3000 m³</td>
<td>21</td>
<td>150 m³ day⁻¹</td>
<td>MSW</td>
<td>9600 m³ day⁻¹</td>
<td>10176 m³ day⁻¹</td>
<td>6.0</td>
</tr>
<tr>
<td>3700 m³</td>
<td>20</td>
<td>150 m³ day⁻¹</td>
<td>MSW</td>
<td>75% slaughter house waste, 15% food waste and 10% cow manure</td>
<td>10959 m³ day⁻¹</td>
<td>11694.6 m³ day⁻¹</td>
</tr>
</tbody>
</table>
4 Feasibility Studies on AD

4.1 Overview of the techno-economic analysis

Techno-economic analysis is a basic criterion to evaluate the feasibility of the process, before it is executed in reality. This analysis can be done on different scales, including the order of magnitude or block flow diagram (BFD), based on a process flow diagram (PFD), preliminary design (scope estimate), and P & ID diagram; the last two methods are detailed ones known as definitive and firm estimate. The order of magnitude estimate is based on a ratio from a previous plant, and it is adjusted for different factors including inflation and capacity. This is a basic estimate, and there are several factors that are taken into consideration when seeking a detailed estimate. Next, is the PFD estimate, which is based on the important equipment’s in the process. The sizing equipment is not calculated accurately; hence, the cost obtained is an approximate value.

The third estimate is based on a P & ID diagram, which provides more details than the previous estimates such as layout of the equipment, piping, instrumentation, and electrical requirements. The accuracy of the P & ID estimate is between 70% – 80%, giving an outlook on the whole process. In the definitive estimate, utility balances and elevation diagrams are taken into consideration. It is calculated when more than 50% of the project is definitive. Lastly, the firm estimate is a deterministic method, which is based on the pricing from the contractors when all the plans are ready. Once this estimate is complete, the chemical plant is ready for the construction stage [47].

Previously, the techno-economic analysis was carried out manually; however, the advancement in computers and chemical engineering has allowed for simple procedures to be calculated. Currently, most of the techno-economic analysis is carried out using process simulators such as Aspen, SuperPro, Prosim, Capcost, etc. of which, Aspen has been widely accepted by many of the process industries. In this thesis, all the simulation was carried out using Aspen Plus™ and the economic analysis with the Aspen Process Economic Analyzer. Some of the main economic parameters involved in the techno-economic analysis are capital cost, operating cost, rate of return on investment (IRR), payback period (PBP), and net present value (NPV).
4.2 Techno-economic analysis on AD

Techno-economic analysis is very essential for any process to check its feasibility. Especially in biofuels, the feasibility is very important, as it has to compete with conventional fuels. In this section, a summary of different techno-economic analysis on the AD processes is elucidated. Commonly, in techno-economic analysis, the processes are first solved from mass and energy balances. Upon successful material balance, the sizing and utilities are specified, before considering the economical parameters. Then, the technical and economical parameters are analyzed on alternating scenarios / sensitivity analysis to find the important factors, which affect the process design and economics.

The common practices for techno-economic analysis in the AD processes include, activated sludge, organic fraction of municipal solid waste (OFMSW), and manure [48-51]. The reason for this is the abundance of the raw material, existing commercial process feasibilities, and demand for energy. The end use application may vary for the commercial processes such as CHP and vehicle fuel. The investment cost for CHP is less, compared to that of vehicle fuel; thus, the economic returns are inversely proportional. The choice of the end-product depends on the demand for the product and the cost of its conventional resource. Other choices, which play an important role in the profitability of the plant include the transportation cost of the waste, technology and size of the plant, taxes, availability of raw materials, gate fees, policies, and incentives [52, 53]. For instance, in Sweden, organic wastes ending up in landfills has been banned, while in some eastern European countries like Romania, the landfill is more than 99%, which is mainly due to the policy issues [54, 55].

The choice of the optimal size of the biogas plant depends on several factors such as the raw materials, collection and transportation cost, and efficiency of the plant. Walla and Schneeberger [56] have reported that for biogas production from maize silage, the size of the biogas plant depends on the land used to grow the maize and the size varies based on the land

- Capital cost - refers to the overall investment for the company
- Operating cost - refers to the annual running/manufacturing costs for the company
- IRR - corresponds to percentage of return on the investment
- PBP - refers to the number of years the investment is said to be recovered
- NPV - refers to the net profit after the lifetime of the process
used [56]. Another factor that needs to be considered is the subsidy. For instance, in India, the subsidy is only available when the electricity production is greater than 1 MW. Here, the size depends on the subsidy, and not on the land availability.

**Process developments on pretreatments**

It was earlier reported that the common substrates, which were used in the techno-economic analysis were activated sludge, manure, and OFMSW. The techno-economic analysis was also carried out when these substrates were subjected to technological changes. Dhar et al. [51] reported a techno-economic evaluation of activated sludge using ultrasound and thermal pretreatments. In this study, the different energy inputs for ultrasound and varying temperatures for thermal pretreatments were considered. The results showed that the operating cost could be reduced between 44 – 66 USD/ton dry solid, compared to the conventional system [51].

Improving the existing system is common with the advancement in technology. Recently, certain new substrates have been exploited for biogas production and have been evaluated for commercial feasibility. Most of the new substrates belong to the class of lignocelluloses, which require a pretreatment. The techno-economic analysis is very common for pretreatment combined processes for AD. Some of the substrates which are explored for techno-economic analysis include citrus wastes by steam explosion [57] and integrating as a biorefinery concept with other products such as limonene and ethanol [58], chicken feathers by alkali pretreatment [59], N-methyl morpholine-N-oxide (NMNO) and organic solvent pretreatment for forest residues [60, 61], wheat straw and paper tube residuals using steam explosion [62], and potato peels using steam pretreatment for products such as hydrogen and biogas by dark fermentation and anaerobic digestion [63]. Substrates other than lignocelluloses considered for techno-economic analysis of biogas production is microalgae [64, 65].

**Upgrading processes**

Apart from the whole process studies, a specific part of the biogas processes and its development was also analyzed from a techno-economic perspective. In particular, the major focus was on upgrading the methods and mechanisms. Bauer et al. [66] compared different technologies available for biogas upgrading based on technology, energy requirements, and economic perspectives. Some of the available technologies are water scrubbing, organic solvent scrubbing, amine scrubbing, pressure swing adsorption, and membranes. The trend in
the world market shows that membrane separation is gaining wide popularity, with the energy requirement ranging between 0.2 – 0.3 kWh/Nm³, while the investment costs are ~2000 €/Nm³/h [66]. Other biogas upgrading processes include the upgradation through polyvinyl alcohol/amine based on membrane separation, where the cost of upgraded biogas was 0.17 USD/Nm³ biogas. The important factors affecting the purity of methane in this study were identified as membrane area, compressor duty, and influence feed rate [67]. In another study reported by Shao et al. [68], with a two-stage membrane coupled with temperature swing adsorption, the process economics had a positive effect with a payback of 6.8 months for 200 m³/h biogas flow [68].

4.3 Process design

In this thesis, the techno-economic feasibility of an existing industrial biogas plant was studied with different scenarios in comparison to the existing plant. Currently, the plant operates on OFMSW, with a capacity of 55,000 m³/year, and the upgradation method was amine-based absorption. In addition, the biogas from the waste water treatment was also upgraded using the amine absorption. The concerns for the local municipality company was to double the capacity of the existing digester, try some new substrates for the AD processes, and use a different upgrading method (water scrubbing). For this purpose, a process simulation was performed considering the problems at the municipality company using six different scenarios (**Paper II**). Figure 4.1 shows the different scenarios compared in this study, and Figure 4.2 shows the process flow diagram for one of the alternate options (**scenario 6**) considered for this study.
Figure 4.1 Different scenarios considered for process simulations in Paper II
Figure 4.2 Process flow diagram for scenario 6 in Paper II
4.4 Energy and economics

For the process development in Aspen Plus®, first the digester was simulated as suggested in Paper I. Later, the remaining unit operations were simulated for the mass and energy balances based on the input from the municipality company. After checking the simulation results in correlation with reality, the economic analysis was carried out. Furthermore, the different scenarios were modified, as mentioned in Paper II. The results suggest that the base case or the existing setup of the biogas industry consumes 4.3 GWh/year, and the energy split up is shown in Figure 4.3. On the other hand, the scenario 6 with two digesters and two upgrading methods, which also includes the biogas from the WWTP had an energy consumption of about 7.74 GWh/year. The output energy from scenario 6 was 38.21 GWh/year, which is 111% increase from the base case, showing the importance of the process design on the industrial acceptance and profitability. The important bottleneck in this study was the upgrading section, which was because of the fact that in the upgrading processes, the energy consumption was almost the same irrespective of the flow rate of the gases. The energy efficiency improved when the biogas from the different sources were combined.

![Figure 4.3 Energy split up for different unit procedures in the base case (Scenario1)](image)

The cost estimate of the different economic parameters is shown in Figure 4.4. The capital cost for the base case was 34.6 million USD, while the best case i.e., scenario 6 had a capital investment of 49.2 million USD. The count on additional investment was 14.6 million USD, while the NPV value was almost four times higher than the base case. The above mentioned suggestions could be beneficial for the future biogas industries when considering if it is a profitable venture. It also eradicates the questions connected to the financial support for the bioenergy, and it can be self-sustainable (Paper II).
Factors affecting profitability

There are different factors, which affect the overall economics of a biogas industry. In this study, the different factors such as alternating cost of MSW (collection and transportation cost, and tipping fee), different sizes of the plant, reduced operations in the plant, and the importance of decentralizing the biogas plants in the big cities were explored. The outcome of this study showed that when the citizens pay a gate fee, the profitability of the plant increases, while the cost of the collection and transportation adversely affects the economics. The fee between these two aspects should always have a balance between them to keep the economics on a positive trend. The cost of collection and transportation plays a huge factor for a small city like Borås (Sweden), and if we consider bigger cities like Bangkok or Hong Kong with a biogas plant and where sometimes the trucks have to carry wastes a large distance, it will affect the overall economics of the process. This is the reason why largely populated countries should consider decentralized solutions to make the biogas venture profitable. The larger plants are usually profitable; however, in the case of big cities, the economics will have a negative trend due to the fact that the cost of collection and transportation will have a major share in the overall economics of the plant (Paper II).

Lastly, the factor explored was the reduced use of operation (50% operation) in a plant. For different reasons, including practical problems such as operational issues or equipment fault,
the plant does not always operate to its fullest design capacity. When the plant is not operating to its design capacity, the losses occurred are high. Figure 4.5 shows the effect of reduced operations in the plant. For the base case (scenario 1), if we compare to an ideal situation, the NPV should result in 27.2 million USD, but if the operations are reduced to 50% of the design, then the NPV of the plant suffers a loss of 67.3 million USD (Paper II). Utilizing the design size is also a major factor in the plant profitability as summarized above.

![Figure 4.5 Effect of reduced operations in a biogas plant (Paper II)](image-url)
5 Rethinking Digester Technology

In this chapter, the focus will be on developing a new digester technology for the AD process. For this purpose, different digesters that are available today and its pros and cons are investigated. This was followed by an introduction of the new concept called “Textile Digesters.” The technical and economic feasibility of the AD process in the textile digester is elucidated from small-scale to industrial-scale and its possibility on commercial acceptance.

5.1 Overview of the biogas digester designs

**CSTR**

CSTR stands for continuous stirred tank reactors. These digesters usually have a long vertical tank, insulated with heating coils for hot water circulation provided by a heat exchanger to the desired temperature. The tanks are provided with a mixer, which can be: (1) from the top known as impeller, (2) paddle mixer provided from the sides, or (3) submersible mixer, where the motor and mixer are placed in the liquid [10]. CSTR are also known as complete mixed digester, and rotate at a lower speed to provide uniform mixing of its contents to avoid agitation, which leads to the breakdown of the microbial community present inside the system. These digesters are built with materials such as steel, mild steel, or concrete and are common in the industrial/agricultural setups and require high-end engineering skills to design and build and hence, expensive. Due to the fact that it is a temperature controlled process, the retention time is considerably less, leading to less volume of the digester to treat a particular unit of waste. The common size of the digester varies between 500 – 12,000 m³ [69, 70].

**UASB**

UASB stands for “up flow anaerobic sludge blanket” and was the most common biogas digester for waste water treatment. In UASB, the liquid or the wastewater flows from the bottom of the digester, which passes through the agglomerated microbial biomass [71]. The microbial consortium has a high contact with the substrate, and it results in the formation of high-rate biogas. The treated effluent is collected from the top, while the loss of the microbial
community is negligible because the digester acts as a fluidized bed, where the biomass is sent back due to the gravity. Most of the UASBs are operated at mesophilic temperatures, as methanogens are highly active at those temperatures. The retention time required to treat the liquid waste is relatively low i.e., <10 days, while the total solids loading cannot go higher than 7% [72, 73].

Figure 5.1 Different biogas digester designs
**Fixed dome**

Fixed dome digesters are not temperature controlled processes, and they are common in China and India, where they are used for domestic/agricultural purposes. The common substrate used with this fixed dome digester is manure, as the anaerobic digestion is a natural process in cattle. The fixed dome is placed beneath the ground and consists of three chambers: (1) to feed the substrate and mix it, (2) the digester - a larger chamber, which has a dome on top to collect the biogas, and (3) the digestate pit to collect the leftovers after the anaerobic digestion [74]. These three chambers are interconnected using pipes. The digester size usually varies between 1–150 m³ [75]. The advantages of this digester include the low-investment, absence of moving parts, no rusting, and long lifespan. On the other hand, the disadvantages are that the gasholder needs special sealants, otherwise the chance of gas leakage is higher as well as fluctuating gas pressure. It is mostly built with bricks and cement, which also requires skilled labor to construct it (Paper III).

**Floating drum**

Floating drum consists of an underground digester, where the movable biogas holder is placed on top. When the gas is collected on top, the biogas holder moves up and ensures that a constant pressure is present for cooking purpose [76]. Once the biogas is utilized, the holder goes down to its original position. Floating drum was originated in India, and the sizes go up to 100 m³. Scaling up is an important factor in this type of digester, as the floating drum is made of an iron drum, which makes it heavy to build and install. Although it has certain advantages such as constant gas pressure [77], there are certain disadvantages as well such as rusting of the iron, cost of steel/iron drum affecting the fibrous material getting stuck in between the floating drum and the digester, thus blocking the movement and causing a failure to the system [78] (Paper III).

**Plug flow**

Plug flow digesters are narrow digesters that have a length to width ratio of 3–5:1 made of different materials such as polyethylene (PE), polyvinyl chloride (PVC), fiber glass, mild steel, or reinforced concrete. It is widely used in the tropical or developing countries, mainly as a cheaper solution to the biogas technology. In plug flow digester, the substrate is fed at
one end, while the digestate is collected at the other end, and there is no mixing equipment present inside, thus having an advantage of a longer lifespan [79, 80]. However, materials such as PE and PVC can be degraded easily when placed in contact with the sun. These digesters have a retention time of between 15–20 days and could be able to take solids content between 11–14%, similar to the CSTR (\textit{Paper III}).

\textit{Lagoon}

Covered lagoon technology is a primitive and cheapest technology available for anaerobic digestion until today. In lagoon, a large sized earth pit is made and a gas cover is placed on top. There is no covering at the bottom of the digester through which large amounts of water is absorbed by the soil, affecting the groundwater system. The sizes of the lagoon are large and can be up to 15,000–20,000 m$^3$ with a depth of up to 5 m. There is no temperature control as well as mixing mechanism in the digesters, leaving a higher retention time of up to 60 days. Lagoons are common in Southeast Asia, especially in cattle farms, plantations, etc. where the amount of waste/wastewater is in magnanimous amounts [81-83].

5.2 \textbf{Materials for construction}

\textit{Concrete/Bricks}

The concrete is quite common in large-scale digesters, which is commonly called reinforced cement concrete (RCC). In RCC, the iron rods are placed inside, and the mixture of small stones together with the cement and the sand provide a reinforced structure. On the other hand, bricks are common in small-scale digesters, for instance, fixed dome/floating drums are commonly built with bricks and cement (\textit{Paper III}). The advantages with the bricks or concrete are the lifetime, robustness, and rigidity. However, there are certain drawbacks including the cost, the leakage from the bricks when a sealant is not provided, and corrosion of the iron rods due to the gases present in the biogas as well as the adequate contact with the liquid [10, 84, 85].
**Steel/Iron**

The second most common material used in building biogas digesters is steel or iron. Steel is common in large-scale digesters, while iron is a common material for the floating drum digester on a small-scale. The pluses with steel and iron are the lifetime and robustness, while the minuses are the rusting of the metal over a given timeframe and that it is expensive. The steel digesters are also helpful in creating a double wall layer, which is common to maintain temperatures in the digesters [85] (*Paper III*).

**PE/PVC**

PE or PVC is now commonly used in small-scale digesters, and the main reason is its cost-effectiveness. However, these digesters cannot be used in large-scale, due to the fact that when the material gets in contact with the sun, the polymer starts to degrade. Due to its easy degradation, the lifespan of the material is very short, and it usually has some dents and holes in less than two years, which is a setback to using this material [86] (*Paper III*).

**FRP/fiberglass**

Fiber-reinforced plastics (FRP) or fiberglass has recently been gaining popularity as a material for the construction of biogas digesters due to its simplicity in building it. Furthermore, additional benefits include its cost-effectiveness and being easy to install and maintain (*Paper III*). Nonetheless, the drawback includes the short lifespan, which lasts less than 3 years. Another factor is that the FRP technology is commonly used for small-scale digesters at a household level, and scaling-up is not possible, as the FRP can easily break [87, 88].

### 5.3 Digester requirements

In the above two sections of this chapter, the different designs and materials used in the biogas technology at different scales was mentioned. Taking a close look, it is obvious that the technology available so far is either too sophisticated and expensive or cheap and not long lasting. A digester is a vessel that contains the material, which is fed, and it should provide anaerobic conditions, i.e., no oxygen transfer from outside the system to inside and vice versa.
The material used for the biogas production should be: gas tight, withstand different weather patterns, be UV protected, maintain a pH between 2.0 – 14.0, be resistant to corrosive gases like hydrogen sulfide and not degrade quickly. Biogas processes have a normal pressure, which should be a slightly higher than the ambient pressure. The pressure factor is important in the digester design, as it helps in the gas flow rate and stability of the system.

Furthermore, other factors of importance include rigidity, robustness, easy to build, install and maintain, a reasonable lifespan, the contents present inside should not stick to the walls of the digester, and the materials should not be reactive to the components present inside and its reactions and lastly, it should be economically feasible and cost-effective to be self-sustainable. There is a big gap in the available digester technology for such a kind of product and material availability, as either of the two extremes are available i.e., sophisticated technology at an expensive price or cheaper price but not technically sound. The need to fill this gap in the biogas digestion process is urgent, as the shortage of energy is increasing and utilizing the waste through biogas is an efficient way to meet the demands.

5.4 Evolution of the textile digester

The need to fill this gap with an appropriate digester technology that is cost-effective yet technically proven has been great. In this thesis, such a digester was designed and developed. The name of the digester developed shall be referred to as the “Textile digester.” In this project, a new digester was developed considering the requirements mentioned above. First, a lab scale digester was built to check the preliminary working function, i.e., to produce biogas without any leakage of gas and liquid phase. The digester contained an inlet and outlet, in addition to the gas outlet and an opening to empty its contents. The digester was in the shape of a pyramid. The choice of the shape was not considered, as the primary objective was to produce biogas using a textile material. Figure 5.2 shows the digester used in this study. The material was initially fed with synthetic substrates such as acetic acid, butyric acid, and propionic acid while the inoculums were granules, which contained highly active methanogens.
The next experiment was performed using the organic fraction of the municipal solid waste using the inoculum from cow dung. The best result obtained from both the experiments was 570 L/kgVS/day, which showed that it was possible to produce biogas from the textile digester (Paper IV). The initial conception of the textile digester was to serve domestic applications such as households and small farms, and an economical evaluation was performed to address this. For the economical evaluation, replacing other sources of fuel such as liquefied petroleum gas (LPG) and kerosene were also considered. The results showed that when a family uses a 2-m$^3$ digester instead of the LPG as a cooking fuel for the household, it could benefit with 800 USD after 15 years, including the money spent for biogas installation, operation, and its maintenance (Paper IV). The economics were highly competitive, compared to some of the previous studies [76, 89, 90]. This shows that this digester could be one of the most cost-effective solutions available for the biogas digesters in the market.

Based on the results from the laboratory size digester, the next generation textile digester was designed. The size of the digester used in this study was 1-m$^3$, which was fed with the restaurant waste from the university. A maximum of 350 L/day biogas was produced at an OLR 1.2 kgVS/m$^3$/day, which was a long-term study for more than 250 days (Figure 5.3). This study helped to investigate the effects of scale-up and design perspective. One of the important considerations in the textile digester was the higher HRT, i.e., between 60–80 days. It was due to the fact that the digester was operated at room temperature (22°C), which was in
the psychrophilic range. However, this digester is mainly aimed for use in tropical countries, and the weather prevailing in such countries is expected to bring down the HRT used.

Figure 5.3 Biogas productions from a 1-m\(^3\) digester

### 5.5 Technology scale-up

From the two previous studies, it was evident that the results obtained were pleasing for a pilot testing. There are several parameters, which should be considered when a technology is scaled-up. The important factors affecting the textile digester for a scale-up includes the effect of mixing, mass transfer, the internal pressure of the material to hold its contents, weather, and some external problems such as biting by rats, sabotaging, and cuts caused by a knife or any sharp objects. Some of the issues mentioned above have been solved; however, not all issues were addressed. Thus, further explorations are needed.

The pilot digesters were installed in countries including India and Indonesia of sizes between 10 and 100-m\(^3\), respectively. The results and performance of these pilot digesters were promising, and they are used in applications including cooking and generating electricity. Below are some of the pictures (Figure 5.4) from the pilot installations of the textile digesters. When it comes to the real life applications, replacing biogas for gas utilization such as biogas for the boilers or for cooking was the most economically viable option, compared to electricity production, as in most places the electricity was subsidized and the capital investment of generators were high.
Some of the issues that were addressed were the biting from the rats and sabotaging. For this, it was proposed to have a netted cage made of iron, which could address the problems. Some of the important parameters such as strength and pressure of the digester were tested with one of the pilot digesters. The digester was loaded with half of its design capacity and was lifted to check its strength and pressure holding (Figure 5.5). The investigations revealed that there was no damage to the digester, proving the strength of the material. During the scale-up, the digesters that were operated in the tropical conditions, which provided a better ambient temperature, reflected a decrease in the retention time of less than 40 days. However, there are other issues that need further exploration, for example, the material development and chemical engineering aspects to study the effects of the digester in larger volumes.
5.6 Commercial acceptance

Currently, the textile digester is being accepted and sold as commercial products in countries including India and Indonesia in different sizes. The lack of available quality products in these countries has paved a way for a better market situation. Several installations are in the pipeline, and the constant improvements in the digester in the upcoming months will lead to a better product and make a change in the technology of anaerobic digestion over the years.
6 Byproducts and Integrated Solutions for Ethanol Production

6.1 First generation ethanol production

Ethanol production can be categorized into first and second generation, based on the substrates used and their manufacturing methods. The substrates, in general, for ethanol production can be classified as three types:

1. Readily fermentable sugars (1st generation)
2. Starch-based feedstock (1st generation)
3. Lignocellulosic biomass (2nd generation)

Feedstock

In the above-mentioned classification, the first generation ethanol production includes substrates such as carbohydrates from crops, i.e., sugarcane, and sugar-beet, which contains mainly sucrose. Ethanol production from sugarcane and sugar-beet is 75 and 86 l/ton (dry content). On the other hand, starch-based materials such as corn and wheat yield more than 350 l/ton (dry content). Starch-based ethanol production is common in the US, and some parts of Europe, while sugarcane based ethanol production is common in Brazil. The choice of substrate largely depends on the following factors: (1) geographical location, (2) economic situation of the country, (3) climate, and (4) need and availability of land and energy.

Production methods

The production methods for sugar-based substrates and starch-based substrates are different (Figure 6.1). For sugarcane to ethanol processes, first the sugarcane is milled, washed, chopped, and crushed between the rollers. The leftover solid called bagasse is used for a variety of purposes including steam generation, electricity, etc. The cane juices are split, as part of it is used for sugar production and the rest for ethanol production [13]. The liquid residue remaining after the sugar processing is called molasses, which is mixed with the fresh cane juice called mash and is sterilized before it enters the fermenter. The concentration of the sugar is adjusted to 14 – 22%, while the outcome of the fermenter contains yeast and xylose.
mother liquor of which, yeast is recycled for processing, using filtration or centrifugation. Through the distillation processes, ethanol is purified while the liquid residue called vinasse is used for the biogas production or as fertilizer (Figure 6.1). Ethanol is further dehydrated using a dehydrator to get more than 99% pure ethanol [13].

On the other hand, starchy materials such as corn or wheat have a different processing method (Figure 6.1). It can be distinguished as dry grind and wet mill processes. In the dry grind processes, the substrates are milled and liquefied using α-amylase at higher temperatures (>85°C), followed by saccharification and fermentation, where the conversion of dextrin to glucose is enabled by gluco-amylase, and yeast is responsible for the conversion of glucose to ethanol, respectively [13]. In this thesis, a process simulation was carried out based on the dry grinding process for ethanol production from the grains. The other method for starch-based substrates is the wet mill processes, in which the corn is ground with the addition of water. Before it is liquefied, products such as corn oil and gluten are extracted. In addition, the byproduct after the distillation is called corn-gluten food [13].

**Techno-economics**

Techno-economic studies determine the profitability of the processes. As mentioned above, for corn-to-ethanol processes, there are two methods i.e., dry grinding and wet milling. Commonly, the dry grinding processes are economically viable, as opposed to the wet milling processes. However, during the wet milling processes, different valuable byproducts such as corn oil, gluten, and corn-gluten food are extracted, which seeds the concept of biorefinery. In the future, when the demand for such products rises, these biorefinery concepts will be said to be more profitable [13].

Solomon et al. [91] have reported that for a dry mill ethanol plant that produces ~200,000 m³ annually, it will have a capital investment of about 80 million USD [91], while the energy output to input ratio could be less than 2 (for corn processes) [92]. With respect to greenhouse gas (GHG) emissions, advanced corn-based processes reach higher reduction levels, compared to the sugarcane processes [93]. The production cost of ethanol is altered by several factors such as local weather, availability of raw material, and feedstock price. In 2010–11, the cost of the Brazilian ethanol production doubled the average production cost and the factors mentioned above played an important role in this regard [93]. Some of the other parameters explored in the techno-economic analysis include the sensitivity of the starch
content in the corn, cost of the raw materials, altering the existing processes with energy efficient processes in DDCS, distillation, etc. [94-100].

Figure 6.1 Block flow diagram on sugarcane and grains based ethanol processes
6.2 Second generation ethanol production

Feedstock

The second generation ethanol production predominantly uses lignocelluloses as the raw materials, as its availability is abundant. Some of the predominant lignocelluloses used for the second generation ethanol production include softwood [101], switch grass, corn stover [102, 103], pine [104], sugarcane bagasse, leaves [105], and straw [106].

Production methods

Lignocelluloses are complex biomass, which contains different fractions including cellulose, hemicellulose, lignin, pectin, extractives, and much more in minor fractions. To obtain ethanol from the lignocelluloses, the release of sugars is necessary. Due to its complex nature, the release of the sugar from the lignocelluloses requires an additional step called pretreatment. In the pretreatment step, the lignocelluloses are broken up into simple polysaccharides, which can be hydrolyzed easily by enzymes to fermentable sugars. However, during the pretreatment processes, there are certain compounds may be formed such as furans, phenolic compounds, etc., which can inhibit the ethanol production [2, 107]. For an efficient ethanol production, the inhibitor formation should be avoided. There are different pretreatment methods available for lignocelluloses, which can be broadly classified as physical, physicochemical, chemical, and biological methods. It is not possible to have a particular pretreatment method in general for lignocelluloses, as different materials have different compositions [2, 107].

After the release of the sugars through the pretreatments and the hydrolysis steps, different fermentation mechanisms can be used to produce the ethanol. The common production methods include batch, fed-batch, and continuous processes. In the batch process, most of the materials are loaded into the fermenter, and the contents are removed after the process. While in a continuous mode of fermentation, the fresh materials and the nutrients are constantly added and simultaneously, the processed media are removed from the fermenter. Unlike batch and continuous processes, in the fed-batch method, one of the materials or nutrients is supplied during the cultivation, and the products remain in the vessel until the end of
fermentation. The fed-batch processes hold the application for having a high concentration of the product formulated [108].

Other production methods include separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) [109]. In the SHF processes, the enzymatic hydrolysis and fermentation take place in separate vessels; however, in the SSF processes, all actions take place in the same time. This reduces the complexity of production processes and the chances of contamination [109]. Recently, some new methods have also been developed such as simultaneous sacccharification filtration and fermentation (SSFF), where a filter is employed to send the sugar-rich stream to the fermentation, and non-fermented materials are recycled to the hydrolysis processes [110]. In this work, SSF process on continuous mode of fermentation was investigated in the integrated first and second generation ethanol production.

**Techno-economics**

Several techno-economic analyses have been performed on the lignocelluloses to ethanol processes. Nonetheless in this thesis, a novel approach of integrating the first and second generation ethanol production was exploited from a process design and techno-economic perspective. Predominantly, corn stover was exploited in assessing the techno-economic potentials, where different methods have been studied, including acid pretreatment [103, 111], ammonia explosion [112], fungal fermentation [113], and lime and steam [102]. For a processing capacity of 2,200 tons/day, corn stover using dilute sulfuric acid pretreatment, the calculated required capital investment was 376 million USD [112].

Besides the capital investment, ethanol production cost plays an important role to be economically sustainable. When the cost to produce the ethanol is lower, the profitability of the plant increases. Different pretreatment methods end up with different minimum costs for selling the ethanol, of which dilute sulphuric acid was reported as the minimum (898 USD/m³ ethanol) and liquid hot water pretreatment as being the most expensive i.e., 1,173 USD/m³ ethanol [114, 115].
6.3 Importance of byproducts in the ethanol industry

The concerns over the biofuels are due to the question about its economic profitability. Most of the current developments within the biofuels are focused on converting or exploring the possibility towards the concepts of biorefinery. In biorefinery, the possibilities include the exploitation of different products that could be produced from the same raw material source, which increases the complete value chain. For instance, the wet milling corn processes require more energy, and its economic returns are not as attractive as the dry milling processes. Nonetheless, it gives rise to several byproducts such as corn oil, gluten, fiber, etc.[13]. In the future, when the demand for such products rises, then the cost of them proportionately increases, leading to better economics. The demand for the products determines the need for its production. With respect to the ethanol industry, it has to compete with the fossil fuels for its cost, which is why the need for revenue from other products becomes inevitable for its economic sustainability.

Some of the new byproducts from the ethanol industry include corn oil, zein, pericarp fiber, germ, endosperm fiber, which are usually extracted prior to the fermentation. Some of the other byproducts which are being explored within the concepts of biorefinery, include sweeteners, polysaccharides, pharmaceuticals, nutraceuticals, organic acids, biodegradable film, amino acids, enzymes, and polyols [94, 97, 98, 116, 117]. In other cases, the process modifications include the recycling of DDGS after being pretreated and hydrolyzed with ground corn and water to the fermentation process again, which had resulted in the increase of ethanol yield [95]. Some other researchers have reported the fractionation of distiller’s soluble into new co-products such as protein-mineral fraction, oil fraction, glycerol fraction, which have been investigated. The results showed that the fractionation of the distiller’s soluble into proteins, minerals, ash, glycerol, and carbohydrates could increase its economic value due to the fact that it is a pure component [118].

Other co-products generation concepts in the ethanol industry include the use of fungi. Arifeen et al. [119] reported the use of fungi for the production of enzymes, in contrast to the conventional methods where the enzymes are brought from other industries, affecting the overall economic, energy, and nutritional balance of the process. This integration is supposed to reduce the waste produced as well as the loss of grains throughout the process [119]. Some new fungal biorefinery concepts include the integration of first and second generation ethanol production processes where the conventional first generation ethanol production shall be
integrated with the lignocellulosic ethanol production. The integration could be possible with the help of filamentous fungi, in which the compromise on the quality of the DDGS is not required. This integrated process could transfer the excess heat from the evaporator to the pretreatment procedures, which can reduce the energy requirements, thus, significantly improving the overall economic returns of the process [120].

6.4 Retrofitting analysis

With a lot of new inventories coming up, the pattern of the ethanol industry is changing over the years with little modification to the processes. The possibility of retrofitting the first generation ethanol industry was explored in Paper V. In this study, grains to ethanol processes were retrofitted in different scenarios, including the conversion of hydrous ethanol, tolerance of strains for different ethanol concentrations, and using the stillage to produce biogas, which, in turn, decreases the net energy consumption. In addition, the sensitivity of the cost of the different commodities such as ethanol, DDGS, and grains were examined. This study was performed based on the largest ethanol producing plant in Sweden (Lantmännen Agroetanol AB) using the modeling software Aspen Plus®. The BFD of the different retrofits and the PFD of the base case are shown in Figure 6.2 and 6.3, respectively.

The simulations of retrofits were compared to that of the base case i.e., the existing industrial scenario. The results revealed that the cost of the grains plays an important role in the overall profitability of the process. When the grain price goes higher than 349 USD/ton, the profits from the plant is out of reach. Another important factor is the cost of ethanol, which when reduced to less than 702 USD/ton means that the plant is not profitable any more. This is a benchmark value, where it has to compete with the fossil fuels (Paper V).

The comparison of different retrofits revealed that converting stillage to biogas production is an energy efficient process, while a higher tolerant ethanol strain could have an overall high performance. The capital investment for the ethanol plant production of 41,600 tons ethanol/year was 68.9 million USD, which could be recovered after 13 years (Paper V).
Grinding and liquefaction → Fermentation → Distillation and dehydration → Evaporation and drying

Water + Enzymes → Water

Grains → Ethanol (93%) → DDGS

Retrofit-1

Grinding and liquefaction → Fermentation → Distillation → Evaporation and drying

Water + Enzymes → Water

Grains → Ethanol (93%) → DDGS

Retrofit-2

Grinding and liquefaction → Fermentation (4% or 17% ethanol tolerant strains) → Distillation and dehydration → Evaporation and drying

Water + Enzymes → Water

Grains → Ethanol → DDGS

Retrofit-3

Grinding and liquefaction → Fermentation → Distillation and dehydration → Biogas

Water + Enzymes → Water

Grains → Ethanol → Steam utilization

Figure 6.2 BFD of the different retrofits (Paper V)
Figure 6.3 PFD of the base case. The red line shows the heat transformation between distillation columns, green dashed line shows the recycled ethanol, and solid green line shows the final product ethanol (Paper V).
The overall energy consumption in the base case was 19.4 GW, and about 40% of the total energy was used for upgrading i.e., distillation and dehydration processes (Figure 6.4). When a 4% tolerant ethanol strain was used (Retrofit 2, Figure 6.2), the energy consumption was more than two times the base case, showing that the tolerance of yeast plays a role. For the base case, the tolerance of the yeast strain was considered as 10%. On the other hand, when a wild strain with a high tolerance of ethanol was investigated in retrofit 3, the energy consumption was decreased by 28.8%, which was mainly due to the decreased water consumption in the process. Of all the retrofits studied, replacing the stillage to biogas was the most energy efficient (38%); however, it was not economically attractive since a valuable byproduct, DDGS, was lost. This shows the importance of byproducts in the ethanol industry and the choice of energy efficiency and economic returns (Paper V).

6.5 Integration processes and byproducts

Previously, the effect of altering the first generation ethanol production was studied in different scenarios. However, certain other new retrofitting’s could benefit the ethanol plant, which could increase its efficiency. The new retrofitting includes the employability of fungi based process for the thin-stillage (scenario A) / stillage (scenario B) in which the fungi could convert the sugars present in the thin stillage/stillage to additional ethanol and biomass (Figure 6.5). This, in turn, reduces the energy consumption in the unit operations, including
evaporation and drying. Furthermore, the integration of the first and second generation ethanol production was also carried out on wheat bran using phosphoric acid pretreatment. The simulations were carried out based on the laboratory data obtained from [121-123].

Figure 6.5 BFD for different scenarios considered in Paper VI. The yellow color refers to the substrate, while the green refers to the products, and the highlights in blue refer to the changes made to the existing 1st generation process. Scenarios A and B represent the thin-stillage and the stillage modifications in the first generation processes, while scenario C represents the integrated lignocellulose processes.
Figure 6.5 shows how the first generation ethanol production is modified using fungi as well as the integration of the first and second generation ethanol production (scenario C). The integration of the first and second generation ethanol production was carried out on the modified scenario, which employed fungi to biomass using the thin-stillage. The results showed that employing fungi for the thin-stillage had an overall increase in the energy efficiency of up to 2.5%, while the NPV could increase up to 31 million USD (Paper VI).

Figure 6.6 Energy share for different scenarios, including thin-stillage and stillage to ethanol, and integration processes (Paper VI).

In addition, the integration of the first and second generation of ethanol production was also studied using phosphoric acid pretreatment on wheat bran (scenario C). The results showed that the integration of lignocelluloses with up to 50% quantity of grains consumed about 33% of the total energy consumption (Figure 6.6). The integrated lignocellulosic process costs 7 million USD more, compared to the retrofits of using the thin-stillage from the first generation processes to produce biomass and ethanol, while the benefits could be summed to NPV of 53 million USD (Figure 6.7). Currently, the ethanol industry in Norrköping, Sweden is operating a pilot plant of 80-m³ for the thin-stillage to biomass process, while further studies are required for the integration of the first and second generation ethanol production.
Figure 6.7 Economic indexes of different scenarios in Paper VI.
7 Concluding Remarks

To summarize this thesis, different scales of approaches were carried out in the biogas and ethanol production for an efficient and profitable process for the industry. Most of the developments obtained in this work were carried out based on the industrial process, which proves that these solutions could be applicable to the real-life problems.

The significant findings of this thesis are:

- A model for the AD processes, which is a useful tool for the biogas industries to explore new substrates for their processes, was developed. The model is based on process parameters used in the biogas industries, and it can effectively predict the biogas production using a simple method.

- The main factors affecting the profitability of a biogas plant were exploited. Some of the important factors include the collection and transportation cost, reduced operations of a plant, and cost to landfill the waste. The main bottleneck in the energy consumption of the biogas plant was the use of the upgrading technology and its utilization, which was solved using the process design approach.

- In developing countries, the migration toward biogas from solid waste is difficult, mainly because of the cost of the digester. In this work, a novel textile digester was developed using a different material for construction i.e., high-tech textiles. They are produced at a lower price and their use for biogas could be a solution for both households and industries. This technology is already being implemented in different countries with commercial remunerations.

- The first generation ethanol production is modified after the thin-stillage production, where the animal feed and the additional ethanol is produced by employing fungi. The modified process is energy efficient (2.5%), and economically attractive (PBP – 11.5 years), which is why it is already being tested on a pilot scale in the industry.

- The integration of the first and second generation ethanol production was showcased. This integration could be a solution for the bioethanol industry by using the lignocelluloses for the bioethanol production, which improves the profitability of the plant.
This thesis involves the development of two main products i.e., biogas and ethanol. There are several factors, which are required to develop a process and apply it in real-life. Some of the factors have been identified and some solutions have been proposed. However, there are certain challenges, which need to be addressed. These are highlighted in this section for further exploration.

**Biogas Modeling**

The process simulation model developed in this thesis is a primitive model, which needs further exploration on multidimensional conjugation. Some of the possible investigations could include the following:

- The effect of inhibitors in different substrates
- Accounting specific microbial activity on different communities
- Including the effect of thermodynamic parameters for different scales
- Correlation with the experimental verification
- Incorporating kinetics for hydrolysis reactions
- Investigation on the intermittent VFA analysis and metabolic pathways with experiments

**Textile Digester**

Textile digesters are now available on the market; however, there is room for their improvements in the years to come. Some of the objectives that could be explored in the following years will be on how these digesters can replace the lagoon technology. One of the ideas is to use a two-sheet technology, where a sheet is laid on the ground in deep-earth pits and after filling it with the contents, another sheet is placed on top and closed. Both the sheets are placed deep into the ground so that there is no leakage of gas or liquid.

Another improvement for the small-scale digesters could be from a design perspective i.e., the previous mentioned design required for the digester to be welded in several places and the
material usage was also high. A new cylindrical design could be studied which will reduce the production costs. Other futuristic approaches in the developments of textile digesters include material developments for a light weight and stronger material [124]. Further opportunities include exploring the possibility of using textile digesters in dry anaerobic fermentations and ethanol productions [125]. The concept of two-stage digestion was studied earlier for the solid waste using CSTR and UASB and proved to be efficient processes [126-128]. Such a two-stage system could be exploited in the textile digesters, which could improve the efficiency of the system.

_Ethanol Simulation_

In this study, the lignocelluloses were integrated into the grains ethanol production in a separate way. However, there are certain changes that could be possible for a better energy and economically efficient process. The considerations are:

- Exploiting pinch and exergy analysis for a better heat and energy efficient system.
- A consolidated bioprocessing method, including substrates such as grains and lignocelluloses and including pretreatment, sagogarification, hydrolysis, and fermentation in a single vessel could be studied, and the results could be of significant importance to prove the acceptance of integrated processes on lignocelluloses.
- Thinking beyond fuels, the exploration of the biorefinery concepts is interesting including a variety of products from a single raw material. For instance, producing biopolymers would be interesting.


A novel process simulation model (PSM) for anaerobic digestion using Aspen Plus

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HIGHLIGHTS

• Process simulation model (PSM) for biogas production was developed using Aspen Plus.
• The model was validated from industrial and previous research studies.
• Any substrates' biogas potential can be predicted using the model.
• PSM is statistically validated.

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ABSTRACT

A novel process simulation model (PSM) was developed for biogas production in anaerobic digesters using Aspen Plus®. The PSM is a library model of anaerobic digestion, which predicts the biogas production from any substrate at any given process condition. A total of 46 reactions were used in the model, which include inhibitions, rate-kinetics, pH, ammonia, volume, loading rate, and retention time. The hydrolysis reactions were based on the extent of the reaction, while the acidogenic, acetogenic, and methanogenic reactions were based on the kinetics. The PSM was validated against a variety of lab and industrial data on anaerobic digestion. The P-value after statistical analysis was found to be 0.701, which showed that there was no significant difference between discrete validations and processing conditions. The sensitivity analysis for a ±10% change in composition of substrate and extent of reaction results in 5.285% higher value than the experimental value. The model is available at http://hdl.handle.net/2320/12358 (Rajendran et al., 2013b).

1. Introduction

Biogas is mainly a combination of methane and carbon dioxide produced by the anaerobic digestion (AD) of organic materials. The methane, an energy-rich compound due to its high calorific value (~39.4 MJ m⁻³) can be used for different purposes such as heating, cooking, and electricity production (British Standards Institution, 2005a,b; Rajendran et al., 2012). If the biogas is upgraded, it can also be used as vehicle fuel (Deublein and Steinhauser, 2008; Rajendran et al., 2012). In AD, several groups of bacteria and archaea work in synergy to form methane and carbon dioxide. Biogas is obtained after four crucial steps including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the first step, the complex substrates such as carbohydrates, fats, and proteins are hydrolyzed into their respective monomers, such as glucose, fatty
acids, and amino acids. Secondly, the hydrolyzed monomers are converted into different volatile fatty acids (VFA), such as caproic acid, valeric acid, iso-valeric acid, butyric acid, iso-butyric acid, propionic acid, and acetic acid. In the third step (acetogenesis), the VFA’s are converted into acetic acid, hydrogen, and carbon dioxide. Finally, methanogens convert acetogenesis products into methane and carbon dioxide (Mata-Alvarez, 2003; Nijiguna, 2006; Rajendran et al., 2013a). Nonetheless, these intermediary reactions mechanism are hardly explained and understood in biogas production.

Biogas production is affected by several factors such as organic loading rate (OLR), hydraulic retention time (HRT), carbon-to-nitrogen ratio, pH, ammonia, temperature, and mixing. Studying these factors, in addition to the bacterial metabolic reactions involved in anaerobic digestion or fermentation, is complicated in experimental studies. However, these factors and the intermediary metabolism in AD could be interpreted with the help of models. The first model to explain AD was a mathematical model, which considered acetate as the rate limiting step (Andrews, 1968; Graef and Andrews, 1974). In this model, only substrate inhibitions were involved, while the later BIOTREAT model explained the intermediary reactions in AD based on electron donors and acceptors (Christensen and McCarty, 1975; Lawrence and McCarty, 1969).

The biogas production is affected by complex inhibitions such as ammonia, specific growth rate of microorganisms, pH, temperature, and other interactions. The important parameter such as pH and temperature determines the amount of ammonia released in the system, and the rate of ionization of ammonia affects the methanogenesis process. The complex models involving the inhibitions were developed by (Angelidakis et al., 2000, 1993; Vavilin et al., 1994). Currently, Anaerobic Digestion Model No. 1 (AD1M) is getting more attention due to its complexity and kinetics of reactions mechanisms (Batstone et al., 2002). Recently, a computational model was proposed by Blesgen and Hass (2010), based on sub-models, including biological factors, physico-chemical factors, reactors, and plants. Most of the models developed were either theoretical or mathematical. Nevertheless, other process parameters, such as OLR, HRT, and thermodynamics of the reactions that affect the biogas production were not investigated in the aforementioned models.

Process simulations are well appreciated by industries and researchers, as these can forecast the real scenario accurately, and the costs to perform simulations are much cheaper. Nevertheless, a process simulation model (PSM) has not been developed to predict and understand the mechanism of AD. Several process simulators are available of which Aspen Plus® is used as a tool to develop PSM for AD. In this work, a PSM was developed using Aspen Plus® V 7.3.2. This PSM is a library model for AD, which includes intermediary reactions, inhibitions, and kinetics. The model was examined for biogas reactors operating at thermophilic conditions (55°C). The PSM was also validated against experimental results obtained from earlier research studies and industrial plants. A sensitivity analysis of the model was performed in Aspen Plus® by changing the composition of the substrate and the extent of the reaction for the hydrolysis reactions by ±5%, ±10%, and ±20%.

2. Methods and model details

2.1. Model description

The process simulation model divides the digestion or fermentation reactions into two groups of reaction-sets: (a) The reactions of hydrolysis operating based on the extent of reaction (Table 1), which is the fractional conversion of reactants into products on a scale of 0.0–1.0. Hydrolysis is one of the rate-limiting steps in AD, and henceforth a separate reaction-set was added. With a separate reactions set for hydrolysis, the effect of pretreatment, which improves the hydrolysis efficiency on different substrates, could be studied in PSM. The other reaction-set (b) constitutes reactions of other phases (acidogenic, acetogenic, and methanogenic reactions) in AD functioning on a kinetic basis.

Fig. 1 shows the block-flow diagram of the PSM. The model is accessible at the Swedish database http://hdl.handle.net/2320/12358 (Rajendran et al., 2013b). The kinetic constants of the reactions were obtained from previous models, such as ADM 1 and comprehensive models (Angelidakis et al., 2000, 1993; Batstone et al., 2002; Serrano, 2011). Reactions from ADM 1, which were not resolved for stoichiometry, were balanced in PSM. The hydrolysis equations were included as carbohydrates, proteins, and fats in the reaction-set (a) (Table 1). Carbohydrates were incorporated as cellulose, starch, and hemicelluloses. Proteins were added based on their solubility, such as soluble proteins and insoluble proteins. Fats comprised of tripalmitate, triolein, palmito-olein, and palmito-linolein can be entered in PSM.

In the reaction-set (b), different sub-set of reactions was added to calculate the kinetics of the reactions. Each sub-set had a FORTRAN program to determine the rate of reactions in acidogenic, acetogenic, and methanogenic phases. In total, ten different subsets or calculator blocks were used for glycerol, valeric acid, butyric acid, propionic acid, linoic acid, amino acids, sugars, palmitic acid, oleic acid, methanogenesis, and hydrogen utilizing reactions (Fig. 1).

Table 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Compound</th>
<th>Hydrolysis reaction</th>
<th>Extent of reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Starch</td>
<td>(C6H12O6)n + H2O → n C2H5OH</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>2</td>
<td>Cellulose</td>
<td>(C6H10O5)n + H2O → n C2H5OH</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>3</td>
<td>Hemicellulose</td>
<td>C6H10O5 + H2O → C5H5O2</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>4</td>
<td>Hemicellulose</td>
<td>C6H10O5 + H2O → C5H5O2</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>5</td>
<td>Xylose</td>
<td>C5H10O5 → C2H4O2 + 3 H2O</td>
<td>0.6 ± 0.0</td>
</tr>
<tr>
<td>6</td>
<td>Cellulose</td>
<td>C6H12O6 + H2O → 2 C2H4O2</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>7</td>
<td>Ethanol</td>
<td>2 C2H4O2 + CH4 + 2 H2O</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>8</td>
<td>Soluble protein</td>
<td>C12H18O6Nσ + 6 H2O → 6.5 C2H4O2 + 6.5 CH4 + 3 H2N + H2S</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>9</td>
<td>Insoluble protein (LP)</td>
<td>C12H22O6NOσ + 0.047 C12H8N4O9 + 0.047 C12H8N4O9 + H2O + 0.172 C2H4NO2 + 0.074 C2H4NO2 + 0.11</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>10</td>
<td>Triolein</td>
<td>C5H9NO2 + 0.25 C2H4O2 + 0.047 C12H8N4O9 + 0.067 C12H8N4O9 + 0.074 C12H4NO2 + 0.07 C2H4NO2 + 0.046 C2H4NO2 + 0.036 C12H4NO2</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>11</td>
<td>Tripalmitate</td>
<td>8.436 H2O → 4 C12H24O2 + 2.43 C12H24O2</td>
<td>0.5 ± 0.3</td>
</tr>
<tr>
<td>12</td>
<td>Palmito-olein</td>
<td>C17H33O2 + 4.1 H2O → 2.1 C2H4O2 + 0.9 C2H4O2 + 0.9 C17H31O2</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>13</td>
<td>Palmito-linolein</td>
<td>C17H33O2 + 4.3 H2O → 2.2 C2H4O2 + 0.9 C17H31O2 + 0.9 C17H31O2</td>
<td>0.6 ± 0.2</td>
</tr>
</tbody>
</table>

Note: Table 1 lists hydrolysis reactions (reaction-set (a)) included in PSM functioning on extent of reaction.
The iterative solutions were obtained by passing the output of the reaction-set (a) to reaction-set (b) functioning on kinetic reactions. The results generated from PSM, are a stream table with mass and energy balance, where the amount of biogas production can be calculated. In each calculator block, the inhibitions in the form of pH, temperature, and ammonia were embedded as logic loops. For every input (fresh or recycled), the calculator blocks calculate the rate of each reaction, thus, rendering the simulation close to reality. Furthermore, process parameters such as OLR, the volume of the reactor, and HRT were entrenched in the model covering the important parameters in the biogas production.

2.2. Model development and operations

The process simulation model is developed mainly based on the four different stages of biogas production such as hydrolysis, acidogenesis, acetogenesis and methanogenesis. These four stages explain the intermediary metabolisms, how the complex substrates such as carbohydrates, proteins and fats are broken down to monomeric forms and finally to methane and carbon dioxide. For this purpose, the reactions involved in these four stages were collected from previous works (Andrews, 1968; Angelidaki et al., 2000, 1993; Batstone et al., 2002; Lawrence and McCarty, 1969; Vavilin et al., 1994). The equations which were not solved for stoichiometry were solved using MATLAB® software (Anderson and Bjedov, 1996).

In this section, the step-by-step procedure for model development is explained. Firstly, all the compounds required for the simulation was obtained from the equations were added to Aspen Plus and its physical properties were simulated. Some of the complex compounds missing physical properties were obtained from Woolery and Putsche (1996). NRTL (Non-Random Two-Liquid model) was chosen as the property method as it correlates and calculates the mole fractions and activity coefficients of different compounds and also to facilitate the liquid and the gas phase in the biogas production. Once, the property check is over, the reactors were included for the simulation. From the reactor models available in Aspen Plus®, stoichiometric reactor was used for the hydrolysis phase of the reactions, and the continuously stirred tank reactor (CSTR) was used for the other phases in digestion reactions.

All the processing conditions such as the total solids (TS), volatile solids (VS), flow rate, mass composition, temperature, and HRT of the substrates were given, the input parameters were processed in the reaction-set (a) (Table 1). This will estimate the amount of monomers released to the second reactor, which contains reactions-set (b) (Table 2). Depending on the monomer, they pass through different calculator blocks. For instance, the amino acids released by the proteins in the reaction-set (a), pass through the amino acid calculator block, where it is broken down to different VFA. Then, the VFA produced pass the butyric acid, valeric acid, and propionic acid calculator blocks before it reaches the final calculator block, methanogenesis. Thereafter, the amount of the methane, carbon dioxide and the left over TS are represented in the form of desired units.

Each calculator block in the reaction-set (b) has a FORTRAN program, which calculates the products released from each reactions. The calculator blocks is assigned with different variables such as the flow rate, VFA's, NH4+, temperature, kinetic parameter and H2, which imports the amount of reactants and the reaction rate for each calculator block based on the inputs from the results of reaction-set (a). The kinetic parameter was obtained from the previous literature studies (Andrews, 1968; Angelidaki et al., 2000, 1993; Batstone et al., 2002). The power law was used to calculate the reaction rate, which includes the specific growth rate of microorganisms, and ammonia inhibitions. The pH was calculated based on the chemical equilibrium constants inside the calculator blocks for each VFA, based on Angelidaki et al. (2000) and Cheng (2010). The results obtained from the simulation are reported in the form of m³ day⁻¹, which can be recalculated, according to the desired units.

2.3. Model validation

The PSM was validated against experimental data, which used different substrates with diverse process conditions, covering data from a small-scale laboratory research to large-scale industrial plants. Each case compared with PSM was further tested for statistical analysis using Minitab® (V 15). The statistical analyses include probability plot to check the significance and normality of the experimental data. Table 3 shows the different cases with substrate and operational data used in PSM for calculating the differences between PSM and experimental data. Each case is described as follows:

Case (1): Cow manure was used as a substrate with a loading rate of 0.33 L day⁻¹ at 15 days HRT. The volume of the reactor was 5 L and produced 353.5 L biogas kg⁻¹ VS day⁻¹ (Kaparaju et al., 2009). The composition of the cow manure were based on Budiyono (2011).

Case (2): In this validation, municipal solid waste (MSW) was used as a substrate in a reactor with 5 L volume at 21 days HRT. The biogas production obtained at 3 gVS L⁻¹ day⁻¹ was 0.54 m³ CH4 kg⁻¹ VS day⁻¹ (Forgács et al., 2012). The MSW consisted of 61.5% carbohydrates, 16% proteins, 10% fats, and the rest was ashes and inorganics (Borás Energy and Environment AB, 2012).

Case (3): A co-digestion study was used in this validation, using 70% MSW and 30% citrus wastes as a substrate. The composition and the wastes of MSW were obtained from Borás Energy and Environment AB (2012), and the citrus wastes from Forgács et al. (2012). The experimental biogas production for an OLR of 3 gVS L⁻¹ day⁻¹ at 21 days HRT was 0.555 m³ CH4 kg⁻¹ VS day⁻¹.

Case (4): In this case, a pilot study with a 600 L reactor volume digesting MSW was used. The biogas production reported was 401 L kg⁻¹ VS removed based on Eliyan et al. (2007).

Case (5): An industrial AD located near Borás, Sweden was validated in PSM with a volume of 3000 m³, operating at a HRT of 19 days. The organic fractions of the MSW was used as a substrate.
in this plant with a loading rate of 150 m³ day⁻¹ and the biogas production was 9600 m³ day⁻¹ [Borás Energy and Environment AB, 2012].

Case (6): Similar to Case 5, another industrial anaerobic fermentor plant in Norrköping (Sweden) operating on co-digestion of 75% slaughterhouse waste, 15% food waste, and 10% cow manure was used in the validation. The overall waste composition was carbohydrates 23.5%, proteins 12.18%, fats 60%, and the rest was ashes. The biogas production from the industrial plant was 10,959 m³ day⁻¹ with a HRT of 20 days [Buđiyno, 2011; Palatić et al., 2011].

Case (7): Pig manure was used as a feed in PSM in this validation. The volume of the reactor was 30 L, with a HRT of 8 days and a loading rate of 230.4 g VS day⁻¹. The experimental biogas production was 0.269 m³ kg⁻¹ VS. The composition of the pig manure was 44.06% carbohydrates, 23% proteins, and 4.9% fats for a total VS of 72% [Fujita et al., 1980].

2.4. Sensitivity analysis

The two important factors in PSM, which affect the simulation results, are the extent of the reactions and the composition of the substrates. Therefore, a sensitivity analysis was performed by changing the extent of the reaction and the composition of the substrates by ±5%, ±10%, and ±20%. A total design was used for the sensitivity analysis considering factors such as carbohydrates, proteins, and fats. The differences between the PSM and experimental data were recalculated based on the sensitivity analysis. Based on the sensitivity analysis, a regression plot was

### Table 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Compound</th>
<th>Chemical reactions</th>
<th>Kinetic constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Glycine</td>
<td>C₆H₁₀N₂O₅ + H₂ → C₅H₆O₂ + H₃N</td>
<td>1.28 × 10⁻³⁰</td>
</tr>
<tr>
<td>2</td>
<td>Threonine</td>
<td>C₆H₁₀N₃O₄ + 4 H₂O + 0.5 H₂ → CH₃NO₂ + C₅H₆O₂ + 0.5 C₆H₂O₂ + 2 H₂N + CO₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>3</td>
<td>Histidine</td>
<td>C₆H₁₂N₄O₆ + 3 H₂O → 0.5 C₆H₂O₂ + 0.5 C₅H₆O₂ + 0.5 C₆H₂O₂ + 4 H₂N + CO₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>4</td>
<td>Arginine</td>
<td>C₆H₁₄N₄O₂ + 4 H₂O + 0.5 H₂ → C₅H₆O₂ + 0.5 C₆H₂O₂ + 0.5 C₆H₂O₂ + H₂N + CO₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>5</td>
<td>Proline</td>
<td>C₅H₉N₂O₂ + H₂O → 0.5 C₆H₂O₂ + 0.5 C₆H₂O₂ + 0.5 C₆H₂O₂ + H₂N + CO₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>6</td>
<td>Methionine</td>
<td>C₆H₁₉N₅S + 2 H₂O → C₅H₆O₂ + CO₂ + H₂N + H₂S</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>7</td>
<td>Serine</td>
<td>C₆H₁₀N₂O₅ + H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>8</td>
<td>Threonine</td>
<td>C₆H₁₀N₃O₄ + H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>9</td>
<td>Glutamic acid</td>
<td>C₆H₁₀N₂O₅ + H₂O → H₂C₅H₄O₂ + 0.5 C₆H₂O₂ + H₂N + CO₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>10</td>
<td>Glutamic acid</td>
<td>C₆H₁₀N₂O₅ + H₂O → H₂C₅H₄O₂ + 0.5 C₆H₂O₂ + H₂N + CO₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>11</td>
<td>Glutamic acid</td>
<td>C₆H₁₂N₄O₂ + H₂O → C₅H₆O₂ + 0.5 C₆H₂O₂ + H₂N + CO₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>12</td>
<td>Histidine</td>
<td>C₆H₁₀N₃O₄ + 5 H₂O → CH₃NO₂ + 2 C₅H₆O₂ + 2 H₂N + CO₂ + 0.5 H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>13</td>
<td>Arginine</td>
<td>C₆H₁₄N₄O₂ + 6 H₂O + 2 H₂O → 4 H₂N + 2 CO₂ + 3 H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>14</td>
<td>Lysine</td>
<td>C₅H₁₂N₄O₅ + 2 H₂O → H₂C₅H₄O₂ + C₅H₆O₂ + 2 H₂N</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>15</td>
<td>Leucine</td>
<td>C₅H₁₅N₂O₂ + 2 H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + 2 H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>16</td>
<td>Isoleucine</td>
<td>C₅H₁₅N₂O₂ + 2 H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + 2 H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>17</td>
<td>Valine</td>
<td>C₅H₁₀N₂O₄ + 2 H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + 2 H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>18</td>
<td>Phenylalanine</td>
<td>C₅H₁₀N₂O₄ + 2 H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + 2 H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>19</td>
<td>Tyrosine</td>
<td>C₅H₁₀N₂O₄ + 2 H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + 2 H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>20</td>
<td>Tryptophan</td>
<td>C₆H₁₂N₄O₂ + 2 H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + 2 H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>21</td>
<td>Glycine</td>
<td>C₆H₁₂N₂O₂ + 0.75 H₂C₅H₄O₂ + H₂N + 0.5 CO₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>22</td>
<td>Alanine</td>
<td>C₅H₁₀N₂O₅ + 2 H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + 2 H₂</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
<tr>
<td>23</td>
<td>Cysteine</td>
<td>C₆H₁₂N₂O₅ + 2 H₂O → H₂C₅H₄O₂ + H₂N + CO₂ + 0.5 H₂ + 0.5 S</td>
<td>1.28 × 10⁻²⁶</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>No.</th>
<th>Case</th>
<th>Volume of the reactor</th>
<th>HRT (days)</th>
<th>Loading rate</th>
<th>TS (%)</th>
<th>VS (%)</th>
<th>Substrate</th>
<th>Experimental results</th>
<th>Simulation results</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Case 1</td>
<td>5 L</td>
<td>15</td>
<td>0.331 L day⁻¹</td>
<td>6</td>
<td>80</td>
<td>Cow manure</td>
<td>353.5 kg VS⁻¹ day⁻¹</td>
<td>365.83 kg VS⁻¹ day⁻¹</td>
<td>3.4</td>
</tr>
<tr>
<td>2</td>
<td>Case 2</td>
<td>5 L</td>
<td>21</td>
<td>3.0 g VS⁻¹ L⁻¹ day⁻¹</td>
<td>15</td>
<td>85</td>
<td>MSW</td>
<td>0.54 m³ CH₄ kg⁻¹ VS⁻¹ day⁻¹</td>
<td>0.473 m³ CH₄ kg⁻¹ VS⁻¹ day⁻¹</td>
<td>-12</td>
</tr>
<tr>
<td>3</td>
<td>Case 3</td>
<td>5 L</td>
<td>21</td>
<td>3.0 g VS⁻¹ L⁻¹ day⁻¹</td>
<td>13</td>
<td>87</td>
<td>70% MSW and 30% citrus waste</td>
<td>0.555 m³ CH₄ kg⁻¹ VS⁻¹ day⁻¹</td>
<td>0.537 m³ CH₄ kg⁻¹ VS⁻¹ day⁻¹</td>
<td>-3.2</td>
</tr>
<tr>
<td>4</td>
<td>Case 4</td>
<td>600 L</td>
<td>25</td>
<td>2.0 g VS⁻¹ L⁻¹ day⁻¹</td>
<td>10</td>
<td>90</td>
<td>MSW</td>
<td>401 kg VS⁻¹ removed</td>
<td>448.76 kg VS⁻¹ removed</td>
<td>-11.9</td>
</tr>
<tr>
<td>5</td>
<td>Case 5</td>
<td>3000 m³</td>
<td>19</td>
<td>150 m³ day⁻¹</td>
<td>15</td>
<td>85</td>
<td>MSW</td>
<td>9600 m³ day⁻¹</td>
<td>10176 m³ day⁻¹</td>
<td>6.0</td>
</tr>
<tr>
<td>6</td>
<td>Case 6</td>
<td>3700 m³</td>
<td>20</td>
<td>150 m³ day⁻¹</td>
<td>12.5</td>
<td>95</td>
<td>75% slaughter house waste, 15% food waste and 10% cow manure</td>
<td>10959 m³ day⁻¹</td>
<td>11694.6 m³ day⁻¹</td>
<td>6.7</td>
</tr>
<tr>
<td>7</td>
<td>Case 7</td>
<td>30 L</td>
<td>8</td>
<td>230.4 g VS⁻¹ day⁻¹</td>
<td>6.4</td>
<td>72</td>
<td>Pig manure</td>
<td>0.268 m³ kg⁻¹ VS⁻¹</td>
<td>0.268 m³ kg⁻¹ VS⁻¹</td>
<td>0.3</td>
</tr>
</tbody>
</table>
The confidence interval (CI) was calculated to show how the change in the substrate or the extent of the reaction affects the simulation results.

3. Results and discussion

The process simulation model (PSM) was developed to explain all the intermediary metabolisms of AD. The extension of stoichiometric reaction-set (a) in PSM could be used to predict the effect of different pretreatment methods used in the biogas production process. The kinetic reaction-set (b) reveals the intermediary metabolism in AD. The PSM was validated with several laboratory experimental and industrial data, and the differences between simulations and the reported data were calculated. Furthermore, the statistical validations and the sensitivity analysis calculate the interval range of the predicted value of biogas production.

Using the PSM provides an approximate prediction of the biogas produced in a wide variety of substrates. In biogas industries, the feed composition and biogas production varies a lot every day due to several parameters and problems. Although PSM prediction shows a difference between experimental data, it could still result in better prediction for biogas production, for a change in substrates.

3.1. Validations in PSM

Table 3 shows the cases validated in PSM, and the differences between the experimental data and simulation data were calculated. The minimum and maximum difference obtained from the different validations used in PSM was 0.3% for Case 7 and −12.4% for Case 2, respectively. The biogas plant in Norrköping (case 6) works on co-digestion of substrates such as slaughterhouse waste, food waste, and cow manure and produced 10,959 m^3 day^{-1}, while the PSM calculated 11,694.6 m^3 day^{-1} biogas production. The difference between simulation and reality for this case was 6.7%. In addition, the different cases considered had various scales of volume from lab until industrial plants. Furthermore, the different loading rate and HRT were different in all the cases, suggesting that the model can be applicable in a variety of scales.

The cases studied in PSM were further validated statistically to check for significant differences between the case studies, which used different process conditions. A probability plot with 95% CI was drawn to check the P-value, to determine if there were any significant differences between the cases. P-value is a tool in...
The changes in the extent of the reaction followed linearity, where an average $R^2$ value was 0.9695 showing the robustness and accuracy of the model. Similarly, the $R^2$ value for the changes in the composition of the substrates was 0.9102 enlightening that the composition of the substrate is an important factor to predict the biogas production using PSM.

CI shows the range of the predicted biogas production from PSM. A 95% CI was calculated for both the extent of the reactions and the composition of the substrates. For a ±5% in the extent of the reaction and the composition of the substrate, CI was in the range of 3.208–7.536%. On average, 5.203% higher value can be expected from PSM for a ±5% and it increases by 5.285% and 5.35% for a change in ±10%, and ±20% in the extent of the reaction and the composition of the substrates. This suggests that even if the composition of the substrate and the extent of the reaction were varied until ±20%, PSM could predict the biogas production accurately.

4. Conclusion

Process simulation model for anaerobic digestion was developed using Aspen Plus. PSM involves intermediary metabolisms of all four phases of anaerobic fermentation. Furthermore, the PSM was validated against industrial and research studies. The average difference in biogas production between simulation results and real scenario up to ±20% change in substrate composition and the extent of the reaction is 5.279%. Using computational and mathematical power, the PSM shows that decoding AD mechanisms is easier with the proposed model. PSM helps to save time, money, and energy to study new substrates or changes in the composition of substrates for industries and researchers.

Acknowledgements

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References


Uncertainty over techno-economic potentials of biogas from municipal solid waste (MSW): A case study on an industrial process

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Highlights

- Uncertainties affecting profitability of biogas from OMSW was evaluated.
- Collection and transportation costs affect the profitability.
- The bigger the plant, the more energy and economic efficient it is.

Graphical Abstract

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Abstract

In this study, biogas production from the organic fraction of the MSW (OMSW) was simulated in six different scenarios, using Aspen Plus® based on industrial data. The economic evaluations were made using the Aspen process economic analyzer, considering the plant size and the upgrading methods. The base case had an annual processing capacity of 55,000 m³ OMSW. The capital costs and the net present value (NPV) after 20 years of operation were 34.6 and 27.2 million USD, respectively. The base case was compared to the modified scenarios, which had different upgrading methods, processing capacities, addition of biogas from wastewater sludge treatment, and variation of the substrate (OMSW) between ±200 USD/ton. The sensitivity analyses were carried out considering the cost of the OMSW imposed on citizens for collection and transportation of wastes and the different sizes of the plant. The result suggests that producing biogas and selling it, as a vehicle fuel from OMSW is a profitable venture in most scenarios. However, there are some uncertainties, including the collection and transportation costs, landfilling fee, and process operation at lower capacities, which affect its profitability.

1. Introduction

The annual generation of municipal solid waste (MSW) has attained more than 2.5 billion tons per year [1]. More than 50% of the MSW ends up in dumping areas or landfills, creating three major problems: (a) loss of fertile or arable land, (b) health hazard, and (c) loss of energy and materials from the waste. Approximately 50% of the MSW is composed of organics in the world, which can be converted into value-added products such as biogas or...
composts [2]. While the aerobic biodegradation in composting results only in CO₂ and fertilizer, biogas from anaerobic digestion contains about 50–70% methane and the rest is practically CO₂. Energy-rich methane (≈37 MJ/m³) can be used for different purposes including heat, electricity, and vehicle- and cooking fuels [3]. It can be calculated that the MSW with an average 33% total solids (TS) content can result in 321 billion m³ pure methane from the global MSW production, based on the average biogas yield of 618 m³/ton TS. The 321 billion m³ methane is equivalent to 3104 TW h/year energy (1 m³ methane equivalent to 9.67 kWh) [4], which is equivalent to 2% of the global energy consumption per year.

Several million bio-digesters for households are available in the world, while industrial biogas plants for commercial applications such as electricity and fuel are relatively few [5,6]. According to International Energy Agency, about 970 plants are in operation for municipal solid waste and industrial waste together in Europe [7]. Very few plants produce methane for vehicle fuel as compressed biogas (CNG); on the contrary, most of the plants produce power or combined heat and power (CHP) from biogas [8]. Biogas from the organic fractions of MSW is not only attractive in terms of energy, but also economically sound. The capital costs of the biogas plants treating 100,000 tons MSW/year was 20 million USD in 2003 [9]. Upgrading the produced biogas to vehicle fuel requires about 13% of the total investment costs [9,10].

Techno-economic models are used as a measure to identify the industrialization potential of a project. Several techno-economic models have been reported for ethanol production; however, for biogas, the literature is mainly based on laboratory data with novel substrates such as citrus wastes, chicken-feather, and its pretreatments [8,11–17]. According to our knowledge, no industrial based biogas plants have been considered for techno-economic evaluation of MSW. The techno-economic evaluation considered in this study was based on an industrial biogas plant located in Borås (Sweden) that is fed with sorted organic MSW.

Borås, with a population of more than 100,000 people, produces on average about 22,600 tons of MSW every year. In addition, the MSW from Norway and other nearby Swedish cities such as Gothenburg, and the industrial wastes from companies, slaughterhouses, restaurants, etc., also end up in the waste station in Borås. Approximately, 27% of the MSW is recycled as materials, 30% (organic wastes) is sent for biological treatment for the production of biogas, and the remaining 43% is combusted to produce electricity and district heat for the city. The biogas produced after the biological treatment is used as CNG for vehicle fuel to run buses, garbage trucks, and other gas vehicles [18,19].

In this study, the techno-economic feasibility of an industrial biogas plant for MSW, located in Borås, Sweden was investigated under six different scenarios. The process was simulated using Aspen Plus® version 8.0 (AspenTech, Massachusetts, U.S.A.) based on the industrial data obtained from Borås Energy and Environment AB, Sweden. The six different scenarios were simulated using Aspen Plus®, and process economics were carried out using the Aspen Process Economic Analyzer (V 8.0). Furthermore, sensitivity analysis was carried out for different costs of the MSW, which varied between ±200 USD/ton, number of digesters operating in the plant, and effect of operational loading in the plant. The main objective of this work was to study the uncertainties around the techno-economic feasibility of the biogas production from OMSW, affected by factors mentioned above.

2. Methods

2.1. Process description

The process scheme for the six scenarios is shown in Fig. 1. The six different scenarios considered were based on the current operation of the plant (scenario 1), and scenarios 2 and 3 were considered to facilitate different upgrading methods and the effect of adding biogas from wastewater treatment respectively. The other three scenarios considered were to double the capacity, to check how the size or the number of digester used, and their effects on the process profitability. Scenarios 1–3 have a capacity of 55,000 m³ MSW/year, while scenarios 4–6 have a base capacity of 110,000 m³ MSW/year. In this study, scenario 1 is the base case, which will be compared to other scenarios. The total solids (TS) content of the MSW fed to the digester was 15%. The preprocessing step for the MSW was common under all scenarios, while the digesters and the biogas upgrading to obtain methane vary for the different scenarios.

Initially, the MSW is crushed using a hammer mill crusher with the addition of water, to reduce the particle size to less than 5 mm. The TS of the MSW is reduced from 33% to 15% with the addition of water. The crushed materials are transported using a centrifugal pump to two storage tanks, buffer tanks 1 and 2, with a respective volume of 200 m³ and 650 m³, which have a combined retention time of 3 days. Then, the waste slurry is pumped into a 3000-m³ anaerobic digester. Scenarios 1–3 have a single digester, whilst scenarios 4–6 have two digesters of the same volume running in parallel. The organic loading rate (OLR) maintained in the digester is 3.3 kgVS/m³/day with a hydraulic retention time (HRT) of 19 days. The digesters operate at 55 °C, heated internally.

The digestate from the digester is pumped into a 340-m³ storage tank with a retention time of 2.2 days. The digestate is further pumped into a big storage tank of 2000 m³, from where it is transported to nearby farmlands. Part of the biogas is produced from the storage tank. All the biogas production is connected to a common upgrading system. The upgrading methods used in this study are water scrubbing and absorption through COOAB (carbon dioxide absorption by amine) using monoethanol amine (MEA). Water scrubbing is a common upgrading method for biogas, while in the COOAB process MEA is used for the absorption of carbon dioxide and hydrogen sulfide. The raw biogas flowing out of the digester passes through a centrifugal compressor to increase the pressure to 8 bar, and is then cooled down to 5 °C using a heat exchanger, before it passes through the upgrading column either by water scrubbing or COOAB [4].

The scrubber column operates at 8 bar, where the CO₂ is removed with the water. The recycling ratio in the scrubber for water was maintained at 0.90. Similarly, the absorption column for the COOAB process was operated at 5 bar. The recycling ratio of the MEA in the absorption column was 0.95. Purified methane (~97%) is sent through another separator to remove final impurities. Thereafter, the CBG (compressed biogas with 99% purity of methane) is stored at 5 °C and 300 bar, before it is sold to the market as car fuel. The CBG is sold at a price of 2.2 USD/L, including 0.4 USD/L tax, resulting in the industry selling CBG at a net price of 1.81 USD/L (Table 1).

Based on the aforementioned processes, six scenarios (Fig. 1) were compared, as follows:

Scenario 1: annually, 55,000 m³ MSW is used with one digester in operation. The upgrading method employed was COOAB only. This scenario was considered as the base case scenario (currently in existence at the plant), which was compared to other scenarios. Fig. 2 shows the process flow diagram for the base case.

Scenario 2: similar to scenario 1, but the upgrading method was water scrubbing.

Scenario 3: in this scenario, the same amount of waste was used; however, the biogas was upgraded by both water scrubbing (30%) and the COOAB process (70%). In addition, 3500 m³/day biogas was added, which was obtained from the
A wastewater treatment plant nearby. The biogas from the wastewater treatment plant was considered because using two upgrading methods is capital intensive.

**Scenario 4**: using two anaerobic digesters, 110,000 m$^3$ MSW/year was used as a capacity. The produced biogas was upgraded by water scrubbing.

**Scenario 5**: the capacity was similar to scenario 4, while the upgrading method was 100% COOAB.

**Scenario 6**: approximately 110,000 m$^3$ MSW/year was used with two anaerobic digesters, while the biogas was upgraded as in scenario 3 with the addition of 3500 m$^3$ biogas from the wastewater treatment plant every day. Fig. 3 shows the process flow diagram of scenario 6.

### 2.2. Equipment and economics

The crusher used in this study was a hammer mill made of carbon steel. The pumps, COOAB and scrubbing towers, compressors, buffer tanks, CSTR, separator, and heat exchangers were made of stainless steel (SS 304). The types of equipment used were centrifugal pumps, centrifugal compressors, and shell and tube heat exchangers. All the equipment, except the upgrading towers, pumps, and heat exchangers, have one identical item, while pumps and heat exchangers have two identical equipment for all four pumps and two heat exchangers. The COOAB tower has a lifetime of five years; henceforth, four, identical equipment were used, whereas for the water scrubber, two identical equipment were considered. The final storage tanks were made of carbon steel, as temperature control was not required.

All the aforementioned equipment were simulated using Aspen Plus$^2$. The anaerobic digesters were simulated based on the PSM developed by Rajendran et al. [20]. The simulations in each scenario were resolved for mass and energy balances. The economic evaluations were carried out using the Aspen process economic analyzer. Table 1 shows the assumptions considered throughout the study.

### Table 1
List of assumptions considered for the techno-economic evaluation of the biogas plant from the MSW.

<table>
<thead>
<tr>
<th>Material Assumption</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual processing capacity</td>
<td>55,000 m$^3$ MSW/year for scenarios 1–3 and 110,000 m$^3$ MSW/year for scenarios 4–6</td>
</tr>
<tr>
<td>Cost index</td>
<td>2012 in USD</td>
</tr>
<tr>
<td>Annual operating time</td>
<td>8000 h</td>
</tr>
<tr>
<td>Depreciation method</td>
<td>Straight line</td>
</tr>
<tr>
<td>Working capital</td>
<td>5% of total investment</td>
</tr>
<tr>
<td>Interest rate</td>
<td>10%</td>
</tr>
<tr>
<td>Tax rate</td>
<td>33%</td>
</tr>
<tr>
<td>Lifetime of the plant</td>
<td>20 years</td>
</tr>
<tr>
<td>Salvage value</td>
<td>5% of total investment</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>0.0775 USD/kWh</td>
</tr>
<tr>
<td>Water</td>
<td>0.001 USD/kg</td>
</tr>
<tr>
<td>Steam</td>
<td>0.01 USD/kg</td>
</tr>
<tr>
<td>Wastewater</td>
<td>0.0001 USD/m$^3$</td>
</tr>
<tr>
<td>MEA</td>
<td>1.5 USD/kg</td>
</tr>
<tr>
<td>MSW</td>
<td>0 USD/kg</td>
</tr>
<tr>
<td>Selling price of CBG</td>
<td>1.83 USD/L</td>
</tr>
</tbody>
</table>
this study. The economics were considered based on the pricing of the 1st quarter in 2012. The process economics, including capital costs, operating cost, utility costs, profitability index such as revenue, payback period (PBP), and net present value (NPV) were calculated and analyzed for all scenarios. CBG was sold at a price of 1.81 USD/L, after the fuel tax and utilities were priced in accordance [21]. The minimum compressed biogas price (CBGmin) is a measure, which determines the minimum price of biogas sold in the market to have a zero profit (NPV = 0) and was calculated for all six scenarios [22].

2.3. Sensitivity analyses

Based on the economic and profitability analysis in the different scenarios, three different sensitivity analyses were carried out to check the economical sustainability of the model. In one sensitivity analysis, the cost of the MSW was changed, while in the second one, the effect of having one or two digesters for the same volume of treatment facility was considered. Finally, the operational loading of the plant was reduced to half to check the dynamic processing effect of the plant and to see how it affects the economical parameters.

MSW was assumed to have zero price in the base scenario, as it can be forecasted in two different ways: (1) the citizens pay a tipping fee to get rid of the waste, resulting in the MSW having a negative price, and (2) the cost of collection and transportation of waste that have an impact on profitability. For this purpose, the price of the MSW in the model varied from −200, −100, 0, 100, and 200 USD/ton, and the (complete) profitability calculations were calculated. Here, the negative price suggests that citizens pay a fee to get rid of the waste, whereas the positive price indicates that the collection and transportation of waste was considered in the profitability analysis.

In the base case, 55,000 m³ MSW was treated annually with COOAB as the upgrading option. In scenario 5, however, double the capacity was considered using two digesters. A sensitivity analysis was carried out by decreasing and increasing the plant capacity in scenarios 1 and 5 by 50% and 200%, respectively, (i.e.,
27,500–200,000 m³ MSW/year). In this sensitivity analysis, 200% of scenario 1 will treat the same volume of waste as in 100% of scenario 5, except that it has two digesters. This comparison will reveal the advantages and disadvantages of having two digesters instead of one, in an industry. As most industrial processes are dynamic, and sometimes the availability of the substrate is an issue throughout the year, having only one large digester means that the plant has to reduce its loading (half operation). On the other hand, if two digesters were in operation, one digester can still run to its full capacity and stopping the other one will not affect the process adversely.

In many biogas industries, the startup of the process takes a longer time, and sometimes due to the instability of the process, the plant has to operate at a reduced capacity than its full potential or what it is designed for. A sensitivity analysis was carried out for the different scenarios to determine how the profitability might be affected if the plant operated on half its capacity. Consequently, the capital investment would be the same; however, the profitability indexes might be affected, revealing the effect of having the plant operations running at half capacity.

3. Results and discussion

Biogas from the MSW in the base case (scenario 1) was compared to other scenarios from a techno-economic perspective. The scenarios were simulated using Aspen Plus®, calculating the mass and energy balances. Fig. 4 shows the capital investment, revenue, utility, operational costs, CBGmin, and NPV for all scenarios. The process simulations using Aspen Plus® could be used as a tool in the debottlenecking of a plant, where new substrates could be tested to evaluate the biogas potential for an industrial outlook.

3.1. Base case scenario

In the base case, 55,000 m³ MSW was used as APC with COOAB as the upgrading option to vehicle fuel. Crushing the MSW is an energy intensive process, which accounts for 14% of the total energy consumption (Fig. 5). While the energy consumption in the digester, together with the mixer and the heater, is about 3.5 MW h/day. The productivity of raw biogas in the base case is 400 m³/h from the digester, while by using COOAB more than 99% methane could be recovered (Table 2). The methane concentration in the raw biogas was 59.9%. Using the COOAB process, MEA was used as amine to purify the biogas with about 95% recycling back to the column. The overall energy consumption of the plant was 4.3 GW h/year, while the net energy production from methane was 18.07 GW h/year. Majority of the energy is consumed by the upgrading section (0.66 kW h/m³ biogas). These results are in accordance with that of Kaparaju and Andjukka Rintala, which varied between 0.3 and 0.6 kW h/m³ biogas [23].

Digestate, the leftovers or the waste from the anaerobic digestion process, comes out from the digester and is pumped into a secondary storage tank. Approximately 12.5% of the raw biogas is produced from this secondary storage tank. This storage tank is not temperature controlled, suggesting that it was used only to collect some leftover biogas. From there, the digestate is sent to a bigger storage tank for final disposal (Fig. 2). About 150 m³/day is pumped into the digester, and the TS is reduced to less than 7% after the digestion process. Today, without any further treatment or centrifugation to process it into compost, the digestate is given to farmers free of charge. However, if centrifuged, it could be sold as compost at a cost of 30 USD/ton, which can bring in an additional revenue of 228,000 USD/year [24]. On the other hand, centrifugation is an energy intensive process, which consumes about 1.2 MW h/day, making it an unreasonable option for composting, as the TS content of the digestate is very low. The digestate is then connected to the wastewater treatment system at a cost of 1 × 10⁻³ USD/m³.

The economical evaluations revealed that the plant requires a capital investment of 34.6 million USD; furthermore, the profits of the plant can be obtained after 10.04 years. In 2010, Economopoulos [25] reported 30 million USD for a similar plant size for treating the MSW in Greece. The NPV of the biogas plant after 20 years of its lifetime would be 27.2 million USD with an IRR of 17.8%. The annual operating cost of the plant was 2.53 million USD, and the utilities costs about 4% of the operating costs. This plant requires about 6 operators and a supervisor to control the processing of the plant. By selling methane as a vehicle fuel, 9.3 million USD could be generated as revenue annually. The CBGmin, price at which NPV becomes zero was 1.15 USD/L, suggesting that the profitability cost in the base case was 0.66 USD/L (Fig. 4).

3.2. Comparison of different scenarios

The base case (scenario 1) was compared to other five scenarios. Scenarios 2 and 3 have the same APC as in the base case. For scenarios 4–6, the APC was 110,000 m³ MSW/year. Table 2 shows the biogas production, methane recovery, energy consumption and net energy production of the full plant under different scenarios. Although, the same amount of biogas is produced in the base case and under scenario 2, the methane loss was more in scenario 2 (10%). This is due to the lower efficiency of the water scrubbing process, compared to COOAB, which has less methane losses (<1%). In contrast, the net energy consumption in scenario 2 was 15.5% less compared to the base case, which increased the utility consumption by 56%.

Doubling the plant capacity in scenarios 4–6 did not double the biogas productivity from the base case. The biogas production was increased by 82.7%. The net energy consumption of the plant in scenarios 4–6 was between 7.09 and 7.74 GW h/year, which is 64.8–80% higher energy consumption compared to the base case. As most energy is utilized in the upgrading section, scenario 6 showed the most energy consumption. Adding the biogas from the wastewater treatment plant was an energy saving option, as more purified methane could be obtained. The methane slip in scenario 6, which utilized both the upgrading methods, was 4.4%. The energy consumption for the upgrading of methane in scenarios 4–6 was 0.515, 0.532, and 0.515 kW h/m³ biogas, respectively.

The net energy production for different scenarios is presented in Table 2. Comparing different scenarios, the scenario 6 had the highest net energy production of 38.21 GW h/year. The ratio between, net energy production and net energy consumption was calculated to check the energy efficiency of the plant. The results indicate that in the base case, the plant is not energy efficient as the COOAB process consumes more energy, with an energy efficiency ratio of 4.2. Comparing the different scenarios, the current operation of the plant can be modified toward scenario 6, which is beneficial in terms of energy and economics.

The capital investments of the biogas plant for scenarios 2 and 3, which treats 55,000 m³ MSW/year was 30.1 and 35.4 million USD, respectively, while that of 110,000 m³ MSW/year in scenarios 4–6 varied between 38.4 and 49.2 million USD. This shows that doubling the capacity of the plant is less capital intensive compared with that of the plant with lower capacities. The net present value (NPV) of all the scenarios was 28.2, 27.2, 47.8, 58.1, 69.8, and 106 million USD after 20 years of operation. The profits were calculated at a 10% discount rate suggesting that biogas from the MSW or household waste is a profitable venture. The annual operating costs varied between 1.83 and 5.38 million USD, while the utility costs varied between 3% and 4% of the operational costs. Scenario 6 was the most profitable of all scenarios, in terms of energy efficiency, energy consumption and economical parameters.
Minimum compressed biogas price (CBGmin) is an indicator, where the minimum price at which the plant has zero NPV at a discount rate of 10% was calculated for all six scenarios. The base case had the highest CBGmin price of 1.15 USD/L, and the lowest was for scenario 6, which was 0.76 USD/L. This profit margin rose to 1.04 USD/L for scenario 6, revealing a high profit with the increase in the capacity and using both upgrading methods.

3.3. Effect of MSW price on different scenarios

The MSW was assumed to have a zero price in the base scenario, while in the sensitivity analysis a different price range from -200 USD/ton to +200 USD/ton was considered. Fig. 6 shows the NPV and PBP for different prices of MSW for the six scenarios. Negative price of the raw material had a significant positive impact on the economics of the process. For scenario 6, when the citizens pay 200 USD/ton to get rid of the waste, the NPV increased to 180 million USD, which is 69% higher compared to the NPV at 0 USD/kg MSW. However, the collection and transportation cost of the MSW affected the final profits adversely. When the cost of the MSW was +200 USD/ton, scenarios 1, 2, and 4 had a negative NPV, suggesting that the collection and transportation costs is a crucial factor in the profitability of the plant.

On the different prices of the MSW, the landfill tipping fee for the MSW was not considered. The tipping fee is around 100 USD/ton for organic wastes, which can save 2.2 million USD annually for the MSW produced in Borås, Sweden[26,27]. When the price of the MSW was increased from 0 USD/kg to +100 USD/ton in the base case (scenario 1), the PBP increased to 13.8 years from 10.04 years suggesting that the plant would only yield profit during the last six years of operation (Fig. 6).

The citizens in Sweden pay a tipping fee (to get rid of the waste) that varies between 165 and 305 USD/year/family, depending on their living area and type of house. It is estimated that the annual collection and transportation fee for the municipalities is between 150 and 400 USD/ton[27]. Considering the net waste generated in Borås, the fee collected from the families should be sufficient for...
the municipality. Abu Qdais [28] reported that only 40–53% of the costs to process the wastes could be recovered in Jordan. Nevertheless, according to our calculations, it showed to be a positive investment to convert biogas into vehicle fuel from the MSW. However, when the waste has to be transported further distances, for example, from Gothenburg (70 km) or Oslo in Norway (350 km), the transportation costs would be a crucial factor. The cost of transportation for one ton of waste from Norway to Borås is approximately 75 USD, excluding the driver’s fee. The driver’s fee is the salary for the labor in transporting the waste and it costs between 15 and 20 USD/h [29]. If we assume 100 USD/ton as the net cost for the transportation of the waste, then for scenario 6 in this study, the NPV would be 69.8 million USD.

3.4. Comparison of base case and scenario 5 on different APC

In the base case, 55,000 m³ MSW was considered as the APC; however, in scenario 5, a double capacity of 110,000 m³ MSW was considered. The base case has one digester of 3000 m³, while two digesters were in operation in scenario 5. If the base case is doubled in its operating capacity, i.e., 200%, then the APC of the base case is the same as in scenario 5, which is 110,000 m³ MSW/year. Although the process capacity of both of these comparative scenarios is the same, the doubled APC in the base case has less capital costs. This is obvious since it only has one digester with a larger volume, compared to scenario 5, which has two digesters with a volume of 3000 m³. Fig. 7 shows the effect of having one and two digesters in the plant. The capital cost for the base case, which has a single digester, with double the capacity was 39.6 million USD. On the other hand, scenario 5, which has two digesters in operation, will have a high capital investment of 40.7 million USD. The NPV also follows the same trend, as the base case with double the capacity will have a higher NPV (21%), compared to scenario 5 with two digesters.

In industrial processes, the continuous input of waste sometimes get affected due to seasonal variations of waste quantity, transportation, competition in the market, etc. Under these circumstances, if the plant has to reduce its capacity of operation, then the microorganisms inside the digester will get affected due to the imbalance of the loading. Accordingly, if two digesters were in operation, it would be easy to stop one digester and still continue with the other digester at full capacity, without affecting the stability inside at least one of the digester. Although having two digesters is capital intensive and less profitable, the stability of the process and the industrial operation will not be affected.

3.5. Effects of reduced operations in the plant

Scenarios 1–3 were designed for 55,000 m³ MSW/year; however, in many industrial situations, due to the long startup process
or unavailability of the raw material or due to instability of the process, the industry has to reduce its loading than its designed capacity. A plant running under these situations will affect its profitability. In this sensitivity analysis, half-operational loading was considered for scenarios 1–3, that is, 75 m$^3$/day was used as the input for a plant designed for 150 m$^3$/day, while the size of the process vessels and other equipment remained the same. Fig. 8 shows the effect of the NPV and product sales in the reduced operation capacity of the plant.

For a plant operating at half its designed capacity, it is much more difficult to recover the capital costs. The reason is that its operational and utility expenses remain almost the same, while the product sales have decreased adversely. If a plant operates at half its capacity for its complete lifetime, then it would result in a negative NPV. The base case (scenario 1) would result in $67 million USD, while that of scenarios 2 and 3 would be $66 and $27 million USD, respectively. Comparing the product sales of a plant operating at full capacity to a plant operating at half capacity, the product sales was reduced by 56% in the base case, followed by 53% and 33% for scenarios 2 and 3, respectively (Figs. 4 and 8). This shows that loading the plant to its fullest capacity plays a vital role in recovering the economics of the plant.

3.6. Paradigms of uncertainty

Biogas from the OMSW gives the impression that it is economically feasible in the different analyses carried out above. However, there are some paradigms of uncertainty revolving around it. It could be due to the collection and transportation costs, sorting of the waste fraction, citizens tipping fee for waste processing, gate fee for landfilling, etc. The citizens pay a fee to get rid of the waste, for its collection and processing, which is on average about 235 USD/family. Since 2006, landfilling of organic wastes is banned in Sweden; thus, if organic wastes are landfilled, a gate fee to get rid of waste has to be paid, which is about 100 USD/ton [26,27].

The sensitivity analysis revealed that the cost for the collection and transportation is a crucial factor in the profitability of the plant. Furthermore, increasing the plant capacity resulted in a higher NPV. The interesting paradigm here is that increasing the volume of the waste, i.e., the capacity of the plant means a higher collection and transportation cost of the plant, which can affect the profitability. For instance, large cities such as Hong Kong or Bangkok generate a large volume of waste every day [30]; however, the availability of the land inside the city is negligible, so the waste needs to be transported long distances outside of the cities. On the other hand, if smaller cities were considered, the waste generation will be less, while the capital costs are high for a small plant, affecting the profitability factor. However, some examples of ways to make biogas processes economically sustainable are to increase the gate fee for landfilling and/or the fee for waste collection from the citizens.

4. Conclusion

Biological treatment of the MSW to produce biogas for vehicle fuel is a positive investment under most of the scenarios, ranging in a wide variety of scales from 27,500 to 220,000 m$^3$/year. High annual processing capacities of the MSW resulted in high NPV, suggesting that it is a positive investment for countries that produce large amounts of waste. The main uncertainties over the techno-economic feasibility of biogas from OMSW are due to the transportation and collection of waste, and reduced operations of the plant. In addition, integrating biogas from a wastewater treatment plant with simultaneous upgrading by using the water scrubbing and/or the COOAB process was reported to be the most economical and profitable venture. Biogas is attractive both economically and environmentally, as it can yield in high profits and utilizes the waste generated as value added products.

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Household Biogas Digesters—A Review

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Abstract: This review is a summary of different aspects of the design and operation of small-scale, household, biogas digesters. It covers different digester designs and materials used for construction, important operating parameters such as pH, temperature, substrate, and loading rate, applications of the biogas, the government policies concerning the use of household digesters, and the social and environmental effects of the digesters. Biogas is a value-added product of anaerobic digestion of organic compounds. Biogas production depends on different factors including: pH, temperature, substrate, loading rate, hydraulic retention time (HRT), C/N ratio, and mixing. Household digesters are cheap, easy to handle, and reduce the amount of organic household waste. The size of these digesters varies between 1 and 150 m³. The common designs include fixed dome, floating drum, and plug flow type. Biogas and fertilizer obtained at the end of anaerobic digestion could be used for cooking, lighting, and electricity.

Keywords: biogas; household digesters; bioenergy; waste management; fixed dome digesters; floating drum digesters; plug flow digesters

1. Introduction

Due to the increasing prices of fossil fuels and taxes on energy sources, finding alternative, clean and economical sources of energy has nowadays become a major concern for households’ and nations’ economies. In addition, economic prosperity and quality of life, which are linked in most countries to per-capita energy consumption, is a great determinant and indicator of economical development [1–4].
Energy demand is a critical reason for extensive climate change, resource exploitation, and also restricts the living standards of humans [5,6].

By the time fuel and fertilizer reaches rural areas, the end price is relatively expensive due to high transport costs, leaving people to find alternative resources other than oil [7]. Starke [8] reported wood as the traditional source of fuel to produce energy for domestic purposes for 2.5 billion people in Asia. Many of the rural communities in developing countries are forced to rely on the traditional energy sources such as firewood, dung, crop residues, and paraffin. These traditional methods are often expensive and/or time-consuming [9–11]. Cooking accounts for 90% of energy consumption in the households of developing countries [12]. Furthermore, access to electricity in rural areas is relatively scarce [13].

Biogas is a substitute for firewood and cattle dung that can meet the energy needs of the rural population [14,15]. Biogas is a renewable source of energy that can be used as a substitute for natural gas or liquefied petroleum gas [16]. There are different models to assess the energy content of different energy sources, which includes water boiling test, controlled cooking test and kitchen performance test [17]. The energy content of 1.0 m³ of purified biogas is equal to 1.1 L of gasoline, 1.7 L of bioethanol, or 0.97 m³ of natural gas [16]. The application for rural and urban waste biogas production is widely spread. It is a challenge for engineers and scientists to build an efficient domestic digesters with the materials available, at the same time taking the local and economical considerations into the account. Although many digesters have been built, additional research and awareness are needed to meet the changing needs and conditions [18].

Biogas production can be carried out in very small reactors ranging from 100-mL serum bottles in the lab up to 10,000 m³ large digesters as normally used, for example, in Europe. This review deals with a summary of different household biogas digesters, their operating parameters, cost and materials used to build them, startup, and maintenance, the variety of applications employed, and associated social and environmental effects.

### 1.1. Biogas

Biogas, the metabolic product of anaerobic digestion, is a mixture of methane and carbon dioxide with small quantities of other gases such as hydrogen sulfide [19,20]. Methane, the desired component of biogas, is a colorless, blue burning gas used for cooking, heating, and lighting [21]. Biogas is a clean, efficient, and renewable source of energy, which can be used as a substitute for other fuels in order to save energy in rural areas [22]. In anaerobic digestion, organic materials are degraded by bacteria, in the absence of oxygen, converting it into a methane and carbon dioxide mixture. The digestate or slurry from the digester is rich in ammonium and other nutrients used as an organic fertilizer [11,23–27].

Methane formation in anaerobic digestion involves four different steps, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Different bacterial/archaea communities work in a syntrophic relationship with each other to form methane. In hydrolysis, complex carbohydrates, fats, and proteins are first hydrolyzed to their monomeric forms by exoenzymes and bacterial cellulose. In the second phase (acidogenesis), monomers are further degraded into short-chain acids such as: acetic acid, propionic acid, butyric acid, isobutyric acid, valeric acid, isovaleric acid, caproic acid,
alcohols, hydrogen, and carbon dioxide. During acetogenesis, these short-chain acids are converted into acetate, hydrogen, and carbon dioxide. In the last phase, methanogens convert the intermediates produced into methane and carbon dioxide. Almost one-third of methane formation is due to reduction of carbon dioxide by hydrogen [28].

1.2. Digestion Factors

Anaerobic digestion depends on several different parameters for an optimum performance. Different groups of microorganisms are involved in the methane production, and suitable conditions have to be established to keep all the microorganisms in balance. Some of these parameters are: pH, temperature, mixing, substrate, C/N ratio, and hydraulic retention time (HRT). Digestion is a slow process and it takes at a minimum of three weeks for the microorganisms to adapt to a new condition when there is a change in substrate or temperature [28].

A symbiotic relationship is necessary between the hydrogen-producing acetogenic microorganisms and the hydrogen-consuming methanogens. Furthermore, a neutral pH is favorable for biogas production, since most of the methanogens grow at the pH range of 6.7–7.5. Temperature is also an important factor in the biogas production. Most of the acid forming microorganisms grows under mesophilic conditions; however, for methanogens, a higher temperature is favorable [28]. Mixing is also an essential parameter for biogas production. Too much mixing stresses the microorganisms and without mixing foaming occurs. Methane-forming microorganisms grow slowly, with a doubling time of around 5–16 days. Therefore, the hydraulic retention time should be at least 10–15 days, unless these bacteria are retained by, for example, entrapment. Substrate and the balance of carbon sources with other nutrients such as nitrogen, phosphorus, and sulfur is also important. The substrate should be slowly digested, otherwise easily degradable substrates may cause a sudden increase in acid content. The carbon and nitrogen ratio should be around 16:1–25:1. Too much increase or decrease in the carbon/nitrogen ratio affects biogas production. The concentration of solids in the digester should vary between 7% and 9%. Particle size is not an important factor compared to other parameters such as pH and temperature. However, the size of the particles used affects the degradation and ultimately the biogas production rate [28–30].

1.3. A Brief Global View on Small Anaerobic Digesters

Unlike other renewable fuels such as biodiesel and bioethanol, biogas production is relatively simple and can operate under any conditions and is not monopolistic [31,32]. Dung is a potential substrate for biogas production, seen only as a floor polish and fertilizer in the garden for hundreds of years. Biogas for rural energy is sustainable, affordable, and has no negative effect on people’s health or the environment, if handled properly [33,34]. Complicated construction, difficult operation of the systems, high investment, and maintenance costs have pushed farmers to adopt cheaper and simpler anaerobic systems [35].

There are currently more than 30 million household digesters in China, followed by India with 3.8 million, 0.2 million in Nepal, and 60,000 in Bangladesh [36–38]. China has increased its investments in biogas infrastructure very rapidly. By 2020, 80 million households in China are expected to have biogas digesters serving 300 million people [39]. India is implementing one of the
world’s largest renewable-energy programs with different scales of technologies. One of the strategies is to promote biogas plants [40,41]. India began the project half a century ago, and was further supported by the National Project on Biogas Development in 1982. Similar trends were more or less observed in other Asian countries. For instance, SNV, a Non Governmental Organization (NGO) from The Netherlands has installed 23,300 plants in Vietnam [42].

In America, 162 farm scale plants were in operation by 2010, providing energy for 41,000 homes; in addition, 17 plants were operating in Canada. The number of farm scale digesters in Europe has increased drastically. At the end of 2011, the number of these digesters was more than 4000 in Germany, 350 in Austria, 72 in Switzerland, 65 in the United Kingdom followed by Denmark with 20 community type and 35 farm scale plants, and Sweden had 12 plants [43–46].

The level of biogas technology for household purposes is very low in many African countries [47]. Kenya has 1884 household biogas plants and Ethiopia has more than 1140 plants [48]. Small-scale biogas plants are located throughout Africa, but only a few are working. Poor technical quality of construction and material used, inexperienced contractors, insufficient knowledge on the system in practice as well as in research institutes and universities are some of the reasons responsible for the failure [49]. Although the potential need is very high in Africa, the technology is at embryonic stage with the countries struggling to meet their energy demands [2,49,50].

2. Household Digesters

It is always difficult to adopt one particular type of digester for household purposes. Design of the digesters is varied based on the geographical location, availability of substrate, and climatic conditions. For instance, a digester used in mountainous regions is designed to have less gas volume in order to avoid gas loss. For tropical countries, it is preferred to have digesters underground due to the geothermal energy [51]. Out of all the different digesters developed, the fixed dome model developed by China and the floating drum model developed by India have continued to perform until today [52]. Recently, plug flow digesters are gaining attention due to its portability and easy operation.

2.1. Fixed Dome Digesters

The fixed dome digesters (Figure 1) also called “Chinese” or “hydraulic” digesters are the most common model developed and used mainly in China for biogas production [27]. The digester is filled through the inlet pipe until the level reaches the bottom level of the expansion chamber. The produced biogas is accumulated at the upper part of the digester called storage part. The difference in the level between slurry inside of the digester and the expansion chamber creates a gas pressure. The collected gas requires space and presses a part of the substrate into an expansion chamber. The slurry flows back into the digester immediately after gas is released [53].

Fixed dome digesters are usually built underground [27]. The size of the digester depends on the location, number of households, and the amount of substrate available every day. For instance, the size of these digesters can typically vary between 4 and 20 m³ in Nepal [54], between 6 and 10 m³ in China [55], between 1 and 150 m³ in India [56] and in Nigeria it is around 6 m³ for a family of 9 [57]. Instead of having a digester for each individual home, a large volume digester is used to produce
biogas for 10–20 homes, and is called community type biogas digesters. In countries where houses are clustered as in Nigeria, these types of biogas digesters are more feasible [58].

**Figure 1.** Schematic sketch of (a) a janta model fixed dome digester and its modifications, (b) a deenbandhu model fixed dome digester and its modifications, and (c) a modified fixed dome digester with straight and curved inlet and outlet tube.
Fixed dome models developed in India include the *janta* and *deenbandhu* models. The *janta* model was introduced in 1978 (Figure 1a). It consists of a shallow well with a dome roof on top. The inlet and outlet were kept above the dome with the gas pipe fitted on top of the dome. The disadvantages of the *janta* model include short circulating path of the slurry, escape of undigested slurry at the top and less volume of gas produced due to the increased gas pressure [59]. Action for Food Production (AFPRO) launched a modified *janta* model called the *deenbandhu* model in 1984 (Figure 1b). It consists of two spheres of different diameters. The lower sphere acts as a fermentation unit, while the upper one is the storage unit. This model was developed to reduce the price without decreasing the efficiency of the process [1].

Many countries have modified the basic shape of the fixed dome model. For instance, the Chinese digester was modified into a hemispherical shape with a wall in the middle as shown in Figure 1a [60,61], and the *deenbandhu* model was modified with a smaller gas holding capacity and reducing the diameter of the arch (Figure 1b) [62]. In mountainous regions, loss of biogas during the winter months is less in the modified model than the *deenbandhu* model. Jash and Basu [63] modified the dome with a vertical cylinder and a gas holder in a bell shape. The cylindrical vessel was partitioned into two using bricks. Since the inlet and outlet tubes were long and straight, some of the heavy particles got stuck, resulting in a modification with a bent inlet and outlet tube (Figure 1c). Fixed dome digesters were surrounded by a steel drum containing biomass to avoid the loss in temperature, which is also called French type digesters [64]. Another modification is to cover the gas storage part of the fixed dome digester with an expanding plastic bag. A wood roof is placed on top of the cover in order to protect the fragile plastic bag against the sunlight and at the same time increase the gas pressure by its weight [53].

2.2. *Floating Drum Digesters*

Khadi and Village Industries Commission (KVIC) is the name of a floating drum digester model developed in 1962 (Figure 2). Even though the model is pretty old, it is one of the most widely accepted and used designs for household purposes in India. The design includes a movable inverted drum placed on a well-shaped digester. An inverted steel drum that acts as a storage tank is placed on the digester, which can move up and down depending on the amount of accumulated gas at the top of the digester. The weight of this inverted drum applies the pressure needed for the gas flow through the pipeline for use [1].

Floating drum digesters produce biogas at a constant pressure with variable volume [33]. From the position of the drum, the amount of biogas accumulated under the drum is easily detectable. However, the floating drum needs to be coated with paint in a constant interval to avoid rust. Additionally, fibrous materials will block the movement of digester. Hence, their accumulation should be avoided if possible [65]. In Thailand, the floating dome has been modified with two cement jars on either side of the floating drum. The average size of these kinds of digesters is around 1.2 m$^3$ [66]. For a small-medium size farms the size varies from around 5–15 m$^3$ [65]. Singh and Gupta [67] compared 14 different biogas plants with a floating drum model. The size of each digester was about 85 m$^3$. The ratio of the waste fed to the plant in one day to the capacity of the plant is called plant utilization.
factor (PUF), and it was found to be 0.36. This result suggests that the full capacity of the plant was not utilized.

**Figure 2.** Schematic sketch of a floating drum digester.

2.3. **Plug Flow Digesters**

The disadvantage with the fixed dome and floating drum models is, once installed they are difficult to move. Hence, portable models built over the ground called tubular or plug flow digesters were developed (Figure 3).

**Figure 3.** Schematic sketch of a plug flow digester.

Plug flow digesters have a constant volume, but produce biogas at a variable pressure [33]. The size of such digesters varies from 2.4 to 7.5 m³. Plug-flow digesters consist of a narrow and long tank with, an average length to width ratio of 5:1. The inlet and outlet of the digester are located at opposite ends, kept above ground, while the remaining parts of the digester is buried in the ground in an inclined position. As the fresh substrate is added from the inlet, the digestate flows towards the outlet at the other end of the tank. The inclined position makes it possible to separate acidogenesis and methanogenesis longitudinally, thus producing a two-phase system. In order to avoid temperature fluctuations during the night and maintain the process temperature, a gable or shed roof is placed on top of the digester to cover it, which acts as an insulation both during day and night [68–74].
The popularity of tubular digesters has increased recently in Peru, due to its portability and low cost [68]. The usefulness of these digesters includes easy installation, easy handling, and adaptation to extreme conditions at high altitudes with low temperatures. The transportation costs for the material to build the digester in hilly areas are high, leading to a high capital cost. On the other hand, plug flow digesters are easy to transport, which ultimately reduces the cost of the digester [68]. It is also difficult to dig a large volume under the ground to build digesters in high altitudes [75].

51% of all digesters installed by United States Environmental Protection Agency (USEPA) were plug flow digesters [76]. Plug flow designs are suitable for manure, and operating semi-continuously with a HRT between 20 and 30 days, and a solid contents varying between 11 and 14%. These digesters do not have moving parts, reducing risks for failure [77–79]. Out of 99 digesters installed by the Bureau of Animal Industry in the Philippines, only one did not produce gas, and three had delayed gas production [80].

2.4. Comparisons of Different Digesters

Hamad et al. [81] compared the performance of the modified Indian digester and the Chinese fixed dome models for the conditions prevailing in Egypt. None of the digesters were suitable for the local conditions, and for the conditions present in Egypt, the plug flow digester and the digester with a solar heater were reported to be more efficient. Biogas production decreased by 70% in the rubber balloon digester compared to 17% in the deenbandhu model during winter. It is not advisable to use the rubber balloon model in hilly areas as it is affected by the ambient temperatures. The fluctuation in temperature changes the microflora in the reactor between lower mesophilic in summer to psychrophilic in winter, affecting the process parameters. Compared to the conventional plant (fixed dome digesters), rubber balloon reactors in hilly areas maintain 2–3 °C lower temperatures during the winter and 2–3 °C higher temperatures during the summer [82]. Mohammad [64] compared the vertical plant (modified floating drum), horizontal (with two partitions), community type, Chinese dome, French type, rubber tube, and polyethylene bag using a common substrate (buffalo dung). The results suggest that the community model was somewhat expensive, but it was very effective.

2.5. Other Digesters

Singh and Anand [83] aimed to decrease the water consumption in domestic digesters. Thus, a solid-state digester (SSD) was built out of a cylindrical vertical vessel with a cone at the bottom. This digester was welded to a tripod for balance. Lagoons with a floating cover could also be used as a digester, which is very cheap for farmers [84]. Qi et al. [85] designed and studied an integrated system of biogas production, using a greenhouse for growing vegetables and a pigsty for feeding the pigs in Laiwu, Shandong province, North of China. The biogas produced from swine manure and urine was used for cooking, lighting, or to maintain the temperature inside the greenhouse for optimum vegetable growth and the digestate were used as a fertilizer to replace chemical fertilizers. During winter, the low temperature and sunlight levels increases the application of chemical fertilizers. This frequent use of chemical fertilizer not only increased the cost of expenses but also decreased the vegetable quality during the winter. However, the substitution of chemical fertilizer with digestate increased the vegetable yield by 18.4% and 17.8% for cucumber and tomato respectively.
3. Parameters in Digesters Operation

3.1. Materials for Construction

Materials for construction of household digesters depend on geological, hydrological, local conditions, and locally available materials [18]. With technological advances, different materials with improved properties and lower costs have been introduced to the market in recent years. In India, underground biogas household digesters are very popular. Stone or bricks are used as the material for construction of these kinds of digesters [86]. High investment costs are required to build fixed structure digesters, which is the main constraint to low-income farmers. Taiwanese engineers in 1960 started to develop digesters from cheaper, locally available materials. Although nylon and neoprene were used initially, this proved to be expensive. With the development of technology, PVC and polyethylene were used instead, since they are relatively cheap [72]. Different construction materials with their advantages and disadvantages are summarized in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modifications</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly vinyl chloride (PVC)</td>
<td>Red mud PVC (mixed with aluminum)</td>
<td>Less weight, Easily portable</td>
<td>Short life span of plastics</td>
<td>[59,68,70,72,73,87–90]</td>
</tr>
<tr>
<td>Polyethylene (PE)</td>
<td>PE with UV filter</td>
<td>PE is much cheaper compared to PVC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neoprene and rubber</td>
<td>Reinforced with nylon</td>
<td>Weather resistance elastic</td>
<td>Expensive, Low pressure, Less life span</td>
<td>[72,82,91]</td>
</tr>
<tr>
<td>Bricks and concrete</td>
<td>Pre fired earthen rings, lime concrete, slag concrete, fired clay, bricks, reinforced concrete, Ferro cement (crack proof)</td>
<td>Everlasting, less maintenance costs</td>
<td>Gas could escape through concrete pores when pressure increases, Built underground, Difficult to clean, Occupies more space.</td>
<td>[18,52,63,86,92,93]</td>
</tr>
<tr>
<td>Bamboo and wood supports</td>
<td>Usually a support material, Reinforced with flax</td>
<td>Locally available material</td>
<td>Can break easily</td>
<td>[54]</td>
</tr>
<tr>
<td>Steel drum</td>
<td>Produce gas at a constant flow, Leak proof</td>
<td></td>
<td>Corrosion, Heavy weight of gas holder</td>
<td>[64,91]</td>
</tr>
</tbody>
</table>

3.2. Effect of Temperature

One of the important and difficult parameters to maintain in domestic biogas digesters is the temperature. Methanogens are active, even at a very low temperature [70,94–96], while the biogas
production increases by tenfold upon increasing the temperature from 10 to 25 °C. According to some observations, the amount of biogas produced by high temperature (mesophilic) and low HRT is comparable to the biogas produced with low temperature (psychrophilic) and high HRT [70]. People living in mountain valleys or outside of tropical regions suffer from low digestion rates during the winter season, when the temperature drops below 15 °C [86]. Different techniques and methods have been developed around the world to maintain the temperature inside the digester. Solar energy could be used as a heating source to increase the temperature of the digester [18]. Misra et al. [97] developed a solar-based heating device, but the efficiency decreased during the wintertime in hilly areas. To keep the temperature as constant as possible, most of the digesters were built underground [98]. Ramana and Singh [99] reported that geothermal energy helped in maintaining the temperature in the digester when buried underground.

Anand and Singh [86] proposed using a charcoal coating on top of the digester. This method increased the temperature by 3 °C and gas production by 7%–15%, but the digester had to be coated every one and a half months. This method is however economical as farmers can prepare charcoal by burning wood pieces. To maintain the temperature in the reactor, it is not enough to only blacken or glaze (coating). Some part of the biogas produced should also be burnt to maintain the temperature in the digester [100]. Paddy husk placed on top of the digester can also help in maintaining the temperature during winter [101]. Singh et al. [102] reported that the decrease of biogas yield during winter could be overcome by providing insulation on the inner surface of the gas holder. A shallow, solar-pond water-heater also reduced the heat loss inside the digester.

The French type digester covered with a polyethylene bag containing municipal solid waste did not affect the temperature drop [64]. Anjan [59] compared the janta model and the plug flow type of digester. The biogas production was more in the summer than in the winter, and the plug flow digester was less influenced by the temperature. Hamad et al. [81] compared the Indian model and the Chinese fixed dome digester. The Chinese dome digester had better insulation properties compared to the Indian type. In the Indian model the temperature decreased with decrease in height. A long-term testing of a biogas digester shows that the digester worked in the lower mesophilic range for almost eight months out of the year and in the psychrophilic range for the remaining part of the year [75].

In order to maintain the temperature in the reactor, the digester is covered by certain insulation materials. The insulation materials include: composites made of glass wool, sawdust, and plaster of Paris in ratio 1:2:2; black cloth coated with pitch, sodium peroxide, glass wool, and a mixture of thermocol and sawdust. The composite and black cloth coating was able to hold the temperature for more than 70 h, but the thermocol-sawdust mixture could only maintain it for 36 h [97].

### 3.3. Substrate Consumption

Almost all biomass is degraded to biogas in theory [103]. However, the choice of substrate will depend on the availability of the raw material, type of the digester, and its operating conditions. [64]. Cattle manure was a traditional source for biogas production in the past. The methane content was high in pig manure, around 60%, followed by cow dung with 50% [89]. Kitchen wastes and crop residues are some underexploited substrates for the domestic biogas production. Kitchen wastes contain a high amount of fat in the form of animal fat and cooking oil. This high-fat content can enhance the biogas production [90,103].
Combinations of different substrates often have a synergistic effect on biogas production [104,105]. Co-digestion can improve the nutrient balance, maintains the pH, and results in positive synergisms [106–108]. Moreover, in several studies co-digestion had a higher methane yield compared to mono substrate digestion [90,109–113]. Different substrates used for biogas production, dry matter, ash content, total digestible nutrients and biogas yield for household digesters are listed in Table 2.

Table 2. Different substrates with corresponding dry matter, ash content, total digestible nutrients and biogas yield used in the household biogas digesters [28,65,114].

<table>
<thead>
<tr>
<th>Main substrate classification</th>
<th>Substrate</th>
<th>Dry matter (%)</th>
<th>Ash (%)</th>
<th>Total digestible nutrients (%)</th>
<th>Biogas yield</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological waste</td>
<td>Manure</td>
<td>Cow</td>
<td>38</td>
<td>14</td>
<td>92</td>
<td>0.6–0.8 m³/kg TS</td>
</tr>
<tr>
<td></td>
<td>Pig</td>
<td>20–25</td>
<td>NA</td>
<td>NA</td>
<td>0.27–0.45 m³/kg TS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Buffalo</td>
<td>14</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poultry</td>
<td>89</td>
<td>33</td>
<td>38</td>
<td>0.3–0.8 m³/kg TS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horse</td>
<td>28</td>
<td>NA</td>
<td>NA</td>
<td>0.4–0.6 m³/kg TS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fecal</td>
<td>Human excreta</td>
<td>20</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Night soil</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Agricultural residues</td>
<td>Rice straw</td>
<td>91</td>
<td>13</td>
<td>40</td>
<td>0.55–0.62 m³/kg TS</td>
<td></td>
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<tr>
<td></td>
<td>Wheat straw</td>
<td>91</td>
<td>8</td>
<td>43</td>
<td>0.188 m³/kg VS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maize straw</td>
<td>86</td>
<td>NA</td>
<td>NA</td>
<td>0.4–1.0 m³/kg TS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grass</td>
<td>88</td>
<td>6</td>
<td>58</td>
<td>0.28–0.55 m³/kg VS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mango leaves</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.6 m³/kg TS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Foliage of</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>parthenium</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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</tr>
<tr>
<td></td>
<td>Coffee pulp</td>
<td>28</td>
<td>8</td>
<td>NA</td>
<td>0.300–0.450 m³/kg VS</td>
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<td></td>
<td>Corn stalk</td>
<td>80</td>
<td>7</td>
<td>54</td>
<td>0.350–0.480 m³/kg VS</td>
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<td>Cassava peels (residues)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.661 m³/kg VS</td>
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</tr>
<tr>
<td></td>
<td>Food wastes</td>
<td>Household grease</td>
<td>94</td>
<td>10</td>
<td>82</td>
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<td></td>
<td></td>
<td>Whey</td>
<td>5–20</td>
<td>NA</td>
<td>0.4 m³/kg TS</td>
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<td></td>
<td></td>
<td>Fruit</td>
<td>17</td>
<td>2</td>
<td>70</td>
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<td></td>
<td></td>
<td>Kitchen/restaura</td>
<td>27/13</td>
<td>13/8</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>nt wastes</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left over’s food</td>
<td>14–18</td>
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<tr>
<td></td>
<td></td>
<td>Egg waste</td>
<td>25</td>
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<td>NA</td>
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<tr>
<td></td>
<td></td>
<td>Cereals</td>
<td>85–90</td>
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Table 2. Cont.

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<tr>
<th>Main substrate</th>
<th>Substrate classification</th>
<th>Dry matter (%)</th>
<th>Ash (%)</th>
<th>Total digestible nutrients (%)</th>
<th>Biogas yield</th>
<th>References</th>
</tr>
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<tr>
<td>Aquatic plants or sea weeds</td>
<td>Algae</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.38–0.55 m³/kg VS</td>
<td>[132]</td>
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<td>Water hyacinth</td>
<td>7</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.2–0.3 m³/kg VS</td>
<td>[93,133]</td>
</tr>
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<td>Giant kelp</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>[118,119]</td>
<td></td>
</tr>
<tr>
<td>Caboma</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.221 m³/kg VS</td>
<td>[133]</td>
<td></td>
</tr>
<tr>
<td>Salvinia</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.155 m³/kg VS</td>
<td>[133]</td>
<td></td>
</tr>
</tbody>
</table>

* NA - Not Available.

3.4. Loading Rate and Yield of Biogas Produced

The solids concentration in the household biogas digesters varies between 5% and 10% [64,69,89,92,103]. Increasing the solids concentration to 19% decreased the biogas production considerably [92]. The common organic loading rate (OLR) of the digester is 2–3 kgVS/m³/day under mesophilic conditions. Nevertheless, it could be possible to achieve higher OLRS if the sludge concentration is over 10% [101]. Anjan [59] reported a maximum of 10.4–10.6 kgVS/m³/day in the janta model and the modified plug flow reactor. The average biogas production in the domestic biogas digester was in the range of 0.26–0.55 m³/kgVS/day [67,84,89].

Hydraulic retention times (HRT) vary between 20 and 100 days for mesophilic household digesters [70,71,89,103]. Studies show that decreasing HRT from 90 days to 60 day and increasing the OLR by diluting the substrate from 1:4 to 1:2 would be beneficial for the better performance of the digester [68]. Many household digesters do not have a stirrer to mix the digester content, which creates stagnant regions in the digesters. Due to these stagnant regions, the digester HRT is decreased compared to its calculated HRT, leading to wash out of the microorganisms [81,134,135].

3.5. Biogas Storage and Maintenance of Digesters

Storing the biogas produced is often a major concern. Biogas can be transported directly to the kitchen or stored in a pressurized tank, floating drum storage, gas cylinders, and gasbags. Storing the biogas reduces the problem of low flow rate during cooking. Biogas can be transported from one place to another by using gasbags [18,52,72,136–138]. The excess pressure in the storage container can be released using a ‘T’ shaped valve [72,139].

The amount of biogas produced in the digester depends on the material fed, type of the material, C/N ratio, digestion time, and temperature [50,140,141]. For instance, highly concentrated influent slows down the fermentation, and diluted influent causes scum formation. To keep the solids concentration, the amount of water and biomass added should be in equal proportion [11,142–144]. The digester should be fed every day. However, free fermentable carbohydrates will increase the volatile fatty acids concentration, which affects the methane forming bacteria. Usually, the steady state of biogas production is observed after two months of operation with a constant OLR [33,145].
4. Applications of Biogas in Household Digesters

4.1. Cooking and Heating

Biogas produced from the household digesters is mainly used for cooking [54,70]. The amount of biogas used for cooking purposes usually varies between 30 and 45 m³ per month. This number can be compared with other commonly used fuels such as kerosene where the consumption is between 15 and 20 L, and Liquefied Petroleum Gas (LPG) between 11 and 15 kg per month, respectively. The energy equivalent was around 300, 200, and 150 kWh for biogas, kerosene, and LPG, respectively [66,146,147]. The surplus biogas in the domestic digester could be used for water and space heating [148–150].

4.2. Biogas Stoves

Biogas burning is not possible in commercial butane and propane burners because of its physiochemical properties. However, it is possible to use these burners after some modifications [103]. Burners are changed in the gas injector, its cross-section, and mixing chambers. The biogas burners are designed to meet a mixture of bio-gas and air in the ratio of 1:10 [101]. Different burners like vertical flame diffuser, horizontal flame diffuser, and no diffuser with biogas have been examined. A vertical flame diffuser had a high heat transfer efficiency compared to other diffusers [68]. The efficiency is obtained by calculating the heat gained by the water subjected for heating and the amount of fuel consumed during this process. The efficiency of the heat entering the vessel from the stove was high for biogas with 57.4%, followed by LPG, kerosene, and wood with 53.6%, 49.5%, and 22.8%, respectively [151]. The biogas consumption and the thermal efficiency in the biogas stoves varied between 0.340–0.450 m³/h and 59–68% [67,145,152–154].

4.3. Fertilizer

The digestate left over from the digester is rich in nitrogen, phosphorus, and potassium, and can be used as a fertilizer [54,73]. Digestate increased the potato cultivation by 27.5% and forage by 1.5% compared to no added fertilizer. Due to the anaerobic digestion of organic matter, these nutrient concentrations were easily taken up by plants [71,116]. The effluent can be directly used as a fertilizer in farming [92]. Digestate has a high commercial value when exported. The dried effluent could also be used as an adsorbent to remove lead from industrial wastewater [155]. Biogas slurry could be helpful in growing algae, water hyacinth [101], duck weed [156], and fish poly-aquaculture [157,158].

4.4. Lighting and Power Generation

The other major application of household biogas is for lighting and power generation. In many developed countries, biogas from the digesters is sent to a combustion engine to convert it into electrical and mechanical energy [64]. Biogas requires a liquid fuel to start ignition [13]. Diesel fuel can also be combined with biogas for power generation [159–163]. For instance, in Pura (India), a well-studied community biogas digester can fuel a modified diesel engine and run an electric generator [164]. Bari [160] reported that carbon dioxide up to 40% will not decrease the engine
performance using biogas as a fuel. Biogas can also be used to power engines when mixed with petrol or diesel, and it can also help in pumping water for irrigation [66,165–167]. Cottage/small scale industries use biogas for pumping, milling, and for some other production activities [168].

For a medium-sized farm in Jordan, the monthly energy consumption for various purposes is about 1282 kWh. The biogas required for producing 982 kWh is around 6.7 m$^3$/day, and for water-heating 2 m$^3$/day. The use of 1 kW generator proved that half of the energy needed could be met by using a domestic digester. Satisfactory results were observed when tested for water-heating and electricity generation from biogas [60,61]. In Earth University (USA), electricity from biogas is used for milking operations [169]. Biogas is blended with jatropha oil in a 12 kW diesel engine generator to act as a dual fuel for rural electrification. Jatropha seeds remain as a waste product after oil production. This waste gets converted into biogas. The oil and biogas is combined in a duel fuel engine for electricity generation [13]. The fertilizer from biogas is used for jatropha plantation. Hence, the nutrients are in the closed cycle, which can act as a bio-refinery [170]. Biogas conversion into electricity using fuel cells is a hot research topic nowadays. However, it is not commercially affordable due to the requirement of clean gas and the cost of fuel cells [103].

Biogas lamps are more efficient than the kerosene powered lamps, but the efficiency is quite low compared to electric-powered lamps. However, the light intensity of the biogas lamp compared to a kerosene lamp or an electric light bulb, was in the power range of 25–75 W [145]. One cubic meter of biogas is equal to lighting 60–100 watt bulb for 6 h, or cooking three meals a day for 5–6 persons. In contrast, 0.7 kg of petrol can run 1 hp motor for 2 h or generate 1.25 kW for electricity [171]. To provide electricity for a home with a family of five, about 0.25 to 0.5 m$^3$ biogas is needed [66]. Until recently, many of the rural areas in India depended on kerosene lamps for lighting due to the energy shortage. Using these kerosene-powered lamps was inefficient as well costly. Battery-operated solar panels were also an expensive means for lighting. This resulted in research to design a digester, which could provide lighting to a home. A mini-biogas digester developed especially for lighting purposes. This digester could produce 0.5 m$^3$/day biogas which is enough for 4 h of use [63].

4.5. Other Applications

Besides common applications, domestic biogas is also utilized for other purposes. Gas-powered refrigerators or a chicken incubator can run on household biogas, which is a well known application in Kenya [98,145]. In India, around 4600 public toilets are connected to biogas digesters by a local NGO to improve social living conditions of the people. Similarly, in Nepal, public toilets are connected to biogas digesters to light these toilets [98,172].

5. Disadvantages

Despite the various advantages of household biogas digesters, there are a few disadvantages to overcome as well. Anaerobic digestion is a slow process, and it requires a long HRT (>30 days) [16]. This increases the volume and cost of the digester. Low loading rates and slow recovery after a failure are other limitations in biogas production [173]. Another limitation is the fluctuation in temperature throughout the year. The decrease in biogas production during the winter months makes it difficult for cold countries to adapt this technology [30]. In the long-run, people often stop using the household
digester due to lack of knowledge, gas leakage, slow recovery, low gas production, and inadequate supply of substrate [174]. Research into these issues is needed. For instance, straw is a potential substrate for household biogas digesters, but it demands more research and development [175].

Leakage from biogas digesters increases emissions of methane and carbon dioxide into the environment. Fire explosions in households are another disadvantage when methane leaks from the digester [40].

Individual economic status is also a concern in biogas technology [176]. Sibisi and Green [98] installed a floating drum digester in a school to meet their energy needs. However, it was impossible for the school to spend a capital investment unless a governmental subsidy was provided. In Thailand, high investment, lack of financial resources, lack of information, and lack of skilled labor are barriers towards adopting biogas stoves, and household biogas digesters [177,178].

Developments in technology can help to rectify these problems by making biogas sustainable for rural energy production. However, low functionality of biogas plants due to defective components, lack of technical knowledge, not adopting a proper size and model based on locality and availability of raw materials, poor supervision, and lack of NGO involvement continue to present obstacles to technology dissemination [91]. It is important to spread basic knowledge among farmers and local people in order to train and educate them about the potential of biogas technology [179].

6. Economics and Policies

Most biogas digesters have lifetimes of 25–35 years [180,181]. The cost of these digesters varies from 200 to 400 USD. For instance, in Thailand a fixed dome model called cement water jar with a size of 1.2 m$^3$ costs around 180 USD [66], in Peru a PVC tubular digester of volume 0.225 m$^3$ costs around 250 USD [70] and a plug flow digester with a size of 0.250 m$^3$ costs 300 USD in Costa Rica [90]. In India, the floating drum model of size 1–6 m$^3$ costs from 200 to 400 USD respectively [66,70,88,90,182]. The payback period (PBP) for different digesters, including deenbandhu, KVIC, and janta models was calculated. The deenbandhu model had a lower PBP around 4.7 and 1.6 years for a digester of size 1 and 6 m$^3$, followed by the janta model with 11.3 and 3.2, PBP and years, respectively, for the same size. The floating drum model had a high PBP of 26.6 for a 1 m$^3$ digester [1]. Amigun and von Blottnitz [47] calculated the capital cost for different sizes of biogas digesters by using the Lang factor ($f_l$). The results revealed that the $f_l$ value of 2.63 and 1.79 gives a better prediction for small/medium digesters and large plants, respectively. Rubab and Kandpal [183] calculated the capital cost using different methodologies, including economies of scale, ratio of size of a reference plant cost, cost of constituents, and the last method included factors like retention time and other important factors for capital cost calculations.

Different economic models to predict the cost of a digester and the cost of benefits obtained using a household biogas digester have been developed in the recent past. An economic model to assess the cost-effectiveness of domestic biogas plants was developed by [35,184,185], which is summarized in Equations (1), (2) and (4). The cost calculation of a biogas digester based on a reference plant is given in Equation (3). In Laboratory of Agricultural Structures (LAS) of the Agricultural University of Athens, an improved version of the original Basic Economic Evaluation Model were developed called Modified Basic Economic Evaluation Model (MBEEM). This model involves many parameters and a
A computer model was developed in order to facilitate the application of the MBEEM. According to the model, the optimum retention time from an economical point of view would be 20 days. The net present benefit increases with the increase in government subsidies, increase in fuel wood cost, and decrease in the cost of the digester. However, net present benefit gets affected if the interest rate is high. The financial stability of the digesters is increased with the increase in digester size. Cooking with firewood suppresses biogas cooking if the efficiency is more than 25%. The biogas plants will be in a critical position, if the cost of wood fuel decreases or the cost of dung increases. Ciotola et al. [169] conducted an energy analysis to assess the sustainability and environmental impact of small-scale digesters. They found that it was better to use biogas for cooking, but not for producing electricity using a generator. Environmental Sustainability Index (ESI) is a way to measure the total sustainability of a process and Environmental Loading Ratio (ELR) is a method to estimate how much impact a process has on the environment. A high ELR corresponds to a high environmental stress. ESI was reduced from 5.67 to 2.22 due to production of electricity from biogas. At the same time, ELR was increased from 0.52 to 0.93.

Equation 1. Model for net present benefit for the digesters in Bangladesh, where $PW$—present worth of the incremental net benefit, $A_g$—Annual incremental benefit from using biogas as cooking fuel, $A_f$—Annual incremental benefit from using treated slurry as fertilizer, $C$—Cost of digester, $N$—Plant life, and $W$—Inflation rate/Interest rate [184]:

$$PW = (A_g + A_f) \sum_{n=1}^{N} W^n - C - \sum_{n=1}^{N} m_n W^n$$

Equation 2. Model for the cost benefit analysis in India for floating drum model, where $NPV$—Net Present Value, $A_b$—Annual benefits, $A_c$—Annual operating costs, $i$—interest rate, $t$—life time of the plant, $C$—Cost of the digester [185].

$$NPV = \frac{(A_b-A_c)[1-(1+i)^{-t}]}{i} - C$$

Equation 3. Generalized cost calculation for a biogas digester, $C$—Cost of the digester, $C_0$—Cost of the reference plant, $a$ and $b$ are constants, $V$—Volume of the digester, $V_o$—Volume of the reference digester [185]:

$$C = C_0[a + b \left(\frac{V}{V_o}\right)]$$

Equation 4. Modified basic economical evaluation model for Greece, where $NPV$—Net Present Value (Euro), $NCF$—Net Cash Flow, $r$—discount rate, $j$—operational life span of installation (year), $I$—capital investment [35]:

$$NPV = \sum_{j=1}^{n} [NCF_j \times (1+r)^{-j}] - I$$

Pütz et al. [186] developed a morphological matrix to sell the biogas produced from the digester to the low-income farmers. Using the right methods to transport and sell biogas can yield a profit to both the seller and the buyer. Li et al. [5] calculated the ecological and environmental benefits by building a biogas digester by using a quantitative model. The equation to calculate economical and environmental benefits is given in Equations (5) and (6), respectively. The results showed that families that have a
biogas digester could benefit by about 100 USD/digester. Peter et al. [187] developed an empirical model for the adoption of biogas technology, and the results showed that the adoption of technology is increasing with high income, more cattle owned, bigger homes and hike in fuel price. However, the adoption for biogas technology decreased with an increase in remote location and area of the household. Van Groenendaal and Gehua [188] analyzed the internal benefits which revealed that 58.5% of people who used a biogas digester could cook three meals a day and most of the people had improved health conditions. Feng et al. [189] calculated the efficiency of energy use for the rural households in Tibet. The comparison of the present scenario and the futuristic change revealed the importance of the biogas not only economically, but also by building a healthier and sustainable society.

Equation 5. Calculation for economical benefits of a digester, \(T_c\)—cost of economical benefits for a household, \(m\)—items consuming energy, \(n\)—kinds of energy resources, \(j\)—type of usage, \(i\)—type of resource, \(C_i\)—unit price for the type of energy [5]:

\[
T_c = \sum_{j=1}^{m} \sum_{i=1}^{n} C_i x_{ij} (i = 1,2 \ldots n, j = 1,2 \ldots m)
\]

Equation 6. Calculations for environmental benefits of a digester, \(T_s\)—cost of environmental benefits for a household, \(m\)—items consuming energy, \(n\)—kinds of energy resources, \(j\)—type of usage, \(i\)—type of resource, \(S_{1i}\)—Environmental costs in a hill, \(S_{2i}\)—environmental costs in a slope [5]:

\[
T_s = \sum_{j=1}^{m} \sum_{i=1}^{n} x_{ij} (S_{1i} + S_{2i}) (i = 1,2 \ldots n, j = 1,2 \ldots m)
\]

Politicians and policymakers must promote efficient ways to meet energy needs in rural areas [190]. By having government subsidy plans and loan or credit schemes, the biogas program for rural households will be more attractive to people [33]. In China, the government pays two-thirds of the digester cost and the farmer pay the remaining amount. However, the construction of digesters decreased when the government reduced the subsidy to one-third of the cost [55]. Millions of people have benefited from this technology, and its popularity is still increasing [54]. Domestic biogas digester programs could be alive with the microfinance schemes available in the developing countries. This could help farmers and poor people to reduce the burden on capital cost investments [191].

7. Environmental and Social Aspects of Biogas Digesters

Climate change is one of the major environmental challenges facing the World today. Unsustainable energy consumption in past has contributed to global warming that needs to be addressed [192]. Household digesters could reduce the pressure on the environment by reducing deforestation and greenhouse gas emissions, soil erosion, loss of cultivable land [54].

A major contributor to global warming are greenhouse gases (GHG), emitted to the atmosphere mainly from burning fossil fuels such as coal, oil and natural gas. Rural biogas production can partially reduce global warming [193]. By utilizing biogas for rural households, environmental, economical, and social benefits were obtained [194]. Even though, both methane and carbon dioxide are major contributors to the greenhouse effect, the global warming potential of methane is 21 times higher than that of carbon dioxide [195]. However, the comparison of the houses equipped with and without biogas systems, including the leakage of gases in the biogas systems revealed that the households with
biogas plants have 48% less emissions compared to households without biogas systems [196]. It is worth mentioning that only 10% of households had methane leakage [194]. Studies show that by replacing firewood and coal with biogas, the emission of CO₂ and SO₂ would be reduced by 397–4193 thousand tons, and 21.3–62.0 thousand tons, respectively [193]. Pathak et al. [193] reported that the global warming mitigation potential from a 3 m³ family size biogas plant in India using dung from four cattles was about 9.7 tons CO₂ equivalent per year. The government of India targeted to install 12.34 million digesters by 2010. This target mitigation potential is equal to 120 million tons CO₂ equivalent per year.

Hamburg [197] did a pilot-scale study on the emission of H₂S and SO₂ by using crop stalks, coal, and biogas for cooking in the regions of Henan province in China. The study revealed that the emission of SO₂ from using crop stalks and coal for cooking was four times higher than that of biogas. Additionally, no significant level of H₂S was found. Khoiyangbam et al. [198] compared the methane emission effect of fixed dome biogas plants installed in the hilly areas of India. The studies showed that methane emission was higher for the janta model compared to the deenbandhu model. A family size biogas plant is a substitute for 316 L of kerosene, 5535 kg of wood and 4400 kg of cattle dung as fuels reducing emissions like NOₓ, SO₂, CO, and volatile compounds into the atmosphere by 16.4, 11.3, 987.0, and 69.7 kg/year, respectively [199].

The slurry from the biogas digesters, if not used properly, becomes an active place for insects to spread diseases [200]. Biogas slurry could be used as a valuable resource for earthworm culture. Slurry mixed with plant rich materials, is also a suitable substrate for vermicomposting [201,202].

A comprehensive study to analyze the rural energy development in China using household-scale biogas digesters and green house gas emission reduction was done by Yu et al [22]. The greenhouse gas emissions from energy sources including straw, fuel wood, coal, refined oil, electricity, LPG, natural gas, and coal gas were compared to emissions from biogas. Biogas as a substitute for other energy sources reduced the greenhouse gases by 73.157 megatons CO₂ equivalents based on the amount of consumption between the years 1991 to 2005.

Another study in the Peruvian Andes by Garfì et al [88] involving 12 rural families in a project to substitute biogas with firewood, showed a decrease of firewood consumption by 50%–60% and cooking time by 1 h. The results are based on a survey which included technical aspects such as type of fuel and time for cooking, environmental aspects such as number of cows in the households and amount of firewood used to cook and economical aspects including income of the family and the expenditure for fuel and fertilizer and social aspects such as time for collecting wood. The effect of the price on firewood, kerosene and fertilizer before and after installing the biogas plant from 2001 to 2005 in India is shown in Figure 4.

Cattle dung is usually used as compost or dung cakes for cooking, which is neither hygienic nor economical [1]. Burning dung cakes does not only creates pollution but also leads to loss of a valuable fertilizer. On the other hand, if the dung cake is applied directly to the field it would also cause total loss of fuel, besides the pollution [184]. Anaerobic digestion is a secure and high-profit yielding way to dispose of this cattle dung [1].
In addition to environmental benefits, there are a number of social and health benefits using biogas as a fuel. Improved health conditions and change in lifestyle for women in the households were observed after installation of a biogas digester [33]. Hiremath et al. [203] mentioned that India could meet their energy demands by a decentralized energy planning. Using the locally available materials, they could fulfill their energy needs in a sustainable way. One of the possible alternatives to producing energy for rural India is biogas. The basic seven goals are: cost minimization, efficiency maximization, employment generation, system reliability, minimization of petroleum product, maximization use of local resource, and minimization of emissions. Biogas can improve sanitation considerably, when linked to a public toilet where waste is no longer stored [204,205]. Green foods (crops grown using fertilizer from biogas plants) were developed by connecting a biogas plant to a toilet and pigpen. This kind of integrated model is very popular in southern China [175]. One-third of the dung produced in India is enough to run 12 million biogas plants [206]. Use of biogas digesters by the rural people could help them financially as well as improve the living conditions such as improved air quality for the health benefits of the people [66].

For instance, burning firewood for cooking also creates a lot of smoke and soot particles. The smoke and soot contributes to air pollution which in turn causes health issues such as respiratory illness [54]. However, Zhang et al. [10] reported that more than 420,000 premature babies died in China every year due to indoor air pollution. Most of the pollution is due to poor combustion fuels and emitted greenhouse gases. The main reason for infant mortality and deaths in developing countries is respiratory diseases. Most of these diseases are due to pollution emission from cooking. In contrast, biogas is a clean fuel compared to biomass or coal combustion. Cleanliness here refers to the cooking vessel not turning black in the bottom of the vessel, when biogas is used for cooking. Air pollution in biogas will be less because they have few larger hydrocarbons. Increase in the concentration of hydrogen sulfide leads to headaches, dizziness, blurry vision, nausea, and vomiting. Sulfur dioxide emissions lead to choking and sneeze-inducing effects [197]. Sustainable energy production for rural-needs and proper sanitation has a significant difference on control of parasitic diseases [204,205]. Figure 5 shows the environmental and social benefits obtained by using a biogas digester.
8. Discussion

Access to energy resources, economic development and environmental pollution, which in turn threaten human health, are major challenges facing developing countries today [207]. Economically feasible and efficient small scale biogas digesters could be the answer of solving some of these problems and needs. By enhancing energy availability and simultaneously protect the surrounding environment such as soil, water and air, a lots of benefits could be gained. Most of small-scale digesters are concentrated in developing countries with India and China as leading countries accounting for the highest share.

More or less, every biodegradable organic waste can be treated in a biogas digester, providing energy for cooking, lighting and heating along with increased of dissolved nutrient concentration in the digestate, thus, providing farmers with an improved organic fertilizer. Many of small scale digesters do not require high maintenance and are more or less adaptable to the climate and condition of many of developing countries [73]. However, adopting of biogas digesters is low in many countries despite the great potential to gain a wide verity of benefits, both from socioeconomic and environmental point of View. Possible negative impacts are suggested such as the potential for pathogens, limitation of economic and material resources, and pollution through losses from damaged digesters, and possible leakage of incomplete combustion of methane to CO₂. Additionally several practical problem have also been suggested as limiting the uptake of small-scale digesters including unaffordable initial investment costs, accessibility of proper materials to avoid leakage in digester construction, lack of efficient functioning digesters in different climate condition, sufficient production of fuel to meet the needs, social acceptability of the fuel produced, etc. [208].

Studies showed that political measures are required to support adoption of the household digesters, by subsidy plans, including training and capacity building to keep up the interest in adopting the
household digesters. However, the interesting paradox is, despite all the benefits that could be gained, the interest fades as soon as the governmental subsidy support is reduced, as the case in China which is the one of leading countries in adopting the biogas digesters. It seems the benefit from implementation of biogas digester alone is not enough to increase the attention. Further, full analysis are needed with a new approach to facilitate communication between the experts from different fields such as engineering, hydrology, biology, social science, economics and systems-modeling to identify and find the best possible optimum solution and strategies needed in implementing household biogas digesters in rural communities [208]. Furthermore, interest is growing slowly in many poor countries and effort should be made to increase the awareness and to introduce affordable and more efficient digesters tailored to take full advantage of the local possibilities in order to succeed.

9. Conclusions

Household digesters represent a boon for farmers and rural people to meet their energy needs. These digesters help in two ways: one is to reduce waste, and the other is to provide valuable energy. Although they have been used for many years, modernization is needed to overcome the drawbacks in the long run. The awareness by people of their technical issues, and governmental subsidy plans could provide even more benefits from household digesters.

Acknowledgments

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Experimental and economical evaluation of a novel biogas digester

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ABSTRACT

Many developing countries face an energy demand to satisfy the daily needs of the people. Household biogas digesters are among the interesting solutions to meet the energy demands for cooking and lighting, and at the same time taking care of the kitchen wastes. In this study, a novel textile-based biogas digester was developed. The digester was evaluated for biogas production from a synthetic nutrient and an organic fraction of municipal solid waste (OFMSW) as substrates for more than a year. The obtained biogas productivity in both experiments was 570 L/kg VS/day, which indicates that the digester is as efficient in handling of OFMSW as the synthetic nutrients. Based on the obtained biogas production data, the techno-economic evaluation and sensitivity analysis for the process were performed, replacing LPG and kerosene consumption with biogas in households. A 2-m³ digester can supply the fuel needed for cooking for a family of 4–6 people. The sum of investment and 15-years operational costs of this digester was 656 USD, which can be compared with 1455 USD for subsidized-LPG and 975 USD for kerosene, respectively. The results from the sensitivity analysis show that it was a positive investment, unless the price of kerosene goes down to less than 0.18 USD/L.

1. Introduction

Many developing countries face a severe energy crisis both domestically and industrially. About 90% of energy consumption for a household in developing countries is used for cooking. The cost of cooking fuel, for example, liquefied petroleum gas (LPG), has also increased more than ten-fold in recent years [1,2]. On the other hand, the amount of waste generated from households is also increasing. Reducing the waste and its conversion into energy solves both these dual problems. It is worth mentioning that household wastes mainly contain organics, which could be converted into biogas, a cost-effective and cleaner way to meet energy demands [3–5].

Biogas is a mixture of methane, carbon dioxide, and traces of hydrogen sulfide formed by anaerobic digestion of organic materials [6,7]. Formation of the biogas involves four different steps, including hydrolysis (breakdown of complex substrates into monomers); acidogenesis (conversion of monomers into volatile fatty acids); acetogenesis (conversion of VFAs into acetic acid, hydrogen, and carbon dioxide); and finally, methanogenesis (conversion of acetate, hydrogen, and carbon dioxide into methane and carbon dioxide). Fig. 1 shows the schematic diagram of the biogas production process. Methane is an energy rich compound, which can be used for applications such as cooking, lighting, and electricity. Digestate or slurry left over after anaerobic digestion contains a high amount of nitrogen, phosphates, and other nutrients, which can be utilized as a natural fertilizer for agricultural use [8,9].

Several designs of digesters in different sizes have been developed, including fixed dome, floating drum, and plug flow digesters. Fixed dome digesters are common in China, where digesters are built underground in the shape of a dome using bricks. However, the formation of pores from the bricks causes gas leakage as well as contamination of ground water, which is a major drawback with these reactors. Floating drum digesters are common in India, built with an iron floating drum on top of the digester. Nonetheless, since iron is corrosive and expensive, it is difficult to maintain these digesters. Recently, plug flow digesters made of polyethylene have been gaining attraction due to its cost-effectiveness. However, the attraction is fading out since the material it is made from can be cut too easily. Most of the digesters were built with materials such as: concrete, fiberglass or plastics, polyethylene or iron, which are either expensive or do not last for an extended period of time [10]. Therefore, cost-effective, easy to use digesters need to be developed.

Some economical evaluations on different biogas digesters have recently been performed. Amigun and Blottnitz [11,12] worked on cost–capacity relationship and fixed capital investment of the biogas digesters built in Africa. They reported the fixed capital investment of 4–100 m³ digesters to be between 500 and 45,000 USD in 2004. Singh and Sooch [3] compared the payback period (PBP) of...
different fixed dome digester models such as janta, KVIC and deenbandhu for digester size between 1 and 6 m³. However, no study has been performed on the biogas digester replacing with LPG and kerosene, which is currently used in many developing countries for cooking.

In this study, a novel portable digester was built from textile supplied by FOV Fabrics AB, Sweden. Textile has never been reported as a material used to build a digester, which is why this work is so novel. This textile digester was tested with a synthetic medium and an organic fraction of municipal solid waste (OFMSW) in two different experiments. In reference to the obtained biogas production, the techno-economical evaluation was also made for the digester, comparing the LPG and kerosene replaced with biogas for cooking on a household scale.

2. Materials and methods

2.1. Digester

The easily transportable digester was constructed of textile supplied from FOV Fabrics AB, Sweden. Fig. 2 shows the schematic sketch of the digester. The shape of the digester resembles a pyramid, with an inlet to feed the digester, an outlet to take out digested material, and a gas line to measure the amount of biogas produced. The digester had 112 and 100 L total and working volumes, respectively. It had an opener in order to empty its contents. The dimensions of the digester were 72 cm width and 65 cm height. The diameter of the inlet and outlet tubes was 30 mm. It was filled with air and water to check for leakage before the inoculum was added.

2.2. Inoculum preparation

Two different inoculums were used for different experiments. For the first one, the digester was filled with granules from a UASB reactor working with municipal wastewater treatment plant (Hammarby Sjöstad, Stockholm, Sweden). Equal volume of granules and water were added to the digester to reach the working volume. For the second experiment, the inoculum was prepared from the cow manure provided by a local farm near Borås, Sweden. The manure was mixed with an equal proportion of water (e.g., 50 L manure and 50 L water), and left undisturbed for 40 days. Once the gas production started after this incubation period, the digester was fed with OFMSW.

2.3. Experimental setup

Two different semi-continuous experiments were carried out with the textile digester. In the first experiment, the digester was filled with granules and fed with a synthetic substrate, i.e., acetic acid, propionic acid, and butyric acid in the ratio 3:1:1. Other concentrations of nutrients fed to the digester, apart from carbon sources include (mg/L): NH₄Cl (76.4), KH₂PO₄ (5.18), MgSO₄·7H₂O (0.27), CaCl₂·2H₂O, (10.00), and trace nutrients (1 ml/L) [13,14]. The OLR was increased step-by-step in the order of 0.25, 0.50, and 1.0 gVS/L/day with the decrease in hydraulic retention time (HRT) of 100, 80, and 75 days, respectively. The digesters were operated at room temperature, which varied between 22 °C and 25 °C. At this temperature, the psychrophilic bacteria are active; therefore, it demands a higher retention time than mesophilic.

---

**Nomenclature**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMPTS</td>
<td>automatic methane potential testing system</td>
</tr>
<tr>
<td>GC</td>
<td>gas chromatography</td>
</tr>
<tr>
<td>HPLC</td>
<td>high performance liquid chromatography</td>
</tr>
<tr>
<td>OFMSW</td>
<td>organic fraction of municipal solid waste</td>
</tr>
<tr>
<td>PBP</td>
<td>payback period</td>
</tr>
<tr>
<td>VFA</td>
<td>volatile fatty acids</td>
</tr>
<tr>
<td>OLR</td>
<td>organic loading rate</td>
</tr>
<tr>
<td>HRT</td>
<td>hydraulic retention time</td>
</tr>
<tr>
<td>NPV</td>
<td>net present value</td>
</tr>
<tr>
<td>IRR</td>
<td>internal rate of return</td>
</tr>
</tbody>
</table>

---

**Fig. 1.** Schematic diagram of the biogas production process.

**Fig. 2.** Schematic sketch of the textile digester.
and thermophilic bacteria. However, many developing countries have tropical conditions, where lower retention times can be effective.

For the second experiment, the digesters were fed with OFMSW obtained from Borås Energy & Environment AB, Sweden. The composition of OFMSW includes carbohydrates 7.1%, proteins 2.6%, fats 2.1%, ash 1.3%, and water 86.9%. OFMSW obtained from the municipal plant is stored at −20 °C in a freezer, before use. The digester was operated in wet conditions with the particle size of OFMSW being less than 10 mm. The digester was fed with OFMSW, starting from OLR 0.1 gVS/L/day to 1 gVS/L/day, and the HRT was decreased from 100 to 75 days. Table 1 shows the experimental setup of the textile biogas digester. Once a day the contents of the digester were mixed by tilting the inlet tube of the digester from vertical position to horizontal position and vice versa after feeding, to ensure that the OFMSW enters into the digester, and does not just stay on the walls of the inlet.

2.4. Analytical methods

The gas produced from the textile digester was discharged through the gas outlet, and it was recorded using Automatic Methane Potential Testing System (AMPTS, Bioprocess control AB, Lund, Sweden). This measuring system works based on the water displacement and buoyancy, with a resolution of 10.5 ml; in addition, the data on the volume of gas produced vs. time was recorded on a computer. The biogas composition was analyzed using a gas chromatography (GC, AutoSystem PerkinElmer, Waltham, MA, USA) equipped with a packed column (PerkinElmer, 6’ × 1.8” OD, 80/100 Mesh) and a thermal conductivity detector (TCD) (PerkinElmer) set to 200 °C. The carrier gas used was nitrogen, maintained at a pressure of 0.70 bar and a flow rate of 40 ml/min at 60 °C. A 250-μl pressure-tight gas syringe was used for the gas sampling. The VFA concentrations were analyzed using HPLC (Waters 2695, Waters Corporation, Milford, MA, USA) with a UV detector (Waters 2414), operating on an ion-exchange column (Aminex HPX-87H Bio-Rad, Hercules, CA, USA) working at 60 °C. The eluent was 5 mM sulfuric acid with a flow rate of 0.6 ml/min.

2.5. Techno-economic studies

From the experimental results performed, a techno-economic analysis was conducted for the digester of size 1.5, 2, 3, and 4 m³, respectively. The portable-textile biogas digester was estimated to have a lifetime of 15 years. The total investment and operational costs of a biogas digester for the given life span, including discount rate and operational costs were calculated according to Eq. (1), where ‘i’ is the interest rate (8%) and ‘n’ is the life span of the digester (15-years) [15]:

\[
\text{Total expenditure on biogas} = \text{Capital cost} + (\text{capital cost} \times i \times n) + \left\{ \frac{\text{operating costs} \times (1+i)^n - 1}{i(1+i)^n} \right\}
\]

Furthermore, an economic analysis was performed for replacing LPG and kerosene with biogas. In developing countries, LPG and kerosene are sold in two-forms: (i) with subsidies from the government and (ii) without subsidies for commercial purposes. In this work, both these forms were compared using the prices in India, which is similar to many other developing countries. For the base case, the cost of subsidized LPG was considered as 0.54 USD/kg and non-subsidized LPG was 1.08 USD/kg [16]. Similarly, the cost of kerosene in subsidized form was 0.27 USD/L and non-subsidized form was double the subsidized form [17]. The consumption of LPG and kerosene for different family sizes was calculated according to [18,19]. The amount of biogas produced from different sizes of digesters was also calculated from the experiments performed. The PBP was calculated by dividing the capital cost of the digester by the annual profits obtained from the digester:

\[
\text{Payback period} = \frac{\text{Capital cost}}{\text{Annual profit}}
\]

Annual profits were calculated by the difference between the annual expenditure on other fuel and operating cost of the biogas digester. The operating costs considered here are minor problems such as changing inlet or outlet tubes and gas leakage. The operating cost of the digester per year was assumed to be 5% of the capital cost for the base case:

\[
\text{Annual profit} = \text{Annual expenditure on other fuels} - 5\% \text{ capital cost}
\]

Net present value (NPV) was calculated according to Eq. (4), where \( C_0 \) is the capital investments, \( C_i \) is the annual profits, \( r \) is the rate of interest, and \( n \) is the number of years:

\[
\text{NPV} = -C_0 + \sum_{i=1}^{n} \frac{C_i}{(1+r)^i}
\]

For the base case, the rate of interest was assumed to be 8%, internal rate of return (IRR) was calculated to find the rate at which NPV becomes zero.

2.6. Sensitivity analysis

To see the flexibility of the digester at different conditions, a sensitivity analysis was carried out by changing the discount rate, the cost of LPG and kerosene, and the operational costs of the digester. In the base case, the digester was assumed to have a discount rate of 8%. A change in ±3% from the base case was calculated to see the effect of NPV with a decrease and increase in interest rates. Similarly, the costs of subsidized LPG and kerosene were changed to 0.54 ± 0.25 USD/kg and 0.27 ± 0.1 USD/L, respectively, to see the effect of IRR and NPV on increasing or decreasing LPG and kerosene costs. Finally, the operational costs of the digesters were altered to 5 ± 5% of capital costs, to see how the operational costs affect the annual profit and the NPV.

3. Results and discussions

The textile digester was examined for more than 380 days with two different experiments by feeding with synthetic nutrients and OFMSW. The digester was also tested for being airproof and waterproof by filling it with air and water for 15-days each. Further, the material of the digester was also tested for different pH conditions (3–12) to check its ability in extreme environments. However, no difference in the material performance was observed. The material

<table>
<thead>
<tr>
<th>Substrate</th>
<th>OLR (gVS/L/day)</th>
<th>Days of operation</th>
<th>HRT (days)</th>
<th>Biogas production (L/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synthetic</td>
<td>0.25</td>
<td>17</td>
<td>100</td>
<td>17.27</td>
</tr>
<tr>
<td>medium</td>
<td>0.5</td>
<td>14</td>
<td>80</td>
<td>38.34</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>28</td>
<td>75</td>
<td>57.04</td>
</tr>
<tr>
<td>OFMSW</td>
<td>0.1</td>
<td>11</td>
<td>100</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>7</td>
<td>100</td>
<td>14.57</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>7</td>
<td>100</td>
<td>16.81</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>18</td>
<td>80</td>
<td>33.15</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>24</td>
<td>80</td>
<td>44.42</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>32</td>
<td>75</td>
<td>56.95</td>
</tr>
</tbody>
</table>
is also UV and temperature resistant (up to 80 °C) ensuring that it can withstand difficult conditions. Based on the obtained biogas production, economical evaluations of the digester were made, considering LPG and kerosene replacement with biogas. Finally, a sensitivity analysis was performed to see how the change in costs in the form of the interest rate, LPG and kerosene rate, and operational costs affects the economical benefits of the digester.

### 3.1. Experimental evaluation

#### 3.1.1. Feeding with synthetic medium

Granules of flocculated methane-producing bacteria have been commonly used in wastewater applications to produce biogas at a faster rate. In this study, the digester was filled with granules and fed with synthetic nutrients to compare the biogas production using synthetic nutrients and real waste as well as to exploit the granules beyond wastewater treatment to household biogas production. The OLR was successfully increased from 0.25 gVS/L/day to 1.0 gVS/L/day with a decrease in HRT from 100 to 75-days. The biogas production was stable during OLR 1.0 gVS/L/day with higher loading rate and lower retention times.

#### 3.1.2. Biogas production from OFMSW

In the second experiment, the digester started with cow manure as inoculum was fed with OFMSW increasing the OLR from 0.1 gVS/L/day to 1.0 gVS/L/day. The biogas production was increased steadily with increasing loading rate, and the average biogas production with OLR 1.0 gVS/L/day was 569 L/kgVS/day, which is equivalent to 88% of the theoretical yield. Fig. 3 shows the biogas production obtained from the digester for 99-days by feeding OFMSW. The amount of biogas produced was significantly higher compared with other studies from previous literature. For instance, Singh and Gupta [20] reported 315 L/kgVS/day, which is 44% lower than the current study using fixed dome digesters. Similar to the results obtained from these experiments, Safely Jr. and Westerman [21] reported 566 L/kgVS/day with 68.9% methane using a lagoon digester, which is similar to plug flow digesters.

Garfi et al. [22] reported 320 L/kgVS/day and maximum loading rate of 0.22 gVS/L/day with an HRT of 90 days by using plug flow digesters. However, in the current study using textile digester, the productivity of biogas could be increased by 44% and loading rate by 78%, and HRT decreased to 75 days, which is a significant achievement. A study by Lou et al. [23] on fixed dome digester of different sizes reported 390 L/kgVS/day, which is 31% lower than the textile digester. These comparisons proved that with different digester designs, textile digester was efficient in higher biogas production with higher loading rate and lower retention times.

The biogas production was stable throughout the feeding period, which means that constant gas production can be obtained from the digester. The accumulation of VFA was less than 2 g/L (Fig. 3), giving a clear indication that the digester was performing better compared to the synthetic nutrients. The composition of biogas was measured as 76% methane and 24% carbon dioxide.

#### 3.2. Economical evaluation

With reference to the laboratory experiments, techno-economic evaluation of the textile digester was performed for four different sizes, including 1.5, 2.0, 3.0, and 4.0 m³. The capital cost of the digester for different sizes was in the range of 200–300 USD (Fig. 4). All the economical calculations were made, assuming no subsidy from the government on capital investment. However, in many developing countries, the governments offer a subsidy on capital investment of biogas digesters, which needs to be considered.

The capital costs of the other digesters of different sizes are as follows: Plug flow digesters of 10 m³ costs 400 USD in 2011 [22], while a digester from Bangladesh reported to be 200 USD in 1992 [24]. Digesters in Uganda cost between 700 and 1200 USD in 2009 [25]. Similarly, an 8-m³ fixed dome digester from China costs 300 USD in 2010 [26]. A 4-m³ digester in Namibia and Ethiopia cost between 600 and 800 USD in 2004 [11]. Nonetheless, inflation is one factor which need to taken into consideration for the comparison of the capital cost of other digesters to textile digester.

In this work, the replacement of fossil cooking fuel, such as LPG and kerosene, with biogas from a textile digester was accounted for in the assessment. The amount of biogas needed for one day cooking was 0.21 m³/capita [27]. Thus, a family of three people requires 19 m³ biogas/month. Based on the experimental results obtained,
the amount of biogas produced from a 1.5 m³ digester is 26 m³ biogas/month (Table 2), which should be more than sufficient for the cooking needs. The amount of biogas produced from different sizes of digesters was compared to the amount of LPG and kerosene consumed for different family sizes, as presented in Table 2. For instance, a family of 3–4 uses 13 kg LPG/month and 17.5 L/month of kerosene [18,19]. This basis was used to calculate the usage of different fuels. Based on this consumption, the operational costs or the running costs per year were calculated. For biogas in the base case, the operational costs were assumed as 5% on capital investment. The cost of LPG and kerosene fuel was obtained from previous reports [16,17]. The total sum of investment and operational costs in 15-years with a discount rate of 8% is presented in Fig. 5. Within its lifetime, the total cost of a 2 m³ digester is 656 USD, while that of a 4 m³ digester is 20% more expensive.

3.2.1. Operational costs and PBP

The operational costs for different fuels per year are presented in Table 3. For a family of 1–3, the annual operational costs using biogas was 10 USD, while subsidized LPG and kerosene users have to spend 71 and 49 USD, respectively. Compared with the biogas operational costs, LPG and kerosene have 85.9% and 79.5% higher prices, respectively. The non-subsidized scenario was even worse, with the running costs increasing to more than 171% and 159%, respectively, for LPG and kerosene users. The percentage of operational costs using LPG and kerosene increases with the number of people in the family. If a family has more than 10 people, the subsidized LPG users will have a 90.7% higher price compared with a family of the same size using biogas from a textile digester, which is a significant difference. If the kerosene users with a family of 4–6 replace it with a biogas digester, they will obtain an annual profit of 53 USD using a subsidized scenario, while in the non-subsidized scenario, the annual profit increases to 118 USD. Comparing the total investment and operational costs of a digester within its 15-year lifetime with a subsidized-LPG and kerosene user for a 3-person family showed that the LPG and kerosene users have to spend 540 and 210 USD, respectively, more than the biogas user. It corresponds to 103% and 40% higher cost for the subsidized LPG and kerosene, respectively, within 15 years, in comparison to an investment on a biogas digester. Nonetheless, an increase in LPG or kerosene costs increases this margin significantly (Table 3 and Fig. 5).

The annual profits were used to calculate the payback period (PBP). The PBP was calculated for subsidized and non-subsidized scenarios for both LPG and kerosene by dividing the capital cost of the digester with the annual profits obtained from using biogas. Table 4 shows the PBP for LPG and kerosene users, who switch to biogas for cooking in subsidized and non-subsidized scenarios. The results show that non-subsidized scenarios had a lower PBP. In addition, the PBP was less for larger size digesters. Non-subsidized LPG users could see a profit in less than 2 years, while subsidized-LPG users get their investments back using textile digesters in about 3 years. Similarly, for non-subsidized kerosene users, the PBP was in the range of 1.32–2.04 years for different sizes of digesters. The subsidized-kerosene users had a double PBP compared to non-subsidized kerosene users. Considering a lifetime of about 15-years, the digester will yield a high profit to the people in all scenarios.

Singh and Sooch [3] compared the PBP for different fixed-dome digester models made of bricks such as: janta, deenbandhu, and KVIC. The PBP for a size of 2 m³ was found to be 6.12, 2.70, and 9.03 years, respectively. A textile digester of the same size had a PBP shorter than 3 years for LPG users, and less than 4 years for kerosene users. The PBP was lower when compared with janta and KVIC models, while it was higher for the deenbandhu model. Given the fact that constructing a digester with bricks results in a problem with leakage in the long run, more benefits could be obtained from the textile digester.

A portable textile digester helps in easy transportation, lowering energy demand, and reducing household waste. However, there are some weaknesses to the digester. For instance, rats or other animals might bite the digester, leading to a leakage. This fact and their possible solutions should be examined in the field under different environmental conditions.

3.3. Sensitivity analysis

Sensitivity analysis provides an insight into how the economics of the process is affected with varying conditions. In this study, variation in the discount rate, the cost of LPG and kerosene, and operational cost of digesters were accounted for in the analysis. An incremental and diminution scenario from the base case was considered for the previously mentioned alterations.

3.3.1. Change in discount rate

In the base case, the discount rate was assumed to be 8%. For sensitivity analysis, a variation of ±3% from the base case was considered, and the changes in NPV were calculated (Fig. 6). NPV corresponds to the profit of the process after the lifetime of the reactors has passed. In every scenario, the NPV was higher for the larger digester size, with non-subsidized users gaining more profit compared to subsidized users. A decrease or increase in discount rate did not affect the economics of the digester adversely. Decreasing the discount rate to 5% increased the NPV considerably, while increasing the discount rate to 11% still gave a positive NPV and profit in all digester sizes for both subsidized and non-subsidized users. For instance, in the base case, a subsidized LPG user with a 2 m³ digester will get 438 USD at 8% discount rate. Decreasing the discount rate to 5% gave 36.3% higher NPV compared with the base case, and increasing the discount rate to 11% reduced the NPV by 26.5%. Nonetheless, in many developing countries, governments give a subsidy or reduce the discount rate for green energy projects, which will bring in additional benefits.

3.3.2. Change in the cost of LPG and kerosene

It is interesting to compare the change in the cost of LPG and kerosene to that of using biogas, as the global oil price is quite

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Usage of different fuels for different family sizes.</th>
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</thead>
<tbody>
<tr>
<td>Digester size (m³)</td>
<td>Family size</td>
</tr>
<tr>
<td>1.5</td>
<td>1–3</td>
</tr>
<tr>
<td>2.0</td>
<td>4–6</td>
</tr>
<tr>
<td>3.0</td>
<td>7–9</td>
</tr>
<tr>
<td>4.0</td>
<td>10+</td>
</tr>
</tbody>
</table>

Fig. 5. Total expenditure for different sizes of biogas digesters after its lifetime.
Kerosene users, replaced with biogas using textile digesters. Payback period analysis for the base case in subsidized and non-subsidized LPG and capital cost, subsidized LPG – 0.54 USD/kg, subsidized kerosene – 0.27 USD/L. Annual operating cost for different fuels for the base case in USD/year: biogas – 5% of 188

Table 4

<table>
<thead>
<tr>
<th>Family size</th>
<th>Biogas subsidized LPG</th>
<th>Biogas subsidized kerosene</th>
<th>Non-subsidized LPG</th>
<th>Non-subsidized kerosene</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–3</td>
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<td>71</td>
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<td>142</td>
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<tr>
<td>4–6</td>
<td>12</td>
<td>97</td>
<td>65</td>
<td>194</td>
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<tr>
<td>7–9</td>
<td>14</td>
<td>130</td>
<td>81</td>
<td>260</td>
</tr>
<tr>
<td>10+</td>
<td>15</td>
<td>162</td>
<td>113</td>
<td>324</td>
</tr>
</tbody>
</table>

Table 3

Annual operating cost for different fuels for the base case in USD/year: biogas – subsidized LPG – 0.22 USD/L. A change of ±0.25 USD/kg for LPG and ±0.1 USD/L was considered to examine its effect on IRR and NPV. Increasing the cost of LPG and kerosene resulted in a very high profit on the whole. For a 3 m³ digester, using the base case, the subsidized LPG users had a NPV of 666 USD, while the non-subsidized LPG users would get 154% more than the subsidized LPG user. Similarly, if the price of LPG was increased, the non-subsidized user would get 945 USD additional profits more than the base case, which is 1697 USD for a 3 m³ digester.

Decreasing the price of LPG and kerosene affected the economics of the process adversely. When the kerosene price decreased to 0.22 USD/L, the digester with a size of 1.5 and 2 m³ would have a loss, i.e., a negative NPV. Given the fact that the demand for oil is increasing, the prices for LPG and kerosene would go higher and not lower, which suggests that it is a profitable investment. A 4-m³ digester in the base case, for a non-subsidized kerosene user, had an IRR of 70%, while increasing the kerosine price increased the IRR to 98% and decreasing the kerosene price reduced the IRR to less than 40%. Fig. 7 shows how the NPV and IRR are affected with an increase and decrease in LPG and kerosene prices.

The incremental analysis for retrofitting investment in the biogas digesters was carried out. The minimum cost of fuels such as LPG, kerosene, or even wood or coal to be substituted with biogas in order to obtain zero NPV was calculated and is presented in Table 5. It is the minimum price that makes the investment on biogas profitable. Increasing the digester size and minimum costs of fuel to be sold for NPV to zero was inversely proportional. In the subsidized scenario, the minimum cost was in the range of 0.16–0.25 USD/kg for LPG users. Subsidized kerosene had a minimum cost of 0.11–0.18 USD/kg, while non-subsidized kerosene could be sold for less than 0.06 USD/L for a digester size of 1.5–4.0 m³.

3.3.3. Variation in the operational costs of the digester

The operational costs of digesters were used either for fixing the gas leakage or for fixing the inlet and outlet pipes (minor problems). For the base scenario, the operational costs of the digesters were assumed to be 5% of the capital costs annually. However, there are scenarios where there would be no operational costs, for example, if there was no problem with the digester. On the other hand, there could be increased operational costs if it is necessary to fix a bigger problem with the digester. For such circumstances, a ±5% capital cost was considered. It is certain that if no operational costs were needed, it would result in more profit. Interestingly, increasing the operational costs to 10% still gave profits for all digester sizes for both LPG and kerosene users. Nonetheless, subsidized kerosene users would get the least amount of profit, if the operational costs were 10% of the capital investment. Fig. 8 shows the effect of NPV in variation of operational costs. The NPV for the subsidized kerosene users would be 45, 85, 169, and 380 USD for a digester size of 1.5, 2, 3, and 4 m³, respectively. IRR showed an increasing trend with the increase in digester size for all scenarios. The IRR varied similar to the change in the operational costs of the digester, i.e., ±5%. A maximum IRR was obtained for a non-subsidized LPG user, who uses a 4 m³ digester, being 108%. In contrast, the minimum IRR was acquired in the subsidized LPG user in a 1.5 m³ digester, being 12%. Comparing this 12% IRR to the different discount rates previously analyzed, i.e., 11% would still give a profit of 1% in the worst case scenario.

Operational costs considered here are for the maintenance and minor problems. However, if a major (technical) problem occurs, the user would most likely have difficulty in resolving the issue, which would have a big impact on the NPV. A technical problem would require, e.g., a specialized person to look at and resolve the issue. Considering a cost of 40–50 USD for examination by a
technical person in developing countries, a 10% operational cost for minor problems will bring the NPV to almost zero for kerosene users. However, LPG users still have a positive NPV if a technical problem is faced. On the other hand, if the digesters are used in developed countries, the examining cost is much higher, and it has a huge effect on the digesters economy. Hence, the users have to be trained well enough to maintain the digesters.

Another interesting issue to consider is the cost of waste treatment. In this work, we have not considered the price of the wastes or raw materials of the biogas digester. However, every household has to pay a tax to get rid of the waste, which means the waste has a minus price. If the household digester is used, then the household will have less waste, and will most likely have to pay a lower tax. This would bring in additional profit to the biogas digester users. For example, here in Borås (Sweden), each household has to pay 1.7 SEK/kg food waste. Approximately, 250 kg of food waste is collected from each household per year by the municipality for waste treatment, which is equivalent to 425 SEK/year or 65 USD/year [28]. This should be considered as an additional benefit to the biogas digester users.

4. Conclusion

Household biogas digesters are a boon to low-income and rural people. The developed portable-textile digester can reduce the consumption of fossil fuels such as LPG and kerosene by replacing with biogas. Developing a user-friendly technology and making it economically viable will enhance the use of biogas digesters. The
biogas produced should be enough for the household for cooking purposes, and it is economically feasible for LPG and kerosene in both subsidized and non-subsidized scenarios. Additional benefits can also be obtained in the form of subsidies from the government and environmental benefits in the form of reducing waste generation and fossil fuel consumption.

Acknowledgements

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References


Impacts of retrofitting analysis on first generation ethanol production: process design and techno-economics

Karthik Rajendran · Sreevathsava Rajoli · Oliver Teichert · Mohammad J. Taherzadeh

Abstract More than half of the bioethanol plants in operation today use corn or grains as raw materials. The downstream processing of mash after fermentation to produce ethanol and distiller grains is an energy-demanding process, which needs retrofitting for optimization. In addition, the fluctuation in the ethanol and grain prices affects the overall profitability of the plant. For this purpose, a process simulation was performed in Aspen Plus® based on an existing industrial plant located in Sweden. The simulations were compared using different scenarios including different concentrations of ethanol, using the stillage for biogas production to produce steam instead of distiller grains as a by-product, and altering the purity of the ethanol produced. Using stillage for biogas production, as well as utilizing the steam, reduced the overall energy consumption by 40 % compared to the plant in operation. The fluctuations in grain prices had a high impact on the net present value (NPV), where grain prices greater than 349 USD/ton reached a zero NPV. After 20 years, the plant in operation producing 41,600 tons ethanol/year can generate a profit of 78 million USD. Compared to the base case, the less purified ethanol resulted in a lower NPV of 30 million USD.

Keywords Process design · Retrofitting analysis · Ethanol · Aspen plus · Techno-economic analysis

Abbreviations
DDGS Dried distillers grains with soluble
TS Total solids
NPV Net present value
PBP Payback period
CCP Cumulative cash position
NFDS Non-fermentable dissolved solids

Introduction

The global depletion of oil and environmental concerns has led to the search for renewable fuel sources. Today, several forms of alternative energies exist of which, the contribution of biofuels ethanol, biodiesel, and biogas is significant. Ethanol was introduced in the transportation sector in the early 1900s in the United States from corn as a raw material [1]. Similarly, ethanol production from sugarcane was introduced in Brazil by the Brazilian Alcohol Program systematized in 1975. In 2012, Brazil and the United States together produced about 85 % of the total ethanol production in the world, equivalent to 72.7 million cubic meters [2, 3].

The majority of ethanol producing plants use food or arable crops including sugarcane, corn, or grains [4]. The choice of this raw material depends on the excess amount of crops generated in the country. For instance, the sugarcane production in Brazil exceeded 721 million tons in 2012, leaving it as a potential substrate for producing ethanol [5]. Correspondingly, in Sweden, the wheat production was about 2.3 million tons in 2012, leaving it as a potential source for ethanol production [5]. In 2011, the overall ethanol generation in Sweden was about 300 tons/day [6].

Ethanol production from food crops is a matured technology and produced as follows depending on the raw
material: for instance, corn or grains are ground either by wet or dry milling, followed by the addition of enzymes such as \( \alpha \)-amylase and gluco-amylase to release the sugars, and thereafter, the temperature of the fluid is increased to liquefy the feed. Furthermore, the liquefied feed is sent to the fermentor, where by the action of the yeast, ethanol is obtained after fermentation. Unlike, corn and grain, ethanol production from sugarcane is obtained after steps such as extracting the sugarcane juices, followed by the addition of sulfuric acid, lime, and thickeners, and the removal of impurities before it is fermented. The fiber residue of the cane, after cane juices have been extracted, called bagasse is sent to the boilers for electricity production. The ethanol produced after fermentation is sent to the distillation columns for downstream processing and purification. The residue from the distillation process, called as stillage contains organics and proteins, is centrifuged, evaporated, and dried to produce dried distillers grains with solubles (DDGS) as a by-product. However, depending on the raw material, milling type, etc., different by-products can be generated. For instance, the wet milling of corn results in gluten feed and gluten meal, which are used in the poultry industries; corn oil and corn steep liquor are other valuable products obtained apart from ethanol [1, 7–12].

Though this technology is commercialized, today many plants face operational problems and need a retrofitting. For instance, some plants are not equipped with a dehydration column when designed or need to be retrofitted by adding or removing a dehydrator. In addition, the evaporation of the stillage is a high energy consuming process, which demands the innovation of a better technology or alternatives. Previously, some techno-economic studies were proposed for sugarcane, grains, or corn [8–11, 13]. Quintero et al. [11] compared the ethanol production from sugarcane and corn, based on Colombian conditions, and evaluated the economic and environmental performance for both the processes. In another study, ethanol production from the corn dry milling process was evaluated using SuperPro Designer, considering different costs for corn, [9] while Sokhansanj et al. [13] studied the effect of the cost on feedstock and supply logistics in the ethanol production. The studies so far, however, do not consider any changes to the plant, which could be a critical factor during the course of time. The main novelty of this work is to study the different retrofit options available for the first generation ethanol production and the effect of economic sensitivities on ethanol and grain prices.

In this work, an industrial ethanol plant using grains as raw materials was simulated to study the techno-economic perspective. Having this as the base simulation, several retrofit scenarios were compared and the energy consumption was studied including the effect of evaporators, usage of a dehydration column to remove the excess moisture, different yeast strains for ethanol production, and sensitivity analyses were performed for the cost of ethanol, grains, and DDGS, etc. The profitability indexes, investments, energy consumptions, technical variations between the base simulations and the modified scenarios were compared and analyzed.

Methods and modeling

Process description (base case)

The base simulation was performed with reference to the data obtained from the ethanol plant in Norrköping (Lantmännens Agroetanol AB, Sweden). All the equipment was modeled using Aspen Plus® (version 8.4). Figure 1 shows the process flow sheet of the ethanol production from grains. The grains were transported to the plant using trucks and stored in a silo. From the stored silo, it was transported through the conveyor belts for milling. About 18.8 t/h grains with TS of 86.5 % were milled using a dry mill process to obtain coarse flour, which contains 66 % starch, 12 % proteins, and 22 % others. Furthermore, the flour feed was sent to a slurry tank of volume 40 m³, to be mixed with the incoming process water and \( \alpha \)-amylase. After that, the feed was sent to two liquefaction tanks, which were operating at 73 and 88 °C to dissolve as much as possible and initiate the conversion of starch to its monomeric form, glucose. The retention times for the liquefaction tanks were 2.2 and 2.1 h, respectively. Once the liquefaction was complete, the feed was cooled down to 33 °C, to facilitate the fermentation process.

About 58.8 t/h cooled feed was pumped into the five fermenters with a retention time of 2.78 days. In the fermentation process, gluco-amylase is added before the mash enters fermentor where yeast is present. The yeast converts the newly released sugars into ethanol and carbon dioxide. Approximately, 5.1 t/h carbon dioxide was released from the fermentor, while 5.4 t/h ethanol was obtained after fermentation. The fermented mash with the ethanol, the residues such as proteins, other glucose based materials, and other non-fermentable dissolved solids were sent to the distillation column for the purification of ethanol. The detailed information about the distillation column data is provided in Table 1. In total, three distillation columns were used, where the initial heat was supplied to the third columns’ reboiler. Subsequently, the heat from the third columns’ condenser was sent to heat the second columns reboiler and it was continued for the first column. The feed from the fermentors was split equally between the distillation columns one and two, respectively, and the ethanol
was purified between 45 and 50%. The top from both the distillation columns was sent to the third column, where the ethanol was purified to about 91%.

The residue remaining after the distillation process called “stillage,” contains the leftovers such as proteins, other glucose-based materials and other non-fermentable dissolved solids (NFDS) that were sent to a decanter where the solid wet cake contain about 32% TS. The solid stream was sent to the dryer for the production of DDGS. For the thin stillage stream, about 19% was recycled back to liquefaction, and the remaining feed was sent to the evaporator, which was a 5-stage evaporator operating between 80 and 85 °C. The concentrated thin stillage called syrup from the evaporator were sent along with the solids from the centrifugation for the production of DDGS. In addition, the condensed water from the evaporators was collected and recycled back to the first mixing tank, as processing water. The dryers were operated at 115 °C and then pelletized to produce DDGS. About 7.7 t/h DDGS was produced, which contained 90% TS. The DDGS is stored in silos, before it is sold to the market.

The purified ethanol stream, resulting after the distillation process, contains excess water, which cannot be removed due to azeotropic nature of ethanol/water mixtures. Therefore, a so-called pressure swing adsorption is used to purify the ethanol according to the specification. When the first dehydration column was in operation, the feed was added from the bottom, where water is retained, while purified ethanol can pass though the column filled with a zeolite. About 70% of the purified stream was sent to the storage tank as a final product, while the other 30% was sent to the second dehydration column which is under regeneration. This regeneration product called purge is given back to the rectification column. About 5.2 t/h ethanol was produced as a final product, which was sold to the market.

Retrofitting analysis

The current ethanol production methods result in fewer by-products; moreover, utilizing the stillage after fermentation can result in different by-products, which can improve the overall economy of the process [14]. With reference to the base case simulation, different retrofitting alternatives were considered in the current flow sheet. Figure 2 shows the block flow diagram for the different retrofits considered in this study. The energy consumption, economical

---

**Table 1** Conditions for the distillation columns used in the base case

<table>
<thead>
<tr>
<th>Condition</th>
<th>Distillation column 1</th>
<th>Distillation column 2</th>
<th>Distillation column 3</th>
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<tr>
<td>Number of trays</td>
<td>25</td>
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<tr>
<td>Optimal feed tray</td>
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<td>15</td>
</tr>
<tr>
<td>Pressure (atm)</td>
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<td>0.7</td>
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</tr>
<tr>
<td>Purity of ethanol in distillate (%)</td>
<td>0.45</td>
<td>0.51</td>
<td>0.91</td>
</tr>
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---

**Fig. 1** Process flow-sheet for the base case (red dashed line heat transformation between distillation columns, green dashed line ethanol recycle flow, solid line Product ethanol flow) (color figure online)
investments, revised payback period, etc., were recalculated. The different retrofits were as follows:

- **Retrofit 1**: In the base case simulation, three distillation columns were used followed by two dehydrator columns to reach a final purity of 99.5%. In this retrofit, the dehydrator columns were replaced by a fourth distillation column. The final purity of ethanol was 93%, and the ethanol was sold at a reduced cost of 775 USD/ton (http://www.alibaba.com).

- **Retrofit 2**: The concentration of ethanol obtained after the fermentation in the base simulation was 10%. However, this concentration was increased to 17% ethanol (retrofit 2A), as there are certain commercial strains of the baker’s yeast that can tolerate this concentration. On the other hand, a 4% ethanol concentration strain (retrofit 2B) was considered to check its effect on energy and economics. The different concentrations of ethanol reflects the amount of water usage in the process, thereby reducing or increasing the effect on the distillation column and the overall size of the equipment considered.

- **Retrofit 3**: Currently, the evaporators are used for the stillage to produce DDGS, and process water is recycled. However, in the developing countries, evaporation is often not used, as it is an energy-intensive process. The stillage contains leftover organics, and proteins, which can be used for the biogas production. Biogas is a combination of methane and carbon dioxide, formed due to the anaerobic digestion of organics (stillage). In this retrofit, the stillage was used to produce biogas, which can be used to produce steam for the process. Even though the DDGS by-product revenue is absent, the cost of the utilities would be considerably low. For this purpose, the biogas process was modeled according to Rajendran et al. [15, 16].

**Energy and economics**

Table 2 shows the list of assumptions made to carry out the simulation in this study. All the equipment considered in this study was made of stainless steel. The economic analysis was carried out using Aspen Process Economic
Analyzer (8.4). The economic calculations were carried out based on the pricing from the first quarter of 2013. The ethanol is sold at a price of 875 USD/ton, before tax. All the profitability indexes such as the capital investment, net present value (NPV), payback period (PBP), revenue, utilities, operational costs, cash-flow diagrams, and cost of raw materials for all the different retrofits were performed and analyzed according to Turton et al. [17]. Here, the PBP refers to the recovery of the investment and working capital, after the operation of the plant.

The energy consumption calculations were performed using the Aspen Process Energy Analyzer (8.4). The energy consumption was summarized in terms of sections in the process flow sheet. Here, the liquefaction section includes the energy consumption for grinding the grains and adding water and enzymes to the liquefaction tanks (1 and 2), where the reactor is heated to liquefy the feed. The second section is the fermentation section, where the energy consumption for cooling the feed as well as the fermentation process is considered. The downstream processing is divided into two sections, namely: evaporation and drying as well as distillation and dehydration. In evaporation and drying, the energy consumption for the centrifugation, evaporation, and drying to produce the by-product DDGS was taken into account. The distillation and dehydration section includes the purification of ethanol through distillation and molecular sieves to remove the moisture until a final product is obtained.

### Table 2 List of assumptions considered while conducting this study

<table>
<thead>
<tr>
<th>Type</th>
<th>Assumption</th>
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</thead>
<tbody>
<tr>
<td>Annual processing capacity</td>
<td>150,400 tons grains/year</td>
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<td>Cost index</td>
<td>2013 1st quarter</td>
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<td>Annual operating time</td>
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<td>Depreciation method</td>
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<td>Tax rate</td>
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<td>Interest rate</td>
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<td>Water</td>
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<tr>
<td>Waste water treatment</td>
<td>0.1 USD/m³</td>
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<td>Steam</td>
<td>0.01 USD/kg</td>
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<tr>
<td>Grains</td>
<td>300 USD/ton</td>
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<tr>
<td>Carbon dioxide</td>
<td>0.1 USD/kg</td>
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<td>Ethanol cost</td>
<td>875 USD/ton</td>
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<tr>
<td>DDGS cost</td>
<td>370 USD/ton</td>
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<tr>
<td>α-Amylase</td>
<td>4.6 USD/kg</td>
</tr>
<tr>
<td>Gluco-amylase</td>
<td>5.3 USD/kg</td>
</tr>
</tbody>
</table>

Sensitivity analysis

A sensitivity analysis was carried out on the base case simulation, by varying the annual processing capacity from 10 to 600 %. Here, 100 % refers to the base case with a processing capacity of 150,400 tons of grains/year. The sensitivity analysis was carried out to a processing capacity between 15,000 and 902,000 tons/year. The investment parameters such as capital investment, cash flow analysis, NPV, PBP, operating cost, raw material cost, and utilities cost were calculated for each of the processing capacities. Varying the process capacity shows the effect of having a divergence scale for the plant, suitable for different countries and the availability of raw materials. The fluctuation in the cost of ethanol, grains and DDGS were the other economic parameters, which affects the overall profitability of the plant. For this purpose, from the preliminary assumptions, the cost of ethanol, grains, and DDGS was altered by ±50, ±100 USD/ton. The minimum selling price of ethanol and DDGS, and the maximum cost of the grains at which the NPV becomes zero were estimated.

Results and discussion

Retrofitting analysis on the ethanol production from grains was performed using Aspen Plus. The energy calculations were performed using Aspen Energy Analyzer, and the economics of the plant was calculated based on Aspen Process Economic Analyzer. The techno-economic performance and the energy utilization studies were compared for the different retrofits and sensitivities.

Base case

For the base case, the plant that is in operation today was considered. All the unit operations were mass- and energy-balanced based on the data obtained from Lantmännen Agroetanol AB, Sweden. The fermentor to produce the ethanol was modeled based on the NREL model [18, 19]. Table 3 shows the allocation of the energy consumption for the different sections of the plant. In the distillation column, the heat was transformed between the condensers in the third column, to the reboiler of the second column. This heat integration reduced the amount of energy consumption in the plant. However, about 40 % of the total energy consumption of the plant was consumed for the downstream processing of the ethanol, which includes the distillation and dehydration processes. The annual ethanol production and DDGS is equivalent to 41,600 and 61,600 tons, respectively. This ethanol production capacity is equivalent to ~40 % of the total ethanol production in Sweden [6].
In terms of economics, the total capital investment required for the plant was 69 million USD (Fig. 3). Arifeen et al. [10] reported a capital investment of 48 million USD for the capacity to produce 30,000 tons ethanol/year. The results in the current study were in accordance with Arifeen et al. and Lang et al. [10, 20], considering the inflation and capacity. The products and the by-products due to the fermentation of the grains include ethanol, carbon dioxide, and DDGS, which resulted in the annual revenue of 63 million USD, while the operating costs were 56 million USD, respectively. The investments and the working capital could be gained back in 13 years, and the NPV after 20 years of operation was 78 million USD. It is a positive investment; however, the cumulative cash position (CCP), i.e., capital investment to the NPV ratio was 1.13, suggesting that it is not economically attractive to the fullest. It would be interesting to compare the proposed retrofitting scenarios to the existing scenario in the plant.

Sensitivity analysis for different processing capacities

With reference to the base case of the capacity of processing 150,400 tons grains/year, a wide range of plant capacities was considered, namely, from 10 % of the base case to 600 % of the base. Figure 3 shows the cash flow diagram and other economic parameters for the different capacities considered in the sensitivity analysis. The results suggest that reducing the plant capacity has adverse effects on the plant profitability and that reducing the capacity less than 75,200 tons/year, i.e., 25 % of the base case, is not profitable. Increasing the plant capacity had an overall positive effect on the economics; however, the PBP of the plant remains around 11 years. It could be that increasing the plant capacity also means a higher investment, which could not be recovered for at least 10 years with the current processing methods. For a plant processing 902,400 tons/year, the NPV obtained after 20 years was 641 million USD, while the capital investment was 258 million USD. This resulted in a CCP of 2.48, which is 120 % higher than the base case.

The cost of ethanol, grains, and DDGS is one of the important factors, which affect the profitability of the plant. A sensitivity analysis was carried out for different prices of raw materials and products, suggesting how the market fluctuation affects the economics of the plant. Figure 4 shows the NPV and PBP for different sensitivity analyses carried out on the ethanol producing plant from the grains. Compared to the selling price of ethanol and DDGS, the

| Table 3 Overall energy consumption of the plant for different retrofits |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Energy (GW/year) | Base case | Retrofit-1 | Retrofit-2 EC-4% | Retrofit-2 EC-17% | Retrofit-3 |
| Liquefaction     | 5.5          | 5.4          | 15.2            | 3.5             | 1.8             |
| Fermentation     | 0.7          | 0.7          | 2.2             | 0.5             | 0.7             |
| Evaporation and d | 5.5          | 5.0          | 12.8            | 3.7             | 2.3             |
| Distillation and dehydration | 7.7          | 10.1         | 13.3            | 6.1             | 7.2             |
| Total energy consumption | 19.4 | 21.2 | 43.5 | 13.8 | 12.0 |

a Ethanol concentrations
b Anaerobic digestion

Fig. 3 Economic parameters such as cash flow diagram (a), NPV, capital investment, operating cost (b), raw materials cost and PBP (c) for different capacities of the plant
purchase price of the grains affects the economics of the plant adversely. Increasing the grains price to 350 USD/ton lowers the NPV to less than ‘0,’ and the maximum price for the grains for the NPV to have a positive NPV was 349 USD/ton. Although the decreasing prices of ethanol and DDGS had a negative effect on the NPV, reducing the product cost to less than 100 USD/ton, respectively, for ethanol and DDGS from the base case, still had a positive NPV. The minimum cost of ethanol to be sold for a zero NPV was 702 USD/ton, whereas for DDGS it was 250 USD/ton. A 59 % increase in the NPV could be obtained by increasing the ethanol price from the base case by 100 USD/ton.

Comparison of different retrofits

The base case was compared to different retrofits such as removal of the dehydrator column to the distillation column, different ethanol-tolerant yeast strains, utilization of biogas to steam instead of producing DDGS, and fungal bio-refinery of stillage to produce fish feed. Figure 5 shows the different economic parameters for the retrofits considered in this study. In the past, some of the ethanol producing industries did not produce a 99.5 % pure ethanol; instead, they produced a lower grade, for instance 93 %. For this purpose, one retrofit scenario was to consider replacing the dehydrator with a distillation column. Compared to the base case, adding a distillation column instead of a dehydrator is a 30 % capital-intensive process. In addition, the purity of the ethanol is lower, resulting in a lower NPV of 30 million USD, compared to 78 million USD in the base case. Thanks to the development in chemical engineering, this resulted in an efficient processing through dehydration, increasing the final purity of the ethanol.

The common yeast strain used today in ethanol production is baker’s yeast. However, there are certain other strains, which can produce ethanol at higher or lower concentrations. Two different ethanol concentrations were considered, i.e., 4 and 17 % to test the sizing and energy consumption of the plant. In principle, the water consumption of the process was altered, resulting in the varying sizes of the different unit operations in the process. For the 4 % ethanol concentration, the sizing of the equipment was increased by 1.5 times compared to the base case, in terms of the direct cost for the equipment; however, a high yeast-tolerant strain could reduce the overall sizing by 10 %. Considering the energy consumption, a 4 % ethanol strain consumes more than double the energy compared to that of the base case. The NPV for 4 % ethanol strain was 51 million USD, while for 17 % ethanol tolerance, the NPV was 60 % higher compared to the base case. In terms of the energy consumption, 4 % ethanol tolerance could use 67 % more energy compared to that of the base case, whilst 17 % ethanol tolerance case could use 4 % less energy.

Currently, in the plant, the stillage is sent to produce the DDGS, which is used as an animal feed after evaporation and drying. From the base case, we could identify that the energy consumption for evaporation and drying of the stillage was 5.5 GW h/year. This is an energy-intensive process, and in retrofit scenario 3, we evaluated the outcome if an anaerobic digester was used instead to produce heat, which can be utilized for the process. The results suggest that using the heat for the process is economically attractive compared to the current scenario today. Barta et al. [21] have utilized biogas from thin stillage in a second generation ethanol production from soft-wood, and showed that it was about a 12 % energy efficient process. In this study, the energy consumption has gone down by 7.4 GWh, compared to the base case, which could be due
to the processing of the stillage for evaporation and drying to produce the DDGS. Nonetheless, the total product sales went down by 8 million USD/year, as the by-product DDGS was not produced.

**Conclusion**

Retrofitting analyses of first generation ethanol production was modeled using Aspen Plus, and it was analyzed based on techno-economic perspectives. The results suggest that the purchase price of grains plays an important factor in the profitability of the plant, while decreasing the ethanol to less than 702 USD/ton is not profitable. The retrofitting comparisons revealed that using the stillage for biogas reduced the overall energy consumption by 39 % compared to the base case. Reducing the plant size to less than 75,000 tons grains/year is not profitable, while increasing the plant size more than 300,000 tons grain/year did not decrease the PBP to less than 11 years.

**Acknowledgments** The authors would like to thank the Swedish Energy Agency for their financial support and Lantmännan Agroetanol AB, Sweden for sharing the data of the plant. We also acknowledge Thomas Södergren for his computer support.

**References**

5. Food and Agricultural Organization (2012) FAOSTAT
Techno-economic analysis of integrating first and second generation ethanol production using filamentous fungi

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Abstract

The 2nd generation ethanol plants from lignocelluloses demand risky and high investment costs. This paper presents the energy- and economical evaluations for integrating the lignocellulose in the current 1st generation dry mill ethanol processes, using filamentous fungi. Dry mills use grains and have mills, liquefactions, saccharifications, fermentation, and distillation to produce ethanol, while their stillage passes centrifugation, and evaporation to recycle the water and dry the cake and evaporated syrup into animal feed. In this work, a bioreactor was considered to cultivate the fungal on the stillage either before or after the centrifuge together with pretreated lignocellulosic wheat bran. The results showed that the integrated 1st and 2nd generation ethanol process requires a capital investment of 77 million USD, which could yield NPV of 162 million USD after 20 years. Compared to the fungal cultivation on thin-stillage modified 1st generation process the integrated process results in 53 million USD higher NPV. The energy analysis showed that the thin-stillage modified 1st generation process could reduce the overall energy consumption by 2.5% and increase the ethanol production by 4%. Such modifications in the 1st generation processes and integration concepts could be interesting for the ethanol industries, as integrating lignocelluloses to their existing setup requires less capital investment.

Keywords: process design, techno-economic analysis, process integration, lignocelluloses
1 Introduction

The cost of fossil fuel has put a barrier to the biofuels that it should be extremely competitive. This limits the price of the biofuels; thus, for such industries to be economically sustainable, the need for economic input from the byproducts plays a pivotal role. Ethanol is the dominant biofuel in the global market. Ethanol production can be distinguished as different generations based on the raw materials used. The first generation ethanol production uses simple sugar- and starch-based raw materials such as corn, grains, and sugarcane, which are currently common in the industrial setups [1]. The choice of raw material depends on its availability. For instance, sugarcane is available in abundance in Brazil, making it probably the cheapest ethanol producing country in the world at a production cost of 0.18 USD/L [2-4]. The second-generation ethanol production includes the use of cellulosic materials such as lignocelluloses to produce ethanol. Unlike the first generation, which has readily available sugars, the lignocelluloses to ethanol process requires an additional step called the pretreatment in order to allow for the release of the sugars from the cellulosases as well as higher enzymes costs [5, 6].

In addition, the profit margin from ethanol and byproducts is relatively small, meaning that a small fluctuation could affect the profitability of the plant adversely [7]. For this purpose, the concept of biorefineries is necessary. One possibility is using ascomycetes or zygomycetes fungi to produce fungal biomass for animal feed [8]. The biomass contains high levels of protein, and it could be sold as a feed; thus, the demand for such products is increasing steadily. Other possible products from fungal integrated process are dietary supplements, and superabsorbent [9]. This study exploits such biorefinery options.
Although the first generation ethanol production is industrialized, this process could be optimized further for an efficient recovery of leftovers after fermentation and distillation, called stillage. This slurry usually ends up as distiller’s grains, a byproduct of low value. Recently, Ferreira et al. [10] developed a process concept to utilize the fungi (*Neurospora intermedia*) to consume the leftover sugars in the thin-stillage to produce ethanol and biomass. The biomass could still be counted as a byproduct, and the additional ethanol could increase the overall economics of the process.

On the other hand, starting a second-generation ethanol production from lignocelluloses means a drawback on the capital investment and economic returns. For this purpose, Lennartsson et al. [7] proposed an option of integrating the first- and second generation ethanol production, which can actually reduce the overall investment risk and cost, as most of the downstream operations are already in place in the first generation ethanol plants. Some of the possible options for an integrated process are: a mixed fermentation of first- and second generation raw materials, where the first generation process enters the fermenter after the liquefaction, while for lignocelluloses it could be after the pretreatment and hydrolysis. Other integration methods include the combined processing of pretreated lignocelluloses, along with the thin-stillage from the first generation process using fungal cultivation for additional ethanol and biomass production. This shows the importance of biorefinery concepts for the future [7].

Previously, certain techno-economic works had been made on the modifications in the first-generation ethanol production. Arora et al. proposed a micro-filtration processes for thin-stillage to increase the solid concentration. This modification resulted in the reduction of operating cost by 50%, while the capital investment increased by 47% [11]. Sosa et al. did a conceptual modeling was performed in the distillation columns for a corn to ethanol process including the
effect of corn contamination with fumonisins[12]. Some other modifications include the recycling of DDGS after pretreatment and hydrolysis with corn to go through fermentation to increase the ethanol yield, which had resulted in 32% increase in NPV[13, 14]. Some experimental works have been proposed for a better first generation processes include the production of coproducts from condensed distiller solubles to protein-mineral fraction, glycerol fractionation using a chemical method [15]. Other retrofitting analysis includes the comparison of conventional corn grind processes and quick-germ process, in which the quick germ process yielded additional 4 million USD in NPV [16]. Similarly, a lot of techno-economic studies have been proposed for the lignocellulosic ethanol production. Some of the substrates considered was corn stover[17-21], rice straw [22, 23], softwood [24-26], bagasse[27]. In addition, the techno-economic possibility of integrating first and second generation ethanol was explored using sugar cane bagasse and leaves integrated with sugar based processes [28].

In this study, retrofitting the thin-stillage and the whole-stillage to the ethanol and biomass was studied through the simulation approach using the AspenPlus® based on the laboratory data. Furthermore, the integration of the first- and second- generation ethanol production was considered for the modified thin-stillage process. Wheat bran with phosphoric acid pretreatment was considered in the integration process for the second-generation ethanol production. Integrating the first- and second-generation ethanol production through techno-economic analysis and process design has never been attempted before, which shows the significance of this work.
2 Method

2.1 Process description

This study was carried out based on a reference ethanol plant located in Norrköping, Sweden, which uses grains as a feedstock. The data for the simulation was obtained from the ethanol plant and the improvements data such as thin-stillage/stillage to ethanol and lignocelluloses to ethanol was based on the laboratory data from Ferreira et al. and Nair et al.[10, 29, 30]. The process simulation was carried out using Aspen Plus® (V8.4). In this ethanol plant, 18.8 t/h grains are dry milled to obtain coarse flour. The coarse flour is mixed with the processing water in a mixing tank, followed by the liquefaction process. The two-step liquefaction step is operated at 73°C and 88°C, during which the starch is converted into oligomers. Thereafter, the yeast along with the glucoamylase converts it into ethanol and carbon dioxide in the fermentation units at 33°C, at a flow rate of 5.4 t/h and 5.1 t/h, respectively. Subsequently, through the distillation process, the mash flows to separate the ethanol from the stillage and dehydrates it to obtain 99% pure ethanol. Thereafter, the stillage undergoes the centrifugation process (decanter) to recover the solids and is sent to the drier. After centrifugation, the thin-stillage passes through a series of evaporators to recover the leftover solids, while the evaporated liquid is recycled as processing water. The syrup collected from the evaporator, along with the solids from the stillage are dried to obtain 7.7 t/h distiller grains named DDGS [31].

2.1.1 Thin-stillage modification (Scenario A)

In the base case, after distillation, the leftovers, referred to as whole-stillage were sent through a decanter to remove the solids. This supernatant stream, called thin-stillage, entered the
evaporation process, while the solid cake was sent to the dryer to obtain the byproduct distiller grains. The thin stillage was then evaporated to recycle the water back to the process. The TS concentration of the thin-stillage was about 10%, with a total stream flow rate of 40 t/h, which was obtained after processing 150,400 tons of grains annually. In the modified process, the thin stillage was sent through a fungal cultivation process, where it was converted into ethanol and biomass[30]. The biomass was separated and dried as a fungal animal feed, while the ethanol produced flowed through the evaporator and was recycled back to the process, for further purification. Figure 1 shows the block flow diagram of all the modifications considered in this study, and scenario A shows the thin-stillage modified process in the first generation ethanol production.

The following data were used for the simulation purposes, using thin stillage to ethanol and biomass production. The fungal bioreactor was operated continuously at 35°C and had a dilution rate of 0.1 h⁻¹. The flow rate of the thin-stillage was 40 t/h; hence, it required a reactor of working volume 400 m³. Air was sparged through the reactor in order to mix and fluidize the contents at a rate of 0.5 vvm. From the fungal cultivation on the thin stillage, 5 g/L ethanol, 7.9 g/L CO₂, and 4 g/L biomass was obtained. After harvesting the fungi, the liquid, containing mainly water, was recycled to the process in two parts: (1) 85% of the material was sent to the evaporator and (2) the rest 15% was recycled to the beginning of the process directly. The carbon dioxide was separated and sold as another byproduct, as mentioned in the base case scenario [10].
2.1.2 Whole-stillage modification (Scenario B)

Similar to the conversion of the thin-stillage into fungal biomass and ethanol, the possibility of converting the whole-stillage into ethanol and biomass was exploited. The whole-stillage possessed higher TS, in the range of 15–16%; however, it contained more sugars compared to the thin-stillage, in which a higher conversion rate to ethanol and biomass could be expected. Since the stillage has higher sugar content, and the cost of the ethanol as a product was higher compared to the biomass, it was important to recover most of the ethanol before the production of the byproduct biomass.

For this purpose, a two-step fungal cultivation process was employed (Figure 1 Scenario B). The objective behind the two-step process is that to remove the excess solids from the first bioreactor after the production of ethanol to cultivate fungi in the second step. In the first step, the stillage was sent to a reactor, where it was mainly converted into ethanol. The operating conditions for the two-step fungal fermentation for the production of ethanol and biomass from the stillage were as follows: temperature 35°C and air 0.2 vvm. In addition, 1-FPU/g cellulase enzymes were added to facilitate the breakdown of the sugars with ease. The ethanol production from the first reactor was 6.9 g/L, while the carbon dioxide and biomass productions were 7 g/L and 0.4 g/L, respectively[30]. After the production of the ethanol, the solids were separated using a decanter and the rest of the stream with less solids passed through the second bioreactor. In the second step, the objective was to convert the remains to produce biomass. It is worth mentioning that the carbon dioxide from both the reactors was to be collected and sold as a byproduct. The operating conditions for the production of the stillage into ethanol and biomass were as follows: temperature 35°C and air 0.2 vvm. In the second reactor, the dominant reaction was the
conversion of the biomass. Around 5.8 g/L biomass was produced, in addition to the 7g/L carbon dioxide and the 0.7 g/L ethanol [10].

2.1.3 Integration of lignocelluloses (Scenario C)

Wheat bran, the outer layer of the grain, is a lignocellulose used as a substrate for the integration of the first- and second-generation ethanol productions. Table 1 show the composition of lignocelluloses (wheat bran) used in this study. Figure 1 (scenario C) shows the block flow diagram of the integrated process, and Figure 2 shows the process flow diagram for the integrated process, with the first-generation modification from the thin-stillage to ethanol and biomass. The flow rate of the grains was 18.8 t/h; for the base case, the lignocellulose integration of 10 t/h wheat bran was considered. Wheat bran had a particle size of <10 mm; thus, no crushing unit operation was required. The wheat bran had 88% TS, while the pretreatment method required a solid loading of 15% TS; hence, water was added to dilute the solids concentration. A chemical pretreatment method was employed using 1.5% phosphoric acid for a residence time of 10 min at 190°C [29]. It should be noted that the choice of the pretreating acid was dictated by the properties of the feed, as the common sulfuric acid could not be used.

After the pretreatment process, SSF (simultaneous saccharification and fermentation) process was employed to convert the pretreated lignocellulose to ethanol. For the hydrolysis step, cellulase enzyme was added in the concentration of 10 FPU/g. During the hydrolysis process, most of the cellulosic parts of the lignocelluloses had been released and converted into simple sugars such as glucose, arabinose, and xylose. Subsequently, the fermentation process occurred in the same vessel with the addition of fungi at 35°C with a residence time of 48 h, where the ethanol yield was 0.12 g/g dry biomass. Carbon dioxide produced during the fermentation was sold along with...
the carbon dioxide produced from the grains to ethanol process, as a byproduct. All the data for this simulation were based on the laboratory data from a previous work [29].

2.2 Energy and Economics

The energy analysis was conducted using the Aspen Energy Analyzer, while the economical evaluations were carried out using the Aspen Process Economic Analyzer. All the calculations were based on the 2013 first quarter pricing, and the economic assumptions were based on Rajendran et al. [31]. Table 2 shows the economic assumptions carried out in this study. The important parameters including investment, net present value (NPV), cash flow, payback period (PBP), and operational costs were indexed according to Turton et al. [32]. The energy consumption was organized into sections such as liquefaction, fermentation, distillation and dehydration, evaporation and drying, energy for fungi reactor, and lignocellulose processes.

2.3 Sensitivity analysis

For the lignocellulose integration process, a sensitivity analysis was carried out. In the base case, the lignocellulose integrated to the first generation ethanol production was 10 t/h. In the sensitivity analysis, different percentages of lignocellulose integration to the first generation ethanol production were exploited. For this purpose, the intake of the lignocelluloses was altered by 50, 100, and 200%, i.e., 5, 10, and 20 t/h, respectively. This suggests how much lignocelluloses could be integrated in the first generation ethanol production. The profitability indexes such as capital investment, PBP, NPV, and cash flow were analyzed. In addition, the energy consumption was also studied.
3 Results and Discussions

3.1 Thin stillage and stillage modification

Technical analysis

The thin-stillage modification using the fungal bioreactor reduced the overall energy consumption of the process. In the base case, the total energy consumption was 19.4 GW, while by cultivating the thin-stillage with the fungus, the overall energy consumption was reduced to 18.9 GW (Scenario A). This is equivalent to 2.5% energy reduction to the ethanol plant[31].

Figure 3 shows the energy consumption for the different modifications employed in this study. The energy was mainly reduced due to the evaporation costs and subsequent drying operations for the concentrated syrup. About 2% of the TS were reduced using the fungi reactor on the thin-stillage, which had reduced this energy consumption. By employing the fungi on the thin-stillage to produce the ethanol and the biomass, it resulted in 0.2 t/h increase in the ethanol production. In the base case, 41,600 tons of ethanol was produced annually, while employing the thin-stillage for ethanol increased the ethanol production by 4%. For the byproduct (DDGS), the flow rate was increased to 8.6 t/h from 7.7 t/h in the base case, which is 14% higher [31]. This overall efficiency also lifted the economic perspective.

The objective for using the thin-stillage to produce the ethanol and the biomass is that the energy consumption in the evaporator and the drying process is higher in the base case (existing industrial setup) due to the amount of solids entering in[31]. The ultimate goal is to reduce the solids content entering in the evaporation process. A similar study was reported by Arora et al.[11], where the thin-stillage was sent to a multi-stage microfiltration process to remove the solids before entering the evaporator to reduce the energy consumption in the evaporator. This modified process can only reduce the energy consumption and will not yield additional revenue.
in the form of ethanol and products. However, in the current study, the modification through the filamentous fungi resulted in reducing the energy consumption as well as the additional ethanol and byproducts, which improved the overall economics substantially [11].

In contrast, for the whole-stillage to ethanol and biomass process, the energy consumption was higher by 20% than with the thin-stillage modifications. The overall energy consumption for the whole-stillage process was 22.7 GW (Figure 3 Scenario B). The main reason for the increase in the energy consumption was that in the stillage modification, the TS of the stillage was 15%, and after the biomass and ethanol production the solids concentration was still >10%, which shows that the overall TS concentration did not decrease to less than the base case. This resulted in the overall energy increase. Although the ethanol production and biomass was higher, this did not have a positive effect on the economics, which was due to the increase in the energy consumption.

**Economic analysis**

Compared to the existing first generation ethanol productions, which had an investment around 69 million USD, for the thin-stillage (A) modifications, the increase in capital investment was around 1.2 million USD, while the NPV was increased by 31 million USD. Comparing this data to a similar study which explored the possibility of recycling DDGS after pretreatment and hydrolysis with corn for a fermentation to additional ethanol production resulted in 32% additional NPV. This thin-stillage modification to ethanol and DDGS resulted in an increased NPV to 40%, which is 8% higher than the study reported by Perkiset. al [14].

In contrast, for the whole-stillage modification process, the investment was higher than the thin-stillage modification, while the NPV was less than the existing industrial setup. Figure 4 shows
the different economic evaluations for the modifications considered in this study, and Figure 5 shows the cash flow diagram over the years. The PBP for the thin-stillage and the stillage modifications was 11.5 years and 14 years, respectively. It is noteworthy that in the base case, the PBP was 13 years. This shows that a thin-stillage retrofit improves the overall economics of the process. The thin-stillage modification was energy efficient, high product yielding, and an economically attractive process, suggesting an improved scenario for the first generation ethanol production.

3.2 Integration of lignocelluloses

Thin-stillage modification had better energy and economic consequences, compared to the whole-stillage modification. Therefore, the integration of the lignocelluloses, i.e., wheat bran using phosphoric acid pretreatment, was examined on the optimized thin-stillage modification process. Lignocelluloses with a flow rate of 10 t/h were integrated to the thin-stillage modified first generation ethanol processes. The lignocelluloses integration processes consumed 33% of the total energy, which was 63.4 GW (Figure 3, Scenario C). From 10 t/h wheat bran, 2.1 t/h ethanol was obtained in addition to the ethanol from the first generation and the thin-stillage modification.

The capital investment for the integrated lignocellulose process was 77 million USD, while the NPV was 162 million USD (Figures 4&5). The cost of the additional investment from the thin-stillage modification was 6.8 million USD, while the investments could be recovered in 10.5 years, which was one year less than the optimum thin-stillage processes. Most of the ethanol industries are finding it difficult to employ a complete new process for the lignocellulose based
ethanol production, as the total investment is extremely high. However, by integrating the first-
and second-generation ethanol production, the investment could be greatly reduced; however, the
economic returns could be high for a short period of time.

In another study[33], it was reported that to produce 207,000 tons ethanol/year, the capital
investment was 220.1 million USD, using corn stover as a lignocellulosic material by
employing dilute sulfuric acid pretreatment. The capital investment to produce one ton of ethanol
was 106 USD, while a similar calculation to the integrated process using bran and phosphoric
acid pretreatment resulted in 130 USD. This cost was calculated only in comparison to ethanol,
and the revenue from the byproducts was not accounted for, which would have reduced the
overall production cost. The cost was 22% higher in the current study; however, it is worth
mentioning that it also included the integrated first generation and second generation process,
which could yield a higher NPV from a long-term perspective.

3.3 Sensitivity analysis

A sensitivity analysis was carried on the different percentages of lignocellulose integration to the
first generation ethanol production. The percentages of lignocellulose integration were altered
between 50% – 200% for scenario C. The sensitivity analysis revealed the impact of integrating a
greater amount of lignocelluloses to the existing ethanol production facility. In the base case, 10
t/h lignocelluloses were integrated to the modified first generation ethanol production. The
different techno-economic parameters such as capital investment, PBP, operating cost, and
product sales were estimated for the different sensitivities. Figure 6 shows the cash flow diagram
and different economical evaluations considered for the sensitivity analysis. The results showed
that there was no significant difference between the payback for the sensitivities, as the payback for all the scenarios were between 10.2 – 10.7 years.

The capital investment for the different sensitivities 50%, 100%, and 200% lignocellulose integration to the first generation ethanol production was 73, 77, and 82 million USD, respectively. The cumulative cash position was the ratio between the net present value and the capital investment, where a higher CCP suggests higher economic returns. For the lignocellulose integration sensitivities, the CCP was the highest for 100% lignocellulose integration, which was 2.41, suggesting that the process was viable for the ethanol plants operating on starch and carbohydrate based raw materials to shift toward lignocellulosic based raw materials with a lower investment and higher returns.

4 Conclusion

Utilizing fungi on thin-stillage and whole-stillage to produce ethanol and biomass was exploited in the first generation ethanol production from grains. The thin-stillage to ethanol and biomass was energy and economically efficient, returning a NPV of 108 million USD after 20 years of operation. This efficient thin-stillage modified first generation process was integrated with lignocellulosic ethanol production with phosphoric acid pretreatment. The results showed that the integration process increased the investment by 6.8 million USD, while the NPV was increased to 53 million USD. The energy consumption for the lignocellulose-integrated processes was 63 GW, while it was 18.9 GW for the thin-stillage modified first generation process. About 33% of the energy consumption in the integrated process was utilized for the lignocellulosic ethanol production.
Acknowledgements

The authors would like to thank the Swedish Energy Agency for providing the financial support and LantmännenAgroetanol for providing the data. The authors would also like to thank Jorge Ferreira and Ramkumar Nair for providing adequate discussions on the laboratory data.
List of figures

Figure 1. Block flow diagram of different scenarios studied, including modifications using filamentous fungi in the thin-stillage (A) and the whole-stillage (B) for the grains ethanol production. The integrated processes using lignocelluloses to thin-stillage modified grains ethanol production is marked as (C).

Figure 2. Process flow diagram of the integrated lignocellulose to the thin-stillage modified first ethanol production (Scenario C). The modified unit operations from the base case are highlighted.

Figure 3. Section-wise energy consumption for the different scenarios in comparison with the existing industrial setup.

Figure 4. Economic evaluations for the different scenarios.

Figure 5. Cash flow diagram for the different scenarios.

Figure 6. Cash flow diagram and economic indexes for the sensitivity analysis.
Table 1. Composition of wheat bran used in this study

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<td>Starch</td>
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Table 2. Economic indicators used in this study

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Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
Figure 6.
Graphical Abstract
5 References


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