FRAMEWORK FOR MULTISTAGE PRE-TREATMENT OF ANAEROBIC DIGESTION FOR MAXIMIZING ELECTRICAL ENERGY PRODUCTION

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To My beloved mother, wife and daughters (Hania, Tayyiba and Humna) for their enduring love, sacrifice, patience, encouragement and best wishes.

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ABSTRACT

Anaerobic digestion (AD) is a complex process involving several dependent variables. Among critical factors are pH value, temperature and type of pre-treatment of raw material. The change in these parameters affects the overall performance of the system in terms of biogas and methane yield, resulting into varying power output. Different pre-treatments of biomass have different impact on the kinetics of AD. Therefore, the overall electrical output power varies with varying the type of pre-treatment and to which extent it is used. In this regard, most of the existing approaches focused only on the multistage reactor design and economic evaluations with single pre-treatment technique. They did not consider the effect of multistage pre-treatment techniques on electrical power output. This research proposes a novel methodology of multistage pre-treatment of organic matters which has the potential to increase the power output from AD to its maximum. The modelling of most common pre-treatment techniques (chemical, mechanical and thermal pre-treatments) of organic matters is presented to calculate the effect of these treatments on the electrical energy production. A framework is developed to evaluate the whole process from pre-treatment to the power output. Multistage pre-treatment is proposed in this research to enhance the electrical energy production from AD. The first order kinetic model of AD is used to calculate the biogas and methane yields and electrical energy as existing literature illustrates that this model is a good choice acceptably for the solution of chemical reactions involved in AD. Three different pre-treatment scenarios, AD with single pre-treatment (Case 1), AD with two stage pre-treatment (Case 2) and AD with three stage pre-treatment (Case 3) are considered for the application of the proposed methods. The proposed scenarios are simulated to use different possible number of combinations in all three pre-treatment cases. The highest production of electrical energy achieved was 0.62 kWh, 0.75 kWh and 0.87 kWh for 1 kg of animal wastes for Case 1, Case 2 and Case 3 respectively. The results are compared with the experimental results of pilot scale plant and Anaerobic Digestion Model No. 1 (ADM1). This shows that biogas, methane yield and electrical energy output can be enhanced to approximately two fold by using multistage pre-treatment. The proposed technique is useful for the prediction of bioenergy yield for different organic matters as well as for other bioenergy conversion routes.

ABSTRAK

Pencernaan anaerobik (AD) adalah satu proses yang kompleks yang melibatkan beberapa pembolehubah bersandar. Antara faktor kritikal adalah nilai pH, suhu dan jenis pra-rawatan bahan mentah. Perubahan parameter ini memberi kesan kepada prestasi keseluruhan sistem dari segi hasil biogas dan metana, mengakibatkan pelbagai kuasa keluaran. Pra-rawatan biojisim yang berbeza mempunyai kesan yang berbeza pada kinetika AD. Oleh itu, kuasa keluaran elektrik keseluruhan berbeza dengan perubahan jenis pra-rawatan dan sejauh mana ia digunakan. Dalam hal ini, sebahagian besar daripada pendekatan yang sedia ada hanya memberi tumpuan kepada reka bentuk reaktor berbilang dan penilaian ekonomi dengan teknik pra-rawatan tunggal. Mereka tidak mengambil kira kesan teknik pra-rawatan berbilang terhadap kuasa keluaran elektrik. Kajian ini mencadangkan satu kaedah baru pra-rawatan berbilang bahan organik yang mempunyai potensi untuk meningkatkan kuasa keluaran dari AD ke maksimum. Pemodelan teknik pra-rawatan yang paling biasa (pra-rawatan kimia, mekanikal dan haba) bagi bahan organik dikemukakan untuk mengira kesan rawatan ini pada penghasilan tenaga elektrik. Satu rangka kerja dibangunkan untuk menilai keseluruhan proses dari pra-rawatan kepada kuasa keluaran. Pra-rawatan berbilang adalah dicadangkan dalam kajian ini untuk meningkatkan pengeluaran tenaga elektrik daripada AD. Model kinetik peringkat pertama AD digunakan untuk mengira penghasilan biogas metana dan tenaga elektrik sebagaimana literatur yang sedia ada menunjukkan bahawa model ini adalah pilihan yang boleh diterima untuk penyelesaian tindak balas kimia yang terlibat dalam AD. Tiga keadaan pra-rawatan yang berbeza, AD dengan pra-rawatan tunggal (Kes 1), AD dengan dua peringkat pra-rawatan (Kes 2) dan AD dengan tiga peringkat pra-rawatan (Kes 3) dipertimbangkan untuk aplikasi kaedah yang dicadangkan. Senario yang dicadangkan disimulasikan untuk menggunakan beberapa kombinasi yang berbeza dalam ketiga-tiga kes pra-rawatan. Pengeluaran tertinggi tenaga elektrik adalah 0.62 kWh, 0.75 kWh dan 0.87 kWh untuk 1 kg sisa haiwan untuk Kes 1, Kes 2 dan Kes 3. Hasilnya dibandingkan dengan hasil eksperimen loji skala perintis dan Model Pencernaan Anaerobik No. 1 (ADM1). Ini menunjukkan bahawa biogas, hasil metana dan keluaran tenaga elektrik boleh ditingkatkan kepada kira-kira dua kali ganda dengan menggunakan pra-rawatan pelbagai peringkat. Teknik yang dicadangkan ini berguna untuk ramalan hasil biotenaga untuk pelbagai perkara organik dan juga untuk laluan penukaran biotenaga yang lain.

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LIST OF ABBREVIATIONS

AD	-	Anaerobic Digestion
ADM1	-	Anaerobic Digestion Model No 1
AEDB	-	Alternative Energy Development Board
AFEX	-	Ammonia Fibre Expansion
ARP	-	Ammonia Recycled Percolation
ASABE	-	American Society of Agriculture and Bio Engineers
BOD	-	Biochemical Oxygen Demand
BVS	-	Biodegradable Volatile Solids
C-M-T	-	Chemical-Mechanical-Thermal
C-T-M	-	Chemical-Thermal-Mechanical
C-T-M	-	Chemical-Thermal-Mechanical
COD	-	Chemical Oxygen Demand
C/N	-	Carbon to Nitrogen Ratio
CRE	-	Combustible Renewable Energy
CSTR	-	Continuous Stirred Tank Reactor
DAE	-	Differential and Algebra Equations
EJ	-	Exa Joule
FIS	-	Fuzzy Inference System
FL	-	Fuzzy Logic
GDP	-	Gross Domestic Product
GHG	-	Green House Gas
HRT	-	Hydrolic Retention Time
IWA	-	International Water Association
LFG	-	Landfilled Gas
LHW	-	Liquid Hot Water
LHV	-	Lower Heating Value
MIMO	-	Multi Input Multi Output
MSW	-	Municipal Solid Waste
M-T-C	-	Mechanical-Thermal-Chemical
M-C-T	-	Mechanical-Chemical-Thermal

MW	-	Mega Watt
NPV	-	Net Present Value
ODE	-	Ordinary Differential Equation
OLR	-	Organic Loading Rate
PH	-	potential Hydrogen
PI	-	Proportional Integration
PID	-	Proportional integration derivative
PKR	-	Pakistani Rupee
PT	-	Pre-treatment Techniques
PV	-	Photo Voltaics
RES	-	Renewable Energy Sources
RMSE	-	Root Mean Square Error
SCOD	-	Chemical Oxygen Demand
SRT	-	Solid Retention Time
SS-AD	-	Solid State- Anaerobib Digestion
SSGPL	-	Sui Southern Gas Pipeline Ltd.
TCOD	-	Chemical oxygen Demand
T-M-C	-	Thermal-Mechanical-Chemical
T-C-M	-	Thermal-Chemical-Mechanical
TOPSIS	-	Technique of Order of Preference by Similarity Ideal
TPES	-	Total Primary Energy Supply
TS	-	Total Solids
UASB	-	Upflow Anaerobic Sludge Blanket
VFA	-	Volatile Fatty Acid Solids
VS	-	Volatile Solids
VFA	-	Volatile Fatty Acids

LIST OF SYMBOLS

A_f	-	Acidity constant
B_0	-	Biodegradibility constant
b	-	Kinetic parameter
^oC	-	Degree Centigrade
$CO2$	-	Carbon Dioxide
dV	-	Change in Volume
dt	-	Change in time
S	-	Substrate concentration
S_0	-	Initial Substrate concentration
K_s	-	Monod constant
μ	-	Specific growth rate
$\mu_m ax$	-	Maximum specific growth rate
ρ	-	Density
P	-	Pressure
V	-	Volume
n	-	No. of moles of substance
R	-	Universal Gas constant
T	-	Absolute Gas Temperature
$q_{in,i}$	-	flow rate of input
$q_{out,i}$	-	flow rate of output
θ	-	Density
Q_{gas}	-	Gas flow rate
H_2	-	Hydrogen
CH_4	-	Methane
X	-	Bacterial culture
B_0	-	Biodegradibility
A_f	-	Acid factor
k_d	-	Death rate constant
μ_c	-	Death rate
P	-	Gas pressure

V	-	Volume of digester
Cu	-	Copper
N	-	Nitrogen
Mn	-	Manganese
Zn	-	Zinc
P	-	Phosphorus
k_m	-	Hydrolysis constant
X_p	-	Disintegration of Proteins
E_a	-	Activation energy
P_{out}	-	Output Power
P_{in}	-	Input Power

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CHAPTER 1

INTRODUCTION

1.1 Research background

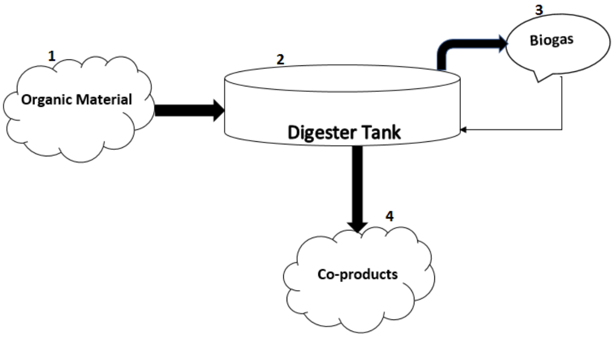
The primary and the most universal measure of all kinds of work by human beings and nature is energy. Everything happens in the world is the expression of flow of energy in one of its forms. Therefore, energy exhibits an important role in social as well as economic growth by maintaining living standard. At present, energy from conventional fossil fuels fulfils about 80 % of demand globally [1]. However, with the passage of time, these conventional types of sources are exhausting for energy generation. This imbalance between energy supply and demand diversifies the world to explore other sources for energy generation [2]. This situation leads to the use of non-conventional renewable energy sources (RES), which are abundant in nature. According to International Energy Agency, conventional energy sources, such as oil and petroleum, are still the most important sources of energy followed by gas and coal. About 80% of Total Primary Energy Supply (TPES) is met by these fossil fuels [3]. Combustible renewable energy (CRE) is the next key contributor, which contributes approximately 10% of TPES share all over the world .

Currently, renewable energy sources (RES) are contributing more at present [3]. According to the statistics of world energy council, if the satisfactory policy initiatives are continued to deliver till 2025, renewable sources will be capable to fulfill 60 % of electricity supplies and 30 % use of direct fossil fuels globally. Indigenous conventional energy resources are already exploited at their maximum [4]. The leading countries in bioenergy production are Finland, Austria and Germany. Currently, it is reported that bioenergy is contributing 20 %, 7 % and 5 % in Finland, Austria, and Germany respectively [5]. These countries are eager to expand total share of power from biomass. Thus, ultimate solution is to focus the methods which are capable for providing enhanced electrical power production from the raw wastes.

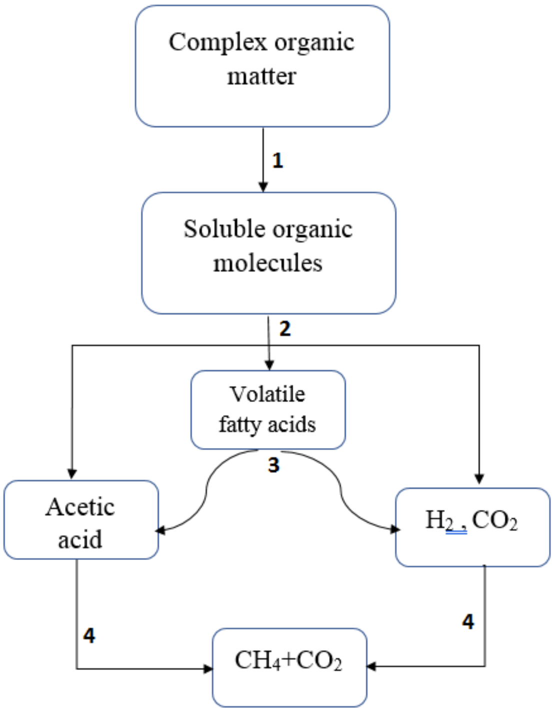
Biogas is the gas produced as a result of anaerobic digestion (AD) of raw wastes. Biogas typically refers to a gas produced by the biochemical degradation of organic substance in the absence of oxygen. This process is known as anaerobic digestion (AD). Biogas, the output of the process, is generated from biogenic material and is used as a type of renewable fuel. There are several reasons for increased use of biogas as a fuel worldwide. These are listed as follows:

1. The fossil fuel cost and taxation are increasing gradually and the users have to bear the increased cost.
2. The potential of different renewable energy sources have been explored a lot for the last decade.
3. The gas generated from anaerobic digestion, mainly methane, is one of the main reasons of the well known greenhouse gas (GHG) effect.
4. The biogas generation is possible from small scale (1 m^3) to large scale (tens of m^3) and is especially useful in remote areas where it is difficult to supply energy.
5. The simple anaerobic digester is easy to build using raw materials, easily available in towns if a few simple design rules are followed.

The biodegradation of organic matters results in the production of biogas. The organic materials include biomass, sewage, green waste, energy crops and municipal waste [6]. Figure 1.1a shows the schematic paradigm of the anaerobic digestion process. There are four main features and parts of the standard process as highlighted with numbers (1,2,3,4).



(a)



(b)

Figure 1.1: Anaerobic digestion process (a) Schematic diagram of Anaerobic Digestion (AD) process (b) Processes involved in AD

The output biogas primarily is a mixture of carbon dioxide and methane. Biogas can also be produced by gasification of wood or other biomass material and is called wood gas. This type of biogas contains mainly hydrogen, nitrogen,and carbon monoxide with trace amounts of methane [7]. The gases obtained from the degradation of other materials are hydrogen, methane, carbon dioxide and carbon monoxide and these are oxidized or combusted with oxygen. The amount of energy released from oxidation or combustion facilitates biogas to be used as a fuel for transportation or to convert it into other form of useful energy. Biogas can be used as a low cost fuel for several purposes like cooking, transportation and electrical energy production. [8].

In modern world, it is beneficial in waste management services where it is used as fuel to run heat engine to generate either electrical or mechanical power. Like a natural gas, the compression of biogas can be accomplished and is used to power motor vehicles as vehicular fuel. For example, England is projected to have the potential to replace about 17% of vehicular fuel. Biogas is a renewable fuel, so it qualifies for renewable energy subsidies in some parts of the world. A biogas plant includes an anaerobic digester that uses dairy manure, farm waste and different crops to be processed. Biogas can be produced utilizing anaerobic digesters. The organic matters undergoes the different sub-processes in the digester namely hydrolysis, acidogenesis, acetogenesis and methanogenesis as shown in Figure 1.1b. These digesters can also be fed with different biomass feedstock such as energy crops or biodegradable organic wastes including sewage sludge and food waste.

Biogas is produced by organic waste diluted with water. The organic waste is decomposed under anaerobic conditions in a digester or landfill. The biomass feedstock is covered and compressed mechanically and by the weight of the material that is deposited from above. This material prevents oxygen from accessing the waste and anaerobic microbes thrive. This gas produced is slowly released into the environment and causes greenhouse gas effect if the digester plant has not been engineered to capture the gas.

1.2 Problem statement

The increased interest in biochemical processes has simulated mathematical modelling because it is typically much faster and less expensive to model a process and to simulate its operation. While, the conventional digestion process, directly accepting raw waste, needs a long retention time and has a low volatile solids (VS) removal rate. So, the digestion of biomass waste by conventional methods could not give satisfied results. It is pointed out that hydrolysis is the rate-limiting step in the complex anaerobic digestion process [9]. Under this principle, pre-treatment of biomass is necessary to compensate the limited rate constant. The different pre-treatments techniques including chemical, mechanical, biological, thermal and ultrasonic may be used as methods to improve the rate-limiting hydrolysis.

The modelling of AD with pre-treatment techniques requires the careful consideration of the parameters involved during the techniques. The time and the temperature are among one of them. For example, in thermal treatment, the organic matters should be heated up to 'how much temperature'. Hence, the utilization of appropriate pre-treatment at the right time for the right time prior to AD is the question which has to be answered. In this regard, it is investigated and established that the pre-treatments techniques of anaerobic digestion of wastes can enhance the biogas yield and increased electrical power can be achieved. Different pre-treatment technologies were evaluated by researchers in different time periods. The chemical, thermal and mechanical treatments prior to the digestion can increase the energy contents of the organic matters.

In addition, different pre-treatment techniques if used simultaneously on biomass waste may give more bioenergy as compared to that with single pre-treatment. Therefore, advanced multistage pre-treatment methodologies are necessary to get the maximum from minimum. At the same time, the determination of electrical energy output and efficiency of the digester of pre-treated material is also not straight forward, since many parameters need to be carefully considered.

1.3 Motivation

Pakistan is facing severe economic crisis due to continuously growing gap between energy demand and supply. The shortage in power and gas supply has already ceased many industrial sectors such as textile, small and medium enterprises and local transportation. The government has spent US $ 9 billion on energy import during 2008–2009 to fulfill current energy requirements. Indigenous energy resources, mainly fossil fuels, have been already exploited at their peaks. Energy demand is expected to become double during the next decade. Figure 1.2 shows the energy consumption in Pakistan by sector wise. It is obvious that the domestic sector is the main consumer of energy and it is approximately 50 % energy consumed by this sector. As the population increases day by day, the domestic sector will need more energy to be consumed. Thus, renewable and sustainable energy resources, such as biomass, wind and solar need to be exploited so that a sustainable energy mix could be employed to ensure energy security. Biomass and bioenergy is one of the renewable energy sources that must be carried out throughout the country.

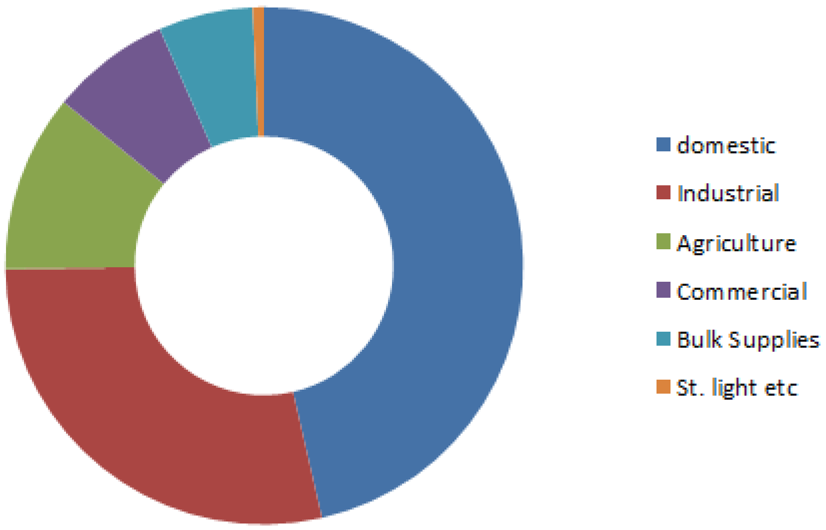


Figure 1.2: Energy Consumption in Pakistan

It is reported that if the available renewable sources is exploited with planning, Pakistan may get rid of the current energy crisis immediately [10]. The limitation in the path of utilizing the renewable energy potential is discussed in [11]. The solutions of the barrier in the penetration of renewable technology are discussed in [12,13]. Still the renewable technologies are not fully penetrating globally, especially in Pakistan [14]. There is a need to utilize the RES at its peak [15, 16].

1.4 Research objectives

The objectives of the research are :

1. To develop a framework for the improvement of anaerobic digestion process to assess the effect of multistage pre-treatments on biomass feedstock for the enhanced methane yield and the electrical energy output.
2. To model three types of pre-treatment techniques to get enhanced bioenergy from the anaerobic digestion process in thermophilic and mesophilic temperature conditions.

3. To apply the proposed framework on multiple stage pre-treatments scenarios with different biomass feedstock used and verify the results by comparing with previous relative research work.

1.5 Scopes of research

The scopes of this research are:

1. The biogas yield for temperature range from 0 ° C to 10 ° C (ambient temperature) is not considered in this research.
2. The concentration of slurry is uniform throughout surface area of the reactor.
3. The volume of the anaerobic digester is kept constant for comparison purpose.
4. The energy output from AD is different for diffrent biomass materials. The present research takes account only animal manure as biomass source.
5. The composition of waste considers only carbon (C), hydrogen (H) and oxygen (O). Other substances like nitrogen and sulphur are not considered.

1.6 Significance of research

The present research offers a paradigm move in pre-treatment techniques used for maximizing energy output from AD process. A significant research has been done on combined pre-treatment techniques of different biomass feedstock to date. However, most researches in this field focused only the sequential reactor design with single pre-treatment techniques. In contrast, present research introduces the new concept of using two or more level of pre-treatment techniques in anaerobic digestion process. The implementation of such concepts present significant modeling and design challenges that have been appropriately addressed in this research. In addition, this research proposes a framework that evaluates three different type of pre-treatment scenarios, single pre-treatment, two stage pre-treatment and three stage pre-treatment prior to AD. In order to explore the effectiveness of the proposed framework design, these techniques are applied on each pre-treatment scenario with varying number of pre-treatment and are validated by comparing the outcomes with previous research work.

Pakistan, being an agricultural country, is facing severe load shedding especially in summer season. The rural areas of the country is facing 12 hour load shedding per day. This research emphasizes the use of biomass as a major source of renewable energy generation. The raw waste is abundant in nature in Pakistan. The country can cop the problem of load shedding by efficient utilization of biomass resources. The present research provides a method to maximize the electrical energy production by incorporating different pre-treatment methods on different biomass feedstock. In this way, the country can get a balance between energy production and demand. This research work will also help to look a deep insight for maximizing energy output from AD process with pre-treatment techniques.

1.7 Organization of thesis

This thesis is organized into five chapters, namely the introduction, literature review, research methodology, results and discussion, and conclusion and future recommendations. Their contents are outlined as follows:

Chapter 2 analyzes availability of different feedstock in developing countries, discusses its utilization to produce energy and different factors that affects the performance of AD technology. The pre-treatment techniques used so far is also given in this chapter. The critical review of the modelling of AD is highlighted in Chapter 2. The merits and drawbacks of each AD model are highlighted. The benefits of applying pre-treatment techniques prior to AD process are stressed.

Chapter 3 aims to focus the framework of anaerobic digestion process which includes pre-treatment modelling, anaerobic digestion modelling and power modelling. The bench mark experimental results are also included in this chapter. In this chapter, research flow charts are proposed to predict the biogas yield from AD technology with multistage pre-treatment techniques used.

Chapter 4 discusses and compares the results of proposed research finding with the Anaerobic Digestion Model No.1 (ADM1) for three cases. Case 1 comprises of single stage pre-treatment AD with three possible combinations. Case 2 has the two stage pre-treatment AD with six possible combinations while case 3 comprises of three stage pre-treatment AD with ten possible combinations. Each combination is evaluated in comparison with ADM1 in terms of kWh production per day for one kilogram of manure.

Chapter 5 concludes the discussion of the work undertaken and highlights the contributions of this research. Several suggestions are recommended for possible directions of future work.

REFERENCES

1. Raheem, A., Hassan, M. Y. and Shakoor, R. Pecuniary Optimization of Biomass/Wind Hybrid Renewable System. *Proceedings of the 1st Int. Electron. Conf. on Energies, 14-31 March 2014;*. Sciforum Electronic Conference Series, Vol. 1, 2014 , c006;. 1–10.

2. Shaahid, S. M. Review of research on autonomous wind farms and solar parks and their feasibility for commercial loads in hot regions. *Renewable and Sustainable Energy Reviews*, 2011. 15(8): 3877–3887.

3. Shakoor, R., Hassan, M. Y., Raheem, A., Rasheed, N. and Na, M. Wind Farm Layout Optimization by Using Definite Point Selection and Genetic Algorithm. *2014 IEEE conference on Power and Energy (PECon)*. 2014. 191–195.

4. Rehman, M. S. U., Rashid, N., Saif, A., Mahmood, T. and Han, J.-I. Potential of bioenergy production from industrial hemp (Cannabis sativa): Pakistan perspective. *Renewable and Sustainable Energy Reviews*, 2013. 18: 154–164.

5. Baños, R., Manzano-Agugliaro, F., Montoya, F. G., Gil, C., Alcayde, a. and Gómez, J. Optimization methods applied to renewable and sustainable energy: A review. *Renewable and Sustainable Energy Reviews*, 2011. 15(4): 1753–1766.

6. Amer, M. and Daim, T. U. Energy for Sustainable Development Selection of renewable energy technologies for a developing county : A case of Pakistan. *Energy for Sustainable Development*, 2011. 15(4): 420–435.

7. Maghanaki, M. M., Ghobadian, B., Najafi, G. and Galogah, R. J. Potential of biogas production in Iran. *Renewable and Sustainable Energy Reviews*, 2013. 28: 702–714.

8. Van Haren, M., Fleming, R. *et al.* Electricity and Heat Production Using Biogas from the Anaerobic Digestion of Livestock Manure-Literature Review. *N0P 2C0, Ridgetown College, University of Guelph, Ontario, Canada*, 2005.

9. Appels, L., Lauwers, J., Degrève, J., Helsen, L., Lievens, B., Willems, K., Van Impe, J. and Dewil, R. Anaerobic digestion in global bio-energy production: Potential and research challenges. *Renewable and Sustainable Energy Reviews*, 2011. 15(9): 4295–4301.

10. Sheikh, M. A. Renewable energy resource potential in Pakistan. *Renewable and Sustainable Energy Reviews*, 2009. 13(9): 2696–2702.

11. Sahir, M. H. and Qureshi, A. H. Assessment of new and renewable energy resources potential and identification of barriers to their significant utilization in Pakistan. *Renewable and Sustainable Energy Reviews*, 2008. 12(1): 290–298.

12. Mirza, U. K., Ahmad, N., Harijan, K. and Majeed, T. Identifying and addressing barriers to renewable energy development in Pakistan. *Renewable and Sustainable Energy Reviews*, 2009. 13(4): 927–931.

13. Khattak, N., Hassnain, S. R., Shah, S. W. and Mutlib, A. Identification and Removal of Barriers for Renewable Energy Technologies in Pakistan. 2006. (November): 13–14.

14. Negro, S. O., Alkemade, F. and Hekkert, M. P. Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renewable and Sustainable Energy Reviews*, 2012. 16(6): 3836–3846.

15. Panwar, N., Kaushik, S. and Kothari, S. Role of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews*, 2011. 15(3): 1513–1524.

16. Lund, P. D. Effects of energy policies on industry expansion in renewable energy. *Renewable Energy*, 2009. 34(1): 53–64.

17. John, R. P., Anisha, G. S., Nampoothiri, K. M. and Pandey, A. Micro and macroalgal biomass: a renewable source for bioethanol. *Bioresource technology*, 2011. 102(1): 186–93.

18. International Energy Agency, Wind 2012 Annual Report, 2012.

19. Butt, S., Hartmann, I. and Lenz, V. Bioenergy potential and consumption in Pakistan. *Biomass and Bioenergy*, 2013. 58: 379–389.

20. Farooq, M. K. and Kumar, S. An assessment of renewable energy potential for electricity generation in Pakistan. *Renewable and Sustainable Energy Reviews*, 2013. 20: 240–254.

21. Ministry of Finance, Pakistan Economic Survey 2014-2015, 2015.

22. Bond, T. and Templeton, M. R. History and future of domestic biogas plants

in the developing world. *Energy for Sustainable Development*, 2011. 15(4): 347–354.

23. Brown, D., Shi, J. and Li, Y. Comparison of solid-state to liquid anaerobic digestion of lignocellulosic feedstocks for biogas production. *Bioresource technology*, 2012. 124: 379–86.

24. Taiganides, E. Composting of feedlot wastes. *Animal Wastes*, 1977: 241–251.

25. Chandra, R., Takeuchi, H. and Hasegawa, T. Hydrothermal pretreatment of rice straw biomass: a potential and promising method for enhanced methane production. *Applied Energy*, 2012. 94: 129–140.

26. Yao, Y., He, M., Ren, Y., Ma, L., Luo, Y., Sheng, H., Xiang, Y., Zhang, H., Li, Q. and An, L. Anaerobic digestion of poplar processing residues for methane production after alkaline treatment. *Bioresource technology*, 2013. 134: 347–52.

27. Zhu, J., Wan, C. and Li, Y. Enhanced solid-state anaerobic digestion of corn stover by alkaline pretreatment. *Bioresource technology*, 2010. 101(19): 7523–8.

28. Kong, F., Engler, C. R. and Soltes, E. J. Effects of cell-wall acetate, xylan backbone, and lignin on enzymatic hydrolysis of aspen wood. *Applied biochemistry and biotechnology*, 1992. 34(1): 23–35.

29. He, Y., Pang, Y., Liu, Y., Li, X. and Wang, K. Physicochemical characterization of rice straw pretreated with sodium hydroxide in the solid state for enhancing biogas production. *Energy & Fuels*, 2008. 22(4): 2775–2781.

30. Liew, L. N., Shi, J. and Li, Y. Enhancing the solid-state anaerobic digestion of fallen leaves through simultaneous alkaline treatment. *Bioresource technology*, 2011. 102(19): 8828–8834.

31. Chen, Y., Cheng, J. J. and Creamer, K. S. Inhibition of anaerobic digestion process: a review. *Bioresource technology*, 2008. 99(10): 4044–4064.

32. Beccari, M., Majone, M., Torrisi, L. and Papini, M. P. Enhancement of anaerobic treatability of olive oil mill effluents by addition of Ca (OH) 2 and bentonite without intermediate solid/liquid separation. *Water science and technology*, 2001. 43(11): 275–282.

33. Chang, V. S., Burr, B. and Holtzapple, M. T. Lime pretreatment of switchgrass. *Applied biochemistry and biotechnology*, 1997. 63(1): 3–19.

34. Knappert, D., Grethlein, H. and Converse, A. Partial acid hydrolysis of poplar wood as a pretreatment for enzymatic hydrolysis. *Biotechnol. Bioeng. Symp.;(United States)*. Dartmouth Coll., Hanover, NH. 1981, vol. 11. 95–115.

35. Song, Z., Yang, G., Guo, Y. and Zhang, T. Comparison of two chemical pretreatments of rice straw for biogas production by anaerobic digestion. *BioResources*, 2012. 7(3): 3223–3236.

36. Garrote, G., Dominguez, H. and Parajo, J. Hydrothermal processing of lignocellulosic materials. *European Journal of Wood and Wood Products*, 1999. 57(3): 191–202.

37. DiStefano, T. and Ambulkar, A. Methane production and solids destruction in an anaerobic solid waste reactor due to post-reactor caustic and heat treatment. *Water science and technology*, 2006. 53(8): 33–41.

38. Wellinger, A., Murphy, J. D. and Baxter, D. *The biogas handbook: science, production and applications*. Elsevier. 2013.

39. Bochmann, G., Ortner, M., Drosg, B., Schonlieb, M., Andres-Lainez, S., Kirchmayr, R. and Braun, R. Influence of thermal pre-treatment to increase digestibility of brewers spent grains. *proceedings of the 12th World Congress on Anaerobic Digestion, Guadalajara, Mexico*. 2010. 33–41.

40. Schieder, D., Schneider, R. and Bischof, F. Thermal hydrolysis (TDH) as a pretreatment method for the digestion of organic waste. *Water Science and Technology*, 2000. 41(3): 181–187.

41. Pakarinen, A., Maijala, P., Jaakkola, S., Stoddard, F. L., Kymäläinen, M. and Viikari, L. Evaluation of preservation methods for improving biogas production and enzymatic conversion yields of annual crops. *Biotechnology for biofuels*, 2011. 4(1): 186–198.

42. Kreuger, E., Nges, I. and Björnsson, L. Ensiling of crops for biogas production: effects on methane yield and total solids determination. *Biotechnology for biofuels*, 2011. 4(1): 441–448.

43. Deublein, D. and Steinhauser, A. *Biogas from waste and renewable resources: an introduction*. John Wiley & Sons. 2011.

44. Thauer, R. K. Biochemistry of methanogenesis: a tribute to Marjory Stephenson: 1998 Marjory Stephenson Prize Lecture. *Microbiology*, 1998. 144(9): 2377–2406.

45. Jagadabhi, P. S., Kaparaju, P. and Rintala, J. Effect of micro-aeration and

leachate replacement on COD solubilization and VFA production during mono-digestion of grass-silage in one-stage leach-bed reactors. *Bioresource technology*, 2010. 101(8): 2818–2824.

46. Jenicek, P., Keclik, F., Maca, J. and Bindzar, J. Use of microaerobic conditions for the improvement of anaerobic digestion of solid wastes. *Water Science and Technology*, 2008. 58(7): 1491–1496.

47. Johansen, J.-E. and Bakke, R. Enhancing hydrolysis with microaeration. *Water science and Technology*, 2006. 53(8): 43–50.

48. Mshandete, A., Björnsson, L., Kivaisi, A. K., Rubindamayugi, S. and Mattiasson, B. Enhancement of anaerobic batch digestion of sisal pulp waste by mesophilic aerobic pre-treatment. *Water Research*, 2005. 39(8): 1569–1575.

49. Barr, D. P. and Aust, S. D. Pollutant degradation by white rot fungi. In: *Reviews of environmental contamination and toxicology*. Springer. 49–72. 1994.

50. Reddy, C. A. The potential for white-rot fungi in the treatment of pollutants. *Current opinion in Biotechnology*, 1995. 6(3): 320–328.

51. Dhouib, A., Ellouz, M., Aloui, F. and Sayadi, S. Effect of bioaugmentation of activated sludge with white-rot fungi on olive mill wastewater detoxification. *Letters in applied microbiology*, 2006. 42(4): 405–411.

52. Hodgson, J., Laugero, C., Leduc, R., Asther, M. and Guiot, S. Fungal pretreatment by Phanerochaete chrysosporium to reduce the inhibition of methanogenesis by dehydroabietic acid. *Applied microbiology and biotechnology*, 1998. 49(5): 538–544.

53. Ghosh, A. and Bhattacharyya, B. Biomethanation of white rotted and brown rotted rice straw. *Bioprocess engineering*, 1999. 20(4): 297–302.

54. Wagner, A. O., Schwarzenauer, T. and Illmer, P. Improvement of methane generation capacity by aerobic pre-treatment of organic waste with a cellulolytic Trichoderma viride culture. *Journal of environmental management*, 2013. 129: 357–360.

55. Binner, R., Menath, V., Huber, H., Thomm, M., Bischof, F., Schmack, D. and Reuter, M. Comparative study of stability and half-life of enzymes and enzyme aggregates implemented in anaerobic biogas processes. *Biomass Conversion and Biorefinery*, 2011. 1(1): 1–8.

56. Rintala, J. A. and Ahring, B. K. Thermophilic anaerobic digestion of source-sorted household solid waste: the effects of enzyme additions. *Applied Microbiology and Biotechnology*, 1994. 40(6): 916–919.

57. Frigon, J.-C., Mehta, P. and Guiot, S. R. Impact of mechanical, chemical and enzymatic pre-treatments on the methane yield from the anaerobic digestion of switchgrass. *Biomass and Bioenergy*, 2012. 36: 1–11.

58. Quiñones, T. S., Plöchl, M., Budde, J. and Heiermann, M. Results of batch anaerobic digestion test–effect of enzyme addition. *Agricultural Engineering International: CIGR Journal*, 2012. 14(1): 38–50.

59. Pakarinen, A., Zhang, J., Brock, T., Maijala, P. and Viikari, L. Enzymatic accessibility of fiber hemp is enhanced by enzymatic or chemical removal of pectin. *Bioresource technology*, 2012. 107: 275–281.

60. Müller, C., Leithner, K., Hauptstein, S., Hintzen, F., Salvenmoser, W. and Bernkop-Schnürch, A. Preparation and characterization of mucus-penetrating papain/poly (acrylic acid) nanoparticles for oral drug delivery applications. *Journal of nanoparticle research*, 2013. 15(1): 1353.

61. Schell, D. J. and Harwood, C. Milling of lignocellulosic biomass. *Applied Biochemistry and biotechnology*, 1994. 45(1): 159–168.

62. Kratky, L. and Jirout, T. Biomass size reduction machines for enhancing biogas production. *Chemical Engineering & Technology*, 2011. 34(3): 391–399.

63. Taherzadeh, M. J. and Karimi, K. Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: a review. *International journal of molecular sciences*, 2008. 9(9): 1621–1651.

64. Menind, A., Normak, A. *et al.* Study on Grinding Biomass as Pre-treatment for Biogasification. *International Scientific Conference of Biosystem Engineering*. 2010. 155–164.

65. Mshandete, A., Björnsson, L., Kivaisi, A. K., Rubindamayugi, M. S. and Mattiasson, B. Effect of particle size on biogas yield from sisal fibre waste. *Renewable energy*, 2006. 31(14): 2385–2392.

66. Menardo, S., Airoldi, G. and Balsari, P. The effect of particle size and thermal pre-treatment on the methane yield of four agricultural by-products. *Bioresource technology*, 2012. 104: 708–714.

67. Bauer, A., Bösch, P., Friedl, A. and Amon, T. Analysis of methane potentials of steam-exploded wheat straw and estimation of energy yields of combined

ethanol and methane production. *Journal of Biotechnology*, 2009. 142(1): 50–55.

68. Hjorth, M., Gränitz, K., Adamsen, A. P. and Møller, H. B. Extrusion as a pretreatment to increase biogas production. *Bioresource Technology*, 2011. 102(8): 4989–4994.

69. Murphy, J. and McCarthy, K. The optimal production of biogas for use as a transport fuel in Ireland. *Renewable Energy*, 2005. 30(14): 2111–2127.

70. Rafique, R., Poulsen, T. G., Nizami, A.-S., Murphy, J. D., Kiely, G. *et al.* Effect of thermal, chemical and thermo-chemical pre-treatments to enhance methane production. *Energy*, 2010. 35(12): 4556–4561.

71. Zhang, Z., Rackemann, D. W., Doherty, W. O. and O Hara, I. M. Glycerol carbonate as green solvent for pretreatment of sugarcane bagasse. *Biotechnology for biofuels*, 2013. 6(1): 153.

72. Brownell, H. H. and Saddler, J. N. Steam pretreatment of lignocellulosic material for enhanced enzymatic hydrolysis. *Biotechnology and bioengineering*, 1987. 29(2): 228–235.

73. Li, M., Cao, S., Meng, X., Studer, M., Wyman, C. E., Ragauskas, A. J. and Pu, Y. The effect of liquid hot water pretreatment on the chemical–structural alteration and the reduced recalcitrance in poplar. *Biotechnology for Biofuels*, 2017. 10(1): 237.

74. Bals, B., Rogers, C., Jin, M., Balan, V. and Dale, B. Evaluation of ammonia fibre expansion (AFEX) pretreatment for enzymatic hydrolysis of switchgrass harvested in different seasons and locations. *Biotechnology for biofuels*, 2010. 3(1): 1.

75. Serna, L. D., Alzate, C. O. and Alzate, C. C. Supercritical fluids as a green technology for the pretreatment of lignocellulosic biomass. *Bioresource technology*, 2016. 199: 113–120.

76. Zhang, B. and Shahbazi, A. Recent developments in pretreatment technologies for production of lignocellulosic biofuels. *J Pet Environ Biotechnol*, 2011. 2(2): 111.

77. McKendry, P. Energy production from biomass (part 3): gasification technologies. *Bioresource technology*, 2002. 83(1): 55–63.

78. Mirza, U. K., Ahmad, N., Harijan, K. and Majeed, T. Identifying and addressing barriers to renewable energy development in Pakistan. 2009. 13: 927–931. doi:10.1016/j.rser.2007.11.006.

79. Singh, R. and Shukla, A. A review on methods of flue gas cleaning from combustion of biomass. *Renewable and Sustainable Energy Reviews*, 2014. 29: 854–864.

80. Delivand, M. K., Barz, M., Gheewala, S. H. and Sajjakulnukit, B. Economic feasibility assessment of rice straw utilization for electricity generating through combustion in Thailand. *Applied Energy*, 2011. 88(11): 3651–3658.

81. Xiong, J., Zhao, H., Zheng, C., Liu, Z., Zeng, L., Liu, H. and Qiu, J. An economic feasibility study of O 2/CO 2 recycle combustion technology based on existing coal-fired power plants in China. *Fuel*, 2009. 88(6): 1135–1142.

82. Caputo, A. C., Palumbo, M., Pelagagge, P. M. and Scacchia, F. Economics of biomass energy utilization in combustion and gasification plants: Effects of logistic variables. *Biomass and Bioenergy*, 2005. 28(1): 35–51.

83. Xingang, Z., Jieyu, W., Xiaomeng, L., Tiantian, F. and Pingkuo, L. Focus on situation and policies for biomass power generation in China. *Renewable and Sustainable Energy Reviews*, 2012. 16(6): 3722–3729.

84. Pragya, N., Pandey, K. K. and Sahoo, P. A review on harvesting, oil extraction and biofuels production technologies from microalgae. *Renewable and Sustainable Energy Reviews*, 2013. 24: 159–171.

85. Inyang, M., Gao, B., Pullammanappallil, P., Ding, W. and Zimmerman, A. R. Biochar from anaerobically digested sugarcane bagasse. *Bioresource technology*, 2010. 101(22): 8868–72.

86. Suali, E. and Sarbatly, R. Conversion of microalgae to biofuel. *Renewable and Sustainable Energy Reviews*, 2012. 16(6): 4316–4342.

87. Khalid, A., Arshad, M., Anjum, M., Mahmood, T. and Dawson, L. The anaerobic digestion of solid organic waste. *Waste management (New York, N.Y.)*, 2011. 31(8): 1737–44.

88. Otero, M., Lobato, a., Cuetos, M. J., Sánchez, M. E. and Gómez, X. Digestion of cattle manure: thermogravimetric kinetic analysis for the evaluation of organic matter conversion. *Bioresource technology*, 2011. 102(3): 3404–10.

89. Jones, H. B. and O, E. A. Biomass Energy Potential from Livestock and Poultry Wastes in the Southern United States. 1984. 6: 25–35.

90. Tan, Z. and Lagerkvist, A. Phosphorus recovery from the biomass ash: A review. *Renewable and Sustainable Energy Reviews*, 2011. 15(8): 3588–3602.

91. Takashima, M., Shimada, K. and Speece, R. E. Minimum requirements for

trace metals (iron, nickel, cobalt, and zinc) in thermophilic and mesophilic methane fermentation from glucose. *Water environment research*, 2011. 83(4): 339–346.

92. Singh, R., Kumar, S. and Ojha, C. Nutrient requirement for UASB process: a review. *Biochemical Engineering Journal*, 1999. 3(1): 35–54.

93. Demirel, B. and Scherer, P. The roles of acetotrophic and hydrogenotrophic methanogens during anaerobic conversion of biomass to methane: a review. *Reviews in Environmental Science and Bio/Technology*, 2008. 7(2): 173–190.

94. Siddiqui, Z., Horan, N. and Anaman, K. Optimisation of C: N ratio for co-digested processed industrial food waste and sewage sludge using the BMP test. *Int J Chem React Eng*, 2011. 9(1): 1–12.

95. Ghasimi, S., Idris, A., Chuah, T. G. and Tey, B. T. The effect of C: N: P ratio, volatile fatty acids and Na+ levels on the performance of an anaerobic treatment of fresh leachate from municipal solid waste transfer station. *African Journal of Biotechnology*, 2009. 8(18): 4572.

96. Porras, J. P. and Gebresenbet, G. *Review of biogas development in developing countries with special emphasis in India*. Sveriges lantbruksuniv. 2003.

97. Hartmann, H. and Ahring, B. K. Strategies for the anaerobic digestion of the organic fraction of municipal solid waste: an overview. *Water science and technology*, 2006. 53(8): 7–22.

98. Abbasi, T. and Abbasi, S. Is the use of renewable energy sources an answer to the problems of global warming and pollution? *Critical Reviews in Environmental Science and Technology*, 2012. 42(2): 99–154.

99. Abbasi, T., Tauseef, S. and Abbasi, S. Anaerobic digestion for global warming control and energy generation an overview. *Renewable and Sustainable Energy Reviews*, 2012. 16(5): 3228–3242.

100. Gajalakshmi, S., Ramasamy, E. and Abbasi, S. Screening of four species of detritivorous (humus–former) earthworms for sustainable vermicomposting of paper waste. *Environmental Technology*, 2001. 22(6): 679–685.

101. Karki, A., Gautam, K. and Karki, A. Biogas Installation from Elephant Dung at Machan Wildlife Resort, Chitwan, Nepal. *Biogas Newsletter, Issue*, 1994. (45): 4.

102. Abbasi, S., Nipaney, P. and Ramasamy, E. Studies on multi-phase anaerobic digestion of Salvinia. *Indian journal of technology*, 1992. 30(10): 483–490.

103. Abbasi, S., Nipaney, P. and Ramasamy, E. Use of aquatic weed Salvinia

(Salvinia molesta, Mitchell) as full/partial fedd in commercial biogas digesters. *Indian journal of technology*, 1992. 30(9): 451–457.

104. Sörenson, S. Enzyme studies II. The measurement and meaning of hydrogen ion concentration in enzymatic processes. *Biochemische Zeitschrift*, 1909. 21: 131–200.

105. Daisy, A., Kamaraj, S. *et al.* The impact and treatment of night soil in anaerobic digester: a review. *Journal of Microbial and Biochemical Technology*, 2011. 3(3): 043–050.

106. Verma, S. *Anaerobic digestion of biodegradable organics in municipal solid wastes*. Ph.D. Thesis. Columbia University. 2002.

107. Abbasi, S., Nipaney, P. and Panholzer, M. Biogas production from the aquatic weed pistia (Pistia stratiotes). *Bioresource technology*, 1991. 37(3): 211–214.

108. Fricke, K., Santen, H., Wallmann, R., Hüttner, A. and Dichtl, N. Operating problems in anaerobic digestion plants resulting from nitrogen in MSW. *Waste Management*, 2007. 27(1): 30–43.

109. Cowan, M. K., Talaro, K. P. and Contemporary, M.-h. *Microbiology: a systems approach*. McGraw-Hill Higher Education. 2009.

110. Niederberger, T. D., Perreault, N. N., Tille, S., Lollar, B. S., Lacrampe-Couloume, G., Andersen, D., Greer, C. W., Pollard, W. and Whyte, L. G. Microbial characterization of a subzero, hypersaline methane seep in the Canadian High Arctic. *The ISME journal*, 2010. 4(10): 1326–1339.

111. Abbasi, S. and Nipaney, P. Effect of temperature on biogas production from aquatic fern Salvinia. *Indian journal of technology*, 1991. 29(6): 306–309.

112. Ferrer, I., Ponsá, S., Vázquez, F. and Font, X. Increasing biogas production by thermal (70 C) sludge pre-treatment prior to thermophilic anaerobic digestion. *Biochemical Engineering Journal*, 2008. 42(2): 186–192.

113. Monnet, F. An introduction to anaerobic digestion of organic wastes. *Remade Scotland*, 2003: 1–48.

114. Suryawanshi, P., Chaudhari, A. and Kothari, R. Thermophilic anaerobic digestion: the best option for waste treatment. *Critical reviews in biotechnology*, 2010. 30(1): 31–40.

115. Eliyan, C. *Anaerobic digestion of municipal solid waste in thermophilic continuous operation*. Ph.D. Thesis. Asian Institute of Technology, Thailand. 2007.

116. Liu, G., Zhang, R., Sun, Z., Li, X. and Dong, R. Research progress

in anaerobic digestion of high moisture. *Agricultural Engineering International: CIGR Journal*, 2007. 9.

117. Abbasi, S. A. and Nipaney, P. C. *Modelling and simulation of biogas systems economics*. APH Publishing. 1993.

118. Ganesh, P. S., Sanjeevi, R., Gajalakshmi, S., Ramasamy, E. and Abbasi, S. Recovery of methane-rich gas from solid-feed anaerobic digestion of ipomoea (Ipomoea carnea). *Bioresource technology*, 2008. 99(4): 812–818.

119. Ramasamy, E. and Abbasi, S. Energy recovery from dairy wastewaters: impacts of biofilm support systems on anaerobic CST reactors. *Applied energy*, 2000. 65(1): 91–98.

120. Coutant, C. C., Pfafflin, J. and Zeigler, E. Encyclopedia of environmental science and engineering, 2006.

121. Trivedi, P. R. *Environmental pollution and control*. APH Publishing. 2004.

122. Burke, D. A. Dairy waste anaerobic digestion handbook: options for recovering beneficial products from dairy manure. Environmental Energy Company, Olympia, WA, 2005.

123. Khanal, S. K. Anaerobic biotechnology for bioenergy production. *Principles and Application Willey and Blackwell*, 2008: 161–86.

124. Ramasamy, E. and Abbasi, S. High-solids anaerobic digestion for the recovery of energy from municipal solid waste (MSW). *Environmental Technology*, 2000. 21(3): 345–349.

125. Beyenal, N. Y., Özbelge, T. A. and Özbelge, H. Ö. Combined effects of Cu 2+ and Zn 2+ on activated sludge process. *Water Research*, 1997. 31(4): 699–704.

126. Juliastuti, S., Baeyens, J., Creemers, C., Bixio, D. and Lodewyckx, E. The inhibitory effects of heavy metals and organic compounds on the net maximum specific growth rate of the autotrophic biomass in activated sludge. *Journal of hazardous materials*, 2003. 100(1): 271–283.

127. Altaş, L. Inhibitory effect of heavy metals on methane-producing anaerobic granular sludge. *Journal of Hazardous Materials*, 2009. 162(2): 1551–1556.

128. Gikas, P. and Romanos, P. Effects of tri-valent (Cr (III)) and hexa-valent (Cr (VI)) chromium on the growth of activated sludge. *Journal of hazardous materials*, 2006. 133(1): 212–217.

129. RISE-AT, N. Review of current status of anaerobic digestion technology for treatment of municipal solid waste. *Regional Information Service Center*

for South East Asia on Appropriate Technology, Institute of Scientific and Technical Research and Development, Chiang Mai University, Thailand, 1998. 111.

130. Sattar, S. and Springthorp, V. Are there any health concerns with handling biosolids. *Water Environment Association of Ontario Technical Symposium, Ottawa*. 1997.

131. Bendixen, H. Hygienic Safety - Results of scientific investigations in Denmark (Sanitation requirements in Danish biogas plants). *IEA BioEnergy Workshop: Hygienic and environmental aspects of AD: Legislation and experiences in Europe*. 1999.

132. Karim, K., Hoffmann, R., Klasson, T. and Al-Dahhan, M. Anaerobic digestion of animal waste: Waste strength versus impact of mixing. *Bioresource technology*, 2005. 96(16): 1771–1781.

133. Massart, N., Doyle, J., Jenkins, J., Rowan, J. and Lage, C. W. Anaerobic digestion-improving energy efficiency with mixing. *Proceedings of the Water Environment Federation*, 2008. 2008(17): 554–568.

134. Kaparaju, P., Buendia, I., Ellegaard, L. and Angelidakia, I. Effects of mixing on methane production during thermophilic anaerobic digestion of manure: lab scale and pilot-scale studies. *Bioresource technology*, 2008. 99(11): 4919–4928.

135. Ward, A. J., Hobbs, P. J., Holliman, P. J. and Jones, D. L. Optimisation of the anaerobic digestion of agricultural resources. *Bioresource Technology*, 2008. 99(17): 7928–7940.

136. Monod, J. The growth of bacterial cultures. *Annual Reviews in Microbiology*, 1949. 3(1): 371–394.

137. Mosey, F. Mathematical modelling of the anaerobic digestion process: regulatory mechanisms for the formation of short-chain volatile acids from glucose. *Water Science and Technology*, 1983. 15(8-9): 209–232.

138. Chen, Y.-R. and Hashimoto, A. G. *Kinetics of methane fermentation*. Technical report. Science and Education Administration, Clay Center, NE (USA). Meat Animal Research Center. 1978.

139. Rao, M. and Singh, S. Bioenergy conversion studies of organic fraction of MSW: kinetic studies and gas yield–organic loading relationships for process optimisation. *Bioresource Technology*, 2004. 95(2): 173–185.

140. Moletta, R., Verrier, D. and Albagnac, G. Dynamic modelling of anaerobic

digestion. *Water Research*, 1986. 20(4): 427–434.

141. Chen, Y. and Hashimoto, A. Substrate utilization kinetic model for biological treatment process. *Biotechnology and Bioengineering*, 1980. 22(10): 2081–2095.

142. Contois, D. Kinetics of bacterial growth: relationship between population density and specific growth rate of continuous cultures. *Microbiology*, 1959. 21(1): 40–50.

143. Hill, D. Simplified Monod kinetics of methane fermentation of animal wastes. *Agricultural wastes*, 1983. 5(1): 1–16.

144. Husain, A. Mathematical models of the kinetics of anaerobic digestion: A selected review. *Biomass and Bioenergy*, 1998. 14(5): 561–571.

145. Batstone, D. J., Keller, J., Angelidaki, I., Kalyuzhnyi, S., Pavlostathis, S., Rozzi, A., Sanders, W., Siegrist, H. and Vavilin, V. The IWA anaerobic digestion model no 1 (ADM1). *Water Science and Technology*, 2002. 45(10): 65–73.

146. Benedict, R. P. *Fundamentals of temperature, pressure, and flow measurements*. John Wiley & Sons. 1984.

147. Zhang, C., Li, J., Liu, C., Liu, X., Wang, J., Li, S., Fan, G. and Zhang, L. Alkaline pretreatment for enhancement of biogas production from banana stem and swine manure by anaerobic codigestion. *Bioresource technology*, 2013. 149: 353–358.

148. Borges, E. S. M. and Chernicharo, C. Effect of thermal treatment of anaerobic sludge on the bioavailability and biodegradability characteristics of the organic fraction. *Brazilian Journal of Chemical Engineering*, 2009. 26(3): 469–480.

149. Wu, B., Bibeau, E. L. and Gebremedhin, K. G. Three-dimensional numerical simulation model of biogas production for anaerobic digesters. *Canadian biosystems engineering*, 2009. 51(7): 3–18.

150. Walker, M., Zhang, Y., Heaven, S. and Banks, C. Potential errors in the quantitative evaluation of biogas production in anaerobic digestion processes. *Bioresource Technology*, 2009. 100(24): 6339–6346.

151. Maile, I. and Muzenda, E. A Review of Biogas Purification through Chemical Absorption. *International Conference on Chemical Engineering & Advanced Computational Technologies*. 2014. 46–50.

152. Jeong, C., Kim, T., Lee, K., Song, S. and Chun, K. M. Generating efficiency

and emissions of a spark-ignition gas engine generator fuelled with biogas–hydrogen blends. *International Journal of hydrogen energy*, 2009. 34(23): 9620–9627.

153. Salomon, K. R. and Lora, E. E. S. Estimate of the electric energy generating potential for different sources of biogas in Brazil. *Biomass and bioenergy*, 2009. 33(9): 1101–1107.

154. Zhang, C., Ye, H., Liu, F., He, Y., Kong, W. and Sheng, K. Determination and visualization of pH values in anaerobic digestion of water hyacinth and rice straw mixtures using hyperspectral imaging with wavelet transform denoising and variable selection. *Sensors*, 2016. 16(2): 244.

APPENDIX A

LIST OF PUBLICATIONS

- Journal Papers

1. A. Raheem, M. Y. Hassan, R. Shakoor, "Bioenergy from anaerobic digestion of animal wastes in Pakistan," Renewable and sustainable energy reviews, 58(2016): pp. 191–195.
2. A. Raheem, M. Y. Hassan, R. Shakoor, and N. Rasheed. "Economic feasibility of stand-alone wind energy hybrid with bioenergy from anaerobic digestion for electrification of remote area of Pakistan." International Journal of Integrated Engineering 6, no. 3: 2015.

- Conference Proceedings

1. A. Raheem, M. Y. Hassan, R. Shakoor. "Pecuniary optimization of biomass/wind hybrid renewable system." In Proceedings of the 1st International Conference on Energies, SciforumElectronic Conference Series c006 2014: pp. 14-31.