Towards Sustainable Treatment and Reuse of Wastewater in the Mediterranean Region

APOC technical guide

(Output 4.1)

Adapted to small and medium sized communities

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The 2014-2020 ENI CBC Mediterranean Sea Basin Programme is a multilateral Cross-Border Cooperation (CBC) initiative funded by the European Neighbourhood Instrument (ENI). The Programme objective is to foster fair, equitable and sustainable economic, social and territorial development, which may advance cross-border integration and valorise participating countries' territories and values. The following 13 countries participate in the Programme: Cyprus, Egypt, France, Greece, Israel, Italy, Jordan, Lebanon, Malta, Palestine, Portugal, Spain, Tunisia. The Managing Authority (JMA) is the Autonomous Region of Sardinia (Italy). Official Programme languages are Arabic, English and French. For more information, please visit: www.enicbcmed.eu.

The European Union is made up of 28 Member States who have decided to gradually link together their know-how, resources and destinies. Together, during a period of enlargement of 50 years, they have built a zone of stability, democracy and sustainable development whilst maintaining cultural diversity, tolerance and individual freedoms. The European Union is committed to sharing its achievements and its values with countries and peoples beyond its borders.

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EXECUTIVE SUMMARY

This document is the first version of the “APOC technical guide” prepared in the context of the project “Towards Sustainable Treatment and Reuse of Wastewater in the Mediterranean Region (AQUACYCLE)”, a project funded and supported by the European Union through the ENI CBC Mediterranean Sea Basin Programme. The general objective of AQUACYCLE is to provide R&D support for sustainable non-conventional water resources management (NCWR) through low-cost eco-innovative technology and participatory governance.

This technical guide has been designed to provide guidance to staff of public and private entities needing info on **APOC system design, operation and maintenance**. This is a **dynamic manual** which is open to periodic updates in response to Frequently Asked Questions, it adapts to the dynamic nature of the systems and integrates the advances of science.

The acronym APOC stands for “**Anaerobic digestion**”, “**Photocatalytic Oxidation**” and “**Constructed wetland**”, the three components of the eco-innovative wastewater treatment system proposed by the AQUACYCLE project. Anaerobic treatment and constructed wetland are two mature and commercialized technologies with wide applications in the wastewater treatment market, that are combined with a novel solar disinfection/photocatalytic oxidation process towards the treatment of municipal wastewater at a level that satisfies the most stringent standards for reuse. The distinctive features of APOC technology make it **eco-friendly**, **efficient** and **cost-effective** as it is based on natural systems, it uses less chemicals, runs on renewable energy (solar irradiation), produces biogas, fertiliser and a clean water for reuse in agriculture, in domestic, industrial or other applications, and the constructed wetland thrives as a habitant, an ecological tourist attraction aside from being a climate change mitigation measure.

This guide has been prepared by a **cross-border multidisciplinary scientific interaction**. Specifically, AQUACYCLE partners which hold expertise in the three different components of the APOC system have provided the necessary technical information and data sheets for the scope of this manual. CERTH, CITET and ESAMUR contributed to Chapter 5 dealing with anaerobic digestion reactors that are frequently applied in domestic-type wastewaters. CERTH, CERTE, CITET and ESAMUR reviewed the recent scientific advancements in constructed wetlands regarding their design and operation for typical to the Mediterranean area arid and semi-arid climates (Chapter 6). Finally, CIEMAT/PSA contributed to Chapter 7 which concerns the application of a solar advanced oxidation process (solar photocatalysis in race-way pond reactors) that has been demonstrated at a semi-industrial scale to be an effective tertiary treatment process due to the generation of nonselective oxidizing species, which make them particularly suitable for the removal of the threats present in urban wastewater effluents. The design, construction, operation and maintenance of all APOC components depend on many parameters, which are covered in this guide. It is noted, however, that this guide does not focus on pretreatment or pumping systems for lifting and conveyance of wastewater.

Abbreviations

ABR	Anaerobic Baffled Reactor
AD	Anaerobic Digestion
AF	Anaerobic Filter
AFBR	Anaerobic Fluidized Bed Reactor
ASBR	Anaerobic Sequencing Batch Reactor
BOD	Biochemical Oxygen Demand
CAPEX	Capital Expenditures
COD	Chemical Oxygen Demand
CPCs	Compound Parabolic Collectors
CW	Constructed Wetland
CSTR	Continuous Stirred Tank Reactor
FWS	Free Water Surface
GHGs	Greenhouse Gas Emissions
HRT	Hydraulic Retention Time
KPIs	Key Performance Indicators
NER	Net Energy Recovery
NCWR	Non-Conventional Water Resources
OLR	Organic Loading Rate
O&M	Operations & Maintenance
OPEX	Operating Expenses
RPR	Raceway Pond Reactor
SPF	Solar Photo-Fenton
SPO	Solar Photocatalytic Oxidation
SRT	Sludge Retention Time
SS	Suspended Solids
SSF	Subsurface Horizontal Flow
TAC	Total Annualized Cost
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket

VF	Vertical Flow
VFAs	Volatile Fatty Acids
VHL	Volumetric Hydraulic Load
VRPA	Volumetric Rate of Photon Absorption
VS	Volatile Solids
WTEI	Water Treatment Energy Index
WWTPs	Waste Water Treatment Plants

1. SCOPE OF THIS GUIDE

This document is meant to guide the staff of public and private entities, sewerage companies, engineers, constructors, operators of wastewater treatment plants (WWTPs), etc., needing info on APOC system design, operation and maintenance. The guide is organized, as much as possible, to follow the treatment path of the domestic wastewater through the three different compartments consisting the APOC system, namely the secondary treatment by anaerobic digestion (AD), the tertiary treatment in a constructed wetland (CW) and finally the post treatment by a novel solar photocatalytic oxidation (SPO) reactor. Preliminary and primary treatments are compulsory but not discussed in this manual. The selection of the primary treatment methods are determined by the raw wastewater characteristics and the recommended wastewater composition in the feed of each compartment, as described in the next Chapters. The structure of this guide is as follows.

STRUCTURE OF THIS GUIDE

- ***Introduction:*** *defining the attributes of APOC technology and justifying its selection, especially for small and medium sized communities;*
- ***APOC selection criteria:*** *selection of APOC systems based on a design-criteria analysis for addressing specific treatment objectives;*
- ***APOC at a glance:*** *short description of system components, general and specific engineering considerations;*
- ***Anaerobic Digestion:*** *description of five types of AD reactors frequently applied for domestic wastewater treatment, operating principles, treatment performance, advantages/limitations, design equations, construction guidelines, operation/control/ monitoring, maintenance;*
- ***Constructed Wetland:*** *description of three types of CW frequently applied for domestic wastewater treatment, operating principles, treatment performance, advantages/ limitations, design equations, construction guidelines, operation/control/monitoring, maintenance;*
- ***Solar Treatment:*** *description of the novel solar photocatalytic raceway pond reactor, operating principle, treatment performance, advantages/limitations, design equations, construction guidelines, operation/control/monitoring, maintenance;*
- ***Evaluation of APOC performance:*** *assessing the performance of APOC systems by relevant key performance indicators;*
- ***APOC pilot studies-practical experiences:*** *lessons learned from the operation of the three APOC pilot plants operated in Spain, Tunisia and Lebanon, that need to be considered during the planning phase of a resource recovery sanitation service.*

It is understood that this manual is not meant to provide details of system components that are mature and commercialized technologies (AD rectors, CWs). Many handbooks and technical manuals are available in literature and some of these are listed in References section for further reading.

2. INTRODUCTION

Sustainable wastewater management of the twenty-first century has to be significantly different from the traditional twentieth century wastewater management paradigm, which focused on meeting the demand for treatment and safe discharge of the water to prevent the pollution and spread of disease. Sustainable urban wastewater systems need to focus on achieving a **'closed loop'** through initiatives such as **water recycling and reuse**. This is especially true for locations where the available supply of fresh water has become inadequate to meet water needs. A short list of benefits of water reuse, especially to local communities, is presented in Table 1. These are classified into 6 categories: 1) economic/financial, 2) legal, 3) environmental, 4) social, 5) strategic, and 6) image. Some items are reported in one category while contributing also to others (Bixio and Wintgens, 2006).

Table 1 Shortlist of benefits reportedly enjoyed by communities that implemented water reuse projects (Bixio and Wintgens, 2006).

CATEGORY	BENEFIT
1. (DIRECT) ECONOMIC AND FINANCIAL	***Overall benefit for the local community*** ✓ Additional water supply that would otherwise be lost and preventing the high cost of importing freshwater and conveying it over a long distance. ✓ Contribute to a better preserved natural capital to the tourism sector. ✓ Often least-cost option when the overall urban water cycle is considered.[1] ***Utility benefits*** ✓ Reduced compliance costs with government regulation on wastewater discharge. ✓ In areas where the water demand is not met: Additional revenue from the sale of reclaimed water and savings in the form of avoided or delayed costs of developing new fresh water sources and less treatment of surface water abstraction. ✓ Customer benefits. ✓ Benefits from reduced water and /or energy charges through potable substitution for uses not needing potable quality water. ✓ In irrigation: additional source of nutrients, lessening the need to apply synthetic fertilizers.

[1] In temperate regions, pilot studies have shown that an integrated approach to urban water cycle management including water reuse can lead to overall savings up to 50% of capital costs, with savings in the range of 15-20% that might be considered the most expected range (Anderson, 2003).

CATEGORY	BENEFIT
2. LEGAL	✓ Solve permit problems related to discharge to sensitive ecosystems and associated liabilities. ✓ Useful means to achieve demand management targets for water conservation programs (in terms of water saved).
3. ENVIRONMENTAL	✓ Decreased abstraction of freshwater from sensitive ecosystems and decreased discharge into sensitive water bodies. ✓ Lower greenhouse emission impact. ✓ Best scenario for nutrient recycling in agriculture, substituting some forms of nitrogen compounds and phosphorus of synthetic fertilizers.[2] ✓ Decentralized reuse systems could reduce the impact of combined sewer overflows emissions and recharge local rivers to maintain the ecology and enable aquifer recharge (Vaes and Berlamont, 1999).
4. SOCIAL	✓ Increased level of service. ✓ Promote sustainability. ✓ Creation of employment.
5. STRATEGIC	✓ Increasing the reliability of the urban water cycle (more drought-proof water supply). ✓ Improvement in public health, by protecting downstream water supplies from contaminations (and so, indirectly decreasing the costs of treatment for those downstream communities). ✓ Locally-controlled water supply, a particularly important aspect in those areas where water demand is met by importing water from neighboring jurisdictions/countries.
6. IMAGE	Enhanced reputation and recognition as good environmental steward. In Australia, for example, today water companies have to push water reuse in order to comply with pressure from the public and their customers. Many citizens consider the right to sufficient quantities of water an urgent necessity, which can only be satisfied without bad conscience, if reclaimed water is used.

[2] This is particularly important in the context of the phosphorus cycle: at the level of exploitation of today, phosphorus ores will be depleted in less than 100 years.

As we have started to acknowledge that wastewater is an all-year-round alternative supplementary water resource from which **water**, **energy**, and **materials** can be recovered, there is a growing demand for building new treatment plants in form of ***resource recovery facilities*** or retrofitting for this scope existing WWTPs. Selecting a robust plant layout which can recover resources from wastewater and at the same time withstand the unforeseeable uncertainty (such as climate change, stringent laws, etc.) is a clear expectation from design engineers and decision-makers.

In this context, **APOC is a promising process scheme which can produce recycled wastewater of a desired quality and meet the environmental and socioeconomic goals that can be practically attained at a given time**.

In comparison to conventional domestic wastewater treatment technologies and other tertiary water reclamation technologies (e.g. membrane processes, UV/O_3 disinfection, etc.) APOC presents salient attributes in relation to cost, cultural acceptability, simplicity of design and construction, operation and maintenance, hydrogeological conditions and local availability of materials and skills (Table 2). These attributes are related with the effective combination of processes which are less intensive, consume less energy, are based on natural processes and result to products of high added value (biogas, solid fertilizer and clean water for reuse). In addition, the following APOC features need to be considered during the planning phase of a resource recovery facility:

- ✓ The system can treat wastewater for both standard discharge and for reuse applications.
- ✓ The system has the ability to treat domestic wastewater from secondary to tertiary level, and can be generally a community/committee-managed system.
- ✓ The system can be constructed according to influent wastewater characteristics.
- ✓ Provides effective solution for ecologically sensitive areas.
- ✓ APOC can be implemented using local skills and know-how to provide context-specific sanitation services and get optimum efficiency of the system.
- ✓ APOC can provide a renewable energy source. Depending on the demand, technical modifications can be made and biogas can be generated by the anaerobic digestion of the organic content to supply energy.
- ✓ APOC can provide a solid byproduct (anaerobic solid digestate) that can be used for land fertilization.
- ✓ APOC effluent can be used for urban uses, industrial uses, agricultural uses and groundwater recharge.

Although APOC requires more land than traditional intensive processes developed for large communities (e.g. activated sludge processes), the investment cost for the three components consisting the APOC system is generally lower, and the operating conditions are simpler, more flexible and allow more energy to be saved. Finally, APOC system requires a lower amount of manpower, little maintenance and less-specialised manpower than intensive techniques.

Table 2 Comparison between conventional domestic wastewater treatment systems and APOC system.

FEATURE	CONVENTIONAL SYSTEMS	APOC
Reliability	Require complex operation and maintenance schedules to ensure optimal performance.	Does not require intensive maintenance for better performance.
Environmental sustainability	Require higher amounts of energy and chemical inputs for their efficient operation.	Reuse of reclaimed water and reduction of pressures on water resources (reduced water abstraction). Reduction of CO_2 emissions for wastewater treatment by using a renewable energy source (solar energy) and natural processes (constructed wetland). Low energy requirements.
Financial sustainability	Substantial grants, government funding and subsidies are required for construction, operation and maintenance.	Requires less capital cost when compared with centralized sewerage systems.
Affordability	Scores low on affordability due to substantial cost of installation, sewerage network, operational and maintenance costs.	Affordable due to lower costs when compared with centralized systems since the system is based on natural technologies (CW, RPR). Requires locally available materials.

According to the pollutant components, APOC system can be appropriately designed so as to meet the water quality required, taking into account the potential constraints due to the levels of remaining residual charge. However, the reuse of treated wastewater needs particular attention on health and safety aspects and each constructor needs to pay special attention to reuse, which is described later in this guide.

3. APOC SELECTION CRITERIA

The selection of the APOC system as an integrated process scheme for domestic wastewater treatment and reuse should be based on a design-criteria analysis with the aim to address current and future treatment objectives. Key objectives of applying APOC systems are those linked to sustainability and circular economy principles mentioned in Chapter 2, which in turn require **careful planning steps**, **economic calculations**, and detailed **social considerations and assessments** (e.g. assessment of human health associated with trace biological and organic substances, environmental risk assessment, etc.). The list of treatment objectives mentioned in Chapter 2 is not exhaustive but shows the benefits of applying APOC system in reuse projects. APOC can be designed for a single objective, which then would be just to treat water, or with multiple objectives, whereby treating water is always included. **Engineers should seek however, multi-objective solutions.** The most important criteria that must be assessed in process analysis and selection of APOC system are identified in Table 3.

Table 3 Important criteria that must be considered when evaluating and selecting the APOC system for domestic wastewater treatment and reuse.

CRITERIA	COMMENT
Process applicability	The applicability of APOC process is evaluated on the basis of past experience mainly from operation of AD and CW full-scale plants. In regards to the solar RPR, the process is evaluated according to published data and especially form pilot plant studies. If new or unusual conditions are encountered, pilot studies are essential, similar to those implemented in the three demo sites of AQUACYCLE project in Spain, Tunisia and Lebanon – experiences and lessons learned from the operation of these plants will be included in Chapter 9.
Applicable flow range	The APOC process is recommended for the implementation of decentralized wastewater treatments, mostly at community scale. The design of the APOC system should be matched to the expected flow rates, which can range from 5 to 1000 m^3/d (which equals to an average of 50 to 10,000 inhabitants).
Applicable flow variation	All three compartments consisting the APOC system have to be designed to operate over a wide range of flowrates. AD and ST processes work best at a relatively constant flowrate. If the flow variation is too great, flow equalization may be necessary.
Influent wastewater characteristics	The characteristics of the influent wastewater affects strongly the selection of the AD and CW types to be used and the requirements for their proper operation (see Chapters 5 and 6, respectively). Considering that AD is the first barrier against organic abatement, a range of 200-1000 mg/L COD and/or 100-500 mg/L BOD, is recommended.

CRITERIA	COMMENT
Inhibiting and unaffected constituents	Toxic compounds and inhibitors can significantly hinder the effective operation of the APOC process due to their negative impact on the metabolic activities of the methanogenic bacteria in the AD. This category of compounds includes inorganic sulphur compounds (sulphate, sulphite and sulphide), toxic organic pollutants and heavy metals. A ratio of 7 between COD and sulphates concentration, both in mg/L, can be used as minimum to have a good anaerobic process.
Climatic constraints	Temperature can affect the performance of all biological and chemical reactions, carried out especially in the AD and the solar RPR. High (>50 ^{o}C) and low (<10 ^{o}C) temperatures can create problems to the operation of the AD, resulting to the reduction of the maximum specific microbial growth and feedstock utilization rates, thus decreasing the efficiency. The optimum temperature is around 35 ^{o}C.
Process sizing based on reaction kinetics or process loading criteria	AD reactor, CW and solar RPR sizing is based on the flow rate and on the governing reaction kinetics and kinetic coefficients. Usually kinetic expressions are not available, therefore process loading criteria can be used (as specified in the following Chapters). Designers and operators are encouraged to collect data for kinetic expressions by preliminary studies at pilot-plant scale.
Performance	APOC performance can be measured in terms of Key Performance Indicators (KPIs), as those identified in Chapter 8. These KPIs are calculated in terms of sustainability, of effluent quality and its variability which must be consistent with the effluent requirements for reuse or safe discharge.
Treatment residuals	The main treatment residuals originate from the primary treatment (large debris, solids, sand, oil & grease) and the CW (residual sludge layers during the emptying period). Pilot studies should be performed to identify and quantify residuals.
Solid Digestate processing	The designer should consider the valorization of the solid digestate produced (as fertilizer) and the possible post-treatment and disposal. Pilot studies should define the recycle load of the solid digestate back to the AD with the aim to optimize both the AD process and the operation of the following CW.
Environmental constraints	No significant environmental constraints exist for implementing APOC projects.
Chemical requirements	AD and ST require chemicals (i.e. micronutrients, pH correction, Fe-EDDS, H_2O_2) that need to be committed for a long period of time for the successful operation of the APOC process. It is noted that the iron catalyst in ST process is minimum and can be effectively regenerated in situ by the solar irradiation.

CRITERIA	COMMENT
Energy requirements	The energy requirements of APOC systems as well as the probable energy cost are generally very low. APOC is based on natural processes (constructed wetland), runs on renewable energy (solar RPR) and produces biogas. However, the energy cost must be known when designing a cost-effective APOC system.
Other resource requirements	No other special resources are required for the successful implementation of an APOC project.
Personnel requirements	APOC presents salient attributes in relation to local availability of materials and skills. APOC can be implemented using local skills and know-how to provide context-specific sanitation services and get optimum efficiency of the system.
Operating and maintenance requirements	APOC systems require minimal operation and maintenance. The main maintenance tasks are related with the cleaning of the pump station, the pipes and distribution devices, the suction sludge devices, etc. which in turn will depend of the pre-treatment quality. In CWs, regular maintenance should ensure that water is not short-circuiting, or backing up because of fallen vegetation blocking the wetland outlet. Vegetation may have to be periodically cut back or thinned out. The most common maintenance activities are pulling out undesirable plant species, removing dead vegetation (not dormant vegetation), and cleaning pipes. In the case of the solar RPR, the major maintenance tasks consist in the photoreactor cleaning, periodic pumps and paddle wheel revision and probes cleaning and calibration.
Ancillary processes	An effective primary treatment is necessary for achieving good APOC performances. As minimum a bar screen (60 to 100 mm) to remove all large objects and sieves with a minimum mesh size of 3 mm and, if possible, of 1 mm are recommended to avoid solids and large debris to enter the anaerobic reactor. Sand and oil are also problematic and should be primarily removed.
Reliability	APOC is a new eco-innovative process which is currently evaluated at pilot-scale (operation of three demo setups in Spain, Tunisia and Lebanon). The long-term reliability of the system operation is, therefore, under assessment.
Complexity	APOC is an easy to operate system under routine conditions. However, training is necessary and includes time-to-time checking and supervision of the hydraulic and electronic equipment as well as cleaning and repairing of system parts (e.g. pumps, gas collection system, de-choking of feeding pipes, etc.).
Compatibility	Selecting a robust APOC plant layout which can recover resources from wastewater and at the same time withstand the unforeseeable uncertainty

CRITERIA	COMMENT
	(such as climate change, stringent laws, etc.) is a clear expectation from design engineers and decision-makers. APOC systems retrofit existing WWTPs and their expansion can be accomplished rather easily, depending on the land availability.
Adaptability	APOC presents easily adaptable output capabilities. APOC systems can be adapted to various climate conditions, being especially effective in regions where solar energy is an abundant resource (for the effective disinfection and non-selective photocatalytic oxidation of persistent organic pollutants exiting the CW).
Economic life-cycle analysis	Cost evaluation must consider initial capital cost, long-term O&M costs and the profits gained from the valorization of the biogas, the fertilizer and the reclaimed water produced.
Land availability	A major component of APOC system is the CW, which requires land availability. A sufficient space should be encountered for fulfilling treatment objectives and possible future expansions.

The purpose for which treated water should be utilised defines the treatment objective. For example, if treated water is to be used for irrigation purposes, it makes less sense to remove nutrients that are beneficial for crop fertigation. However, restrictive regulations in various countries often obstruct the producing of effluent with a desired quality for a particular purpose.

The full potential of circular management of water and substances will therefore only be possible after a revision of the respective guidelines.

Such a revision should aim at protecting water users and the consumers of products that have come into contact with the reused water, but also eliminating unnecessary obstacles. A zero-risk approach, as applied e.g. in Italy for treated wastewater for irrigation, leads to difficulties in spreading this practice. A different view of the same concern is offered by the World Health Organization, which proposed a pragmatic approach based on microbial risk assessment, evaluating case by case the pathogen reduction for treated wastewater to be used in agriculture, and how to achieve this (Licciardello et al., 2018). Since many countries have different effluent discharge and reuse standards, this guide has been prepared under the notion of providing technical know-how to meet the standards required by the EU legislation and general guidelines applied in the Mediterranean Partner Countries. However, the constructor is advised to check the country standards of effluent discharge while designing an APOC system.

4. APOC AT A GLANCE

In conventional domestic wastewater treatment plants the main objective is to reduce the organic matter. The most common system to do that is the biological activated sludge process, which uses microorganisms to convert the suspended and dissolved organic matter into gases and new cell tissue. Historically, aerobic processes are more used, because they are more intensive than anaerobic ones, but consume a lot of energy and produce a big amount of sludge. On the other hand, anaerobic processes consume very little energy and produce less sludge, however, the treatment efficiencies are lower at similar retention times (10 to 24 hours). Taking into consideration the current state-of-the-art in municipal wastewater treatment and the need for an alternative to conventional centralized treatment plants, which require large capital costs and running costs, APOC technology is proposed as an eco-innovative process which combines an **Anaerobic Digestion Reactor**, a **Constructed Wetland** and a novel **Advanced Oxidation Process (AOP) based on solar irradiation**. APOC takes advantage the attributes of the anaerobic treatment, the improved organic matter abatement efficiencies achieved by natural-based processes and the effective disinfection of the final effluent by a novel solar race-way pond reactor. The cascade of the three processes, the treatment objective(s) and the main beneficial attributes are shown in Figure 1. APOC can be considered as an integrated system that treats wastewater, both black and grey water, mostly at community, or even larger, scale and can be a promising process scheme for the implementation of decentralized wastewater treatments.

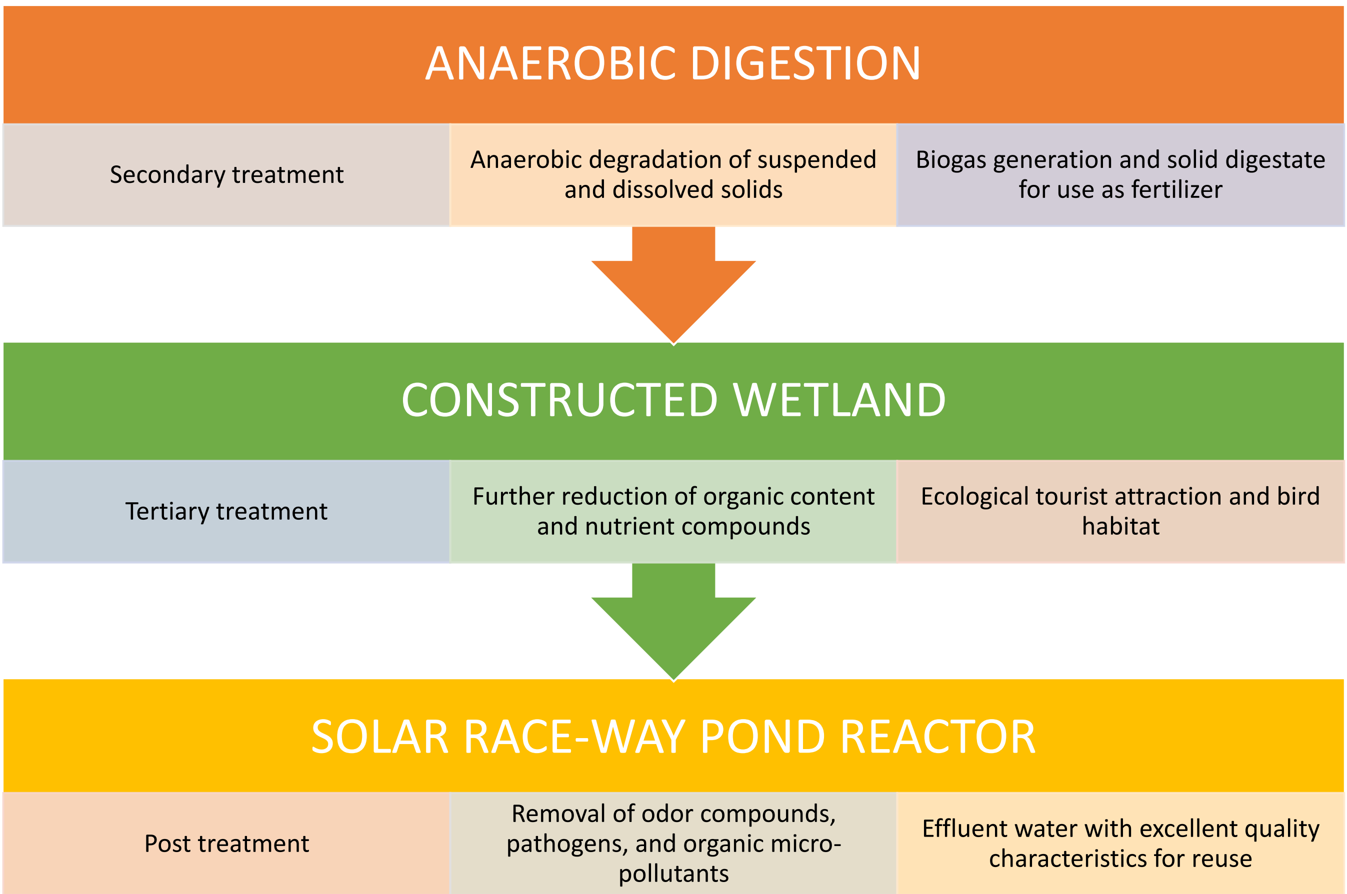

Figure 1 APOC at a glance: components, treatment objectives and beneficial attributes.

A generic APOC plant layout is shown in Figure 2. The components of this layout are strictly indicative and can be modified by the plant designer, depending on the influent characteristics and the treatment objectives. Specifically, different types of AD reactors and CWs can be applied, as explained in details in the following Chapters, whereas the post-treatment in the novel solar RPR is a distinctive feature of the APOC system.

Primary treatment

The extent and the type of the primary treatment depends on the influent characteristics. Since AD reactors are based on the propensity of anaerobic sludge (biomass) to aggregate into dense flocs or granules with good settling properties, it´s crucial to avoid the solids to enter the anaerobic reactor, because the hydrolysis of those compounds will be very difficult and they will fill up the reactor very soon, thus causing problems of blocking the pipes and mixing systems (organic dry matter can be broken down into proteins, lipids, carbohydrates, volatile fatty acids (VFA), and lignin, which corresponds to the non-biodegradable part). Therefore, a good pretreatment of the receiving wastewater is compulsory to control the dry matter content of the AD reactor (dry solids content of up to 7%). As minimum, a bar screen of 60 to 100 mm can be applied to remove all large objects and sieves with a minimum mesh size of 3 mm and, if possible, of 1 mm. Sand and oil are also problematic and they should be primarily removed.

Secondary treatment

The secondary treatment of the domestic wastewater is based on the anaerobic digestion process. The objective is to promote a sustainable practice focussing on energy efficiency of biogas production and utilisation of the nutrient-rich by-product generated (solid digestate). During AD, microorganisms break down the organic matter contained in the wastewater and convert it into biogas, a mixture of mainly methane and carbon dioxide, which can be used for electricity, heat and biofuel production. At the same time, the sludge is stabilised and its dry matter content is reduced. The benefits of AD are widely recognised and the technology is well established in many countries. Today, a high proportion of biogas produced in AD plants is from those on municipal wastewater treatment sites, and there is still an enormous potential to exploit worldwide. AD is also an important pillar of the European circular economy concept as it mitigates greenhouse gas emissions, it recycles nutrients, it prevents nitrogen leakage into groundwater, and it avoids the spread of harmful diseases through extended landfilling. The capital investment costs, wastewater characteristics and methane production are the most important parameters, which will define the required size of the AD system.

Tertiary treatment

Anaerobic treatment will reduce the organic matter of wastewater in a high percentage, but the quality of the effluent is not enough to get the requirements for discharge or reuse. Constructed wetland is the chosen system to improve the quality of the anaerobic reactor effluent. CWs fit into the urban fabric and provide additional ecosystem services and benefits beyond water quality improvement. They have been largely considered for water reuse, nutrient recovery (as a pretreatment for fertigation, disease vector reduction, separation of liquid and solid phase) and ecosystem services. CWs can “trap” hazardous or recalcitrant substances, thus increasing the possible usages of the treated water and control of the spread of harmful substances in the environment. Finally, they are productive systems in themselves, producing biomass by harvesting CW vegetation (further used as pelletized slow-releasing soil amendment/fertilizer), cooling through evapotranspiration, providing habitats, etc. A few particular advantages of CWs are their flexibility in size, with little economy of scale, their simple maintenance requirements, demanding skills very similar to widespread irrigation systems, and the very limited to no disturbance that most applications cause in their immediate vicinity if properly designed and operated. One of the most important advantages of CWs, is their high buffer capacity and their ability to treat effluents with considerable hydraulic and pollutants loading rates variability. This combination of characteristics allows a high flexibility in size, location and vicinity of their implantation and makes them particularly appropriate for urban applications.

Post treatment

The post treatment of the CW effluent in a novel solar Raceway Pond Reactor (RPR) consists an interesting and feasible option for treating substantial amount of wastewaters by the solar photo-Fenton (SPF) process. SPF is a promising technology for wastewater reuse applications due to its high disinfection and contaminants of emerging concern (CEC) removal efficiency associated with low reagents' consumption (Fe and H_2O_2) and different strategies to work at near-neutral pH. RPRs are proven more efficient and cost-effective in comparison to well-known solar photoreactors (such as Compound Parabolic Collectors, CPCs) that are more suitable for the treatment of bio-recalcitrant industrial wastewaters with high organic load. The most important parameters that play a relevant role in the optimization of RPRs are the liquid depth and iron concentration, which could be changed according to the solar radiation availability. In this sense, the number of photons in the reactor may be adjusted to improve the kinetics and treatment capacity, depending on the season, the weather conditions (sunny or cloudy) and even geographic position.

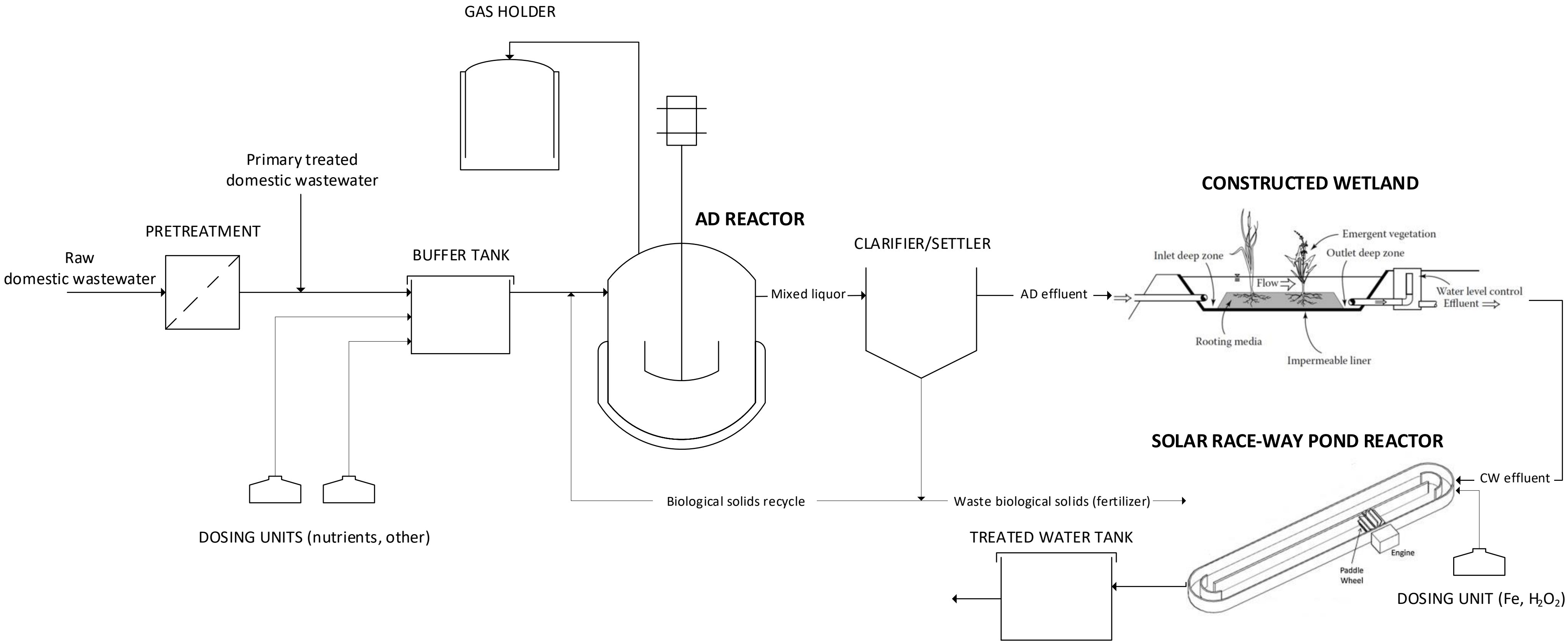

Figure 2 Flow diagram of a typical APOC system comprised of a CSTR Anaerobic Digester, a Surface Flow Constructed Wetland and a Solar Race-Way Pond Reactor.

5. ANAEROBIC TREATMENT

5.1 Introduction

Anaerobic treatment is based on the degradation of organic matter by microorganisms present in the waste water obtaining, with the absence of oxygen, methane, carbon dioxide, hydrogen sulfide, ammonia and other compounds. The process involved is a complex biochemical process known in literature as Anaerobic Digestion [AD] that involves the sequential breakdown of biodegradable organic matter with the help of a diverse microbiological ecosystem (bacteria and archaea) in an oxygen-free environment, leading simultaneously to production of a solid digestate (organic fertilizer) and high-value bioenergy in the form of biogas as renewable energy source (Jain *et al.*, 2015; Aziz *et al.*, 2019). In general, the whole AD process can be divided into four key stages: i) hydrolysis, ii) acidogenesis, iii) acetogenesis and finally iv) methanogenesis (Krishna and Kalamdhad, 2014; Arif, Liaquat and Adil, 2018).

Phase 1 – Hydrolysis

Usually, organic matter is made of large organic chains, usually carbohydrates, proteins and lipids and these molecules are too big to pass through the cell membrane. Before the anaerobic microorganisms can metabolize this organic matter, it´s necessary to break down them in smaller constituent parts to be available to the bacteria. AD process starts with the stage of hydrolysis in which the insoluble complex organic compounds of high molecular mass such as carbohydrates, polysaccharides, proteins, nucleic acids and fats are converted by enzymes (e.g. lipases, proteases, cellulases, amylases, etc.) into smaller and simpler soluble organic molecules such as monosaccharides, sugars soluble in amino acids, glycerol and carboxylic acids (Krishna and Kalamdhad, 2014; Arif, Liaquat and Adil, 2018). This is a key and limiting stage, especially when the effluents have a large amount of solids. It´s considered that the speed of biogas production depends on the solubilization of organic matter, because is the slowest phase of the process.

Phase 2 – Acidogenesis

AD process continues with the stage of acidogenesis or acidification in which the hydrolyzed products are degraded by acid-forming obligatory and facultative anaerobic microorganisms to a mixture of short-chain volatile fatty acids (VFAs) [e.g. acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), etc.] and other minor products such as carbon dioxide [CO_2], hydrogen [H_2], ethanol [C_2H_5OH], ammonia [NH_3], hydrogen sulfide [H_2S], etc. (Krishna and Kalamdhad, 2014; Arif, Liaquat and Adil, 2018). This process stage is fast.

Phase 3 – Acetogenesis

The third stage of AD process is known as acetogenesis and comprises of anaerobic oxidation reactions. More specifically, in this phase all VFAs and some of the other short-chain organic molecules produced during acidogenesis are catalytically transformed into acetate [CH_3COO^-], carbon dioxide [CO_2] and hydrogen [H_2] by the acetogenic facultative bacteria. These above end-products constitute the precursors for methane production (Krishna and Kalamdhad, 2014; Arif, Liaquat and Adil, 2018).

Phase 4 – Methanogenesis

Finally, the AD process is completed with the stage of methanogenesis. This phase is the slowest biochemical reaction of the AD process, because the kinetic of the process and the formation of new methanogenic bacteria is really slow, and is considered a critical step due to the requirements for stringent anaerobic conditions. Thus, during this last stage, methane can be produced by methanogenic bacteria in two ways: i) production of methane from acetate via aceticlastic methanogenesis and ii) production of methane from carbon dioxide and hydrogen gas via hydrogenotrophic methanogenesis (Krishna and Kalamdhad, 2014; Arif, Liaquat and Adil, 2018). It is noted that this part of the AD process is very sensitive to the environmental conditions in the reactor (pH, toxic compounds, oxygen, lack of nutrients).

Biogas is a combustible mix of gases, consisting of methane [CH_4] (50 %–75 %), carbon dioxide [CO_2] (25 %–50 %), nitrogen gas [N_2] (0 %–10 %), hydrogen sulphide [H_2S] (0 %–3 %), hydrogen gas [H_2] (0 %–1 %) and negligible amount of oxygen, water vapor, ammonia, mercaptans, and other noxious gases (Lee and Ofori-Boateng, 2013). Biogas is a promising and alternative biofuel, which has multiple end-use applications including: co-generation of heat and electrical power in combined heat and power (CHP) generation plants, cooking and rural electrification, application as natural gas substitute and as a transportation fuel (Lee and Ofori-Boateng, 2013; Nguyen *et al.*, 2019).

Nowadays, AD has been recognized as an eco-friendly and cost-effective technology for pollution control, energy and nutrient recovery, as well as for utilization and re-use of organic residues (Abdelgadir *et al.*, 2014; Arif, Liaquat and Adil, 2018; Rahman *et al.*, 2019). In fact, this technology can be characterized as a globally emerging waste management strategy (Franke-Whittle *et al.*, 2014), which has been successfully implemented in the treatment of a wide range of feedstocks including sewage sludge, domestic and municipal and high-strength (agro-) industrial wastewaters, agricultural wastes, food industry wastes, organic fraction of municipal solid wastes (OFMSW) plant residues, among others (Jain *et al.*, 2015; Nguyen *et al.*, 2019; Pramanik *et al.*, 2019).

The continuously increasing interest and publicity of the AD as a wastewater treatment process is due to the significant number of advantages it presents over other technologies (Abdelgadir *et al.*, 2014; Kiyasudeen S *et al.*, 2016). Thus, the category of AD advantages includes: i) production of renewable bioenergy in the form of biogas, ii) reduction of net greenhouse gas emissions implicated in climate change through methane recovery, iii) improvement of water quality due to AD capability of high reducing chemical oxygen demand (COD) and biological oxygen demand (BOD) from waste streams, iv) utilisation of the digestate produced as fertilizer, v) Less biodegradable sludge is produced, vi) greater flexibility as AD has the potential to be easily applied on either a very large or a very small scale, vii) process simplicity and good process stability, viii) elimination of odor emissions due to the almost complete oxidative decomposition of volatile compounds upon combustion, ix) less energy consumption as AD reduces dependence on huge burden of electricity requirements of surface aerators or blowers, x) less nutrients and chemicals requirements, xi) less space requirements as smaller reactor volumes are needed in the case of higher loading rates and xii) less operating costs, which are associated with reduced levels of nutrients and electricity, as well as the lower sludge production (Seghezzo *et al.*, 1998; Kangle *et al.*, 2012; Abdelgadir *et al.*, 2014; Kiyasudeen S *et al.*, 2016; Nguyen *et al.*, 2019).

However, the AD technology has a number of disadvantages/limitations in which is involved: i) long start-up time is required to attain a biomass concentration due to the lower growth rate of methanogenic organisms, ii) long recovery time as it may take longer time for the anaerobic system to return to normal operating condition in the case of biomass wash-out, toxic substances or shock loading, iii) high sensitivity of anaerobic microorganisms, especially methanogens, to changes in physicochemical parameters (e.g. temperature, pH, redox potential, chemical compounds, etc.), iv) anaerobic microorganisms, especially methanogens, have specific micro-nutrients requirements for optimum growth (e.g. Fe, Ni, Co, Mo), v) reduction of methane yield and inhibition of the methanogens due to the sulphide production [H_2S], when sulfate compounds are presented, vi) low pathogen and nutrient removal: partially pathogens removal and incomplete nitrogen and phosphorus removal and vii) implement necessity of anaerobic effluent post – treatment in order to reach the discharge standards for organic matter, nutrients and pathogens (Seghezzo *et al.*, 1998; Kangle *et al.*, 2012; Abdelgadir *et al.*, 2014).

AD can occur both naturally in anaerobic environments including watercourses, river sediments, waterlogged soils and the mammalian gut and artificially in controlled environments in order to take place in a properly designed reactor known as an anaerobic digester (Hilkiah Igoni *et al.*, 2008; Kiyasudeen S *et al.*, 2016).

As descripted above, AD is a multi-step biochemical process, which engages various kinds of anaerobic microorganisms in order to convert a biomass to biogas. However, the growth of the anaerobic bacteria and the maintenance of their high microbial activity requires a favorable and controlled environment, which is connected and affected by a multitude of operating parameters. It has been recognized that the most important factors affecting the successful operation and performance of the AD process are the following (Abdelgadir *et al.*, 2014; Jain *et al.*, 2015; Leung and Wang, 2016; Nguyen *et al.*, 2019; Pramanik *et al.*, 2019):

i. **Temperature**

AD process, like other biochemical process, is strongly connected with the temperature which is one of the most important and crucial environmental parameter, during the operation of the anaerobic digesters. More specifically, the AD process can take place over a wide range of temperatures, which can normally be classified into three categories: (1) psychrophilic, (2) mesophilic and (3) thermophilic temperatures. Psychrophilic temperature ranges are < 20°C, mesophilic between 20 and 40°C (optimum 35°C), while thermophilic temperatures are 50 – 65°C (optimum 55°C) (Jain *et al.*, 2015). Generally, higher temperature ranges lead to improvement of the microbial growth kinetics, enzymes secretion, feedstock diffusion and mixing among others. Furthermore, temperature impacts on the gas solubility (e.g. CH_4, H_2, H_2S), affecting the sulfide and ammonia toxicity, especially to methanogenic microorganisms (Khanal *et al.*, 2017). However, the thermophilic temperature range has not been put to use due to the problems which are connected with heating and maintaining of the anaerobic digesters to such high temperatures (Nguyen *et al.*, 2019). On the other hand, lower operating temperatures in the reactor generally lead to the reduction of the maximum specific microbial growth and feedstock utilization rates, thus decreasing the efficiency (Daud *et al.*, 2018). Below 10 ^oC the methanogenesis activity is extremely poor. Therefore, the optimum temperature of anaerobic processes, mainly due to methanogenic bacteria, is around 35 ^{o}C.

ii. pH Value

The pH of the anaerobic digester plays one of the most significant and critical roles in the AD process efficiency and stability, since it is directly connected with the survival of anaerobic bacteria in the reactor. Anaerobic bacteria are highly sensitive to pH, as every group of them needs a different pH range for their growth. The optimal pH range for hydrolysis and acetogenesis is almost 6.0 and 6.0–7.0, while methanogenic micro-organisms work effectively between pH range of 6.5–8.2, with an optimum pH 7.0. However, it has been proven that the optimal range of pH for obtaining maximal biogas yield in AD process is 6.3–7.8 (Krishna and Kalamdhad, 2014; Pramanik *et al.*, 2019).

iii. Type of feed wastewater (feedstock)

The potential substrate which can be used for the AD process presents significant differences regarding its composition, biodegradability, homogeneity and its fluid dynamics. The above characteristics of the incoming feedstock combined with the application of appropriate operating parameters can lead to the success or failure of the AD process (Jain *et al.*, 2015).

iv. Total Solid [TS] content of feedstock

Optimum total solid content of digesters for the AD process is a function of the type of substrate and the design of the reactor. For instance, up-flow anaerobic sludge blanket (UASB) reactors are typically used to treat wastewater (e.g. domestic and municipal sewage) with low TS content (3 – 7 %) (De Farias Silva *et al.*, 2019).

v. Carbon to Nitrogen [C/N] Ratio

The ratio of the C/N represents the relationship between the quantity of carbon and nitrogen which are presented in the incoming feedstock (e.g. domestic wastewater). In fact, the elements of carbon and nitrogen are the food of anaerobic microorganisms, with carbon to act as the energy source of the bacteria and nitrogen to play a role in growthing of the microbial population. According to literature, it has been proven that an operating C/N ratio range of 20/1 – 30/1 can lead to a better AD efficiency, with the C/N ratio of 25/ 1 to be considered as optimal for the anaerobic bacterial growth in an AD digester. Inappropriate C/N ratios can result in over-accumulation of inhibitory substrates (e.g. VFAs, total ammonia nitrogen), reducing the effectiveness of the AD process (Krishna and Kalamdhad, 2014).

vi. Nutrients and Trace Elements Concentrations

Appropriate concentrations of macro-nutrients (e.g. N, P, S), micro-nutrients (e.g. K, Ca, Mg) and trace metals (e.g. Fe, Ni, Co, Mn, Mo) into the incoming feedstock (wastewater) have to be in desired in order to be achieved an adequate microbial growth in AD process for enhancing the efficiency of the anaerobic reactors (Krishna and Kalamdhad, 2014).

vii. **Toxic Compounds and Inhibitors**

Toxic compounds and inhibitors is the major limitation of AD process due to their negative impact on the metabolic activities of the methanogenic bacteria, which are responsible for CH_4 production during the AD treatment. This category of compounds includes: low-molecular-weight-organic compounds (e.g. VFAs, alcohols, sugars), oxidants (e.g. O_2, H_2O_2), inorganic sulphur compounds (sulphate, sulphite and sulphide), heavy metals, molecular hydrogen (H_2) and wood constituents (Bajpai, 2017). A high concentration of sulphates in the waste water will produce also a inhibition in the methanogenesis, because the sulphate reduction bacteria compete against methanogenic ones and sulphur will be produced instead of methane. Really, the organic matter is reduced but methane won´t be produced and the sulphur will consume oxygen in the next aerobic step. The problems are higher with low organic matter concentrations, typical of urban waste water. *A ratio of 7 between COD and sulphates concentration, both in mg/L, is used by some researchers as minimum to have a good anaerobic process*.

viii. Organic Loading Rate [OLR]

Organic loading rate is a crucial operating parameter of the anaerobic system and is expressed as the mass amount of organic matter (COD) of feedstock, which can be fed into the digester per day per unit volume of digester capacity. Overloading of digester beyond the suitable values of OLR can lead to the performance reduction of the reactor as a consequence of VFAs over-accumulation into the digester. Thus, it is necessary to control the OLR of the AD process reactor (Meegoda *et al.*, 2018).

ix. Hydraulic Retention Time [HRT]

Hydraulic retention time constitutes one of the most important criteria for the design of the anaerobic reactors, representing the average time that the incoming wastewater (liquid) spends in the digester. Therefore, HRT can also be considered to correspond to the average time that the organic matter of the feedstock remains in contact with anaerobic bacteria. Generally, low values of HRT can result in insufficient time for the optimal degradation of the substrate (Meegoda *et al.*, 2018).

x. Solid Retention Time [SRT]

Solid retention time is a key parameter for the design and operation of anaerobic reactors and represents the average time that the microorganisms (biomass) spend in the digester. In fact, the maintenance of the bacterial population in the reactor by applying an appropriate value of SRT can lead to a satisfactory effectiveness of pollutant removal, as the consumption of the feedstock is controlled by the kinetics of the microbes. Practically, high values of SRT can result in a better waste stabilization, better toxic or shock load tolerance and a quick recovery from perturbation (Pramanik *et al.*, 2019).

xi. Up-flow Velocity [V_{up}]

The up-flow velocity is a useful parameter which mainly impacts on the efficiency of up-flow anaerobic reactors, providing a sufficient mixing of the feedstock and sludge (biomass) without channeling and maintaining the hydraulic retention time (Abdelgadir *et al.*, 2014).

xii. Mixing

Mixing is another important operating characteristic for anaerobic reactors as it is desirable in order to be achieved effective contact time to anaerobic bacteria and waste stream, reducing hurdles of transfer of mass, lowering the growth of repressive by-products and providing uniform environmental conditions. In this way, the production of biogas can be increased, offering enhanced efficiency for the anaerobic digesters (Daud *et al.*, 2018).

5.2 General guidelines

The design of an AD reactor should comply the following two major tasks:

- a good mixing between wastewater and microorganisms (usually forming flocs), and
- control of scape of flocs, due to the slow formation of methanogenic bacteria.

Several types of reactors are available in the market, with different systems of mixing and separation. The most known technologies for anaerobic reactors that have been largely applied for domestic waste water treatment are (i) the Upflow Anaerobic Sludge Blanket [UASB], (ii) the Anaerobic Baffled Reactor [ABR], (iii) the Anaerobic Sequencing Batch Reactor [ASBR], (iv) the Anaerobic Fluidized Bed Reactor [AFBR] and (v) the Anaerobic Filter [AF] reactor or Anaerobic Fixed Film Reactor [AFFR] (often referred to as fixed bed). Details on the process mechanism, design, construction, operation and maintenance of the aforementioned five types of AD reactors are described in the following sub-charters.

KEY O&M POINTS OF AD REACTORS

- to keep the water and gas tightness,
- to ensure good stirring between water and sludge avoiding the scape of sludge and to get a good distribution in the inlet wastewater,
- to use corrosion resistance materials,
- to install suitable systems for the emptying (when it´s necessary) of the sludge excess removal and,
- in general, to make as comfortable as possible, the maintenance of the equipment.

To assure the tightness of the tanks and pipes, hydrostatic tests and pressure tests for the pipes should be carried out.

Although the reactor designer should get an adequate distribution of inlet wastewater over the entire surface of the reactor, to avoid shortcuts and dead zones, collaboration with the designer will be necessary to help in this task with the adequate piping from the pre-treatment to the reactor inlet connections, to improve the distribution, to let the cleaning if it is necessary and to avoid air entrance.

Corrosion resistance materials are necessary for the reactor tank, the pipes and other equipment due to the corrosivity of compounds, such as H_2S, especially if the concentration of sulphates is high in the wastewater.

5.3 Upflow Anaerobic Sludge Blanket Reactor

5.3.1 Description

The Up-flow Anaerobic Sludge Blanket [UASB] reactor is the main representative of the category of the high-rate anaerobic systems and has been proven to be **the most appropriate solution in the field of the anaerobic domestic and municipal wastewater treatment**, due to its numerous and distinct advantages (Bobade and Lomte, 2015; Hamza, Iorhemen and Tay, 2016; Daud *et al.*, 2018). However, the UASB digester is also characterized by some noteworthy disadvantages, which still need to be solved (Hamza, Iorhemen and Tay, 2016; Daud *et al.*, 2018). The overall advantages and disadvantages of the UASB reactor for the anaerobic treatment of the domestic and municipal sewage are presented in Table 4.

Table 4 Advantages and disadvantages/limitations of the UASB reactor technology (Hamza, Iorhemen and Tay, 2016; Daud et al., 2018).

Advantages	Disadvantages
Provides a remarkable compact design which combines the whole anaerobic digestion process and settlement in a single reactor, leading to reduction of footprint requirements	Long periods of time are required to start-up the AD process along with the requirement for an ample amount of granular seed sludge for faster start-up
Simple design and construction, which are connected with low construction, operating and maintenance costs	Significant wash-out of biomass during the initial phase of the AD process is likely, due to high concentrations of suspended solids which reduces settleability of sludge. In this case skilled personnel are required for the UASB system operation
The unique gas-liquid-solid [GLS] separator assists in maximizing biomass retention without the need for external clarifier	Need for an adequate post-treatment stage as pathogens and coloring agents are not removed completely, except for helminthes eggs that are successfully entrapped in the sludge. Post-treatment stage is also necessary in the case of nutrients incomplete removal
Production of renewable bioenergy in the form of biogas which can be used to heat the UASB reactor and run the system, achieving	Possibility of bad odours release, like H_2S that are dissolved in the effluent

Advantages	Disadvantages
the appropriate AD temperature and reducing the energy consumption	
Production of lower amounts of sludge, which is stabilized having good dewatering characteristics, providing the opportunity to be stored for extended time periods and reused as an inoculum for seeding UASB digester	
Formation of granular sludge, without any packing medium for biomass attachment, providing dense and strong microbial structure, good settling ability, high biomass retention, tolerance to toxicity and resistance to shock loading	
Provides high COD and BOD removal efficiencies, even at high OLR and low temperature and thus requires smaller reactor volume	
Can handle periodic high organic and hydraulic loading rates effectively with very less retention time	
Reduction of net CO_2 emissions due to less energy requirements	
Wide applicability from very small to very large scale and validity in anaerobic treatment efficiency	

5.3.2 Design

The concept of the UASB design is based on the propensity of anaerobic sludge (biomass) to aggregate into dense flocs or granules with good settling properties over a long period of time (Lettinga *et al.*, 1980). The UASB reactor is a suspended-growth digester, which is characterized by four main components: i) the sludge bed, ii) the sludge blanket, iii) the gas-liquid-solid [GLS] separator and iv) the settler compartment (Lin and Yang, 1991; Nguyen *et al.*, 2019). In the UASB system, the influent wastewater stream is introduced and distributed as uniformly as possible through the bottom of the reactor, flowing upward through a bed of anaerobic suspended granular sludge at the lower part of the digester (sludge bed). In this fermentation zone, the anaerobic bacteria come in contact with the biodegradable organic matter, entrapping and converting it into biogas and a small fraction of anaerobic biomass. After that, the wastewater continues to move upward and the remaining organic part of the sublayer passes and acts with a less dense biomass named the sludge blanket. Then, a unique three-phase (gas-liquid-solid or GLS) separator above the sludge blanket separates efficiently the biogas produced (CH_4 and CO_2) from the solid particles (sludge) and treated liquid (wastewater) after treatment, allowing the liquid to leave the UASB digester and the gas to be collected in the gas collector. Finally, the remaining liquid and smaller-size solid particles (flocculent/granular) enter the settling compartment, where the biomass can settle and flow back to the sludge bed, while the rest can be washed-out via the effluent (Lettinga *et al.*, 1980; Souza, 1986; Lin and Yang, 1991; Sperling and Lemos Chernicharo, 2005; Tauseef, Abbasi and Abbasi, 2013; Khanal *et al.*, 2017). All of the above procedure is referred to the anaerobic treatment of industrial wastewater effluents from the UASB reactors. In the case of the domestic and municipal sewages the influent distribution device is located in the upper part of the UASB digester (Sperling and Lemos Chernicharo, 2005). A schematic illustration of a typical UASB reactor is shown in Figure 3.

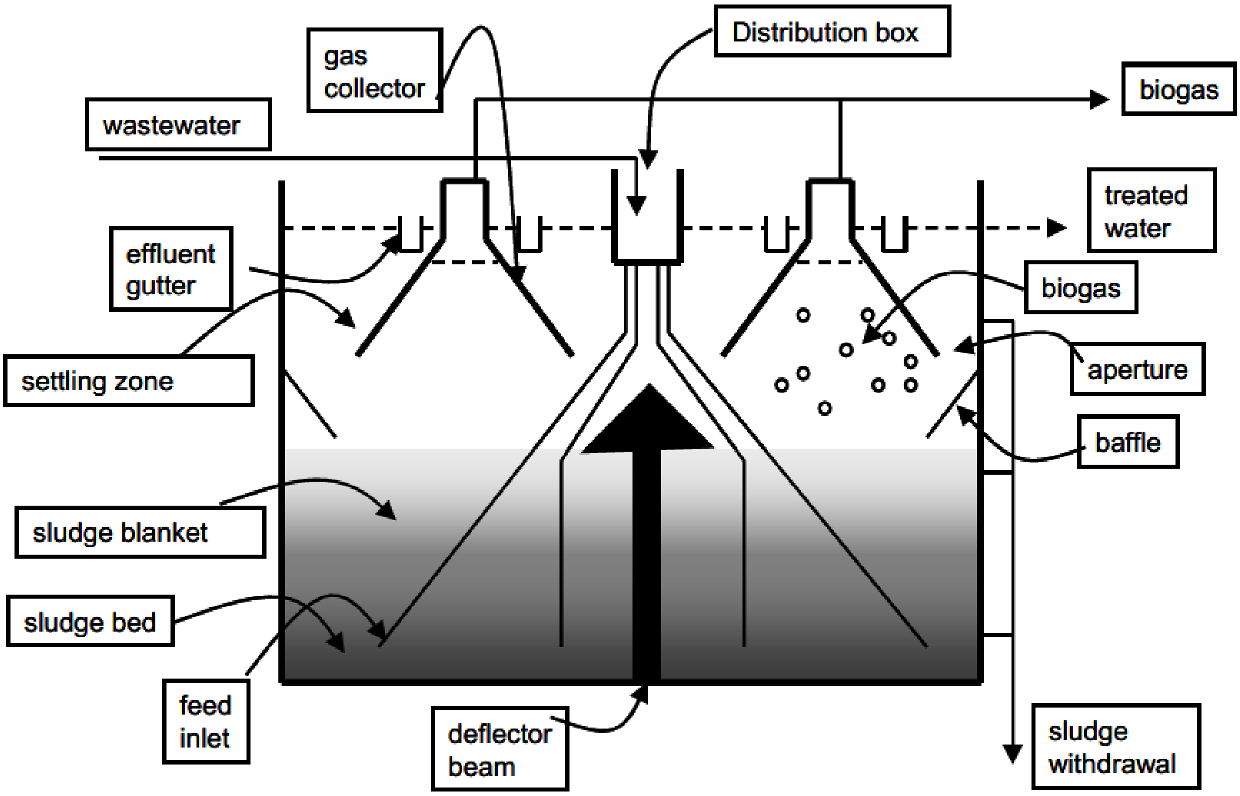

Figure 3 Schematic illustration of a typical UASB reactor.

The design of a UASB reactor is characterized by its simplicity and zero installation requirements of sophisticated and electromechanical equipment or packing medium for biomass attachment and retention (Tilche *et al.*, 1991; Sperling and Lemos Chernicharo, 2005). The shape of the UASB reactors which are used for the domestic sewage treatment can be either circular (small populations) or rectangular (larger populations) (Souza, 1986; Sperling and Lemos Chernicharo, 2005; Bobade and Lomte, 2015). Other than the reactor, the following additional equipment should be taken into consideration during the design of an UASB installation:

- System for adding chemical reagents, if necessary (lack of nutrients, pH correction, etc.)
- Condensate separator
- Torch
- Cogeneration engine

Photos of the different components consisting the UASB reactor operating in Blanca WWTP, provided by ESAMUR, are shown as follows.

Photo 1 a) Inlet of a single distribution system unit, b) view of the integrated distribution system.

Photo 2 Inner of the UASB reactor.

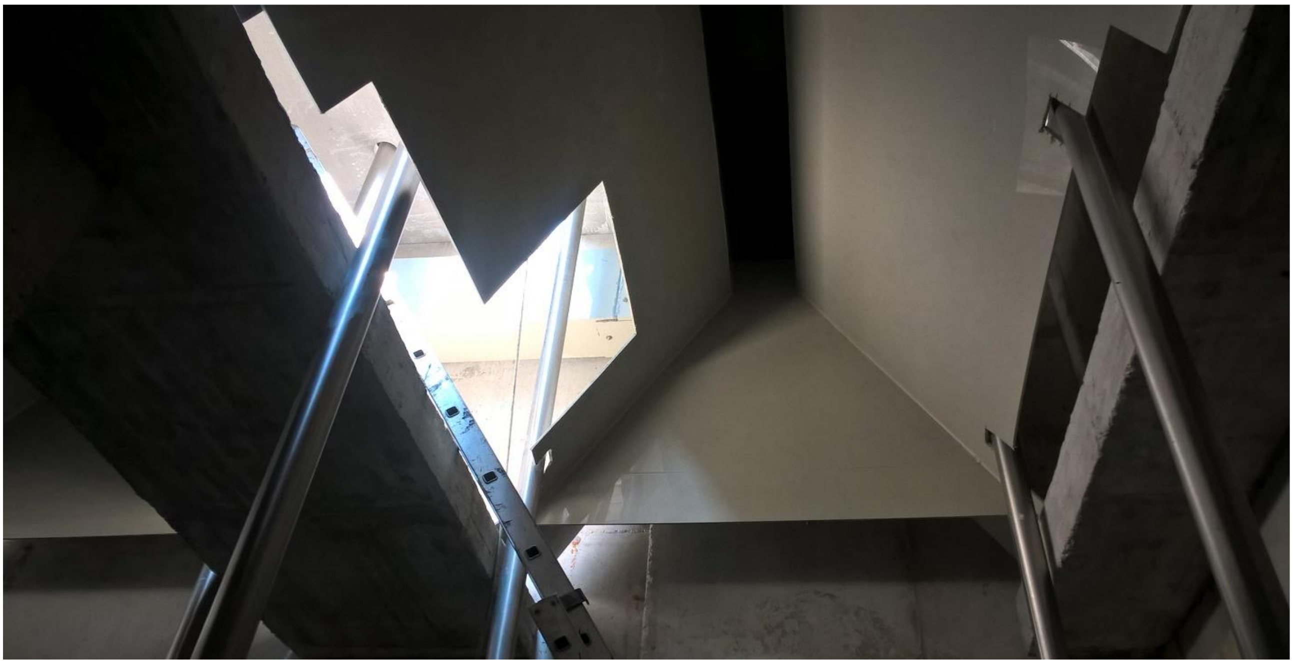

Photo 3 Three phases separator.

Photo 4 Sludge withdrawal system.

Photo 5 Treated water collection.

In spite of the significant experience in designing of the UASB digesters, there are still no clear, systematised design guidelines accessible for these types of anaerobic reactors. Therefore, given the increasing importance of the UASB reactor for the domestic wastewater treatment, it is important to be taken into account several criteria and parameters in order to achieve the suitable design of the UASB system (Souza, 1986; Lin and Yang, 1991; Sperling and Lemos Chernicharo, 2005; Chernicharo *et al.*, 2015; Khanal *et al.*, 2017).

Current Design Criteria of the UASB Digester for the Domestic Wastewater Treatment

The main design criteria for the UASB digesters treating domestic and municipal wastewaters are presented in Table 5 (Souza, 1986; Lin and Yang, 1991; Tilche *et al.*, 1991; Sperling and Lemos Chernicharo, 2005; Chernicharo *et al.*, 2012, 2015).

Table 5 Design Criteria/Parameters of the UASB reactor for the domestic and municipal wastewater treatment.

Design Criteria	Unit	Range of Values
Volumetric Hydraulic Load [VHL] (at average flow)	$m^3/m^3 \cdot d$	≤ 5.0
Hydraulic Retention Time [HRT]	hour	8 to 10 hours (at 20°C)
Organic Loading Rate [OLR]	kg COD/m^3d	2.5 to 3.5
Biological or Sludge Loading Rate	kg COD/kg VSd	0.3 to 0.4
COD Removal Efficiencies	%	40 to 70

Design Criteria	Unit	Range of Values
BOD Removal Efficiencies	%	45 to 90
Up-flow Velocity [V_{up}] (at average flow)	m/hour	0.5 to 0.7*
Reactor Depths	m	3 – 6
<u>Influent Distribution System</u>		
Diameter of the influent distribution tube	mm	75 to 100
Diameter of the distribution tube exit mouth	mm	40 to 50
Distance between the top of the distribution tube and the water level in the settler	m	0.20 to 0.30
Distance between the exit mouth and the bottom of the reactor	m	0.10 to 0.15
Influence area of each distribution tube	m^2	2.0 to 3.0
Effluent Collection System		
Submergence of the scum baffle or the perforated collection tube	m	0.20 to 0.30
Number of triangular weirs	Units/m^2 of the reactor	1 to 2
Gas-Liquid-Solid [GLS] Separator		
Overlap of the gas deflectors in relation to the opening for the settler compartment	m	0.10 to 0.15
Minimum slope of the settler walls	°	45
Optimum slope of the settler walls	°	50 to 60
Depth of the settler compartment	m	1.5 to 2.0
Biogas Collection System		
Minimum biogas release rate	$m^3/m^2 \cdot hour$	1.0
Maximum biogas release rate	$m^3/m^2 \cdot hour$	3.0 to 5.0
Methane concentration in the biogas	%	70 to 80
Sludge Sampling and Discharge System		
Solids production yield	kg TSS/kg $COD_{applied}$	0.10 to 0.20
Solids production yield, in terms of COD	kg COD_{sludge}/kg $COD_{applied}$	0.11 to 0.23

Design Criteria	Unit	Range of Values
Expected solids concentration in the excess sludge	%	2 to 5
Sludge density	kg/m^3	1020 to 1040
Diameter of the sludge discharge pipes	mm	100 to 150
Diameter of the sludge sampling pipes	mm	25 to 50

*Temporary flow peaks up to 1.5 to 2.0 m/hour being tolerated for 2 to 4 hours

It should be understood that the design of UASB reactors is ruled by the hydraulic loading rate criteria and not by the organic loading rate criteria in the case of the domestic and municipal wastewaters (low-concentration sewages) (Sperling and Lemos Chernicharo, 2005).

Important Equations of the UASB Digester Technology

(i) Volumetric Hydraulic Load [VHL] & Hydraulic Retention Time [HRT]

The Volumetric Hydraulic Load [VHL] can be calculated by the following equation:

$$VHL = \frac{Q}{V} \tag{5.1}$$

where,

VHL = volumetric hydraulic load [d^{-1}]

Q = average flow rate of the incoming wastewater [m^3/d]

V = total volume of the digester [m^3]

On the other hand, the Hydraulic Retention Time [HRT] is inversely proportional to VHL and is calculated by the equation:

$$HRT = \frac{1}{VHL} \quad \text{or} \quad HRT = \frac{V}{Q} \tag{5.2}$$

where,

HRT = hydraulic retention time [d]

(ii) Organic Loading Rate [OLR]

The Organic Loading Rate [OLR] is calculated by the following equation:

$$OLR = \frac{Q\ x\ S_0}{V} \tag{5.3}$$

where,

OLR = organic loading rate [kg COD/m^3·d]

Q = average flow rate of incoming wastewater [m^3/d]

S_0 = concentration of the incoming wastewater [kg COD/m^3]

V = total volume of the digester [m^3]

(iii) Biological or Sludge Loading Rate [L_s]

The Biological or Sludge Loading Rate can be calculated as follows:

$$L_s = \frac{Q \, x \, S_0}{M} \tag{5.4}$$

where,

L_s = biological or sludge loading rate [kg COD/kg VS·d]

Q = average flow rate of the incoming wastewater [m^3/d]

S_0 = concentration of the incoming wastewater [kg COD/m^3]

M = mass of anaerobic bacteria present in the digester [kg VS/m^3]

(iv) Up-flow Velocity [V_{up}] & Reactor Height

The Up-flow Velocity [V_{up}] can be calculated by the following equation:

$$V_{up} = \frac{Q}{A} \quad \text{or alternatively} \quad V_{up} = \frac{Q \, x \, H}{V} = \frac{H}{HRT} \tag{5.5}$$

where,

V_{up} = up-flow velocity [m/hour]

Q = average flow rate of incoming wastewater [m^3/hour]

A = area of the cross section of the digester, in this case the surface area [m^2]

H = height of the digester [m]

HRT = hydraulic retention time [d]

(v) COD & BOD Removal Efficiencies

The COD removal efficiency of UASB digester treating domestic and municipal wastewaters can be calculated by the following equation:

$$E_{COD} = 100 \, x \, (1 - 0.68 \, x \, HRT^{-0.35}) \tag{5.6}$$

where,

E_{COD} = efficiency of the UASB digester in terms of COD removal [%]

HRT = hydraulic retention time [hour]

0.68 = empirical constant

0.35 = empirical constant

On the other hand, the BOD removal efficiency of UASB digester is calculated as follows:

$$E_{BOD} = 100\ x\ (1 - 0.70\ xHRT^{-0.50}) \quad (5.7)$$

where,

E_{BOD} = efficiency of the UASB digester in terms of BOD removal [%]

HRT = hydraulic retention time [hour]

0.70 = empirical constant

0.50 = empirical constant

__(vi) Estimation of the COD and BOD concentrations in the final treated wastewater__

The COD and BOD concentrations in the treated wastewater are estimated by the following equation:

$$C_{eff} = S_0 - \frac{E\ x\ S_0}{100} \quad (5.8)$$

where,

C_{eff} = effluent total COD or BOD concentration [mg/L]

S_0 = influent total COD or BOD concentration [mg/L]

E = COD or BOD removal efficiency [%]

__(vii) Estimation of the suspended solids [SS] concentrations in the final treated wastewater__

The SS concentrations in the treated wastewater are calculated as follows:

$$SS = 102\ x\ HRT^{-0.24} \quad (5.9)$$

where,

SS = effluent suspended solids concentration [mg/L]

HRT = hydraulic retention time [hour]

102 = empirical constant

0.24 = empirical constant

__(viii) Biogas Release Rate [K_g]__

The Biogas Release Rate [K_g] is calculated by the following equation:

$$K_g = \frac{Q_g}{A_i} \quad (5.10)$$

where,

K_g = biogas release rate [$m^3/m^2 \cdot hour$]

Q_g = expected biogas production [m^3/hour]

A_i = area of the liquid–gas interface [m^2]

(ix) Evaluation of the Biogas Production

The Biogas Production can be calculated by the following equation:

$$COD_{CH4} = Q\ x\ (S_0 - S) - \ Y_{obs}\ x\ Q\ x\ S_0 \quad (5.11)$$

where,

COD_{CH4} = COD load converted into methane [kg COD_{CH4}/d]

Q = average flow rate of the incoming wastewater [m^3/d]

S_0 = influent COD concentration [kg COD/m^3]

S = effluent COD concentration [kg COD/m^3]

Y_{obs} = coefficient of solids production in the digester, in terms of COD [0.11 to 0.23 kg COD_{sludge}/kg $COD_{applied}$]

(x) Evaluation of the Sludge Production

The Sludge Production can be determined by the following equation:

$$P_s = Y\ x\ COD_{applied} \quad (5.12)$$

where,

P_s = production of solids in the system [kg TSS/d]

Y = yield or solids production coefficient [kg TSS/kg $COD_{applied}$]

$COD_{applied}$ = COD load applied to the digester [kg COD/d]

5.3.3 Construction

The key construction aspects of the UASB reactor for the domestic and municipal wastewater treatment are presented below (Lin and Yang, 1991; Sperling and Lemos Chernicharo, 2005; Chernicharo *et al.*, 2012; Lettinga and Pol, 1991):

i) **UASB Reactor Dimensions**
The height of the UASB reactors is directly connected with (1) the volumetric hydraulic loads, which define the up-flow velocities imposed to the anaerobic system, (2) the organic loads applied and (3) the type of sludge present in the digester. In the case of the domestic wastewater treatment in reactors that mainly develop flocculent-type sludge, the up-flow

velocities imposed to the system lead to digesters with useful heights between 4.0 and 5.0 m (Sperling and Lemos Chernicharo, 2005):

Table 6 Dimensions of the UASB Digesters (Sperling and Lemos Chernicharo, 2005).

UASB Reactor Dimensions	Unit	Range of Values
Height of Digestion Compartment	m	2.5 to 3.5
Height of Settler Compartment	m	1.5 to 2.0

ii) Construction Materials

Concrete and steel with epoxy-coating corrosion protection constitute the materials which are most commonly used in UASB reactors, for construction and cost reasons. However, the biggest problem occurs in the upper part of the UASB digester, where the H_2S produced is oxidized to sulfate by air (oxygen). In this case, the gas-liquid-solid [GLS] separator should be fabricated of a more resistant material or more heavily coated in order to prevent corrosion and gas leakage. Consequently, non-corrosive and less bulky materials such as PVC, fibreglass and stainless steel, canvas (heavy duty woven cotton with plastic coating) and corrugated iron are more attractive options, nowadays (Lin and Yang, 1991; Sperling and Lemos Chernicharo, 2005; Chernicharo *et al.*, 2012; Lettinga and Pol, 2018).

iii) Corrosion Protection

The ability of the materials to withstand corrosion can be intrinsic (e.g. PVC, fibreglass, stainless steel) or can be obtained it through special additives or coating (e.g. concrete, steel). In the case of reinforced concrete UASB digesters, the concern with the corrosion protection of the configuration should be prior to the construction of the reactor. Thus, some factors such as the selection of an adequate curing process or the use of a concrete with a low water–cement ratio should be considered in order to be achieved lower rates of absorption and permeability. Finally, in the case of steel UASB digesters, the care needs to be greater in order to avoided corrosion, including the use of special steels and the rigorous control of the coatings employed (Sperling and Lemos Chernicharo, 2005; Chernicharo *et al.*, 2012).

5.3.4 Operation and Maintenance

The start phase is the most important and delicate part of the UASB process. One of the most relevant points is the selection of the inoculum. The process will be faster and more stable if we use sludge of other anaerobic digester. The main parameter to control in the start phase will be the VFA content and the evolution over time. Also the volumetric load in the first days should be low, and rise it progressively. A typical volumetric load, in the start, could be 0.2 kg COD/m^3/d , increasing gradually until 4 kg COD/m^3. VFA should be below 500 mg/L and it will be problematic after 4000 mg/L.

The main control parameters for the effective operation of the reactor are:

- Flow
- Hydraulic retention time, with values between 4 and 12 hours.
- Volumetric organic load, usually between 2 and 12 kg COD/m^3/d
- pH: The optimum value should be between 6.8 and 7.5, being acceptable between 6 and 8
- Relation between VFA and alkalinity should be always below 0.3- 0.4
- Biogas production (typical value is 0.35 Nm^3 CH4/kg COD removed)

Necessary instrumentation for the system should be:

- Influent flow meter
- Biogas flow meter
- Temperature and pH meters
- Biogas composition

Other than the aforementioned operating conditions/parameters followed by ESAMUR in Blanca WWTP, typical ranges of operating parameters for UASB digesters reported in literature for the domestic and municipal wastewater treatment are presented in Table 7 (Vieira and Souza, 1986; Barbosa and Sant'Anna, 1989; Vieira *et al.*, 1994; Seghezzo *et al.*, 1998; Chernicharo *et al.*, 2012, 2015; Pandey and Dubey, 2014; Daud *et al.*, 2018; Rizvi *et al.*, 2018).

Table 7 Operating parameters and performance of a typical UASB digester for the domestic and municipal wastewater treatment.

Parameters	Unit	Range of Values
Reactor Volume	m^3	64 - 55,000
Temperature	°C	8 - 35
pH	-	6.3 - 7.8
HRT	h	3 - 20 (at average flow)
OLR	kg COD/m^3 d	1.0 - 20.0
SRT	d	20 - 30
V_{up}	m/h	0.2 - 1.0 (at average flow)
Alkalinity	mg CaCO3/L	50 - 200
CH_4 Production	%	70 - 80
COD_{in}	mg/L	> 400

Parameters	Unit	Range of Values
COD_{rem}	%	up to 80
BOD_{in}	mg/L	95 - 515
BOD_{rem}	%	up to 85
TSS_{in}	mg/L	100 - 500
TS	%	3 - 7
TSS_{rem}	%	up to 90
TDS	mg/L	250 - 850
TN	mg/L	20 - 85
TP	mg/L	6 - 30
VSS	mg/L	80 - 300
VFAs	mg/L	100 - 200
Sulphates	mg/L	15 - 124
Chlorides	mg/L	30 - 110

The most important parameters that need to be monitored are the following:

- ✓ Samples of influent wastewater to analyze COD, SS, NT, PT and sulphates.
- ✓ Samples of treated water to analyze COD, SS, VS, NT, PT, pH and sulphates.
- ✓ Samples of biogas to measure H_2S and CH_4.
- ✓ Samples of sludge, to analyze pH, COD, DM and VM, alkalinity and VFA.

A usual regularity of sampling is 3 times a week.

The most important parameter is probably the upflow velocity, with standard values ranging between 0.3 to 2 m/h. This parameter is very important to get a good mixing and contact of sludge and water, avoiding a sludge scape if the velocity is too high.

The UASB is an anaerobic treatment technology which is characterized by the simplicity of its maintenance. More specifically, maintenance of the UASB reactor is carried out by professionals and includes checking of the wastewater gutters, gas collection system, valves and weirs, feeding boxes, cleaning of screen and grit chambers, de-choking of feeding pipes, time-to-time checking of pumps and electrical equipment, as well as repairing of system parts (e.g. pumps) in case of problems (Khalil *et al.*, 2006). The main maintenance tasks are related with the cleaning and it will depend of the pre-treatment quality. Cleaning of pump station, pipes, distribution devices, suction sludge devices, etc. are the most usual maintenance actions and the regularity will depend on the needs.

5.4 Anaerobic Baffle Reactor

5.4.1 Description

The Anaerobic Baffled Reactor [ABR] is an innovative and modern high-rate anaerobic digester which has been recognized as a promising solution in the anaerobic treatment of domestic and municipal wastewaters, due to its numerous and attractive advantages over other anaerobic systems such as the UASB and the anaerobic filter [AF] (Barber and Stuckey, 1999; Krishna, Kumar and Kumar, 2009; Stazi and Tomei, 2018). However, the ABR is also characterized by some notable limitations (Barber and Stuckey, 1999; Stazi and Tomei, 2018). The overall advantages and disadvantages of the ABR for the anaerobic treatment of the domestic and municipal sewage are presented in Table 8.

Table 8 Advantages and disadvantages/limitations of the ABR technology (Barber and Stuckey, 1999; Stazi and Tomei, 2018).

Advantages	Disadvantages
Provides a remarkable and unique baffled design which enables the AD system to reduce the washout of biomass, retaining a high active biological solids content	Long periods of time are required to start-up the AD process
Simple design and construction, which are connected with low construction, operating and maintenance costs	Expert design and construction are required
Ability to separate acidogenesis and methanogenesis process longitudinally down the digester, allowing it to operate as a two-phase system without employment of complex control devices and high costs	Low reduction of pathogens and nutrients
High tolerance to hydraulic and organic shock loads	Problems with ensuring an even distribution of the influent
Quick recovery after shock hydraulic or organic loading	Wastewater effluent and sludge require further treatment and/or appropriate discharge
High stability and reliability due to attachment of the biological solids onto and between the filter media	Clear design guidelines are not available yet
High void volume as the microbial mass itself functions like the support medium for microorganism attachment	
No requirement of biomass with unusual settling properties	

Advantages	Disadvantages
High biogas yields with easy collection approaches	
Low sludge production	
High solids retention times (SRT)	
Low hydraulic retention times (HRT)	
Provides high COD and BOD removal efficiencies	
Can be used for almost all soluble organic wastewater from low to high strength	

5.4.2 Design

The Anaerobic Baffled Reactor [ABR] can be characterized as a set of several UASB reactors connected in a series. As the name suggests, the ABR essentially consists of a series of vertical baffles containing large active microbial mass, which are arranged in such a way in order to force the incoming wastewater (liquid) to flow under and over (or through) the baffles, making a sequential down-flow and up-flow movement, as it passes from the inlet to the outlet. In this way, it is guaranteed a larger contact of the wastewater with the biomass present at the bottom of the ABR system. Finally, the anaerobic bacteria within the reactor tend to rise and settle with gas production in each compartment of ABR. In fact, this configuration provides a plug-flow design, allowing the ABR system to produce an effluent that has a low COD (Sperling and Lemos Chernicharo, 2005; Aqaneghad and Moussavi, 2016; Khanal et al., 2017). A schematic illustration of a typical ABR is shown in Figure 4.

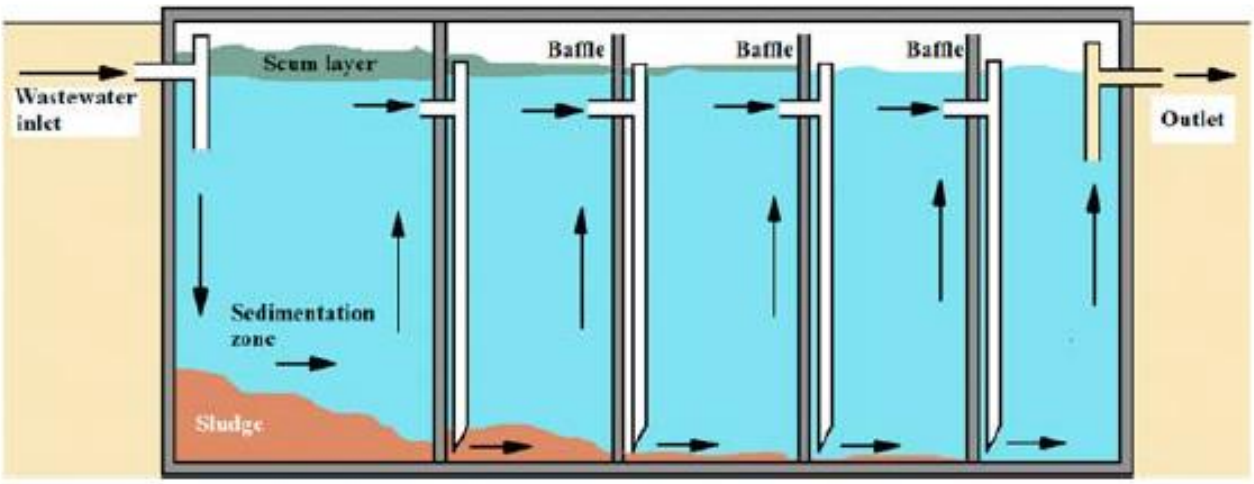

Figure 4 Schematic illustration of a typical ABR.

Current Design Criteria of the ABR for the Domestic Wastewater Treatment

As previously mentioned, there are no clear guidelines for the ABR yet. However, for a specific wastewater flow rate, the design of ABR can fully be specified by the following parameters, which are presented in Table 9 (Foxon and Buckley, 2006; Yulistyorini et al., 2019).

Table 9 Design Criteria/Parameters of the ABR for the domestic and municipal wastewater treatment.

Design Criteria	Unit	Recommended Range of Values or Equation
Flow rate of the incoming wastewater [F]	m^3/d	-
Hydraulic Retention Time [HRT]	h	3 to 48 (but 40 to 60 during start-up)
Digester working volume [V_W]	m^3	(F x HRT)/24
Design up-flow velocity [v_d]	m/h	$v_p/1.8 = 0.30$
Peak up-flow velocity [v_p]	m/h	0.54
Number of compartments [N]	-	4 to 6
Compartment up-flow area [A_U]	m^2	$F/(v_d \times 24)$
Hanging baffle clearance [d_h]	m	0.15 to 0.20
Compartment width to length ratio [$C_{W:L}$]	m/m	3 to 4
Up-flow to down-flow area ratio [$R_{U:D}$]	m^2/m^2	2 to 3
Total compartment area [A_C]	m^2	$A_U \times (1+R_{U:D})/R_{U:D}$
Digester depth [r_D]	m	1 to 3 (The digester depth is largely governed by the cost of excavation)
Digester width [r_W]	m	$\sqrt{\frac{V_W \times C_{W:L}}{N \times r_D}}$
Digester length [r_L]	m	$(N \times r_W)/C_{W:L}$

5.4.3 Construction

Concrete constitute the material which are most commonly used in ABR due to its availability as a construction material but also for economic reasons. In addition, plastics and metals such as alloys, stainless steels, and coated metals, which are more expensive, can be used as construction materials, saving on space and footprint requirements. Moreover, these can be constructed off site and shipped to the location (Sperling and Lemos Chernicharo, 2005).

5.4.4 Operation and Maintenance

The operating conditions/parameters and performance of a typical ABR for the domestic and municipal wastewater treatment are presented in Table 10 (Bachmann, Beard and McCarty, 1985; Manariotis and Grigoropoulos, 2002; Gopala Krishna, Kumar and Kumar, 2008; Rongrong, Qing and Jihua, 2010; Aqaneghad and Moussavi, 2016; Mahatyanta and Razif, 2016; Reynaud and Buckley, 2016; Moradgholi et al., 2019).

Table 10 Operating parameters and performance of a typical ABR for the domestic and municipal wastewater treatment.

Parameters	Unit	Range of Values
Reactor Volume	m^3	0.015 - 290
Temperature	°C	16 - 37
pH	-	6.6 - 7.8
HRT	h	3 - 48
OLR	kg COD/m^3 d	0.4 - 6.9
SRT	d	> 30
V_{up}	m/h	0.1 - 2.0
Alkalinity	mg $CaCO_3$/L	240 - 500
CH_4 Production	%	44 - 74
COD_{in}	mg/L	200 - 1000
COD_{rem}	%	up to 93
BOD_{in}	mg/L	150 - 560
BOD_{rem}	%	up to 95
TSS_{in}	mg/L	150 - 970
TSS_{rem}	%	up to 92
TS	%	2 - 10
TDS	mg/L	-
VSS	mg/L	-
TN	mg/L	100 - 150
TP	mg/L	4 - 19
VFAs	mg/L	30 - 44

Parameters	Unit	Range of Values
Sulphates	mg/L	-
Chlorides	mg/L	-

The ABR is a robust anaerobic treatment technology which is characterized by the simplicity and cost reduction of its maintenance. More specifically, maintenance of the ABR does not require special supervision by a skilled operator and does not need to be monitored full time (Zhu *et al.*, 2015; Mahatyanta and Razif, 2016; Reynaud and Buckley, 2016). Thus, the ABR maintenance is limited to the removal of accumulated sludge and scum every 1 to 3 years (https://sswm.info/factsheet/anaerobic-baffled-reactor-%28abr%29).

5.5 Anaerobic Sequencing Batch Reactor

5.5.1 Description

The Anaerobic Sequencing Batch Reactor [ASBR] belongs to the category of high-rate anaerobic digesters and constitutes a variation of the anaerobic activated sludge (suspended growth) process. More specifically, the ASBR uses a modified form of the "fill and draw" method, where four basic cyclic sequence steps of feeding, reaction, settling and decantation take place sequentially in a single batch digester (Dutta and Sarkar, 2015; Khanal et al., 2017; Aziz et al., 2019). The ASBR is considered as a promising, viable and efficient technology for the wastewater treatment, especially for the domestic and municipal sewage, due to its operational and performance advantages over continuous anaerobic digesters (Mahvi, 2008; Fernandes et al., 2013; Tauseef, Abbasi and Abbasi, 2013). The overall advantages and disadvantages of the ASBR for the anaerobic treatment of the domestic and municipal sewage are presented in Table 11 (Poltak, 2005; Arvanitoyannis, Kassaveti and Ladas, 2008; Mahvi, 2008; Gupta, Ramakrishnan and Hung, 2012; Tauseef, Abbasi and Abbasi, 2013; Aziz et al., 2019).

Table 11 Advantages and disadvantages/limitations of the ASBR technology.

Advantages	Disadvantages
Process simplicity and operational flexibility	High construction and operational costs due to the requirements for a higher level of sophistication, timing units and controls, especially in the case of larger anaerobic systems
Reduction of footprint requirements	Requirements for a higher level of maintenance, which is connected with more sophisticated controls, automated switches, and automated valves

Advantages	Disadvantages
Less equipment to maintain	Potential of discharging floating or/and settled sludge during the draw or decant stage with some ASBR configurations
Eliminating the need for secondary sedimentation tanks and sludge re-cycle pumps	Potential requirements for equalization after the ASBR treatment, depending on the down-stream processes
Efficient quality control of the effluent wastewater	Low coliform removal efficiencies
Capability of handling wide ranges of hydraulic and organic loadings	
Settling problems can be easily recognized and corrected	
High solids retention times (SRT)	
Provides high COD and BOD removal efficiencies	
Satisfactory N and P removal efficiencies	
High biogas yield	
Biomass cannot be washed out	

5.5.2 Design

As previously mentioned, ASBR can be characterized as a “fill and draw” type modified activated sludge process of four cyclic sequence steps: fill (feed), reaction, settle (sedimentation/clarification) and draw (decant) (Aziz *et al.*, 2019). Thus, the “fill and draw” process begins with the stage of feeding in which the incoming wastewater stream enters into the batch reactor of ASBR system having a fixed volume. Thereafter, during the react phase, the organic matter of the influent wastewater and the anaerobic sludge (biomass) of the ASBR are mixed either continuously or intermittently with the help of mixer for a fixed interval of time, leading to the production of biogas (CH_4 and CO_2). Upon completion of the biogas production, the mixing stops to allow the microbial biomass settle to the lower part of the ASBR, leading to its separation from the liquid supernatant (treated wastewater), during the stage of settling. Then, a floating pump removes most of the liquid supernatant from the ASBR system until the treated wastewater level drops to a preset level (decant or draw stage). Finally, the ASBR is then refilled and another cycle begins in the same manner, with the number of cycles depends upon the system's HRT (Irvine and Ketchum, 1989; Editorial, 2009; Gupta, Ramakrishnan and Hung, 2012; Khanal *et al.*, 2017). A schematic illustration of a typical ASBR is shown in Figure 5.

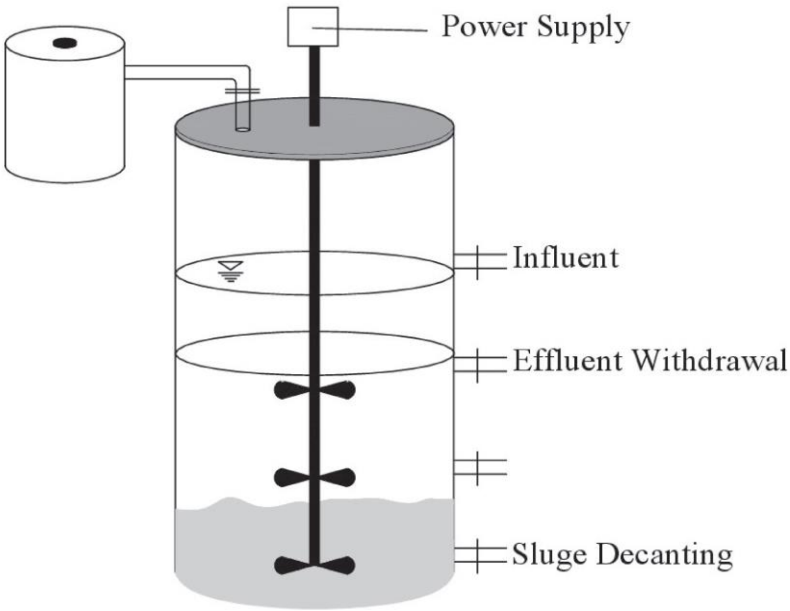

Figure 5 Schematic illustration of a typical ASBR.

Current Design Criteria of the ASBR for the Domestic Wastewater Treatment

Generally, the design of a SBR system and therefore an ASBR system should be based on the results of pilot-scale studies regarding the anaerobic treatment of domestic and municipal wastewaters (Wilderer *et al.,* 2001). However, a basic guideline for the designing of an ASBR system includes the following parameters (Kirschenman and Hameed, 2000; Wilderer *et al.*, 2001; Huo, 2005; Sarti *et al.*, 2007; Castro-Barros, 2013; GÜRTEKİN, 2014):

i. **Definition of Input Data**
   - ✓ Inflow under dry weather and peak flow conditions
   - ✓ Loads (e.g. hydraulic, organic, nitrogen and phosphorus loadings)
   - ✓ Time variations

ii. **Process Configuration**
   - ✓ Plant with or without influent holding tank
   - ✓ Operating strategy (e.g. continuous, short or long fill period)

iii. **Process Parameters/Cycle Design**
   - ✓ Sludge age
   - ✓ Volumetric exchange ratio
   - ✓ Duration of a cycle
   - ✓ Sequence of phases (filling, mixing, sedimentation, drawing, excess sludge removal)
   - ✓ Duration of phases
   - ✓ Start and stop of single actions

iv. **Hydraulic Dimensioning**
   - ✓ Number of ASBRs

- ✓ Volume of the reactors, pre-storage and post tanks (if necessary)

v. **Dimensioning of Machines**
- ✓ Pumps
- ✓ Mixers

vi. **Verification of Function**
- ✓ Nitrogen balance
- ✓ Dynamic simulation (if necessary)
- ✓ Pilot tests (if necessary)

In Table 12 a set of basic geometric characteristics of the ASBR are presented in order to obtain a first approach of the ASBR design.

Table 12 Design criteria/parameters of the ASBR for the domestic and municipal wastewater treatment.

Design Criteria	Symbol	Unit	Equation
Total volume of the reactor	V_R	m^3	$V_0 + V_f$
Volume fed (incoming wastewater)	V_f	m^3	-
Volume that remains from the previous cycle (wastewater + sludge)	V_0	m^3	-
Volume purged (sludge)	V_w	m^3	-
Volume decanted (treated wastewater)	V_d	m^3	-
Total time of the cycle	t_c	h	Σt_i
Time of each phase	t_i*	h	-
Feeding time ratio	FTR	-	t_f/t_c
Volumetric exchange ratio	VER	-	V_f/V_R
Hydraulic retention time	HRT	h	V_R/Q

*t_i: t_f (feeding time) or t_a (active time, for the reaction) or t_s (settling time) or t_d (decanting time)

Important Equations of the ASBR Technology

Hydraulic Retention Time [HRT]

The Hydraulic Retention Time [HRT] can be calculated by the following equation:

$$HRT = \frac{V_R}{Q} \text{ or } HRT = \frac{t_c}{VER} \tag{5.13}$$

where,

HRT = hydraulic retention time [d]

Q = average flow rate of the incoming wastewater [m^3/d]

V_R = total volume of the reactor [m^3]

t_c = total time of the cycle [h]

VER = volumetric exchange ratio

Effective Fraction of the Cycle [EFC]

The Effective Fraction of the Cycle [EFC] can be calculated by the following equation:

$$EFC = \frac{t_c - t_s - t_d - t_a}{t_c} \tag{5.14}$$

where,

EFC = effective fraction of the cycle

t_c = total time of the cycle [h]

t_s = settling time [h]

t_d = decanting time [h]

t_a = active time, for the reaction [h]

Total Sludge Mass [M_X]

The Total Sludge Mass [M_X] can be determined by the following equation:

$$M_X = Y_{H,net} \ x \ Q \ x \ \Delta C_s \ x \ HRT \ x \ \frac{1}{EFC} \tag{5.15}$$

where,

M_X = total sludge mass

$Y_{H,\,net}$ = net. yield including decay and production of particulate products [kg TSS/kg $COD_{applied}$]

Q = average flow rate of the incoming wastewater [m^3/d]

ΔC_s = the difference between the substrate concentration in the influent and in the effluent wastewater [mg/L]

HRT = hydraulic retention time [d]

EFC = effective fraction of the cycle

Volume of the settled sludge [V_0]

The Volume of the settled sludge [V_0] is estimated by the following equation:

$$n \ x \ V_0 = M_X \ x \ SVI \ x \ SF_V \tag{5.16}$$

where,

V_0 = volume of the settled sludge [m^3]

M_X = total sludge mass

SVI = sludge-volume index

SF_V = safety factor for design (around 25%)

5.5.3 Construction

The ASBR tanks are usually constructed from concrete, steel or as sealed earthen lagoons, and in any shape and size. The construction of ASBR systems is typically characterized by reduced footprint requirements than conventional activated sludge systems as the ASBRs often eliminates the need for primary clarification. In addition, it should be emphasized that the ASBR never requires secondary clarifiers. The dimensions of the ASBR tanks themselves have to be site specific. However, the ASBR systems are more advantageous if space is limited at the proposed site (USEPA, 1999; Wilderer *et al.*, 2001; GÜRTEKİN, 2014).

5.5.4 Operation and Maintenance

The operating conditions/parameters and performance of a typical ASBR for the domestic and municipal wastewater treatment are presented in Table 13 (Ndon and Dague, 1997; USEPA, 1999; Teichgräber *et al.*, 2001; Sarti *et al.*, 2007; Kornaros, Marazioti and Lyberatos, 2008; Mahvi, 2008; Liu *et al.*, 2017; Aziz *et al.*, 2019).

Table 13 Operating parameters and performance of a typical ASBR for the domestic and municipal wastewater treatment.

Parameters	Unit	Range of Values
Reactor Volume	m^3	1.2 -
Temperature	°C	15 - 35
pH	-	6.6 - 7.2
HRT	h	6 - 48
OLR	kg COD/m^3 d	0.6 – 12.0
SRT	d	15 - 30
V_{up}	m/h	-
Alkalinity	mg $CaCO_3$/L	40 - 110
CH_4 Production	%	up to 78
COD_{in}	mg/L	345 - 1000

Parameters	Unit	Range of Values
COD_{rem}	%	up to 95
BOD_{in}	mg/L	105 - 514
BOD_{rem}	%	up to 98
TSS_{in}	mg/L	120 - 783
TSS_{rem}	%	up to 97
TS	%	2.5 - 8.0
TDS	mg/L	-
VSS	mg/L	112 - 451
TN	mg/L	-
TN_{rem}	%	up to 89
TP	mg/L	-
TP_{rem}	%	up to 69
VFAs	mg/L	-
Sulphates	mg/L	-
Chlorides	mg/L	-

The controls, automatic valves and automatic switches may require sufficient and frequent maintenance than a conventional activated sludge system as they constitute the heart of the ASBR system. However, the level of sophistication can be very advanced in larger ASBR wastewater treatment plants, leading to a higher level of maintenance on the automatic valves and switches. On the other hand, the elimination of the need for primary and secondary clarification in most domestic and municipal ASBR wastewater systems leads to reduced maintenance requirements (USEPA, 1999; Wilderer *et al.*, 2001; GÜRTEKİN, 2014).

5.6 Anaerobic Fluidized Bed Reactor

5.6.1 Description

The Anaerobic Fluidized Bed Reactor [AFBR] is a high-rate anaerobic digester which can be considered as an advanced and promising anaerobic treatment technology for domestic and municipal wastewaters, due to its numerous and significant advantages over other anaerobic systems such as the UASB and the anaerobic filter [AF]. However, the AFBR is also characterized by some notable limitations (Heijnen *et al.*, 1989; Sanz and Fdz-Polanco, 1990; Mao *et al.*, 2015; Hamza, Iorhemen and Tay, 2016; Ohimain and Izah, 2017; Bhattacharya, Dev and Das, 2018). The overall advantages and disadvantages of the AFBR for the anaerobic treatment of the domestic and municipal sewage are presented in Table 14.

Table 14 Advantages and disadvantages/limitations of the AFBR technology.

Advantages	Disadvantages
Good process control	Long periods of time are required to start-up the AD process due to the long attachment and growth time of the biomass on the support medium
High purification capacity	Difficulties in maintaining optimum mixing and fluidizing velocity and conditions without anaerobic sludge (biomass) stripping or washout
Potential to be used small reactor volumes, leading to reduced footprint requirements	Difficulty in controlling of the bio-layer thickness
Low maintenance and capital cost due to reduced reactor volumes	General difficulties in scaling up from pilot to effective full-scale operating conditions
Great surface area of inert medium per unit of reactor volume	High energy requirements due to very high liquid recirculation ratio
Eliminating channeling and clogging due to the fluidization of anaerobic sludge carrier materials inside the reactor	In case of large scale reactors, the liquid distributors to obtain uniform fluidization are costly, do not function well and lead to clogging problems
Great resistance to inhibitors	
High organic loading rates (OLR)	
Low hydraulic retention times (HRT)	
Good hydraulic circulation	
Provides high COD, BOD and nitrogen removal efficiencies	
Low sludge production	
High settling velocities	
Reactor of any shape can be utilized and its capacity can be	

Advantages	Disadvantages
altered by simply changing the degree of filling	
Suitable for low-strength and low-solids wastewaters	

5.6.2 Design

The AFBR can be characterized as a submerged attached-growth reactor which consists of a bed of granular and inert material (small-inert particles) such as fine sand, alumina, activated carbon, iron chips, porous glass beads, limestone or pumice as the physical support medium on which the anaerobic bacteria can attach and grow themselves in the form of microbial films (bio-layer), providing close contact with the incoming wastewater stream (Mao *et al.*, 2015; Hamza, Iorhemen and Tay, 2016; Bhattacharya, Dev and Das, 2018). These bio-layer covered particles are maintained in a fluidized state by an upwards directed and high flow rates of the incoming wastewater influent, leading to a fluidized bed with 25 to 300 % expansion (Heijnen *et al.*, 1989; Tauseef, Abbasi and Abbasi, 2013; Hamza, Iorhemen and Tay, 2016). Thus, the incoming wastewater stream is introduced from the bottom of the reactor, flowing upward through the fluidized bed which allows intense contact between the organic matter of the wastewater influent and the attached anaerobic bacteria that effectively degrades it (Heijnen *et al.*, 1989; Sanz and Fdz-Polanco, 1990; Tauseef, Abbasi and Abbasi, 2013). A schematic illustration of a typical AFBR is shown in Figure 6.

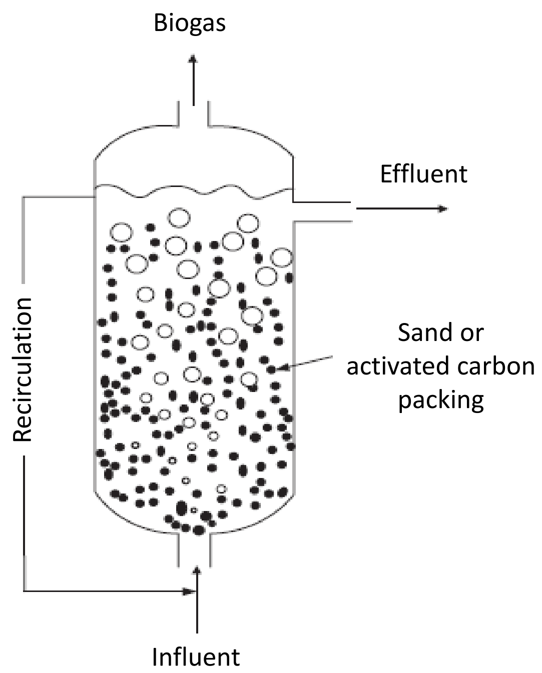

Figure 6 Schematic illustration of a typical AFBR.

AFBRs are built in height with a small diameter to maximize the liquid upflow speed (8-10 m/h). In AFBR, anaerobic microorganisms are immobilized on a support made up of inert fine particles (0.1-1 mm in diameter). The support is fluidized by a liquid flow depending on the density of the support (Wheatley, 1990). The lower part of the reactor introduces water through a distribution system at a high enough velocity to fluidize or expand the bed. The expansion rate of the particle bed is greater than 30%. Generally, the speed required for fluidization is much higher than that required to achieve the retention time for the biological reaction, so the bed effluent has thereby to be recycled, increasing the upward flow velocity. The major advantage of fluidized beds comes from the mobility of the particles, which ensures good mixing of the substrate and the suspended biomass (Roustan *et al*., 1993). Support-biofilm assembly (bio-particle) are in continuous relative movement but are not transported by the flow and not washed off from the reactor.

The design steps of AFBR may be described as follows:

1) Select the support material and its size.
2) Select expansion and calculate the surface velocity.
3) Calculate size of the bed (diameter and height) and peripherals.
4) Determine the residence time needed for the removal of the organics of the influent to an acceptable level according to design conditions.

One of the crucial aspects of AFBR design is the support material. Sand and other high-density materials have relatively low adsorption capacity, while clay, volcanic stone and activated carbon show very high adsorptive power. The selection of the adequate support material has to consider several aspects, besides those related to fluidization, and experimental steps to choose the best are almost unavoidable. Other considerations have to do with the cost of the material and physical and chemical properties. The physical characteristics, which have to be considered, are size, shape, particle density, hardness, rigidity and surface area.

5.6.3 Construction

Stainless steel and fiber glass constitute the materials which are most commonly used in AFBR, for construction and cost reasons (Sanz and Fdz-Polanco, 1990; Balaguer, Vicent and Parfs, 1997; Bello, Abdul Raman and Purushothaman, 2017; Sattler, 2011). In addition, the category of the support material includes: fine sand, alumina, granular activated carbon, iron chips, porous glass beads, limestone, pumice, high-density plastics, styrene, polyvinylbenzene, etc. (Heijnen *et al.*, 1989; Sanz and Fdz-Polanco, 1990; Marín *et al.*, 1999; Tauseef, Abbasi and Abbasi, 2013; Hamza, Iorhemen and Tay, 2016). However, the final choice of the adequate support material depends on its physical and chemical properties, on economic considerations and on operational parameters (Marín *et al.*, 1999).

5.6.4 Operation and Maintenance

The fluidized bed reactor is a more complex than other high-rate anaerobic digesters and its operation and start-up are extremely delicate. A better operability of this type of process is linked to the development of control systems which allow real-time monitoring of fermentation and respond quickly and appropriately to signs of destabilization (Steyer *et al*., 1999). The need for recirculation of the effluent in order to reach the fluidization rates is nevertheless translated into an additional cost (Shimodaira *et al*., 1983; Nicolella *et al*., 2000).

The AFBR has been used to treat all types of wastewaters from sewage (low load) to wastewaters from beer and sugar plants (high load). Reactors with mobile support are generally more efficient than anaerobic filters. OLR of 10-50 kg COD/m^3/day can be applied in AFB reactors (Ozturk, 2007). The biomass concentrations in fluidized bed reactor are commonly between 15 and 30 g/L (Elmaleh *et al*. 1984; Chen et *al*., 1988) and can reach 50 g/L (van Loosdrecht *et al*., 1993).

In fluidized bed reactors, the effluent is usually recycled, so as to achieve the fluidization velocity and the ratio used reaches moderately high values. At high anaerobic conversions where large amounts of CO_2 are generated, the effluent tends to be alkaline, which by mixing with the fresh influent helps the pH control and stabilization.

All the known systems operate at mesophilic temperatures. However, studies in psychrophilic conditions have reported also acceptable results. The presence of the solid support and the small particle size provides somehow thermal stabilization to minor temperature changes in the influent, provided it has a good conductivity.

The operating conditions/parameters and performance of a typical AFBR for the domestic and municipal wastewater treatment are presented in Table 15 (Chen *et al.,* 1985; Heijnen *et al.*, 1989; Sanz and Fdz-Polanco, 1990; Rovatti, Nicolella and Converti, 1995; Patel, Zhu and Nakhla, 2006; Ozgun *et al.*, 2013; Andalib *et al.*, 2014; Gao *et al.*, 2014; Düppenbecker and Cornel, 2016; Bello, Abdul Raman and Purushothaman, 2017).

Table 15 Operating parameters and performance of a typical AFBR for the domestic and municipal wastewater treatment.

Parameters	Unit	Range of Values
Reactor Volume	m^3	0.00054 - 360
Temperature	°C	20 - 35
pH	-	6.9 - 8.2
HRT	h	1 - 12
OLR	kg COD/m^3 d	2 - 50
SRT	d	15 - 50
V_{up}	m/h	10 - 30
Alkalinity	mg $CaCO_3$/L	130 - 360
CH_4 Production	%	up to 75

Parameters	Unit	Range of Values
COD_{in}	mg/L	150 - 1560
COD_{rem}	%	up to 90
BOD_{in}	mg/L	215 - 630
BOD_{rem}	%	up to 85
TSS_{in}	mg/L	104 - 761
TSS_{rem}	%	up to 90
TS	%	< 5
TDS	mg/L	-
VSS	mg/L	110 - 605
TN	mg/L	9 - 67
TN_{rem}	%	up to 80
TP	mg/L	4.8 - 71
TP_{rem}	%	up to 65
VFAs	mg/L	-
Sulphates	mg/L	99 - 230
Chlorides	mg/L	-

5.7 Anaerobic Filter

5.7.1 Description

The Anaerobic Filter [AF] reactor or Anaerobic Fixed Film Reactor [AFFR] (often referred to as fixed bed) constitutes a member of the category of the high-rate anaerobic systems (Hamza, Iorhemen and Tay, 2016; Khanal *et al.*, 2017; Aziz *et al.*, 2019).

The AF reactor is a packed-bed attached-growth reactor which includes one or more vertical filtration chambers containing an inert medium (natural or synthetic) such as rocks, ceramic blocks, quartz, granite, bamboo or plastic media, with a high void volume and specific surface area (Sperling and Lemos Chernicharo, 2005; Tilley *et al.*, 2008; Hamza, Iorhemen and Tay, 2016). These packing media act as a stationary support surface for the anaerobic bacteria to attach and grow themselves in the form of microbial films, providing close contact with the incoming wastewater stream and leading to separation of bacterial mass and biogas produced from the treated wastewater effluent (Singh and Prerna, 2009; Tauseef, Abbasi and Abbasi, 2013; Mao *et al.*, 2015; Hamza, Iorhemen and Tay, 2016). More specifically, the AF reactors can be operated under either an up-flow or down-flow mode, depending upon the reactor's configuration (Mao *et al.*, 2015; Aziz *et al.*, 2019). In the case of an up-flow AF [UAF], the incoming wastewater stream is introduced from the bottom of the reactor, having an up-flow pathway through the packing medium which allows intense contact between the organic matter of the wastewater influent and the attached bacterial mass that effectively degrades it (Singh and Prerna, 2009; Tauseef, Abbasi and Abbasi, 2013; Khanal *et al.*, 2017). On the other hand, in a down-flow AF [DAF], the incoming wastewater stream is introduced from the top of the reactor and flows downwards through the support medium, where is removed by anaerobic microorganisms attached to that filter media (Tauseef, Abbasi and Abbasi, 2013; Khanal *et al.*, 2017). In both of the above cases, the anaerobic microbes remain attached to the packing media when the treated wastewater effluent is discharged, remaining in action when a new wastewater influent is added in the reactor (Singh and Prerna, 2009). In UAF, the packing medium is necessarily submerged, while the DAF can work either submerged or non-submerged (Sperling and Lemos Chernicharo, 2005).

Today, the Anaerobic Filter [AF] represents an advanced and effective technology for the domestic and municipal wastewater treatment, due to its noteworthy advantages. However, the AF reactor is also characterized by some important disadvantages (Tilley *et al.*, 2008; Singh and Prerna, 2009; Hamza, Iorhemen and Tay, 2016; Ohimain and Izah, 2017; Akunna, 2018). The overall advantages and disadvantages of the AF reactor for the anaerobic treatment of the domestic and municipal sewage are presented in Table 16.

Table 16 Advantages and disadvantages/limitations of the AF reactor technology.

Advantages	Disadvantages
Small reactor volumes leading to reduced footprint requirements	Expert design and construction requirements
Low operating costs and no electrical energy requirements	Low reduction of pathogens and nutrients
Good process stability and control	Wastewater effluent and sludge require further treatment and/or appropriate discharge
Long service life	Filter clogging and short circuiting problems
Low hydraulic retention times (HRT)	Clogged filter media removal and cleaning is unwieldy
Ability to tolerance to shock hydraulic or organic loadings	Not suitable for wastewater streams with high solids content
Ability to maintain high concentration of anaerobic sludge (biomass) in contact with the incoming wastewater, without affecting treatment efficiency	
Low sludge production	

Advantages	Disadvantages
Eliminating the need for solid separation or recycle	
Eliminating the need for mechanical mixing and sludge settling and return for wastewater fermentation	
Provides high COD and BOD removal efficiencies	
Suitable for low-strength and low-solids wastewaters	

5.7.2 Design

The design of an AF reactor is characterized by a significant number of different shapes, configurations and dimensions, provided that the flow pathway of the AF reactor is well distributed over the packed bed. In case of full-scale, the shape of the AF reactors which are used for the domestic and municipal sewage treatment can be either cylindrical or rectangular (Sperling and Lemos Chernicharo, 2005). On the other hand, the packing medium have been designed to typically occupy from the total depth of the AF reactor to approximately 50 to 70% of the height of the reactor (Sperling and Lemos Chernicharo, 2005; Moran, 2018). A schematic illustration of a typical AF reactor is shown in Figure 7.

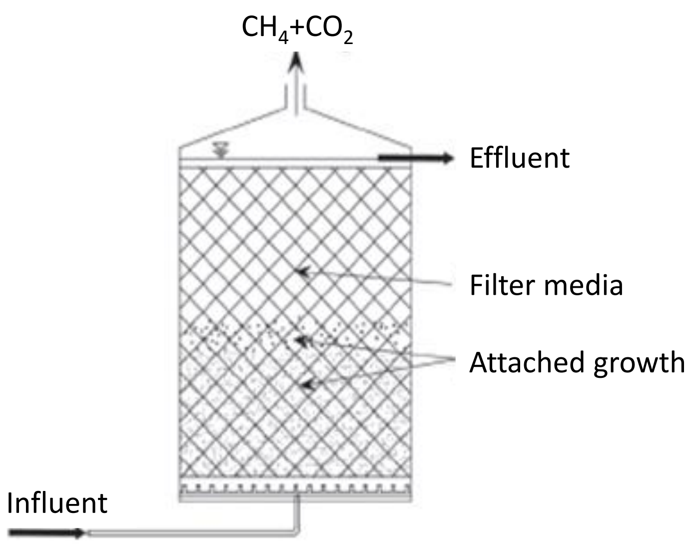

Figure 7 Schematic illustration of a typical AF reactor.

Current Design Criteria of the AF for the Domestic Wastewater Treatment

The main design criteria for the AF reactors treating domestic and municipal wastewaters are presented in Table 17 (Sperling and Lemos Chernicharo, 2005; Tilley *et al.*, 2008).

Table 17 Design Criteria/Parameters of the AF reactor for the domestic and municipal wastewater treatment.

Design Criteria	Unit	Range of Values
Hydraulic Loading Rate [HLR] (at average flow)	$m^3/m^2 \cdot d$	6 to 15
Hydraulic Retention Time [HRT]*	hour	4 to 10
Organic Loading Rate [OLR]	kg COD/$m^3 \cdot$ d	up to 16
Organic Loading Rate [OLR] (total filter volume)	kg BOD/$m^3 \cdot$ d	0.15 to 0.50
Organic Loading Rate [OLR] (packed bed volume)	kg BOD/$m^3 \cdot$ d	0.25 to 0.75
COD Removal Efficiencies	%	68 to 95
BOD Removal Efficiencies	%	75 to 85
Packing Bed Height	m	0.8 to 3.0

*The adoption of the lower limits of HRT for the design of the AF reactors requires special care regarding the type of packing medium, the presence of TSS in the incoming influent and the packing bed height.

It should be understood that HRT is the most significant parameter for the design of AF reactors, influencing the filter performance in the case of the domestic and municipal wastewaters (low-concentration sewages) (Tilley *et al.*, 2008).

Important Equations of the AF Technology

Efficiency of the AF system [E]

The performance of AFs treating different types of wastewater effluents can be estimated by the following equation:

$$E = 100\ x\ (1 - S_k\ x\ HRT^{-m}) \qquad (5.17)$$

where,

E = efficiency of the AF system [%]

HRT = hydraulic retention time [h]

S_k = coefficient of the AF system [0.87 = empirical constant]

m = coefficient of the packing medium [0.50 = empirical constant]

The performance of AFs can be also calculated by the following equation:

$$E_T = 1 - (1 - E_{30})\ x\ \theta^{(T-30)} \qquad (5.18)$$

where,

E_T = efficiency of the AF process at temperature T [°C]

E_{30} = efficiency of the AF process at the temperature of 30°C

T = operational temperature [°C]

θ = temperature coefficient [1.02 to 1.04]

Hydraulic Retention Time [HRT]

The Hydraulic Retention Time [HRT] is calculated by the following equation:

$$HRT = \frac{V}{Q} \tag{5.19}$$

where,

HRT = hydraulic retention time [d]

Q = average flow rate of the incoming wastewater [m^3/d]

V = total volume of the reactor [m^3]

Hydraulic Loading Rate [HLR]

The Hydraulic Loading Rate [HLR] is estimated by the following equation:

$$HLR = \frac{Q}{A} \tag{5.20}$$

where,

HLR = hydraulic loading rate [$m^3/m^2 \cdot d$]

Q = average flow rate of the incoming wastewater [m^3/d]

A = surface area of the packing medium [m^2]

Organic Loading Rate [OLR]

The Organic Loading Rate [OLR] is calculated by the following equation:

$$OLR = \frac{Q \; x \; S_0}{V} \tag{5.21}$$

where,

OLR = organic loading rate [kg BOD/$m^3 \cdot$d or kg COD/$m^3 \cdot$d]

Q = average flow rate of the incoming wastewater [m^3/d]

S_0 = influent BOD or COD concentration [kg BOD/m^3 or kg COD/m^3]

V = total volume of the filter or volume occupied by the packing medium [m^3]

Estimation of the COD and BOD concentrations in the final treated wastewater

The COD and BOD concentrations in the treated wastewater are estimated by the following equation:

$$C_{eff} = S_0 - \frac{E \, x \, S_0}{100} \tag{5.22}$$

where,

C_{eff} = effluent total COD or BOD concentration [mg/L]

S_0 = influent total COD or BOD concentration [mg/L]

E = COD or BOD removal efficiency [%]

5.7.3 Construction

Reinforced concrete, (stainless) steel and fiberglass constitute the materials which are most commonly used in AF reactors, for construction and cost reasons (Singh and Prerna, 2009; Tonon *et al.*, 2015; Ülgüdür *et al.*, 2019; Sattler, 2011). In addition, a wide variety of both natural and synthetic materials can be used as a packing medium. Thus, the category of the support media includes: granite, quartz, ceramic bricks, oysters, mussel and coconut shells, crushed stone, limestone, bamboo rings, polypropylene, polyethylene balls, plastic rings, PVC modular blocks, hollow cylinders, etc. (Omil *et al.*, 2003; Sperling and Lemos Chernicharo, 2005; Manariotis and Grigoropoulos, 2013; Tonon *et al.*, 2015; Science, 2017; Ülgüdür *et al.*, 2019). However, in spite of that some types of packing medium are more efficient than others in the retention of anaerobic sludge (biomass), the final choice depends on the local specific conditions, on economic considerations and on operational parameters (Sperling and Lemos Chernicharo, 2005).

5.7.4 Operation and Maintenance

The operating conditions/parameters and performance of a typical AF digester for the domestic and municipal wastewater treatment are presented in Table 18 (Henry, Prasad and Young, 1987; Weiland and Rozzi, 1991; Bodík, Herdová and Kratochvíl, 2000; Przywara, Mrowiec and Suschka, 2001; Bodík, Herdová and Drtil, 2002; Cakir and Stenstrom, 2003; Sperling and Lemos Chernicharo, 2005; Manariotis and Grigoropoulos, 2006, 2008; Bodkhe, 2008; Aziz *et al.*, 2019).

Table 18 Operating parameters and performance of a typical AF digester for the domestic and municipal wastewater treatment.

Parameters	Unit	Range of Values
Reactor Volume	m^3	100 - 10,000
Temperature	°C	25 - 38
pH	-	6.8 - 7.6
HRT	h	5 - 48
OLR	kg COD/m^3 d	0.9 - 16.0

Parameters	Unit	Range of Values
SRT	d	1 - 10
V_{up}	m/h	is usually around 2 (in case of an UAF)
Alkalinity	mg $CaCO_3$/L	230 - 300
CH_4 Production	%	up to 70
COD_{in}	mg/L	350 - 890
COD_{rem}	%	up to 90
BOD_{in}	mg/L	44 - 573
BOD_{rem}	%	up to 88
TSS_{in}	mg/L	58 - 672
TSS_{rem}	%	up to 85
TS	%	1 - 5
TDS	mg/L	-
VSS	mg/L	240 - 382
TN	mg/L	-
TN_{rem}	%	up to 15
TP	mg/L	5 - 6
TP_{rem}	%	up to
VFAs	mg/L	-
Sulphates	mg/L	15 - 115
Chlorides	mg/L	-

The AF is an anaerobic treatment technology which is characterized by the simplicity and cost reduction of its maintenance. More specifically, maintenance of the AF reactor is carried out by skilled operators and includes monitoring of the scum and sludge levels produced in order to ensure that the AF reactor is functioning properly, time-to-time checking of the AF reactor to ensure that it is watertight and system running in reverse mode (backwashing) in order to be achieved displacement of the accumulated biomass and particles in case of the packing media clogging. Alternatively, the filter material can be removed and cleaned, when the efficiency of the AF reactor decreases. Moreover, the seeding is required in order to grow the anaerobic bio culture attached on the support media. Finally, the appropriate management of flammable gases (e.g. methane) is necessary either by collection, venting or burning in the air (Tilley *et al.*, 2008; http://archive.sswm.info/category/step-nawatech/m1-nawatech-basics/appropriate-technologies/appropriate-technologies/conten-6).

6. CONSTRUCTED WETLAND

6.1 Introduction

Constructed Wetlands (CW) are a natural, low-cost, eco-technological biological wastewater treatment technology designed to mimic processes found in natural wetland ecosystems, which is now standing as the potential alternative or supplementary systems for the treatment of wastewater. The five major components of a constructed wetland are:

- Basin
- Substrate
- Vegetation
- Liner
- Inlet/Outlet arrangement system

There are various design configurations of constructed wetlands which can be classified according to the following elements (UN-HABITAT, 2008):

- Life form of the dominating macrophytes (free-floating, emergent, submerged)
- Flow pattern in the wetland systems (free water surface flow; subsurface flow: horizontal and vertical)
- Type of configurations of the wetland cells (hybrid systems, one-stage, multi-stage systems)
- Type of wastewater to be treated
- Treatment level of wastewater (primary, secondary or tertiary)
- Type of substrate (gravel, soil, sand, etc.)
- Type of loading (continuous or intermittent loading)

The two most important criteria of classification however are the water flow regime (surface and sub-surface) and the type of macrophytic growth (Figure 8).

Different types of constructed wetlands may be combined with each other (so called hybrid or combined systems) in order to exploit the specific advantages of the different systems.

Among the various classifications listed above and for the needs of the AQUACYCLE project only the following 3 types of CWs are considered:

- Free Water Surface CW (FWS)
- Subsurface Horizontal Flow CW (SSF)
- Vertical Flow CW (VF)

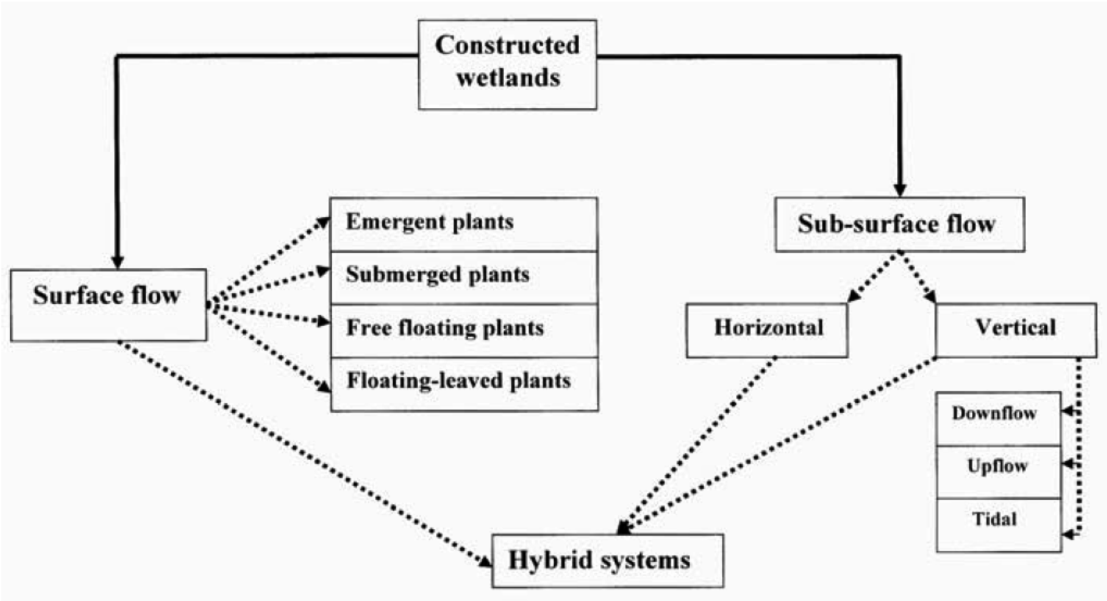

Figure 8 Classification of CWs based on water flow regime and vegetation type.

Constructed wetlands are attractive ecological systems for municipal, industrial, and agricultural wastewater treatment. Constructed wetlands have the ability to efficiently treat a variety of wastewaters by removing organics, suspended solids, pathogens, nutrients and heavy metals. The water treatment mechanisms and pathways occurring in constructed wetlands are similar to those that occur in natural wetland ecosystems. In general, the nature and magnitude of the organic load determines the balance between the treatment mechanisms and the dominant removal pathways in a constructed wetland used to treat wastewater. The main wastewater treatment processes occurring in constructed wetlands (Kadlec and Knight 1996, Brix *et al*., 2000) are presented in Table 19.

Table 19 Wastewater Treatment processes occurring in constructed wetlands.

Physical	Chemical	Biological
Sedimentation of denser particle fractions	Precipitation	Microbial decomposition and mineralisation of organic material
Filtration of lighter particle fractions by macrophytes and biofilms	Adsorption onto wetland substratum and detritus	Microbial nutrient transformation (nitrification/denitrification)
Aggregation of particles leading to removal by either sedimentation or filtration	Volatilisation	Direct biological uptake from the water column (algal and bacterial biofilms)
Exposure of influent to UV radiation via sunlight	Oxidation-reduction	In-direct biological uptake from within the rootzone (benthic

Physical	Chemical	Biological
		biofilms and emergent aquatic macrophytes)
		Microbial competition resulting in the die-off of pathogens
		Direct animal grazing of influent organic material

Since these systems are practically self-sufficient, the cost to build and maintain them is relatively low. Adapting wetland design to wastewater treatment needs, involves a trade-off between efficiency and sizing of constructed wetlands (Wetzel, 2001; Pastor et al., 2003).

6.2 Free-water surface constructed wetland (FWS)

6.2.1 Description

Surface flow constructed wetlands appear similar to natural swamp area's in which plants are rooted in a submerged layer of sand or gravel. **Free-water surface constructed wetland allows water to flow above ground** exposed to the atmosphere and to direct sunlight (Figure 9). Aeration of the sediment takes place by the unique property of wetland plants which act as oxygen pumps providing dissolved oxygen with their roots to a wide variety of microorganisms. FWS constructed wetlands are applied generally when flow rates are highly unpredictable (run-off from roads) and when anaerobic pretreatment in a septic tank or biodigester is not required, this because of the odour nuisance it would cause. The design is mainly dependent on spatial limitations, ambient temperatures, matrix characteristics, and organic and hydraulic load.

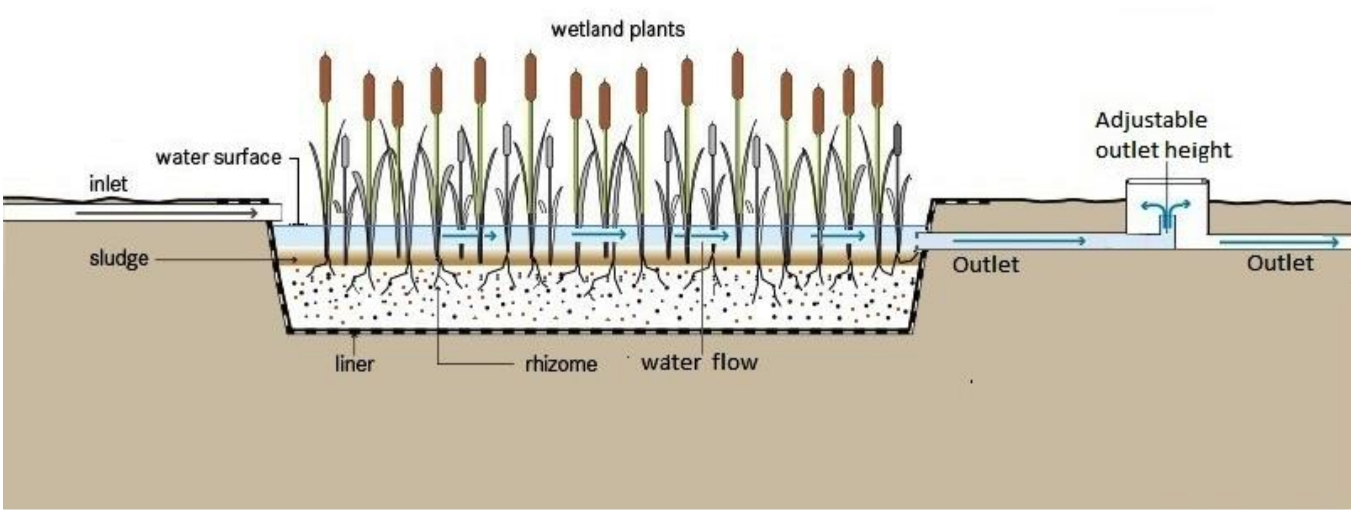

Figure 9 Schematic illustration of a free water surface flow constructed wetland (modified after Tilley et al. 2014).

6.2.2 Design

The design of a surface flow constructed wetland depends on the treatment target and the amount and quality of the influent. It includes decisions about the amount of parallel flow paths and compartmentation. The removal efficiency of the wetland is a function of the surface area (length multiplied by width).

The most common design approaches include:

- Rule-of-thumb
- Regression equations
- Plug-flow *k-C**
- Loading charts
- *P-k-C**

Based on the Rule-of-thumb, **a surface area of about 5 to 10 m^2 per person equivalent is required**. With the exception of the "rule-of-thumb" approach, all others consider a specific pollutant (e.g., BOD_5) to be removed for a particular water quality target. In practice, most treatment wetlands are designed to remove multiple pollutants. Like with other treatment technologies, the designer needs to conduct the calculations for all pollutants of interest and select the resulting design that will enable all the target pollutants to be removed (Dotro *et al*. 2017).

FWS constructed wetlands must be designed to be compatible with the macrophytes that would be established in the wetland. Thus the **water depth should not exceed 35 cm above ground level** (WERF, 2006).

6.2.3 Construction

The channel or basin should be lined with an impermeable barrier (e.g. clay, liner, geo-textile) covered with rocks, gravel and soil and planted with native vegetation (e.g., cattails, reeds and/or rushes). Operational flexibility is greatly increased with multiple cells having appropriate piping between them in order to route wastewater around a cell that needs to be taken off line. Therefore, it is recommended that a minimum of **two parallel trains should be designed and constructed for any FWS** type of constructed wetlands. The number of compartments in series depends on the treatment target. **Aspect ratio's between 3:1 and 5:1 are optimal** (US EPA, 2000). The efficiency of the free-water surface constructed wetland also depends on how well the water is distributed at the inlet. Wastewater can be fed into the wetland, using weirs or by drilling holes in a distribution pipe, to allow it to enter at evenly spaced intervals and thus achieving plug flow in the system.

6.2.4 Operation and Maintenance

FWS and SSF systems require minimal operational and maintenance effort, however, they should be inspected at least every month. Regular maintenance should ensure that water is not short-circuiting, or backing up because of fallen vegetation blocking the wetland outlet. Vegetation may have to be periodically cut back or thinned out. The most common maintenance activities are pulling out undesirable plant species, removing dead vegetation (not dormant vegetation), and cleaning pipes.

The open surface can act as a potential breeding ground for mosquitoes. However, good design and maintenance can prevent this. Free-water surface constructed wetlands are generally aesthetically pleasing, especially when they are integrated into pre-existing natural areas.

Care should be taken to prevent people from coming in contact with the effluent because of the potential for disease transmission and the risk of drowning in deep water.

6.3 Subsurface horizontal flow constructed wetland (SSF)

6.3.1 Description

In SSF wetlands the wastewater is fed in at the inlet and flows slowly through the porous **substrate under the surface of the bed** in a more or less horizontal path until it reaches the outlet zone (Figure 10). During this passage the wastewater will come into contact with a network of aerobic, anoxic and anaerobic zones. The aerobic zones will be around the roots and rhizomes of the wetland vegetation that leak oxygen into the substrate.

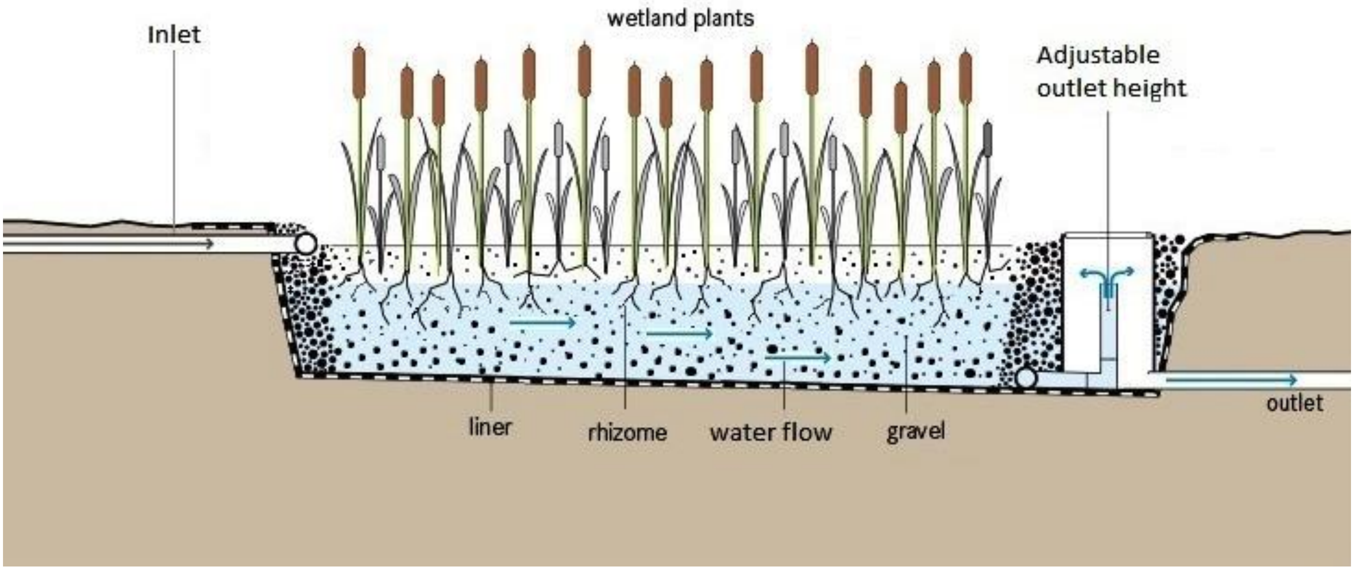

Figure 10 Schematic illustration of a subsurface flow constructed wetland (modified after Tilley et al. 2014).

During the passage of wastewater through the rhizosphere, the wastewater is cleaned by microbiological degradation and by physical and chemical processes. SSF wetland can effectively remove the organic pollutants from the wastewater. **Due to the limited oxygen transfer inside the wetland, the removal of nutrients (especially nitrogen) is limited comparing to other types of CWs, however, SSF wetlands remove the nitrates in the wastewater**. This type of constructed wetland is most commonly used for **aerobic post treatment of domestic wastewater and can take a higher hydraulic load than a surface flow constructed wetland**.

In order to dissolve solid organic matter anaerobic pretreatment in a septic tank or biodigester is required. A thick layer of gravel above the aquifer holds a layer of stagnant air and prevents odor nuisance in the vicinity. Aeration takes place as in surface flow constructed wetlands. The wastewater is however forced to pass thorough the matrix ensuring intensive contact between wastewater and the bacteria in the rhizosphere (root zone of the plants). In this manner all wastewater is treated as no short circuit flow is possible. Horizontal subsurface flow constructed wetlands, when accurately designed, provide an extremely reliable low cost aerobic post treatment solution which is applicable all over the world.

6.3.2 Design

The design of a horizontal subsurface flow constructed wetland depends on the treatment target and the amount and quality of the influent. It includes decisions about the amount of parallel flow paths and compartmentation. The removal efficiency of the wetland is a function of the surface area (length multiplied by width), while the cross-sectional area (width multiplied by depth) determines the maximum possible flow.

The most common design approaches include:

- Rule-of-thumb
- Regression equations
- Plug-flow *k-C**
- Loading charts
- *P-k-C**

Based on the rule-of-thumb, **a surface area of about 4 to 6 m^2 per person equivalent is required**. With the exception of the "rule-of-thumb" approach, all others consider a specific pollutant (e.g., BOD_5) to be removed for a particular water quality target. In practice, most treatment wetlands are designed to remove multiple pollutants. Like with other treatment technologies, the designer needs to conduct the calculations for all pollutants of interest and select the resulting design that will enable all the target pollutants to be removed (Dotro *et al*. 2017).

For SSF wetlands some common regression equations are provided in Table 20. An extensive list of regression equations for SSF wetlands can be found in Rousseau *et al*. (2004).

The first-order plug-flow k-C* approach takes into account influent and effluent concentrations as well as background concentration, but assumes ideal plug-flow hydraulics. This approach is currently less used by design engineers, but is still often reported in the literature.

In terms of mass loading charts, the small-scale treatment wetland design manual written by Wallace and Knight (2006) was created from a collection of water quality data from over 1,500 small-scale treatment wetlands around the world. The data was used to create scatter plots that display influent mass loading rates versus effluent concentrations. This design manual is the first of its kind to consider the concept of risk tolerance in wetland design. The loading charts in Wallace and Knight (2006) provide a visualization of the risk tolerance of the design, including lines that correspond to the 50^{th}, 75^{th}, and

90th percentile of data collected. Using these charts, the design of a new small-scale treatment wetland can be chosen based on influent mass loading rate, desired effluent concentration, and risk tolerance. A design chosen based on the 50th percentile indicates that a system would meet the desired effluent concentration 50% of the time. A design chosen based on the 90th percentile line would be predicted to meet the desired effluent concentration 90% of the time (e.g., nine times out of ten), but would require a much larger area.

The *P-k-C** approach accounts for influent and effluent concentration (*Ci* and *Co*), as well as background concentration (*C**). Furthermore it accounts for areal or volumetric reaction rate coefficients (*k*A or *k*V) and temperature correction factors. The designer can choose the level of risk (50%, 80% or 90% compliance) for certain design variables. On the other hand the main disadvantages of this method are (a) There are many variables to assess and many have only limited information from which to select appropriate design values for a specific condition, and (b) he designer must be extremely familiar with all of the material provided in Kadlec and Wallace (2009) in order to understand and locate the required design information.

Table 20 Example regression equations for SSF wetlands.

Parameter	Equation	Input Range	Output Range
BOD_5	$Mo = (0.13 \times Mi) + 0.27$	$6 < Mi < 76$	$0.32 < Mo < 21.7$
	$Co = (0.11 \times Ci) + 1.87$	$1 < Ci < 330$	$1 < Co < 50$
TSS	$Mo = (0.048 \times Mi) + 4.7$	$3 < Mi < 78$	$0.9 < Mo < 6.3$
	$Co = (0.09 \times Ci) + 0.27$	$0 < Ci < 330$	$0 < Co < 60$
TN	$Mo = (0.67 \times Mi) - 18.75$	$300 < Mi < 2,400$	$200 < Mo < 1,550$
TP	$Mo = (0.58 \times Mi) - 4.09$	$25 < Mi < 320$	$20 < Mo < 200$
	$Co = (0.65 \times Ci) + 0.71$	$0.5 < Ci < 19$	$0.1 < Co < 14$

Mi and Mo are mass loads into and out of the system, respectively, in kg/ha·d (Vymazal, 1998). Ci and Co are concentrations into and out of the system, respectively, in mg/L (Brix, 1994).

6.3.3 Construction

Pre- and primary treatment is essential to prevent clogging and ensure efficient treatment. The bed should be lined with an impermeable liner (clay or geotextile) to prevent leaching. Round, evenly sized gravel (3 to 32 mm in diameter) is most commonly used to fill the bed to a depth of 0.5 to 1 m, usually using 3-4 layers of different particle size. For secondary treatment of domestic wastewater, the gravel depth is generally 0.5 to 0.7 m and the water level is kept 5 – 10 cm below the surface.

In tertiary treatment the depth of the basin itself is 1.0 to 1.5 m, of which approximately 0.60 m is filled with gravel. To limit clogging, the gravel should be clean and free of fines. SSF systems are generally constructed with a longitudinal sloped base (1%) to facilitate draining of the bed if needed. The remaining bed volume is used for water storage during high flows or storm events. Length-to-width ratios for secondary HF wetlands generally fall between 2:1 and 4:1, whereas for tertiary systems width is typically greater than the length to maximize the cross-sectional area and reduce clogging potential with the higher hydraulic rates applied.

6.3.4 Operation and Maintenance

SSF as SF systems require minimal operational and maintenance effort and should be inspected at least every month. During the first growing season, it is important to remove weeds that can compete with the planted wetland vegetation. With time, the gravel will become clogged with accumulated solids and bacterial film. The filter material at the inlet zone will require replacement every 10 or more years. Maintenance activities should also focus on ensuring that primary treatment is effective at reducing the concentration of solids in the wastewater before it enters the wetland. Maintenance should also ensure that trees do not grow in the area as the roots can harm the liner.

6.4 Vertical flow constructed wetland (VF)

6.4.1 Description

The desire to further reduce the size of constructed wetlands led to the development of vertical flow constructed wetlands. VF constructed wetland comprises a flat bed of sand/gravel topped with sand/gravel and vegetation (Figure 11). **Wastewater is fed from the top and then gradually percolates down through the bed and is collected by a drainage network at the base**. Anaerobic pretreated wastewater coming from a septic tank or biodigester is intermittedly pumped on top of the constructed wetland. By trickling down the wastewater effectively sucks air in the constructed wetland whenever the pump stops, forcing aeration of the rhizosphere. This increases the aeration capacity up to approximately twenty times, compared to horizontal subsurface flow constructed wetlands. **Due to good oxygen transfer, vertical flow wetlands have the ability to nitrify, but denitrification is limited**. In order to create a nitrification-denitrification treatment train, this technology can be combined with a FWS or SSF system.

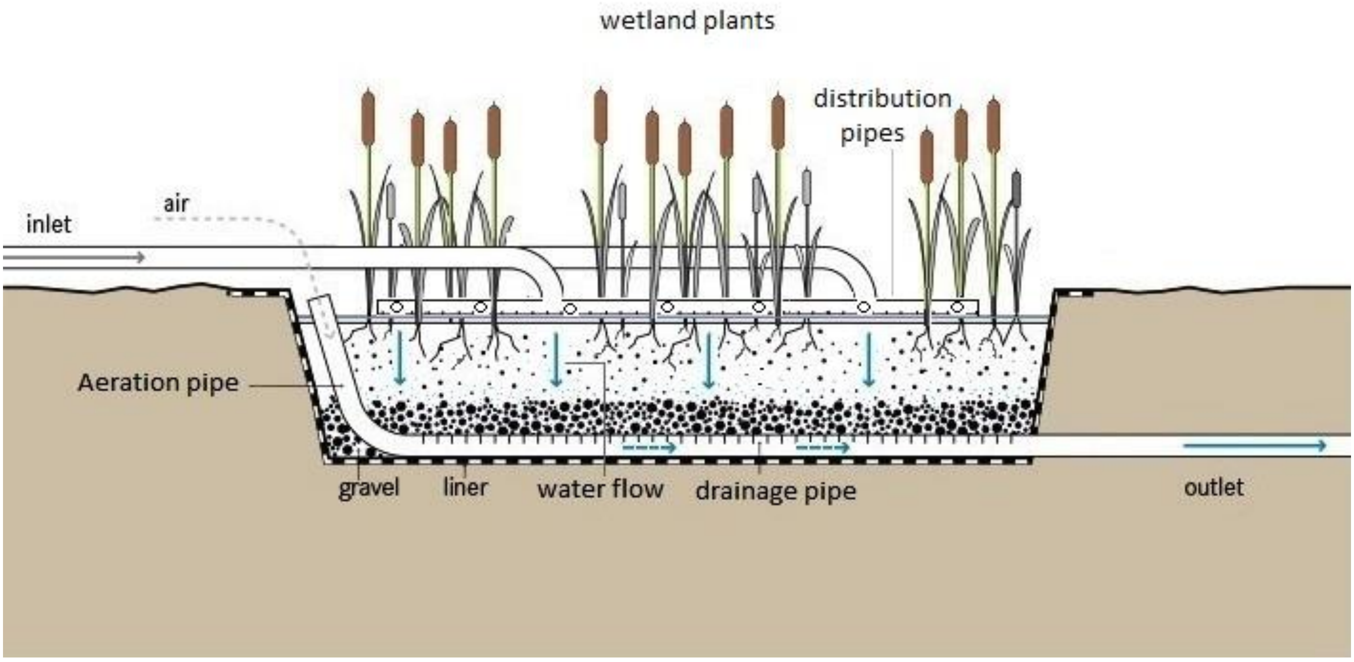

Figure 11 Schematic illustration of vertical flow constructed wetland (modified after Tilley et all. 2014).

6.4.2 Design

The vertical flow constructed wetland can be designed as a shallow excavation or as an above ground construction. **Clogging is a common problem. Therefore, the influent should be well settled in a primary treatment stage before flowing into the wetland**. The design and size of the wetland is dependent on hydraulic and organic loads. Available design guidelines for VF wetlands are based on empirical rules-of-thumb and such as those using specific surface area requirements (Brix and Johansen, 2004; DWA, 2017; ÖNORM, 2009). Based on the rule-of-thumb, a surface area of about 1 to 4 m^2 per person equivalent is required. An alternative design model for VF wetlands that is based on oxygen demand was proposed by Platzer (1999) and is based on the oxygen requirements for aerobic processes (oxidation of COD and nitrification).

The main filter material that is used, it is directly related to the treatment efficiency of a VF wetland. If fine material is used, the retention time of the wastewater in the filter is longer, often enabling higher removal efficiencies; however, the HLRs are limited, as it takes longer for water to infiltrate and the potential for clogging increases. Coarser filter material enables higher HLRs and less clogging potential, but results in lower removal efficiencies. In addition to the main filter material, a drainage layer of gravel at the bottom of the bed and an intermediate or transition layer (e.g. 10 cm gravel of 4 – 8 mm in diameter) between main and drainage layer are applied. The intermediate layer prevents grains from the filtration layer from migrating into the drainage layer. The coarse gravel in the drainage layer allows for good drainage and together with the drainage pipes, provides oxygen to the deepest layer of the bed. The design guidelines include a non-compulsory top layer of gravel (e.g. 4 – 8 mm) to prevent erosion during intermittent loading as well as to allow no free water on the surface (Dotro *et al*. 2017).

The maximum HLR should not exceed 80 L/m²d (0.08 m^3/m^2d) and the interval between loadings should be ≥ 6 hours (DWA, 2017), or between 3 and 6 hours (ÖNORM, 2009).

6.4.3 Construction

Each filter should have an impermeable liner and an effluent collection system. A ventilation pipe connected to the drainage system can contribute to aerobic conditions in the filter. Structurally, there is a layer of gravel for drainage (a minimum of 20 cm), followed by layers of sand and gravel.

The distribution pipes should have a diameter of about 40 mm with circular opening holes with a diameter of not less than 8 mm to avoid blocking of the openings with solids. Intermittent loading of the VF wetlands is achieved with a pump or, if the landscape allows and adequate slope is available, intermitted dosing can be achieved with siphons (which do not require external energy). In any case, a good distribution of the wastewater on the surface of the VF wetland must be guaranteed to utilize the whole filter volume (Dotro *et al*. 2017).

6.3.4 Operation and Maintenance

Because of the mechanical dosing system, this technology is most appropriate where trained maintenance staff, constant power supply, and spare parts are available. During the first growing season, it is important to remove weeds that can compete with the planted wetland vegetation while wetland plants should be cut every two to three years. Maintenance activities should also focus on ensuring that primary treatment is effective at reducing the concentration of solids in the wastewater before it enters the wetland. Distribution pipes should be cleaned once a year to remove sludge and biofilm that might block the holes. With time, the gravel will become clogged by accumulated solids and bacterial film. As passive remediation treatment, resting intervals may restore the hydraulic conductivity of the bed. If this does not help, active treatment using oxidizing or solubilisation agents may be applied. In worst cases destructive methods are suggested such as excavation and replacement of media (Pucher and Langergrabe, 2019).

7. SOLAR TREATMENT

7.1 Race-way pond reactor

7.1.1 Description

The photoreactors commonly used for solar applications are tubular reactors provided with compound parabolic collectors (CPCs). They efficiently collect direct and diffuse solar radiation focusing them on the tubes. CPC reactors are suitable for the treatment of wastewater containing contaminants in the hundreds of mg/L range (Belalcázar-Saldarriaga *et al*., 2018). **Nevertheless, for the application of municipal wastewater treatment and reuse, in which the elimination of pathogens and micropollutants is required, less oxidant conditions are necessary and so much shorter treatment times (few minutes) and accumulated energy are envisaged**. In such cases, there is the possibility of using reactors which collect light less efficiently, but are much cheaper than CPCs; these are the **raceway pond reactors (RPRs)** (De la Opra *et al*., 2017).

RPRs are open photoreactors which consist of open channels through which the water is moved by a paddle wheel (Figure 12). RPRs, normally used for algae cultivation under solar radiation, have arisen as an interesting and feasible scaling-up option for disinfection (Malato *et al*., 2009; Ortega-Gómez *et al*., 2014, 2016) and elimination of organic contaminants of emerging concern (CECs) (De la Obra Jiménez *et al*., 2017), i.e. pesticides, hormones, personal care products, drugs of abuse, etc., contained in MWWTPs effluents by **solar photo-Fenton process** (SPF). SPF is an advanced chemical oxidation process (AOP) that has attracted major scientific interest as a promising alternative for the degradation of CECs in wastewater. They involve chemical reactions that generate highly reactive radical species, such as the **hydroxyl radical ($^{\bullet}OH$)**. The $^{\bullet}OH$ is considered the most important free radical in chemistry and biology because of its multiple implications and applications. This radical is generated in situ in the reaction medium and acts in a nonselective oxidation way onto organic compounds. Hydroxyl radical is the second strongest oxidizing agent after fluorine. It destroys most organic and organometallic pollutants until total mineralization, i.e., conversion into CO_2, water, and inorganic ions. Moreover, hydroxyl radicals can cause the inactivation of microorganisms including enteric viruses (Nieto-Juarez *et al*., 2010), bacteria, spores and protozoa (Malato *et al*., 2009). Hydroxyl radicals inflict damage on bacteria cells through direct external membrane structure; oxidize proteins; harm the integrity of DNA molecules and disrupt several metabolic activities compromising microorganism viability, leading to bacterial inactivation (García-Fernández *et al*., 2012).

SPF accelerates the conventional Fenton process, which is based on the production of $^{\bullet}OH$ from the reaction between hydrogen peroxide (H_2O_2) and ferrous ions (Fe^{2+}) in acidic medium by Fenton reaction (7.1). Specifically, the drawback of the large accumulation of Fe($^{3+}$) species decelerating the treatment in conventional Fenton processes is avoided from the reductive solar photolysis of $[Fe(OH)]^{2+}$ according to reaction (7.2), thus regenerating the Fe^{2+} that catalyzes the Fenton's reaction (7.1) and producing additional $^{\bullet}OH$ (Brillas *et al*., 2009).

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {}^{\bullet}OH + OH^- \qquad (7.1)$$

$$[Fe(OH)]^{2+} + h\nu \rightarrow Fe^{2+} + {}^{\bullet}OH \qquad (7.2)$$

In addition, the combination of H_2O_2 and natural sunlight has been shown to be effective for the inactivation of several microorganisms in water (Ferro *et al*., 2016). The photolysis of H_2O_2 under solar radiation can produce $^{\bullet}OH$ as the result of the absorption of photons at wavelengths lower than 300 nm (equation 7.3).

$$H_2O_2 + hv \rightarrow 2^{\bullet}OH \tag{7.3}$$

In a recent work by Ndounla *et al*. (2013) it was found that H_2O_2/hv was similarly efficient to the photo-Fenton system (Fe/H_2O_2/hv) in significantly increasing the inactivation rate of enteric bacteria.

The most important parameters that play a relevant role in the optimization of RPRs are the liquid depth and iron concentration, which could be changed according to the solar radiation availability. In this sense, the number of photons in the RPR may be adjusted to improve the kinetics and treatment capacity, depending on the season, the weather conditions (sunny or cloudy) and even geographic position. Soriano-Molina *et al.* (2018) worked on the concept of the volumetric rate of photon absorption (VRPA) for kinetics of organics removal by solar photo-Fenton modified with EDDS at neutral pH and obtained that the VRPA is not directly related to treatment's capacity, but to the reaction kinetics. It was also pointed out by these authors that when working at the same VRPA conditions, the treatment capacity was considerably improved increasing the reactor's liquid depth from 5 cm to 15 cm, but keeping the same treatment time.

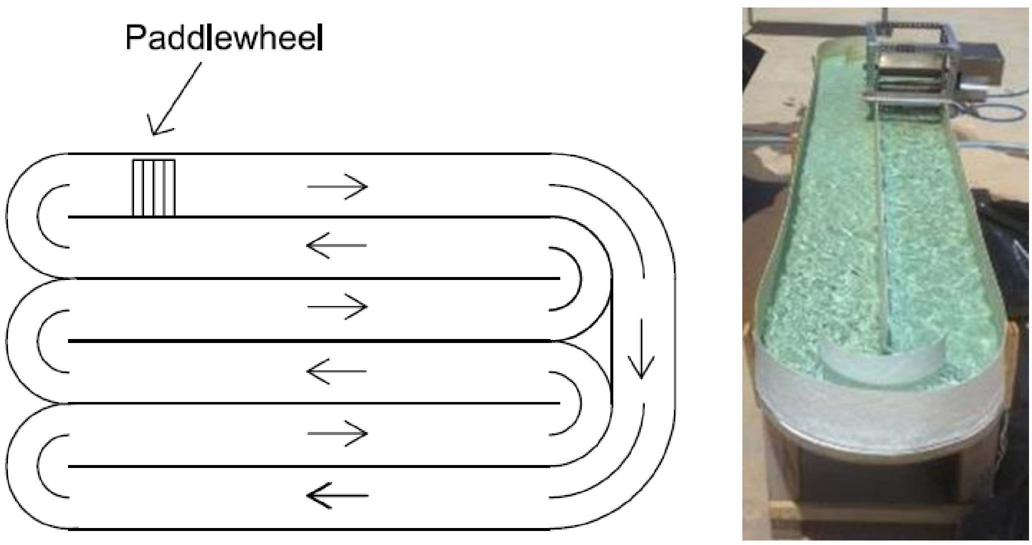

Figure 12 Schematic illustration of a typical raceway pond reactor (left). RPR picture at pilot plant scale installed at CIESOL (mixed energy research centre between Plataforma Solar de Almería (CIEMAT) and the Universidity of Almería (right) (Carra et al., 2014).

The feasibility of low cost solar reactors such as RPRs for pathogen inactivation as well as micropollutant removal has recently been reported by several scientific reports. Hydraulic residence times, liquid depth, reagents dosage and the seasonal period are the most important and limiting variables to carry out the disinfection process to operate in continuous mode (De la Obra Jiménez *et al*., 2019).

7.1.2 Design

The design of this type of solar photo-reactor as tertiary water treatment plant allows the construction and operation of a plant as simple, versatile and economical as possible, taking into account the critical parameters in the scale up of the process from a technical point of view.

The design will be based on economic and operational criteria beginning with the study of the variables involved in the considered disinfection processes, such as (Arzate *et al*., 2017):

- the annual distribution of the irradiance,
- the geographical location,
- the temperature and
- the number of solar hours,
- the evaluation of the controlling transport phenomena, especially considering the availability of radiation and the reagents mixture in the whole working volume.

The reactor design must consider also the mixing requirements, the drainage and overflow; and the cleaning aspects (Arzate *et al*., 2017). In Figure 13 details on equations to be used for RPR design are shown.

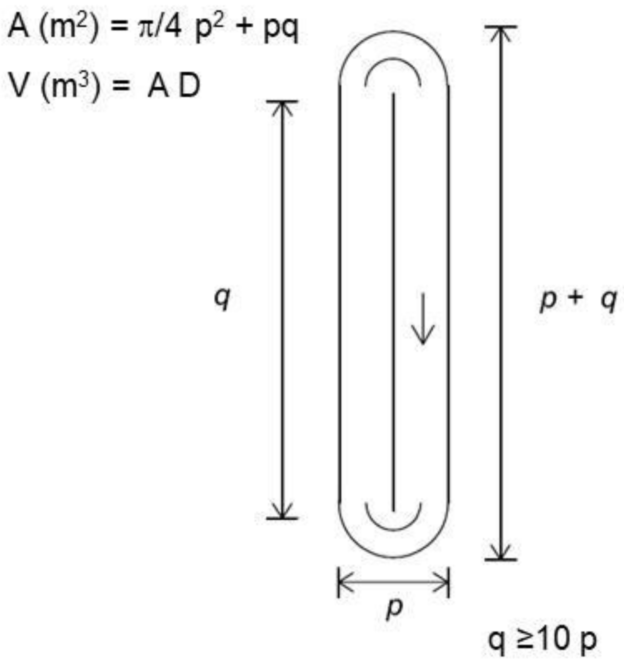

Figure 13 Details on equations to be used for RPRs design.

7.1.3 Construction

Most favorable location within the WWTP should be chosen in a way that facilitates the construction, operation and access to water from the constructed wetland. A typical RPR is equipped with paddle wheel, reactive dosing pumps, pH, temperature and UV sensors. Data acquisition and process control is normally automated via PC. The construction of the plant shall follow criteria of versatility that allow to make modifications of operation such as changes in the height of liquid, circulation speed or location of the reagent's addition points.

The photoreactor is made of concrete with block walls over compacted land and is divided and covered with a plastic ultraviolet resistant membrane (polyvinyl chloride (PVC), polyethylene, or polypropylene) to avoid seepage.

7.1.4 Operation and Maintenance

The objective is to design and implement a control strategy that allows the stable and safe operation of the plant maximizing the treatment capacity minimizing the consumption of reagents at different seasons of the year. The control loops must assure the automatic and stable operation of the plant by robust and generalizable process control systems.

In this direction the evolution of hydrogen peroxide, iron (when required), pH, temperature and irradiance should be followed. These operating parameters are tracked along the tested solar disinfection process(es) with the main objective of their optimization for meeting national/regional requirements regarding water pathogens limits for treated water reuse. In addition, microcontaminants elimination should be also monitored along the studied oxidation processes (solar/H_2O_2 and SPF).

The design of the control loops shall be based on a mathematical model (defined by on site pilot tests) aiming to automate the addition of reagents to optimize their use and ensure the obtaining of a water that meets the requirements for reuse. Additionally, the stability of the plant operation against external disturbances such as the environmental conditions and the composition of the water shall be evaluated.

The microbiological characterization and monitoring of wastewater samples should be determined to identify possible threats (i.e. human and plant pathogens) for the later reuse of treated effluents on crops irrigation. In addition, it is envisage to investigate best operating conditions for attaining not only the inactivation of pathogens but also the possible elimination of microcontaminants. Such operating parameters will be tracked through prior solar disinfection tests (solar/H2O2 and solar photo-Fenton)., towards their optimization for meeting requirements of national regulations regarding water pathogens limits for treated water reuse in crops irrigation.

It is noted that the RPR technology has been validated according to the new European proposal for urban wastewater reuse in agriculture (2018/169), which specifically includes the following microbial indicators and their corresponding Log Reduction Values (LRV):

- E. coli (≥ 5.0 LRV),
- Total coliphages/F-specific coliphages/somatic coliphages/coliphages (≥ 6.0 LRV) and
- Clostridium perfringens spores/spore-forming sulfate-reducing bacteria (≥ 5.0 LRV).

Besides, other microbial targets should include total coliforms and Salmonella spp and Legionella spp to accomplish with the limits established on different regulations (e.g. in the case of the Spanish RD 1620/2007), but also for research purposes. Microbiological concentration can be determined via classic diagnostic methods, microscopical observation and colony enumeration following standard characterization and quantification protocols.

The design and construction of the RPR plant is carried out in such way that allows an easy maintenance. In this sense the major maintenance tasks consist in the photoreactor cleaning, periodic pumps and paddle wheel revision and probes cleaning and calibration.

8. EVALUATION OF APOC PERFORMANCE

To evaluate the operational performance and success of APOC systems, Key Performance Indicators (KPIs) can be used to measure and compare performance results against the specific objectives set during the design process. For water professionals the selection of right KPIs relies on understanding what is important to a treatment project and what are the objectives that will add the most value. The goal is to provide a wastewater treatment system that creates consistent outcomes as often as possible. Unfortunately, there are no general standards in place for the wastewater industry, so it means one community may have local, regional and national standards to achieve. It can make it difficult, but measurement will improve operations.

There are a number of KPIs that can be considered. Some of the measures could be:

- Water stress index
- Days of operation at required standards
- Removal of total faecal coliforms
- Removal of Biochemical and/or Chemical Oxygen Demand
- Removal of Total Suspended Solids
- Removal of potentially dangerous organisms (i.e., E. coli, protozoa, naked amoebae, etc.)
- Compliance in quality when compared to legal standards
- Minimizing the total annualized cost (TAC)
- Maximizing the net energy recovery (NER)
- Minimizing greenhouse gas emissions (GHGs), etc.

Recently, a performance measurement tool based on a set of KPIs, financial and non-financial, was proposed by Guerrini *et al*. (2016) to improve efficiency and profitability of WWTPs from an internal and managerial perspective, with a process of **plan-do-check-act**. In Figure 14 a set of 11 KPIs, grouped in three different clusters, are proposed, similarly to Guerrini *et al*. (2016).

COST	QUALITY	EFFICIENCY
• WTEI	• R_{TSS}	• E_{TREAT}
• C_{REAG}	• R_{COD}	• NER
• C_{DISP}	• $R_{NH4\text{-}N}$	
• TAC	• R_{PATH}	

Figure 14 Proposed KPIs for assessing the performance of the APOC system.

Cost perspective

Three KPIs are related to the cost perspective and referred to direct and variable cost items. They include energy, reagents, and sludge disposal costs. In the case of energy consumption cost, the Water Treatment Energy Index (*WTEI*) proposed by the ENERWATER H2020 project (grant agreement No 649819) is considered here. The WTEI summarizes the general performance and makes results readily comparable. WTEI is based on sub-KPIs identified to account for the key pollutants removed at the different stages of the APOC process as well as the process efficiency. However, these data might not be available in the required detail or resources might be limited preventing the attainment of the WTEI. To respond to this pressure a number of scenarios is proposed (Table 21) when calculating the WTEI with the Platinum WTEI benefiting from more detailed data and consequently high levels of confidence all the way to Bronze WTEI that is based on text book information and general assumptions, and hence providing the lowest WTEI confidence values (Table 22). For calculating the individual KPIs consisting the WTEI, it is vital to gain a full understanding of all the electrical equipment responsible for energy consumption/production on the APOC. A full inventory should be created to ensure the pre-identification of the equipment with highest energy consumption, which should be monitored during the assessment but also, it will provide valuable information for the validation of the data recorded. The inventory should identify the name of the equipment, location within the WWTP, power requirement in kW and working hours. With the information collected it is possible to calculate the specific power consumption of each item of equipment according to equation 8.1.

$$E_p = PxT \tag{8.1}$$

Where E_p is the specific power consumption in kWh, P the rated power of the electrical motor in kilowatt (kW) and T is the working hours in a day (h/day). A limitation of calculating the specific power consumption using equation 8.1 is that the age of the equipment is not taken into consideration and some equipment were likely to be operating outside the best efficiency point. Hence, it is recommended that information such as age, maintenance schedule is also recorded.

The reagent cost (C_{REAG}) includes the cost of all reagents applied during the treatment by the AD and ST units of the APOC system, such as the micronutrients dosed in the AD reactor and the iron oxide species and hydrogen peroxide (H_2O_2) dosed in the solar RPR. The disposal cost (C_{DISP}) is measured for the expenditure of storing the waste biological solids (solid digestate), of further treating (thickening, dewatering) or for their transport to the field for application (as fertilizer). Costs can be calculated in reference to the volume of wastewater treated; i.e. €/m^3. An alternative measure could be the unit cost per kg of pollutants removed; i.e. €/kg COD. Both measures have their own advantages and limits. The former quantifies pure cost efficiency, but is affected by the rate of storm water that mixes with the sewage. Actually, the cost per cubic meter usually decreases when this rate increases, consequently sewer networks with higher infiltrations could appear more efficient than others with equivalent volume. The latter relates to costs of the effective output of the APOC, but could be affected by exogenous variables such as the COD concentration of the influent wastewater, which cannot be wholly controlled by the plant manager. In general the pollution concentration of the input wastewater has a negative effect on efficiency and removal rate which normally explains the higher costs incurred to remove an intense pollutant load.

Table 21 Identification of energy consumption KPIs according to treatment stage for various scenarios (ENERWATER, 2015).

WTEI scenario				
Treatment	**Platinum**	**Gold**	**Silver**	**Bronze**
Primary treatment	**kWh/kg TSS removed** Requires measurement of TSS before and after the treatment. Measurements should be taken >2/month using grab and composite samples. Data can be reported based on daily, monthly or yearly averages.	**kWh/kg TSS removed** Requires measurement of TSS before and after the treatment. Measurements should be taken at least once a month using grab or composite samples. Data can be reported based on monthly or yearly averages.	**kWh/kg TSS removed** Requires measurement of TSS before and after the treatment. Only a few measurements per year (<12/year) might be available. Data can be reported based on yearly averages.	**kWh/kg TSS removed** Text book assumptions or data from nearby sites might be used to assume a TSS removal (Table 3.3).
Secondary/Anaerobic Digestion treatment	**kWh produced/m^3 processed; kWh/kg COD removed, kWh/kg TSS removed** Requires measurement of weight or volume of wastewater in relation to the TS content. Requires measurement of COD before and after treatment. Measurements should be taken >2/ month using grab and composite samples. Data can be reported based on daily, monthly or yearly averages.	**kWh produced/m^3 processed; kWh/kg COD removed, kWh/kg TSS removed** Requires measurement of weight or volume of wastewater in relation to the TS content. Requires measurement of COD before and after treatment. Measurements should be taken at least once a month using grab or composite samples. Data can be reported based on monthly or yearly averages.	**kWh produced/m^3 processed; kWh/kg COD removed, kWh/kg TSS removed** Requires measurement of weight or volume of wastewater in relation to the TS content. Requires measurement of COD before and after treatment. Only a few measurements per year (<12/year) might be available. Data can be reported based on yearly averages	**kWh produced/m^3 processed; kWh/kg COD removed, kWh/kg TSS removed** Requires measurement of weight or volume of wastewater in relation to the TS content. Text book assumptions or data from nearby sites might be used to assume a COD removal (Table 3.3).
Tertiary/Constructed Wetland treatment	**kWh/kg TSS removed; kWh/kg NH_4-N removed; kWh/kg TN removed; kWh/kg P removed; kWh/log reduction** Requires measurement of TSS, NH_4-N, TN and PO_4-P and Log pathogen reduction before and after treatment.	**kWh/kg TSS removed; kWh/kg NH_4-N removed; kWh/kg TN removed; kWh/kg P removed; kWh/log reduction** Requires measurement of TSS, NH_4-N, TN and PO_4-P and Log pathogen reduction before and after treatment.	**kWh/kg TSS removed; kWh/kg NH_4-N removed; kWh/kg TN removed; kWh/kg P removed; kWh/log reduction** Requires measurement of TSS, NH_4-N, TN and PO_4-P and Log pathogen reduction before and after treatment.	**kWh/kg TSS removed; kWh/kg NH_4-N removed; kWh/kg TN removed; kWh/kg P removed; kWh/log reduction** Text book assumptions or data from nearby sites might be used to assume

WTEI scenario				
	Measurements should be taken >2/ month using grab and composite samples. Data can be reported based on daily, monthly or yearly averages.	Measurements should be taken at least once a month using grab or composite samples. Data can be reported based on monthly or yearly averages.	Only a few measurements per year (<12/year) might be available. Data can be reported based on yearly averages.	a TSS, COD, NH4-N, TN, PO4-P and Log pathogen removal (Table 3.3).
Post/Solar treatment	**kWh/log reduction** Requires measurement of Log pathogen reduction before and after treatment. Measurements should be taken >2/ month using grab and composite samples. Data can be reported based on daily, monthly or yearly averages.	**kWh/log reduction** Requires measurement of Log pathogen reduction before and after treatment. Measurements should be taken at least once a month using grab or composite samples. Data can be reported based on monthly or yearly averages.	**kWh/log reduction** Requires measurement of Log pathogen reduction before and after treatment. Only a few measurements per year (<12/year) might be available. Data can be reported based on yearly averages.	**kWh/log reduction** Text book assumptions to assume a Log pathogen removal (Table 3.3).
Auxiliaries	**kWh/m^2 office or kWh/number of persons on site or kWh/m^2 site foot print** Based on measured data on site.	**kWh/m^2 office or kWh/number of persons on site or kWh/m^2 site foot print** Based on measured data on site.	**kWh/m^2 office or kWh/number of persons on site or kWh/m^2 site foot print** Based on measured data on site or information from nearby site.	**kWh/m^2 office or kWh/number of persons on site or kWh/m^2 site foot print** Text book assumptions or data from nearby sites (Table 3.3).

Table 22 Key assumptions for Bronze WTEI; data based on ENERWATER (2015) and literature.

Treatment	Target
Primary treatment	kWh/kg TSS removed: 60% solids removal
Secondary/Anaerobic Digestion treatment	kWh produced/m^3 processed: 0.03-0.05 kWh/kg COD removed: 80% COD removal kWh/kg TSS removed: 90% solids removal
Tertiary/Constructed Wetland treatment	kWh/kg TSS removed: 100% solids removal kWh/kg NH_4-N removed: 95% NH4-N removal kWh/kg TN removed: 90% TN removal kWh/kg P removed: 90% TP removal kWh/log reduction: log 2
Post/Solar treatment	kWh/log reduction: log 4
Auxiliaries	Assume 1.9 kWh/m^2 of office space Assume 0.01 kWh/m^2 site foot print

The Total Annualized Cost (TAC), which includes both capital and operating cost, can be calculated according to the following equations.

$$TAC = \frac{OPEX}{Q_{in}} + \frac{CAPEX}{nxQ_{in}} \quad (8.2)$$

$$OPEX = Electricity + C_{REAG} + C_{DISP} \quad (8.3)$$

where TAC is in €/m^3/year, Q_{in} is the annual volumetric flow rate of the wastewater (m^3/year) and n is the plant life cycle.

The CAPEX mainly considers equipment and construction cost, while the OPEX includes electricity cost, reagents cost and solids digestate disposal cost.

<u>Quality perspective</u>

The quality perspective includes four KPIs measuring the removal rate of four pollutants: total suspended solids (TSS), COD, NH_4-N, and Log pathogen reduction. The suspended solids and the COD are two classic indices of pollution. The ammonium nitrogen removal rate (R_{NH4-N}) is included since toxic ammonium ions can form in the AD process as a reduction product of the microbially mediated biochemical breakdown of proteins or non-protein nitrogenous compounds. The removal of pathogens (R_{PATH}) is a must of all reuse projects and therefore its measurement should be pursued on a frequent basis (monthly). The four indicators can be estimated using the following equation (Guerrini et al., 2016):

$$R\ (TSS, COD, NH_4 - N, PATH) = \frac{RR_{act}}{RR_{exp}} \tag{8.4}$$

where R_{TSS}, R_{COD}, $R_{NH4\text{-}N}$, R_{PATH} are the quality indexes for the removal of TSS, COD, NH_4-N and Log pathogens, respectively; RR_{exp} is the expected removal rate, estimated as the average removal rate recorded in the previous years; and RR_{act} is the actual removal rate measured in the current period. This method of computation assigns a score that increases with higher removal rate.

Efficiency perspective

A similar score is estimated when technical efficiency is measured. The efficiency of treatment (E_{TREAT}) quantifies the capability of the APOC plant to reduce (%) the amount of the pathogens (i.e. total faecal coliforms) (E_{PATH}), the removal of BOD (E_{BOD}), and COD (E_{COD}), the removal of TSS (E_{TSS}), the removal of ammonium ($E_{NH4\text{-}N}$) and the removal of potentially dangerous micropollutants (i.e. synthetic organic chemicals) or organisms (i.e., E. coli, protozoa, naked amoebae, etc.) (E_{DANG}). The global score of efficiency can be calculated using a weighted average of the scores estimated for the aforementioned six types of pollutants. The weights should be chosen by the plant operators, considering their relative importance in the process of the treatment and the compliance in quality when compared to legal standards (for reuse or safe discharge). These weights range between 0 to 1. If equal weights are assigned then $w_1= w_2=w_3=w_4=w_5=w_6=0.166$.

$$E_{TREAT} = w_1 x E_{PATH} + w_2 x E_{BOD} + w_3 x E_{COD} + w_4 x E_{TSS} + w_5 x E_{NH4\text{-}N} + w_6 x E_{DANG} \tag{8.5}$$

The Net Energy Recovery (NER) is both a KPI and a key objective function of every APOC system. To calculate NER, first, plant-wide energy consumption (EC) and production should be estimated using equations 8.6 and 8.7. The EC includes mainly mixing and heating energy for the AD and miscellaneous (pretreatment, pumping, paddle wheel).

$$\text{EC} = \text{Mixing energy} + \text{Heating energy} + \text{Miscellaneous} \tag{8.6}$$

Likewise, the energy production (EP) is calculated from the heat and electricity produced from the AD unit, which is the only energy-producing source in the APOC system. In the real plant, the biogas producing from the AD is further purified and converted to electricity and heat by using combined heat and power (CHP) engine. Heat and electricity conversion factors are necessary to calculate heat and electricity production from methane gas mass flow, as indicated in equation 8.7.

$$EP = m_{methane}\ x\ \phi_{heat} + m_{methane}\ x\ \phi_{electricity} \tag{8.7}$$

$$NER = EP - EC \tag{8.8}$$

where $m_{methane}$ is the mass flow rate of methane gas (kg CH_4/d), ϕ_{heat} is the heat conversion factor, and $\phi_{electricity}$ is the electricity conversion factor. All form of energy production have MWh/d unit. In Table 23 typical conversion factors for heat and electricity from methane gas mass flow rate are presented for two Danish sludge digestion plants (Avedøre and Lynetten).

Table 23 Conversion factors for heat and electricity from methane gas mass flow rate (BIOFOS Årsberetning 2017).

Plant	Φ_{heat}	$\Phi_{electricity}$
Avedøre	6.44	5.06
Lynetten	17.0	0.0

It is noted that establishing indicators standards is only the first step in implementing a process. Policies and procedures are required to ensure that the measurement is consistent and meets standards. There needs to be a plan in place with a roadmap on how to achieve the targets or KPIs are meaningless. KPIs are not static and unchanging. There may be times when even the best planned processes need work. Having a Plan B is not a plan for failure but is a realistic consideration and can be used to bring an affected system back into compliance.

9. APOC PILOT STUDIES: PRACTICAL EXPERIENCES

This Chapter will summarize the practical experiences and lessons learned from the operation of the three APOC pilot plant units in Spain, Tunisia and Lebanon. All plants will be designed for a treatment capacity of 5 m^3/d, each, considering the influent characteristics and the special climatic conditions in each demo area.

The establishment/construction/installation of the three demo plants will be carried out during the second year of project implementation (from September 2020-April 2021) after the foreseen preparatory actions; i.e. development of tender specifications, obtaining necessary permits for construction and operation, tender procedures for the establishment of the systems.

All APOC pilot systems will be demonstrated with real municipal effluents, in an operational environment, with the aim to:

- ensure the technology designated is effective;
- assess the operating performance of each system;
- determine the optimum operating parameters to be recommended for full-scale systems;
- report problems and O&M issues and find solutions;
- evaluate the economic feasibility of APOC systems by performing a cost-benefit analysis as compared to conventional wastewater treatment systems.

Environmental monitoring activities will be carried out in the three demo sites for 12 months, in terms of treatment and reuse efficiency: consistent monitoring of physicochemical and biological parameters of wastewater under treatment along with the analytical record of system operational requirements and carbon footprint. Moreover, in the reuse areas, soil quality eco-toxicity will be assessed along with the improvement of water footprint.

10. REFERENCES

Abdelgadir, A., Chen, X., Liu, J., Xie, X., Zhang, J., Zhang, K., Wang, H., Li, N. (2014) Characteristics, process parameters, and inner components of anaerobic bioreactors, *BioMed Research International*, 2014, 1–10.

Akil, K., Jayanthi, S. (2012) Anaerobic sequencing batch reactors and its influencing factors: an overview, *Journal of Environmental Science & Engineering*, 54(2), 317–322.

Andalib, M., Elsayed, E., Nizar, M., Hisham, H., George, N., Jesse, Z. (2014) Performance of an anaerobic fluidized bed bioreactor (AnFBR) for digestion of primary municipal wastewater treatment biosolids and bioethanol thin stillage, *Renewable Energy*, 71, 276–285.

Anderson, J. (2003) The environmental benefits of water recycling and reuse, *Water Supply*, 3(4), 1-10.

Aqaneghad, M., Moussavi, G. (2016) Electrochemically enhancement of the anaerobic baffled reactor performance as an appropriate technology for treatment of municipal wastewater in developing countries, *Sustainable Environment Research*, 26(5), 203–208.

Arif, S., Liaquat, R., Adil, M. (2018) Applications of materials as additives in anaerobic digestion technology, *Renewable and Sustainable Energy Reviews*, 97, 354–366.

Arvanitoyannis, S. I., Kassaveti, A., Ladas, D. (2008) Food waste treatment methodologies, *Food Science and Technology*, 345-410.

Arzate, S., García Sánchez, J. L., Soriano-Molina, P., Casas López, J. L., Campos-Mañas, M. C., Agüera, A., Sánchez Pérez, J. A. (2017) Effect of residence time on micropollutant removal in WWTP secondary effluents by continuous solar photo-fenton process in raceway pond reactors, *Chemical Engineering Journal*, 316, 1114–1121.

Aziz, A., Basheer, F., Sengar, A., Irfanullah, Khan, S. U., Farooqi, I. H. (2019) Biological wastewater treatment (anaerobic-aerobic) technologies for safe discharge of treated slaughterhouse and meat processing wastewater, *Science of the Total Environment*, 686, 681–708.

Bachmann, A., Beard, V. L., McCarty, P. L. (1985) Performance characteristics of the anaerobic baffled reactor, *Water Research*, 19(1), 99–106.

Bajpai, P. (2017) Process parameters affecting anaerobic digestion, *Anaerobic Technology in Pulp and Paper Industry*, 13–27.

Balaguer, M. D., Vicent, M. T., Parfs, J. M. (1997) A comparison of different support materials in anaerobic fluidized bed reactors for the treatment of vinasse, *Environmental Technology*, 18(5), 539–544.

Barber, W. P., Stuckey, D. C. (1999) The use of the anaerobic buffled reactor (ABR) for wastewater treatment: A review, *Water Research*, 33(7), 1559-1578.

Barbosa, R. A., Sant' Anna, G. L. (1989) Treatment of raw domestic sewage in an UASB reactor, *Water Research*, 23(12), 1483–1490.

Basile, A., Gallucci, F. (2009) Guest editorial: membrane reactors part I, *Asia-Pacific Journal of Chemical Engineering*, 4(3), 237-238.

Belalcázar-Saldarriaga, A., Prato-García, D., Vasquez-Medrano, R. (2018) Photo-fenton processes in raceway reactors: technical, economic, and environmental implications during treatment of colored wastewaters, *Journal of Cleaner Production,* 182, 818–829.

Bello, M. M., Abdul Raman, A. A., Purushothaman, M. (2017) Applications of fluidized bed reactors in wastewater treatment – a review of the major design and operational parameters, *Journal of Cleaner Production*, 141, 1492–1514.

Bhattacharya, J., Dev, S., Das, B. (2018) Microbial treatment of industrial wastewater, low cost wastewater bioremediation technology

BIOFOS (2017) Available at https://biofos.dk/wwwroot/media/1161/2017_biofos_aarsberetning.pdf.

Bixio, D., Wintgens, T. (2006) Water reuse system management manual AQUAREC, *Directorate-General for Research*, European Commission, Brussels, Belgium.

Bobade, V., Lomte, A. T. (2015) Challenges in UASB reactor system design : a review, *Asia Pacific Confederation of Chemical Engineering Congress 2015: APCChE 2015, incorporating CHEMECA 2015*, 318-325.

Bodík, I., Herdová, B., Drtil, M. (2002) The use of upflow anaerobic filter and AnSBR for wastewater treatment at ambient temperature, *Water Research*, 36(4), 1084–1088.

Bodík, I., Herdová, B., Kratochvíl, K. (2000) The application of anaerobic filter for municipal wastewater treatment, *Chemical Papers*, 54(3), 159–164.

Bodkhe, S. (2008) Development of an improved anaerobic filter for municipal wastewater treatment, *Bioresource Technology*, 99(1), 222–226.

Brillas, E., Sirés, I., Oturan, M. A (2009) Electro-fenton process and related electrochemical technologies based on fenton's reaction chemistry, *Chemical Reviews*, 109, 6570-6631.

Brix, H., Kadlec, R. H., Knight, R. L., Vymazal, J., Cooper, P., Haberl, R. (2000) Constructed wetlands for pollution control: processes, performance, design and operation. Scientific and Technical Report No. 8, *IWA Publishing*, London.

Brix, H., Johansen, N. H. (2004) Guidelines for the establishment of reed bed systems up to 30 PE (in Danish: Retningslinier for etablering af beplantede filteranlæg op til 30 PE), Århus, Denmark.

Burghate, S. P., Ingole, N. W. (2013) Fluidized bed biofilm reactor – a novel wastewater treatment reactor, *International Journal of Research in Environmental Science and Technology*, 3(4), 145–155.

Cakir, F. Y., Stenstrom, M. K. (2003) A dynamic model for anaerobic filter, *Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering*, 38(10), 2069–2076.

Castro-Barros, C. M. (2013) Guideline for granular sludge reactor design, *SANITAS Tech. Reports Ser. Model*, 1–18.

Chen, S. J., Li, C. T., Shieh, W. K. (1985) Performance evaluation of the anaerobic fluidised bed system: II. biomass holdup and characteristics, *Journal of Chemical Technology and Biotechnology. Biotechnology*, 35, 183-190.

Chen, S. J., Li, C. T., Shieh, W. K. (1988) Anaerobic fluidized bed treatment of an industrial wastewater, *Journal of Water Pollution Control Federation*, 60 (10), 1826-1832.

Chernicharo, C. A. L., Van Lier, J. B., Noyola, A., Ribeiro, T. B. (2015) Anaerobic sewage treatment in Latin America, *Anaerobic Biotechnology*, 263-296.

Chernicharo, C. A. L., Van Lier, J. B., Noyola, A., Ribeiro, T. B. (2015) Anaerobic sewage treatment: state of the art, constraints and challenges, *Reviews in Environmental Science and Bio/Technology*, 14(4), 649–679.

Christensen, D. R., Gerick, J. A., Eblen, J. E. (1984) Design and operation of anaerobic blanket sludge upflow reactor, *Water Pollution Control Federation*, Vol. 56, 1059–1062.

Daud, M. K., Rizvi, H., Akram, M. F., Ali, S., Rizwan, M., Nafees, M., Jin, Z. S. (2018) Review of upflow anaerobic sludge blanket reactor technology: effect of different parameters and developments for domestic wastewater treatment, *Journal of Chemistry 2018 (3, article 10)*, 1–13.

Silva, C. E. D. F., Gois, G. N. S. B., Abud, A. K. S., Amorim, N. C. S., Girotto, F., Markou, G., Carvalho, C. M., Tonholo, J., Amorim, E. L. (2019) Anaerobic digestion: biogas production from agro-industrial wastewater, Food Waste, and Biomass, *Plant Long Non-Coding RNAs*, 431-470.

De la Obra, I., Ponce-Robles, L., Miralles-Cuevas, S., Oller, I., Malato, S., Sánchez Pérez, J. A. (2017) Microcontaminant removal in secondary effluents by solar photo-Fenton at circumneutral pH in raceway pond reactors, *Catalysis Today*, 287, 10–14.

De la Obra, I., Esteban García, B., Rivas Ibáñez, G., Casas López, J. L., Sánchez Pérez, J. A. (2019) Continuous flow disinfection of WWTP secondary effluents by solar photo-Fenton at neutral pH in raceway pond reactors at pilot plant scale, *Applied Catalysis B: Environmental*, 247, 115–123.

Di Berardino, S. E. (2019) Production of biogas/bioSNG from anaerobic pretreatment of milk-processing wastewater, *Substitute Natural Gas from Waste*, 397–424.

Dotro, G., Langergraber, G., Molle, P., J. Nivala, J., Juárez, J. P., Stein, O. R., von Sperling, M. (2017) Treatment wetlands, Biological wastewater treatment series Vol. 7., *IWA Publishing*, London.

Düppenbecker, B., Cornel, P. (2016) Anaerobic treatment of sulfate-containing municipal wastewater with a fluidized bed reactor at 20^{o}C, *Water Science and Technology*, 73(10), 2446–2452.

Dutta, A., Sarkar, S. (2015) Sequencing batch reactor for wastewater treatment: recent advances, *Current Pollution Reports*, 1(3), 177–190.

DWA-A-262E. (2017) Principles for dimensioning, construction and operation of wastewater treatment plants with planted and unplanted filters for treatment of domestic and municipal wastewater, German Association for water, Wastewater and Waste: Hennet, Germany, 2017.

Elmaleh, S., Grasmick A., Guitonas, A. (1984) Epuration par cellules anaerobies immobilisées sur un support fluidisé, *37th Int. Conf. Cebedeau*, Liege (Belgium).

ENERWATER (2015) Standard method and online tool for assessing and improving the energy efficiency of waste water treatment plants, D 3.1: identification of key parameters and key performance indicators (KPIs) and ENERWATER methodology (draft 0), available at http://www.enerwater.eu/wp-content/uploads/2015/10/ENERWATER-D3.1-ENERWATER-Methodology-v0.pdf.

Fernandes, H., Jungles, M. K., Hoffmann, H., Antonio, R. V., Costa, R. H. R. (2013) Full-scale sequencing batch reactor (SBR) for domestic wastewater: performance and diversity of microbial communities, *Bioresource Technology*, 132, 262–268.

Ferro, G., Guarino, F., Castiglione, S., Rizzo, L. (2016) Antibiotic resistance spread potential in urban wastewater effluents disinfected by UV/H_2O_2 process, *Science of The Total Environment*, 560-561, 29–35.

Foxon, K., Buckley, C. (2006) Guidelines for the implementation of anaerobic baffled reactors for on-site or decentralised sanitation, *Proceedings: WISA Conference*, (1), 1–12.

Franke-Whittle, I. H., Walter, A., Ebner, C., Insam, H. (2014) Investigation into the effect of high concentrations of volatile fatty acids in anaerobic digestion on methanogenic communities, *Waste Management*, 34(11), 2080–2089.

Frankin, R. J. (2001) Full-scale experiences with anaerobic treatment of industrial wastewater, *Water Science and Technology*, 44(8), 1–6.

Gao, D., Hu, Q., Yao, C., Ren, N., Wu, W. (2014) Integrated anaerobic fluidized-bed membrane bioreactor for domestic wastewater treatment, *Chemical Engineering Journal*, 240, 362–368.

García-Fernández, I., Polo-López, M. I., Oller, I., Fernández-Ibáñez, P. (2012) Bacteria and fungi inactivation using Fe^{3+}/sunlight, H_2O_2/sunlight and near neutral photo-Fenton: A comparative study, *Applied Catalysis B: Environmental*, 121-122, 20–29.

Gopala Krishna, G. V. T., Kumar, P., Kumar, P. (2008) Treatment of low strength complex wastewater using an anaerobic baffled reactor (ABR), *Bioresource Technology*, 99(17), 8193–8200.

Guerrini, A., Romano, G., Ferretti, S., Fibbi, D., Daddi, D. (2016) A performance measurement tool leading wastewater treatment plants toward economic efficiency and sustainability, *Sustainability*, 8(12), 1–14.

Gupta, S. K., Ramakrishnan, A., Hung, Y. T. (2012) Sequencing batch reactors, *Handbook of Environment and Waste Management*, 511–562.

Gürtekin, E. (2014) Sequencing batch reactor, *Faculty of Engineering, Department of Environmental Engineering Firat University, Turkey*, 472–480.

Hamza, R. A., Iorhemen, O. T., Tay, J. H. (2016) Advances in biological systems for the treatment of high-strength wastewater, *Journal of Water Process Engineering*, 10, 128–142.

Heijnen, J. J., Mulder, A., Enger, W., Hoeks, F. (1989) Review on the application of anaerobic fluidized bed reactors in waste-water treatment, *Chemical Engineering Journal*, 41(3), 37–50.

Henry, J. G., Prasad, D., Young, H. (1987) Removal of organics from leachates by anaerobic filter, *Water Research*, 21(11), 1395–1399.

Huo, C. X. (2005) SBR performance with an excessive long sludge age, *Environmental Technology*, 26(2), 199–210.

Igoni, A. H., Ayotamuno, M. J., Eze, C. L., Ogaji, S. O. T., Probert, S. D. (2008) Designs of anaerobic digesters for producing biogas from municipal solid-waste, *Applied Energy*, 85(6), 430–438.

Irvine, R. L., Ketchum, L. H. (1989) Sequencing batch reactors for biological wastewater treatment, *Critical Reviews in Environmental Control*, 18(4), 255–294.

Jain, S., Jain, S., Wolf, I. T., Lee, J., Tong, Y. W. (2015) A comprehensive review on operating parameters and different pretreatment methodologies for anaerobic digestion of municipal solid waste, *Renewable and Sustainable Energy Reviews*, 52, 142–154.

Kadlec, R. H., Knight, R. L. (1996) Treatment wetlands, First Edition. *CRC Press*, Boca Raton, Florida.

Kadlec R. H. and S. D. Wallace. (2009) Treatment wetlands, Second Edition. *CRC Press*, Boca Raton, Florida.

Kangle, K. M., Kore, S. V., Kore, V. S., Kulkarni, G. S. (2012) Recent trends in anaerobic codigestion : a review, *Universal journal of environmental research and technology*, 2(4), 210–219.

Khalil, N., Mittal, A. K., Raghav, A. K., Rajeev, S. (2006) UASB technology for sewage treatment in India: 20 Years Experience, *Environmental Engineering and Management Journal*, 5(5), 1059–1069.

Khanal, S. K., Giri, B., Nitayavardhana, S., Gadhamshetty, V. (2017) Anaerobic bioreactors/digesters: design and development, *Current Developments in Biotechnology and Bioengineering: Biological Treatment of Industrial Effluents*, 261–279.

Kirschenman, T. L., Hameed, S. (2000) A regulatory guide to sequencing batch reactors, 2nd International Symposium on Sequencing Batch Reactor Technology, 1–9.

Kiyasudeen, K., Ibrahim, M. H., Quaik, S., Ismail, S. A. (2016) Prospects of organic waste management and the significance of earthworms, *Applied Environmental Science and Engineering for a Sustainable Future*, 23–44.

Kornaros, M., Marazioti, C., Lyberatos, G. (2008) A pilot scale study of a sequencing batch reactor treating municipal wastewater operated via the UP-PND process, *Water Science & Technology*, 435–439.

Krishna, D., Kalamdhad, A. S. (2014) Pre-treatment and anaerobic digestion of food waste for high rate methane production - A review, *Journal of Environmental Chemical Engineering*, 2(3), 1821–1830.

Krishna, G. V. T. G., Pradeep, K. (2009) Treatment of low-strength soluble wastewater using an anaerobic baffled reactor (ABR), *Journal of Environmental Management*, 90(1), 166–176.

Ladu, J. L. C., Xi-wu, L., Zhaoping, Z. (2017) Experimentation on the anaerobic filter reactor for biogas production using rural domestic wastewater*, IOP Conference Series: Earth and Environmental Science*, 81(1), 012099.

Lee, K. T., Ofori-Boateng, C. (2013) Sustainability of biofuel production from oil palm biomass, *Green Energy and Technology*, Springer Press.

León-Becerril, E., García-Camacho, J. E., Del Real-Olvera, J., López-López, A. (2016) Performance of an upflow anaerobic filter in the treatment of cold meat industry wastewater, *Process Safety and Environmental Protection*, 102, 385–391.

Lettinga, G., van Velsen, A. F. M., Hobma, S. W., de Zeeuw, W., Klapwijk, A. (1980) Use of the upflow sludge blanket (USB) reactor concept for biological wastewater treatment, especially for anaerobic treatment, *Biotechnology and bioengineering*, 22, 699–734.

Lettinga, O., Pol, L. W. H. (1991) UASB-process design for various types of wastewaters, *Water Science and Technology*, 24(8), 87-107.

Leung, D. Y. C., Wang, J. (2016) An overview on biogas generation from anaerobic digestion of food waste, *International Journal of Green Energy*, 13(2), 119–131.

Licciardello, F., Milani, M., Consoli, S., Pappalardo, N., Barbagallo, S., Cirelli, G. (2018). Wastewater tertiary treatment options to match reuse standards in agriculture. *Agricultural Water Management*, 210, 232–242.

Lin, K. C., Yang, Z. (1991) Technical review on the uasb process, *International Journal of Environmental Studies*, 39(3), 203–222.

Liu, J., Yuan, Y., Li, B., Zhang, Q., Wu, L., Li, X., Peng, Y. (2017) Enhanced nitrogen and phosphorus removal from municipal wastewater in an anaerobic-aerobic-anoxic sequencing batch reactor with sludge fermentation products as carbon source, *Bioresource technology*, 244, 1158–1165.

Mahatyanta, A., Razif, M. (2016) Alternative design of wastewater treatment plant with anaerobic baffled reactor and anaerobic filter for romokalisari flats surabaya, *International Journal of ChemTech Research*, 9(11), 195–200.

Mahvi, A. H. (2008) Sequencing batch reactor: a promising technology in wastewater treatment, *Iranian Journal of Environmental Health Science and Engineering*, 5(2), 79–90.

Malato, S., Fernández-Ibáñez, P., Maldonado, M.I., Blanco, J., Gernjak, W. (2009) Decontamination and disinfection of water by solar photocatalysis: Recent overview and trends, *Catalysis Today*, 147, 1-59.

Manariotis, I. D., Grigoropoulos, S. G. (2002) Low-strength wastewater treatment using an anaerobic baffled reactor, *Water Environment Research*, 74(2), 170–176.

Manariotis, I. D., Grigoropoulos, S. G. (2006) Municipal wastewater treatment using upflow-anaerobic filters, *Water Environment Research*, 78(3), 233–242.

Manariotis, I. D., Grigoropoulos, S. G. (2008) Restart of anaerobic filters treating low-strength wastewater, *Bioresource Technology*, 99(9), 3579–3589.

Manariotis, I., Grigoropoulos, S. G. (2013) Anaerobic filter treatment of municipal wastewater: biosolids behavior, *Journal of Environmental Engineering*, 132(1), 23–31.

Mao, C., Feng, Y., Wang X., Ren, G. (2015) Review on research achievements of biogas from anaerobic digestion, *Renewable and Sustainable Energy Reviews*, 45, 540–555.

Marín, P., Alkalay, D., Guerrero, L., Chamy, R., Schiappacasse, M. C. (1999) Design and startup of an anaerobic fluidized bed reactor, *Water Science and Technology*, 40(8), 63–70.

Meegoda, J. N., Li, B., Patel, K., Wang, L. B. (2018) A review of the processes, parameters, and optimization of anaerobic digestion, *International Journal of Environmental Research and Public Health*, 15(10), 1–16.

Moradgholi, M., Massoudinejad, M., Aghayani, E., Yazdanbakhsh, A. (2019) Performance of electrical stimulated anaerobic baffled reactor for removal of typical pollutants from low-strength municipal wastewater at low temperatures, *Environmental Health Engineering and Management*, 6(2), 121–128.

Ndon, U. J., Dague, R. R. (1997) Effects of temperature and hydraulic retention time on anaerobic sequencing batch reactor treatment of low-strength wastewater, *Water Research*, 31(10), 2455–2466.

Ndounla, J., Spuhler, D., Kenfack, S., Wéthé, J., Pulgarin, C. (2013) Inactivation by solar photo-Fenton in pet bottles of wild enteric bacteria of natural well water: Absence of re-growth after one week of subsequent storage, *Applied Catalysis B: Environmental*, 129, 309–317.

Nguyen, D., Nitayavardhana, S., Sawatdeenarunat, C., Surendra, K.C., Khanal, S. K. (2019) Biogas production by anaerobic digestion: status and perspectives, *Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels (Second Edition)*, 763-778.

Nicolella, C. M., van Loosdrecht, C. M., Heijnen, S. J. (2000) Particle-based biofilm reactor technology, *Trends in Biotechnology*, 18 (7), 312-320.

Nieto-Juarez, J. I., Pierzchła, K., Sienkiewicz, A., Kohn, T. (2010) Inactivation of MS2 coliphage in Fenton and Fenton-like systems: role of transition metals, hydrogen peroxide and sunlight. *Environmental Science & Technology*, 44(9), 3351–3356.

Ohimain, E. I., Izah, S. C. (2017) A review of biogas production from palm oil mill effluents using different configurations of bioreactors, *Renewable and Sustainable Energy Reviews*, 70, 242–253.

Omil, F., Garrido, J. M., Arrojo, B., Méndez, R. (2003) Anaerobic filter reactor performance for the treatment of complex dairy wastewater at industrial scale, *Water Research*, 37(17), 4099–4108.

Ong, Y. H., Chua, A. S. M., Ngoh, G. C. (2010) Establishment of enhanced biological phosphorus removal in a sequencing batch reactor by using seed sludge from a conventional activated sludge wastewater treatment process, *Journal of Applied Sciences*, 10(21), 2643–2647.

ÖNORM B 2505 (2009) Bepflanzte Bodenfilter (Pflanzenkläranlagen) – Anwendung, Bemessung, Bau und Betrieb (Subsurface-flow constructed wetlands – Application, dimensioning, installation and operation), Österreichisches Normungsinstitut, Vienna, Austria [in German].

Ortega-Gómez, E., Ballesteros Martín, M. M., Esteban García, B., Sánchez Pérez, J. A., & Fernández Ibáñez, P. (2014). Solar photo-Fenton for water disinfection: An investigation of the competitive role of model organic matter for oxidative species, *Applied Catalysis B: Environmental*, 148-149, 484–489.

Ortega-Gómez, E., Martín, M. M. B., García, B. E., Pérez, J. A. S., & Ibáñez, P. F. (2016). Wastewater disinfection by neutral pH photo-Fenton: The role of solar radiation intensity, *Applied Catalysis B: Environmental*, 181, 1–6.

Ozgun, H., Dereli, R. K., Ersahin, M. E., Kinaci, C., Spanjers, H., van Lier, J. B. (2013) A review of anaerobic membrane bioreactors for municipal wastewater treatment: integration options, limitations and expectations, *Separation and Purification Technology*, 118, 89–104.

Ozturk, I. (2007) Anaerobic treatment and applications, Water Foundation Press, ISBN, 978-975-6455-30-2, Istanbul Technical University, Istanbul, Turkey (In Turkish).

Pandey, N., Dubey, S. K. (2014) Up-flow Anaerobic Sludge Bed (UASB) based sewage treatment plant (STP) at Mirzapur : a review, *International Research Journal of Environment Sciences*, 3, 67–71.

Pastor, R., Benqlilou, C., Paz, D., Cardenas, G., Espuna, A., Puigjaner, L. (2003) Design optimization of constructed wetlands for wastewater treatment, *Resources, Conservation and Recycling*, 37, 193-204.

Patel, A., Zhu, J. and Nakhla, G. (2006) Simultaneous carbon, nitrogen and phosphorous removal from municipal wastewater in a circulating fluidized bed bioreactor, *Chemosphere*, 65, 1103–1112.

Platzer, C. (1999) Design recommendations for subsurface flow constructed wetlands for nitrification and denitrification, *Water Science and Technology*, 40(3), 257-264.

Poltak, R. F. (2005) Sequencing Batch Reactor: Design and operational considerations manual, *New England Interstate Water Pollution Control Commission: Massachusetts, USA*, 1–27.

Pramanik, S. K., Suja, F. B., Zain, S. M., Pramanik, B. K. (2019) The anaerobic digestion process of biogas production from food waste: prospects and constraints, *Bioresource Technology Reports 8*, 1–15.

Przywara, L., Mrowiec, B., Suschka, J. (2001) Municipal sewage treatment in upflow anaerobic filter, 89–98.

Pucher, B., Langergrabe, G. (2019) The state of the art of clogging in vertical flow wetlands, *Water*, 11, 2400.

Rahman, M. A., Saha, C. K., Feng, L., Møller, H. B., Alam, M. M. (2019) Anaerobic digestion of agro-industrial wastes of Bangladesh: influence of total solids content, *Engineering in Agriculture, Environment and Food*, 12(4), 484-493.

Reynaud, N., Buckley, C. A. (2016) The anaerobic baffled reactor (ABR) treating communal wastewater under mesophilic conditions: a review, *Water Science and Technology*, 73(3), 463–478.

Rizvi, H., Ali, S., Yasar, A., Ali, M., Rizwan, M. (2018) Applicability of upflow anaerobic sludge blanket (UASB) reactor for typical sewage of a small community: its biomass reactivation after shutdown, *International Journal of Environmental Science and Technology*, 15(8), 1745–1756.

Rongrong, L., Qing, T., Jihua, C. (2010) The developments of anaerobic baffled reactor for wastewater treatment: a review, *African Journal of Biotechnology*, 9(11), 1535–1542.

Rousseau, D. P. L., Vanrolleghem, P. A., De Pauw, N. (2004) Model-based design of horizontal subsurface flow constructed treatment wetlands: a review, *Water Research,* 38, 1484-1493.

Rovatti, M., Nicolella, C., Converti, A. (1995) Phosphorus removal in fluidized bed biological reactor (FBBR), *Water Research*, 29(12), 2627-2634.

Roustan, M. Bastoul, D., Capdeville, B. (1993) Influence of the hydrodynamic behaviour of a three phase fluidized bed for effluent treatment, *3rd Int. Conf. on Bioreactor and Bioprocess Fluid Dynamics*, pp. 323-333, Cambridge, UK.

Sanz, I., Fdz-Polanco, F. (1990) Low temperature treatment of municipal sewage in anaerobic fluidized bed reactors, *Water Research*, 24(4), 463–469.

Sarti, A., Fernandes, B. S., Zaiat, M., Foresti, E. (2007) Anaerobic sequencing batch reactors in pilot-scale for domestic sewage treatment, *Desalination*, 216(1–3), 174–182.

Sattler, M. (2011) Anaerobic processes for waste treatment and energy generation, *Integrated Waste Management*, 2, 215–246.

Seghezzo, L., Zeeman, G., van Lier, J. B., Hamelers, H. V. M., Lettinga, G. (1998) A review: the anaerobic treatment of sewage in UASB and EGSB reactors, *Bioresource Technology*, 65(3), 175–190.

Shida, G. M., Sader, L. T., de Amorim, E. L. C., Sakamoto, I. K., Maintinguer, S. I., Saavedra, N. K., Varesche, M. B. A., Silva, E. L. (2012) Performance and composition of bacterial communities in anaerobic fluidized bed reactors for hydrogen production: effects of organic loading rate and alkalinity, *International Journal of Hydrogen Energy*, 37(22), 16925–16934.

Singh, S. P., Prerna, P. (2009) Review of recent advances in anaerobic packed-bed biogas reactors, *Renewable and Sustainable Energy Reviews*, 13(6–7), 1569–1575.

Soriano-Molina, P., García Sánchez, J. L., Malato, S., Pérez-Estrada, L. A., Sánchez Pérez, J. A. (2018) Effect of volumetric rate of photon absorption on the kinetics of micro-pollutant removal by solar photo-Fenton with Fe^{3+}-EDDS at neutral pH, *Chemical Engineering Journal*, 331, 84–92.

Souza, M. E. (1986) Criteria for the utilization, design and operation of UASB reactors, *Water Science and Technology*, 18(12), 55–69.

Stazi, V., Tomei, M. C. (2018) Enhancing anaerobic treatment of domestic wastewater: state of the art, innovative technologies and future perspectives, *Science of the Total Environment*, 635, 78–91.

Steyer, J. P., Buffiere, P., Rolland, D., Moletta, R. (1999) Advanced control of anaerobic digestion processes through disturbances monitoring, *Water Research*, 33 (9), 2059-2068.

Tauseef, S. M., Abbasi, T., Abbasi, S. A. (2013) Energy recovery from wastewaters with high-rate anaerobic digesters, *Renewable and Sustainable Energy Reviews*, 19, 704–741.

Teichgräber, B., Schreff, D., Ekkerlein, C., Wilderer, P. A. (2001) SBR technology in Germany - an overview, *Water Science and Technology*, 43(3), 323–330.

Tilche, A., Vieira, S. M. M. (1991) Discussion report on reactor design of anaerobic filters and sludge bed reactors, *Water Science and Technology*, 24(8), 193–206.

Tilley, E., Lüthi, C., Morel, A., Zurbrugg, C., Schertenleib, R. (2008) Compendium of sanitation systems and technologies, *Swiss Federal Institute for Environmental Science and Technology (EAWAG)*, IWA Publishing, Duebendorf, Switzerland.

Tilley E., L. Ulrich, C. Luethi, P. Reymond, C. Zurbruegg (2014) *Compendium of Sanitation Systems and Technologies*. 2nd Revised Edition. Duebendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology (Eawag).

Tonon, D., Tonetti, A. L., Filho B. C., Bueno, D. A. C. (2015) Wastewater treatment by anaerobic filter and sand filter: hydraulic loading rates for removing organic matter, phosphorus, pathogens and nitrogen in tropical countries, *Ecological Engineering*, 82, 583–589.

Ülgüdür, N., Ergüder, T. H., Uludağ-Demirer, S., Demirer, G. N. (2019) High-rate anaerobic treatment of digestate using fixed film reactors, *Environmental Pollution*, 252, pp. 1622–1632.

UN-HABITAT (2008) Constructed wetlands manual, *UN-HABITAT Water for Asian Cities Programme*, Nepal, Kathmandu.

USEPA (2000) Constructed wetlands treatment for municipal wastewaters, *United States Environmental Protection Agency (USEPA)*, 625/R-99/010.

Vaes, G., Berlamont, J. (1999) The impact of rainwater reuse on CSO emissions, *Water Science and Technology*, 39(5), 57-64.

Van Loosdrecht, M. C. M., Heijnen, J. J. (1993) Biofilm bioreactors for wastewater treatment, *TIBTECH* 11(April), 117-121.

Vieira, S. M. M., Souza, M. E. (1986) Development of technology for the use of the UASB reactor in domestic sewage treatment, *Water Science and Technology*, 18(12), 109–121.

Vieira, S. M. M., Carvalho, J. L., Barijan, F. P. O., Rech, C. M. (1994) Application of the UASB technology for sewage treatment in a small community at Sumare, Sao Paulo State, *Water Science and Technology*, 30(12), 203–210.

Von Sperling, M., de Lemos Chernicharo, C. A. (2005) Biological wastewater treatment in warm climate regions, *IWA Publishing*, 1–856.

Wallace, S. D., Knight, R. L. (2006) Small-scale constructed wetland treatment systems: feasibility, design criteria, and operation & maintenance requirements, *Water Environment Research Foundation (WERF)*, IWA Publications.

Weiland, P., Rozzi, A. (1991) The start-up, operation and monitoring of high-rate anaerobic treatment systems: discusser's report, *Water Science and Technology*, 24(8), 257–277.

Wetzel, R. G. (2001) Fundamental processes within natural and constructed wetland ecosystems: short-term vs long-term objectives, *Water Science and Technology*, 44(11/12), 1-8.

Wheatley, A. (1990) Anaerobic digestion: a waste treatment technology, Elsevier applied science, London, *Critical Reports on Applied Chemistry*, 31, 229.

Wilderer, P. A. (1998) Sequencing batch reactor technology: concepts, design and experiences, *Water and Environment Journal*, 12(5), 314-320.

Yeshanew, M. M., Frunzo, L., Luongo, V., Pirozzi, F., Lens, P. N. L., Esposito, G. (2016) Start-up of an anaerobic fluidized bed reactor treating synthetic carbohydrate rich wastewater, *Journal of Environmental Management*, 184, 456–464.

Young, J. C., Dahab, M. F. (1983) Effect of media design on the performance of fixed-bed anaerobic reactors, *Water Science and Technology*, 15(8–9), 369–383.

Yulistyorini, A., Camargo-Valero, M. A., Sukarni, S., Suryoputro, N., Mujiyono, M., Santoso, H., Tri Rahayu, E. (2019) Performance of anaerobic baffled reactor for decentralized waste water treatment in urban Malang, Indonesia, *Processes*, 7(4), 1–12.

Zhu, G., Zou, R., Jha, A. K., Huang, X., Liu, L., Liu, C. (2015) Recent developments and future perspectives of anaerobic baffled bioreactor for wastewater treatment and energy recovery, *Critical Reviews in Environmental Science and Technology*, 45(12), 1243–1276.