University of
South-Eastern Norway

www.usn.no

FMH606 Master's Thesis 201

Techno-Economic Evaluation of Sludge Valorization in Kathmandu Valley

Ayush Nath Ghimire

Faculty of Technology, Natural sciences and Maritime Sciences
Campus Porsgrunn

University of South-Eastern Norway

www.usn.no

Course: FMH606 Master's Thesis, 201

Title: Techno Economic Evaluation of Sludge Valorization in Kathmandu Valley

Number of pages: 53

Keywords: Anaerobic Digestion, BioCNG, Circular Economy, Kathmandu Valley, Mass Balance, Organic Manure, Sewage Sludge, Wastewater

Student: Ayush Nath Ghimire

Supervisor: Eshetu Janka Wakjera, Sunil Prasad Lohani

External partner: Kathmandu University

University of South-Eastern Norway

www.usn.no

Summary:

The Bagmati River, revered as the cradle of the Kathmandu Valley civilization, holds profound cultural and religious significance. The rapid and unregulated urban expansion, coupled with the absence of adequate sewage collection systems and wastewater treatment plants (WWTPs), has transformed the river and its tributaries into conduits for sewage.

Anaerobic digestion (AD) accepted globally as a prominent stabilization method, offering resource recovery opportunities to enhance the financial viability of WWTPs. Nevertheless, a critical data gap exists in wastewater management within the Kathmandu Valley. This thesis addresses this gap by evaluating household wastewater generation from 2024 to 2044, considering parameters such as population, per capita water consumption, and sewer network coverage.

Additionally, a comprehensive plant-wide mass balance was conducted on a reference Activated Sludge Process WWTP to establish benchmark values, including per million liters per day (MLD) sludge generation, per MLD methane production, and per MLD organic manure production. Subsequently, an overall estimation of BioCNG and organic manure was derived based on wastewater generation data and mass balance benchmark values.

The study reveals that 299 MLD of wastewater will be generated in the Kathmandu Valley in 2024, increasing to 551 MLD by 2044. BioCNG potential for 2024 is estimated at 5701 kg per day, sufficient to fuel 73 public buses daily in Kathmandu Valley. The generated organic manure amounts to 61 metric tons, equivalent to 5% of the daily fertilizer import.

Furthermore, a financial analysis was conducted on an 80-tonnes-per-day AD plant processing sewage sludge. The results indicate a Net Present Value (NPV) of Rs 240,416,222, an Internal Rate of Return (IRR) of 6.2%, and a Payback Period (PBP) of 8 years.

This thesis establishes a technical and economic foundation supporting the integration and promotion of WWTPs coupled with AD plants in the Kathmandu Valley. This approach serves as an environmentally sustainable solution to preserve the Bagmati River basin and create a viable market for AD in the country.

Preface

This thesis, entitled "Techno-Economic Evaluation of Sludge Valorization in Kathmandu Valley," was conducted in the autumn of 2023 to fulfill the master's exchange program requirement of the Energy and Environment Technology department at the University of South-Eastern Norway. The exchange program is funded by the NORPART Re-Tech Project.

Wastewater Management remains a pressing issue in Kathmandu Valley, with its negative effects felt and observed by residents daily. Although the solution appears straightforward – treating all wastewater before disposal – the reality is different. The problem seems to exacerbate with the increasing population in the valley. This thesis seeks to provide a financially feasible solution to this persistent problem. If there is potential for economic gain in managing waste, it transforms from mere waste into a valuable resource that everyone would want to utilize.

The journey with this thesis has been a captivating learning experience. It marks my first engagement with a real-life problem. The challenges in collecting data and information in a country like Nepal, where most government documents are still paper-based, were substantial.

Researching the problems in Kathmandu from Norway posed a unique set of challenges. Without the unwavering support of my father, Mr. Ashish Ghimire, a wastewater engineer himself, I would not have successfully completed the thesis as planned.

I extend my gratitude to Eshetu Janka Wakjera, my supervisor here at USN, crediting him for the thesis you are currently reading. Eshetu has not only supported me academically but has also been a great moral support. His relentless encouragement and positivity have given both me and this thesis meaning and purpose.

Special thanks to the coordinator of the NORTPART project, Professor Britt Margethe Moldestad, for providing us with the invaluable opportunity to conduct our thesis here at USN. I would also like to express my appreciation to Dr. Sunil Prasad Lohani for believing in me and recommending my name for the exchange program. I acknowledge the guidance and support provided by both Britt and Sunil throughout the duration of the exchange.

Lastly, I want to express my gratitude to my friends here in Porsgrunn – Tamman, Ashish, Rajani, Sujesh, Niroj, Subham, Inigo, and Thomas – for making my time in Porsgrunn memorable. Their presence provided the energy needed to dedicate hours to this thesis.

To my family, whose unwavering support has been instrumental, I am forever grateful. Thank you to everyone for their love and encouragement.

I belive I have established a scientific ground to adress the problem of wastewater and sludge management in Kathmandu Valley. The findings of this thesis would support policy makers planners to acknoweldge sewage sluge as a valuable resource.

Porsgrunn, 26/01/2024

Ayush Nath Ghimire

Contents

Figures

Tables

Nomenclature

AD	Anaerobic Digestion
ASP	Activated Sludge Process
BioCNG	Bio Compressed Natural Gas
BOD	Biochemical Oxygen Demand
BRBIP	Bagmati River Basin Improvement Project
COD	Chemical Oxygen Demand
d	Day
DS	Dry Solids
g	gram
GWWTP	Guheshwori Wastewater Treatment Plant
HPCIDBC	High Powered Committee for Integrated Development of Bagmati Civilization
IRR	Internal Rate of Return
KVMP	Kathmandu Valley Wastewater Management Project
Kg	Kilogram
KUKL	Kathmandu Upataptyaka Khanepani Limited
L	liter
LPCD	Liter Per Capita Per Day
m^3	Meter Cube
mg	milli gram
ml	milli liter
MJ	Mega Joule
MLD	Million Liters Per Day
MLY	Million Liters Per Year
MWSP	Melamchi Water Supply Project
Mt	Metric Ton
Nm^3	Newton Meter Cube
O&M	Operation and Maintenance
NPV	Net Present Value
PBP	Pay Back Period
Rs	Nepali Rupees
TDS	Total Dissolved Solids

TPD	Ton Per Day
TS	Total Solids
TSS	Total Suspended Solids
VFA	Volatile Fatty Acid
VS	Volatile Solids
VSS	Volatile Suspended Solids
WUSC	Water Users and Sanitation Committee
WWTP	Wastewater Treatment Plant
WW	Wastewater
Yr	Year

1 Introduction

The Bagmati river is the cradle of the Kathmandu Valley civilization holding immense cultural and religious significance. It is revered as a holy river and is adorned with many cremation ghats and temples along its bank. However, the rapid and unplanned expansion of settlements in the valley have exerted tremendous pressure on the water resources of the Bagmati River Basin.

Due to the absence of appropriate sewage collection and wastewater treatment plants, the river and its tributaries have turned into sewage collector drains. To reverse this situation, it is essential that all the wastewater generated within the Valley undergoes treatment before disposal. While waste water treatment plants effectively address the water pollution problem, they give rise to a new challenge in the form of solid waste management, particularly dealing with sludge generated during the treatment process.

Historically, most of the solid waste generated in the valley has been dumped in a site located 60 km northwest of the valley. Recent attempts to establish a sanitary landfill site, however, have faced local opposition, leading to situations where trucks were barred from accessing the landfill, leaving waste uncollected for up to 30 days. To mitigate the impact of such issues, it is necessary to implement measures for waste reduction, reuse, and recycling.

The government has uninitiated the Bagmati River Improvement Project to clean the Bagmati river and its tributaries. This project is expected to produce a significant quantity of sewage sludge daily from wastewater treatment plants. Traditional management of sewage sludge would exacerbate the already fragile solid waste management situation in the valley.

Wastewater sludge presents itself as an abundant and sustainable resource, offering potential applications in bioenergy. While Nepal heavily relies on importing petroleum products and fertilizers to meet its demands, annual supply chain issues consistently result in shortages of chemical fertilizers. Transforming sludge into methane-rich biogas and nutrient-rich organic fertilizers could offer a promising solution to this recurring problem, addressing both energy needs and environmental concerns.

Beyond alleviating the shortage of chemical fertilizers, organic fertilizers produced from sludge can contribute to soil conditioning. Sludge isn't solely a byproduct of centralized wastewater plants; it is also generated wherever onsite sanitation practices are in place. Redirecting this abundant resource toward recovery initiatives could unlock new opportunities for Nepal.

Currently, Kathmandu stands as the only city in Nepal with some degree of sewage coverage. Small-scale enterprises can potentially establish successful business models by collecting onsite sanitation sludge and utilizing it to operate central biogas plants. This decentralized approach not only addresses the challenges posed by sludge but also creates a domestic market for manufacturing, servicing, and managing biogas plants. By tapping into the potential of wastewater sludge, Nepal can not only enhance its resource efficiency but also foster sustainable practices that benefit both the environment and the economy.

Globally, anaerobic digestion has been used for sewage sludge, providing, energy recovery and volumetric reduction. This proven technology is deemed suitable for the Kathmandu Valley.

1.1 Contribution

This thesis aims to estimate the annual yield of methane and organic manure through the anaerobic digestion of sewage sludge. Additionally, it aims to establish a credible measure of financial feasibility for the project, whether undertaken by the government or any interested private institutions.

The thesis takes into account factors that directly impact the amount of waste water collected, such as population changes, improvements in wastewater infrastructure, and changes in per capita water consumption. These factors, in turn, impact the amount of sludge generated. To establish benchmark values, a mass balance has been computed for a functional wastewater treatment plant in the valley. The financial analysis is based on a reference model created for a functional biogas plant situated in Western Nepal.

1.2 Outcomes

The thesis will deliver the following outcomes.

1.2.1 Sludge Produced

The sludge originating from the Primary Sedimentation tank is referred to as primary sludge, while the sludge wasted from the biological treatment unit is known as secondary sludge or waste activated sludge. The combination of both these sludge categories is collectively termed sewage sludge, which is produced in a wastewater treatment plant.

1.2.2 BioCNG Produced

The sludge produced in a wastewater treatment plant is utilized as a substrate to operate an anaerobic digestion plant. This plant generates biogas as its primary product and digested solids as a byproduct. The produced biogas undergoes treatment and upgrading to yield a methane-rich gas known as BioCNG.

1.2.3 Organic Manure Produced

The residual digested solids from the anaerobic digestion plant undergo a dewatering process to achieve a total solids (TS) content of 24.2%. Subsequently, the biosolids undergo manual drying and processing to attain a TS level of 70%. This nutrient-rich substance is then classified as organic manure.

1.2.4 Waste Water Generated

The majority of water consumed by an individual is converted into wastewater. The total wastewater generated in the Kathmandu Valley is directly influenced by both the population of the valley and per capita water consumption.

1.2.5 Waste Water Collected

The wastewater generated needs to be collected and transported to a treatment plant for processing. The collection process relies on the coverage of the sewage network in the Kathmandu Valley.

1.2.6 Profit and Loss Statement for Anaerobic Digestor Plant

The Profit and Loss Statement provides an annual snapshot of the plant's financial status. It encompasses all expenses and revenue incurred from the construction to the operation of the plant.

1.2.7 Cash Flow for Anaerobic Digestor Plant

The cash flow statement illustrates the status of cash flow in the plant at the end of each year. It comprehensively accounts for all parameters related to cash inflow and outflow from the plant.

1.2.8 Financial Indicators for Anaerobic Digestor Plant

The Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP) provide an overview of the financial performance of the plant. These indicators are essential for determining whether the plant can attract investment from the private sector as well.

1.3 Outline

Section 1 contains the Introduction to the thesis. The contribution and outcomes of the thesis are also included in this section.

Section 0 contains Background information related to status of water supply and sanitation in Kathmandu Valley. The section also contains literature related to Anaerobic Digestion of sewage sludge. At the end of the section, a brief introduction for reference plants considered in the thesis is given.

Section 3 contains the detailed methodology adopted in this thesis.

Section 0 contains the Result section

Section 5 contains the Discussion section

Section 6 contains the Conclusion

2 Background

2.1 Study Area

Nepal is a small landlocked country in the Indian Subcontinent, bordered by China to the north and India to the east, south, and west. It is classified as one of the 48 least developed countries globally.[1]Nepal's current Gross Domestic Product (GDP) is $41.31 billion, with a GDP per capita of $1,350. About 28.6% of the population still experiences multidimensional poverty.[2]

Kathmandu Valley, as the name suggests, is a valley surrounded by hills in the central part of Nepal. It comprises the capital city of Kathmandu, along with Lalitpur and Bhaktapur metropolitan areas and other small towns and hill settlements.[3] The valley is primarily drained by the Bagmati River, originating in the Shivpuri National Park. All other rivers flowing in the valley are tributaries to the Bagmati River.[4]

Kathmandu Valley serves as a center for trade, commerce, education, and transportation. It also hosts the government, leading to significant migration, causing the population to increase at an alarming rate of 2.15% per annum.[5] The population of Kathmandu Valley was 1,557,831 in 2001, 2,383,698 in 2011, and reached 3,025,586 in 2021.[6]The population has doubled in 20 years. For a sprawling urban center, providing basic infrastructure such as safe drinking water, proper sanitation, reliable power supply, a smooth transportation system, efficient administration, clean air, open spaces, and affordable housing is essential for ensuring a happy and healthy living condition for its residents.[7]However, in the case of Kathmandu Valley, the boom in population has outpaced the rate of infrastructure development.

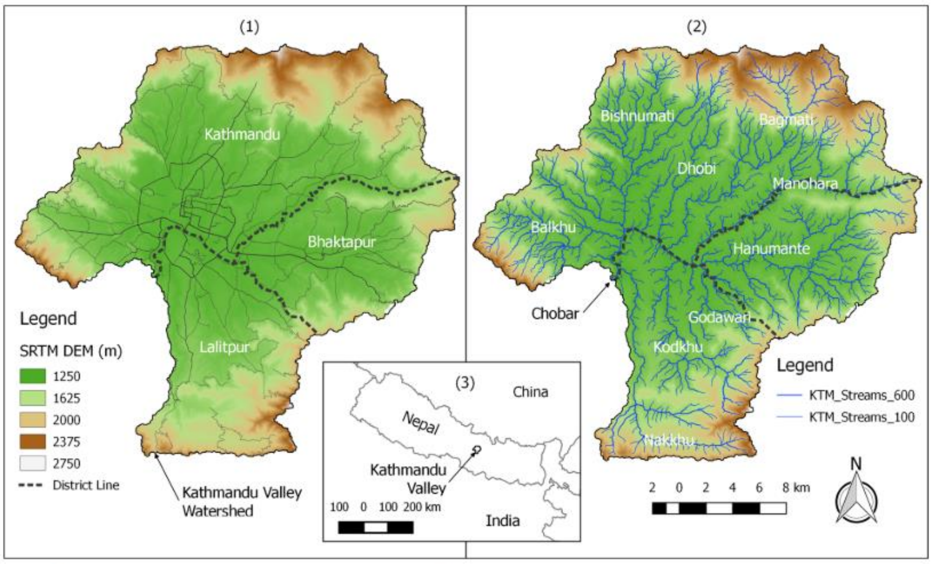

Figure 1: Kathmandu Valley watershed with roads, district boundary [7]

With the increasing population, the demand for water has risen significantly. The government has struggled to match the water demand in the valley, forcing residents to manage their household water supply through exploiting groundwater, purchasing from private vendors, or using bottled water for drinking.[8] Wastewater, a byproduct of using fresh water, poses severe challenges in the valley. Currently, only 4% of the total domestic wastewater generated is treated, while the rest is disposed of directly into the rivers and streams flowing through the valley. The current condition of these rivers and streams resembles open sewers, posing hazards to public health, the ecosystem, aquatic life, and the overall appearance of the valley.[9]

2.2 Status of Water Supply and Sanitation in Kathmandu Valley

2.2.1 Supply, Demand and Use of Domestic Water

The World Health Organization defines "domestic water" as water used for all domestic purposes including consumption bathing and food preparation. The quantity of consumption of domestic water is one of the important indirect parameters in economic development. [10]

The population of Kathmandu Valley was 3,025,586 in 2021, with a total of 793,737 households. Out of this number only 46% of the households, i.e., 364,657 of the households used piped drinking water.[6] Kathmandu Upataptyaka Khanepani Limited (KUKL) is the primary body responsible for the operation and management of water supply and wastewater services in the valley. KUKL supplies water to almost 2.56 million people in the valley. The daily average water supply is 57 liters per capita. The water sources used are both surface and ground water.[11]

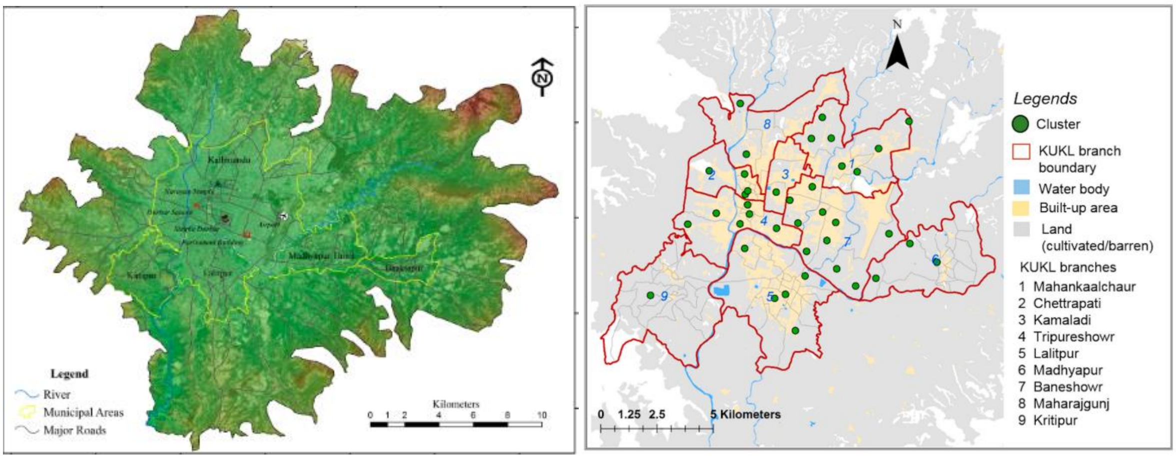

Figure 2: Kathmandu Valley with roads, settlements and KUKL branch boundary [6], [11]

Likewise, the community-level Water Users and Sanitation Committee (WUSC) manages small-scale water supply projects in areas where KUKL does not provide water. The Kathmandu Valley is home to 147 WUSCs, with an estimated 510 thousand people in total requiring water supply. The average daily amount of water supplied is estimated to be around 50 LCPD.[11]

There have been researches carried out to calculate the actual consumption of domestic water in the valley. The water used is an important parameter to estimate the waste water generated and to identify alternatives sources used by households to cope with the supply deficit. According to [10] the water consumption is 117 LPCD, and households are using multiple sources such as private wells, stone sprout, spring water, water tankers, bore wells, 20L water jar and rainwater as an alternative to the utility.

The current supply of water in the valley is significantly lower than the demand. Ideally, when assuming 135 liters per capita per day (LPCD), the demand is approximately 409 million Liters per day (MLD). [12]

The Melamchi Water Supply Project (MWSP), initiated in 1988, aims to provide sustainable water supply for Kathmandu Valley, addressing the rising demand due to population growth. The project, divided into two phases, targets supplying 170 MLD (phase 1) and an additional 340 MLD (phase 2) through the bulk distribution system, with an upgraded water treatment plant complemented by adequate wastewater treatment plant and sewage coverage. Despite the planned completion by 2006 (phase 1) and 2018 (phase 2), neither phase is fully operational. The first phase is expected to be fully operational by early 2024 and the second phase is expected to operational by 2034. The project's objective is to enhance the quality of life by ensuring a consistent supply of clean water, efficient distribution, and managing sewer systems.

2.2.2 Status of Wastewater Generation and Management

Approximately 70% of the households in Kathmandu Valley have a flushed toilet connected to the public sewerage. Remaining 30% use on site sanitation such as septic tank and pit latrine. [6] Kathmandu Valley has only one operational waste water treatment facility with a capacity of 32.4 MLD.

S. N	Treatment Plants	Plant Capacity in MLD			
		Completed 2023	Under Construction	Proposed Additional Capacity of the Plant (2050)	Total Planned Capacity (2050)
1	Guheshwori WWTP	32.4	-	16.2	48.6
2	Gokarna DEWATS	-	3	3	6
3	Sallaghari DEWATS	-	14.2	-	14.2
4	Hanumanghat DEWATS	-	1	-	1
5	Kodku WWTP	-	17.5	17.5	35
6	Dhobighat WWTP	-	74	286.6	360.6
7	Tukucha WWTP	-	17.2	-	17.2
8	Nakhu WWTP	-	-	17	17
Total		32.4	126.9	340.3	**499.6**

Table 1: Status of WWTPs in Kathmandu Valley

The estimated waste water generated taking in account 80% of the water consumption value given by [10] is 283 MLD. Only 70% of this is connected to public sewage, which is 198 MLD. Kathmandu has an existing WWTP of 32.4 MLD capacity. Only 16.3% of the sewered waste water is treated, remaining is dumped into the rivers and streams of Kathmandu valley without any treatment.

On-site sanitation treats about 30% of wastewater that is not connected to the sewage system. Private companies use vacuum cars to collect sludge from on-site sanitation and then dispose of it into rivers untreated. As a result, the on-site sanitation system's sludge treatment situation is inadequate. Since there is no system in place for business licenses or contracts with local municipalities regarding the collection of sludge by private companies, these businesses are not well managed.[11]

Kathmandu Valley Wastewater Management Project (KVMP) was initiated in 2013 with the objective of discharging only treated water to the Bagmati river. The scope of the project includes rehabilitation and construction of five WWTPs and two decentralized waste water treatment plants. To realize the scope, the project is also working extensively on constructing intercepting sewers and rehabilitating old ones in the valley. [8]

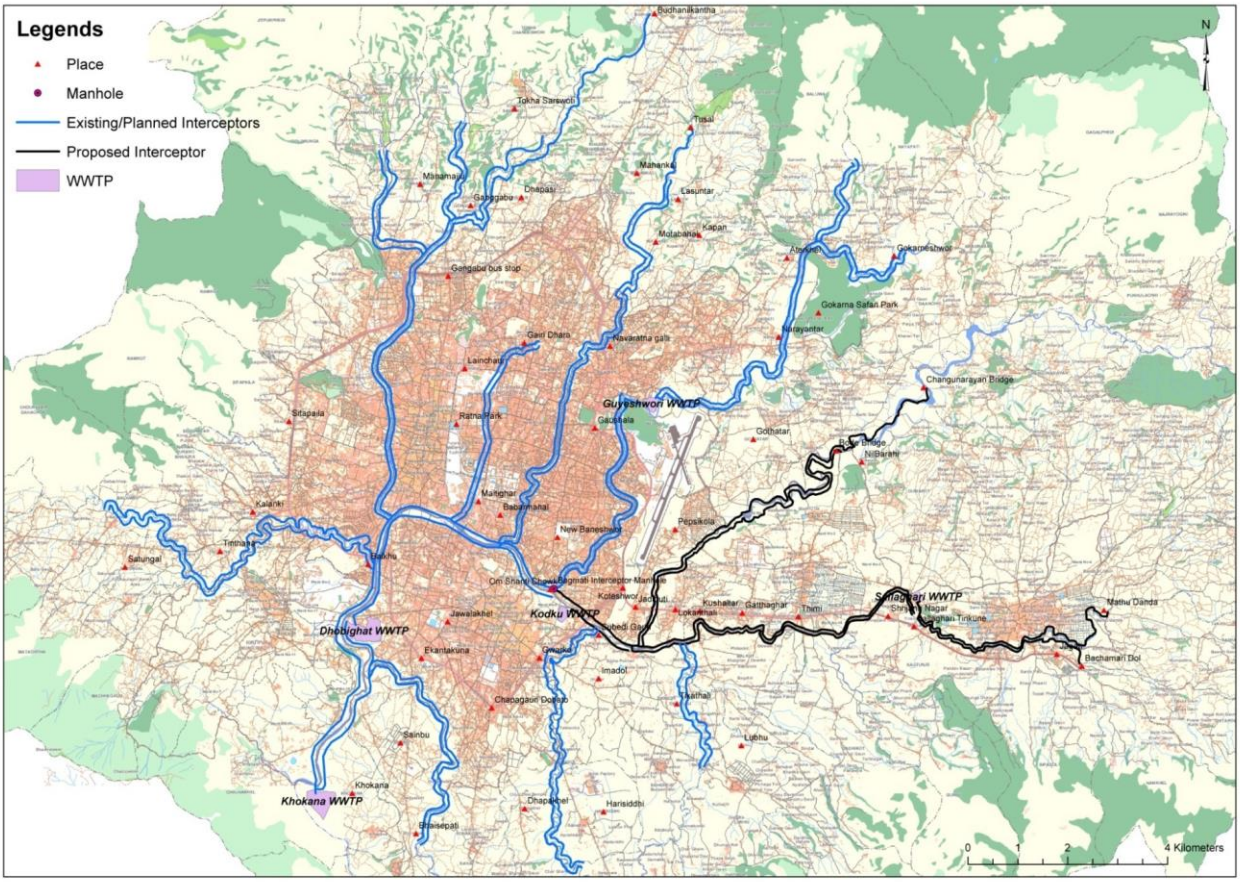

Figure 3: Location of Components of KVWMP

2.3 Sewage Sludge Management

Sewage Sludge is a biomass produced as a byproduct during waste water treatment. The production of sewage has increased and will increase further with more efficient wastewater treatment. Treatment and disposal of sewage sludge accounts for 50-60% of the total plant operating costs. [13]

In developed parts of the world such as Europe, North America and Japan, the generated sludge is incinerated, used as a raw material for producing biogas, reused in the agricultural lands, used as filler materials in road construction and building material production such as cement and also some fraction of the sludge has been landfilled.

Incineration produces heat and energy, and a great volumetric reduction can be achieved. Use of this technology has greatly reduced landfill pressure. In Japan, many cities rely on incineration to deal with sewage sludge. [14]

In Europe with strict regulation, land application of sludge is limited due to the presence of contaminants such as heavy metals. Thus, landfilling of sludge will gradually decrease and adoption of Anaerobic Digestion, Incineration, Gasification, Hydrothermal Carbonization etc. will significantly increase. [15]

Similarly, in developing countries, sewage sludge has historically been either used as a compost or has been landfilled. Countries are adopting proven technologies such as incineration and Anaerobic Digestion. [16] In Oman most of the sewage sludge is used as compost.[17] In Nigeria most Waste Water Treatment Plants have sludge drying beds for the drying of sludge, where some of it used as manure. Other forms of management practices include burial in covered and open pits, landfilling and discharge into water bodies.[18] In India only 35% of the sewage sludge is treated and rest is disposed in dumpsites. Some plants have anerobic digestors for sludge, however most of them flare the biogas produced. [16]

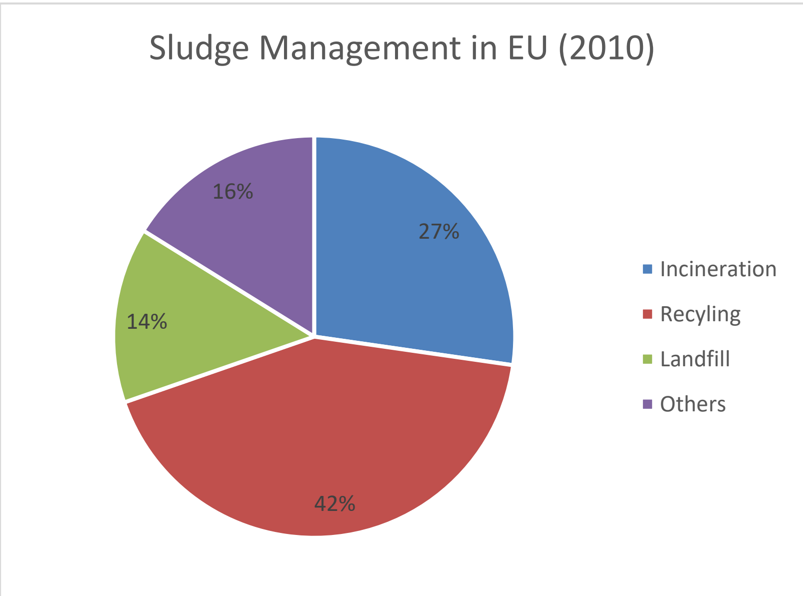

Figure 4: Sludge Management in EU for the year 2010.[13]

The sludge generated from WWTPs in Kathmandu is disposed in a landfill site. For the 30% of the households having on site sanitation system, sludge from their homes is collected by private contractors and disposed openly without any treatment.

In Pokhara and Hetauda the sludge collected from households are stabilized in a sludge bed before disposal. In remaining urban areas, the sludge is either dumped into an open area or into the rivers without treatment. Overall, it can be seen that there has been no management of sludge, it has only been regarded as a waste and disposed without any stabilization, causing harm to the environment.

However, new Wastewater Treatment Plants under construction in Kathmandu Valley have addressed sludge management by incorporating a combined heat and power anerobic digestor plant. The biogas generated will used to power steam engines which will produce heat and electricity. The heat will be used to regulate the heat in the digestors whereas the electricity will be used to power the treatment plant. [19]

2.4 Anaerobic Digestion of Sewage Sludge

Anerobic sewage sludge digestion is thought to be a crucial component of a contemporary WWTP and enhances WWTP. These four processes—hydrolysis, acidogenesis, acetogenesis and methanogenesis—are what organic materials go through during AD. Both high molecular weight compounds and insoluble organic materials are broken down into soluble organic substances during the hydrolysis stage. A further breakdown of the components created during hydrolysis results in the formation of volatile fatty acids, ammonia, carbon dioxide, hydrogen sulfide, and other byproducts during acidogenesis. The process that is thought to be rate-limiting is hydrolysis. The third stage, called acetogenesis, primarily produces acetic acid from the acids and alcohol along with hydrogen and carbon iodide. The final stage involves the dissolution of acetic acid into methane while hydrogen and carbon dioxide react concurrently to produce methane**.**[20]

Various parameters impact the rates of distinct steps in the digestion process, primarily encompassing pH, alkalinity, temperature, and retention time. An optimal pH range of 6.5 to 7.2 is imperative. Within the digestor, it is crucial to uphold a stable temperature, as deviations of 1°C per day pose a risk of disrupting the digestion process. A substantial solids retention time is necessary to sustain the bacterial population within the reactor.[20]

The biogas produced comprises C_O2, H_2S, CH_4, and water vapor. To procure a methane-rich gas, it is essential to eliminate all impurities from the biogas.[21], [22]

2.5 Reference Plants

In this thesis, technical and economic evaluation have been done based on data obtained from real plants. For the purpose of Mass Balance calculations, the Guheshwori Wastewater Treatment Plant has been taken as reference. The financial Analysis for Anaerobic Digestion of Sewage Sludge has been prepared based on a modified commercial plan of Gandaki Urja Waste to Energy Plant.

2.5.1 Guheshwori Wastewater Treatment Plant

The Guheshwori WWTP was constructed in 2002 to treat an average flow of 16.2 MLD and later upgraded in 2019 to treat an average flow of 32.4 MLD. It is at present operated and maintained by the High Powered Committee for Integrated Development of Bagmati Civilization (HPCIDBC).

The major pollutants in the wastewater are BOD and suspended solids. The treatment scheme provided is of four stage treatment comprising Pre-treatment, Primary clarification and Secondary (biological) treatment and tertiary treatment for the disposal of treated effluent to the stipulated Treated Effluent Characteristics. The sludge produced from primary and secondary treatment is thickened anddigested in anaerobic digesters. Biogas produced from anaerobic digester is used for power generation and power is utilized for running the plant equipments. The Plant Layout and the treatment process can be found in Annex X.

2.5.2 Gandaki Urja W2E plant

The 45TPD Compressed Biogas Bottling Plant is being operate under the ownership of Gandaki Urja Pvt. Ltd. The large biogas plant uses cattle manure, poultry litter and vegetable waste sourced from nearby livestock farms and vegetable markets and produces Bio-CNG and organic fertilizers as valued commercial products.

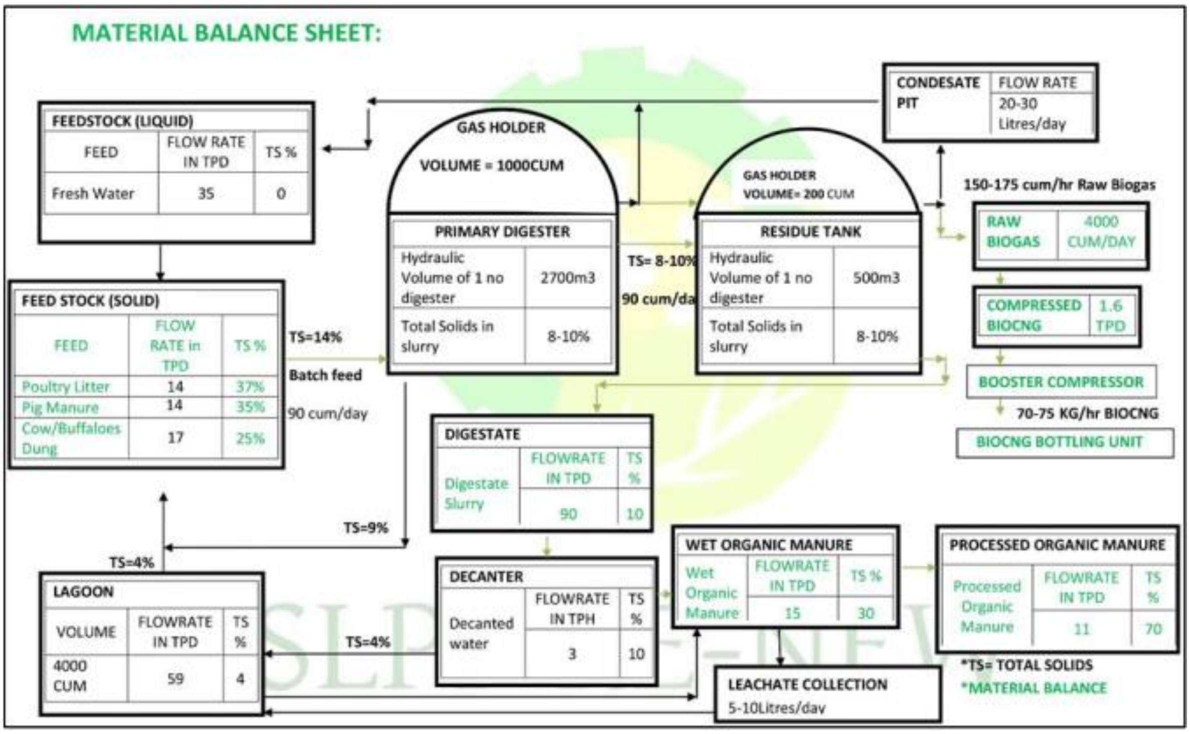

Figure 5: Material Balance Sheet for Gandaki Urja

The biogas plant shall uses a continuous stirred tank reactor (CSTR) type mesophilic digester with a double membrane roof. After generation of biogas in the digester, the raw biogas undergoes membrane based purification and upgradation to produce enriched biogas of 90%

and above methane gas concentration. After upgradation, the enriched biogas is compressed using a suitable compressor and bottled at 200bar pressure. This compressed biogas (CBG) is then distributed to the market as valued substitute of Liquid Petroleum Gas (LPG). In addition, the plant shall make use of the digested slurry to produce organic fertilizer by employing a solid liquid separator unit.

3 Methodology

To deliver the Outcomes mentioned in Section 1.2, certain methodologies have been identified, which are discussed below.

3.1 Mass Balances

To obtain the required values for Outcome 1,2 and 3 a plant-wide mass balance calculation is required. Guheshwori Wastewater Treatment Plant in Kathmandu is taken as the reference plant. For the computation of the mass balance calculations, values for parameters have been taken from the reference plant and some values have been taken from Metcalf & Eddy as shown in **Error! Reference source not found.**.

The treatment process is explained in Annex X. The mass flow has been computed in terms of Flowrate, TSS and BOD. The Mass balance calculation is based on iterations.

The first iteration begins with just average flow data and does not consider any return flows. The second iteration also considers the return flow calculated at the end of first iteration. For third iteration the return flow value computed in the second iteration is used. The obtained new return flow values are compared with that of the second iteration. If the difference in values is less than 1%, the calculations are stopped and the third iteration is regarded as the steady state condition and values from the iteration are taken for further calculation. If not, subsequent iterations are performed until the difference in values are less than 1%. The last iteration is considered as the steady state condition and values are taken from this iteration for further calculation. Some calculations have been performed for the mass balance, and are given below. The values and the detail calculations for the entire mass balance is given in Annex I.

3.1.1 Soluble BOD (sBOD)

BOD_e = sBOD + $(\frac{g\ BOD}{gUBOD})(\frac{g\ UBOD}{gVSS})(\frac{g\ VSS}{gTSS})$ (TSS_e,mg/L)

Where, BODe is the BOD of the effluent, TSS_e is the TSS of the effluent, $\frac{g\ BOD}{gUBOD}$ is the ratio of BOD and UBOD, $\frac{g\ BOD}{gUBOD}$ is the ration between BOD and VSS and $\frac{g\ VSS}{gTSS}$ is the ratio given for the biodegradability of the sample. All these rations are a constant value based on the wastewater characteristics. For the purpose of this study, these values have been assumed.

3.1.2 MLVSS (X) concentration in Aeration Tank

MLVSS, $X = \left(\frac{(Q)(Y)(So-S)(SRT)}{[1+b(SRT)](V_r)}\right)$

Where, Q is the flowrate, Y is the yield Co-efficient, S_o is the influent BOD, S is the effluent BOD, SRT is the Solid Retention Time, B is the delay co-efficient, and V_r is the Volume of the aeration tank.

Parameters taken as Reference	
Parameters taken from GWWTP	Parameters taken From Metcalf & Eddy
Annual average flowrate	(VSSC/TSSC) ratio in influent
Influent characteristics	The mixed-liquor VSS_C/ TSS_C ratio
TSS removed in grit	(VSS_C/ TSS_C) ratio going to secondary treatment
Volatile fraction of grit	Yeld Cofficient for Aeration Tank
Specific Gravity of Grit	Decay Co-efficient for Aeration Tank
Solids Concentration in Grit	Aeration tank volume
BOD removal in Primary Sedimentation	Solids Retention Time for Aeration Tank
TSS removal in Primary Sedimentation	Special Gravity of Solids
Concentration of primary sludge	Biodegradability of biological solids
(Solids Capture in Gravity Thickener)	Ratio of (BOD_c/UBOD)
Concentration of Thickened sludge	Ratio of (UBOD/VSS)
MLSS in Return Activated Sludge=	Yield Coefficient for Digestor
Solids capture in the flotation thickeners	Endogenous coefficient for Digestor
Concentration of thickened WAS	BOD_C in digester supernatant
Secondary Clarifier Outlet characteristics	TSS_C of Supernatant
Effluent characteristics	Centrate BOD_C
Solids Rentention Rate in Digestor	Density of Water
Volatile Solids Reduction	
Total suspended solids in digested sludge	
BODC in digester supernatant	
TSSC in digested sludge	
Sludge cake	
Specific gravity of sludge	
Solids capture in centrifuge	

Table 2:List of Reference Parameters

3.1.3 Observed Yield (Y_o)

$$Y_o = \frac{Y}{1+b(SRT)}$$

Where, Y_o is the observed yield, which is computed on the basis of theoritical yield, decay co-efficient and solid retention time.

3.1.4 Net activated Sludge Produced ($P_{x,VSS}$)

$$P_{x,\,VSS} = Yo(Q)(So - S)\left(\frac{1kg}{10^3 g}\right)$$

Where, $P_{x,\,VSS}$ is the amount of sludge wasted each day from the aeration tank.

3.1.5 Net Mass of Cell Tissue produced per day (P_X)

$$P_X = \left(\frac{(Q)(Y)(So-S)}{1+b(SRT)}\right)\left(\frac{1kg}{10^3 g}\right)$$

Where, Y is the yield co-efficient for digestor, Q is the flow entering the digestor, So is the concentration of BOD entering the digestor and S is the concentration of BOD consumed in the digestor. B is the endogenous coefficient of the digestor and SRT is the solids retention time for the digestor.

3.1.6 Volume of Methane Produced (V_{CH4})

$$V_{CH_4} = (0.35)\left[(So - S)(Q)\left(\frac{1kg}{10^3 g}\right) - 1.42P_X\right]$$

Where, V_{CH_4} is the volume of Methane produced at STP.

From the plant wide mass balance, the following relationships are needed to be established.

1. Sludge Generated per MLD of Wastewater (SG)
2. Methane Produced per MLD of Wastewater (MP)
3. Methane Produced per TON of Sludge (MPS)
4. Biosolids Generated (22% TSS) per MLD of Wastewater (BSP)
5. Organic Manure (70% TS) Generated per TON of Sludge (OMG)
6. Organic Manure (70% TS) Generated per MLD of Wastewater (OMW)
7. Total Dry Solids Per MLD of Wastewater (DS)

These seven relationships are our constants for the purpose of our study.

3.2 BioCNG and Organic Manure production

3.2.1 Wastewater Collected

The Wastewater generated is estimated as 80% of the water used by a person per day (W_{CD})[18] W_{CD} is obtained from the Ministry of Water Supply report.[19]. The Waste Water generated per capita per day can be calculated as:

WW_{CD} =0.8x W_{CD} (1)

The total Wastewater Generated per day is given as:

WW_{PY} = WW_{CD} x P / 1000000
(2)

P = $P_0(1+r)^t$ (3)

The population, P of each year will be forcasted on the basis of the growth rate for each district. The growth rate is taken as r, t is the number of extrapolated years and P_0 is the base year population of 2021.

Wastewater collected (WW_{CPY}) in Million Litres per Day (MLD) is given as :

WW_{CPY} = WW_{CD} x P x WW_{CR} (4)

Where WW_{CR} = Wastewater collection rate, is adapted from the percentage of housholds connected to a central sewer network. [19] Annex II contain the detailed calculation along with the required values.

The change in per capita water consumption, and sewage coverage for the study period taken in this thesis will follow the information provided below.

I. (Year 2024-Year 2033) Water consumption is 117 LPCD. Sewerage connection will increase from 79% in 2024 to 95% in 2033. Wastewater treatment capacity will increase from 32.4 MLD in 2024 to 159.3 MLD in 2030 and remain constant till 2033. The population increases linearly in this period.
II. (Year 2034-Year 2044) Waste consumption will be 150 LPCD. Sewage connection will increase from 97 % in 2034 to 100% in 2036. Wastewater treatment capacity will remain stagnant at 159.3 MLD. The population increases linearly in this period.

3.2.2 BioCNG Produced

BioCNG = MP x WW_{CPY}

Where, MP is the Methane produced per MLD of Wastewater.

3.2.3 Organic Manure Produced

Organic Manure = BSP x WW_{CPY} x SC_{BS} / SC_{OF}

Where, BSP is the biosolids produced per MLD of Wastewater, SC_{BS} is the solids concentration of biosolids, and SC_{OF} is the solids concentration of organic manure.

3.3 Economic Viability of AD process

An Anaerobic Digestion Plant with an 80 TPD capacity is under consideration, modeled after the Gandaki Urja W2E Plant detailed in Section 2.5. The key modification involves substituting cow manure, chicken litter, and pig manure with sewage sludge as the primary substrate.

The plant's primary objective is to convert the volatile matter in the sewage sludge into biogas, which is subsequently refined into Bio CNG. The resulting digestate is processed into nutrient-rich organic manure, while the Bio CNG is packaged in cylinders and sold as fuel for internal combustion engine (ICE) vehicles.

For the analysis, cost estimate prepared for Gandaki Urja in the 2018 have been adjusted for an average yearly inflation rate of 5.3%. Specific adjustments, excluding irrelevant sections and costs. Given that sewage sludge is the primary substrate and transported from the wastewater treatment plant (WWTP) to the AD plant at no cost, raw material expenses related to transportation have been omitted.

Additionally, as the plant is strategically located in close proximity to the WWTP, the need for transportation vehicles has been eliminated, and associated costs, including vehicle purchase, fuel, and driver salaries, have been excluded. Current electricity and fuel prices have been updated based on NEA and NOC reports. It is assumed that the compression and bottling costs for BioCNG as vehicular fuel are equivalent to those used as cylinders for cooking.

The debt interest is set at 7%, with a 10-year repayment period. The cumulative interest rate applied to the installment increases annually by 10% as the repayment amount diminishes. Operating and maintenance (O&M) costs will annually increase by 3%, while the selling prices for BioCNG and Organic Manure will experience a 5% annual increment.

Depreciation is calculated using the declining balance method, and the project is assumed to be exempt from income tax. Further details, including all assumptions and detailed calculations for the Financial Analysis, can be found in Annex III.

3.3.1 Sale and Revenue

The selling price of Bio CNG is Rs 154 per kg and selling price of fertilizer is Rs 27 per kg for the year 2025. The selling price is assumed to increase every year by 5%.

$$Revenue\ per\ year\ =\ Sale\ of\ BioCNG\ per\ year + Sale\ of\ Organic\ Manure\ per\ year$$

$$Sale\ of\ BioCNG\ per\ year\ =\ MPS\ x\ 80\ x\ 0.7157\ x\ 365\ x\ SPCNG$$

Where, MPS is the Methane Production per Ton of Sludge, 80 is the weight of substrate given to the given to the plant, 0.7157 is the density of Methane at STP and 365 is the number of operational days of the plant in a year. SP_{CNG} is the selling price of the BioCNG in the given year.

$$Sale\ of\ Organic\ Manure\ per\ year\ =\ OMG\ x\ 80\ x\ 365\ x\ SPOM$$

Where, OMG is the Organic Manure generated per Ton of Sludge, 80 is the total weight of substrate given as input to the plant, 365 is the number of operational days of the plant in a year. SP_{OM} is the selling price of the Organic Manure in the given year.

3.3.2 Loan Installment

The debt amount is the total amount inclusive of fixed capital cost and variable capital cost. The amount after the end of loan period is calculated based on the fixed interest rate. The loan installment is calculated by dividing the final amount by the loan period.

$$Final\ Amount(A)\ =\ Capital\ Cost\ (1 + r_1)\hat{}(t)$$

Where, r_1 is the fixed rate of interest, t is the number of years of loan period.

3.3.3 Fixed Operation and Maintenance Cost (FO&M)

Any cost associated with the operation and maintenance of the plant which remains constant regardless of the quantity of substrate used or the days of operation of the plant or the numbers of years of operation planned for the plant is regarded as the Fixed O&M cost. The Fixed O&M cost is predicted to increase by 3% every year. The following are Fixed O&M cost of the plant considered in the study.

3.3.3.1 Depreciation

Physical commodities loose value over time, this is known as depreciation. In this study it is considered that the buildings and civil work($r_{B\&C}$) depreciate at 5% per annum, machinery and equipment($r_{M\&E}$) depreciate at 10% per annum and vehicles(r_V) depreciate at 20% per annum.

Total Depreciation for a fiscal year = Depreciation of Buildings and Civil work + Depreciation of Machinery and Equipment + Depreciation of Vehicles, The individual depreciation is calculated as shown below for each fiscal year.

For year 1,

$$Depreciation\ for\ \ year\ 1\ (D_{B\&C1}) =\ Capital\ cost\ of\ building\ x(r_{B\&C})$$
$$Depreciation\ for\ \ year\ 1\ (D_{M\&E1})\ =\ \ Capital\ cost\ of Machinery\ x(r_{M\&E})$$
$$Depreciation\ for\ \ year\ 1\ (D_{V1})\ =\ \ Capital\ cost\ of\ Vehicle\ x(r_V)$$

For year 2,

$$Depreciation\ for\ \ year\ 2\ (D_{B\&C2}) = (Capital\ cost\ of\ building - D_{B\&C1})\ \ x(r_{B\&C})$$
$$Depreciation\ for\ \ year\ 2\ (D_{M\&E2}) = (\ Capital\ cost\ of\ Machinery - D_{M\&E1)}\ x(r_{M\&E})$$
$$Depreciation\ for\ \ year\ 2\ (D_{V2}) =\ \ Capital\ cost\ of\ Vehicle - D_{V1})\ x(r_V)$$

3.3.3.2 Office Overheads

The expenses associated with the operation of an office is known as office overheads. The items included in calculating the office overheads are as follows.

i. Office Materials
ii. Stationary
iii. Communication
iv. Legal fees
v. Auditing fees
vi. Travelling Expenses

vii. Annual General Meeting

viii. Tea/Coffee

3.3.3.3 Indirect Workers Salary

Management and employees who are paid on a monthly basis are regarded as indirect workers. The management and employees who are included in the list are as follows.

i. Chief Executive Officer (CEO)
ii. Plant Manager
iii. Account Manager
iv. Marketing Employee
v. Office Assistant
vi. Guard (2)

3.3.4 Variable Operation and Maintenance Cost (VO&M)

Any cost associated with the operation and maintenance of the plant which is directly related to the quantity of substrate used or the days of operation of the plant or the numbers of years of operation planned for the plant is regarded as the Variable O&M cost. The variable O&M cost is predicted to increase by 3% every year. The following are variable O&M cost of the plant considered in the study.

3.3.4.1 Repair and Maintenance (R&M)

The repair and maintenance cost are taken as small percentage of the initial cost of each item. For building and civil works($r_{B\&C}$), it is taken as 2% of the initial setup cost, and for machinery and equipment($r_{M\&E}$) and for vehicles(r_V) it is taken as 3% of the initial cost. Total Cost for R&M for a fiscal year = R&M of Buildings and Civil work ($R\&M_{B\&C}$) + R&M of Machinery and Equipment($R\&M_{M\&E}$) + R&M of Vehicles($R\&M_V$), the individual repair and maintenance cost is calculated as shown below for each fiscal year.

$$R\&M\ of\ Buildings\ and\ Civil\ Works\ (R\&M_{B\&C}) = \ Capital\ cost\ of\ building\ x(r_{B\&C})$$
$$R\&M\ for\ Machinery\ (R\&M_{M\&E})\ =\ \ Capital\ cost\ of Machinery\ x(r_{M\&E})$$
$$R\&M\ for\ Vehciles\ (R\&M_V)\ =\ \ Capital\ cost\ of\ Vehicle\ x(r_V)$$

3.3.4.2 Direct Worker Salary

The workers who are paid on a daily basis based on their requirement in the plant are considered as direct workers. The workers who make up the list of direct workers are as follows.

i. Driver (1)

ii. Helper (4)

iii. Plant Labor (4)

3.3.4.3 Raw Materials and Utility Cost

In case of the plant considered in this study, the feed material for the plant which is sewage sludge, is obtained for free. The material for fertilizer packaging is required and its cost is considered for a single fiscal year. The cost associated with utilities such as water, electricity and fuel are also considered for a single fiscal year.

3.3.4.4 Interest on Loan

The loan amount is calculated based on the cumulative rate of interest subjected to the final amount to be repaid at the end of loan period.

$$Interest\ for\ year\ 1\ (I_1) = A\ x(1 + r_2)\ \hat{}(t)$$

$$Interest\ for\ Year\ 2(I_2) = (A - I_1)\ x\ (1 + r_2)\ \hat{}(t)$$

$$Interest\ for\ year\ 3(I_3) = (A - I_1 - I_2)\ x\ (1 + r_2)\ \hat{}(t)$$

Where, r_2 is the cumulative rate of interest applied to the Final Amount.

3.3.5 Profit and Loss Statement

Profit and Loss statement is used to summarize the predicted revenue, cost and expenses incurred over the 20-year period for the anerobic digestor plant. The profit and Loss statement considers all current assets and liabilities of the plant. The parameters needed to be considered for the preparation of the profit and loss statement are as follows: -

i. Operating Income

The total income generated by the company by selling BioCNG and Organic Manure in a single year.

$$Operating\ Income(OI) = Revenue - (Utility\ Cost + Raw\ Material\ Cost)$$

The total revenue can be computed using information in Section 3.3.1

The Utility Cost and Raw Material Cost can be Computed using information in Section 3.3.4

ii. O&M Cost

The fixed operational and maintenance cost and the variable operational and maintenance cost for a fiscal year is considered. The details are given in Section 3.3.3 and Section 3.3.4

iii. Interest on Loan

The interest paid is taken for each fiscal year. The details are given in Section 3.3.4

iv. Depreciation

The depreciation calculated for each fiscal year for buildings and civil work, machinery and equipment and for vehicles is cumulatively added. The details are given in Section 3.3.3

3.3.6 Cash Flow Statement

The cash flow statement is a summary of the flow of cash coming into the plant and going out of the plant. The difference in preparing a cash flow statement from Profit & Loss statement is the consideration of only parameters that involve actual cash flows. The debt initially generates a positive cash flow, the capital cost of constructing buildings, buying machinery and vehicle and preoperational cost all require capital; thus, they generate a negative cash flow. While in operation, the sale generates a positive cash flow, the cost of raw materials and utilities, the operating cost, and the loan installment contribute to negative cash flow. A table which summarizes all these cash coming into and out is generated over the 20-year period to prepare a cash flow statement.

3.3.7 Net Present Value (NPV)

This is the present value of all the revenue that the plant generated over its lifetime, minus the present value of all the cost it incurs over its lifetime. Its value must be positive for the system to be economically viable. [23] NPV can be calculated as follows:

$$\sum_{n=0}^{N} \frac{F_n}{(1+d)^n} = F_o + \frac{F_1}{(1+d)^1} + \frac{F_2}{(1+d)^2} + \cdots \ldots + \frac{F_N}{(1+d)^N}$$

Where, F_o is the initial investment, $F_1 = R_1 - C_1$ and d = discount rate, and N=20 years. R_1 is the revenue earned in year 1, C_1 is the submission of the cost incurred in operation and loan installment.

3.3.8 Internal Rate of Return (IRR)

The discount rate that brings the NPV to zero is the IRR. It is approximately the maximum discount rate at which the project breaks even. The plant is deemed to be financially feasible only when NPV is greater than zero and IRR is at its highest possible mark.

3.3.9 Payback Period (PBP)

Payback Period (PBP) is one of the metrics to be considered in taking decision to embark on a project. It is the number of years at which the project cost breaks even. It is the time at which the investment cost equals the submission of Net Profit.

$$\text{PBP} = \frac{F_O}{\sum_{n=1}^{N} = P_1 + P_2 + \cdots \ldots\ldots + P_n}$$

Where, P_1 is the Net Profit made in 1st year of Operation, The N value when the denominator is equal to or greater than numerator is the Payback Period of the project.

4 Result

4.1 Mass Balance

It took six iterations of mass balance calculations to obtain a mass flow with less than 1% variation in the obtained result. The details of the calculations and the respective iterations can be found on Annex I. The mass flow obtained after the fourth iteration has been presented in Figure 6: Plant-wide Mass Balance for GWWTP

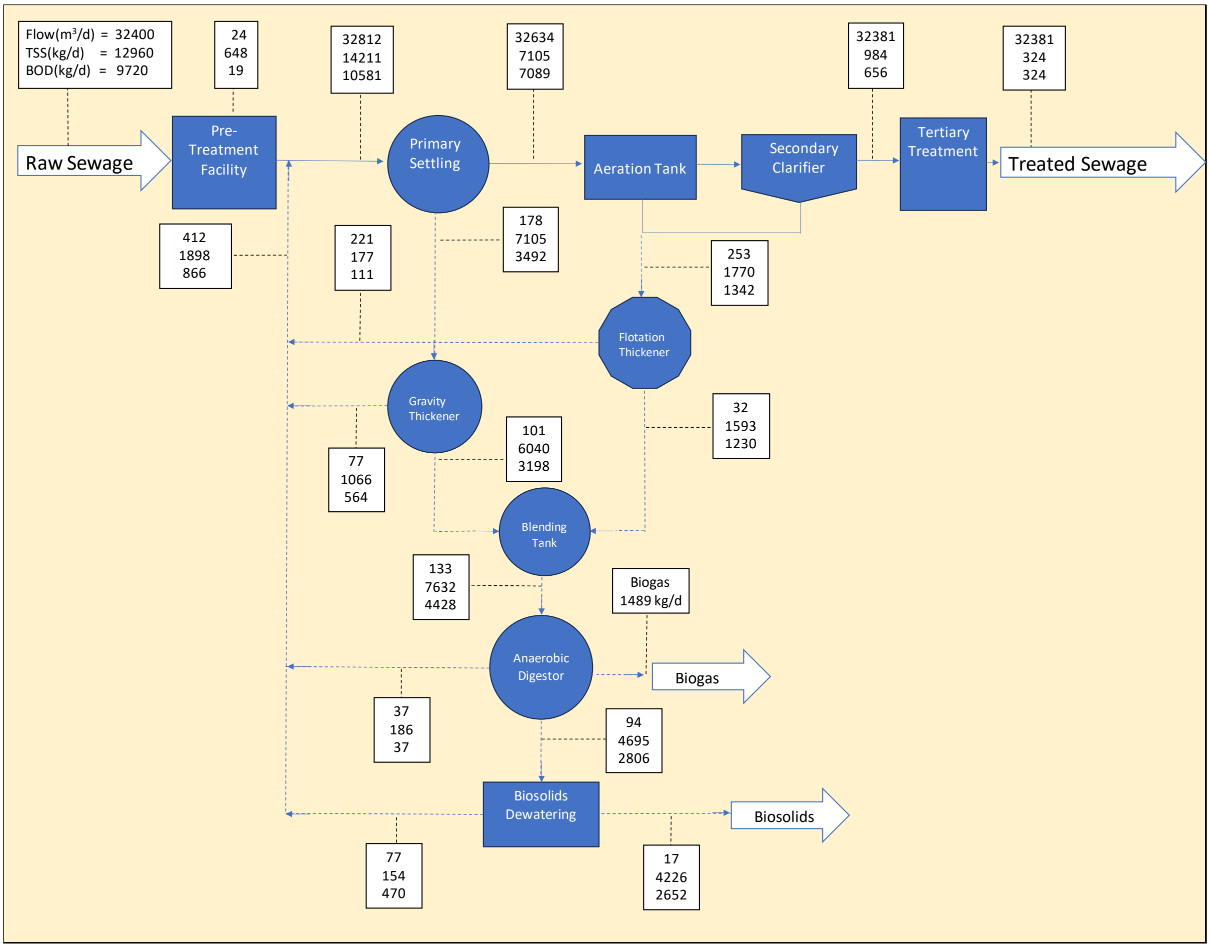

Figure 6: Plant-wide Mass Balance for GWWTP

Some important relationships have been obtained from the plant-wide mass balance. They are listed below with the obtained value.

1. Sludge generated per MLD of Wastewater (SG) = 4152 kg/MLD
2. Methane produced per MLD of Wastewater (MP) = 27.07 Nm^3/MLD
3. Methane produced per Ton of Wastewater (MPS) = 6.52 Nm^3/ TON
4. Biosolid (24% TS) per MLD of Wastewater (BSP) = 601 kg/MLD
5. Organic Manure (70% TS) per MLD of Wastewater (OMG) = 208 kg/MLD
6. Organic Manure (70% TS) per Ton of Sludge (OMW) = 50 kg/ TON
7. Total Dry Solids Per MLD of Wastewater (DS) = 145 kg/MLD

Other relationships have also been established to validate the result with existing literature.

1. Primary Sludge Production per m^3 of wastewater = 222.36 gTSS/ m^3
2. Secondary Sludge Produced per m^3 of wastewater = 55.67 gTSS/ m^3
3. Specific Production of Secondary Sludge = 0.35 kgTSS/kgBOD
4. Specific Biogas Production = 724.53 L/kg VSS

Operation	Flowrate, m^3/d	BOD_M, kg/d	TSS_M, kg/d
Raw Sewage	32400	9720	12960
Grit Removal	24	19	648
Primary Sedimentation Inlet	32812	10581	14211
Primary Sludge	178	3492	7105
Gravity Thickened Sludge	101	3198	6040
Centrate	77	564	1066
Aeration Tank Inlet	32634	7089	7105
Secondary Clarifier Outlet	32381	656	984
Effluent	32381	324	324
Waste Activated Sludge	253	1342	1770
Flotation Thickener Sludge	32	1230	1593
Centrate	221	111	177
Inlet for AD	133	4428	7632
Gas	1489	kg/d	
Supernatant	37	37	186
Digestate	94	2806	4695
Dewatered Disgestate	17	2652	4226
Centrate	77	154	470
Return Flows	412	866	1898

Table 3: Mass Flow Values obtained from Mass Balance

4.2 Wastewater Generated and Wastewater Collected

Table 4: Data for Wastewater Collection in Kathmandu between 2024-20 shows the population increase, sewage coverage over the same period, and how it is clearly impacting the amount of Wastewater Collected compared to the Wastewater Generated. A full table for the 20 years period of the study can be found in Annex II.

Year	Population	Sewage Coverage	Wastewater Generated (WWG) , MLY	Wastewater Collected (WWC), MLY
2024	3190738	79.09%	109008	86216
2025	3248100	80.91%	110968	89783
2026	3306629	82.73%	112968	93455
2027	3366352	84.55%	115008	97234
2028	3427298	86.36%	117090	101123
2029	3489495	88.18%	119215	105126
2030	3552974	90.00%	121384	109245

Table 4: Data for Wastewater Collection in Kathmandu between 2024-2030

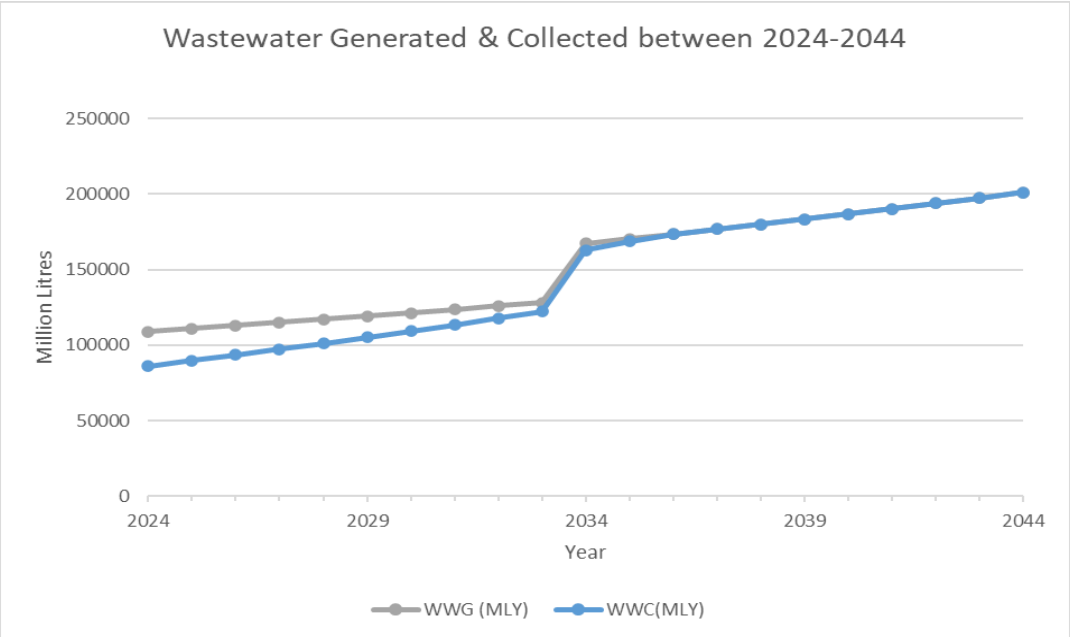

Figure 7 : Trend of WWG and WWC over 20 years period.

The data presented in Table 4 is supported by the Line Chart shown in Figure 7 : Trend of WWG and WWC over 20 years period. From Figure 7 it can be observed that the collection rate meets the generation rate in the year 2036. Additionally, there is a sudden spike in the rate of both collection and generation in between 2033 and 2034. The amount of Wastewater Collected doubles in the 20-year period from 86,216 MLY in 2024 to 202,264 MLY in 2044.

4.3 Potential Production of BioCNG

Figure 8: Trend of BioCNG productionshows trends based on generation, collection and treatment. From the scatter chart we can see that there is huge potential for BioCNG production, however the due to the limitation of treatment capacity, that potential cannot be realized. It is also shown in chart how the gap based on collection and generation is nullified after year 2035.

Year	BIO CNG, 200 bar		
	Based on Treatment Mt/Yr	Based on Collection, Mt/Yr	Based on Generation, Mt/Yr
2024	229	1671	2112
2025	229	1740	2150
2026	229	1811	2189
2027	229	1884	2228
2028	229	1959	2269
2029	229	2037	2310
2030	1127	2117	2352
2031	1127	2199	2395
2032	1127	2283	2439
2033	1127	2370	2483
2034	1127	3154	3242

Table 5: Estimated BioCNG production data for 2024-2034

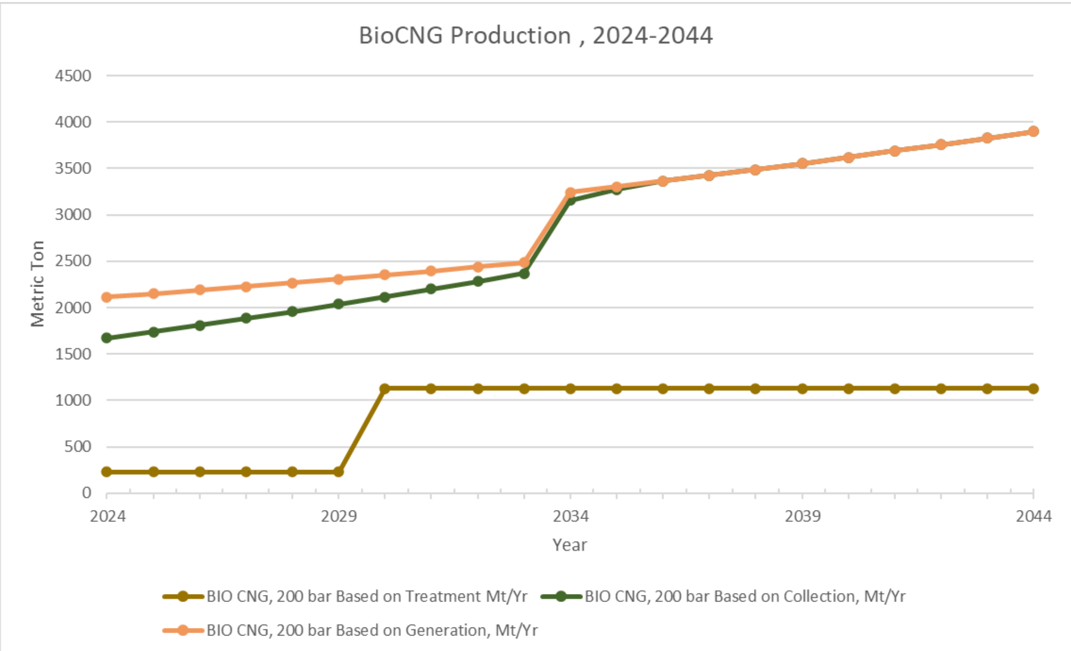

Figure 8: Trend of BioCNG production

Table 5: Estimated BioCNG production data for 2024-2034 shows the estimated values for BioCNG production based on generation, collection and treatment. For the year 2024, based on treatment 229 MT of BioCNG can be produced, similarly, the potential based on collection is 1671 MT and based on generation is 2112 MT. There is a gap of 1883 MT between the values based on treatment and generation and a gap of 442 MT between the values based on

collection and generation. The gap between treatment and generation, gets reduced in the year 2030, when additional treatment plants are connected to the treatment network of Kathmandu Valley. The gap between collection and generation is gradually decreasing with time. The full table for the entire study period can be found in Annex II.

4.4 Potential Production of Organic Manure

Year	Organic Manure (70% TS)		
	Based on Treatment, Mt/Yr	Based on Collection, Mt/Yr	Based on Generation, Mt/Yr
2024	2459	17928	22667
2025	2459	18669	23075
2026	2459	19433	23490
2027	2459	20219	23915
2028	2459	21028	24348
2029	2459	21860	24790
2030	12091	22716	25240
2031	12091	23598	25701
2032	12091	24505	26171
2033	12091	25439	26650
2034	12091	33846	34795

Table 6: Estimated Organic Manure Production data for 2024-2034

Figure 9: Trend of Organic Manure Production shows the trend for Organic Manure production based on generation, collection and treatment. From the scatter chart we can see that there is huge potential for BioCNG production, however the due to the limitation of treatment capacity, that potential cannot be realized. It is also shown in chart how the gap based on collection and generation is nullified after year 2035.

Table 6: Estimated Organic Manure Production data for 2024-2034 shows the estimated values for Organic Manure production based on generation, collection and treatment. For the year 2024, based on treatment 2459 MT of Organic Manure can be produced, similarly, the potential based on collection is 17928 MT and based on generation is 22667 MT. There is a gap of 20208MT between the values based on treatment and generation and a gap of 4739 MT between the values based on collection and generation. The gap between treatment and generation, gets reduced in the year 2030, when additional treatment plants are connected to the treatment network of Kathmandu Valley. The gap between collection and generation is gradually decreasing with time. The full table for the entire study period can be found in Annex II.

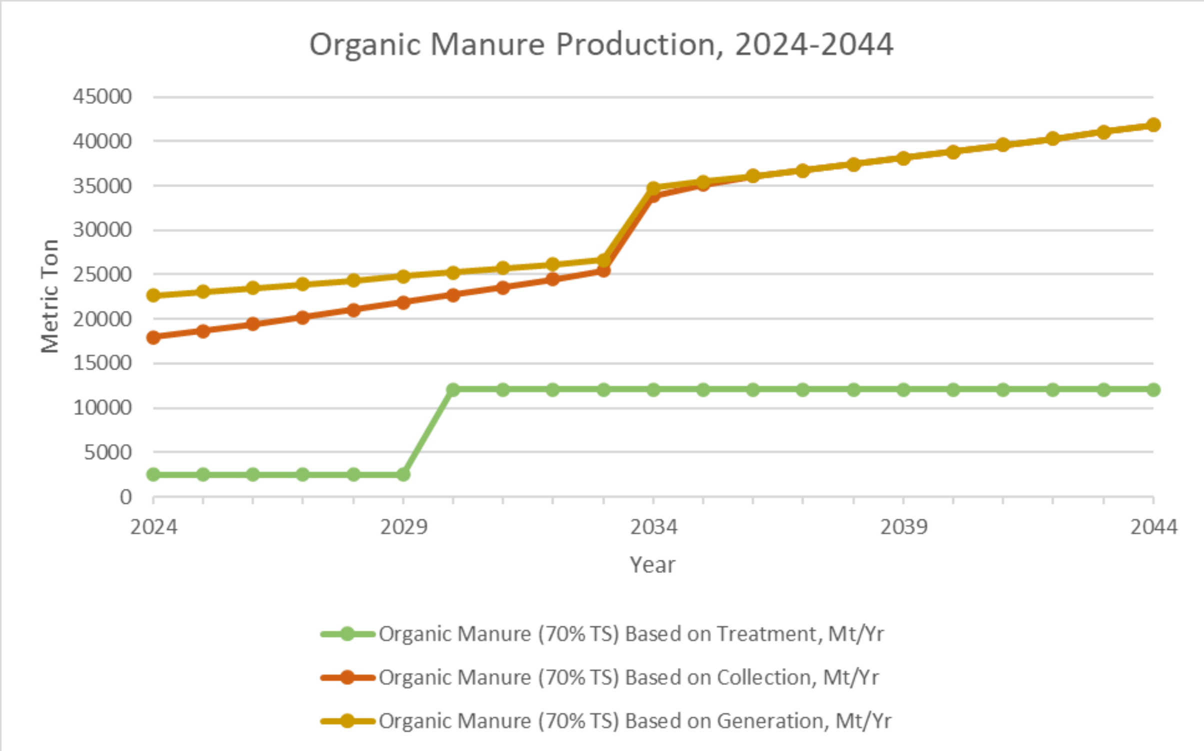

Figure 9: Trend of Organic Manure Production

4.5 Financial Analysis of Anaerobic Digestion Plant

Table 7: Sales Figure for 2025-2030 shows that, the sale of BioCNG accounts to 35% of the revenue generated while, the sale of Organic manure accounts for 65% of the revenue generated. The entire table for sales for the duration of the study period can be found in Annex III.

Sales						
Year	2025	2026	2027	2028	2029	2030
Bio CNG	20984506.90	22033732.25	23135418.86	24292189.80	25506799.29	26782139.26
Fertilizer	39483129.01	41457285.46	43530149.73	45706657.22	47991990.08	50391589.58
Net Sales	60,467,635.91	63,491,017.71	66,665,568.59	69,998,847.02	73,498,789.37	77,173,728.84

Table 7: Sales Figure for 2025-2030

According to Table 8:Installment and Interest Calculation for 2025-2030, it can be seen that the installment amount remains constant for the loan repayment period and the interest has been structured to increase every year. The increase is based on the cumulative rate of interest taken for calculation. The entire table for sales for interest and installment calculation for duration the study period can be found in Annex III.

Interest Calculation						
Year	2025	2026	2027	2028	2029	2030
Installement to be paid for 10 years	40,522,865.00	40,522,865.00	40,522,865.00	40,522,865.00	40,522,865.00	40,522,865.00
Interest to be paid(Amount-Principal)	4,052,286.50	4,457,515.15	4,862,743.80	5,267,972.45	5,673,201.10	6,078,429.75

Table 8:Installment and Interest Calculation for 2025-2030

Table 9: Depreciation Calculation for 2025-2028 shows the calulated depreciation amount for Buildings and Civil Structure, Machinery and Equipments and Vehicles based on their rate of depreciation. The entire table for depreciation calculation for the duration of the study period can be found in Annex III.

Depreciation Calculation						
	Rate	Cost of Asset	2025	2026	2027	2028
Buildings and Civil Structure	5%	46,907,753.55	2,345,387.68	2,228,118.29	2,116,712.38	2,010,876.76
Machinery and Equipments	10%	137,346,183.94	13,734,618.39	12,361,156.55	11,125,040.90	10,012,536.81
Vehicles	20%	5,459,150.84	1,091,830.17	873,464.13	698,771.31	559,017.05
Total		189,713,088.32	17,171,836.24	15,462,738.98	13,940,524.58	12,582,430.61

Table 9: Depreciation Calculation for 2025-2028

Profit and Loss Statement						
Year	2024	2025	2026	2027	2028	2029
Sales						
BIO CNG		20,984,506.90	22,033,732.25	23,135,418.86	24,292,189.80	25,506,799.29
Fertilizer		39,483,129.01	41,457,285.46	43,530,149.73	45,706,657.22	47,991,990.08
Total Sales		60,467,635.91	63,491,017.71	66,665,568.59	69,998,847.02	73,498,789.37
Cost						
Cost of Raw Materials		2,097,808.82	2,160,743.08	2,225,565.37	2,292,332.33	2,361,102.30
Utilities		3,363,568.00	3,464,475.04	3,568,409.29	3,675,461.57	3,785,725.42
Total Cost		5,461,376.82	5,625,218.12	5,793,974.66	5,967,793.90	6,146,827.72
Operating Income		55,006,259.09	57,865,799.59	60,871,593.93	64,031,053.12	67,351,961.65
Expenses						
Repair and Maintenance		5,378,984.57	5,540,354.10	5,706,564.73	5,877,761.67	6,054,094.52
Direct Worker Salary		2,631,479.97	2,710,424.37	2,791,737.10	2,875,489.21	2,961,753.89
Indirect Worker Salary		3,107,774.89	3,201,008.13	3,297,038.38	3,395,949.53	3,497,828.02
Meeting/Training		699,269.61	720,247.69	741,855.12	764,110.78	787,034.10
Office Overheads		671,298.82	691,437.79	712,180.92	733,546.35	755,552.74
Pre Operating Cost	14,534,989.10	-	-	-	-	-
Total Expenses	14,534,989.10	12,488,807.85	12,863,472.08	13,249,376.25	13,646,857.53	14,056,263.26
EBIDTA	(14534989)	42,517,451.25	45,002,327.50	47,622,217.68	50,384,195.58	53,295,698.39
EBIDTA Margin	0.00%	70.31%	70.88%	71.43%	71.98%	72.51%
Depreciation		17,171,836.2	15,462,739.0	13,940,524.6	12,582,430.6	11,368,829.7
EBITA	(14534989)	25,345,615.01	29,539,588.52	33,681,693.10	37,801,764.97	41,926,868.70
Interest on Loan		4,052,286.50	4,457,515.15	4,862,743.80	5,267,972.45	5,673,201.10
Net Profit	(14534989)	21,293,328.51	25,082,073.37	28,818,949.30	32,533,792.52	36,253,667.60
Net Profit Margin	-	35.21%	39.50%	43.23%	46.48%	49.33%

Table 10: Profit and Loss Statement for 2024-2029

The Plant has a substantial Net Profit Margin, and it can be seen that the Net profit Margin is increasing every year. The entire table for the profit and loss statement for the duration of the study period can be found in Annex III.

Table 11: Cash Flow Statement for 2024-2029 for the plant shows that there is positive cash flow right from the start of the project. The annual cash flow is increasing every year. It can be seen that once the loan installement period is over, the annual cash flow will increase drastically. The entire table for cash flow for the duration of the study period can be found in Annex III.

Cash Flow						
	2024	2025	2026	2027	2028	2029
INFLOW						
Debt	205,997,697.39					
Subsidy	-					
Net Sales		60,467,635.91	63,491,017.71	66,665,568.59	69,998,847.02	73,498,789.37
Total Inflow	205,997,697.39	60,467,635.91	63,491,017.71	66,665,568.59	69,998,847.02	73,498,789.37
OUTFLOW						
Building and Civil Works	46,907,753.55					
Machinery and Equipments	137,346,183.94					
Vehicles	5,459,150.84					
Pre Operating Cost	14,534,989.10					
Loan Installment		40,522,865.00	40,522,865.00	40,522,865.00	40,522,865.00	40,522,865.00
Operating Cost		17,950,184.66	18,488,690.20	19,043,350.91	19,614,651.44	20,203,090.98
Total Outflow	204,248,077.42	58,473,049.67	59,011,555.21	59,566,215.91	60,137,516.44	60,725,955.98
Annual Cash Flow	1,749,619.97	1,994,586.24	4,479,462.50	7,099,352.68	9,861,330.58	12,772,833.39
Opening Balance	-	1,749,619.97	3,744,206.21	8,223,668.71	15,323,021.39	25,184,351.97
Closing Balance	1,749,619.97	3,744,206.21	8,223,668.71	15,323,021.39	25,184,351.97	37,957,185.36

Table 11: Cash Flow Statement for 2024-2029

The Net present value (NPV) of the project is Rs 240,416,222.37. The project Internal Rate of Return (IRR) is 6.196% and the payback period is 8 Years. The Profit and Loss statement and the annual cash flow for the project duration is given in Annex III along with the entire calculations required for performing the financial analysis.

4.6 Sensitivity Analysis

Digestor Efficiency determines the methane conversion from substrate. According to Table 12: Sensitivity Analysis with Digestor Efficiency as base term the significant impact on financial indicators is evident with a positive correlation. When the digestor efficiency is at the highest, the financial indicators are showing the best results. The detailed calculations can be found in Annex VI.

Digester Efficiency	Financial Indicators		
	NPV	IRR	Pay Back Period(Years)
72%	308,425,537.22	7.86%	7
66%	274,421,144.63	7.03%	7
60%(Baseline)	240,416,222.37	6.20%	8
54%	206,410,769.37	5.35%	9
48%	172,404,784.51	4.50%	10

Table 12: Sensitivity Analysis with Digestor Efficiency as base term

The variation in price of BioCNG reflects on the overall revenue of the plant. In Table 13: Sensitivity Analysis with BioCNG price as base term, it can be seen that there is a positive correlation between the price of BioCNG and the financial indicators. Even though there is some difference in the NPV value for different price adjustments, there is not much difference in IRR and Pay Back Period between 10%, and 20% decrement or increment but there is difference with respect to baseline price. The entire calculation for each increment and decrement can be found in Annex IV.

	Bio CNG Price (Rs/kg)	Financial Indicators		
		NPV	IRR	Pay Back Period (Years)
20% Increment	184.80	308,431,941.84	7.86%	7
10% Increment	169.40	274,424,082.11	7.03%	7
Baseline Price	154.00	240,416,222.37	6.20%	8
10% Decrement	138.60	206,408,362.64	5.35%	9
20% Decrement	123.20	172,400,502.91	4.50%	10

Table 13: Sensitivity Analysis with BioCNG price as base term

The sale of Organic Manure has 65% contribution to the total revenue of the plant.Table 14: Sensitivity Analysis with Organic Manure price as base term shows significant impact with a positive correlation between the price of the organic manure and all the financial indicators. The details of the calculations can be found in Annex VII.

	Organic Manure Price (Rs/kg)	Financial Indicators		
		NPV	IRR	Pay Back Period (Years)
20% Increment	32.40	368,390,324.35	9.32%	6
10% Increment	29.70	304,403,273.36	7.76%	7
Baseline Price	27.00	240,416,222.37	6.20%	8
10% Decrement	24.30	176,429,171.39	4.61%	10
20% Decrement	21.60	112,442,120.40	2.98%	13

Table 14: Sensitivity Analysis with Organic Manure price as base term

The Capital Cost is the only major investment required for the construction and operation of the plant. Table 15: Sensitivity Analysis with Capital Cost as base terms indicates the clear impact of cost of capital to the financial indicators. The correlation is positive. The entire calculation can be found in Annex V.

	Capital Cost	Financial Indicators		
		NPV	IRR	Pay Back Period (Years)
20% Increment	247,197,236.87	146,334,276.44	3.26%	12
10% Increment	226,597,467.13	193,375,249.41	4.62%	10
Baseline Price	205,997,697.39	240,416,222.37	6.20%	8
10% Decrement	185,397,927.65	287,457,195.34	8.07%	6
20% Decrement	164,798,157.91	334,498,168.31	10.37%	5

Table 15: Sensitivity Analysis with Capital Cost as base term

Subsidy is given for projects of public interest which are not very profitable without government support. Table 16: Sensitivity Analysis with Subsidy as base termshows the sensitivity of the Financial Indicators to percentage of subsidy given. There is a positive correlation and a significant impact of subsidy on all the financial indicators. The details of the calculations can be found in Annex VIII.

	Financial Indicators		
Subsidy	NPV	IRR	Pay Back Period (Years)
10%	269,317,068.37	7.14%	7
20%	298,217,914.37	8.14%	6
30%	327,118,760.37	9.19%	5
40%	356,019,606.37	10.30%	5
No Subsidy	240,416,222.37	6.20%	8

Table 16: Sensitivity Analysis with Subsidy as base term

5 Discussion

The sustainable management of sewage sludge in the Kathmandu Valley has the potential to positively impact both the environment and the economy. Efficient management practices necessitate the availability of a reliable database encompassing wastewater generated, wastewater collected, wastewater treated, and sewage sludge produced from wastewater treatment plants. Furthermore, a detailed financial analysis is essential for assessing the sludge stabilization processes.

Anaerobic digestion has proven to be an energy-efficient technology for the stabilization of sewage sludge. The end products derived from anaerobic digestion, namely BioCNG and organic manure, contribute to the overall environmental and economic benefits. In the course of this thesis, a credible database for sewage sludge generation has been established. Additionally, a financial analysis of an anaerobic digestion plant utilizing sewage sludge as a substrate has been presented.

The population of Kathmandu valley was 30,25,386 in the year 2021, taking into consideration the growth rate of the three districts within the valley, the population will reach 45,95,066 in the year 2044. The per capita water consumption in the valley is 117 liters in the year 2021 and will continue to do so until 2033.After the year 2033, it is predicted that water consumption per capital will reach 150 liters.

A plant wide mass balance of Guheshwori Wastewater Treatment Plant has been performed to establish benchmark values. From the mass balance, it can be inferred that the total sludge produced per MLD of Wastewater is 4154 kg. Similarly, the methane yield from anaerobic digestion of sewage sludge is 6.52 Nm^3 per ton of sewage sludge and 27.07 Nm^3 per MLD of wastewater being treated in the plant. Also, the Organic Manure processed from the plant per Ton of Sewage Sludge is 50 kg and per MLD of wastewater is 208 kg. The total dry solids in the sludge per MLD of Wastewater is 145 kg.

The wastewater generated in Kathmandu Valley is 299 MLD in the year 2024 and reaches 551 MLD in the year 2044. The wastewater collected is 236 MLD in 2024 with 79.09% collection rate and reaches 476 MLD in the year 2036 when 100% collection is achieved. The treatment capacity is of 32.4 MLD in the year 2021, and by the year 2023, the treatment capacity is expected to reach 159.30 MLD. Daily methane yield based on the wastewater generated in 2024 is 5787 kg, and 62 Mt of organic manure is obtained by processing the residual digestate.

Financial Analysis has been done for an Anaerobic Digestion plant incorporated in a wastewater treatment plant producing 80 Ton of Sewage Sludge per day. The Net Present value for the Plant (NPV) is Rs 240,416,222.37, the Internal Rate of Return (IRR) is 6.196% and the Payback Period is 8 years.

5.1 Mass Balance

The steady-state mass balance of the 32.4 MLD Guheshwori Wastewater Treatment Plant provides benchmark values used in the thesis to predict other important parameters. The accuracy of the mass balance depends on the parameters chosen for the calculation steps and the values reported from the WWTP. The primary sludge generated is based on the removal efficiency assumption of the primary sedimentation tank, primarily composed of the nonbiodegradable fraction of COD. The secondary sludge, or waste activated sludge, is part of the recycled flow from the secondary clarifier to the aeration tank.

The biological system is designed based on the concentration of Mixed Liquor Volatile Suspended Solids (MLVSS). The primary sludge production per unit of wastewater is 222 gTSS/m3. Similarly, the wasted sludge per unit of wastewater is 55 gTSS/m3. The specific production of excess sludge per kg of BOD removed is 0.35 kgTSS/kgBOD. Literature reports values for primary sludge production per unit as 110-170 gTSSs/m3 and for excess sludge per unit as 60-110 gTSS/m3. The specific production of excess sludge is reported to be within 0.69±0.29 kgTSS/kgBOD.[24]

The primary sludge production depends on the removal efficiency of the primary sedimentation tank, leading to potential differences from literature values in the mass balance. The wasted sludge consists of heterotrophic biomass, autotrophic biomass, endogenous residue, and inert solids. For the mass balance, only heterotrophic biomass and endogenous residue were considered, possibly explaining the variation in values between literature and the mass balance calculations.

The biogas produced is 724 litres per kg of VSS destroyed, exceeding the reported literature range of 400-600 L[24].This value falls beyond the specified literature range. The solids retention time (SRT) considered is 15 days. However, for the mass balance conducted in the thesis, an SRT of 20 days is employed. It is important to note that the solids retention time is indirectly proportional to the net mass of cell tissue produced per day. Simultaneously, the net mass of cell tissue produced per day is inversely proportional to the volume of methane generated.

The total dry solids per million liters per day (MLD) of wastewater are calculated to be 145 kg/MLD based on mass balance calculations. In China, reported dry sludge production is 150 kg/MLD, while in India, it is reported as 144 kg/MLD.[16] The per-person equivalent of dry sludge produced per day is 17g according to the mass balance. Similar mass balances have been performed in Italy, where the per-person equivalent of dry sludge produced per day for different reference plants was reported to be between 66-84g.[13] Per capita water consumption directly impacts the solids entering the plant as influents; furthermore, strict disposal regulations increase sludge production. The per capita water consumption in Nepal is taken as 117 litres, and for the study carried out in Italy, the per capita water consumption is considered as 215 litres.

The values obtained from the mass balance of the plant can be used to estimate both the sludge quantity and the methane yield for wastewater with similar characteristics. In this thesis, the results from the mass balance have been utilized to estimate the annual potential of methane and organic manure obtained from wastewater generated within the Kathmandu Valley for a period of 20 years from 2024 to 2044.

5.2 Wastewater Generated and Collected

The wastewater generated in the Kathmandu Valley for the year 2024 is estimated to be 224 MLD, while the wastewater collected is projected to reach 236 MLD in the same year. Uniformity in both wastewater generation and collection is anticipated post the year 2036, with the assumption that there will be 100% sewage coverage in the valley by that time. Wastewater generation experiences a consistent increase until 2034, attributed solely to the rising population in the valley. However, in 2034, a sudden surge in wastewater generation occurs due to the assumption of per capita water consumption being 150 Liters. This deviation breaks the uniform trend observed before and after 2034. These assumptions align with the SDG targets set by the government of Nepal.[19]

Research in the wastewater sector in Nepal has been limited, resulting in a scarcity of literature to validate the thesis findings. A study focused on the status and generation of wastewater in urban Nepal estimated wastewater generation with a per capita water demand of 100 liters. There exists a clear gap between supply and demand in the Kathmandu Valley. Therefore, relying solely on either water demand or water supply values does not accurately reflect actual per capita water use. A study conducted in the Kathmandu Valley aimed to calculate the actual quantity of water consumed, revealing that resident of low- and middle-income countries manage their own alternative sources to address supply deficits. For this thesis, per capita water use is based on actual consumption obtained from field research.[10] The accuracy of the estimation is further ensured by considering the population of respective districts within the valley and calculating their population increase based on district-wise growth rates. The calculated wastewater generation data can be useful for planning the required wastewater treatment plants in the valley. Wastewater sludge has the potential for energy recovery; thus, the management of wastewater not only solves the water pollution problem but also creates new sources of energy. In this thesis, using the benchmark values obtained from the mass balance and the estimated wastewater generation and collection values, the total annual yield of methane and organic manure generated from the wastewater plant has been estimated.

5.3 Potential Production of BioCNG

The BioCNG potential of wastewater generated per day is projected to be 5787 kg in the year 2024. In the same year, the BioCNG potential based on treatment is estimated at 628 kg, while the potential based on collection is 4577 kg. This BioCNG potential demonstrates an increasing trend over the study period, directly proportional to wastewater generation. By the conclusion of the study in the year 2044, the anticipated BioCNG potential based on both generation and collection is projected to reach 10684 kg, with an additional potential of 3087 kg based on treatment. Notably, there is a significant disparity between the amounts of BioCNG potential based on treatment and generation. This disparity not only contributes to the deterioration of the environmental conditions in the Bagmati River basin but also signifies a missed opportunity in harnessing energy from wastewater in the form of BioCNG.

In this thesis, digestor efficiency is assumed to be 60%. However, literature reports a VSS reduction value of 60% for primary sludge and 30% for secondary sludge, resulting in a combined reduction of 42%. [24]Therefore, the results obtained for the BioCNG production may be an overestimation.

As indicated in Section 1, the primary objective of this thesis is to present an alternative to fossil fuels in the transportation sector by substituting it with BioCNG produced from wastewater generated in the Kathmandu Valley. Diesel fuel stands as Nepal's primary imported commodity. The calorific value of one kilogram of BioCNG is determined to be 47.5 MJ. A study conducted in the Kathmandu Valley, focusing on electrifying public transportation, reveals that, on average, a bus covers 256 km in a day and consumes 101 liters of diesel. The calorific value of a liter of diesel is measured at 36.9 MJ. Consequently, a public bus in

Kathmandu would require a calorific value of 3723 MJ in a day. Based on the BioCNG potential of wastewater generated daily, a total calorific value of 274870 MJ can be obtained, which would be sufficient to operate 74 public buses each day. By the conclusion of the study period in the year 2044, it is estimated that 136 public buses can be operated. Further details on the estimation of the average distance and fuel consumption by public buses in Kathmandu, as well as the estimation for the number of buses that can be operated based on BioCNG, can be found in Annex IX.

5.4 Potential Production of Organic Manure

The potential organic manure production based on generation for the year 2024 is 62.1 tons per day. The potential production based on collection for the same year is 49.1 tons per day, and based on treatment is 6.7 tons per day. Looking ahead to the year 2044, the potential organic manure production based on generation and collection is 114.7 tons per day, with treatment accounting for 33.1 tons per day. The gap between generation and treatment mirrors that of BioCNG production.

The absence of a treatment plant for the collected wastewater is significant and requires immediate attention from the government to mitigate the adverse impacts of untreated wastewater disposal into the environment.

As highlighted in Section 1, the primary objective of this thesis is to complement the import of fertilizers with organic manure produced from wastewater generated in the Kathmandu Valley.

It is necessary to promote the adoption of Organic manure to serve as a complement to chemical fertilizers. While direct competition with chemical fertilizers is not feasible due to their substantial impact on crop yield, Organic Manure stands out as an excellent soil conditioner, capable of restoring soil fertility.

In the fiscal year 2079/2080, Nepal imported a total of 426,008 tons of fertilizers [25]. The fertilizer import of Nepal is insufficient to meet the demand generated within the country. Given the well-known adverse effects of chemical fertilizers on land, water, and human health, there is a growing awareness and push towards promoting organic products. This shift in focus aligns with the broader goal of encouraging sustainable and environmentally friendly agricultural practices.

The 22,667 tons of organic manure produced in the year 2024 can be utilized in the Kathmandu Valley and its surrounding areas. The amount of organic manure generated in the Kathmandu Valley represents 5% of the total fertilizer import in the year 2024. The detailed import data of Fertilizers can be found in Annex XI.

5.5 Financial Analysis of Anaerobic Digestion Plant

The capital cost for constructing the plant is Rs 205,997,697.39, with a total O&M cost of Rs 58,473,049.67 in the first year of operation. Generating a revenue of Rs 60,467,635.91 during the same period, the plant, fully financed by debt, has a Net Present Value (NPV) of Rs 240,416,222.37, an Internal Rate of Return (IRR) of 6.196%, and a payback period of 8 years.

The BioCNG price is determined by considering the price of diesel. This study incorporates the compression and bottling of BioCNG in the O&M cost. However, if bus operators purchase the BioCNG cylinders themselves and set up their own filling unit, significant cost reduction can be achieved.

In a technoeconomic study of co-digestion in Scandinavia, scenarios similar to the AD plant in this thesis were explored. Capital investments of €3.76 million and €4.44 million, operating costs of €2.36 million and €2.58 million, and revenues of €0.39 million and €0.49 million were reported.[26] However, the NPV in this context was €-25.6 million and €-27.1 million. Unlike the financially favorable conditions in Nepal, Scandinavia's scenario presents challenges, with O&M costs nearly equivalent to the initial capital outlay, and revenue unable to cover even 20% of the O&M costs.

Another technoeconomic study in Morocco showcased financial viability for a scenario similar to the AD plant in this thesis. With a capital cost of $711.78 million, O&M cost of $16.93 million, and revenue of $114.43 million, the NPV stood at $10.66 million, and the IRR at 10.14%. [27]Notably, this plant demonstrated financial sustainability, functioning without external government support.

In biobased economy, energy from the biomass is categorized as the least profitable product from biomass. Researchers have highlighted the importance of favorable policies and programs from the government in the form of subsidies or tax exemptions for machinery and equipment. Support from the government should not create market disruptions but create a ground from greener technologies to compete and sustain on the long run.[26]

These financial indicators align with findings from various international studies. Capital investment is contingent on technology and material selection, while O&M costs vary based on geographic location, raw material costs, and labor charges. Co-digestion has been identified as a means to enhance digestion efficiency and reduce costs by up to 30%.[28] The financial metrics provided in this thesis could pique the interest of both government and private sectors. Stable, long-term government policies, coupled with co-digestion of municipal organic waste, could transform the AD plant into a compelling investment opportunity for the private sector—a potential game-changer in revitalizing the Bagmati River Basin.

5.6 Sensitivity Analysis

The Sensitivity Analysis, considering Digestor Efficiency as the base term, and the Sensitivity Analysis, considering the Price of BioCNG as the base term, yield almost the same values. Digestor efficiency directly impacts methane yield; a 10% increase in efficiency results in a corresponding 10% increase in methane yield. Similarly, a 10% increase in the price of BioCNG may yield the same value if quantity is increased by 10%, while keeping the price constant. This suggests that the financial indicators show similar sensitivity to both the price of BioCNG and digestor efficiency.

The financial indicators are highly sensitive to the price of Organic Manure, with its sale contributing 65% to the plant's revenue. A mere 20% increase in the price of Organic Manure has the potential to transform the plant into a highly profitable venture, boasting an Internal Rate of Return (IRR) of 9.32% and achieving payback within just 6 years.

The financial indicators are highly sensitive to the capital cost of the plant. This cost represents a significant one-time investment required for the plant. Consequently, variations in the capital cost led to substantial changes in the values of financial indicators. The payback period, for instance, has been reduced to less than half the number of years with a capital cost fluctuation ranging from a 20% increment to a 20% decrement. Similarly, the internal rate of return (IRR) has also doubled under the same circumstances.

The positive impact of the subsidy is evident in the Sensitivity Analysis, with the subsidy as the base term. The provision of the subsidy has a positive effect on the financial indicators of the project. With the subsidy, the profitability of the biomass energy project can significantly improve. The payback period, with a 40% subsidy, is 5 years compared to 8 years without the subsidy. Additionally, the IRR of the project is 10.30% with a 40% subsidy, whereas it is 6.20% without the subsidy. The NPV has also seen improvement with a 40% subsidy, increasing from Rs 240,416,222.37 to Rs 356,019,606.37.

5.7 General Implications and Limitations

The analysis presented in the thesis may be subject to certain limitations and uncertainties, as certain assumptions made during the investigation warrant further scrutiny. The precision, dependability, or applicability of the results and deductions derived from this study may be influenced by these presumptions.

To begin, the mass balance calculations were executed for a complete mixed activated sludge process wastewater treatment plant. Subsequent estimations were based on benchmark values derived from these calculations, as this technology represents the sole functional wastewater treatment plant utilizing the activated sludge process. However, it is essential to acknowledge that the assumption of the entire treatment system within the Kathmandu Valley adopting the complete mixed activated sludge process might not be universally accurate. Other wastewater treatment technologies may be adopted, influenced by various factors, and the constraints of available space may render the completely mixed activated sludge process less preferable compared to more compact technologies.

Despite utilizing parameters from an actual wastewater treatment plant in Nepal, missing parameters were adapted from literature. Since the wastewater treatment plant in Nepal is not operating optimally, the results obtained from mass balance calculations could not be validated.

The estimation of wastewater generation in the Kathmandu Valley relies on population data, per capita water consumption, and wastewater generation as a percentage of water use. However, the possibility of omitting a segment of the population residing in the valley exists when considering only the population of districts based on census data. The assumption of per capita water use being 117 liters until 2033 and 150 liters beyond 2033 is based on field study data. The water consumption figure for 2034 and beyond is assumed, considering the completion of the second phase of the Melamchi drinking water project.

Similarly, the estimation of wastewater collection is based on the percentage of sewage coverage in the valley, assuming 100% coverage by 2035 as per the SDG targets. However, achieving this target may be challenging within the specified timeframe, and the increase in sewage coverage may not progress linearly as assumed in the thesis.

The bulk estimation of BioCNG and Organic Manure production over a 20-year period from 2024 to 2044 is computed using benchmark values from mass balance calculations. However, this estimation, employing the principle of the unitary method, may be debated as it does not consider factors influencing production based on scale. In reality, the efficiency of the digester and other factors impacting methane yield will vary based on the size of the digester and sludge characteristics, potentially resulting in overestimation or underestimation.

The financial model applied for the anaerobic digestion of wastewater sludge is adapted from a Waste to Energy plant using cow manure and chicken litter as substrates. An assumption is made that the costs associated with methane upgrading, compression, and bottling for vehicle use will be equivalent to the costs associated with bottling for cooking fuel.

The focus of this thesis has centered on technical and environmental aspects, without delving into the environmental and social impacts of sludge valorization in the Kathmandu Valley.

5.8 Recommendation for Future Research

Research in wastewater and sludge management in Nepal is virtually nonexistent, leaving significant gaps in knowledge and information dissemination. Several key domains necessitate further investigation, and the following recommendations for future research emerge:

1. Conduct a technical comparison of different activated sludge processes within the context of Nepal.
2. Undertake a financial analysis of anaerobic digestion plants, considering the entire spectrum of wastewater treatment costs.
3. Conduct a techno-economic study on the co-digestion of the organic fraction of municipal waste with sewage sludge.
4. Perform a techno-economic study on the bio methanation process in the anaerobic digestion of sewage sludge.
5. Conduct a life cycle analysis of the anaerobic digestion process and biogas upgrading for use in internal combustion engine (ICE) vehicles.
6. Evaluate the economic impact of centralized sludge valorization in districts without sewage coverage.
7. Conduct a techno-economic assessment of both centralized and decentralized sludge valorization in areas lacking sewage connections.

These research recommendations aim to address the existing knowledge gaps, enhance the understanding of wastewater and sludge management in Nepal, and contribute valuable insights to sustainable practices in this critical field.

6 Conclusion

In summary, this research addresses wastewater and sludge management in Kathmandu Valley from 2024 to 2044, revealing the potential of Anaerobic Digestion (AD). Wastewater generation is projected to increase from 299 MLD in 2024 to 551 MLD in 2044, necessitating innovative solutions.

The integration of wastewater treatment plants (WWTPs) with AD plants emerges as a promising approach, offering environmental and economic benefits. BioCNG produced could efficiently power 74 buses in 2024, expanding to 136 buses by 2044. Additionally, the 22,667 Mt of Organic Manure in 2024 constitutes 5% of Nepal's total fertilizer import in 2023.

Financial analysis of an 80 TPD AD plant shows a positive NPV of Rs 240,416,222.37, an IRR of 6.196%, and a PBP of 8 years. Sensitivity analysis underscores the importance of factors like digestor efficiency, BioCNG and Organic Manure prices, capital costs, and subsidies.

This thesis establishes a technical and economic foundation for WWTPs coupled with AD plants in Kathmandu Valley, providing an environmentally sustainable solution to preserve the Bagmati River basin. It also lays the groundwork for a viable market for AD technology in Nepal, contributing to a circular economy aligned with global sustainability goals.

References

[1] "Nepal's Sustainable Development Goals Baseline Report National Planning Commission, Government of Nepal," 2017. [Online]. Available: www.npc.gov.np

[2] "Status and Roadmap: 2016-2030 N E P A L Sustainable Development Goals N AT I O N A L P L A N N I N G C O M M I S S I O N K AT H M A N D U."

[3] A. Ishtiaque, M. Shrestha, and N. Chhetri, "Rapid urban growth in the kathmandu valley, nepal: Monitoring land use land cover dynamics of a himalayan city with landsat imageries," *Environments - MDPI*, vol. 4, no. 4, pp. 1–16, Dec. 2017, doi: 10.3390/environments4040072.

[4] J. C. Davids *et al.*, "Quantifying the connections—linkages between land-use and water in the Kathmandu Valley, Nepal," *Environ Monit Assess*, vol. 190, no. 5, May 2018, doi: 10.1007/s10661-018-6687-2.

[5] S. P. Lohani, M. Keitsch, S. Shakya, and D. Fulford, "Waste to energy in Kathmandu Nepal—A way toward achieving sustainable development goals," *Sustainable Development*, vol. 29, no. 5. John Wiley and Sons Ltd, pp. 906–914, Sep. 01, 2021. doi: 10.1002/sd.2183.

[6] Ramshahpath, *National Population and Housing Census 2021 (National Report) National Statistics Offi ce*. [Online]. Available: www.censusnepal.cbs.gov.np

[7] Y. Ren, L. Shen, J. Wang, and Y. Wu, "How to address properly the scale of urban infrastructures? –An empirical study of 35 large Chinese cities," *Habitat Int*, vol. 118, Dec. 2021, doi: 10.1016/j.habitatint.2021.102464.

[8] "Kathmandu Upatyaka Khanepani Limited," 2079.

[9] S. Adhikary and S. P. Sharma, "In Pursuit of Safe Sanitation Services: Governing Fecal Sludge Management in Nepal," 2021.

[10] S. Shrestha *et al.*, "Dynamics of domesticwater consumption in the Urban area of the kathmandu valley: Situation analysis pre and post 2015 Gorkha Earthquake," *Water (Switzerland)*, vol. 9, no. 3, 2017, doi: 10.3390/w9030222.

[11] "Federal Democratic Republic of Nepal Ministry of Water Supply Federal Democratic Republic of Nepal Data Collection Survey on Water Supply and Waste Water Sector in Nepal Final Report Federal Democratic Republic of Nepal Data Collection Survey on Water Supply and Waste Water Sector in Nepal Final Report Federal Democratic Republic of Nepal Data Collection Survey on Water Supply and Waste Water Sector in Nepal Final Report," 2019.

[12] P. Udmale, H. Ishidaira, B. R. Thapa, and N. M. Shakya, "The status of domestic water demand: Supply deficit in the Kathmandu Valley, Nepal," *Water (Switzerland)*, vol. 8, no. 5, 2016, doi: 10.3390/w8050196.

[13] G. Mininni, G. Laera, G. Bertanza, M. Canato, and A. Sbrilli, "Mass and energy balances of sludge processing in reference and upgraded wastewater treatment plants," *Environmental Science and Pollution Research*, vol. 22, no. 10, pp. 7203–7215, May 2015, doi: 10.1007/s11356-014-4013-2.

[14] K. Wang and T. Nakakubo, "Strategy for introducing sewage sludge energy utilization systems at sewage treatment plants in large cities in Japan: A comparative assessment," *J Clean Prod*, vol. 316, Sep. 2021, doi: 10.1016/j.jclepro.2021.128282.

[15] M. C. Samolada and A. A. Zabaniotou, "Comparative assessment of municipal sewage sludge incineration, gasification and pyrolysis for a sustainable sludge-to-energy management in Greece," *Waste Management*, vol. 34, no. 2, pp. 411–420, Feb. 2014, doi: 10.1016/j.wasman.2013.11.003.

[16] V. Singh, H. C. Phuleria, and M. K. Chandel, "Estimation of energy recovery potential of sewage sludge in India: Waste to watt approach," *J Clean Prod*, vol. 276, Dec. 2020, doi: 10.1016/j.jclepro.2020.122538.

[17] O. Al Samsami, T. Etri, and M. Baawain, "Characterization of sewage sludge in Muscat and estimation of their energy recovery," *Sustainable Energy Technologies and Assessments*, vol. 58, Aug. 2023, doi: 10.1016/j.seta.2023.103351.

[18] C. A. Ogbu, T. Alexiou Ivanova, T. A. Ewemoje, C. O. Okolie, and H. Roubík, "Techno-economic analysis of electricity generation from household sewage sludge in different regions of Nigeria," *Science of the Total Environment*, vol. 903, Dec. 2023, doi: 10.1016/j.scitotenv.2023.166554.

[19] "Federal Democratic Republic of Nepal Ministry of Water Supply Federal Democratic Republic of Nepal Data Collection Survey on Water Supply and Waste Water Sector in Nepal Final Report Federal Democratic Republic of Nepal Data Collection Survey on Water Supply and Waste Water Sector in Nepal Final Report Federal Democratic Republic of Nepal Data Collection Survey on Water Supply and Waste Water Sector in Nepal Final Report," 2019.

[20] L. Appels, J. Baeyens, J. Degrève, and R. Dewil, "Principles and potential of the anaerobic digestion of waste-activated sludge," *Progress in Energy and Combustion Science*, vol. 34, no. 6. pp. 755–781, Dec. 2008. doi: 10.1016/j.pecs.2008.06.002.

[21] Q. Sun, H. Li, J. Yan, L. Liu, Z. Yu, and X. Yu, "Selection of appropriate biogas upgrading technology-a review of biogas cleaning, upgrading and utilisation," *Renewable and Sustainable Energy Reviews*, vol. 51. Elsevier Ltd, pp. 521–532, Jul. 06, 2015. doi: 10.1016/j.rser.2015.06.029.

[22] I. Ullah Khan *et al.*, "Biogas as a renewable energy fuel – A review of biogas upgrading, utilisation and storage," *Energy Conversion and Management*, vol. 150. Elsevier Ltd, pp. 277–294, 2017. doi: 10.1016/j.enconman.2017.08.035.

[23] A. S. O. Ogunjuyigbe, T. R. Ayodele, and M. A. Alao, "Electricity generation from municipal solid waste in some selected cities of Nigeria: An assessment of feasibility, potential and technologies," *Renewable and Sustainable Energy Reviews*, vol. 80. Elsevier Ltd, pp. 149–162, 2017. doi: 10.1016/j.rser.2017.05.177.

[24] P. Foladori, G. Andreottola, and G. Ziglio, "Sludge Reduction Technologies in Wastewater Treatment Plants."

[25] "NEPAL FOREIGN TRADE STATISTICS." [Online]. Available: www.customs.gov.np

[26] C. Fernando-Foncillas and C. Varrone, “Potential of the sewage sludge valorization in Scandinavia by co-digestion with other organic wastes: A techno-economic assessment,” *J Clean Prod*, vol. 324, Nov. 2021, doi: 10.1016/j.jclepro.2021.129239.

[27] M. El Ibrahimi, I. Khay, A. El Maakoul, and M. Bakhouya, “Techno-economic and environmental assessment of anaerobic co-digestion plants under different energy scenarios: A case study in Morocco,” *Energy Convers Manag*, vol. 245, Oct. 2021, doi: 10.1016/j.enconman.2021.114553.

[28] W. E. Tan, P. Y. Liew, C. P. C. Bong, Y. van Fan, L. S. Tan, and N. R. Jamian, “Life Cycle Assessment and Techno-Economic Assessment of Anaerobic Co-Digestion: A Short Review,” *Chemical Engineering Transactions*, vol. 88. Italian Association of Chemical Engineering - AIDIC, pp. 907–912, 2021. doi: 10.3303/CET2188151.

Annex