JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535

–Polish Academy of Sciences (PAN), Committee on Agronomic Sciences
Section of Land Reclamation and Environmental Engineering in Agriculture
Institute of Technology and Life Sciences (ITP)

JOURNAL OF WATER AND LAND DEVELOPMENT
2020, No. 47 (X–XII): 66–76
https://doi.org/10.24425/jwld.2020.135033

Received 21.02.2020
Reviewed 19.08.2020
Accepted 21.08.2020

Sustainable management of wastewater: Theoretical design of combined upflow anaerobic reactors and artificial wetlands systems

Yans GUARDIA-PUEBLA[1] ✉, **Edilberto LLANES-CEDEÑO**[2],
Suyén RODRÍGUEZ-PÉREZ[3], **Quirino ARIAS-CEDEÑO**[1],
Víctor SÁNCHEZ-GIRÓN[4], **Gert MORSCHECK**[5],
Bettina EICHLER-LÖBERMANN[5]

[1] University of Granma, Study Center for Applied Chemistry, Carretera de Manzanillo Km 17 1/2. Peralejo. Apartado 21 (8559.38 km), 85149 Bayamo, Cuba
[2] International SEK University, Faculty of Architecture and Engineering, Quito, Ecuador
[3] Center for Molecular Immunology, Santiago de Cuba, Cuba
[4] Technical University of Madrid, College of Agricultural, Food and Biosystems Engineering, Spain
[5] University of Rostock, Faculty of Agronomy and Crop Science, Rostock, Germany

For citation: Guardia-Puebla Y., Llanes-Cedeño E., Rodríguez-Pérez S., Arias-Cedeño Q., Sánchez-Girón V., Morscheck G., Eichler-Löbermann B. 2020. Sustainable management of wastewater: Theoretical design of combined upflow anaerobic reactors and artificial wetlands systems. Journal of Water and Land Development. No. 47 (X–XII) p. 66–76. DOI: 10.24425/jwld.2020.135033.

Abstract

Anaerobic digestion (AD) is an adequate alternative to treat wastewater generated from fruit and vegetable processing (FVWW); likewise, in recent years, artificial wetlands (AWs) have been applied as a post-treatment process for anaerobically pre-treated wastewater. The objective of this work was to design a sustainable treatment system for FVWW composed of upflow anaerobic reactors (UASB) with phase separation and an AW system that receive the anaerobically pretreated effluent. Using the design methodologies for the UASB reactors and artificial wetlands with sub-surface flow (AW-SSF), the parameters of the combined AD-AW system that treat a wastewater flow of 300 $m^3 \cdot d^{-1}$ were calculated. The UASB acidogenic system was adjusted to a hydraulic retention time (*HRT*) of 10 h and organic loading rate (*OLR*) of 13.84 kg *COD* $m^{-3} \cdot d^{-1}$; meanwhile, the methanogenic and cascade UASB reactors with *OLR*s of 10.0 and 3.0 kg *COD* $m^3 \cdot d^{-1}$, and *HRT*s of 11 and 10 h, respectively, achieve a high *COD* removal efficiency (above 94%), and an overall biogas production rate of 1.53 m^3 of biogas per m^3 of reactor capacity per day. According to the results obtained with the theoretical design, anaerobic-wetland combined system achieves an overall efficiency greater than 98%. The wastewater treated by the proposed system will allow the reuse of 30% of the water used in the washing of fruits and vegetables.

Key words: *anaerobic digestion, artificial wetland, design methodology, fruit and vegetable wastewater, upflow anaerobic reactors (UASB), wastewater*

INTRODUCTION

In recent years, new and promising wastewater treatment technologies have been developed to address current and future scenarios. Although there are many process-specific technologies capable of treating industrial wastewaters, no single technology or group of technologies has been developed to provide a global solution for the almost infinite numbers of wastewater scenarios. Expert knowledge, mathematical models, statistical tools, life cycle analysis, environmental benefits analysis, and cost-benefit analysis are some of the criteria considered for an accurate decision-making process [DI MARIA *et al.* 2015]. Wastewater generated from fruit and vegetable processing (FVWW) provides high levels of organic pollution and nitrogen compounds. An adequate wastewater treatment system must be simple and efficient to treat completely, or almost completely the pollutants generated. The energy consumption of these systems must be negligible; while water reuse and obtaining valuable byproducts must be maximized with a smallest requirement of sophisticated equipment [ARHOUN *et al.* 2019**]**.

The anaerobic digestion (AD) is an effective technique for treating FVWW. However, sometimes a separation of phases in the process is necessary to achieve an efficient removal of these contaminants, what is called two-phase AD. This treatment scheme, which has been used for several types of easily biodegradable organic waste, can provide the following advantages compared with a single-stage configuration: increase removal efficiency, better process control and stability, greater resistance to inhibitor compounds and acidification buffering [CARAMILLO, RINCÓN 2012].

Mono-digestion of fruit and vegetable wastes in a single substrate has often been reported as an unstable process due to the degradation of simple sugars, the accumulation of volatile fatty acids (*VFA*s) and, subsequently, the rapid acidification of the system [EDWIGES *et al.* 2018]. Two-phase AD system is a complex process of substrate conversion which involves four continuous main steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These four steps are grouped into two stages: acidification (hydrolysis and acidogenesis), and methanation (acetogenesis and methanogenesis) to achieve the optimal conditions of each group of microorganisms. Due to that reason, two-phase AD can offer significant benefits for the treatment of FVWW, since they generally have the following characteristics: i) methane production is affected by low pH vales in wastewaters, usually below 6.5; ii) the C:N values may vary slightly, they tend to be closed to 20 when wastes contain different types of fruits and vegetables; iii) as the cellulose content in fruits and vegetables is low, the hydrolytic process during the AD is not the rate-limiting step, the total solids content (*TS*) is low, and high the volatile solids (*VS*) content. Therefore, fruit and vegetable wastes are acidified (an increase in *VFA*s levels) by rapid hydrolysis and, consequently, methane production can be inhibited; and iv) these limitations could be reduced basically using several approaches: by the co-digestion with others substrates with high nitrogen content, which could result in a natural regulation of the pH; with the addition of chemical reagents; or with the use of two-phase AD [JI *et al.* 2017]. Several studies have reported an improved stability and a 14–28% increase in methane generation with two-phase systems in comparison with single-stage systems [MU *et al.* 2014]. The rapid acidification of the FVWW in the first stage (acidogenic reactor) does not affect the stability of the second stage (methanogenic reactor) when the *VFA* compounds inlet in the methanogenic compartment is controlled. For that reason, two-phase AD systems seems to be a highly efficient technology to treat the FVWW [RAVI *et al.* 2017].

Among the anaerobic reactors, those with a high processing capacity can handle high organic loading rates (*OLR*), high up-flow velocities and low hydraulic retention times (*HRT*). Hence, a smaller volume of reactor is required, that also needs less ground space, while a large amount of biogas is produced at the same time. An example of a system with these characteristics is the up-flow anaerobic sludge blanket (UASB) reactor, which has been widely used for the treatment of several types of wastewaters [CHAN *et al.* 2009]. The UASB reactor performs an advanced wastewater pretreatment that reaches average removal efficiencies of 74±12% of the chemical oxygen demand (*COD*), 68±17% of the total suspended solids (*TSS*); 83±9% of the biochemical oxygen demand (BOD_5); 49±22% of total nitrogen, 51±26% of total phosphorus; and 94±13% of total coliforms. However, the treated effluents still have important pollution characteristics and do not comply with the current regulations for safe dumping into the environment [CHONG *et al.* 2012].

In the scientific literature it is quite easy to find several studies on AD of fruit and vegetable wastes [DI MARIA, BARRATTA 2015; LIU, LIAO 2018; SMITH, ALMQUIST 2014; WANG *et al.* 2017], but only in some of them the results were obtained using FVWW as a single substrate and, according to the knowledge of the authors, most of these experiments had been performed in laboratory-scale reactors (maximum size of about 20 dm^3). The proper design of a large-scale PVWW treatment plant requires extensive knowledge of the entire AD process, particularly in the effects produced by the chemical composition of the substrate in both the rate of biogas production and removal efficiency of *COD*.

On the other hand, several studies have focused on the design, development and operation of artificial wetlands (AWs), showing in all of them that they are efficient in the removal of various wastewaters pollutants (organic matter, nutrients, trace elements, pharmaceutical contaminants and pathogens). Figure 1 shows the purification processes involved in a wetland. The treatment in the AWs entail the convergence of a variety of processes that take place when the wastewater passes through a porous media, such as disinfection, filtration, precipitation, adsorption, volatilization and nutrient assimilation, in combination with the action of several microorganisms and aquatic plants [VYMAZAL 2014].

Anaerobic digesters and AWs are sustainable wastewaters treatment systems that involve low energy input requirements, slight operating costs and small production of sewage sludge. Several studies of wastewater treatment systems use an anaerobic pretreatment followed by an AW, where the use of the UASB is the reference pretreatment technology used in these combined AD-AWs systems. Anaerobic pretreatment prevents the obstruction of the Aws and, depending on the amount of organic matter removed, allows a reduction of 30 to 60% of the wetland surface [ÁLVAREZ *et al.* 2008]. Therefore, combined AD-AWs systems could be a feasible technological solution for an appropriate treatment strategy for FVWW. The literature mentioned above shows the feasibility of both systems for the treatment of industrial wastewater, but there is no

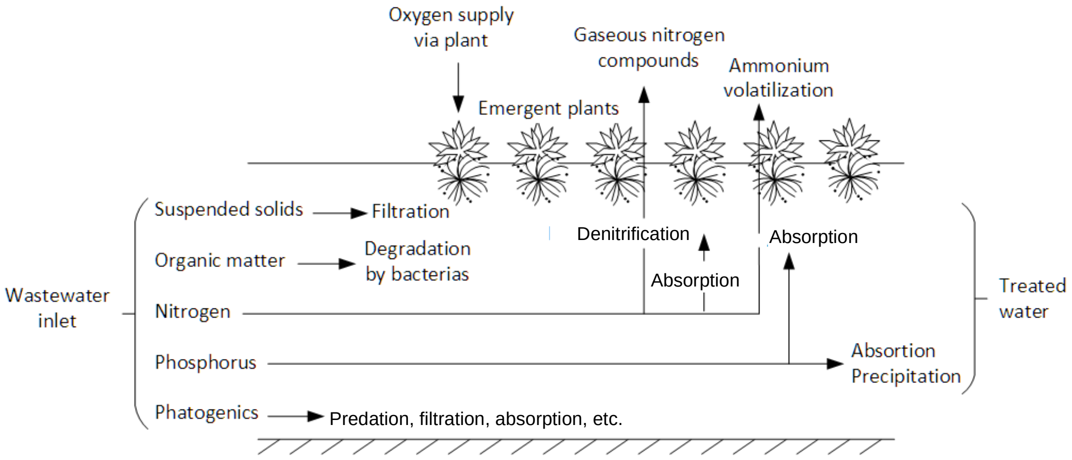


Fig. 1. Purification processes involved in artificial wetlands; source: own elaboration

information in peer-reviewed journals about the design and dimensioning of UASB and AWs systems for full scale treatment plants.

The objective of this paper is to develop the design methodology of the UASB and AW systems. An analysis is made of the fundamental design and operation characteristics of the two-phase AD systems and of the acidogenic and methanogenic UASB reactors that treat wastewater from fruit and vegetable processing; as well as the factors that influence the arrangement of the subsurface artificial wetland systems, and the possible end uses in the water treatment industry.

MATERIAL AND METHODS

THE FRUIT AND VEGETABLE PROCESSING CENTER

The industrial processing of fruits and vegetables has become one of the main agro-industrial activities in the Central American countries. The seasonal nature of fruit and vegetable processing centers translates into the generation of wastewaters with a high concentration of organic matter in a relatively short period of time. On the other hand, solid wastes are produced that could be used as animal feed or obtaining biofertilizers; meanwhile, air and noise pollution are of less importance in that industrial activity [SIDDIQ *et al.* 2012].

The fruit and vegetable processing center is located in the municipality of Yara, province of Granma, Cuba. A macro and micro location of the fruit and vegetable processing centre is shown in Figure 2. The purpose of this factory is the production and wholesale marketing of canned fruit and vegetable food products. The factory records average volumes of wastewater of 300±15 $m^3 \cdot d^{-1}$.

SUBSTRATE

The characteristics of the wastewater from the washing and processing facility of fruits and vegetables can be seen in Table 1. The values shown correspond to the average of

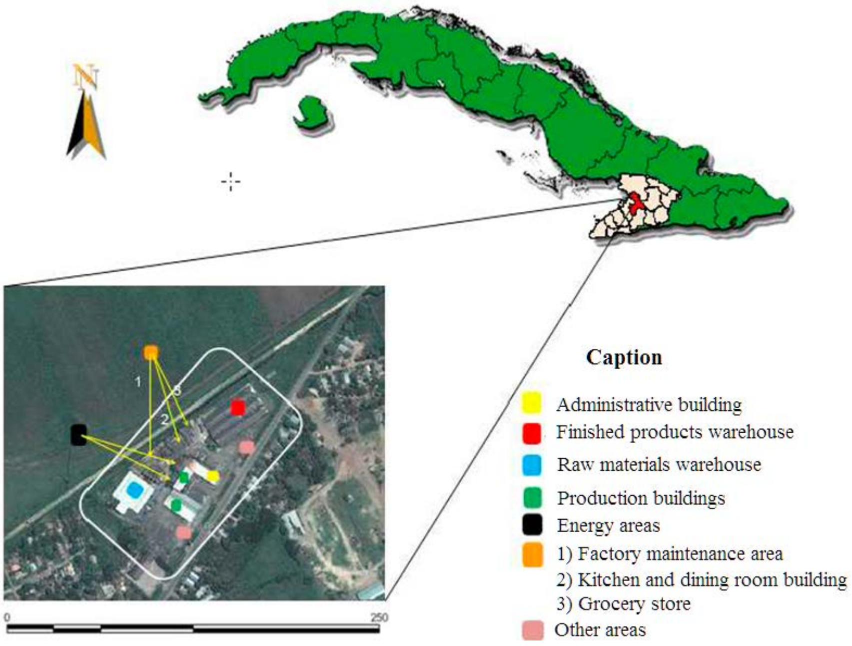


Fig. 2. Macro- and micro-location of the fruit and vegetable processing centre; source: own elaboration

Table 1. Characteristics of raw wastewater from fruit and vegetable processing

Parameter	Average value	Unit
pH	3.69±0.4	–
Biological oxygen demand (BOD_5)	5 025±82	mg·dm^{-3}
Chemical oxygen demand (*COD*)	5 538±135	mg·dm^{-3}
Total suspended solids (*TSS*)	332±27	mg·dm^{-3}
Total volatile solids (*TVS*)	282±32	mg·dm^{-3}
TVS:*TSS*	85	%
Total coliforms (*TC*)	1.6·10^6	NMP·(100 cm^3)$^{-1}$
Faecal coliforms (*FC*)	1.3·10^6	NMP·(100 cm^3)$^{-1}$
TC:*FC*	92	%

Source: own study.

five repeated samples, with a coefficient of variation of less than 10%.

SYSTEM CONFIGURATION

The configuration of the treatment system consisted of two UASB reactors for the hydrolysis-acidogenesis process. Next, a system consisting of two others methanogenic UASB reactors followed by a cascade UASB reactor was arranged, and finally an AW-SSF system was inserted as a tertiary treatment (Fig. 3). Four empty storage tanks were used as acidogenic and methanogenic UASB reactors, each with a useful volume of 60 m^3 (diameter of 2.77 m and height of 10.0 m). On the other hand, medium and fine gravels, as well as coarse sand, were considered suitable support materials for the growth of microbial biomass in the wetland.

DESIGN OF THE UASB SYSTEM

Table 2 contains the main design parameters of the UASB reactors, while the design methodology for the treatment of soluble and partially soluble wastewater is shown in Table 3 [CHERNICHARO 2007]. The UASB system depends on several factors, such as organic loading rate applied, up-flow velocity rate, the permissible hydraulic loading, temperature, strength of the wastewaters (e.g. characteristics and complexity of the pollutant compounds), the required treatment efficiency and the stabilization degree of the sludge. This system has been successfully applied in the treatment of a wide variety of industrial wastewater, as well as for the treatment of domestic wastewater [CHONG *et al.* 2012]. Its distinctive feature is the retention of biomass inside the reactor itself without the need for any support medium, and this thanks to the formation of a granular sludge, so it turns out to be cheaper and with technical advantages over other types of anaerobic reactors.

Table 2. Design parameters of an upflow anaerobic (UASB) reactor

Parameter	Symbol list	Measurement unit
Average flow rate	Q_{avg}	m^3·d^{-1}
COD inlet	$S_{0-UASB-COD}$	mg·dm^{-3}
Hydraulic retention time	*HRT*	h
Total volume of the UASB reactor	V_T	m^3
Number of reactors	N_r	–
Volume of each reactor	V_r	m^3
Reactor height	*H*	m
Total area	A_T	m^2
Area of each reactor	A_r	m^2
Influence area of each distributor	A_d	m^2
Volumetric hydraulic load	*VHL*	m^3·m^{-3}·d^{-1}
Organic loading rate	*OLR*	kg *COD*·m^{-3}·d^{-1}
Surface velocity of flow	V_s	m·h^{-1}
Estimation of UASB system removal	$E_{COD\ removal}$	–
Estimation of *COD* concentration in the effluent	$S_{UASB-COD}$	mg·dm^{-3}
Estimation of methane production	COD_{CH4}	kg·d^{-1}
Coefficient of sludge production by the UASB system, in terms of *COD*	Y_{obs}	kg COD_{sludge} kg $COD_{apl}$$^{-1}$
Volumetric methane production	Q_{CH4}	m^3·d^{-1}
Volumetric biogas production	Q_{biogas}	m^3·d^{-1}
Methane concentration in biogas, usually between 60–70%	C_{CH4}	%

Source: own elaboration.

DESIGN OF ARTIFICIAL WETLANDS

Used for wastewater treatment, AWs can be built based on two systems: artificial wetlands with free water surface (AW-FWS) and artificial wetlands with subsurface flow (AW-SSF) – Figure 4. In AW-FWS systems, shallow wastewater streams circulate on a saturated sub-

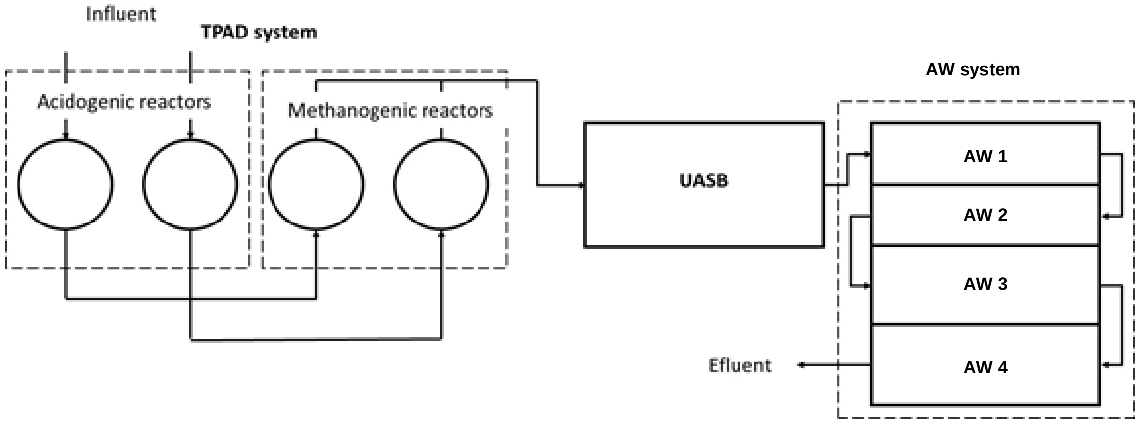


Fig. 3. Configuration of the treatment system for wastewater generated from fruit and vegetable processing; TPAD = two-phase anaerobic digestion, UASB = upflow anaerobic reactors; AW = artificial wetland; source: own elaboration

Table 3. Design methodology of the upflow anaerobic (UASB) system

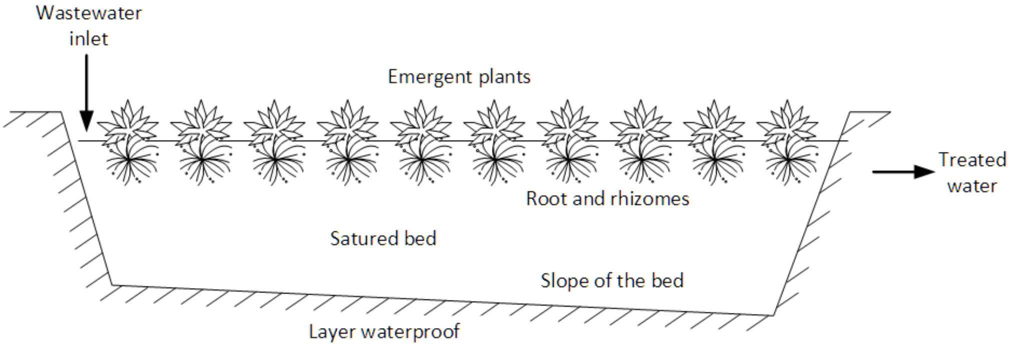
Variable	Mathematical formula	Measurement unit
Organic load inlet	$L_{0-UASB-COD} = S_{0-UASB-COD} \cdot Q_{avg}$	$kg \cdot d^{-1}$
Hydraulic retention time	$HRT = \frac{V_T}{Q_{avg}}$	d
Total volume of the UASB reactor	$V_T = Q_{avg} \cdot HRT$	m^3
Number of reactors	$N_r \leq 500; N_r = 1$	–
Volume of each reactor	$V_r = \frac{V_T}{N_r}$	m^3
Area of each reactor	$A_r = \frac{V_r}{H}$	m^2
Up-flow velocity	$V_{up} = \frac{Q_{avg}}{A_T}$	$m \cdot h^{-1}$
Number of distributors in the UASB reactor	$N_d = \frac{A_T}{A_d}$	–
System removal efficiency	$E_{COD} = 100(1 - 0.68HRT^{0.35})$	%
Estimated *COD* in the effluent	$S_{UASB-COD} = S_{0-UASB-COD} - \frac{(E_{COD} \cdot S_{0-UASB-COD})}{100}$	$mg \cdot dm^{-3}$
Estimated methane production	$COD_{CH4} = Q_{avg} [(S_{0-UASB-COD} - S_{UASB-COD}) - Y_{obs} \cdot Q_{avg} \cdot S_{0-UASB-COD}]$	$kg \cdot d^{-1}$
Correction factor for the temperature	$f(T) = \frac{P \cdot K_{COD}}{R(273+T)}$	–
Theoretical volumetric methane production	$Q_{CH4} = COD_{CH4} \cdot f(T)$	$m^3{}_{CH4} \cdot d^{-1}$
Theoretical daily biogas production	$Q_{biogas} = \frac{Q_{CH4}}{C_{CH4}}$	$m^3{}_{CH4} \cdot d^{-1}$
Sludge production	$P_{sludge} = Y \cdot L_{0-UASB-COD}$	$m^3 \cdot d^{-1}$
Sludge bed volume	$V_{sludge} = \frac{P_{sludge}}{\gamma_{sludge} \cdot C_{sludge}}$	$m^3 \cdot d^{-1}$

Explanations: P = atmospheric pressure, K_{COD} = COD corresponding to 1 mole of CH_4, R = universal constant of ideal gases, other symbols as in Tab. 1.
Source: own elaboration.

strate; while in AW-SSF systems, wastewater flows horizontally (AW-HSSF) or vertically (HA-VSSF) through a filter medium, located in the direction of flow, that allows plant growth. Several factors influence the microbial processes of the AWs, among which are: availability of organic matter, redox conditions, temperature, pH, the characteristics of the filter medium and the presence of plants in the wetland. Plants play an important role in wetland treatment processes, not only for nutrient absorption but also for being useful for the microbial adhesion. Several studies have shown that microbial density, activity and diversity are improved in the plant rhizomes [Faulwetter *et al*. 2009].

Currently, there are reports of more than 150 species of macrophytes that have been used in the AWs. Among the commonly used emergent species are *Phragmites* spp. (Poaceae), *Typha* spp. (Typhaceae), *Scirpus* spp. (Cyperaceae), *Iris* spp. (Iridaceae), *Juncus* spp. (Juncaceae) and *Eleocharis* spp. (Cyperaceae). Meanwhile, among frequently used submerged plants are: waterthyme (*Hydrilla verticillata*), coontail (*Ceratophyllum demersum*), whorl-leaf watermilfoil (*Myriophyllum verticillatum*), tape grass (*Vallisneria natans*), and curly-leaf pondweed (*Potamogeton crispus*) [Vymazal 2013]; also other floating plants, such as: waterlilies (*Nymphaea tetragona*), water fringe (*Nymphoides peltata*), water caltrop (*Trapa bispinosa*), European water clover (*Marsilea quadrifolia*), commom water hyacinth (*Eichhornia crassipes*), floating fern (*Salvinia natans*), frogbit (*Hydrocharis dubia*) and common duckweed (*Lemna minor*), they have also been used in the AWs [Guardia-Puebla *et al*. 2019].

Several studies have shown that *Typha* spp. have a significant tolerance and high contaminant uptake capacity proper to decontamination water or soil [Gomes *et al.* 2014]. *Typha domingensis* is an emergent aquatic macrophyte plant that grows in all tropical and temperate climate regions, this plant grows naturally in flooded lands, swamps, on the banks of water reservoirs, and drainage channels. Although many times this plant has been considered an invasive species, it has received a lot of attention for its usefulness in the ecological field, mainly in the treatment of domestic and industrial wastewaters. Due to the extensive knowledge acquired on productivity, physiology, competition with other plants and nutrient recycling in wastewater [Eid *et al.* 2012], the emergent plant *Typha domingensis* was selected as plant material for the AW system. Tables 4 and 5 contain the variables and method-



AW-FWS: The water level is above the ground surface; vegetation is planted and fixed, and emerges on the water surface; the water flow is mainly superficial.

AW-SSF: The water level is below the ground surface; the water flows through a filter medium (natural and/or artificial); the roots penetrate to the bottom of the bed.

Fig. 4. Types of artificial wetlands (AWs) built for wastewater treatment; source: own elaboration

Table 4. Design parameters of the artificial wetlands with sub-surface flow

Parameter	Symbol list	Measurement unit
Inlet flow	Q_0	$m^3 \cdot d^{-1}$
Influent characteristics (BOD_5, concentration of nitrogen, phosphorus, heavy metals, pathogens)	C_0	$mg \cdot dm^{-3}$
Effluent characteristics	C_e	$mg \cdot dm^{-3}$
Total reaction rate constant	K_T	d^{-1}
Rate constant at 20°C	$K_{20°C}$	d^{-1}
Available surface area of the wetland	A_s	$m^2 \cdot m^{-3}$
BOD_5 fraction not removed	A	–
Wetland width	W	m
Wetland length	L	m
Wetland depth	y	m
Porosity of the filter medium	n	%
Slope of the filter medium	m	%
Average water temperature	T	°C
Hydraulic conductivity of the wetland	k_s	$m^3 \cdot d^{-1}$
Transversal area perpendicular to the flow	A_c	$m^{-3} \cdot m^{-2} \cdot d^{-1}$
Hydraulic gradient of the water in the system	s	$m \cdot m^{-1}$
Flow rate through the cross-sectional area of the filter medium	v	$m \cdot d^{-1}$
Reynolds number	Re	–

Source: own elaboration.

Table 5. Design methodology of the artificial wetlands with sub-surface flow

Variable	Mathematical formula	Measure-ment unit
***BOD*₅ removal design**		
General model for contaminant removal	$\frac{C_e}{C_0} = A \cdot e^{\left[-\frac{0.7 \cdot K_T \cdot A_v{}^{1.75} \cdot L \cdot W \cdot y \cdot n}{Q}\right]^2}$	
Flow through the wetland	$Q = \frac{Q_e + Q_o}{2}$	$m^3 \cdot d^{-1}$
Surface area of the wetland	$A_s = L \cdot W = \frac{Q(\ln(C_o) - \ln(C_e) + \ln(A))}{K_T \cdot y \cdot n}$	m^2
Total reaction rate constant	$K_T = K_{20} \cdot 1.06^{(T-20)}$	d^{-1}
Hydraulic retention time	$HRT = \frac{L \cdot W \cdot y \cdot n}{Q}$	d
Hydraulic design		
Average flow in the system	$Q = k_s \cdot A_c \cdot s$	$m^3 \cdot d^{-1}$
Wetland length	$L = \frac{A_s}{W} \cdot A_c = W \cdot y$	m
Width of each cell in the wetland	$W = \frac{1}{y}\left[\frac{Q \cdot A_s}{m \cdot k_s}\right]$	m

Explanations: e = exponential function, Q_e = flow rate outlet, other symbols as in Tab. 3.
Source: own elaboration.

ology that correspond to the design of the AW-SSF for the treatment of low-strength wastewater, respectively [GONZÁLEZ, DEAS 2011].

On the other hand, the model used for the hydraulic design of a wetland is as important as the one that calculates the removal of contaminants. This method considers that a uniform movement of water flow through the entire wetland section is assumed, with minimal preferential paths. Darcy's law describes the movement of water in a saturated porous medium and is the most hydraulically accepted model for the AW-SSF design. When the fluid has a laminar regime along the empty spaces of the medium, that is, when the Reynolds number is less than a value of 2100, Darcy's law is valid. In addition, the hydraulic conductivity varies with the quantity and size of the empty spaces of the filter media in the wetland. Table 6 shows the typical characteristics of *n* and k_s that are commonly used in AW-SSF.

Table 6. Typical characteristics of the filter medium used in artificial wetlands with sub-surface flow

Material type	Effective size (mm)	Porosity *n* (%)	Hydraulic conductivity k_s ($m^3 \cdot m^{-2} \cdot d^{-1}$)
Gross sand	2	28–32	100–1 000
Gravel sand	8	30–35	500–5 000
Fine gravel	16	35–38	1 000–10 000
Medium gravel	32	36–40	10 000–50 000
Thick rock	128	38–45	50 000–250 000

Source: own elaboration.

RESULTS AND DISCUSSION

CHARACTERIZATION OF THE FVWW

As it can be seen in Table 1 the wastewater generated from fruit and vegetable processing (FVWW) showed a high acidity with an average pH value of 3.69 ±0.4. On the other hand, the total suspended solids (*TSS*) and total volatile solids (*TVS*) concentrations had average values of 332±27 $mg \cdot dm^{-3}$ and 282±32 $mg \cdot dm^{-3}$, respectively, with a *TVS*:*TSS* ratio of 85%. Similarly, the BOD_5 and *COD* concentrations presented values of 5025±82 $mg \cdot dm^{-3}$ and 5538±135 $mg \cdot dm^{-3}$, respectively. Due to its high moisture and biodegradable biomass contents, low total solids content (*TS*) concentrations, and high volatile solids (*VS*) concentrations, the FVWW is a substrate with a high potential to obtain biogas through anaerobic digestion (AD). However, rapid hydrolysis and acidification of these residues result in a sharp decrease in pH, thanks to the production of highly volatile fatty acids (*VFA*), which can inhibit the activity of methanogenic bacteria. The methanogenic bacteria are the main responsible for pollutant degradation and biogas production [WU *et al.* 2016]. For that reason, two-phase AD offers significant advantages for the treatment of FVWW. However, the characteristics of wastewater vary from one plant to another, depending on the type of industrial process and water consumption per ton of processed fruit. Also, a high faecal coliforms:total coliforms (*FC*:*TC*) ratio was observed, indicating that approximately 92% of the coliforms present in the sewage studied were fecal. This phenomenon may be due to the incorporation into the liquid effluent of sewage from the sanitary network, as well as to the accumulation of power in some registers.

Several types of research on the treatment of fruit and vegetable residues have evaluated the effect of increasing the organic loading rate (*OLR*) and reducing the hydraulic retention time (*HRT*) applied to the anaerobic reactor [BOUALLAGUI *et al.* 2004]. Other studies, however, have focused on the assessment of different combinations of anaerobic acidogenic and methanogenic reactors [RAJESHWARI *et al.* 2001; WU *et al.* 2016] and on anaerobic co-digestion with other substrates [BOUALLAGUI *et al.* 2009; SHENG *et al.* 2013].

DESIGN OF THE TREATMENT SYSTEM

Table 7 summarizes the initial data required for the design of the UASB and AW-SSF systems. An appropriate design methodology for acidogenic reactors is not completely defined; however, they are simple systems, in which some mixing processes occur. The main objective pursued with the design is the retention of high concentrations of acidogenic sludge in the reactor. Since the acidogenesis process is relatively rapid, the complete acidification for all the substrates is not required, for example, sewage with high contents of protein and fat. The extension of acidification, i.e. pH, is more or less controlled by the addition of an alkalizing chemical compounds, e.g. sodium hydroxide (NaOH) or potassium hydroxide (KOH), because the acidic bacteria activity increases when the pH drops.

Table 7. Initial design data for upflow anaerobic (UASB) and artificial wetlands with sub-surface flow (AW-SSF) systems

UASB			AW-SSF		
parameter	value	unit	parameter	value	unit
Q_{avg}	300	$m^3 \cdot d^{-1}$	Q_o	300	$m^3 \cdot d^{-1}$
$S_{0–UASB-COD}$	5538	$mg \cdot dm^{-3}$	C_e	326	$mg \cdot dm^{-3}$
T	30	ºC	C_o	60	$mg \cdot dm^{-3}$
$E_{COD\ removal}$	74	%	A_v	15.7	$m^{-2} \cdot m^{-3}$
Q_{biogas}	experimental	$m^3 \cdot d^{-1}$	y	0.6	m
C_{CH4}	experimental	%	$n_{medium\ gravel}$	38	%
			$n_{fine\ gravel}$	36	%
			$n_{gravel\ sand}$	30	%
			T	30	ºC
			vegetation	*Typha domingensis*	

Explanations: parameters' symbols as in Tabs. 1, 2, and 4.
Source: own study.

The fundamental characteristics that an anaerobic acidogenic reactor must have are: (1) produce *VFA* and retain high concentrations of acidogenic sludge in the reactor; (2) the *HRT* will be established between 6–24 h according to the characteristics of the wastes to be treated, the temperature of the reactor and the degree of acidification desired; (3) high *OLR*s, within the range of 8–20 kg *COD*$\cdot m^{-3} \cdot d^{-1}$, can be applied to the reactor; (4) the AD stability is improved due to better control of the acidogenic phase; (5) the acidogenic reactor acts as a pH buffer to the methanogenic populations of the second reactor; (6) average values of the solids production coefficient (Y), specific weight of the sludge (γ) and expected percentage of sludge (C_{sludge}) have to be considered in the ranges of 0.1–0.2 kg TSS·kg $COD_{applied}^{-1}$, 1020–1040 $kg \cdot m^{-3}$, and 2–6%, respectively; and (7) removal of contaminants will be between 10–300% of the pollution load [BOUALLAGUI *et al.* 2005; JI *et al.* 2017]. In addition, in these types of reactors it is necessary to add an efficient sludge separation device, particularly for highly concentrated wastewater. Acidified suspended matter must remain in the reactor since its possible entry into the methanogenic reactor can affect its performance, as well as the formation of methanogenic granular sludge. Therefore, this operational configuration allows the selection and enrichment of the different groups of microorganisms separately in each reactor. The main objective is to provide a suitable environment for the production of *VFA*s (acetic, propionic, butyric, valeric acids, etc.), which constitute the main substrates of methanogenic bacteria. For that reason, at this stage a high removal of contaminants will not be achieved. However, the acidogenic reactors generate relative high amounts of sludge, due to the sedimentation process of the incoming solid material, and are responsible for acidic bacteria production [SOLERA *et al.* 2002].

On the other hand, the methanogenic stage has the following particularities: (1) UASB technology has shown that *OLR*s between 5.0 and 12.0 kg COD$\cdot m^{-3} \cdot d^{-1}$ has been successfully applied; (2) the size of methanogenic UASB reactors is determined by the *HRT* or *OLR*, and the up-flow velocity in the sedimentation compartment; (3) sludge production is lower than that produced in acidogenic reactors, since the methane conversion rate to biogas is much higher; (4) a greater contaminant removal is achieved at this stage [DIAMANTIS, AIVASIDIS 2007; WU *et al.* 2015; 2016].

Table 8 shows a design summary of the anaerobic-wetland combined system; meanwhile, Figure 5 shows the performance of *COD*, *TSS* and *TC* removals.

The theoretical estimate of the overall efficiency of the anaerobic system was 94.1%. This value is similar to that reported by other researchers that used experimental anaerobic systems for the treatment of fruit and vegetable wastes. RAJESHWARI *et al.* [2001] applied the two-phase AD to treat vegetable market waste. These authors achieved a 94% conversion of the organic solid waste into biogas; first, the residue was acidified in a solid bed reactor, and then the leachate was treated in a UASB reactor. Likewise, RAYNAL *et al.* [1998] achieved a high removal efficiency (greater than 80%) using phase separation when treating fruit and vegetable wastes; also BOUALLAGUI *et al.* [2004] reported a *COD* removal efficiency of 96% by applying the separation of phases with anaerobic reactors, resulting in a high stability of the process and quality of the effluent. So, it is possible that the anaerobic system increases the operation efficiency, greater than 85%, with an adequate start-up and operation strategy of the reactors. According to DIAMANTIS and AIVASIDIS [2007], high efficiencies can be achieved, up to 90% of *COD* removal, using two-stage UASB methanogenic reactors in cascade arrangement. A global *HRT* of around 9–10 h was applied, while the *HRT* in each reactor remain between 4 and 5 h. Different authors have mentioned that this operational arrangement can reduce the volume of each reactor between 40 and 50%, maximizing the efficiency of the system. LIU and LIAO [2018] used a two-stage laboratory-scale anaerobic digestion system to reduce fruit and vegetable waste, and to produce biogas at mesophilic. Their results showed that it was possible to obtain a global volatile solids (*VS*) removal of 70.9%, as well as a VFA concentration of 7.6 $g \cdot dm^{-3}$ at a *HRT* of 10 h in the leachate. Finally, over 90% of VFA compounds were reduced in the methanogenic reactor.

Table 8. Design summary of the anaerobic-wetland combined system for the treatment of wastewater generated from fruit and vegetable processing

Anaerobic system (two-phase AD+UASB)					
Two-phase AD				UASB reactor	
acidogenic reactor		methanogenic reactor			
parameter	value	parameter	value	parameter	value
HRT	10 h	HRT	11 h	HRT	10 h
N_r	2	N_r	2	N_r	1
A_r	10 m^2	A_r	10 m^2	A_r	38.3 m^2
VHL	5 m^3·m^{-3}·d^{-1}	VHL	2.5 m^3·m^{-3}·d^{-1}	VHL	2.6 m^3·m^{-3}·d^{-1}
OLR	13.84 kg COD·m^{-3}·d^{-1}	OLR	10 kg COD · m^{-3} · d^{-1}	OLR	3 kg COD·m^{-3}·d^{-1}
V_s	0.62 m·h^{-1}	V_s	0.62 m·h^{-1}	V_s	0.32 m·h^{-1}
N_d	10 distributors	N_d	10 distributors	N_d	28 distributors
E_{COD}	20%	E_{COD}	74.1%	E_{COD}	71.6%
$S_{-UASB-COD}$	4430 mg·dm^{-3}	$S_{-UASB-COD}$	1150 mg·dm^{-3}	$S_{-UASB-COD}$	326 mg·dm^{-3}
Y	0.2 kg TSS·(kg COD)$^{-1}$	Q_{CH4}	174 m^3·d^{-1}	Q_{CH4}	42 m^3·d^{-1}
$\gamma_{\mathrm{acid\ sludge}}$	1020 kg·m^{-3}	Q_{biogas}	290 m^3·d^{-1}	Q_{biogas}	70 m^3·d^{-1}
$C_{\mathrm{acid\ sludge}}$	6%	Y	0.1 kg TSS·(kg COD)$^{-1}$	Y	0.15 TSS·(kg COD)$^{-1}$
$P_{\mathrm{acid\ sludge}}$	332.4 kg TSS·d^{-1}	$\gamma_{\mathrm{meth.slud.}}$	1040 kg·m^{-3}	γ_{sludge}	1040 kg·m^{-3}
$V_{\mathrm{acid\ sludge}}$	5.4 m^3·d^{-1}	$C_{\mathrm{meth.slud.}}$	4%	C_{sludge}	4%
		$P_{\mathrm{meth.slud.}}$	132.9 kg TSS·d^{-1}	P_{sludge}	51.7 kg TSS·d^{-1}
		$V_{\mathrm{meth.slud.}}$	3.2 m^3·d^{-1}	V_{sludge}	0.28 m^3·d^{-1}

Artificial wetland (AW)							
AW1		AW2		AW3		AW4	
parameter	value	parameter	value	parameter	value	parameter	value
$n_{\mathrm{medium\ gravel}}$	38%	$n_{\mathrm{fine\ gravel}}$	36%	$n_{\mathrm{gravel\ sand}}$	30%	$n_{\mathrm{gravel\ sand}}$	30%
W_1	5 m	W_2	9.17 m	W_3	10.12 m	W_3	10.12 m
y_1	0.6 m	y_2	0.6 m	y_3	0.6 m	y_3	0.6 m
L_1	20.21 m	L_2	20.21 m	L_3	40.42 m	L_3	40.42 m
L_1:W_1 ratio	4:1	L_2:W_2 ratio	2.2:1	L_3:W_3 ratio	4:1	L_3:W_3 ratio	4:1
A_{s1}	101.0 m^2	A_{s2}	185.3 m^2	A_{s3}	427.3 m^2	A_{s4}	438.2 m^2
HRT_1	1.84 h	HRT_2	3.2 h	HRT_3	5.9 h	HRT_4	6 h
A_{c1}	3 m^2	A_{c2}	5.5 m^2	A_{c3}	6.1 m^2	A_{c4}	6.2 m^2
k_{s1}	1·10^4 m^3·m^{-2}·d^{-1}	k_{s2}	5.4·10^3 m^3·m^{-2}·d^{-1}	k_{s3}	4.9·10^3 m^3·m^{-2}·d^{-1}	k_{s4}	4.8·10^3 m^3·m^{-2}·d^{-1}
v_1	1.15 dm^3·s^{-1}	v_2	0.6 dm^3·s^{-1}	v_3	0.5 dm^3·s^{-1}	v_4	0.5 dm^3·s^{-1}
N_{R1}	2875 (transition)	N_{R2}	12 (laminar regime)	N_{R3}	20 (laminar regime)	N_{R4}	20 (laminar regime)

Explanations: parameters' symbols as in Tabs. 1, 2 and 4.
Source: own study.

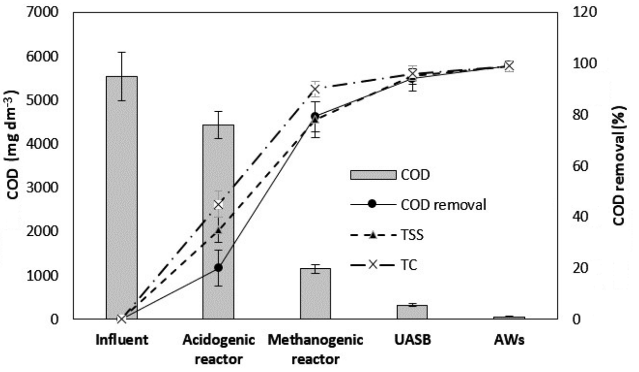


Fig. 5. Performance of chemical oxygen demand (COD), total suspended solids (TSS) and faecal coliforms (FC) removals in the anaerobic – artificial wetland system; UASB = upflow anaerobic reactors, AWs = artificial wetlands, source: own study

On the other hand, RAVI *et al.* [2017] treated a mixture of vegetable wastes with carrot mousse, carrots, celery, cabbage and potatoes in a two-stage system at target pH values of 5.5 and 6 in the acidification reactor. The organic residues added were efficiently converted to organic acids and subsequently to biogas. According to these authors, the absolute amount of hydrolysate produced was 32.6% higher at pH 5.5 (27.55 dm^3·d^{-1}) than at pH 6 (18.56 dm^3·d^{-1}); on the contrary, the COD value in the acidogenic reactor was 21.8% higher at pH 6 compared to the experimental phase with pH 5.5. The organic acid concentrations in the acidogenic reactor showed distinctive differences at target pH values.

According to the results obtained with the theoretical design (Tab. 8), an overall biogas production rate of 1.53 m^3 of biogas per m^3 of reactor capacity per day was obtained. BOUALLAGUI *et al.* [2004] reached a biogas production of 0.74 m^3 of biogas per m^3 of reactor capacity per day with a methane content of 71% using an ASBR methanogenic reactor treating FVWW. Likewise, a biogas production of 2.53 m^3 of biogas per m^3 of reactor capacity per day, with similar methane percentages in gas, was reported by BOUALLAGUI *et al.* [2009] when they investigated the performance of the anaerobic digestion with co-substrate addition of fruit and vegetable waste. SRIDEVI *et al.* [2015] have successfully used a two-phase AD system to treat vegetable market wastes. In fact, they obtained an optimum biogas production of 0.598±0.01 m^3·kg VS^{-1}_{add} at an OLR of 4.5 kg VS·m^{-3}·d^{-1}. In addition, these authors concluded that the high loading rates and low *HRT* values used in two-phase systems reduce the overall volume of the reactor and, thus, the investment cost of biomethanization in comparison with a single stage system. Wu *et al.* [2016] published a study about a two-phase AD system, using a completely stirred-tank acid reactor and an up-flow anaerobic sludge bed methane reactor, to treat a simulated fruit and vegetable waste consisting of 57% watermelon, 29% apple, and 14% potato by wet weight. The anaerobic system worked with a low *HRT* of 3.56 days and produced a high methane yield of 0.348 $m^3 \cdot (kg \cdot VS)^{-1}$ removed.

Recently, Masebinu *et al.* [2018] treated a mixture of fruit and vegetable wastes in a two-stage semi-continuous digester for optimality of biogas yield. The experimental setup of the micro-pilot plant consisted on a 6-dm^3 hydrolysis unit operating at 35±1ºC, and a vertical continuously stirred 35-dm^3 digester operating at 35±1°C. Optimal *OLR* ranged between 2.68–2.97 kg VS $m^{-3} \cdot d^{-1}$ which resulted in a specific biogas yield of 0.87 $m^3 \cdot kg \cdot VS^{-1}$ with 57.58% of methane on average. The results of the experimental study were used as a viable assessment for a full-scale 45 $t \cdot d^{-1}$ plant for Joburg Market considering three energy pathways. The plant has the potential to produce 1.6 mln of $m^3 \cdot year^{-1}$ of biogas with the potential for offsetting 15.2% of the Joburg Market energy demand. The study showed that the anaerobic digestion of FVWs as unique substrate is possible with financial and environmental attractiveness. Montes-García *et al.* [2019] determined the maximum organic load that can be treated in a two–stage anaerobic system for the stabilization of fruit and vegetable wastes. The hydrolysis-acidogenesis step was carried out in a batch-operated stirred-tank reactor (STR) and the methanogenic step was carried out in a UASB reactor. The maximum overall *OLR* applied was 13 kg VS $m^{-3} \cdot d^{-1}$, and the methane productivity reached 3.0 m^3 $CH_4 \cdot m^{-3} \cdot d^{-1}$ with a *COD* removal of 80%. Results showed that the anaerobic treatment of FVWW allows the production of a significant amount of biogas that can be used for the production of electricity and/or heat.

Artificial wetlands are considered biological reactors whose yield is described by an empirical first order kinetic model ($C_0/C_e = e^{-K_T t}$) that is based on large datasets. Recommendations of design and operation of AW-SSF is showed in Table 9. In summary: (1) L:W ratios of 1:1 and up to 3:1 are accepted since higher ratios could increase the flow resistance caused by the accumulation of plant residues; (2) flow short-circuiting can be minimized with careful construction and maintenance of the wetland, and this implies the use of multiple cells and areas without plants to have a better distribution of the flow; (3) the depth of the AW-SSF varies between 0.4 and 1.6 m, but the most commonly used in artificial wetlands is 0.6 m. However, in regions of warm weather, where there is no risk of water freezing, the depth of the wetland can reach 0.3 m. In these systems, *COD* and ammoniacal nitrogen removal performances are directly related to the plant rooting depth. These latter will be considered as the maximum growth potential limit for the wetland design depth; (4) the surface of the filter medium must be even and the bottom slope must not be greater than 3%, because the wastewater to be treated has to flow through the substrate overcoming the friction of the medium; (5) the equitable distribution of the inlet flow is very important, this must be made through triangular or rectangular weirs conveniently located at the inlet and outlet of the artificial wetland; (7) to minimize the localized drag of biological particles, the fluid circulation speed should be limited to a maximum value of 6.8 $m \cdot d^{-1}$; and (8) 10% of the depth of the filter medium can be taken as the maximum height difference between the entrance and the exit of the system. Increasing the bed height by 10% is sufficient for the proper functioning of the wetland when excessive loads occur during rain floods [Vymazal 2014; Wu *et al.* 2015].

Table 9. Recommendations for the design and operation of an artificial wetlands with sub-surface flow for wastewater treatment

Parameter	Design criteria	Unit
Wetland length:wetland width ratio	1:1–1:3	–
Water depth	0.4–1.6	m
Hydraulic slope	0.5–1.0	%
Organic loading rate	<0.5	$m \cdot d^{-1}$
Hydraulic retention time	2–5	d
Filter medium	natural and artificial filter medium can be used with a porosity between 28–45%, particle size 32–128 mm for the inflow, and 2–8 mm for the outflow	
Vegetation	native plant are preferred, plant density 80% coverage	

Source: own elaboration.

USE OF TREATED WATER

According to the results of the design carried out, the treated water will have an average *COD* concentration of 60 mg dm^{-3} in the effluent. Therefore, it does not satisfy the recycling requirements for canning, but it can be reused for washing fruits and vegetables. With the recycling, 30% of the water consumed in the industry can be saved. As another alternative, treated water could also be used for crop irrigation, both agricultural and ornamental, in areas planted near industry facility. Due to this condition, an additional income could be obtained from the sale of irrigation water in agriculture.

CONCLUSIONS

Anaerobic digestion is an effective technique to treat fruit and vegetable wastes. However, efficient removal of pollutants can be obtained using the concept of phase separation in the process and a high-rate anaerobic reactor. A phytodepuration treatment system with artificial wetlands is suitable for treating the effluent of previous anaerobic technologies for fruit and vegetable processing. Therefore, a system composed of UASB reactors and artificial wetlands is an adequate treatment alternative in regions of hot climate for wastewater generated by fruit and vegetable processing companies. An acidogenic anaerobic system handled an *OLR* of 13.84 kg *COD*$\cdot m^{-3} \cdot d^{-1}$ produce a leachate capable to be degraded in the methanogenic stage of the anaerobic treatment. Afterward, the UASB methanogenic system obtain high value pollution removal and biogas production at a OLR of 10 kg $COD \cdot \mathrm{m}^{-3} \cdot \mathrm{d}^{-1}$. The combination of two-phase AD system, followed by a cascade UASB reactor, and an AW system as tertiary treatment achieve global removal efficiencies upper at 98% and, at the same time, produce biogas. The quality of the water treated by the proposed system will allow recycling for the washing of fruit, which significantly reduce the water consumption of the industry facility, or an extra income could be obtained from the sale of irrigation water for agriculture.

ACKNOWLEDGEMENT

This study was partly supported by the Federal Ministry of Education and Research (BMBF) project InFertRes (CUB17WTZ-042).

REFERENCES

Álvarez J.A., Ruíz I., Soto M. 2008. Anaerobic digesters as a pretreatment for constructed wetlands. Ecological Engineering. Vol. 33 p. 54–67. DOI 10.1016/j.ecoleng.2008.02.001.

Arhoun B., Villen-Guzman M., Vereda-Alonso C., Rodríguez-Maroto J. García-Herruzo F., Gómez-Lahoz C. 2019. Anaerobic co-digestion of municipal sewage sludge and fruit/vegetable waste: Effect of different mixtures on digester stability and methane yield effect of different mixtures on digester stability and methane yield. Journal of Environmental Science and Health. Part A. Vol. 54. Iss. 7 p. 1–7. DOI 10.1080/10934529.2019.1579523.

Bouallagui H., Lahdheb H., Ben-Romdan E., Rachdi B., Hamdi M. 2009. Improvement of fruit and vegetable waste anaerobic digestion performance and stability with co-substrates addition. Journal of Environmental Management. Vol. 90 p. 1844–1849. DOI 10.1016/j.jenvman.2008.12.002.

Bouallagui H., Torrijos M., Godon J., Moletta R., Cheikh R., Touhami Y., Delgenes J., Hamdi M. 2004. Two phases anaerobic digestion of fruit and vegetable wastes: Bioreactors performance. Biochemical Engineering Journal. Vol. 21. Iss. 2 p. 193–197. DOI 10.1016/j.bej.2004.05.001.

Bouallagui H., Touhami Y., Cheikh R., Hamdia M. 2005. Bioreactor performance in anaerobic digestion of fruit and vegetable wastes. Process Biochemistry. Vol. 40 p. 989–95. DOI 10.1016/j.procbio.2004.03.007.

Caramillo R., Rincón J. 2012. Effect of inhibitory compounds on the two-phase anaerobic digestion performance of diluted wastewaters from the alimentary industry. Chemical Engineering Journal. Vol. 193–194 p. 68–76. DOI 10.1016/j.cej.2012.04.022.

Chan Y., Chong M., Law L., Hassell D. 2009. A review on anaerobic-aerobic treatment of industrial and municipal wastewater. Chemical Engineering Journal. Vol. 155 p. 1–18. DOI 10.1016.j.cej.2009.06.041.

Chernicharo C. 2007. Reatores anaeróbios [Anaerobic reactors]. Editorial UFMG pp. 379.

Chong S., Sen T., Kayaalp A., Ang H. 2012. The performance enhancements of UASB reactors for domestic sludge treatment: A state-of-the-art review. Water Research. Vol. 46 p. 3434–3470. DOI 10.1016/j.watres.2012.03.066.

Di Maria F., Barratta M. 2015. Boosting methane generation by co-digestion of sludge with fruit and vegetable waste: Internal environment of digester and methanogenic pathway. Waste Management. Vol. 43 p. 130–136. DOI 10.1016/j.wasman.2015.06.007.

Di Maria F., Sordi A., Cirulli G., Micale C. 2015. Amount of energy recoverable from an existing sludge digester with the co-digestion with fruit and vegetable waste at reduced retention time. Applied Energy. Vol. 150 p. 9–14. DOI 10.1016/j.apenergy.2015.01.146.

Diamantis V., Aivasidis A. 2007. Comparison of single- and two-stage UASB reactors used for anaerobic treatment of synthetic fruit wastewater. Enzyme and Microbial Technology. Vol. 42 p. 6–10. DOI 10.1016/j.enzmictec.2007.07.014.

Edwiges T., Frare L., Alino J., Triolo J., Flotats X., Costa M. 2018. Methane potential of fruit and vegetable waste: An evaluation of the semi-continuous anaerobic. Environmental Technology. Vol. 41. Iss. 7 p. 921–930. DOI 10.1080/09593330.2018.1515262.

Eid E., Shaltout K., Asaeda T. 2012. Modeling growth dynamics of *Typha domingensis* (Pers.) Poir. ex Steud. in Lake Burullus, Egypt. Ecological Engineering. Vol. 243 p. 63–72. DOI 10.1016/j.ecolmodel.2012.05.028.

Faulwetter J., Gagnon V., Sundberg C., Chazarenc F., Burr M., Brisson J., Camper A., Stein O. 2009. Microbial processes influencing performance of treatment wetlands: A review. Ecological Engineering. Vol. 35 p. 987–1004. DOI 10.1016/j.ecoleng.2008.12.030.

Gomes M., Souza R., Teles V., Mendes É. 2014. Phytoremediation of water contaminated with mercury using *Typha domingensis* in constructed wetland. Chemosphere. Vol. 103 p. 228–233. DOI 10.1016/j.chemosphere.2013.11. 071.

González O., Deas G. 2011. Metodología para el diseño de humedales con flujo subsuperficial horizontal [Design methodology of artificial wetlands with sub-surface flow]. Ingeniería Hidráulica y Ambiental. Vol. 32 p. 61–70.

Guardia-Puebla Y., Pérez-Quintero F., Rodríguez-Pérez S., Sánchez-Girón V., Llanes-Cedeño E., Rocha-Hoyos J., Peralta-Zurita D. 2019. Effect of hydraulic loading rate and vegetation on phytoremediation with artificial wetlands associated to natural swimming pools. Journal of Water and Land Development. Vol. 40 p. 39–51. DOI 10.2478/jwld-2019-0004.

Ji C., Kong C., Mei Z., Li J. 2017. A review of the anaerobic digestion of fruit and vegetable waste. Applied Biochemistry and Biotechnology. Vol. 183. Iss. 3 p. 906–922. DOI 10.1007/s12010-017-2472-x.

Liu W., Liao B. 2018. Anaerobic co-digestion of vegetable and fruit market waste in LBR + CSTR two-stage process for waste reduction and biogas production. Applied Biochemistry and Biotechnology. Vol. 188. Iss. 1 p. 185–193. DOI 10.1007/s12010-018-2910-4.

Masebinu S, Akinlabi E., Muzenda E., Aboyade A. 2018. Experimental and feasibility assessment of biogas production by anaerobic digestion of fruit and vegetable waste from Joburg market. Waste Management. Vol. 75 p. 236–250. DOI 10.1016/j.wasman.2018.02.011.

Montes-García M., Vigueras-Carmona S., Pérez-Vargas J., Zafra-Jiménez G., Velasco-Pérez A., Chang-Solís C. 2019. Two-stage anaerobic digestion of fruit and vegetable wastes. Journal of Biotech Research. Vol. 10 p. 29–37.

Mu H., Zhao Y., Hua D., Zhang X., Li Y., Zhang J. 2014. Comparision of treatment performance for fruit and vegetable waste (FVW) by single-phase and two-phase anaerobic digestion. Applied Mechanics and Materials. Vol. 535 p. 572–76. DOI 10.4028/www.scientific.net/AMM.535.572.

Rajeshwari K., Panth D., Lata K., Kishore V. 2001. A novel process using enhanced acidification and a UASB reactor for biomethanation of vegetable market waste. Waste Management and Research. Vol. 19. Iss. 4 p. 292–300. DOI 10.1177/0734242x0101900405.

Ravi P., Lindner J., Oechsner H., Lemmer A. 2017. Effects of target pH-value on organic acids and methane production in two-stage anaerobic digestion of vegetable waste. Bioresource Technology. Vol. 247 p. 96–102. DOI 10.1016/j.biortech.2017.09.068.

RAYNAL J., DELGENES J., MOLETTA R. 1998. Two-phase anaerobic digestion of solid waste by a multiple liquefaction reactors process. Bioresource Technology. Vol. 65 p. 97–103. DOI 10.1016/S0960-8524(98)00009-1.

SHENG K., CHEN X., PAN J., KLOSS R., WEI Y., YING Y. 2013. Effect of ammonia and nitrate on biogas production from food waste via anaerobic digestion. Biosystems Engineering. Vol. 116 p. 205–212. DOI 10.1016/j.biosystemseng.2013.08.005.

SIDDIQ M., AHMED J., LOBO, M.G., OZADALI F. 2012. Tropical and subtropical fruits: Postharvest physiology, processing and packaging. John Wiley & Sons. USA. ISBN 978-0-8138-1142-0.

SMITH D., ALMQUIST C. 2014. The anaerobic co-digestion of fruit and vegetable waste and horse manure mixtures in a bench-scale, two-phase anaerobic digestion system. Environmental Technology. Vol. 35. Iss 7 p. 859–867.

SOLERA R., ROMERO L., SALES D. 2002. The evolution of biomass in a two-phase anaerobic treatment process during start-up. Chemical Biochemical and Engineering Quality. Vol. 16. Iss. 1 p. 25–29. DOI 10.1080/09593330.2013.854398.

SRIDEVI V., REMA T., SRINIVASAN S. 2015. Studies on biogas production from vegetable market wastes in a two-phase anaerobic reactor. Clean Technologies and Environmental Policy. Vol. 17 p. 1689–1697. DOI 10.1007/s10098-014-0883-8.

VYMAZAL J. 2013. Emergent plants used in free water surface constructed wetlands: A review. Ecological Engineering. Vol. 61 p. 582–592. DOI 10.1016/j.ecoleng.2013.06.023.

VYMAZAL J. 2014. Constructed wetlands for treatment of industrial wastewaters: A review. Ecological Engineering. Vol. 73 p. 724–751. DOI 10.1016/j.ecoleng.2014.09.034

WANG X., LI Z., BAI X., ZHOU X., CHENG S., GAO R., SUN J. 2017. Study on improving anaerobic co-digestion of cow manure and corn straw by fruit and vegetable waste: Methane production and microbial community in CSTR process. Bioresource Technology. DOI 10.1016/j.biortech.2017.10.038.

WU L., KOBAYASHI T., LI Y., XU K. 2015. Comparison of single-stage and temperature-phased two-stage anaerobic digestion of oily food waste. Energy Conversion and Management. Vol. 106 p. 1174–1182. DOI 10.1016/j.enconman.2015.10.059.

WU Y., WANG C., LIU X., MA H., WU J., ZUO J., WANG K. 2016. New method of two-phase anaerobic digestion for fruit and vegetable waste treatment. Bioresource Technology. Vol. 211 p. 16–23. DOI 10.1016/j.biortech.2016.03.050.