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M.Sc. Thesis

Monitoring and Evaluation of a UASB System for Wastewater Pretreatment from a Palestinian Poultry Slaughterhouse

مراقبة وتقييم مفاعل حمأة لاهوائي صاعد (UASB) لمعالجة أولية لمياه صرف صحي من مسلخ دجاج فلسطيني

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Examination Committee Approval

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Date of Defense: 13.06.2020

The findings, interpretations and conclusions expressed in this study, do not necessary express the views of Birzeit University, the views of the individual members of M.Sc. Committee or the views of their respective employers.

DEDICATION

This research is dedicated to the spirit of my father, with sincere longing and prayer, and my wonderful, loving mother who has always encouraged me to succeed and Illuminates my way with her continuous prayers, to my loved wife and children, who motivated me throughout my study journey,

To my friends and all those who stand on my side,

To every detail related to Palestine with my wishes for a better future.

I Dedicate My Work

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LIST OF ABBREVIATIONS

ABR	Anaerobic Baffled Reactor
AD	Anaerobic Digester
AF	Anaerobic Filter
AL	Anaerobic Lagoon
ANZECC	Australian and New Zealand Environment and Conservation Council
AOP	Advanced Oxidation Process
AS	Activated Sludge
BOD	Biochemical Oxygen Demand
CEC	Council of the European Communities
COD	Chemical Oxygen Demand
CSTR	Continuously Stirred Tank Reactor
CW	Constructed Wetland
DAF	Dissolved Air Floatation
DO	Dissolved Oxygen
EC	Electrocoagulation
EGSB	Expanded granular sludge blanket
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FBR	Fluidized Bed Reactor
GRABR	Granular-bed Anaerobic Baffled Reactor
HRT	Hydraulic Retention Time
MBR	Membrane Bioreactor
MF	Microfiltration
MPP	Meat Processing Plant
NF	Nanofiltration
OLR	Organic Loading Rates
OMAFRA	Ontario Ministry of Agricultural and Rural Affairs

SBR	Sequencing Batch Reactor
ST	Septic Tank
SWW	Slaughterhouse Wastewater
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TSS	Total Suspended Solids
UAF	Upflow Anaerobic Filter
UAPF	Upflow Anaerobic Packed-bed Filters
UASB	Upflow Anaerobic Sludge Blanket
UF	Ultrafiltration
U.S. EPA	United States Environmental Protection Agency
UV	Ultraviolet Light
UV/H_2O_2	Ultraviolet light and Hydrogen Peroxide
VFA	Volatile Fatty Acid

Abstract

Palestinian regulators face big challenges to enforce laws on industrial pollution. Discharge of untreated "Industrial" wastewater leads to environmental degradation. In the case of disposal into the municipal sewer, it leads to treatment plant malfunctions. With current operational 21 Livestock and 14 Poultry Slaughterhouse in Palestine (PCBS, 2018), many slaughterhouses discharge untreated wastewater to Wadi or directly into the municipal sewer system without any treatment. Meat processing produce huge quantities of wastewater due to the slaughtering processes and facilities cleaning. Slaughterhouse wastewater contains high amounts of organics and nutrients e.g., COD (5,000-15,000 mg/l), where the wastewater characteristics can vary depending on the numbers and types of animals slaughtered and the water requirements for the process. The main source of slaughterhouse wastewater is blood, non-digested food in the intestines of the slaughtered animals, urine, feces, lint, fat, carcasses and the production leftovers and the cleaning of the facilities. Thus, due the high-strength characteristics of the slaughterhouse wastewater (effluent), an extensive treatment is needed for a safe effluent discharge into the environment.

This study evaluates the design, operation and monitoring a pilot scale system for slaughterhouse wastewater treatment at Birzeit University campus. The aim entails checking the feasibility of using an upflow anaerobic sludge blanket (UASB) system as a pretreatment option to reduce the organic pollution loads before entering the sewer network. To achieve this purpose, the UASB pilot system was designed, installed put into operation, operated under process optimization as a pretreatment stage to comply with Palestinian regulations for slaughterhouse wastewater connection to public sewerage system. The evaluation of the system performance and process efficacy of the UASB pilot scale was evaluated under variable hydraulic and organic pollution loads.

Samples were taken from two different slaughterhouses in Ramallah district, (Albireh Municipality Centralized Slaughterhouse-Hooved Livestock), and Birzeit Poultry Slaughterhouse. Chemical Oxygen Demand (COD) was the first indicator to compare between the two (2) slaughterhouses, the results were 9,630.0 mg/l and 14,188.0 mg/l, respectively. Since Albireh Livestock slaughterhouse has a direct connection to the municipal sewerage network, it was not possible to obtain representative wastewater samples reflecting slaughterhouse wastewater. Therefore, wastewater form Birzeit Poultry Slaughterhouse formed the feed of the UASB using a vacuum truck. The Poultry slaughterhouse consumes about 200-300 m^3 per day and sometimes during hot season (Ramadan, etc.) reaching 400.0 m^3/day. Two

wastewater samples were analyzed from different wastewater sources from inside the slaughterhouse; the first sampling source was from the fresh wastewater stream directly after the slaughtering and cleaning process. The second sampling was taken from inside the underground storage tank, which contains the whole wastewater originating from inside the slaughterhouse, where all wastewater streams are mixed inside it. A full analysis was made for the two samples, and the results obtained from fresh wastewater stream for (BOD_5, COD, TSS and VSS) was 6790, 14188, 1436 and 1500 mg/l respectively, while the results obtained from the storage tank for (BOD_5, COD, TSS and VSS) was 7239, 14901, 1509 and 1450 mg/l, respectively.

Since the Slaughterhouse lacks a central sewerage service, produced daily wastewater is stored in a large septic tank with intermittent discharge on a daily basis forming the feed source for the UASB systems.

The possibility of slaughterhouse wastewater treatment using a UASB reactor as a decentralized treatment solution was investigated. The system was operated at two different operating conditions (different feed flow rates → hydraulic retention time) under unsteady organic loading rate, for removal of organic matter and solids from the wastewater. The UASB reactor was operated under two variable flow rates (225 ml/min and 450 ml/min. Organic pollutants were partially removed in the UASB reactor, COD, TSS, VSS average removal efficiency was 77%, 55% and 58% respectively at an average organic loading rate [8.6 kg COD/(m^3.day)]. The COD removal ranged from 20-96%, TSS removal ranged 11-90%, while VSS removal rate was 15-97%. The overall removal efficiency of the UASB system during the applied phases was promising, complying with local standards for sewer network connection. These results obtained help water policymakers and legislators endorse the wide application of the UASB technology at all operational slaughterhouses in Palestine. Finally, the UASB system has environmental and economic benefits pertinent to the reduction of current environmental degradation and reduces wastewater expenditures at slaughterhouses.

الملخص

تواجه الجهات التشريعية الفلسطينية تحديات كبيرة في فرض وتطبيق قوانين وتشريعات خاصة بالملوثات الناتجة عن الأنشطة الصناعية، حيث يؤدي تصريف المياه العادمة "الصناعية" غير المعالجة إلى تدهور البيئة، سواء تم التخلص منها بشكل مباشر الى مجاري الاودية او عن طريق ضخها داخل شبة التصريف، ففي حالة التخلص منها في الشبكة العامة دون معالجة، فإن ذلك يؤدي إلى حدوث اعطال في محطات المعالجة، وفي حال ضخها مباشرة الى مجاري الاودية والسيول فإن ذلك يترتب عليه خطر كبير على تلوث المياه الجوفية. تقاوم الأنشطة الصناعية في كثير من الأحيان تنفيذ اللوائح والتشريعات التي تضعها السلطات، خوفا من التكاليف الإضافية والتي بالتالي ستتم إضافتها الى سعر المنتج النهائي. تصميم وتنفيذ حلول وممارسات المعالجة المتطورة بما في ذلك ممارسات الإنتاج الأنظف (CPs) للصناعات الغذائية (معاصر الزيتون ، المسالخ ، مصانع الألبان والأغذية وغيرها) يعطي لأصحاب هذه الصناعات فرص هائلة لتقليل مخرجات التلوث وتوفير الأموال من خلال استخدام أفضل للموارد، ففي فلسطين ما لا يقل عن 35 مسلخ قيد التشغيل حاليًا، 14 مسلخ للدواجن، و 21 مسلخ للخراف والابقار ، تقوم عدة مسالخ في فلسطين بتصريف كميات كبيرة من مياه الصرف الصحي الخاصة بها والناجمة عن عملية الذبح والتنظيف من مرافقها مباشرةً إلى شبكة الصرف الصحي دون أي معالجة أولية، او قد تذهب لأبعد من ذلك وتقوم بتصريف هذه المياه الى مجاري الوديان مباشرة، عادة ما تحتوي هذه المياه العادمة على مستويات عالية من المواد العضوية والعناصر الغذائية مثل COD (5,000 – 15,000 ملغم / لتر)، وتختلف مكونات هذه المياه العادمة حسب نوع وعدد الحيوانات المذبوحة ومتطلبات المياه في عملية الذبح والسلخ والتنظيف وغيرها، مصادر الملوثات الرئيسية في المسالخ هي البراز والبول والدم والعرق والدهون والجثث والأطعمة غير المهضومة في أمعاء الحيوانات المذبوحة، بالإضافة الى بقايا الإنتاج، وتنظيف المنشآت، ونظرا لهذه الخصائص والحمل المرتفع لهذه المياه العادمة يجب إيجاد طريقة ناجعة لمعالجة هذه المياه العادمة بشكل امن بيئيا قبل تصريفها الى شبكة المجاري العامة او مصبات الاودية.

تحاول هذه الدراسة حل هذه المشكلة عن طريق تصميم وبناء نظام تجريبي في حرم جامعة بيرزيت لمعالجة المياه العادمة في المسالخ، والتحقق من جدوى استخدام مفاعل الحمأة اللاهوائي الصاعد UASB (UPFLOW ANAEROBIC SLUDGE BLANKET) كخيار للمعالجة لتقليل تلوث مياه الصرف الصحي من خلال تحقيق تخفيض في النسب المئوية للمواد الصلبة العالقة والزيت والشحوم والمحتوى الكربوني وغيرها قبل التصريف إلى شبكة الصرف الصحي ومحطة معالجة مياه الصرف الصحي (إن وجدت). من ثم تشغيل وتحسين مراحل المعالجة وما بعد المعالجة لإنتاج مياه مستصلحة تتوافق مع المواصفات الفلسطينية لتصريف المياه العادمة للمسالخ في المسطحات المائية، وأخيراً تقييم أداء النظام

وفعالية بعد تغذيته بمياه المسالخ العادمة، ومن ثم اقتراح استراتيجية الإدارة الممكنة لمعالجة المياه العادمة في المسالخ، سواء عن طريق عملية الفصل أو الخلط.

تم أخذ عينات من مسلخين مختلفين في منطقة رام الله، مسلخ بلدية البيرة المركزي للماشية، ومسلخ بيرزيت للدواجن، الاكسجين الممتص كيميائيا (COD) كان المؤشر الأولي للمقارنة بين المسلخين، وكانت النتائج 9,630.0 ملغم/لتر و 14,188.0 ملغم/لتر على التوالي. نظرًا لأن مسلخ بلدية البيرة المركزي للماشية موصول مباشرة بشبكة الصرف الصحي، لم يكن من الممكن الحصول على عينات ممثلة من مياه الصرف الصحي التي تعكس مواصفات المياه العادمة للمسلخ. لذلك تم اعتماد مسلخ بيرزيت للدواجن كمصدر مستمر لتغذية نظام المعالجة اللاهوائي، وتم نقل المياه العادمة باستخدام شاحنة نضح، وتجدر الإشارة إلى أن مسلخ الدواجن يستهلك حوالي 200.0-300.0 متر مكعب يوميا، وأحيانًا خلال موسم الصيف وشهر رمضان يصل الاستهلاك إلى 400.0 متر مكعب يوميا.

تم تحليل عينتين من مصدرين مختلفين لمياه الصرف من داخل مسلخ الدواجن، تم أخذ العينة الأولى من مياه الصرف الصحي المخرجة مباشرة بعد عملية الذبح والتنظيف، والثانية من داخل خزان التجميع الذي يحتوي على مياه الصرف الصحي الخاصة بالمسلخ ككل. حيث يختلط كل شيء بداخله، وقد تم إجراء تحليلات كاملة للعينتين، وكانت نتائج تحليل عينة المياه العادمة بعد الذبح والتنظيف مباشرة على النحو التالي: (BOD5 6,790) (COD 14,188) (TSS 1,500) (VSS 1,436) ملغرام\ ليتر، بينما كانت نتائج تحليل عينة المياه العادمة لبئر التجميع على النحو التالي:

(BOD5 7,239) (COD 14,901) (TSS 1509) (VSS 1450) ملغرام\ ليتر.

نظرًا لأن المسلخ غير متصل بشبكة الصرف الصحي، ويتم التخلص من مياه الصرف الصحي من خزان التجميع الرئيسي بشكل يومي، لذلك قررنا اعتبار خزان تجميع الصرف الصحي مصدرًا لتغذية النظام البحثي التجريبي.

تمت دراسة إمكانية معالجة مياه الصرف الصحي في المسالخ باستخدام مفاعل UASB كمعالجة لا مركزية على مدار 10 أشهر. تم تشغيل النظام في ظروف تشغيل مختلفة (معدلات تدفق تغذية مختلفة - زمن الاحتفاظ الهيدروليكي) تحت معدل تحميل عضوي غير مستقر، لإزالة المواد العضوية والمواد الصلبة من مياه الصرف الصحي. تم تشغيل مفاعل UASB تحت معدلين مختلفين لتدفق التغذية وهما 225 مل/ دقيقة و450 مل / دقيقة. تمت إزالة الملوثات العضوية جزئيًا في مفاعل UASB اللاهوائي، وكان متوسط كفاءة الازالة لكل من COD TSS VSS، 77٪، 55٪ ، 58٪ على التوالي، بمتوسط معدل التحميل العضوي[8.6 kg COD / m3.day]، تراوحت نسبة إزالة COD بين 20-96 ٪،

تراوحت نسبة إزالة TSS بين 11-90٪ ، بينما تراوح معدل إزالة VSS بين 15-90% ، كانت كفاءة الإزالة الإجمالية للنظام خلال المراحل المطبقة واعدة ، واستوفت معايير تصريف شبكة الصرف الصحي في معظم الاحيان.

هذه النتائج التي تم الحصول عليها تساعد واضعي السياسات والمشرعين في مجال المياه على اعتماد التطبيق الواسع لتقنية UASB في جميع المسالخ العاملة في فلسطين. وأخيرًا، يتمتع نظام UASB بفوائد بيئية واقتصادية ذات صلة بخفض التدهور البيئي الحالي وتقليل نفقات مياه الصرف الصحي في المسالخ.

Chapter 1 INTRODUCTION

1.1 Back ground

This thesis studies and evaluates the performance and effectiveness of using “Up Flow Anaerobic Sludge Blanket” system as a decentralized treatment system for Slaughterhouse Wastewater treatment, to reduce the sewer fouling by achieving high percentages reduction in organic load and suspended solids, before entering the sewer network and the WWTP (if any). Then operate and optimize this system to produce a reclaimed water complying with Palestinian regulations for Slaughterhouse wastewater discharge into surface water bodies. Finally, evaluate the system performance and process efficacy of UASB pilot scale after fed by slaughterhouse wastewater before suggesting a feasible management strategy for the slaughterhouse wastewater treatment, clarifying individual or mixed effluents management.

Slaughterhouses are one of the largest food industries in Palestine and it generates big quantities of wastewater. Such wastewater requires technically feasible and environmentally sound treatment technologies if its release to the receiving environment. Literature review revealed that a number of reviews have been published on this topic (Cimino, 1987; Johns, 1995; Salah and Mahmood, 2007). there have been fundamental and technical advances in waste reduction and pollution control issues, such as cleaner production, innovative pre-treatment processes, nutrient recovery/removal, high-rate anaerobic technology development and water reuse. Johns (1995) identified in his review the latest trends in waste management and treatment technologies in the meat process industry and presented a published data on the design and performance of pre-treatment and secondary treatment technologies. Pollutants concentrations in various wastewater streams from slaughterhouses or rendering plants are inherent with substantial variation in the results. However, a careful care is required while interpreting published data, since slaughterhouses in a given country is not similar to production streams applied in another one. Different animal types, sizes and processes lead to variable pollution loads and waste generation. Knowing those as a baseline provides design guidelines for the wastewater treatment system and helps in waste minimization at source.

In earlier studies, Bull et al., (1982) investigated electro flotation and ion exchange processes to replace dissolved air floatation (DAF) systems which were not successful due to inherent technical difficulties or unfeasible economics. Large DAF units with co-precipitation in Europe, New Zealand and the US were introduced for protein recovery from wastewater. These processes gave 75-80% BOD_5 reduction (Hopwood, 1977). However, most systems had high capital and operating costs and operational troubleshooting problems. The latter include long sludge and hydraulic retention times and low surface loading rates, which led to solids settling, large volumes of unstable and bulky sludge. To avoid sludge bulking, increased sludge production and operational difficulties in activated sludge systems, Chen and Lo (2003) combined a 2-phase activated system/contact aeration process by adding a biological filter. In doing so, practical experiments at a slaughterhouse wastewater treatment plant in Taiwan had been done, activated sludge process produced an effluent (COD and SS) to about 40 mg/L and 22 mg/L, respectively, after integrating a biological filter into the two-phase biological treatment system of activated sludge/contact aeration process.

In Palestine, though the industrial liquid discharges form about 7% of municipal wastewater stream, industrial wastewater management still among the priorities of the Palestinian Water Authority and municipalities. According to industrial cadasters made for Al-Bireh, Nablus and Hebron cities, heavy industrial polluters include among others tanning, leather, stone cutting, olive oil mills, leachate, and slaughterhouses (GTZ, 2000; GIZ, 2013; USAID, 2015). Few research studies investigated how to reduce the pollution loads discharged by selective industries. Nazer et al., (2006) applied the cleaner production (CP) principle to reduce the organic and inorganic contents by recycling the industrial stream within the unhairing process of a tannery in Hebron using a pilot system. Amended by chemicals consumed, recycling of industrial discharges five times using a pilot system for the production of leather did not impact the leather quality when compared with leather samples produced through conventional practices. Using membrane technologies and conventional technologies for municipal wastewater in Palestine was reported earlier with no pilots or large scale treatment systems installed (Al-Sa`ed et al., 2008a; 2008b; Lousada-Ferreira et al., 2015). Due to weak financial and hesitant enforcement measures of municipal water by-laws, the industrial sector in Palestine did not invest in installing wastewater treatment systems. The industrial sector maximized financial benefits on the costs of environment and public health. Currently, most urban wastewater treatment plants [WWTPs] in Palestine are designed for domestic wastewater from commercial residential areas and commercial sites. All industrial discharges in Palestinian urban centers (e.g. Nablus, Jericho, Alteereh, and Hebron cities) are either centrally collected in sewer networks or discharged onsite into receiving environment without prior pre-treatment (Al-Sa`ed, 2015). Local research studies (Nazer et al., 2006; Abu Alfeilat, 2013; Shkoukani and Al-Sa`ed, 2015) made in Palestine are limited and tackled pre-treatment of selective industrial wastewater using physical-chemical and anaerobic process at lab and pilot scales. The impacts of co-treatment of industrial wastewater on efficacy, biosolids and effluent quality of Palestinian municipal WWTPs are still unknown. Published literature reviews on industrial wastewater treatment revealed that heavy organic and inorganic pollution loads from industrial heavy polluters (tanneries, leather, stone cutting and olive oil mills, slaughterhouses) are diversified. The negative impacts include high capital and annual operational costs, process malfunctioning, health and environmental risks, and impaired quality of biosolids and reclaimed water. We argue that sustainable industrial wastewater management in Palestine can only be achieved through innovative and integrated treatment technologies. Hence, pilot-scale studies considering pre-treatment or co-treatment (full-treatment) warrant further investigations.

Treating Industrial wastewater faces many challenges in Palestine; some of the challenges are listed below:

1. Industrial wastewater contains a High strength pollution load, (Slaughterhouse; COD: 5,000.0-16,000.0 mg/l) (Bustillo et al 2015).
2. Random spreading of factories and industrial businesses.
3. Lack of investments in in-house treatment or even pretreatment inside the factories; lack of CIP (in house wastewater treatment plants).
4. Hard to separate domestic from industrial wastewater due to the lack of industrial zones; No separate industrial sewer network thus, No specialized industrial wastewater treatment plants
5. Not all industries are covered with the sewer network; some industries directly discharge its industrial Effluent to Wadi.
6. Lack of legislations and regulations that forces the factories to take actions regarding the discharged wastewater.

1.2 Slaughterhouse wastewater

Slaughterhouse wastewater contains suspended solids, blood, protein and fat, so the organic and nutrient concentration in it is very high, this leads to high contamination effect on water bodies if directly discharged without being treated. Slaughterhouse wastewater has been classified as industrial heavy polluter and one of the most harmful to the environment according to Environmental Protection Agency (USEPA). For hygienic reasons, slaughterhouses produce a huge quantities of effluents (Melo et al. 2008). The quantity of water consumed per slaughtered animal varies differently according to the animal type and the process employed in each industry, most of this quantity is discharged as wastewater, with quantities from 400 to 3,100 litter per slaughtered animal (Saddoud and Sayadi, 2007). Slaughterhouse wastewater contains high quantity of biodegradable organic matter, mostly proteins and fats and adequate nutrient concentrations for biological growth (Masse and Massé, 2005; Al-Mutairi, 2006). it also contains high total suspended solids (TSS) grease, hair, feather, flesh, manure, grit and undigested feed (Asselin et al. 2008). What operational impacts might these characteristics on the treated effluent quality using UASB technology is worth to explore.

Biological processes are widely used for the slaughter wastewater treatment. Since it contains high concentrations of biodegradable organic substances, Slaughterhouse processes in industrialized countries are monitored and governed by strict legislation to protect public health and environment (Ün et al. 2009). Palestinian municipal by-laws (PWA, 2014) require a desirable quality for industrial discharges into public sewerage networks. Due to high organic and inorganic contents, industrial liquid streams could pose a serious environmental threat if they are not treated properly. Biological treatment, especially anaerobic digestion, which is more attractive compared to physical and chemical treatment alternatives because of its lower treatment costs, biogas recovery and less production of biosolids (Lin et al., 2011; Chong et al., 2012). Compared to conventional anaerobic digestion (UASB). Therefore, there is a research need to improve the waste digestibility and biogas production from high strength industrial wastewater from slaughterhouses.

Table 1.1 lists research studies (Ruiz et al., 1997; Akinro, 2009; Bello and Ovedemi, 2009; Singh and Neelam, 2011) on available treatment alternatives. Based on the performance efficiencies of investigated treatment systems, natural treatment units are not feasible due to low removal efficiency. Anaerobic pre-treatment units like anaerobic filters and up flow anaerobic sludge blanket (UASB) are much more feasible for the removal of carbonaceous

BOD and for the biogas recovery. Local experience on use of UASB septic tank and UASB integrated digester for domestic and high strength wastewater treatment revealed adequate pretreatment stages (Mahmoud, 2008). However, no experience is available locally pertinent to use of UASB-septic tank for the reduction of COD loads in slaughterhouse wastewater; a heavy industrial polluter. The feasibility of using a low-cost pilot scale UASB septic tank will be investigated in this research study.

TABLE 1-1: Short review on available treatment systems for slaughterhouse wastewater

Treatment Option	**Advantages**	**Disadvantages**
Natural Treatment Systems		
Anaerobic Digesters	Biogas recovery, low cost	Large areal demand, effluent quality, need post treatment, flies and odors.
Anaerobic Ponds or Lagoons	Low cost	Large areal demand, effluent quality, need post treatment, flies and odors.
Mechanized systems		
Sequential Batch Reactor SBR	Flexible operating conditions	More energy and operating skills
UASB	Partial treatment, low-cost	Post treatment necessary, odors, and no permit to connect into sewer networks
MBR [aerobic/anaerobic]	Efficient treatment & reuse, biogas recovery, foot print, pathogens reduction	Higher capital and operational costs
Hybrid systems	Efficient treatment, effluent reuse, biogas recovery, foot print, and pathogens reduction	Moderate capital and lower operational costs

Source: adapted from Ruiz et al., (1997); Akinro, (2009); Bello and Ovedemi, (2009); Singh and Neelam, (2011)

1.3 Problem statement

In Palestinian urban areas, raw industrial liquid waste streams, containing high organic, inorganic loads and pathogens, are currently discharged into open channels without prior pretreatment, thus causing water, soil and health risks. The Palestinian Water Authority, municipalities and industrial sector are facing management challenges pertinent to pollution control, treatment and reuse of organic-rich industrial discharges (PWA, 2012, Nablus Municipality, 2015). little research efforts have been made regarding industrial wastewater, cleaner production, and pre-treatment of heavy polluters from the industrial sector. This research study investigates firstly, the design, operation and monitoring of a pilot scale UASB system. Secondly, the cleaner production principle shall be applied to explore water and pollution reductions in a selected slaughterhouse in Al-Bireh/Ramallah district. We argue that the treatment efficacy of the anaerobic pilot system shall produce an effluent quality meeting the Palestinian regulations for the discharge of industrial wastewater into sewer networks. The results obtained shall provide design criteria for a full-scale WWT.

The main research problems behind the current study are the following:

- The increasing discharge of wastewater from slaughterhouses with negative environmental impacts caused by the Increasing population calls for an increasing in meat production for protein needs.
- High organic pollution loads in slaughterhouse wastewater causes operational problems in sewerage networks and increased energy in wastewater treatment plants as well as water bodies' pollution.
- Lack of local baseline data related to hydraulic and pollution loads in slaughterhouse wastewater effluent. Knowing this provides necessary input data for the design and possible treatment strategies.
- Slaughterhouse wastewater (a heavy industrial polluter) faces management challenges such as; posing financial expenditures, causes environmental and public health threats, unsatisfactory of the current disposal practices, Lack of pre-treatment options.

1.4 Aim and objectives

The main aim of this study is to check the feasibility of using an upflow anaerobic sludge blanket (UASB) system as a pretreatment option to reduce the organic pollution loads before entering the sewer network, the specific objectives are:

1. Increase the scientific understanding of anaerobic digestion as a pre-treatment stage of industrial slaughterhouse wastewater under variable operational parameters.
2. Find the optimal design conditions for an adequate biological pretreatment system using UASB-septic tank for discharge into public sewerage network.
3. Facilitate a national policy dialogue for a cleaner production application associated with sustainable strategies for slaughterhouse industrial management in Palestine.
4. Provide recommendations on optimized design for a large-scale anaerobic pretreatment unit for Palestinian Slaughterhouse Facilities.

1.5 Thesis Structure

This research thesis consists of five chapters, by which the UASB System for Wastewater Pretreatment from a Palestinian poultry slaughterhouse will be monitored and evaluated.

Chapter One: Introduction

This chapter presents the precursory background that introduces for the following contents of the research; it recognizes the scope and level of intervention of the research. Moreover, it clearly identifies the problem statements, goals and methodology, and systematically itemized on research theme and context.

Chapter Two: Literature review

This chapter provides an overview of the local and global slaughterhouses wastewater treatment practices and existing knowledge. It also identifies the relevant theories regarding the SWW, and collecting, evaluating and analyzing the publications related to the research questions; this chapter also analyzes, synthesizes, and critically evaluates the previous related research studies in order to give a clear picture of the state of knowledge on SWW treatment.

Chapter Three: Materials and methods

This chapter explains the materials that were used to conduct the research in addition to the methodology that was followed to conduct this research. The timetable presents the activities that have been completed and the period of each activity. In addition to the stages of system design and the calculations that have been adopted to perform the necessary calculations to analyze the results.

Chapter Four: Results and discussions

This section represents the results obtained by analyzing the UASB pilot scale influent/effluent samples in addition to the records that were taken from the site measurements and monitoring and evaluation processes of the system and then discussing the results obtained after analyzing the achieved data.

Chapter Six: Conclusions and Recommendations

The closing chapter briefly checks the ability of the research to achieve its goals. It also provides a general policy framework of strategies, for promoting results and methodologies for future studies and in case of applying the UASB system in a full scale, by identifying the preconditions to initiate such development, through a brief discussion for the generalization ideas and recommendations for policy making.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

Recently, Pollution of freshwater sources is increasing rapidly, caused by the population growth and unsuitable discharge of wastewater (US EPA, 2004). Therefore, treating the effluent has become serious for the humanity improvement. Moreover, the effluent discharge strict standards worldwide and the lack of freshwater resources have rearranged the objectives of the wastewater treatment from direct disposal to recycle and reuse. For this reason, a high level of treatment must to be accomplished for a safe and sustainable release to the environment (Environment Canada, 2000, 2012; US EPA, 2004; World Bank Group, 2007).

meat processing consumes a huge amount of fresh water and produces big quantities wastewater (SWW) for a propose of animals slaughtering, facilities cleaning and meat processing plants (MPPs). It consumes about 24% of the total freshwater consumed by the food and beverage industry (Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2013). SWW composition varies significantly depending on the different industrial processes and specific water demand (Matsumura and Mierzwa, 2008; Debik and Coskun, 2009; Bustillo-Lecompte et al., 2013, 2014).

2.2 Slaughterhouse Wastewater Characteristics

Globally, during the last three decades meat production had been doubled and expected to have a steady growth until 2050 (Mekonnen and Hoekstra, 2012; FAO, 2013; Bouwman et al. 2013). Worldwide; the annual beef production has reached about 14.7 million metric tons between 2002 and 2007, showing 29% increase over eight years (FAO, 2013). Because of this, the number of slaughterhouses facilities also increased and so the amounts polluted wastewater. Due to its complex and environmentally harmful composition, SWW is considered detrimental worldwide (Johns, 1995; Ruiz et al., 1997; Bustillo-Lecompte et al., 2014).

SWW contains high levels of blood, microorganisms (pathogenic and non-pathogenic), detergents, disinfectants, organics, stomach and intestinal mucus (Masse and Masse, 2000; Debik and Coskun, 2009). It also contains heavy metals, nutrients, color, turbidity, disinfectant and pharmaceuticals for veterinary purposes (Tritt and Schuchardt, 1992). To evaluate the quality of the SWW it is more practical to express its characteristics in term of bulk parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), total organic carbon (TOC).

Table 2.1 lists the parameters, which are commonly used for SWW characterization.

TABLE 2-1: slaughterhouse wastewater General characteristics

SWW Parameter	Value (mg/l)
BOD_5	150 – 4635
COD	500 – 15,900
TN	50 – 841
TOC	70 – 1200
TSS	270 – 6400
pH	4.90 – 8.10

Adapted from: Bustillo-Lecompte and Mehrvar, 2015.

2.3 Slaughterhouse wastewater regulations and guidelines

The methods used to treat SWW must be applied as a regulatory requirement. An additional cost on the final product will be added when adapting any treatment method, and this will increase the investment, operational and maintenance cost, but on the other hand a source of revenues can be achieved the treatment by-products like biogas that can be harvested from the anaerobic treatment methods. Worldwide, different legislations and standards control the meat process industry, but all the countries classify it as one of the most harmful industrial waste since it can cause rivers deoxygenation and groundwater contamination (US EPA, 2004). Different legislations and standards that governing the SWW discharging to water bodies are listed in Table 2.2.

TABLE 2-2: slaughterhouse wastewater effluent discharge standards of different authorities worldwide

Parameter (mg/ltr)	Palestinian standards (Ground water recharge)	Palestinian standards (discharge to sewer network)	World Bank	Canada	Australia	European Union	United Sates
BOD_5	60.0	500.0	30.0	5.0-30.0	6.0-10.0	25.0	26.0
COD	200.0	2000.0	125.0	***	3*BOD	125.0	***
TSS	50.0	500.0	50	5.0-30.0	10-15.0	35.0	30.0
TN	50.0	60.0	10.0	1.0	0.1-15.0	10.0	8.0

Source: Adapted from: Environment Canada (2012), (CEC, 1991), US EPA (2004), ANZECC (2000), World Bank (2007), Palestinian Standards Institution (PS, 2010), Ministry of Environmental Affairs (MEA, 2001)

2.4 Slaughterhouse wastewater treatmen

Slaughterhouse produces big amounts of wastewater and discharges its untreated SWW effluents into water bodies which is forbidden globally, for the reason of its high organic strength and degradation impact on the environment, thus, an appropriate disposal, treatment, must be performed. Minimizing the quantity of wastewater generation in house is the first solution. Currently, with high-quality effluents, MPPs focusing on by-products Recovery such as nutrients, biogas and fertilizers (Amorim et al., 2007).

Stages of SWW treatment contains preliminary, primary, secondary and tertiary treatment in some cases when reuse is considered. This thesis focusing on secondary treatment that contains the biological treatment. Biological treatment can be aerobic and anaerobic. Aerobic treatment is more commonly used than anaerobic as its suitable for high loading rate, but, anaerobic treatment is less complex and more easy to operate and less expensive regarding the O&M cost as it doesn't contain aeration system. Recent trends are moving towards combined processes that contains both aerobic and anaerobic treatment systems that proved a cost effective with a good pollutants removal, which reduces the O&M costs. (Bustillo-Lecompte et al., 2013, 2014).

2.4.1 Preliminary treatment

In this stage, particles (solids) are separated/screened/ trapped from wastewater (TSS removal) using fixed or rotating screeners, strainers or sieves. This treatment stage is needed to prevent clogging, fouling, and jamming of the equipment since the solids and BOD removal efficiency during this stage can reach 60%, 30% respectively (Mittal, 2006).

2.4.2 Physical/chemical treatment

the remaining solids after preliminary are separated in this stage, several methods are commonly used in this stage such as Dissolved air floatation (DAF), Coagulation/Flocculation, Electrocoagulation, Membrane technology,

2.4.3 Biological treatment

In Biological treatment aerobic and anaerobic digestions might be used, since microorganisms take the lead to degrade organics and pathogens from SWW, this treatment stage is considered as a secondary treatment in municipal, industrial and SWW, depending on the characteristics of SWW aerobic and anaerobic treatment can be used individually or combined (Martínez et al., 1995). 90% BOD removal from SWW can be achieved by using Biological treatment process (Mittal, 2006).

Biological processes which are involved in pollution control and bioenergy production are chemical reactions in principal, and therefore can be otherwise referred as biochemical processes. These biochemical reactions need external source of energy for initiation. In the case of biodegradable organics and other nutrients, microorganisms utilize these materials for food and activation energy. This process called metabolism. Each type of organism has its own metabolic pathway, starting from specific reactants till reaching specific end products. the concept of the metabolic pathways in natural systems is shown in Figure 2.1.

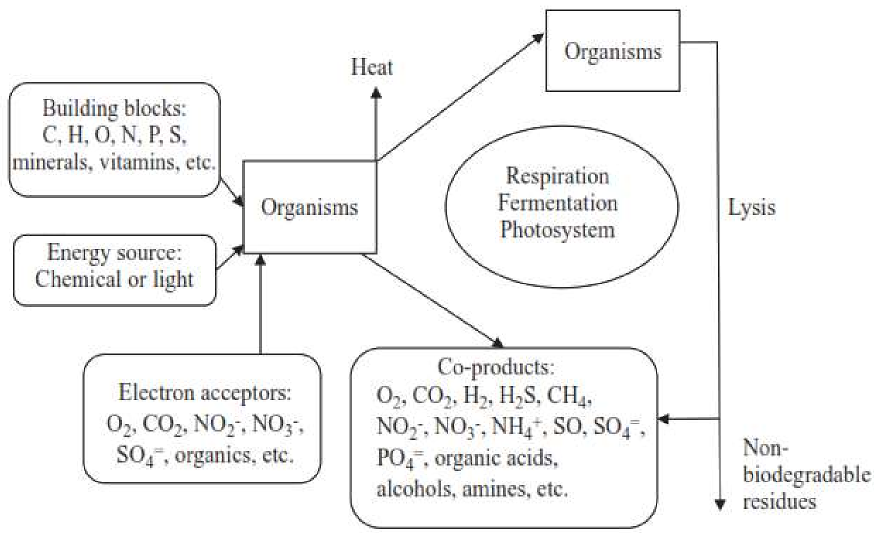

FIGURE 2.1: Generalized biochemical metabolic pathways.

Source: Adpated from: Abdullahi, 2008.

Figure 2.1 shows that in biological processes, the substrates, available electron donors will be transported into the microbial cell and all by-products, including extra microbial biomass and waste products that will be taken out of the cell by physical and chemical (physico-chemical) processes. Organic substrates can be in soluble or particulate form. The soluble and simpler monomers can diffuse into the cell through the cell wall, while the more complex fractions and particulate matter can be physically adsorbed on the cell wall where they are hydrolyzed to soluble and simpler monomers by extra-cellular enzymes produced by the microorganisms. These monomers are subsequently transported into the cell. Hence, the biodegradation of colloidal, particulate, and long-chain organic matter takes longer time than the biodegradation of volatile fatty acids and simple sugars.

2.4.3.1 Aerobic Processes

1. Process fundamentals

Aerobic biological processes executed in the presence of molecular oxygen as an electron acceptor or oxidizing agent. For the biodegradation of organic matter, or carbonaceous oxidation, main final end products are CO2 and H2O in addition to liquid slurry or sludge consisting of micro- organisms, nutrients (nitrogen, phosphorus, etc.), metals, inert materials, and un-degraded organic matter consisting of biodegradable and non-biodegraded materials. Equation 2.1 describes the main elements of aerobic reactions.

- Carbonaceous oxidation

$$\text{organic matter} + O_2 + \text{ nutrients} \rightarrow CO_2 + H_2O + NH_3 + C_5H_7NO_{2\,(\text{new cells})} + SO_4^- + \text{others} + \text{heat} \qquad (2.1)$$

Aerobic biodegradation of nitrogenous wastes produce ammonia. However, the ammonia can be further oxidized ultimately to nitrates (NO_3^-) in a sustained aerobic treatment in a nitrogenous oxidation or nitrification process. Nitrification is a two stage process: first; formation of nitrite (NO_2^-) from ammonia (NH_3)by a group of bacterial known as Nitrosomonas, second; oxidation of nitrite to nitrate by another group of microorganisms known as Nitrobacter. Equations 2.2a and 2.2b explains these two reactions. While the overall process is represented by Equation 2.2c. The Transformation of nitrite to nitrate is a swift process, and any accumulation of nitrite might be caused by oxygen deficiency, environmental conditions (e.g., pH, temperature), or microbial imbalance brought about by the presence of inhibitory compounds most times.

- Nitrification

Ammonia oxidation: $2NH_4^+ + O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O + \text{new cells}$ (2.2a)

Nitrite oxidation: $2NO_2^- + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O + \text{new cells}$ (2.2b)

Overall: $NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+ + \text{new cells}$ (2.2c)

Different microbial groups, heterotrophs and autotrophs, respectively carry out carbonaceous and nitrogenous oxidations. Autotrophic microorganisms utilize carbon from inorganic sources such as carbon dioxide for their metabolic processes, while heterotrophic microorganisms utilize organic carbon for their synthesis. The transformation of carbon dioxide to cell carbon requires more energy than the heterotrophic process; hence, less energy is available for the production of new cells in autotrophic driven processes. so, autotrophs have lower growth rates and cell mass yield than the heterotrophs. The heterotrophs usually outperform the autotrophs for nutrients and oxygen, resulting in nitrification processes becoming more dominant only after most of the easily biodegradable organic compounds have been oxidized. During carbonaceous oxidation, organic nitrogen presented is converted to ammonia, and any surplus remaining after its use -due to its use in producing new cells- is converted to nitrate. Where oxygen is still available after complete carbonaceous and nitrogenous oxidations, and without any new external substrate added to the system, the microorganisms will undergo *endogenous respiration* or *lysis* to release some of the nutrients used in the formation of the cell. The endogenous reaction is shown in Equation 2.3.

- Endogenous respiration

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 \quad (2.3)$$

If aeration is continued, nitrification will occur, as shown in Equation 2.4.

$$C_5H_7NO_2 + 7O_2 \rightarrow 5CO_2 + NO_3^- + 3H_2O + H^- \quad (2.4)$$

2. Aerobic wastewater treatment

Carbonaceous and nitrogenous oxidations can occur in the production of high amounts of new cells or *sludge* or *biosolids*. Where both carbonaceous and nitrogenous oxidations are needed, the treatment period or Hydraulic retention time (HRT) is longer if only carbonaceous oxidation is required. Up to 60% of the organic carbon constituent of the wastewater, being treated can be used in the production of biosolids in aerobic processes.

The major operational costs in aerobic treatment processes consists of the supply of oxygen and the management of resulting biosolids. By estimation, the energy requirement for oxygen supply consumes up to 65% of the total energy needed during operation, thus, highly effective artificial oxygen supply facilities are used in aerobic municipal wastewater treatment. Municipal wastewater is considered as a medium strength wastewater because of its relatively low COD levels of less than 2,000 mg/ltr. Hence, the cost of oxygen supply and sludge management will be much greater in treating medium to high strength wastewaters. Oxygen can be introduced either artificially (using mechanical aeration systems) or naturally by letting

oxygen from atmosphere to diffuse in the treatment system. latter system is used in ecological wastewater treatment systems like constructed wetlands and aerated lagoons. Systems with natural oxygen transfer are used to treat dilute wastewaters, and post-treatment, the treatment efficiencies depend on the treatment system surface area. Which means, the greater the surface-air contact area, the greater the amount of natural oxygen to transfer and so the higher the treatment efficiency. For medium to high strength wastes (industrial wastewaters and slurries), artificial oxygen might be necessary to reduce the space requirements and to prevent uncontrolled anaerobic conditions from developing within the system.
Aerobic microorganisms can be either suspended or take the form of biofilms on stones or plastic media (attached Growth or suspended growth). Plastic materials have greater surface area/volume ratios than stones, and so less space is required.

The biosolids have to be removed from the treated effluent before discharging into receiving waterbodies or streams. The suitable solid separation method is chosen depending on the system type and the desired treated effluent quality.

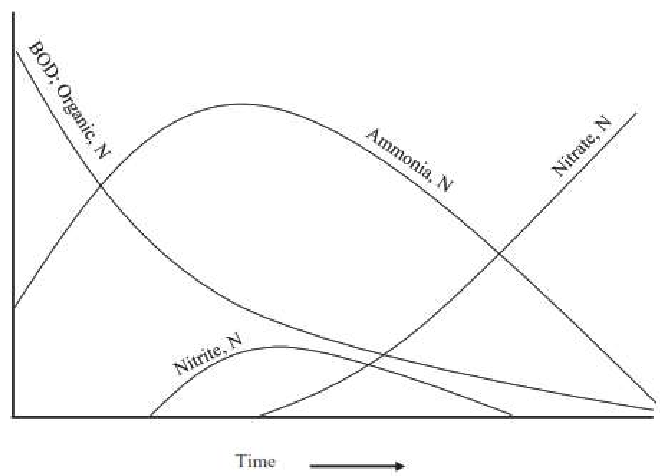

FIGURE 2.2: Fate of some of carbonaceous and nitrogenous compounds in aerobic treatment systems.
Source: Adapted from: Masters, 2001

3. Aerobic digestion or composting

aerobic digestion or *composting* is The process applied for solid and semi-solid wastes treatment and its defined as the biological decomposition and stabilization of the organic constituents of solid wastes. As the organic material decomposed, the biological process can heat up to temperatures between 50–70 °C, and decreases as the amount of easily biodegradable organic matter decreases. at this temperature range Enteric pathogen contained in wastes can usually

be destroyed. Composting is carried out by a succession of mesophilic and thermophilic microorganisms and usually lead to pasteurization of organic residues.
Under long duration aeration, ammonia nitrification by-product can also take place. Where the stoichiometric equation of the waste is known (Tchobanoglous et al. 1993), Equations 5 and 6 can be used for quantitative estimation of composting, oxygen demand and by-products.

- Carbonaceous oxidation

$$C_aH_bO_cN_d + 0.25(4a + b - 2c - 3d)O_2 \rightarrow aCO_2 + 0.5(b - 3d)H_2O + dNH_3 \quad (2.5)$$

- Nitrification

$$NH_3 + 2O_2 \rightarrow H_3O + HNO_3 \quad (2.6)$$

Aerobic digestion is a fast reaction and can be used as an alternative to anaerobic digestion for the treatment of organic solid residues and bio solids. It can lead to solid reduction where the amount of hydrolysable solids in the untreated waste is greater than the amount of new aerobic microorganisms produced during the treatment process. Aerobic digestion can also be used as a pretreatment for anaerobic treatment process, where its relatively high hydrolytic efficiency can be used to replace the slower anaerobic hydrolytic stage for certain types of organic solids. Moreover, the heat by-product of aerobic digestion can reduce the heat needed for anaerobic digestion.

4. Aerobic versus anaerobic processes

Biosolids are the main by-products of aerobic treatment processes, while biogas and lower amounts of biosolids are resulted from anaerobic treatment processes. Both processes need external energy source where high process efficiency is required, aerobic process requires oxygen supply while anaerobic requires mesophilic or thermophilic operation. However, in anaerobic treatment, the energy requirement can be obtained from the biogas production (Methane), where its production and recovery is economically viable. Moreover, the by-products of aerobic processes can be treated by anaerobic processes; just as the aerobic processes can be used for post-treatment of the liquid by-product of anaerobic processes. For wastewaters, aerobic processes can ensure a better effluent quality than that which can be produced by only anaerobic processes in terms of carbonaceous and nitrogenous pollutants removal. In treating high strength wastewaters therefore, it might be cheaper to start with anaerobic treatment or anaerobic pretreatment and followed by aerobic treatment or "aerobic

polishing" For low strength wastewaters, such as municipal wastewaters. Therefore, low biogas yield and mesophilic or thermophilic operation may result in anaerobic pretreatment being less cost-effective than direct application of aerobic treatment. However, in tropical countries with high ambient temperatures, anaerobic pretreatment of low strength wastewaters can offer a net positive energy gain because of its low external energy required to bring the system to the more efficient mesophilic or thermophilic temperature ranges. Many countries e.g., Brazil, Columbia, Ghana, etc. use Anaerobic pretreatment of municipal wastewater.
Further information about anaerobic process/treatment will be discussed at section *2.4.3.3 Anaerobic Processes.*

2.4.3.2 Anoxic processes

Anoxic process is the biochemical reaction happens in presence of nitrogen oxides i.e., nitrate and/or nitrite but in the absence of molecular oxygen. The nitrogen oxides serve as electron acceptors for the oxidation of organic or inorganic electron donors presented, giving out gaseous nitrogen in the process. This process is called *denitrification* and equation 2.7 represents it. Nitrates and nitrites can also be transformed back into ammonia in a process known as *ammonification*.

- Denitrification

$$NO_3^- \rightarrow NO_2^- \rightarrow NO_2 \rightarrow N_2 \quad (2.7)$$

This process is part of biological nitrogen removal used in post treatment of wastewaters to be discharged to certain receiving waterbodies. Biological nitrogen removal involves nitrification, followed by denitrification in an organic carbon-rich environment in the absence of molecular oxygen. Since nitrification occurs in an environment that is deficient in biodegradable organic carbon; addition of external organic carbon sources is necessary to bring about denitrification. For example, using acetate as a source of external carbon source, the denitrification reaction is represented as follows:

$$5CH_3COOH + 8NO_3^- \rightarrow 4N_2 + 10CO_2 + 6H_2O + 8OH^- \quad (2.8)$$

2.4.3.3 Anaerobic processes

Because of its effectiveness in treating high strength wastewater such as SWW; Anaerobic treatment is the favored choice of biological treatment (Cao and Mehrvar, 2011).

In the absence of oxygen, different bacteria degrade organic compounds into CO_2 and CH_4. Compared to aerobic systems; anaerobic treatment has numerous advantages for example high removal efficiency of COD, low requirement of energy and low sludge production, with the possible recovery of bi-products such as biogas and nutrient (Bustillo-Lecompte et al., 2014). Beside the advantages of the anaerobic process, there are also some disadvantages, since the effluent characteristics do not comply with the recent strict standards and regulations. Hence, to get over this issue, further treatment must be applied to complete treatment process and achieve the standards (Gomec, 2010).

1. Process description

Anaerobic process is defined as the Biological process that occurs in the absence of molecular oxygen, and the electron acceptors are carbon dioxide and sulfate. This process is similar to those occurring inside stomachs of ruminant animals naturally, marshes, organic sediments from lakes and rivers and sanitary landfills. The main by-products gases are carbon dioxide (CO_2), methane (CH_4), hydrogen sulfide (H_2S), hydrogen (H_2) there are also some liquid or semiliquid by-product which known as digestate that consists of un-degraded organic matter, nutrients, microorganisms, metals and inert materials.

Anaerobic processes typically occur in four steps (1) hydrolysis (2) acidogenesis (3) acetogenesis (4) methanogenesis, Figure 2.3 shows a schematic diagram for the different reactions happen during anaerobic digestion of complex organic matter.

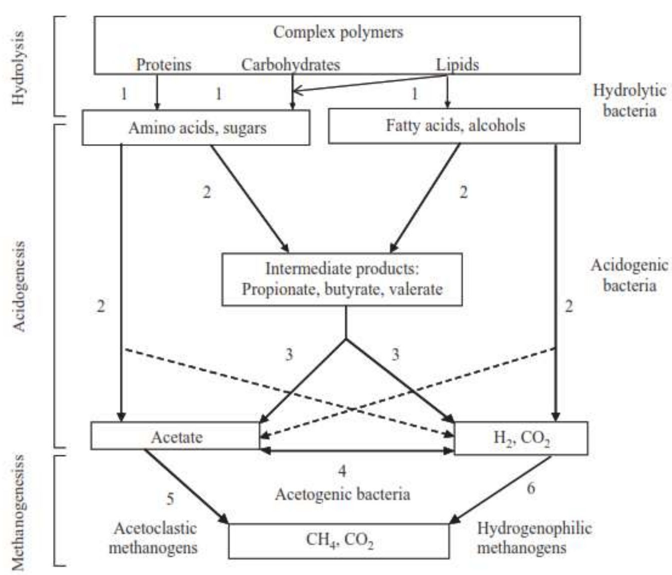

FIGURE 2.3: Anaerobic Digestion Reactions

Source: Adapted from: Gujer and Zehnder, 1983.

Hydrolysis involves the breakdown of complex polymeric organic substrates such as proteins, carbohydrates and lipids into smaller monomeric compounds such as amino acids, sugars, and fatty acids. This reaction is assisted by a specific enzymes formed by a consortium of varied hydrolytic bacteria. The monomers released during hydrolysis are converted by acid forming bacterial metabolism, also known as fermentative bacteria into hydrogen or formate, carbon dioxide, pyruvate, ammonia, volatile fatty acids, lactic acid, and alcohols (Mata-Alvarez 2003). During carbohydrate catabolism; Carbon dioxide and hydrogen gases are also produced. In acetogenesis, some of the compounds produced by acidogenesis are oxidized to carbon dioxide, hydrogen, and acetic acid (acetate) by the action of obligate hydrogen-producing acetogens. In addition, acetic acid is produced during the catabolism of bicarbonate and hydrogen by homoacetogenic bacteria. Methanogenesis leads to form CH_4.

The methanogenic bacteria use carbon dioxide, methanol, acetic acid, and hydrogen to produce methane gas and carbon dioxide. 70% of methane is produced from acetic acid by acetoclastic methanogenic bacteria, making it the most important substrate for methane formation (Mata-Alvarez 2003).

The other 30% is then produced from carbon dioxide and hydrogen by hydrogenophilic (or hydrogenotrophic) methanogenic bacteria. Equations 2.9 and 2.10 represent the biochemical processes; the former representing hydrolysis and acidogenesis, and the latter representing acetogenesis and methanogenesis.

$$\text{Organics} + \text{Nutrients} \rightarrow \text{Volatile acids} + \text{Alcohols} + H_2 + CO_2 + H_2S + NH_3 + \text{new cells} \quad (2.9)$$

$$\text{Volatile acids} + \text{Alcohols} + H_2 + CO_2 + \text{Nutrients} \rightarrow CH_4 + CO_2 + \text{new cells.} \quad (2.10)$$

Table 2.3 lists the compositions of anaerobic treatment process gaseous by-products. While Table 2.4. lists The main microorganisms linked to different stages of the process. In the nonexistence of microbial inhibition, the spreading and balancing of these microbial groups in any anaerobic biological processes system depends on the available substrates nature and the environmental conditions (e.g., pH, temperature, potential redox, etc.).

Anaerobic microorganisms can be suspended or take the form of biofilm (attached growth). Biofilm systems as support media utilize various types of organic and inorganic materials, they are able to keep a greater amount of biomass, and generally, they are more effective than suspended growth systems in wastewater treatment and hence can be considered as *high-rate* systems.

TABLE 2-3: Anaerobic Treatment Process Biogas Composition

Composition	Volume Percentage %
Methane	50–75
Carbon dioxide	25–50
Nitrogen	0.0–10
Hydrogen	0.01–5
Oxygen	0.1–2
Water vapor	0.0–10
Ammonia	< 1
Hydrogen sulfide	0.01–3

Source: Adapted from: IEA Bioenergy (2006).

TABLE 2-4: Stages of Anaerobic Digestion with Associated Microbial Types

Stage	Microbial Species
Hydrolysis	Acetovibrio, Bacillus, Butyrivibrio, Clostridium, Eubacterium, Micrococcus, Lactabaccillius, Peptococcus, Proteus vulgaris, Ruminococcus, Staphylococcus, Streptococcus, etc.
Acidogenesis	Bacillus, Butyrivibrio, Clostridium, Eubacterium, Desulfobacter, Desulforomonas, Desulfovibrio, Lactabaccillius, Pelobacter, Pseudomonas, Sarcina, Staphylococcus, Selenomonas, Streptococcus, Veillonella, etc.
Acetogenesis	Methanobacillus omelionskii, Clostridium, Syntrophomonas buswelii, Syntrophomonas wolfei, Syntrophomonas wolinii, etc
Methanogenesis	Acetoclastic methanogens: Methanosaeta, Methanosarcina, etc. Hydrogenophilic methanogens: Methanobacterium, Methanobrevibacter, Methanoplanus, Methanospirillium, etc

Source: Adapted from Wheatley (1991) and Stronach et al. (1986).

In anaerobic wastewater treatment, biomass produced during treatment have to be taken out from the treated effluent before disposal or moving to additional treatment phase. The selection of suitable solid separation methods depends on the process type and the desired treated effluent quality. A separate gravity sedimentation tank might be used; some of the separated solids can be returned to the anaerobic system (biomass Circulation), and the excess is then disposed of.

2. Biomass production

Anaerobic processes generally result in lower cell production rate than the aerobic processes by a factor of 8–10 times, and less microbial nutrients are required in anaerobic processes as shown in Figure 2.4 (Speece 2008). In anaerobic systems, all of the microbial groups described in Figure 2.1 work together; hence, the cell production reported by many researchers are usually for the combined microbial populations, even though there are clear differences between the fast-growing acid forming (acidogens) and the slow-growing methane forming (methanogens) bacteria. The generalized combined yield in a single anaerobic treatment system is in the range of 0.05–0.10 volatile solids (VS)/g chemical oxygen demand (COD), and the average yield for acid forming and methane forming bacteria are in the ranges of 0.06–0.12 and 0.02–0.06 g.VS/g.COD, respectively. The yield varies with types of substrate and the amount of time the microorganisms spent in the biodegradation process as shown in Figure 2.4. This time is referred to the solid retention time or SRT (Speece 2008).

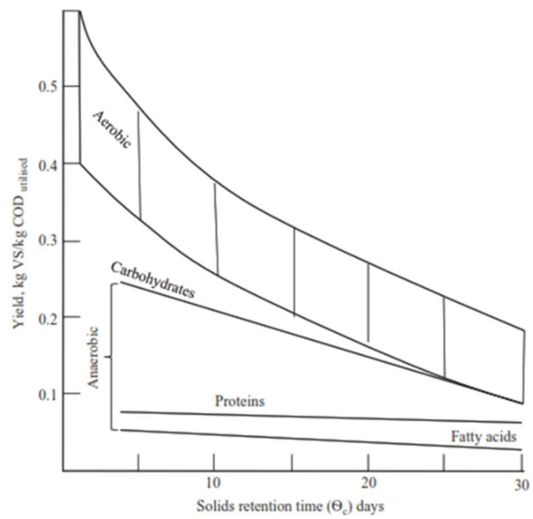

FIGURE 2.4: Biomass yield for aerobic and anaerobic biodegradation processes.
Source: Adapted from Speece 2008.

3. Factors affecting the anaerobic process efficiency

Several important factors affect the anaerobic process efficiency; most of them are listed below:

- Start-Up inoculum

The performance and stability of anaerobic processes depend on the quantity and quality of the active methanogens presented in the system. External active microorganisms (anaerobic) are commonly used to inoculate the systems in the start-up phase so as to shorten the lag phase of a balanced microbial consortium development. (in this research an amount of 150 ltr of anaerobically digested sludge were added to the UASB during the startup phase), The microbial characteristics of an inoculum depend on the operational conditions and type of substrate. Appropriate inoculum can be obtained from active anaerobic reactors, preferably those treating similar types of wastes or sewage sludge (biosolids). Anaerobic reactors are usually started up by heavy seeding (at least 10% of the reactor volume or wastewater VS) or by maintaining the waste or wastewater pH in the range of 6.8 and 7.2 to encourage natural development of appropriate microbial populations and leading, to shorter (up to 30 days) or longer start-up time. Low inoculum/feed ratio may lead to the dominance of acidogens over methanogens and can result in low pH. when this occurs, recovery might be possible depending on the alkalinity of the system. where alkalinity is low, chemical buffer might be added in the feed to avoid system failure. In "*dry*" solid anaerobic digestion, inoculum/feed ratios of greater than ten during start-up are recommended. In *batch* and *plug-flow* reactors or systems, fresh feed is usually pre-mixed (or pre-inoculated) with some of the digested residues.

- Flow equalization

The aim of flow equalization is to minimize and control the variations in wastewater characteristics passing through the anaerobic treatment system that responds better to gradual changes in operating conditions. sudden and shock changes in wastewater characteristics and quantities can lead to process instability and poor performance. Flow equalization can prevent feed overload or underload, and ensure continuous operation even during periods of low or no wastewater production. For some industries, peak wastewater flows can occur only during daytime hours of weekdays, while low or zero production days occur in the nights, at weekends and during plant breakdown or routine shut down maintenance. Flow equalization ensures that the microorganisms in the treatment system are fed and kept alive at all times. The size of the equalization tanks or basins must be sufficient to accommodate the variability of wastewater streams and dilute the concentrated batches periodically produced. The tank must always be properly mixed to prevent short circuiting, unwanted settling of solids and uncontrolled fermentation, which can lead to odor nuisance, health and safety issues. Mixing can be achieved by distribution of inlet flow and baffling, mechanical turbine mixing, mild diffused aeration with air or biogas. Where necessary and possible, flow equalization can be combined with nutrient and pH correction operations.

- Waste organic content and biodegradability

Anaerobic treatment is most suitable for solid residues, slurries and intermediate-high strength range wastewaters with COD concentrations around 2,000 mg/ltr COD. removal efficiencies of the Organic compounds increase when the influent organic strength increase. But only 80%–90% COD removal efficiency can be achieved. *Post-treatment* (aerobic processes) might be necessary if further COD reduction is required. For low strength wastewaters (with COD <2,000 mg/L), aerobic treatment may be more appropriate.

The chemical composition of wastewater is one of the initial indicators of amenability of the organic constituents to biological treatment. Figure 2.5 shows the relation between degradation rate and retention time for various types of organic compound.

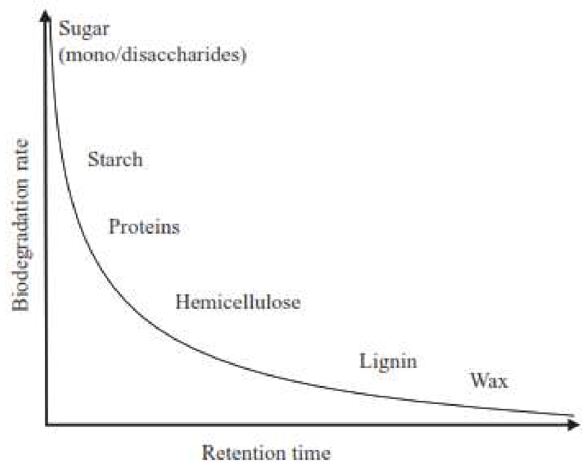

FIGURE 2.5: biodegradation rates Versus reaction time for different types of organic compounds

Source: Adapted from Eder and Schulz (2006).

- Nutrient availability

For hydrolysis and acidogenesis, the composition ratio for (carbon C: nitrogen N: phosphorus P: sulfur S) is considered to be (500:15:5:3), and for methanogenesis, (600:15:5:3) (Weiland 2001). The C:N ratio indicates the nitrogen adequacy in wastewater that needs to be treated using biological processes, for anaerobic processes the suitable values ranges between 20–30 (Deublein and Steinhauser 2008). higher ratio may cause decreasing in bacterial growth caused by nitrogen deficiency, lower ratios may cause ammonia toxicity of the microbes. Wastewater that contains low protein content have a high C/N ratio and vice versa.

- Alkalinity and pH

The anaerobic treatment processes stability depends on pH. the acidogens are more surviving when pH less than 6.0, for methanogens the ideal pH lies between 7.0 and 8.0. Thus, the suitable pH range for the whole anaerobic process is 6.5–7.8. (Rosato, 2018).

- Temperature

Anaerobic processes are affected by temperature like all biological processes. Figure 2.6 displays the relationship between the rate of anaerobic biodegradation and temperature. Anaerobic treatment systems can operate at psychrophilic (<20°C), mesophilic (25–40°C), or thermophilic (45–60°C), ideal temperatures for the mesophilic and thermophilic processes are 37 and 55°C, respectively (Raposo et al. 2012).

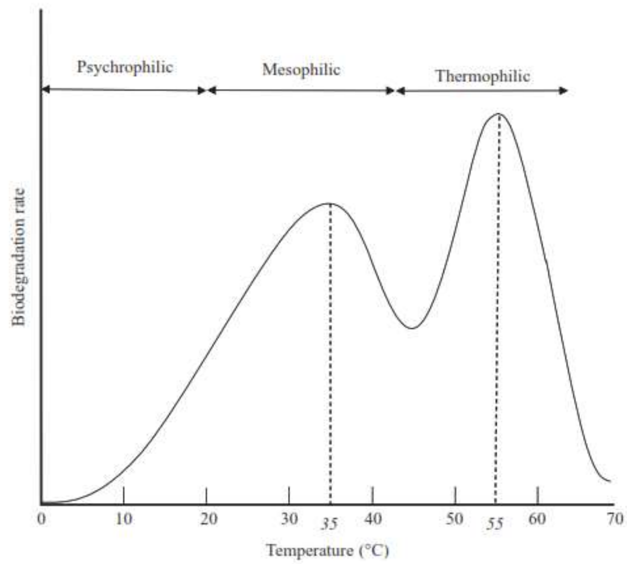

FIGURE 2.6: Anaerobic treatment processes Temperature ranges.
Adapted from: Mata-Alvarez 2003.

Temperature Control

Although anaerobic processes can take place in psychrophilic, mesophilic, and thermophilic temperature ranges, mesophilic systems operating at optimum values of 35°C ± 2°C remain the most widely used for wastewater treatment. Lower temperature treatment systems are associated with low biodegradation rates and poor methane recovery, the latter is worsened by the relatively high solubility of methane gas in water at low temperatures. Although high temperatures generally improve biodegradation rates, temperature fluctuations can cause process instability. Systems should normally be operated to avoid temperature changes of more than 1.0 °C per day. where the wastewater streams temperature is variable due to the nature of processes and/or operations producing the wastewater, it is essential to provide a pretreatment in the form of cooling, heating, or mixing, preferably in equalization tanks to control the temperature variability of wastewater that enters the treatment system.

- Solids and hydraulic retention times

Solid retention time (SRT) is the average time that the microorganisms spend of inside the treatment system (vessel). SRT is affected by the microbial growth rate and the excess sludge (microbial biomass) removal rate of from the treatment system. The former is affected by the nature of the constituent organic compounds as shown in Figures 2-3 and 2-4. Methanogens have slower growth rates than other microbial groups related to anaerobic processes. So, controlling the appropriate SRT can be done by reducing the rate of removal of the methanogenic microorganisms from the treatment system. Temperature plays a major role in the biodegradation rate, and consequently on the microbial regeneration time and SRT.

On the other hand, Hydraulic retention time (HRT) refers to the time that the wastewater stays within the treatment system or reactor. HRT is same as SRT for completely mixed suspended growth systems without recycling of biomass. However, *high rate* wastewater treatment systems are designed and operated to separate HRT from SRT by encouraging greater biomass retention. Thereby ensuring that SRT is always longer than HRT, this can be achieved by the up flow technique that uses the gravity to keep the biomass almost settled down in the bottom part of the reactor.

The need for solids reduction!

When the wastewater is constituted of significant concentrations of particulate biodegradable organic matter, the hydrolysis stage becomes the rate determining step. Hydrolysis of particulate materials is a relatively slow biological reaction. Consequently, wastewaters with high solids content will require higher HRT and larger reactor size than those with low solids. Solids separation, and their disposal or separate treatment, can lead to reduced reactor size, resulting in reduction of the overall treatment cost. Many high rate systems are not suitable for treating high solids wastewaters, therefore prior solids reduction may sometimes be necessary where these systems are to be used. The following methods can be used to reduce wastewater solids before entering the anaerobic treatment stage:

1. *Sedimentation*: This is effective as a sole pretreatment where significant amounts of the particles are settleable in sufficient amounts within a relatively short period of 2–4 hours.

2. *Chemical precipitation*: This consists of coagulation, flocculation, followed by sedimentation. Chemical precipitation can achieve up to 80%–90% total suspended solids

reduction within a relatively short period of time. Table 2.5 lists some of the characteristics and mode of actions of common coagulants. Certain coagulants are only effective at alkaline pH range; hence, pH correction before and after solids reduction might be required before anaerobic treatment. It is noteworthy that chemical precipitation can result in the precipitation of phosphorus, which is an important macronutrient in biological processes. Therefore, a special attention has to be taken to ensure that the pretreated wastewater contains sufficient C/N/P ratio for biological treatment (Eckenfelder Jr. 1989).

3. *Size reduction*: Particular size reduction increases the surface area of the particles available for biochemical actions. Examples of size reduction treatment methods including physical (e.g., grinding, ultra-sound, thermal, etc.), chemical (acid and alkaline treatments), and biological treatment (e.g., enzymatic hydrolysis). These operations and processes can be carried out within the wastewater or in a separate reactor where the removed solids are stored. For the latter, the treated solids can be returned to the wastewater streams for further treatment in anaerobic reactor (Eckenfelder Jr. 1989).

TABLE 2-5: Solids Reduction by Chemical Precipitation Processes

Coagulant	Dosage range (mg/l)	pH	Comments
Lime	150—500	9.0—11.0	For solids reduction in wastewater with low alkalinity Reactions: Ca(OH)2 + Ca(HCO3)2 → 2CaCO3↓ +2H2O MgCO3 + Ca(OH)2 → Mg(OH)2 + CaCO3↓ @ pH 11, Mg(OH)2 and CaCO3 are insoluble
Aluminum	75—250	4.5—7.0	For solids reduction in wastewater with high alkalinity Reactions: Al2(SO4)3 + 6H2O →2Al(OH)3↓ + 3H2SO4
$FeCl_3, FeCl_2$	35—150	4.0—7.0	For solids reduction in wastewater with high alkalinity. Presence of iron in the treated effluent Reactions: FeCl3 + 3H2O → Fe(OH)3↓ + 3HCl
$FeSO_4.7H_2O$	70—200	4.0—7.0	
Cationic polymers	2—5	No change	For solids reduction or as coagulant aid to metallic coagulants. No build-up of metallic ions in the effluent

Source: Adapted from Eckenfelder, (1989).

- Organic loading rate

The organic loading rate (OLR) identifies the relationship between the organic matter weight thatcan be fed inside the reactor and the volume of the reactor((COD, VS or TS) added / reactor volume. day). The higher the OLR the higher the system can treat properly, and so the higher the system efficiency regarding to cost. High rate systems generally cope with relatively high OLR.

- Toxic compounds

Anaerobic processes can be restrained by toxic constituents contained in the wastewater, which affect microorganisms. Typical microbial inhibitors include heavy metals, phenolic compounds, xenobiotics, ammonia, sulfide, long-chain fatty acids and salts, (Chen et al. 2008; Metcalf and Eddy 2014).

Reduction of toxic compounds:

creating a safe and suitable environment for the anaerobic bacteria (to develop and stay functioning) requires reduction of toxic compound, since Industrial wastewaters often contain substances that are toxic to microorganisms.

Sulfide and ammonia toxicity are very common in anaerobic treatment of food and drinks processing wastewaters. Sulfide toxicity can be removed by recycling of treated wastewater to dilute incoming wastewater and/or by combining sulfate rich and non sulfate rich wastewater streams. For example, in treating brewery wastewaters, combining wastewater streams from operations discharging excess yeast (which is rich in sulfate) with other less sulfate-containing wastewater streams can help in reducing potential sulfide toxicity in treating excess yeast wastewater alone. Other possible remedial measures include:

- Adding iron salts, such as ferric chloride directly inside the reactor to precipitate sulfides.
- Adding air or oxygen to the gas headspace of the reactor to oxidize and precipitate sulfide.

While Ammonia toxicity can be reduced by:

- Mixing wastewater with ammonium deficient wastewater streams.
- Post-treatment (nitrification and denitrification) followed by recycling of treated effluent to dilute incoming wastewater.

4. Treatment arrangement, single and multi-stage systems

Reactor configurations for single and multi-stage treatment systems are shown in Figure 2.7. In single-stage systems, schematically shown in Figure 2.7a, all the processes described in Figure 2.3 take place within a single reactor.

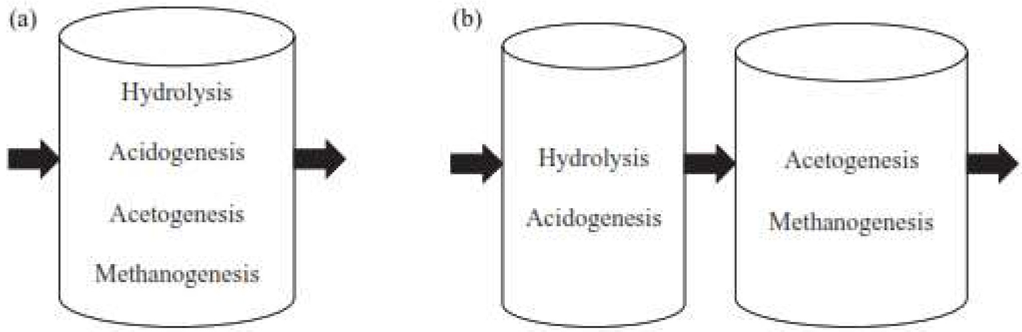

FIGURE 2.7: (a) Single stage and (b) multi-stage anaerobic treatment systems.

Single system has low capital and operational costs compared to multi-stage system, but it may not effectively deal with environmental standards and regulations, also it might not be able to deal with influent substrates variations, Multi-stage systems contain quasi separation of the key process stages in time and/or space. Space-based stage separation involves two or more reactors connected together in series as shown in Figure 2.9 b, or using reactor systems that can provide *plug flow* regime such as a compartmentalized reactor system shown in Figure 2.8. Examples of the latter include the anaerobic baffled reactor (ABR) (Barber and Stuckey 1999) or the granular-bed anaerobic baffled reactor (GRABR) (Akunna and Clark 2000; Baloch and Akunna 2003; Shanmugam and Akunna 2008, 2010).

5. Types of anaerobic systems

Worldwide; several types of anaerobic systems have been used, each system has advantages and disadvantages, there is no rule to pick which system is the most convenient, type and strength of the wastewater, the environment, the assorted budget, the effluent discharge standards etc., all manage the decision.

Some examples of the anaerobic treatment systems are listed below:

- Anaerobic baffled reactor

Anaerobic baffled reactor (ABR) is a common septic tank improved version that contains a number of baffles, SWW flows over and under these baffles from inlet till reach the outlet, which causes and increase in the contact time between SWW and attached biomass that causes an efficient biodegradation. (Barber and Stuckey, 1999).

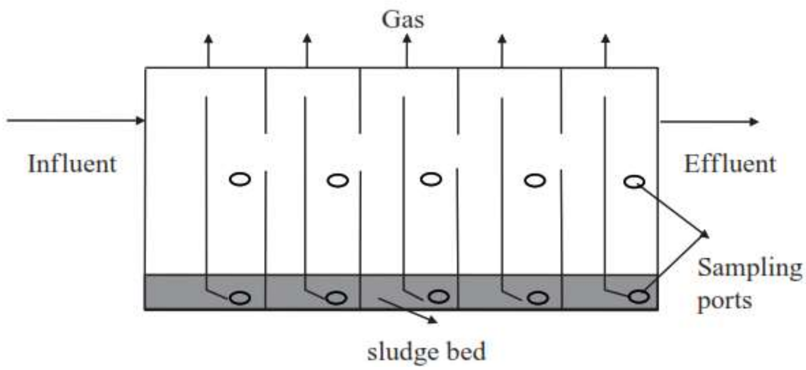

FIGURE 2.8: Anaerobic baffled reactor (ABR)

- Anaerobic filter

Anaerobic filter (AF) is a fixed-bed biological treatment reactors that contains a filtration chamber. It might be single or multi-stage system with more than one reactor connected in series. SWW enters the chambers, where particles are then contained in it; after that, active biomass inside the filter starts to remove organic material. The advantage of the AFs is that it has a good removal of solids and biogas recovery. Fig. 2.9. shows a typical anaerobic filter. (Rajakumar et al. (2011)

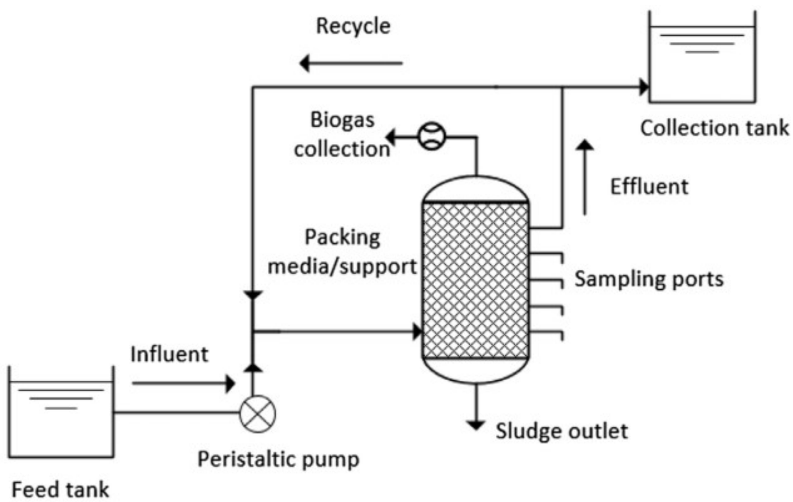

*FIGURE 2.9: up flow anaerobic filters (UAFs), A*dapted from: Rajakumar et al. (2011).

- Anaerobic lagoon

Anaerobic lagoon (AL) is a good anaerobic treatment system when land and suitable weather are available, (Mittal, 2006). Wastewater in Anaerobic lagoons is not getting mixed. Thus, a scum layer appears on the surface of the lagoon, creating a suitable anaerobic conditions and heat. The main disadvantages of the system is odor and the effect of the unsuitable weather (Mittal, 2006).

- Anaerobic sequencing batch reactor

In anaerobic sequencing batch reactor (SBR), feeding stage, settling, reactions, and decanting stages occur in the same reactor, the complete mixing requirements also happened naturally inside the same basin. The system doesn’t need an equalization tank or recycling stream because of the discontinuous feeding regime (Masse and Masse, 2005).

- Up-flow anaerobic sludge blanket reactor

In Up-flow anaerobic sludge blanket reactor (UASB), all treatment processes happen inside the reactor like anaerobic SBR, SWW enters the reactor from the bottom inlet side, then moves upward through the settled biomass that is called sludge blanket then flows outside the reactor through the V notches fixed at the top of the reactor. The system entails three components; liquid (SWW), solid (biomass) and gas (CO_2,CH_4) which produced during digestion (Mittal, 2006). Caldera et al. (2005) evaluated UASB performance for 90 days at 24 hours HRT treating SWW under mesophilic conditions with variable Influent COD concentrations, which varied between 1,820 mg/l and 12,790 mg/l, a satisfactory COD removal efficiency (94.31%) was achieved.
The BOD removal efficiency for using UASB reactor in treating SWW was tested under optimum conditions by Chavez et al. (2005), 95% BOD removal efficiency was achieved under the following conditions: HRT between 3.5 and 4.5 h, OLRs 31,000 mg/ltr, temperature between 25 and 39°C.

6. Anaerobic process variations

There are two types of anaerobic systems based on the physical occurrence of microorganisms, i.e., suspended and attached growth (or fixed film) systems. Some examples of these systems are shown in Table 2.6 and Figure 2.10. There are also *hybrid systems*, which are combinations of both systems. The performance of attached growth or fixed film systems depends on the chemical and physical properties of the carrier media (e.g., porosity, surface area, size, density, chemical composition, etc.), methods of mixing (e.g., fluidization, up-flow or down-flow velocities), hydraulic control features, scouring and clog prevention facilities utilized, etc. Each of these can be utilized as sole or combined with the same or different systems depending on costs and the desired process outcome. Therefore, the design and operational criteria of each system depends on a lot of factors such as the type of reactors, system configuration, wastewater characteristics, treatment temperature, desired treated effluent quality, land availability, manpower requirements, etc. Some system design and performance criteria, particularly for high-rate systems, are often based on empirical formula obtained from laboratory and field trials. Table 2.7 summarizes some the characteristics of typical systems.

TABLE 2-6: Types of Anaerobic Wastewater Treatment Systems

Conventional Systems: Suspended Growth	High Rate Systems (Suspended Growth)	High Rate Systems (Attached Growth)
a. Septic tanks	a. Multi-stage reactors	a. Fixed bed reactors
b. Continuously stirred tank reactor (CSTR)	b. Baffled reactors	b. Expanded bed or fluidized bed reactors
c. Sewage sludge digesters	c. Upflow sludge blanket reactors	c. Rotating bed reactors
d. Anaerobic ponds	d. systems with internal circulator	
	e. Sequencing batch reactors	
	f. Anaerobic contact process	
	g. Plug flow reactors with recirculation	
	h. Membrane bioreactors (MBR)	

Source: Adapted from: Malina and Pohland (1992); Metcalf and Eddy (2014); von Sperling and de Lemos Chernicharo (2005).

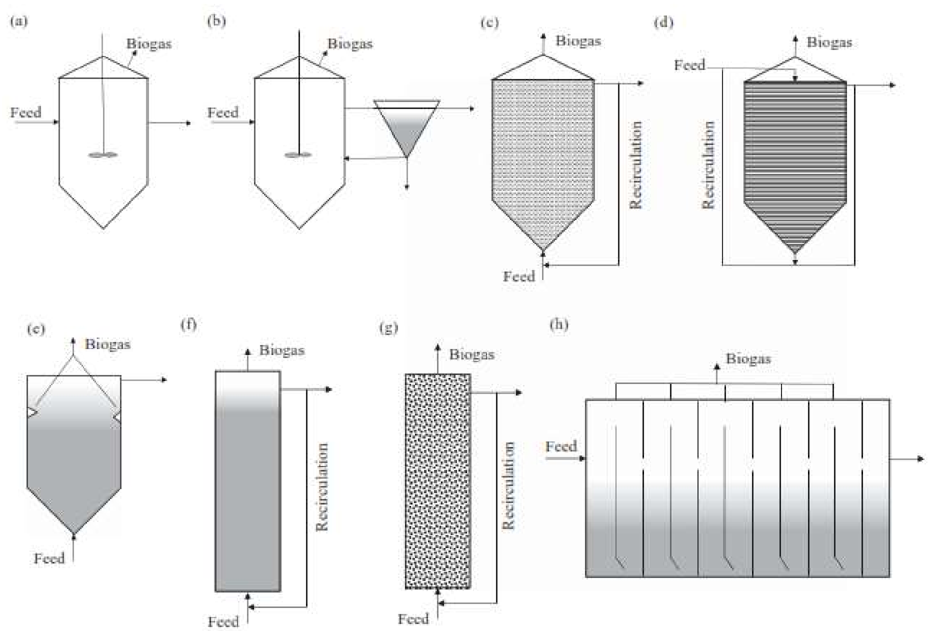

FIGURE 2.10: Types of anaerobic systems (a) Continuous stirred tank reactor (CSTR) without biomass recirculation (or conventional system), (b) contact process, (c) up-flow filter, (d) down-flow filter, (e) UASB, (f) expanded granular sludge blanket (EGSB), (g) fluidized bed, and (h) baffled reactor (ABR)
Source: adapted from Stamatelatou et al. (2014)

TABLE 2-7: Key Characteristics of Some Anaerobic Treatment Systems

Technology	Characteristics	Possible Challenges
Conventional system	a. Low energy consumption	a. Biomass washout
	b. Suitable for sewage sludge and high solids WWT	b. Low OLR/High HRT
	c. SRT is generally equal to HRT	c. Low treatment efficiency
		d. High space requirement
Anaerobic contact process	a. CSTR with biomass recirculation	a. No phase separation
	b. SRT can be separated from HRT	b. High space requirement
	c. Suitable for low to medium strength wastewaters	c. Not suitable for high OLR
		d. Poor settling due to “rising sludge”
		e. Cover settling tank to prevent odor nuisance
UASB	a. Formation of active biomass in granules forms	a. No phase separation
	b. Suitable for low solids high strength wastewaters	b. Performance dependent on granule formation
	c. SRT is greater than HRT	c. Suitable inoculum rapid start-up
	d. Low energy requirement	d. Sludge blanket difficult to maintain
	e. Suitable for low to medium OLR	
Expanded granular sludge blanket (EGSB)	a. Modify UASB with higher upflow velocities to enhance hydraulic properties	a. No phase separation
	b. Suitable for medium to high OLR	b. Poor process stability at high OLR and low HRT
	c. SRT is greater than HRT	c. Less flexible operation
	d. Good process control	d. Not suitable for high solids wastewaters
	e. Low space requirement	e. High energy requirement
	f. Suitable for low strength wastewaters	
Fluidized bed reactor (FBR)	a. Development of anaerobic biomass on inert particles, and fluidization as in EGSB	a. Difficulties in maintain optimum mixing and fluidizing velocity and conditions without biomass stripping or washout
	b. Suitable for medium to high OLR	b. General difficulties in scaling up from pilot to effective full-scale operating conditions
	c. SRT is greater than HRT	c. Difficult to start-up
	d. Good process control	
	e. Low space requirement	
	f. Suitable for low strength and low solids wastewaters	
Anaerobic baffled reactor (ABR)	a. Plug flow regime	a. Difficulties with variable system hydraulics due to sludge accumulation and biomass growth
	b. Phase separation	b. Limited full scale experience
	c. SRT can be separated from HRT via sludge recirculation	
	d. Mechanical mixing not required	
	e. Suitable for low strength and low solids wastewaters	
	f. Possible selective recovery of high methane content biogas	

Table 2-7: Key Characteristics of Some Anaerobic Treatment Systems [continued]

Technology	Characteristics	Possible Challenges
Anaerobic upflow filter (UF)/ down flow filter (DF)	a. Anaerobic biomass attached on fixed inert media and quasi plug flow	a. No phase separation
	b. Performance is dependent on the type of media	b. Not suitable for high solids wastewaters
	c. attached and suspended biomass, while DF involves mainly attached biomass	c. Mixing and short circuiting problems
	d. Suitable for medium to high OLR	d. High energy requirement
	e. Extremely high SRT:HRT ratio f. Good process control	
	g. Low space requirement	
	h. Suitable for low strength and low solids wastewaters	

Source: Adapted from Malina and Pohland (1992); Metcalf and Eddy (2014)

7. Anaerobic treatment system: applications, benefits, and drawbacks

Anaerobic system is considered as an economical and cost-effective system compared to other treatment technologies, specially aerobic systems, regarding the capital cost and the operational cost (energy cost). When compared under same influent characteristics and removal efficiency, the space required for the anaerobic system is 50% less than that needed for aerobic system, and regarding the energy consumption the aerobic system consumes 3-4 times higher than anaerobic system (Bajpai. 2017). The average energy consumption in WWTPs regardless of technology differences varies between 0.38-1.122 kWh/m3 (Wakeel et al. 2016).

In aerobic system. The aeration consumes about 53% of the total energy, flow equalization and sludge dewatering also had a great contribution in operational expenditures. (Vilanova et al. 2015), On average, 30% of the WWTP costs are attributed to the sludge treatment, stabilization and disposal (Shen et, al 2015). The sludge treatment, until its final disposal, can consume between 0.074 and 0.15 kWh/m3 based on sludge management strategy used (Longo et al. 2016). Biogas recovery from anaerobic wastewater treatment plants can provide 39-76% of the total energy consumed in WWTP (Silvestre et, al 2015), In the United States alone, between 628 and 4,940 million kWh can be saved annually by the anaerobic digestion of the wastewater sludge (Wakeel et al. 2016). The recovery of biogas in the WWTPs can reduce the energy consumption by 33%, Further research also indicates that the anaerobic digestion may generate 0.1 kWh/m3 (Wang et al. 2016), and 1.16 kWh/ kg COD removed (Bajpai. 2017).

The advantages and disadvantages of anaerobic treatment system is summarized in Table 2.8.

TABLE 2-8: Anaerobic treatment system Advantages and Disadvantages Compared to Aerobic Treatment system

Advantages	Disadvantages
• Low nutrient requirement	• Long start-up times
• Low sludge production	• Requires high temperatures for effective performance
• Methane production (potential fuel)	• Sensitive to shock and variable organic load, changes in waste characteristics and temperature fluctuations
• Treated effluent and digestate can be used as soil conditioner	• Requires regular monitoring of input and by-products to ensure process stability
• No oxygen requirement, hence, low capital and operating costs	• Requires skilled operational manpower
• Microorganisms can survive a long period of little or no feeding	
• Waste pasteurization can be achieved	

Source: Adapted from: Hall (1992) and Malina (1992).

8. Anaerobic system performance and monitoring indicators

A generalized performance template for anaerobic wastewater treatment is shown in Table 2.9. A number of parameters have been used as an indicators of process imbalance in anaerobic systems. Some of the commonly used indicators are listed in Table 2.10. Most of the parameters are inter-related, indicating that no parameter alone can provide a complete assessment of a treatment system. While biogas production, composition, and reactor temperature are relatively simple to measure, the others are more time consuming and expensive to quantify. The simpler measurements can be carried out more frequently, while others less routinely and when the simpler measurements suggest looming instability.

TABLE 2-9: Performance Levels for Anaerobic Treatment

Parameter	**Removal Value**
BOD	80%–90%
COD	$1.5 \times BOD_{removed}$
Biogas	500 ltr / kg $COD_{removed}$
Methane	350 ltr / kg $COD_{removed}$
Sludge	0.05–0.10 kg VS / kg $COD_{removed}$

Source: adapted from Pohland (1992).

TABLE 2-10: Anaerobic Digestion Imbalance Indicators

Indicator	Principle
Biogas production	Specific gas production changing can be caused by the change in feed characteristics, mainly the nature and biodegradability of the organic compunds (i.e., VS and COD)
Biogas composition	Changes in CH_4/CO_2 biogas ratios are signs of process instability. Higher CO_2 content may be indicative of organic overload or organic shock load and/or inhibition of methanogenesis, caused by some or all of the following: high levels of VFA accumulation, ammonia, sulfide, or other inhibitors and changes in temperature. Hydrogen (H_2) in the biogas is usually low, and where detected, is also a sign of process instability commonly associated with high VFA accumulation
pH	Changes depend on VFA and ammonium concentrations. decrease in pH can be caused by VFA accumulation, and/or drop in alkalinity. High CO_2 biogas content can be related to low pH
Alkalinity (TA)	Detects changes in buffer capacity, and can affect pH levels
VFA	Accumulation indicates process instability, which can be caused by one or more of the following: lower methanogenic activities and/or higher acidogenic than methanogenic activities, lower acetogenic activities for some individual VFAs (commonly propionic acid), lower alkalinity of medium, temperature changes, organic overload and/or shock load, etc.
Individual VFA	Accumulation of individual VFA
VFA/TA (or VOA/ TAC) ratio	Values of about 0.3 indicate process stability, and greater values are indicative of (looming) process instability
COD or VS content	Changes in biodegradation rate
Temperature	A variation of 2°C–3°C can cause fundamental changes in the microbial dynamics in the system. Different temperature ranges are associated with different microbial populations, particularly for methanogenesis. Excessive VFA accumulation and high biogas CO_2 content can also be caused by temperature changes

Source: adapted from Akunna (2011)

9. Foaming and control

Foaming is an undesirable occurrence in anaerobic wastewater treatment systems which can lead to both *physical* effects e.g., overflow of effluents to surrounding areas, blockage of biogas pipework, interference with monitoring and process control devices, high solids in the effluent pipes, etc. and biological effects with overall impact of reduced biological efficiency. Overall, foaming can cause high operational costs and general losses.

There has been a lot of research about the possible causes of foaming, ranging from wastewater characteristics and composition, operational conditions (e.g., temperature, OLR, HRT, mixing methods, start-up procedures, etc.), biological factors (e.g., bio-surfactants production by microbial decomposition, protein denaturation, extracellular polymers substances excreted by microorganisms subjected to certain environmental stress, etc.).

When foaming occurs, the causes might be so complex to be known, and it may not be cost effective to try to understand them, many of which may be difficult to change. The most effective method of foaming control is treating the foam directly rather than trying to find the root causes and implementing edits in the reactor operation or wastewater characteristics. Direct methods for foam control include the following (Speece 2008):

- Chemical methods: Anti-foaming agents (e.g., polydimethylsiloxane), chlorine, etc. The majority of anti- foaming agents have been reported to be very effective and work within 2–10 minutes (Barber 2005).
- Mechanical methods: e.g., foam breakers, disintegration methods, water sprays, etc.
- Biological: Enrichment of surfactant utilizing microorganisms.
- Ultrasound treatment and pasteurization.

10. Sludge stability

The stability of waste sludge in UASB is related to the remaining biodegradable organics in the sludge mass, which refers to the remaining volatile suspended solids percentage inside the sludge biomass, if the sludge age is high enough, it may be expected that the produced sludge is stable. The sludge stability can be examined by several methods, in this study we analyzed several sample from the biomass inside the UASB reactor for the VSS and TSS concentrations. The VSS/TSS ratio method is used as an indicator for the sludge stability, as the higher the active fraction, the greater the proportion of biodegradable organics remaining in the sludge mass. Also the greater the utilizable energy content remaining in the sludge mass (Henze et al 2008), for sludge to be stable the remaining utilizable organic content should be low so that no odor will be generated through significant biological activities (Van Haandel et al 2019). Table 4.6 represents the data collected by analyzing the TSS and VSS for the biomass inside the UASB reactor, and calculating the VSS/TSS ration to check the stability of sludge inside the reactor.

11. Anaerobic treatment process design and operational control

Several parameters needed to be considered during the anaerobic treatment system design and operation phase, these matters will be discussed briefly in the following subsections.

- Hydraulic retention time (HRT)

Hydraulic retention time (HRT) is the average time the liquid stays in the treatment reactor before being discharged. it can be calculated by the following equation:

$$\theta = \frac{V}{Q} \qquad (2.1)$$

where

θ = Hydraulic retention time, h

V = Reactor volume, m^3

Q = Average wastewater flow rate, m^3 / h

HRT can vary from 4 to 48 h, depending on the wastewater characteristics. Equation 2.1. shows that HRT is directly related to the size of reactor. The higher the wastewater organic matter concentration, the longer the necessary time needed for treatment. High wastewater solids require usually longer treatment time due to the extra time needed for solids hydrolysis. Very low HRT can lead to high biomass washout in suspended growth systems that are not equipped with suitable biomass retention or recovery recirculation facilities.

- Solids retention time (SRT)

SRT or sludge age provides an estimation of the average time microorganisms or biomass produced during the biodegradation process stay within the system before being removed as waste or excess biomass. The use of SRT for process design and operation design is only applicable in suspended growth systems, where it is relatively easy to estimate the amount of biomass in the reactor. It can be controlled by the rate of removal of excess biomass or desludging from the system as shown in the following equation:

$$\theta_c = \frac{VX}{(Q-Q_w)X_e+Q_wX_w} \qquad (2.2)$$

where

θ_c = Solids retention time, day

V = Reactor volume, m^3

Q = Average wastewater flow rate, m^3 / day

Q_w = Average waste biomass flow rate or desludging rate, m^3 / day

X = Average concentration of biomass inside the reactor, kg VS / m^3

X_e = Average concentration of biomass in the treated effluent, kg VS / m^3

X_w = Average concentration of biomass in waste or excess biomass stream, kg VS / m^3

Where Qw ≪ Q and X_e ≪ X, Equation 2.2 approximates to the following equation:

$$\theta_c = \frac{VX}{Q_w X_w} \quad (2.3)$$

Equation 2.3 shows that in absence of excessive hydraulic load or very low HRT that can cause unwelcome biomass washout, excess biomass withdrawal rate is the single most important tool for controlling the SRT. The choice of biomass withdrawal rate is dictated by organic loading and biodegradation rates. High-rate reactors are generally designed and operated in a manner that will ensure high biomass retention, i.e., SRT >> HRT. This is normally achieved by recirculation of biosolids separated from treated effluent or by the use of attached growth systems.

- Hydraulic loading rate (HLR)

HLR measures the amount of liquid applied per unit area of the reactor, as expressed in Equation 2.4. It is commonly used in the design of fixed bed reactors.

$$HLR = \frac{Q}{A} \quad (2.4)$$

where

HLR = Hydraulic loading rate, $m^3/m^2 \cdot day$

Q = Average wastewater flow rate, m^3/day

A = Surface area of the packing medium, m^2

The higher the HLR, the lower the HRT. Optimal values for HLR vary with wastewater characteristics and types of support media. Plastic media have higher surface area to volume ratio than stone media. Hence, plastic media anaerobic reactors are usually operated at higher HLR than stone media reactors.

- Organic loading rate (OLR)

OLR or *Volumetric Organic Load* represents the amount of biodegradable organic matter, expressed in term of BOD or COD, applied daily per unit volume of the reactor, as expressed in the following equation:

$$OLR = \frac{QS_0}{V} \quad (2.5)$$

Where:

OLR = Organic loading rate, kg COD/ $m^3 \cdot day$ (or kg BOD/ $m^3 \cdot day$)

S_0 = Influent BOD or biodegradable COD in wastewater, mg / L

V = Reactor volume, m^3

Q = Average wastewater flow rate, m^3 / day

Suitable OLR values depend on many factors like wastewater characteristics, operating temperature, and the level of microbial activity within the reactor. OLR values are usually kept low during start-up and gradually increased as the reactor stability increases evidenced by optimum pH range and low volatile fatty acids VFA.

- Food/Microorganism ratio

The Food/Microorganism (F/M) ratio or *sludge loading rate* (SLR) represents the amount of biodegradable organic matter, expressed in terms of COD, applied daily per unit biomass present in the reactor, as expressed in Equation 2.6. It is only used in suspended growth systems where the amount of biomass can be more accurately estimated. The total volatile solids (VS) concentration in the reactor is assumed as a measure of the biomass content.

$$\frac{F}{M} ration = \frac{QS_0}{VX} \quad (2.6)$$

where

F/M = Food/Microorganism ratio, kg COD / kg VS · day (or 1/day)

S_0 = Influent biodegradable COD in wastewater, kg / m^3

Q = Average wastewater flow rate, m^3 / day

V = Volume of reactor, m^3

X = Average concentration of microorganisms present in the reactor, kg VS / m^3

In anaerobic systems, the methods used for the determination of the parameter X do not distinguish between the fast-growing acidogens and the slow- growing and rate-limiting methanogens. so, the F/M ratio is seldom used. It is, however, an important design and operational control parameter in aerobic treatment and post-treatment, where there is less distinction between the activities of the participating microorganisms.

- Specific biogas yield

The specific biogas yield measures the maximum biogas production capability of a given amount of organic compound. It is estimated using the following equation:

$$Y_{biogas} = \frac{Q_{biogas}}{Q(S_0 - S_e)} \quad (2.7)$$

Where

Y_{biogas} = Specific biogas yield, m^3 biogas / kg COD_{removed}

Q_{biogas} = Biogas production rate, m^3 / day

Q = Average wastewater flow rate, m^3 / day

S_0 = Influent COD in wastewater, kg / m^3

S_e = Effluent COD in wastewater, kg / m^3

The theoretical value of Y_{biogas} is a constant and stoichiometrically equals to 0.5 m^3/COD_{removed}, comprising 0.35 (or 70%) and 0.15 (or 30%) for methane and carbon dioxide, respectively. A comparison of actual Y_{biogas} value with the theoretical value for various types of wastewaters is important in understanding system performance and assessing the accuracy of monitoring devices.

- Specific biogas production rate (BPR)

BPR is used to compare the rates of biogas production by different anaerobic treatment systems. It is given by the following equation:

$$BPR = \frac{Q_{biogas}}{V} \qquad (2.8)$$

where

BPR = Specific biogas production yield, m^3 biogas/$m^3 \cdot$ day

Q_{biogas} = Biogas production rate, m^3 / day

V = Reactor volume, m^3

- Treatment efficiency

Treatment efficiency is a measure of the proportion of the target determinant removed or transformed in the treatment system. In anaerobic wastewater treatment, the treatment efficiency is the amount of *settled* COD removed in the system, and expressed in percentage as shown the following equation:

$$\%COD\ removal = \frac{S_0 - S_e}{S_0} \times 100 \qquad (2.9)$$

where

S_O = Influent settled wastewater COD, mg/L

S_e = Effluent settled wastewater COD, mg/L

Equation 2.9. also be used to measure the of BOD, TSS, VSS etc. removal efficiencies.

- Temperature

as mentioned previously, Anaerobic treatment systems can be operated in the following temperatures:

a. Psychrophilic: 5°C–20°C

b. Mesophilic: 20°C–45°C (Optimum 35°C)

c. Thermophilic: 45°C–70°C (Optimum 55°C)

The values of most of the design parameters are also dependent on the operating temperatures. For example, thermophilic and mesophilic systems have higher tolerance for lower HRT and higher OLR than psychrophilic systems.

Chapter 3 MATERIALS AND METHODS

3.1 Materials

Figure 3.1 shows a schematic diagram of the pilot scale Upflow Anaerobic Sludge Blanket Septic Tank (UASB). The reactor, a cylindrical shape with 45 cm diameter base and 200 cm high, gives a total reactor volume of 300 l. The reactor is made of epoxy coated Galvanized steel with 0.2 mm thickness that contains a liquid-gas separator that is connected to a digital gas flow meter, which counts that current and accumulative amount of total gas production and scale the ambient temperature on the same screen. The UASB was fed by a variable and adjustable peristaltic feed pump (100-1000 l/day) which was connected to the inlet pipe of the reactor, is made of galvanized steel with 16.0 mm diameter apertures located at the bottom vessel. Such arrangement generates an up-flow. The equalization tank with a total capacity of 10.0 m^3 that feeds the UASB is provided with mechanical mixer to avoid settling and keep the fresh sewage homogenous and equalized. at the side all of the reactor; 6 wall mounted sample tabs to visually check the sludge accumulation inside the reactor, and there was another tab fixed at the bottom of the reactor to be used for excess sludge transferring, and the outlet of the reactor there was a sampling point for taking samples.

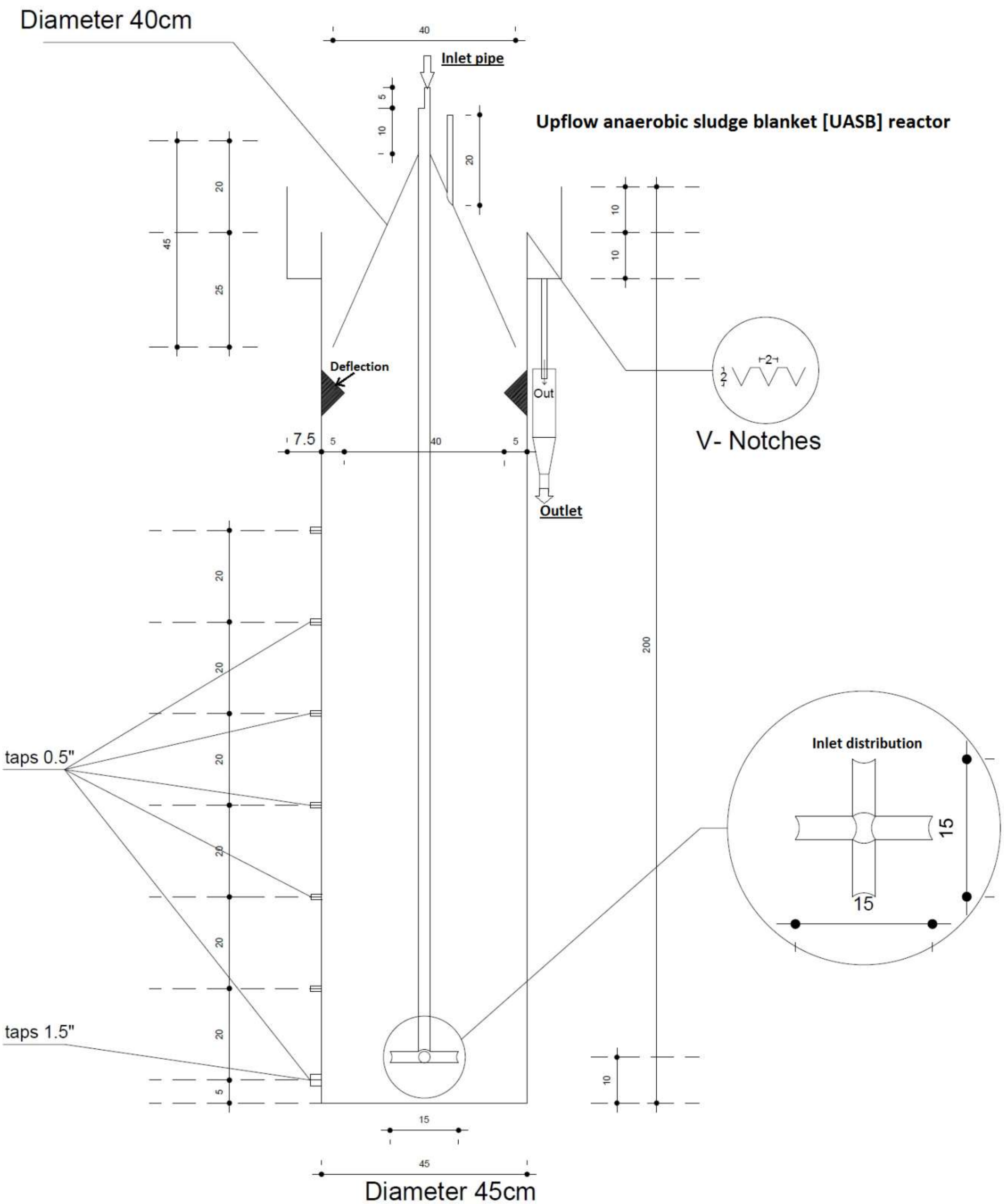

FIGURE 3.1: Schematic diagram of the pilot scale UASB reactor

Photo 3.1: Constructed Pilot Scale UASB-septic tank installed at BZU Campus

3.2 Methodology

[1] Research type: Applied research using locally assembled pilot scale UASB system installed inside Birzeit university campus

[2] Target and group samples: Water and environmental related institutions, municipalities, NGOs, Slaughterhouse owners

[3] Research tools/equipment: Pilot scale treatment units [Integrated UASB system]

[4] Research methods of Analysis: Lab tests and analysis, statistical evaluation, field observations and data collection, system operation and process monitoring.

3.3 Sampling and analysis

- A 5.0 l off raw and composite wastewater sample was compiled from a local slaughterhouse effluent in Birzeit city, Palestine, wastewater samples were collected during a working day.
- During a week with variable slaughtering intensities, composite samples were collected during two different days, resulting in two composite samples to reflect the variable strengths of the organic matter depicted as COD parameter.

- The relevant physical, chemical and microbiological characteristics of the UASB influent and effluent was analyzed based on the standard methods for the analyzing water and wastewater (APHA, 2005).
- The raw effluent was collected from the Slaughterhouse septic tank, and then transferred by a truck to the pilot system location on a monthly basis, each batch contains 10.0 m^3. The slaughterhouse wastewater transported was fed into the equalization tank, preceding the UASB system.
- 250.0 ml sample was taken from each feed batch, to be analyzed either immediately or sometimes stored inside the lab refrigerator to be analyzed later, 250.0 ml outlet samples were also taken from the UASB effluent each 2 to 4 weeks, the ambient temperature, system temperature, total gas production were also recorder on a weekly basis.
- inlet and outlet samples from the reactor were analyzed for BOD, COD, TSS, VSS, according to standard methods. The reactor sludge samples were also analyzed for VSS and TSS according to the standard method.

3.4 System start-up and operation

The start-up and operation of the UASB under continuous flow was begun with preliminary tests using fresh wastewater to check the system insulation and fix leakage (if any). To check the balance of the system and the equal distribution of the treated effluent between the V notches, the system was emptied totally from fresh water, and the injection of the fresh sewage was started gradually. On June 2019 with the following characteristics (COD: 14,901 mg/l, BOD: 7,239 mg/l TSS: 1,509 mg/l VSS: 1,450 mg/l) with 150.0 ml/min, to establish biomass production and a stable granular sludge. The COD concentration was progressively increased from 3500 to 7000 mg/l over a period of 14 days, then another 14 days to reach the 14,901 mg/l.

The establishment of the granular sludge in the UASB septic tank was enhanced using 150.0 l (3.45gr/l TSS and 2.077 g/l VSS) of anaerobic sludge from Nablus West WWTP that treats domestic wastewater from the city of Nablus Western side. Having a stable organic matter removal rate, the UASB reached the steady state conditions after 3-4 week of operation.

The UASB performance was tested under constant COD concentration and constant feed flow rate (hydraulic retention time) for a period of 3-4 months, then with variable (increasing feed flow rate and shorten HRT and OLR). Energy recovery (production) of biogas was measured and recorded weekly, but this research did not analyze the gas components. The system storage tanks where fed by batches method, each batch with a total volume of 10.0 m^3, with around one-month period between each batch.

3.5 Time framework

First batch was fed to the system In June 2019, with the following characteristics:

COD: 14,901 mg/l BOD: 7,239 mg/l TSS: 1,509 mg/l VSS: 1,450 mg/l.

Last samples of the system treated effluent was analyzed on April 2020. The following result were achieved: (COD: 1,286 mg/l, BOD: N/A (due to the complexity of making the analyses during the COVID 19 Corona virus pandemic) but using the COD:BOD ration achieved from the previous analyzed data which was 2:1, estimated BOD achieved is 643 mg/l, TSS: 92 mg/l VSS: 20 mg/l.

The total operation period of the pilot scale UASB was 10 months.

3.6 UASB Design

System equipment's volume & capacities were used in the pilot scale UASB is listed below:

1. UASB reactor: active volume 300 l
2. Adjustable Peristaltic feed pump: 100-1000 l/day
3. equalization tank: 2 * 5.0 m^3
4. Gas flow meter: 0-200 SLPM
5. Mechanical mixer: 200 rpm

3.7 Calculations

Several calculations had been made using the data achieved from the samples analyses for the following parameters:

3.7.1 Up flow velocity

Up flow velocity were calculated using the following equation:

Velocity = feed flow rate / reactor surface area

following results were achieved:

V: 0.03 m/h during the start up phase

V: 0.085 m/h during the operation phase

V: 0.17 m/h during the final and closure phase

3.7.2 Hydraulic retention time HRT

HRT were calculated using equation 2.1,

following results were achieved:

- 66.6 hour during the start up phase (4-6) weeks
- 22.2 hours during the normal operation period (7-8) months
- 11.1 hours during the final stage (2-3) weeks

3.7.3 COD removal efficiency %COD

%COD was calculated using equation 2.9,

following results were achieved:

- maximum removal efficiency achieved: 95%
- minimum removal efficiency achieved: 23% (during system troubleshooting-chock loading-foaming)
- average removal efficiency achieved: 77%

3.7.4 TSS removal efficiency %TSS

TSS % was calculated using equation 2.9,

following results were achieved:

- maximum removal efficiency achieved: 90%
- minimum removal efficiency achieved: 11% (during system troubleshooting-chock loading-foaming)
- average removal efficiency achieved: 55%

3.7.5 VSS removal efficiency %VSS

VSS % was calculated using equation 2.9,

following results were achieved:

- maximum removal efficiency achieved: 96%
- minimum removal efficiency achieved: 23% (during system troubleshooting-chock loading-foaming)
- average removal efficiency achieved: 58%

3.7.6 Specific biogas yield $\boldsymbol{Y_{biogas}}$

Biogas yield calculated using equation 2.7, assuming Q biogas is the total biogas produced during the whole research period, Q is the total SWW fed inside the reactor and taking the average values of both influent and effluent COD:

The following results were achieved:

- average daily biogas production quantity: 0.128 m^3/day
- average daily amount of SWW fed inside the reactor: 0.32 m^3/day
- average influent COD: 8.32 kg/m^3
- average effluent COD: 1.57 kg/m^3
- Specific biogas yield Y_{biogas} : $Y_{biogas} = \frac{0.128}{0.32(8.32-1.57)}$` = 0.059 m^3 biogas/ kg.$COD_{removed}$

Chapter 4 RESULTS AND DISCUSSION

This section summarizes the findings and contributions made during this research study, and gives a brief discussion about them.

4.1 Start up and operation of the reactor

During the first 4-6 weeks of the startup period (feed flow rate of 4.5 l/h, HRT of 67 hour). The UASB system did not show a good treatment indications regarding the COD, TSS, VSS and gas production, to speed up the treatment process, they system was fed by anaerobic digested sludge with a high concentration of TSS, VSS (3.45 g/l, 2.077 g/l respectively) with a quantity of 120 l (30%) of the total active reactor volume. Then 1 week after, the gas flow meter stated to give reading, and an effluent samples were analyzed, and good efficiencies were achieved regarding the COD, TSS and VSS removal.

4.2 System optimal operation conditions

The feed flow rate, HRT then adjusted and the system worked on 13.5 l/h feed flow rate and 22 hours HRT for a period of 7 months.

Photo 4.1: influent Vs Effluent visual results, 3 months' operation. (Date: 30.09.2019)

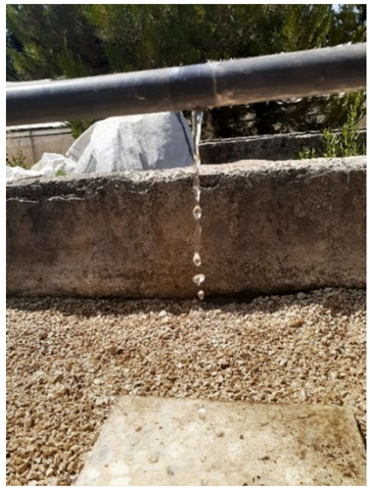

Photo 4.2: UASB effluent to constructed wetland. Date: 06.08.2019

4.3 Effect of the batch feeding regime

Using batch regime to feed up of the system with SWW affected the influent and effluent results, since each batch was stored in a feeding tank, and the feed take itself started to work as a reactor, and solids started to settle at the bottom of it, and a reduction of COD concentration in the influent was noticed. To solve these issues a mechanical mixer was installed inside the storage tank to turn it to become and equalization tank, keep the feed batch homogenized, and avoid any sedimentation.

Photo 4.3: Feed storage tank prior mixer installation (August, 2019)

4.4 Effect of shock load

After reaching the steady state condition, good performance started to show up and a good COD, TSS and VSS removal efficiencies started to be noticed. But then a sudden increase in the feeding flowrate happened mistakenly, the feed flow rate was tripled by just one click. As a result of this, less than one day was enough to cause a major troubleshooting in the system. A huge foaming layer was formed, and overflowed from the top of the reactor causing an outlet tube blockage and a big bio solids washout Photo 1, effluent samples were analyzed and a noticeable drop in the system efficiency was recorded, they system needed 3 weeks to be back to normal steady state condition.

Photo 4.4: several troubleshooting photos show huge foaming layer was formed, and overflowed from the top of the reactor causing an outlet tube blockage and a big bio solids washout. (Date:17.11.2019)

4.5 Maximum loading capacity

After achieving an improvement in the system performance, the decision of checking the maximum load capacity of the system was made. The feed flow rate was doubled (27.0 l/h), and so the HRT was cut to half (11 hours), effluent samples were analyzed, results didn't show any drop in the system performance efficiencies, on the contrary a better performance was noted. This improvement was referred to the system working period and the better climate conditions since this step was took on march and it was accompanied by a rise in ambient temperature.

The decision was took to increase the feed flow rate furthermore and check the maximum system capacity, but during the COVID 19 Corona virus pandemic, monitoring the system and analyzing more sample was not easy to be done due to the transportation obstacles and the university labs shutting down.

Photo 4.5: Influent Vs Effluent increasing the feed flow rate. Date (April, 2020) Sludge Production

The sludge inside the reactor was of rapidly settling nature. The rate of sludge production in the reactor was found to be very low. Desludging process had to be done only once during the entire period of the study (10 months, 90.0 m^3 feed). The reason might be that most of the soluble and settled matter in the wastewater had been degraded during the treatment process in the UASB, a sample of the excess sludge was analyzed and the results of VSS, TSS was the quantities of sludge removed was 55.14 g/l, 42.37 g/l respectively. The results show that getting rid of the excess sludge has a good effect on the system performance, since a lot of improvement indication in the COD, TSS and VSS removal and were notices just few days after the desludging process took place.

4.6 Influent variations

The characteristics of the influent SWW were not stable, each batch has a different characteristic, but all batches were considered to be a very strong pollutant, the influent COD, TSS and VSS concentration range was (4373-14901 mg/l) (816-2364 mg/l) (768-2272 mg/l) respectively.

4.7 Data analyses

4.7.1 COD removal efficiency

Table 4.1 below shows the data achieved from COD analyses for SWW influent/ effluent, and calculates the removal efficiency:

TABLE 4-1: COD influent/effluent, organic loading rate and removal efficiency

DATE	COD IN kg/m3	COD OUT kg/m3	OLR Kg COD /m3 day	COD REMOVAL EFF %	NOTES
20.06.2019	9.63	1.93	3.47	80	
15.07.2019	14.19	1.82	5.11	87	BIOMASS FEED
22.07.2019	14.9	1.56	16.09	90	
04.08.2019	13.8	1.33	14.9	91	
13.08.2019	13.3	1.03	14.36	92	
11.09.2019	12.75	0.81	13.77	94	
14.09.2019	11.35	0.66	12.26	94	
20.09.2109	9.5	0.47	10.26	95	
30.09.2019	7.66	0.33	8.27	96	
07.10.2019	6.58	0.29	7.11	96	
18.10.2019	5.89	0.31	6.36	95	SHOCK LOAD
12.11.2019	5.21	0.29	5.63	94	SYSTEM FAILUR
21.11.2019	4.7	N/A	5.08	N/A	EFFICIENCY DROP
02.12.2019	4.76	2.56	5.14	46	
09.12.2019	4.91	N/A	5.3	N/A	
15.01.2020	5.12	4.09	5.53	20	
27.01.2020	4.37	3.37	4.72	23	
10.02.2020	8.85	1.99	9.55	78	
17.02.2020	9.25	N/A	9.99	N/A	
05.03.2020	6.22	2.54	6.71	59	SLUDGE TRANSFER
13.04.2020	6.78	1.6	7.33	76	
21.04.2020	6.71	3.29	7.25	51	DOUBLE LOADING
24.04.2020	6.68	N/A	7.22	N/A	
29.04.2020	6.62	1.29	14.31	81	

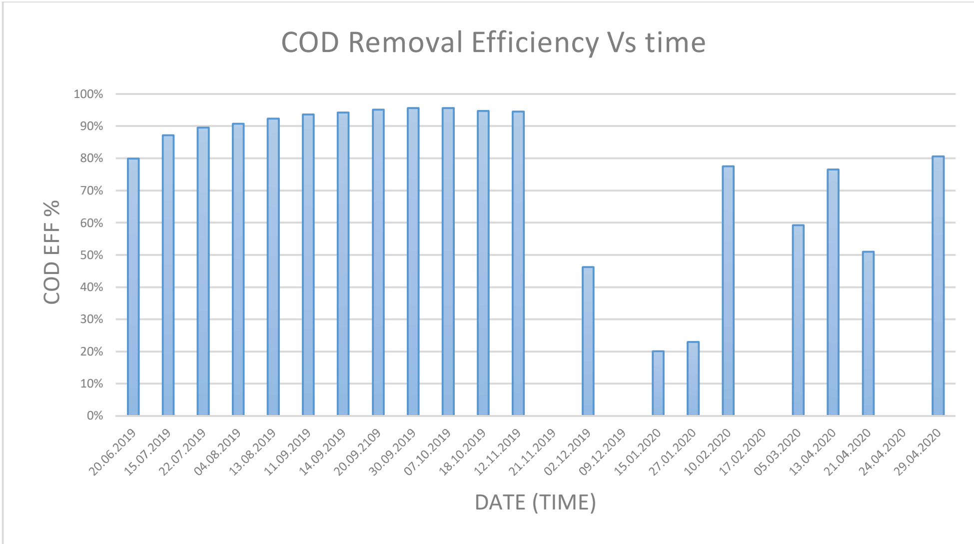

Chart 4-1: COD Removal Efficiency Vs Time

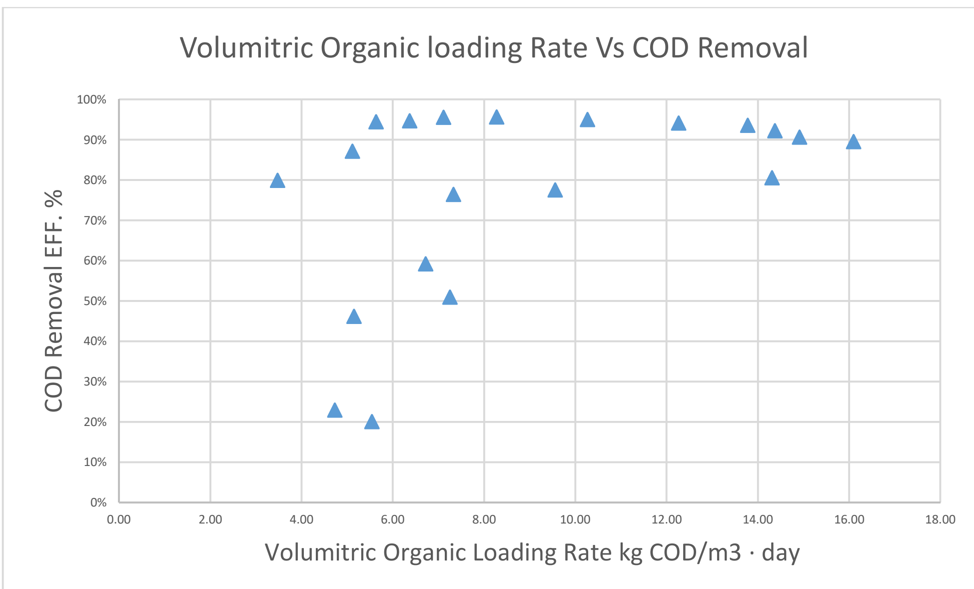

Chart 4-2: COD Removal Efficiency Vs Volumetric Loading Rate

From the results achieved and the outcome graph above, we can find the following:

- SWW influent COD range (4373-14901 mg /l), Average value (8,323 mg /l)
- SWW effluent COD range (292-4093 mg/l), Average value (1,577 mg / l)
- OLR range (3.47-16.09 Kg COD / m^3.day), Average value (8.6 Kg COD / m^3.day)
- COD removal efficiency range (20-96%), Average value (77.0 %)

There is a big variation in the COD influent characteristic and so the organic loading rate. This is not suitable for the UASB system stability, because anaerobic process is sensitive to the variation in inlet load. The reason behind could be the batched feed regime and carrying the SWW from the slaughterhouse storage tank, and this can be solved when installing the UASB inside the Slaughterhouse plant. Even though, the pilot UASB was able to handle these variations and continue to give a good performance and removal efficiency that reached 96% just 10 weeks after the steady state phase of the system operation, under the optimal operation conditions and during a warm period with around 35°C ambient temperature.

Graph also shows a severe drop in the system performance and it was reflected on the removal efficiency. This suddenly happened and during the best performance of the system, when the system has subjected to a sudden shock load as the inlet flow has tripled from 13.5 l/h to 40.1 l/h. The system biomass turbulence with huge foaming layer formation caused a washout of settled biomass and then mixed it with the effluent. This caused a decrease in the COD removal efficiency, then few weeks later and after making the needed adjustment, then system started to recover, and the removal efficiency started to raise. This was on November during the cold season, the improvement was not as fast as it was during the hot season but still a noticeable improvement was noted, and the overall removal efficiency reached 77%, which shows that SWW responds well to anaerobic degradation and so using the UASB has a good potential in treating SWW. and since the COD is a very important factor that express the pollution load in SWW, this result should be taken into consideration by the Palestinian policy makers to apply the UASB system as a pretreatment option in all slaughterhouses and forcing them to use it prior discharging their untreated effluent to the sewer network.

4.7.2 TSS & VSS removal efficiency

Tables 4.2, 4.3 below show the data achieved from TSS & VSS analyses for SWW influent/effluent, and calculate the removal efficiency.

4.7.2.1 VSS removal efficiency

Tables 4.2 shows the data collected from TSS analyses for SWW influent/effluent during the research period, and calculate the removal efficiency.

TABLE 4-2: TSS influent/effluent, TSS Organic loading rate, TSS removal efficiency

DATE	TSS IN mg/l	TSS OUT mg/l	OLR, Kg TSS /m3 day	TSS EFF. %	NOTES
20.06.2019	N/A	N/A	N/A	N/A	
15.07.2019	1436	1205	0.52	16	BIOMASS FEED
22.07.2019	1509	1253	1.63	17	
04.08.2019	1753	1240	1.89	29	
13.08.2019	2364	1305	2.55	45	
11.09.2019	2023	825	2.18	59	
14.09.2019	1816	613	1.96	66	
20.09.2109	1653	498	1.79	70	
30.09.2019	1702	228	1.84	87	
07.10.2019	1715	492	1.85	71	
18.10.2019	1730	356	1.87	79	SHOCK LOAD
12.11.2019	1685	344	1.82	80	SYSTEM FAILUR
21.11.2019	1844	325	1.99	82	EFFICIENCY DROP
02.12.2019	1352	820	1.46	39	
09.12.2019	1024	628	1.11	0.39	
15.01.2020	1600	1208	1.73	25	
27.01.2020	1596	604	1.72	62	
10.02.2020	1702	N/A	1.84	N/A	
17.02.2020	N/A	N/A	N/A	N/A	
05.03.2020	1236	716	1.33	42	SLUDGE TRANSFER
13.04.2020	1120	204	1.21	82	
21.04.2020	816	724	0.88	11	DOUBLE LOADING
24.04.2020	N/A	N/A	N/A	N/A	
29.04.2020	925	92	2	90	

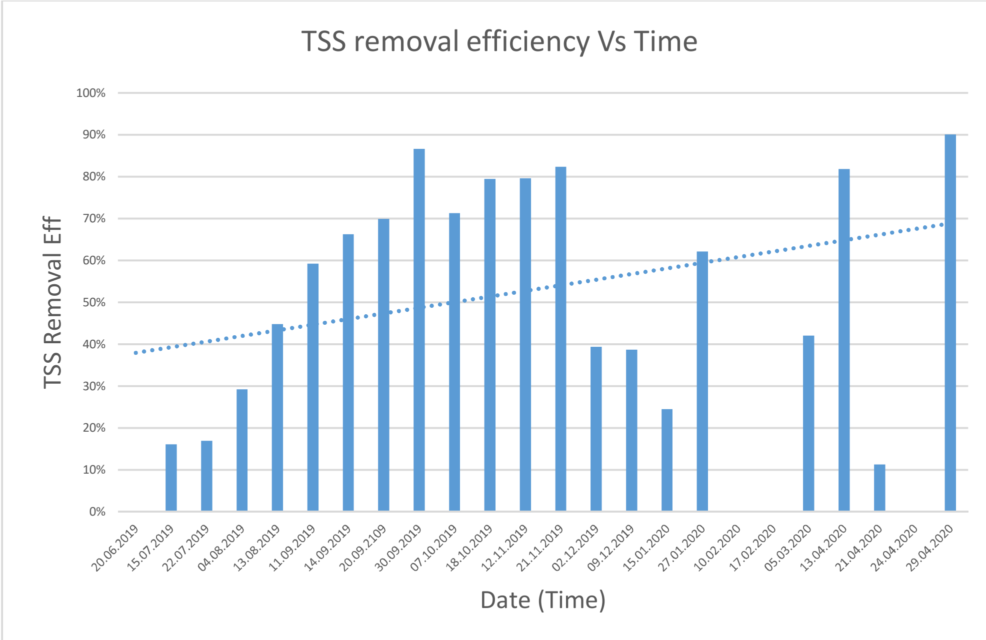

Chart 4-3: TSS removal efficiency Vs Time

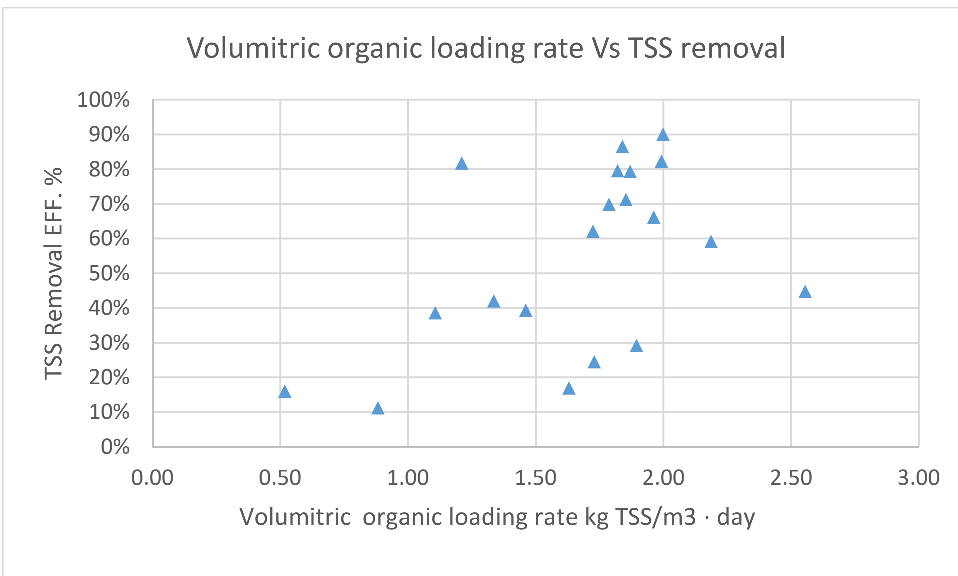

Chart 4-4: TSS Removal efficiency Vs Volumetric loading rate

4.7.2.2 VSS removal efficiency

Tables 4.3 shows the data collected from VSS analyses for SWW influent/effluent during the research period, and calculate the removal efficiency.

TABLE 4-3: VSS influent/effluent, TSS organic loading rate, TSS removal efficiency

DATE	VSS IN mg/l	VSS OUT mg/l	OLR, Kg COD /m3 day	VSS EFF. %	NOTES
20.06.2019	N/A	N/A	N/A	N/A	
15.07.2019	1500	1156	1.5	23	BIOMASS FEED
22.07.2019	1450	1112	1.45	23	
04.08.2019	1695	1098	1.7	35	
13.08.2019	2272	1256	2.27	45	
11.09.2019	1917	723	1.92	62	
14.09.2019	1705	545	1.71	68	
20.09.2109	1515	413	1.52	73	
30.09.2019	1603	208	1.6	87	
07.10.2019	1575	402	1.58	74	
18.10.2019	1506	385	1.51	74	SHOCK LOAD
12.11.2019	1612	312	1.61	81	SYSTEM FAILUR
21.11.2019	1552	292	1.55	81	EFFICIENCY DROP
02.12.2019	1282	696	1.28	46	
09.12.2019	968	568	0.97	41	
15.01.2020	1480	1096	1.48	26	
27.01.2020	1513	495	1.51	67	
10.02.2020	1860	495	1.86	73	
17.02.2020	N/A	N/A	N/A	N/A	
05.03.2020	1175	672	1.18	43	SLUDGE TRANSFER
13.04.2020	1016	124	1.02	88	
21.04.2020	768	656	0.77	15	DOUBLE LOADING
24.04.2020	N/A	N/A	N/A	N/A	
29.04.2020	615	20	0.62	97	

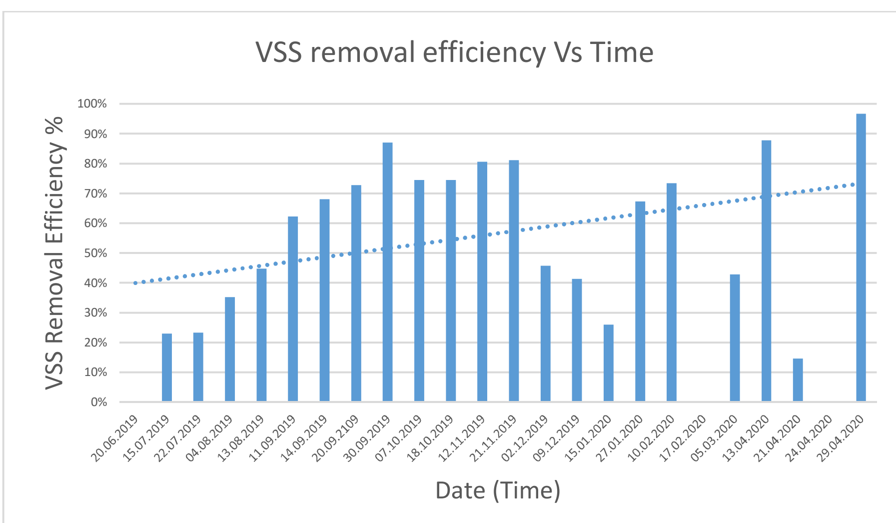

Chart 4-5: TSS removal efficiency Vs Time

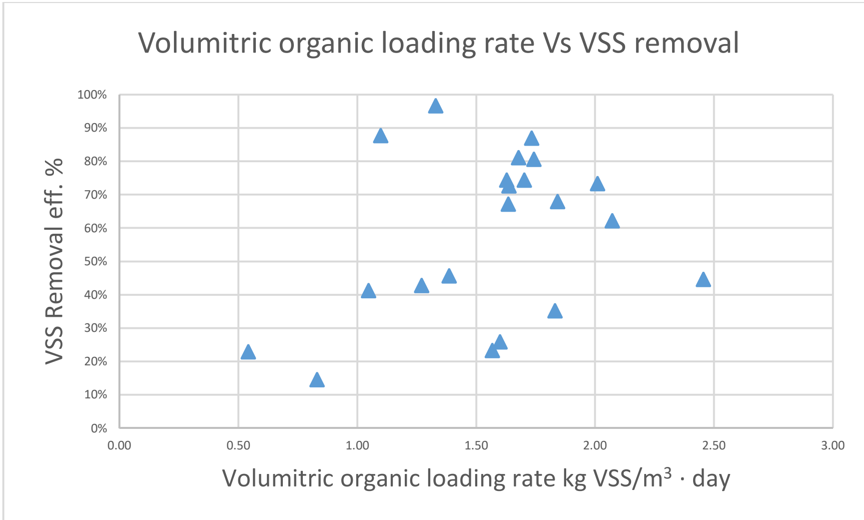

Chart 4-6: VSS removal efficiency Vs Time

From the results achieved in table 4.2, 4.3 and Charts 4.3, 4.4, 4.5, 4.6, we can find the following:

- SWW influent TSS, VSS range (816-2364 mg/ltr), (615-2272 mg/ltr) respectively.
- Average Value of SWW influent TSS, VSS (1,552, 1,456 mg/ltr) respectively
- SWW effluent TSS, VSS range (92-1305 mg/ltr), (20-1115 mg/ltr) respectively.
- Average Value of SWW influent TSS, VSS (684, 606 mg/ltr) respectively.
- TSS, VSS removal efficiency range (11-90%), (15-97%) respectively.
- Average TSS, VSS removal efficiency (55%, 58.2%) respectively.

Data and graphs show the both effluent TSS and VSS varies significantly between each inlet batch and another, and this variation had reflected on the UASB effluent results and so the system removal efficiency. This shows that the UASB alone does not work properly regarding the TSS, VSS removal, in order to improve the system efficiency an equalization. Therefore, a pretreatment stage is recommended to avoid accumulation of solids inside the reactor and reduction the active volume of treatment if short circuits occur.

The graphs also show that TSS, VSS removal efficiency is highly connected to the ambient temperature since a severe drop is noticed but even though and under these operational conditions, the UASB overall SS, VSS removal efficiencies reached 55% and 58.2% respectively. The curve also shows that the system removal efficiency is getting improved by time.

Graph show that TSS, VSS removal efficiency range between 70-90% @ OLR between 1.5-2.0 kg VSS/m^3·day and most of the samples laid within these ranges.

The TSS and VSS removal efficiencies are important indicators to express the overall treatment efficiency of the system. The decision makers when thinking about the UASB treatment system as an option to solve the untreated SWW problem should consider achieving these results using the UASB system.

4.7.3 Biogas production

Table 4.4 shows the data achieved from Biogas flow meter at the outlet of the liquid/gas separator on the top of the reactor, table includes two reading, the accumulative reading and the calculated daily gas production.

TABLE 4-4: Biogas daily accumulation reading, daily production, specific yield and ambient temperature

DATE	ACCOMULATION READING m^3	DAILY GAS PRODUCTION m^3/day	Specific biogas yield m^3/kg.CODremoved	AMBIANT TEMP °C	WW TEMP. °C	NOTES
27.06.2019	0	0	0	32	22	
09.07.2019	0.13	0.01	0.008	39	23	
15.07.2019	0.51	0.06	N/A	38	23	BIOMASS FEED
24.07.2019	0.77	0.03	0.014	38	22	
27.07.2019	1.9	0.38	N/A	36	23	
29.07.2019	2.34	0.22	0.007	41	27	
03.08.2019	3.34	0.25	0.095	33	21	
11.09.2019	7.49	0.11	N/A	39	24	
07.10.2019	9.3	0.07	0.057	35	21	SHOCK LOAD
12.10.2019	9.65	0.07	0.072	34	20	SYSTEM FAILUR
17.10.2019	10.27	0.12	0.037	38	25	EFFICIENCY DROP
22.10.2019	10.79	0.1	0.029	34	20	
28.10.2019	11.37	0.1	0.034	30	19	
04.11.2019	12.04	0.1	0.068	33	17	
17.11.2019	13.39	0.1	0.065	18	15	
21.11.2019	13.53	0.04	0.064	25	16	
23.11.2019	13.62	0.04	0.134	31	15	
03.12.2019	14.61	0.1	0.081	25	14	
09.12.2019	15.22	0.1	N/A	18	15	
13.01.2020	18.17	0.09	0.065	15	9	
15.01.2020	18.45	0.14	0.106	21	16	
23.01.2020	19.7	0.16	0.135	14	9	
27.01.2020	20.1	0.1	0.044	14	9	
30.01.2020	20.8	0.23	0.034	27	16	
10.02.2020	22.16	0.19	N/A	17	12	
12.02.2020	22.4	0.12	0.073	23	15	
17.02.2020	23.03	0.13	0.084	24	15	
05.03.2020	26.47	0.19	0.141	22	14	SLUDGE TRANSFER
09.03.2020	27.24	0.19	0.046	24	15	
13.04.2020	32.21	0.15	N/A	25	15	DOUBLE LOADING
21.04.2020	33.38	0.15	0.068	23	14	

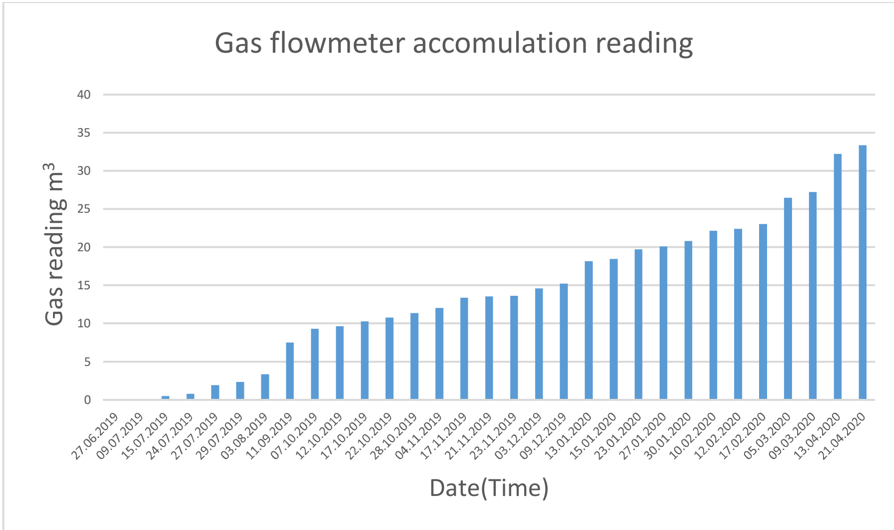

Chart 4-7: Biogas flowmeter reading Vs Time

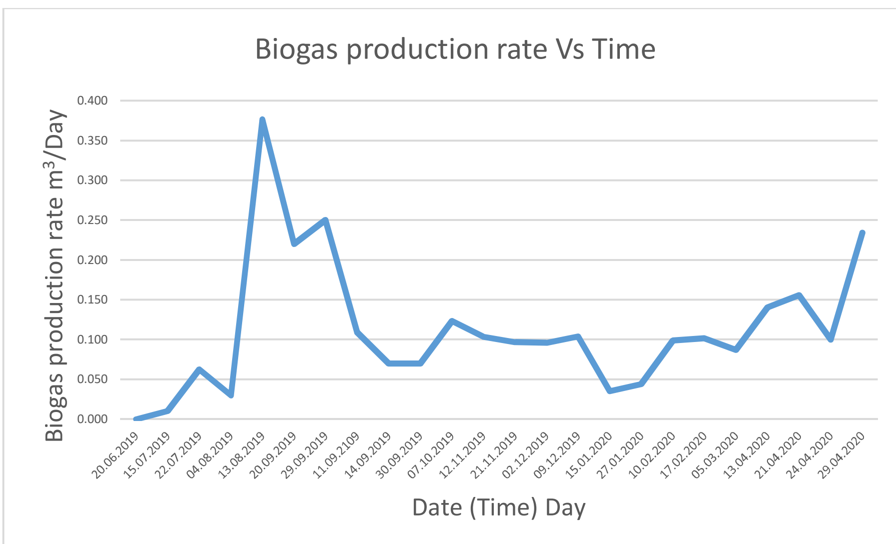

Chart 4-8: Daily biogas production rate Vs Time

From the results achieved in table 4.4 and Charts 4.7, 4.8, we can find the following:

It's clearly seen that biogas production is directly related to, total amount of gas produced during the entire study period reached more than 33 m^3 and the average anaerobic treatment daily gas production was 0.128 m^3/day. The specific gas yield =0.059 m^3 biogas/ kg.$COD_{removed}$, this value was expected to be higher as it reached the value of 0.138 m^3 biogas/ kg.$COD_{removed}$. Due to the variation of temperature, organic load and the system troubleshooting, the average value was found to be this low. This amount of biogas produced by the UASB system should not be ignored, since a good amount of energy can be produced from this biogas. Biogas recovery must be highlighted when the policy makers are advised to opt for SWW treatment. Selecting UASB system can bring environmental and economic benefits regarding biogas recovery as a renewable energy source.

4.7.3.1 Biogas production Vs Ambient temperature

- Studying the effect of temperature on biogas production could not be done during this research since all other factors like the stability of the system and feed flow rate, HRT, organic loading rate, etc. That affect the biogas production were not steady during the research period and varied from time to time. After all; data and graphs shows that the amount of gas production is highly related ambient temperature.
- other important thing that this study didn't cover was the biogas Constituents, since no gas analyses was done to figure the percentage of each component, thus find out the exact amount of methane yield, as the gas flow meter used in the system count the total amount of gas produced inside the reactor.

4.7.4 Biomass production

Table 4.5 shows the data achieved from analyzing the TSS inside the UASB reactor to count the accumulation of Biosolids inside it and see its reflection on the performance of the system.

TABLE 4-5: UASB Biomass accumulation, volatile suspended solids to total suspended solids ratio

DATE	BIOMASS TSS mg/l	BIOMASS VSS mg/l	VSS/TSS	VSS/TSS %	Remarks
15.07.2019	1,610	1,565	0.97	97%	Sludge feed 120 l @ 3.45g/ltr TSS, 2.077 g/l VSS
04.08.2019	1,680	1,625	0.97	97%	
11.09.2019	8,500	6,400	0.75	75%	
20.09.2109	14,597	10,338	0.71	71%	
30.09.2019	29,850	26,122	0.88	88%	
12.11.2019	32,915	29,526	0.9	90%	Chock load, sludge blanket
02.12.2019	23,850	20,960	0.88	88%	
15.01.2020	45,140	36,876	0.82	82%	
10.02.2020	48,259	38,313	0.79	79%	Excess sludge transfer 100 l @ 45gr/l TSS, 37gr/l VSS
17.02.2020	32,566	26,165	0.8	80%	

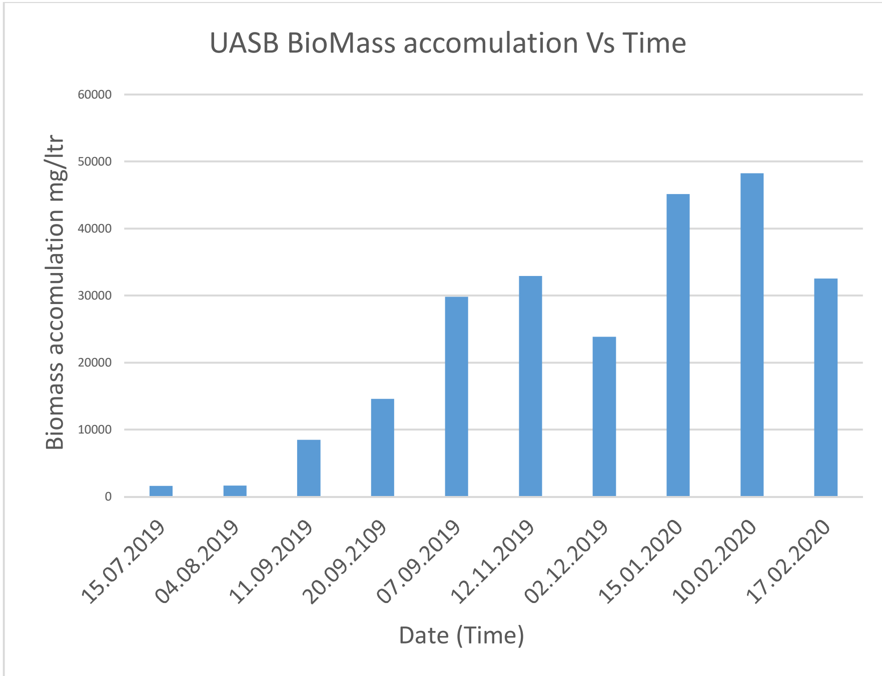

Chart 4-9: UASB Biomass accumulation Vs Time

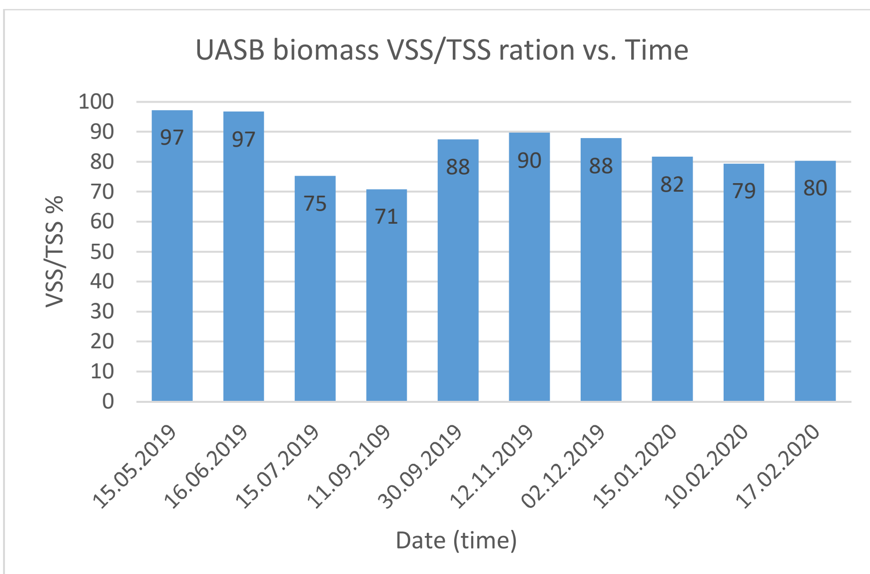

Chart 4-10: UASB biomass VSS/TSS ratio Vs Time

- Chart 4.9 shows that the amount of sludge accumulation inside the reactor increases by time.
- During the troubleshooting of the system caused by the shock load, a severe drop in the amount of biomass inside the reactor is clearly seen.
- The system did not take long time to recover and rebalance the amount of sludge inside it.
- The sludge production rate in the UASB system is very little compared to other treatment technologies.
- During the whole research study period, system desludging (waste sludge) was made once with a quantity of 10 l (30% of the reactor total volume).
- Chart 4.10 represents the VSS/TSS ratio which was calculated in order to check the stability of sludge inside the reactor. During the startup phase and prior adding the anaerobically digested sludge inside the reactor, the ratio was more than 97%. This represents a very low sludge stability, then after feeding the reactor with sludge a noticeable increase in sludge stability were observed. The VSS/TSS ratio reached 71%, few weeks after, the sludge started to accumulate inside the reactor. An excess sludge wastage was required then the troubleshooting caused by the shock load (sudden increase in the feed flowrate) occurred. This resulted in washing excess sludge, then the ratio started to get lower again, after that, an increase in the biomass was achieved causing the ratio to get higher again. Then an excess sludge transfer was needed to reduce the VSS/TSS ratio and so to get a more stable sludge.
- Most municipalities face big problems in dealing with sludge produced in aerobic treatment systems. The results achieved in this research, and the small amount of the produced sludge using the UASB system. This will partially solve the problem, save a lot of energy that is consumed in dewatering the sludge, and transfer it to the landfills locations especially in Palestine, lacking enough landfill pace, and the transportation costs are relatively high.

Chapter 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- The slaughterhouse effluent responds well to anaerobic treatment using Upflow anaerobic sludge blanket system, satisfactory results regarding COD, TSS and VSS removal were achieved with a good potential for biogas (methane) recovery.
- The SWW treatment efficiency varies extensively, several factors like, the characteristics and concentrations of the SWW effluent, HRT and the ambient temperature.
- Considering the average value of the system outputs, effluent quality during the whole research period met the Palestinian standards for sewer network discharge regarding the COD (1,577 mg/l), TSS and VSS. However, after the troubleshooting (shock load), TSS, VSS became higher than standard limits (684, 606 mg/l) respectively. The system needed time to recover then TSS, VSS values came back to lay within the standards. This proves that further system improvement and/or additional treatment phases and preventive measures is therefore required to bring the quality of the effluent within the standard limits all the time.
- The UASB system showed easy operation with process recovery and stable effluent quality. The reactor stability was easily achieved after intermittent operation or a short break down. The UASB showed high sensitivity to chock loads caused by a sudden increase in inlet flow rate.
- UASB has low investment operational cost, low maintenance and energy consumption, low sludge production, thus low maintenance compared to other aerobic wastewater treatment technologies.
- Flies and odor is an easily controllable issue in the UASB system since the reactor is sealed, and the only odor source is the biogas that could be collected and reused.

5.2 Recommendations

Based on the main outcomes of this research which were extracted directly from the observations, the following key recommendations are suggested within namely outlined interventions according to some gaps and overlooks that must be studied and some steps that could minimize the degradation effect of SWW on the environment:

- Achieving sustainable slaughterhouse management calls for the development of an integrated environmental management strategy (IEMS) considering all types of waste streams prior to discharge into the environment. This IEMS, aiming at recoverable resources (biogas, nutrient treated water) is recommended towards enhanced cleaner production in the meat processing industry.
- UASB treatment system and based on the results of this research must be considered by the policy makers and slaughterhouses owners as a treatment option in solving the SWW problem.
- To raise the UASB overall efficiency, recirculation of outlet into inlet line, use of synthetic media as biofilm in UASB reactor, post treatment systems warrant further investigations.
- pH is an important factor that should be monitored adjusted and stabilized, because the stability of the anaerobic treatment process and creating the suitable environment for the anaerobic bacteria to develop and do its job in digesting are highly dependent on it. This research overlooked this factor so I highly recommend to consider it in any future research related to this topic and if this anaerobic treatment method to be applied at full scale.
- UASB system is a sensitive process, for this reason; Chock load; biologically and quantitatively must be avoided during the operation of such treatment system, to avoid foaming, overflowing and undesired output result. Any increase in the feed flow rate of the UASB system must follow gradually.
- Controlling the bioprocess temperature in the UASB system during summer and winter seasons, it is recommended to shade the UASB and recirculate hot outlet water with inlet cold water line.

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Appendices

APPENDIX 1*: Palestinian Standard for Industrial Wastewater Discharge to Sewerage System, 2001*

Quality/Parameter mg/ltr. Except otherwise indicated	Maximum limit Except otherwise indicated
Physical Properties	
Temperature (C°)	45
Color (PCU)	150
TSS	500
TDS	250
Chemical Properties	
pH	6-9
BOD_5	500
COD	2000
TKN	60
NH3-N	45
NO3-N	30
Fluorides	2
Total Phosphorus	15
Sulfides	1
Phenols	3
Fat Oil & Grease	100
Mineral Oil	20
Detergent (MBAS) (1)	25
Residual Chlorine	3
Cyanide	1
Beryllium	0.5
Boron	3
Lithium	0.3
Aluminum	10
Chromium total	1
Tin	1
Nickel	1
Cadmium	0.5
Arsenic	0.25
Lead	1
Manganese	1
Silver	0.5
Mercury	0.05
Iron	50
Zinc	5
Cobalt	1
Selenium	0.05
Vanadium	0.5
Molybdenum	0.15
Copper	2

Source: Adapted from: (MEA, 2001)

APPENDIX 2*: Pilot Scale UASB Patches, Quantities and date*

PILOT SCALE UASB INLET PATCHES		
Patch #	Date	Quantity (m3)
1	16.06.2019	10
2	15.07.2019	10
3	14.08.2019	10
4	11.09.2109	10
5	07.10.2019	10
6	12.11.2019	10
7	15.01.2020	10
8	17.02.2020	10
9	13.04.2020	10
TOTAL(m^3)		90

Photos

Photo A-1 and 2: Poultry Slaughterhouse feather separation system

Photo A-3: Poultry Slaughterhouse blood collection system