Journal of Water Process Engineering 47 (2022) 102676

Contents lists available at ScienceDirect

Journal of Water Process Engineering

journal homepage: www.elsevier.com/locate/jwpe

Modelling and simulation of subsurface horizontal flow constructed wetlands

Roberto Aguado [a,b,*], Onintze Parra [a,b], Leire García [a], Mikel Manso [a], Leire Urkijo [a], Federico Mijangos [a]

[a] Dept. of Chemical Engineering, University of the Basque Country UPV/EHU, PO Box 644, E48080 Bilbao, Spain
[b] Engineering Without Borders — Basque Country, Ingeniero Torres Quevedo 1, E48013 Bilbao, Spain

ARTICLE INFO

Keywords:
Wastewater reuse
Constructed wetland
Grey water treatment
Modelling
Simulation

ABSTRACT

As a consequence of the poor implantation of sanitation systems, more than 80% of the wastewater from human activity is dumped, which poses a threat to public health and generates water stress. In contrast, its depuration and reuse for irrigation improves the efficiency of the water management cycle and reduces the use of fresh water. In the context of grey water purification in rural areas of Europe, constructed wetlands are the preferred option. Furthermore, in developing countries, they are particularly attractive as an alternative to conventional purification systems. The design of such facilities tends to avoid the complexity of the interactions between solids, pollutants, microorganisms, and plants. In this work, a more rigorous mathematical model is proposed, which considers the mass balances of the substrate and the microorganisms, in addition to the degradation kinetics typical of biotechnological processes, the life cycles of microorganisms, and their horizontal and vertical transport processes. This model was tuned based on the responses of already installed systems located in Zapote (Costa Rica) and San Salvador (El Salvador). The model foresees start-up times close to three months, in addition to depuration efficiencies reaching above 90%, which corresponds with previously reported values. The developed simulation tool is also employed to study the response of the model to various disturbances, such as punctual stops or seasonal variations in the incoming flow.

1. Introduction

The 2030 Sustainable Development Agenda, which was approved by UN Member States in 2015, aims to explore new ways to improve the quality of life, ensuring that no-one is left behind. With this aim, the Agenda establishes 17 objectives, among which the sixth objective seeks to guarantee the availability of water for all, in addition to its sustainable management and sanitation. Although progress has been made in the coverage of water supplies and sanitation systems, billions of individuals worldwide still lack such services, especially in rural areas. More specifically, according to UN data [1], 6 out of 10 individuals lack access to safely managed sanitation facilities, which is equivalent to more than 4 billion people worldwide, and implies that over 80% of the water resulting from human activity is dumped without any kind of treatment. Among the targets corresponding to this Objective, number 6.3 claims that water quality should be improved by reducing pollution, eliminating dumping, and minimising the release of hazardous chemicals and materials. This could halve the proportion of untreated wastewater and substantially increase recycling and safe reuse globally. In addition to protecting public health, wastewater treatment through recycling, reuse, and recovery can alleviate water stress and provide social, economic, and environmental benefits [2,3]. Taking into account that 69% of global water withdrawals correspond to agriculture (including irrigation, livestock, and aquaculture) [2], wastewater reuse for irrigation purposes has received attention to improve the efficiency of the water management cycle, ultimately alleviating the exploitation of fresh water sources and decreasing their pollution after use and discharge [4,5].

Grey water is defined as domestic wastewater generated from sinks, laundry, and showers, but excludes toilet water, or black water [6]. When grey water originates exclusively from personal hygiene, it is referred to as light grey water. In contrast, the sources of dark grey water include laundry machines, dishwashers, and kitchen sinks [7,8]. Grey water represents up to 75% of total domestic wastewater, with approximately 100–150 L person^{-1} d^{-1} being generated in developed countries, although smaller volumes are generally generated in developing countries [9]. Grey water presents a lower organic, nutrient, and

* Corresponding author at: Dept. of Chemical Engineering, University of the Basque Country UPV/EHU, PO Box 644, E48080 Bilbao, Spain
E-mail address: roberto.aguado@ehu.eus (R. Aguado).

https://doi.org/10.1016/j.jwpe.2022.102676
Received 12 November 2021; Received in revised form 5 February 2022; Accepted 20 February 2022
Available online 8 March 2022

Nomenclature

Δz	Length of the node, L
ε	Gravel bed voidage
η	Removal efficiency, %
μ_F, μ_S	Specific growth rate of the microorganisms in the grease trap and in the gravel bed, t^{-1}
$\mu_{F,\ max}$, $\mu_{S,\ max}$	Maximum growth rate of the microorganisms added to the grease trap and those in the gravel bed, t^{-1}
ρ_O	Average density of the oils and fats, $M\ L^{-3}$
σ	Temperature dependence coefficient corresponding to the growth of microorganisms, dimensionless
τ	Hydraulic retention time, t
A	Required wetland area, L^2
a	Interface surface of the grease trap, L^2
C^*	Background concentration, $M\ L^{-3}$
C_o, $'C_l$	Pollutant concentrations at the wetland inlet and outlet, respectively, $M\ L^{-3}$
E	Enzyme concentration at the interface of the grease trap, $M\ L^{-2}$
ET	Evapotranspiration, $L\ t^{-1}$
F	Concentration of the enzymatic reaction products in the aqueous fraction of the grease trap, $M\ L^{-3}$
f_h	Coefficient of proportionality for vertical transport of the microorganisms, dimensionless
f_v	Coefficient of proportionality for horizontal transport of the microorganisms, dimensionless
H	Flooded height of the gravel bed, L
h_i	Height of the sludge layer in the *i* node of the gravel bed, L
h_O	Height of the fat and oil layer in the grease trap, L
k_A	Kinetic constant for pollutant degradation in the model $K - C^*$, $L\ t^{-1}$
K_E	Proportionality constant for calculating the concentration of enzymes at the interface, L^{-1}
K_F, K_S	Half-velocity constant for the microorganisms added to the grease trap and those in the gravel bed, $M\ L^{-3}$
k_H	Hydraulic conductivity, $L^2\ L^{-2}\ t^{-1}$
K_O	Michaelis-Menten constant for the enzymatic reaction taking place at the interface of the grease trap, $M\ L^{-2}$
k_{cat}	Kinetic constant of the enzymatic reaction, t^{-1}
k_{dt}, k_{dw}	Constant desorption rate for the microorganisms added to the grease trap and for those in the gravel bed, t^{-1}
L	Length of the constructed wetland, L
m	Wetland slope, $L\ L^{-1}$
m_O	Mass of the oils and fats in the grease trap, M
M_t	Concentration of microorganisms in the aqueous fraction of the grease trap, $M\ L^{-3}$
n	Number of nodes
O	Concentration of the oils and fats at the interface of the grease trap, $M\ L^{-2}$
P	Precipitation, $L\ t^{-1}$
Q	Feed flow rate, $L^3\ t^{-1}$
r_O	Enzymatic reaction rate of the oils and fats, $M\ L^{-2}\ t^{-1}$
r_{20}	Rate constant of microbial growth to the standard temperature of 20 °C t^{-1}
S_{in}, S_i	Substrate concentration in the incoming stream and at the *i* node of the gravel bed, respectively, $M\ L^{-3}$
T	Water temperature, T
V_t	Grease trap volume, L^3
W	Width of the constructed wetland, L
X_i	Concentration of microorganisms in the *i* node of the gravel bed, $M\ L^{-3}$
x_i	Distance of the *i* node from the inlet, L
X_O	Volume fraction of the oils and fats in the incoming stream, $L^3\ L^{-3}$
X_s	Concentration of microorganisms in the sludge layer, $M\ L^{-3}$
y_i	Height of the free flow section in the *i* node of the gravel bed, L
Y_{XSt}, Y_{XSw}	Yield rate of the microorganisms added to the grease trap and of those in the gravel bed, $M\ M^{-1}$
BOD	Biochemical oxygen demand
BOD_5	Biochemical oxygen demand after five days
COD	Chemical oxygen demand
EC	*Escherichia coli*
TN	Total nitrogen
TP	Total phosphorous
TSS	Total suspended solids

pathogen load than black water, and consequently is easier to treat [7,10], thereby rendering on-site treatment possible [11]. Thus, the source separation of grey and black water can contribute to reducing discharge to wastewater treatment plants, and can also help address the issue of potable water scarcity worldwide [6,12,13]. Moreover, the reuse of grey water for non-potable uses (e.g., in toilets, washing, and irrigation) reduces the consumption of high-quality water to promote a circular economy [14].

Among the wide technological proposals suggested for the treatment of grey water, ranging from sand filters to sophisticated biological and chemical treatments [13,15], constructed wetlands have proven to be nature-based solutions which enable reduction of massive energy consumption [16,17]. In fact these facilities are economically and energetically efficient for reducing the contents of organic species and biological organisms, which ultimately allows the requirements of non-potable reuse to be met [7,13]. Constructed wetlands are made up of shallow lagoons or channels (depths less than 1 m) that are planted with local species typical of humid areas, and in which decontamination processes take place through interactions between water, solid substrates, microorganisms, vegetation, and even fauna [18]. Based on the water circulation characteristics, constructed wetlands can be classified into surface and subsurface flows [19,20]. In contrast to surface flow wetlands, their subsurface equivalents admit higher organic loads, reduce the risk of contact with the population, and prevent the appearance of insects [21]. Although they are less attractive to environmental projects due to the absence of an accessible sheet of water, subsurface flow constructed wetlands are the preferred option for grey water purification in rural areas of Europe [18,12]. Subsurface constructed wetlands consist of a gravel bed that acts as a substrate for plant growth, and depending on the configuration employed, the wastewater flows vertically or horizontally through the bed [6], which acts as a biofilter. In addition, a large number of physical, chemical, and biological processes also take place in the bed, including sedimentation, filtration, precipitation, adsorption, plant uptake, and microbial decomposition [22,23]. Furthermore, subsurface vertical flow constructed wetlands enhance oxygen transfer from the air to the wastewater flow, improving their nitrification capacity with respect to that of the horizontal configuration [4,5]. However, the pulsed water circulation is discontinuous, and so the granular medium is not permanently flooded. In developed countries, vertical systems are combined with horizontal ones, and although this configuration appears superior, it requires more sophisticated and expensive installations, not to mention additional maintenance. Hence, due to the low economic and energetic costs of horizontal subsurface flow constructed wetlands, in addition to their particularly low impact on the environment and landscape, the implementation of such configurations is especially attractive for developing countries [24,25], where natural biodegradation processes can be applied to improve N removal [26]. Among the disadvantages of this type of natural wastewater treatment system, it should be taken into account that they require large surface areas, start-up lasts between three and six months, and once running there are few options for their control. Thus, at the design stage, the maximum and minimum flow peaks should be considered. Furthermore, it should be considered that they require periodic maintenance, consisting of the removal of flocs from the inlet pipes, the pruning of plants, cleaning of the outer surface of the bed, and control of the height of the flooded bed. Moreover, in the case of observing the appearance of water on the surface, the removal, clearance, and/or replacement of the gravel with a new material of the same characteristics is required.

When constructed wetlands are used for the purification of dark grey water, it must be considered that fats and oils prevent contact between the microorganisms and the water, and could even provoke flow blockage. To avoid this issue, flotation is commonly employed [27], wherein a grease trap is employed for pretreatment. Such devices are effective for the removal of emulsified oil and grease droplets, and so they are commonly employed in restaurants prior to wastewater disposal into the sanitation system [28]. These devices require periodical maintenance to remove the hydrophobic layer of fats that accumulates on top to avoid overflow and bad odours. An alternative method to reduce the amount of accumulated fats and avoid its subsequent treatment is bioactivation by the addition of lipases, which are enzymes that catalyse the hydrolysis of lipids to glycerol and fatty acids [29,30]. These compounds can pass through the cell walls of microorganisms [31], and so can be digested with the organic load upon reaching the sanitation system.

The interest in constructed wetlands as a natural-based solution for wastewater treatment began in the 1980s, although scientific production during the last century has been limited. Despite the fact that, in the last decade the scientific community has returned to focus on these kinds of solutions [7], there are very few studies addressing the rigorous design of these complex systems and their dynamic responses to possible disturbances [32,33,34]. Grey water treatment in constructed wetlands is a complex process that includes sedimentation, filtration, sorption, plant uptake, and microbial decomposition [35], wherein each factor influences the other factors. Moreover, modelling these interactions is difficult and complex due to a lack of appropriate models. Until the beginning of the 21st century, the use of first order $k - C^*$ models was common. These models assume an ideal plug flow and consider that the various parameters do not depend on the inlet concentration or the incoming flow. In 2000, Kadlec [36] demonstrated that these models present serious limitations for the rigorous modelling of constructed wetlands, and proposed the $P - k - C^*$ model, which is based on a scheme of tanks in series. Indeed, Laaffat et al. [23] used this model to estimate the profiles of degradation at the simulated gravel bed. More recently Mohammed and Ismail [37] proposed the use of a multi-layer artificial neural network model to predict the efficiency of a lab-scale constructed wetland to treat real food industry wastewater from a cheese factory. Gomes Ferreira et al. [38] validated the utility of the model proposed by Chan and Chu for the reaction kinetics of Fenton's process on the removal of atrazine [39]. Dittrich et al. [40] and Samsó et al. [41] focused on modelling single physicochemical phenomena occurring on SSHFCW (transport processes and clogging), while Yuan et al. [42] reviewed several single models that describe these and other complex processes occurring in CWs, including biochemical, hydraulic, reactive-transport, plant and clogging models. These authors conclude that a single or a composite model coupling a small number of sub-models cannot fully predict the decontamination processes, while a comprehensive model including all sub-models involves numerous parameters, making the model complex and leading to diffuse interaction. However, the most common design procedure, which is explained in detail in various technical manuals, such as those published by García and Serrano [18] and Delgadillo et al. [19], is based on the experience accumulated by companies and organisations from the civil engineering field, and does not address the complexity of the processes and interactions that occur between solids, pollutants, microorganisms, and plants. These semi-empirical models usually propose simplifications regarding the flow of wastewater though the bed, the substrate degradation kinetics, the kinetics of the proliferation and death of microorganisms, the effect of pretreatment, the horizontal transport promoted by dragging, and the vertical sedimentation of microorganisms. Thus, the current work aims to address this lack of knowledge to develop a more rigorous mathematical model than those previously published, and which will describe the dynamic behaviour of a horizontal subsurface constructed wetland containing a bioactive grease trap. Subsequently, the model will be tuned based on the response of already installed systems. In addition, this simulation tool will be used to study the response of the model to various disturbances, such as punctual stops or seasonal variations in the incoming flow. Furthermore, our model will consider the mass balances of the substrate and the microorganisms, in addition to the degradation kinetics typical of biotechnological processes, the life cycle of the microorganisms, and their horizontal and vertical transport.

2. Modelling

Fig. 1 shows a diagrammatic scheme of the system proposed for modelling, consisting of a grease trap followed by a subsurface horizontal flow constructed wetland.

2.1. The bioactive grease trap

Lipases are enzymes belonging to the class of esterases that catalyse the hydrolysis of lipids. They use water to break the bonds of triglycerides, generating glycerol and fatty acids. The interfacial properties of such enzymes allow them to activate reactions that occur at the interface, which is the point at which they are active [43]. These unique properties render lipases an interesting additive for grease traps. More specifically, lipases can be added after their isolation or by means of specialised microorganisms that produce these biocatalysts. Such microorganisms are very common in nature, where they can be collected and cultivated; this is common practice in certain communities of El Salvador. Importantly, the addition of microorganisms instead of isolated enzymes is cheaper, easier, and more effective for the self-maintenance of constructed wetland. In this case, the enzymatic reaction products, which pass into the aqueous phase, serve as the substrates for microbial activity, since they can pass through the cell wall. Therefore, the aqueous phase contains biomass (microorganisms), grey water, and the enzymatic reaction products, as outlined in Fig. 2. The kinetic mechanism of enzymatic lipid hydrolysis has been previously described in the literature [44]. More specifically, the kinetic models of such reactions that occur in biphasic organic-aqueous systems consider a reaction rate based on the interfacial substrate concentration [45,46] that may be reduced to the Michaelis-Menten form [47]:

$$r_O = \frac{k_{cat} E O}{K_O + O} \tag{1}$$

where K_O is the Michaelis-Menten constant of the enzymatic reaction, r_O is the enzymatic reaction rate of the oils and fats, k_{cat} is the kinetic constant of the enzymatic reaction, and E and O are the enzyme and oil + fat concentrations at the interface, respectively, which are assumed to be constant. E is proportional to the concentration of microorganisms in the aqueous fraction.

The evolution of the microbial population in the grease trap has been modelled assuming Monod-type kinetics:

$$\mu_F = \mu_{F,max} \frac{F}{K_F + F} \tag{2}$$

where μ_F is the specific growth rate of the microorganisms in the grease

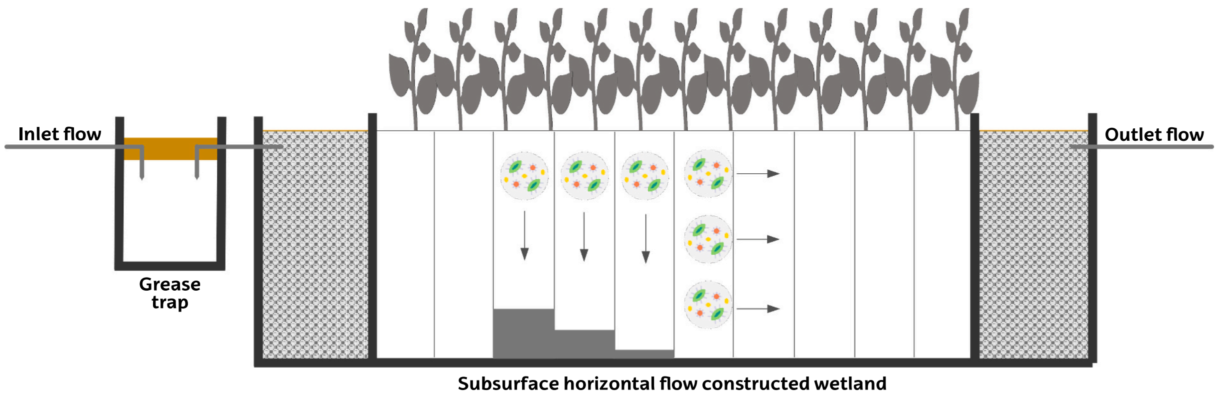

Fig. 1. Diagrammatic scheme of the modelled facility.

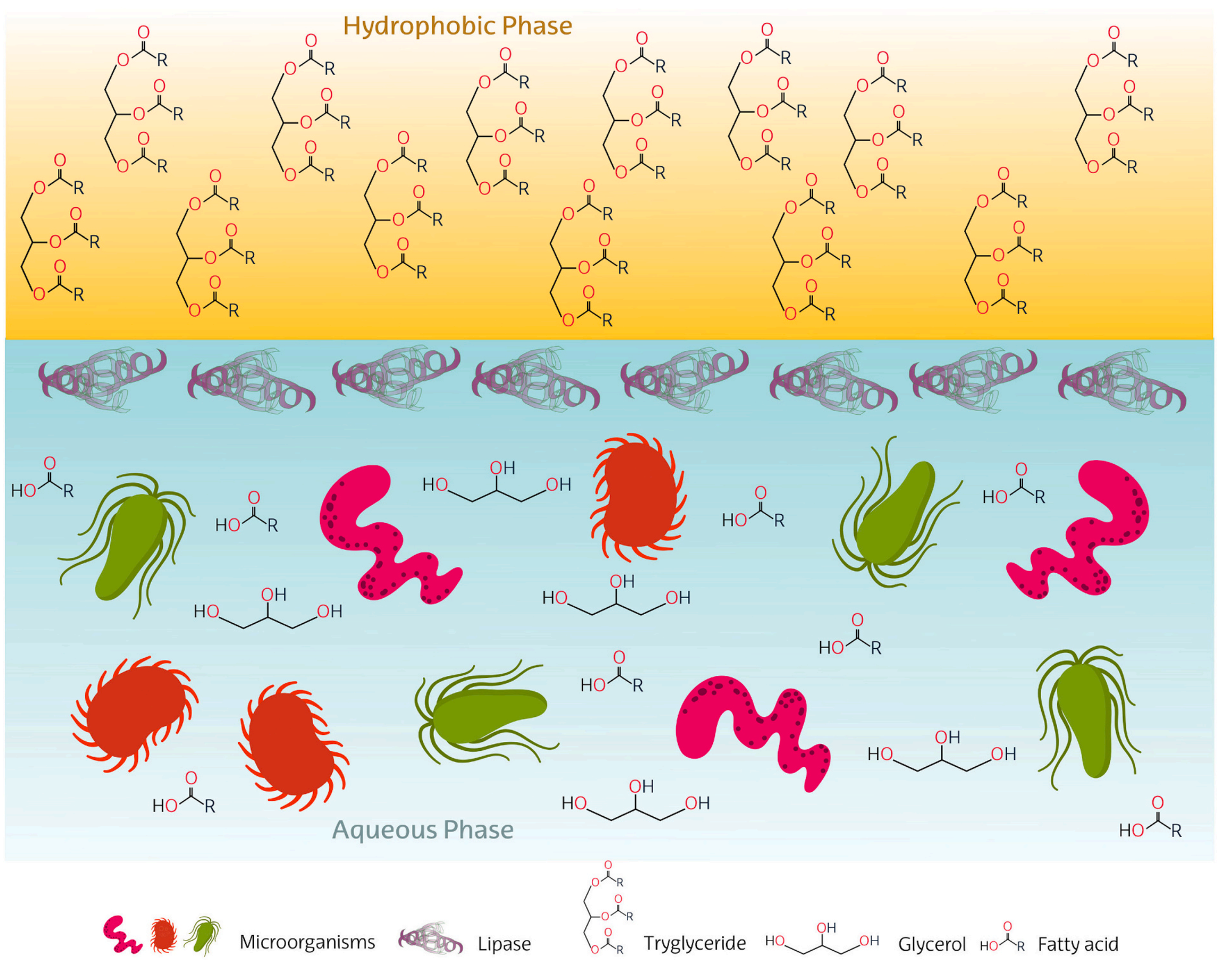

Fig. 2. Schematic representation of the grease trap interface.

trap, $\mu_{F,\ max}$ is the maximum growth rate of these microorganisms, F is the concentration of the enzymatic reaction products in the aqueous phase, and K_F the Monod constant or half-velocity constant for the growth rate of the microorganisms in the grease trap, i.e., the value of F when $\mu / \mu_{F,\ max} = 0.5$.

Modelling of the grease trap requires solving mass balances for the oils and fats, and also for the microorganisms and enzymatic reaction products. Taking into account the high disaffinity of oils and fats towards water, it can be assumed that phase segregation occurs instantaneously. On the other hand, due to the turbulence generated by the incoming stream, the aqueous phase can be modelled as a stirred tank reactor. Therefore, the mass balances can be written as follows:

$$\frac{dm_O}{dt} = QX_O\rho_O - r_Oa \tag{3}$$

$$\frac{dM_t}{dt}V_t = (\mu_F - k_{dt})M_tV_t \tag{4}$$

$$\frac{dF}{dt}V_t = (-QF + r_Oa) - \frac{\mu_F M_t}{Y_{XSt}}V_t \tag{5}$$

where V_t is the grease trap volume, Q is the feed flow rate, m_O is the mass of the oils and fats in the grease trap, X_O is the volume fraction of the oils and fats in the incoming stream, ρ_O is the average density of the oils and fats, a is the biphasic organic-aqueous interface surface, M_t is the concentration of microorganisms in the aqueous fraction, k_{dt} is the constant desorption rate, and Y_{XSt} is the yield rate of the microorganisms.

During ordinary operation, constructed wetlands do not receive a constant flow rate of grey water, since this flow rate is directly determined by domestic rhythms. For example kitchen sinks are used most commonly during mealtime hours, while taps, showers, and washing machines are used at specific and punctual times. The proposed model therefore simulates the inflow through pulses of adjustable durations, in addition to changes in the flow rate and concentration. As a result, it can be adapted to the constructed wetlands that serve homes, restaurants, and rural hotels. Likewise, the addition of the biocatalysts (in the form of cultivated microorganisms) is not constant, but is carried out periodically.

2.2. *The constructed wetland*

Wastewater reaches the constructed wetland after leaving the grease trap, and so it accesses the gravel bed free of oils and fats, but with an additional load of organic matter, namely the fatty acids and glycerol components generated during enzymatic digestion of the grease. Likewise, the microorganisms added to the grease trap for enzyme production are carried away by the water flow and enter the gravel bed, mixing with the local microbial population and participating in the removal of organic matter. As mentioned previously, the evolution of the microbial population in the gravel bed can been modelled according to the concentration of organic matter when assuming Monod-type kinetics:

$$\mu_S = \mu_{S,max}\frac{S}{K_S + S} \tag{6}$$

where μ_S is the specific growth rate of microorganisms in the gravel bed, $\mu_{S,\,max}$ is the maximum growth rate of this microbial population, S is the concentration of the substrate (organic matter as BOD), and K_S is the Monod constant for the growth rate of microorganisms in the wetland. $\mu_{S,\,max}$ increases with temperature according to the modified Arrhenius equation:

$$\mu_{S,max} = r_{20}\sigma^{(T-20)} \tag{7}$$

where r_{20} is the rate constant of microbial growth at a standard temperature of 20 °C, σ is the temperature dependence coefficient corresponding to the growth of microorganisms, and T is the water temperature in °C. Nevertheless it should be noted that several authors have demonstrated that the efficiency of wetlands in removing organic matter is not significantly affected by seasonal temperature variations [35].

Inside the bed, microorganisms are attached to gravel particles and are also suspended in the stream to form large clusters or flocs. The model should therefore consider microorganism transport, both horizontally and vertically, wherein the former facilitates colonisation and extends the microbial activity to the entire bed. Furthermore, vertical transport is taken into account to consider that the sedimentation of flocs can generate a layer of sludge that blocks the interparticular voids and reduces the flow section for the wastewater, thereby rendering the wetland useless.

The properties of the wastewater depend on both the time and the longitudinal position along the process, and so for modelling purposes, the gravel bed is divided longitudinally into n nodes, wherein the cross-section is WH and the length is $\Delta z = L/n$. W is the total width of the constructed wetland, H is the flooded height of the gravel bed, and L is the total length of the wetland. In each node, this model should resolve the mass balance of the substrate and the microorganisms, in addition to the height of the sludge layer, which determines the flow velocity. It has also been considered that the amount of microorganisms passing from one node to the next (horizontal transport) as well as the amount of sludge accumulated in the bottom of the gravel bed due to settling (vertical transport) are both proportional to the concentration of microorganisms in each node. Thus, the quantification coefficients f_h and f_v are proposed for horizontal and vertical transport, respectively, and the mass balances in the i node can be written as follows:

$$W\Delta z\varepsilon\frac{d(y_iS_i)}{dt} = Q(S_{i-1} - S_i) - \frac{\mu_{S,i}}{Y_{XSw}}X_iy_iW\Delta z\varepsilon \tag{8}$$

$$W\Delta z\varepsilon\frac{d(y_iX_i)}{dt} = Q(X_{i-1}f_h - X_i(f_h + f_v)) + (\mu_{S,i} - k_{dw})X_iy_iW\Delta z\varepsilon \tag{9}$$

$$W\Delta z\varepsilon X_s\frac{dh_i}{dt} = QX_if_v \tag{10}$$

where ε is the gravel bed voidage, X_i is the concentration of microorganisms in the i node, y_i is the height of the free flow section in the i node, X_s is the concentration of microorganisms in the sludge layer, and h_i is the height of the sludge layer, so that $y_i = H - h_i$.

As can be deduced from the previous equations, the proposed model resembles that developed by Kadlec [36,35] and used by Laaffat et al. [23] with regard to the division of the gravel bed into tanks in series. However, the $P - k - C^*$ model does not consider sludge sedimentation or colonisation of the subsequent tanks by the entrapment of microorganisms, and does not include grease trap modelling. Furthermore, the degradation rate is described in terms of first order kinetics instead of using the kinetic equations of microbiological processes. Although the effect of evapotranspiration, ET, and precipitation, P, have not been considered in the proposed development, Eqs. 8 and 9 can be easily adapted to take into account dilution and an increase in the flow rate at each node due to meteorological conditions (ΔQ_i):

$$\Delta Q_i = Wx_i(P - ET) \tag{11}$$

where $x_i = iL/n$.

An algorithm written in *Scilab* was employed for model implementation, and this algorithm includes the subroutine *ode* for solving the set of $3n + 3$ ordinary differential equations (Eqs. 3–5 and Eqs. 8–10).

3. Model parameters

3.1. *Dimensioning*

The use of the model proposed in this paper for simulating real or projected facilities requires establishing values for all the parameters defined in Section 2. To date, several studies have been published in the literature that are useful to determine the flow rate [32,15,48,4,5], the average grey water production per inhabitant and day, and its composition in different regions throughout the world [7,49], as well as the physicochemical and biological properties of different types of wastewaters (i.e., light, mixed, and dark) [6]. Likewise, several works have focused on characterisation of the outflow of operating facilities, both in terms of the composition [50,20,51,13] and the efficiency of the wetland in removing the usual pollutants [12,52,53,54,55], which usually is defined as follows:

$$\eta = \frac{C_o - C_l}{C_o} \tag{12}$$

where C_o and C_l are the pollutant concentration at the wetland inlet and outlet, respectively. Investigations that gather information regarding the specifications for possible reuses established in various regulations [7,10] are also useful since they allow the establishment of design objectives to size future wetlands.

To date, several configurations have been proposed for the grease trap; however, its dimensions usually depend on the flow rate and the oil/fat concentration in the treatment stream [28]. To carry out dimensioning of the constructed wetland, the standard procedure employed is based on the $k - C^*$ model, which, as mentioned above, is based on the assumption that the wetland behaves as a plug flow biological reactor and that the degradation of pollutants can be described by first order kinetic equations related to the concentration of each pollutant. Instead of the degradation kinetic constant, whose dimension is t^{-1}, it is usual to use the product of this based on the porosity, ε, and the flooded height of the gravel beds, H, so that the dimensions of this kinetic constant, k_A, are $L\,t^{-1}$. Table 1 lists several of the values proposed in the literature.

Integrating the mass balance of the pollutant in the bed and taking into account that the hydraulic retention time, τ (i.e., the time that grey water remains retained in the gravel bed) is defined as:

$$\tau = \frac{\varepsilon WHL}{Q} \tag{13}$$

the required wetland area, $A = WL$, can be estimated by the following equation:

$$A = \frac{Q}{k_A} log\left(\frac{C_o}{C_l}\right) \tag{14}$$

It should be noted that the $k - C^*$ model is not valid when horizontal constructed wetland is integrated in a combined system and when it is located after a subsurface vertical flow constructed wetland. In this case it should be considered that the previous system generates a certain amount of pollutants, which is referred to as the background concentration, C^*. For these cases, Kadlec [36] proposed the $P - k - C^*$ model. Accordingly the required wetland area should be estimated by:

$$A = \frac{Q}{k_A} log\left(\frac{C_o - C^*}{C_l - C^*}\right) \tag{15}$$

To calculate the background concentration, Kadlec and Wallace [35] proposed the following equations. More specifically, for the BOD_5:

$$C^* = 3.5 + 0.053C_o \tag{16}$$

where $0 < C_o < 200$ mg L^{-1},
for the TSS:

$$C^* = 7.8 + 0.063C_o \tag{17}$$

for the TN:

$$C^* = 1.5 \text{ mg L}^{-1} \tag{18}$$

and for the TP:

$$C^* = 0.02 \text{ mg L}^{-1} \tag{19}$$

Once the wetland area has been defined, its width, W, can be calculated using the following expression derived from Darcy's Law, which describes the flow of a fluid through a porous bed:

$$W = \frac{Q}{k_H mH} \tag{20}$$

where k_H is the hydraulic conductivity of the bed and m is the wetland slope. As in the case of ε, k_H depends on the particle diameter of the gravel [58]. On the other hand, m tends to be approximately $1 - 2\%$ [18], while $H < 1$ m [52,57]. Finally the length of the gravel bed, L, can be determined by:

$$L = \frac{A}{W} \tag{21}$$

Table 1
Previously published values for the kinetic constant of pollutant degradation.

Reference	Contaminant	k_A (m d^{-1})
[36]	BOD	0.05 − 0.12
[18]	BOD	0.08
[18]	TN	0.03
[56]	BOD_5	0.22 ± 0.04
[56]	COD	0.17 ± 0.03
[56]	TN	0.03 ± 0.02
[56]	TP	0.02 ± 0.01
[56]	EC	0.35 ± 0.14
[4]	BOD	0.16
[57]	BOD	0.31

3.2. Enzymatic activity in the bioactive grease trap

In addition to the physicochemical parameters of the inlet stream, the facility requirements (i.e., the removal efficiency of pollutants), and the geometric dimensioning (which can be carried out based on previously published literature), the simulation of a wetland using the model proposed in this work requires the definition of all parameters related to the biological activity, both in the grease trap and also in the gravel bed of the wetland.

Thus, microorganisms collected from the soil of forested areas of the Santa Marta Community in El Salvador were used to obtain reference values for the kinetic constant of the enzymatic reaction and the corresponding Michaelis-Menten constant (Eq. 1), the constant of proportionality to determine the surface concentration of the enzymes at the interface, the maximum growth rate and the Monod constant corresponding to the growth rate of the microorganisms (Eq. 2), the constant desorption rate (Eq. 4), and the yield rate of the microorganisms added to the bioactive grease trap (Eq. 5). The microorganisms were isolated and grown according to a procedure developed by the ADES Santa Marta technicians (i.e., an association for community economic and social development). This procedure was based on the common practices of local farmers, who use these crops for organic amendment and for soil decontamination. Indeed, these microorganisms have demonstrated a remarkable enzymatic activity in regulating the fat and oil levels in the pretreatment stages of constructed wetlands. Following their cultivation, which was carried out under anoxic conditions and in the absence of sunlight, the microorganisms were dispersed in water to obtain the additive that will be periodically added to the grease trap. In the case of the additive prepared in our laboratory, several hydrolysis tests were carried out using sunflower oil and olive oil with constant stirring of the aqueous phase. Fatty acid production was measured via acid-base titrations using phenolphthalein as the indicator, and it was found that the microorganisms exhibited a slightly higher degradation capacity in the case of sunflower oil. Although it would be interesting to carry out the same experiments using other types of vegetable oils (e.g., rapeseed, soybean, and palm) and also using animal fats (e.g., chicken, pork, cow, and lamb), the average values obtained in the tests carried out using sunflower and olive oil were considered valid (see Table 2).

Based on the values shown in Table 2, the behaviour of the bioactive grease trap of a typical catering establishment was simulated. The volume of the simulated trap was 0.62 m^3 and the radius was 0.38 m. The inlet flow rate was 600 L h^{-1}, the concentration of fats and oils was 550 g m^{-3}, and ρ_O=900 kg m^{-3}. Finally, the grease concentration at the interface was estimated to be 50 g m^{-2}. To simulate discontinued use of the kitchen, it was assumed that the service was open from 7:00 AM to

Table 2
Proposed values for kinetic modelling of the enzymatic degradation of fats and oils.

Parameter	Units	Proposed value
k_{cat}	h^{-1}	2.6
K_O	g m^{-2}	0.13
K_E	m^{-1}	0.062
$\mu_{F,\,max}$	h^{-1}	0.010
K_F	g m^{-3}	65
k_{dt}	h^{-1}	0.012
Y_{XSt}	g g^{-1}	0.52

1:00 PM for breakfast and lunch, and from 7:00 PM to 11:00 PM for the dinner shift. Microorganisms were added periodically every 15 d, which is the usual recharge time at the ADES Santa Marta facilities. Fig. 3(a) shows the evolution over time for the height of the layer of oils and fats, while Fig. 3(b) reflects the concentrations of fatty acids and glycerol in the aqueous phase, and Fig. 3(c) shows the evolution of the microorganism concentration. The proposed values for the parameters that describe the microbiological activity in the bioactive grease trap are given in Table 2, and allow us to predict the usual behaviour of this type of facility when the appropriate additive (i.e., that prepared following the ADES Santa Marta procedure) is employed. It can be observed that during a three month period of operation, the layer of fats and oils was not expected to exceed 3.5 cm, as shown in Fig. 3(a). Moreover, the periodic feeding of the additive prepared from the oil microorganisms significantly reduced its thickness, and following the second addition, the layer practically disappeared during the 5 days after recharge. The subsequent exponential increase in the layer thickness was attributed to a reduction in the microbial population due to its transport by the influent towards the constructed wetland. The concentration of fatty acids and glycerol in the aqueous phase, both of which are products from the enzymatic reaction (Fig. 3(b)), followed an inverse trend, with maximum values reaching approximately 3000 g m^{-3} after use of the kitchen and in the initial days following addition of the bioadditive. The minimum values, which were approximately between 100 and 300 g m^{-3}, occurred in the hours prior to the use of the kitchen, and particularly in the days prior to recharging, when the concentration of microorganisms in the aqueous phase reached its minimum value of approximately 850 g m^{-3} (Fig. 3(c)).

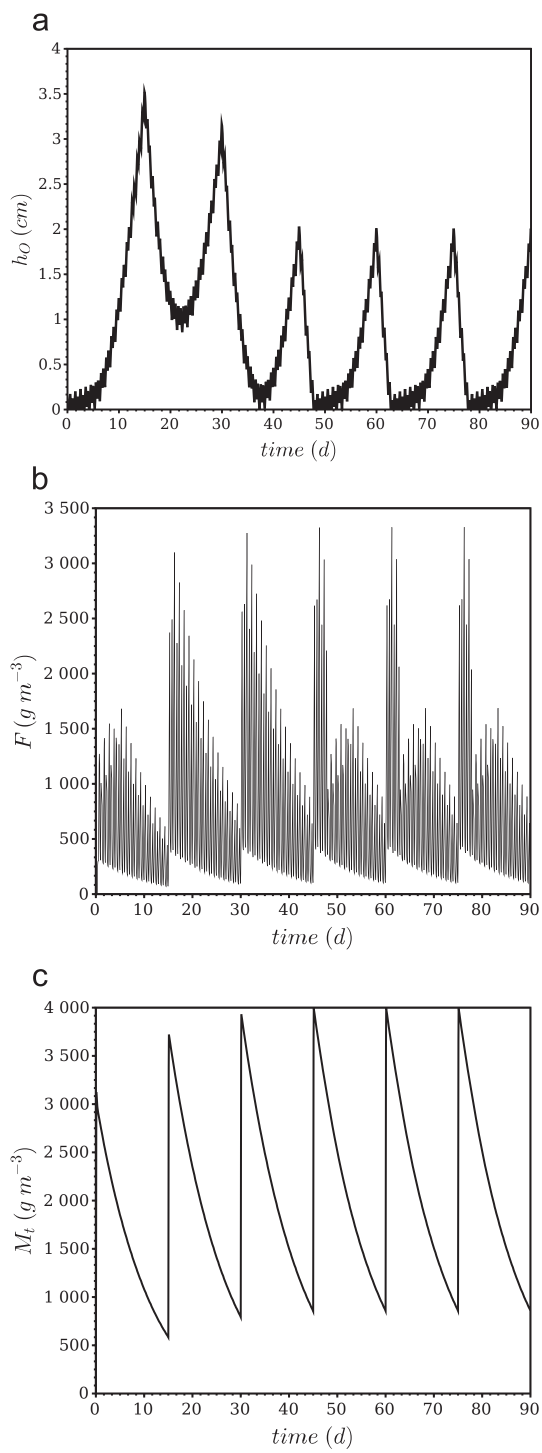

Fig. 3. Evolution over time of a) the height of the fat and oil layer, b) the concentration of fatty acids and glycerol in the aqueous phase, and c) the microorganism concentration.

3.3. Biological activity in the wetland bed

To establish reference values for the parameters that describe the biological activity in the wetland bed, the results published by Moncada [56] and Bolaños and González [57] have been particularly useful. More specifically, the first of these works evaluated the design of a horizontal constructed wetland installed in Zapote, Costa Rica, while the latter evaluated the efficiency of a constructed wetland designed to treat dark grey water from the kitchens of the University of El Salvador. Although in both cases the facilities included pretreatment systems for fat and oil elimination, the authors only reported information related to pollutant concentrations of the inlet and outlet streams. The dimensions of the Costa Rican wetland were as follows: W=1.0 m, H=0.7 m, and L=5 m, Q=70 L h^{-1}, S_{in}=230 g m^{-3}, and ε=0.5. The organic matter concentration in the outlet stream measured by Moncada was 18.1 g m^{-3}, which is equivalent to a removal efficiency of 92%. In contrast, the wetland built in the Salvadoran university campus was markedly larger, where W=5.0 m, H=0.8 m, and L=15 m. This larger size was necessary since it is designed to treat a significantly higher flow rate of Q=14.5 m^3 d^{-1}, and has an estimated organic load approximately three times higher than that of the first facility, i.e., S_{in}=700 g m^{-3}. The gravel used in the construction of this second facility is also finer, and consequently, its voidage is lower, ε=0.35. The organic matter concentration in the outlet of the gravel bed measured by Bolaños and González was 35 g m^{-3},

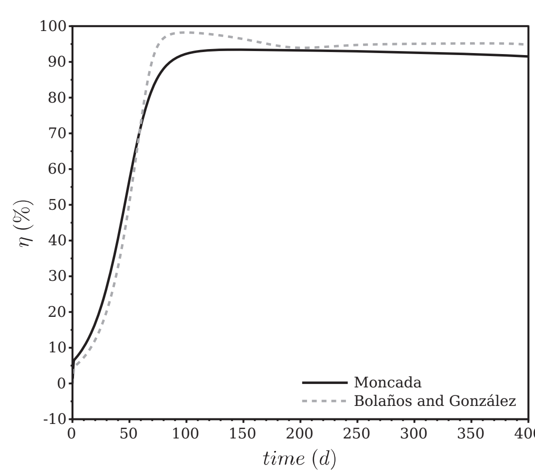

Fig. 4. Evolution over time of the removal efficiency in the simulations of constructed wetlands, as studied by Moncada [56] and Bolaños and González [57].

which is equivalent to a removal efficiency of 95%. Fig. 4 shows the evolution over time of the removal efficiency estimated based on the simulation of these two constructed wetlands, and using the parameters proposed in Table 3. These parameters were determined by establishing ranges based on the usual values in biological reactions of degradation of organic matter in wastewater. The optimum values set out in Table 3 were obtained by constrained optimization using the subroutine *fminsearch* in Scilab, which is based on the modified Nelder-Mead algorithm. The Objective Function was defined as the variance associated with the differences between the results published in the literature and those predicted by the model.

It can be seen that in both cases, the fitting between the results obtained with the model and those measured experimentally is reasonably good, since after one year of operation, the estimated efficiencies agree with the reported values and remain stable over time. The model also predicts start-up periods of approximately three months for the facilities, which is a typical time scale in tropical regions. In the smaller wetland, studied by Moncada, the start-up time was slightly faster, although a few additional weeks were required to reach a stable operating value, η=92%. Furthermore, the model was able to foresee a slight decrease in efficiency as the operating time increased; this will be discussed in the following section. In the larger facility, the start-up was initially slower, but after the first month, the microbial activity increased and quickly reached values above 90%. The model also foresees slightly higher efficiency values during the first weeks after reaching optimal operation levels, in addition to a slight decrease from the fifth month to stabilise at the value reported by the authors, i.e., η=95%. These slight differences in the behaviours of the two wetlands can be attributed to the differences in their dimensions, the influent flow, and the organic load in the treated water. Thus, when treating wastewater with a significantly higher organic load, it is expected that the Salvadoran wetland is more efficient. The values proposed in Table 3 have been also used to simulate the facility studied by Laaffat et al. [23] and built at a primary school in Marrakech (Morocco). In this case, the model was able to foresee an efficiency of approximately 94%, which agrees with the data reported by the authors. It would be interesting to simulate additional facilities to confirm these values or to extend the ranges proposed in Table 3, since it is foreseeable that these will be affected by the type of organic load (i.e., light or dark grey water), by the average annual temperature, by the rainfall regime, and even by the plant species present on the surface. Nevertheless, the results obtained in the simulations show that the model is able to accurately simulate the operation of three facilities installed in two different regions with widely different nominal dimensions and capacities. It can therefore be expected that it will be well suited for the modelling and simulation of any subsurface horizontal flow constructed wetland.

4. Simulations

Although future works will produce additional experimental data to consolidate the tuning of the model, the developed simulation tool has demonstrated its ability to simulate real systems, and it can also be used to analyse the evolution of non-measurable parameters in operating facilities and to study the effect of modifying the operating parameters. As a result, our simulation tool can be used to anticipate the response of the system, to establish stabilisation measures in case of occasional disturbances, and to predict the future behaviours of projected facilities. To demonstrate some of these possibilities, the results obtained in several simulations that aim to address these situations are discussed below.

More specifically, Fig. 5 shows the evolution of the amount of organic matter (as BOD) and microorganism concentrations over time at the outlet of a system consisting of a 250 L bioactive grease trap and a constructed wetland with a 1 m width, a 5 m length and a 0.7 m height. This wetland is assumed to be fed with a flow rate of 70 L h^{-1} and a substrate load of 230 g m^{-3} in the same hourly intervals previously defined for the simulation of the grease trap in Fig. 3. The other model parameters are comparable to those presented in Tables 2 and 3. In Fig. 5 (a), it can be seen that the model foresees a period close to two months until the substrate concentration in the outlet reaches values that allow the reuse of water for agriculture applications, and one additional month until it is stabilised at values that correspond to an efficiency close to 94%, which is typical for this type of facility. Fig. 5(b), where the evolution of the outlet microorganism concentration over time can be observed, shows that using the proposed values, this parameter reaches a maximum slightly higher than 45 g m^{-3} during the start-up phase, which rapidly reduces to negligible values once the steady state is reached. This maximum, which occurs after approximately 50 d, can be attributed to the poor performance of the constructed wetland during the initial weeks, which results in higher substrate and microorganism concentrations throughout the entire gravel bed. Once the bacterial population grows and stabilises in the section close to the wastewater

Table 3
Proposed values for the modelling of organic matter degradation in the gravel bed.

Parameter	Units	Proposed value
r_{20}	h^{-1}	0.20/24
σ		1.00
K_S	g m^{-3}	100
f_h		0.004 – 0.005
k_{dw}	h^{-1}	(0.02 – 0.08)/24
Y_{XSw}	g g^{-1}	0.08 – 0.10

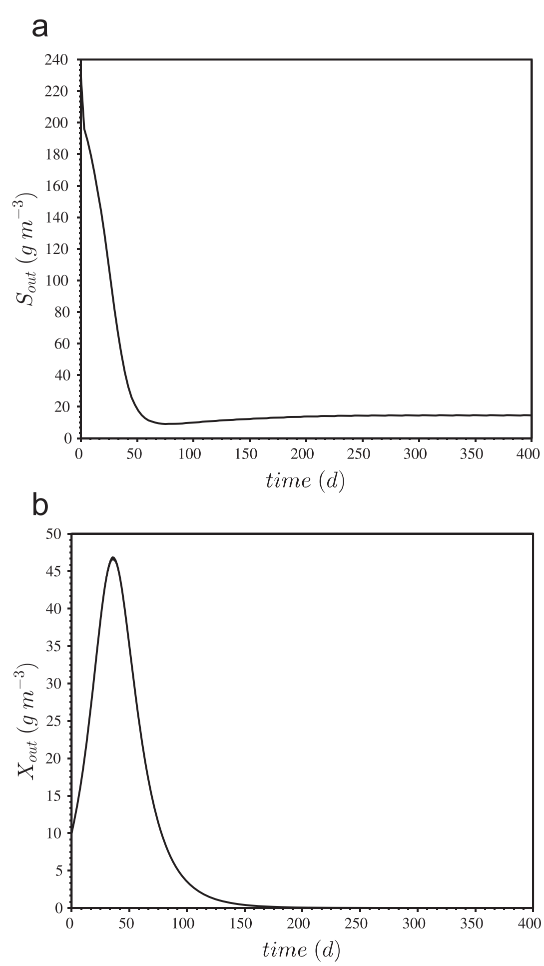

Fig. 5. Evolution of the a) substrate and b) microorganism concentrations at the end of the gravel bed over time.

inlet, the microbiological activity is sufficient to significantly reduce the substrate concentration as the wastewater flows towards the outlet, thereby limiting the growth of microorganisms in this section of the bed.

This hypothesis was confirmed by analysing the evolution of the substrate and microorganism concentrations over time, in addition to their analysing longitudinal positions, as shown in Figs. 6 and 7. Accordingly, in Fig. 6 it can be seen that although the substrate concentration profile along the gravel bed is always descending, during the initial weeks after start-up of the facility, the achieved reduction in the organic load is moderate, but it increases during the subsequent weeks of operation, reaching pronounced levels after two months of operation. In Fig. 7, it can be seen that bacterial population in the bed (which initially does not contain microorganisms), grows rapidly during the first weeks, and in particular in the section closest to the inlet, where it reaches values above 600 g m^{-3} after the first two months of operation. As a consequence of this increase of the bacterial population close to the entrance, the supply of substrate to the subsequent sections is notably reduced, and the microorganism colony becomes unable to find adequate conditions to continue proliferating. As a result, its growth is contained. This reduction in the digestion capacity of the bed explains the slight decrease in efficiency after the maximum is reached during the third month of operation. This correlates with the observations made for the simulated installation based on the study by Bolaños and González [57] (Fig. 4).

Complementing this information, Fig. 8 shows the evolution over time and the longitudinal position of the thickness of the sludge layer in the gravel bed. This sludge layer is formed by the sedimentation of flocs suspended in the wastewater. It can be seen that the increase in the bacterial population in the section closest to the entrance leads to a linear increase in the amount of sludge deposited, although after one year of operation, the sludge does not block any more than 6 cm of the bed, and this only occurs in specific longitudinal positions, since the thickness of the settled layer is significantly lower in the latter sections of the wetland. Consequently the reduction in the hydraulic retention time is moderate, i.e., less than 0.2%, with values slightly higher than 1 d being achieved during the entire period of time simulated.

Using this model, it should also be possible to study the response of the system to a variation in the operating conditions. As an example, the effect of a six-week shutdown was studied in a facility containing a grease trap similar to that simulated in Fig. 3 (volume 0.62 m^3, radius 0.38 m), in addition to a constructed wetland similar to the one analysed by Bolaños and González [57] (W=5.0 m, H=0.8 m, L=15 m), which is fed with a flow of 14.5 m^3 d^{-1} and an organic load of 700 g m^{-3} in the same hourly intervals previously defined for the simulation above. This facility is located on a university campus, and so the simulation of this shutdown allows anticipation of the system response to the holiday period, during which time the coffee shops are closed. For this simulation, it was considered that the shutdown begins after 200 d, when the steady state has been reached and the concentration profiles of the substrate and the microorganisms along the bed are stable. It was assumed that during the shutdown period, no wastewater is fed into the system, although maintenance of the grease trap is continued. Fig. 9 shows the evolution over time of the microorganism concentration, in addition to its longitudinal position. From this figure, it can be observed that as a consequence of the shutdown, when no substrate is fed into the system, the microbial population is unable to proliferate and is greatly affected by the death rate. Consequently the microorganisms concentration decreases rapidly below 200 g m^{-3}. Accordingly, it should be pointed out that the model proposed does not include the death rate of microorganisms. Thus the results of the simulations showed that, under the usual operating conditions in the constructed wetland, the residence times are rather short, and therefore the decrease in the microbial population is much more affected by the horizontal and vertical transport than by the death rate. Nevertheless, this parameter should be considered when the set-up does not receive inlet flow, given that in this case the residence time increases considerably, and therefore the horizontal transport of microorganisms is cancelled. When campus activity is resumed and wastewater is fed once again into the constructed wetland, the microbiological growth is quickly reactivated, and over a period of two or three weeks, high microbial concentrations are reached, although these concentrations are slightly lower than those predicted by the simulation during the period prior to the shutdown. It is remarkable that this new start-up of the facility is faster than that foreseen by the model at the beginning of the simulation, and it is also noteworthy that concentration of microorganisms at the outlet does not increase, as is observed in the initial weeks after commissioning. This phenomenon was also observed when studying the behaviour of the other simulated facility (see Fig. 7).

The decrease in the bacterial population has a very significant effect on the efficiency of the constructed wetland in the purification of wastewater. As can be observed in Fig. 10, at the end of the holiday shutdown, activity returns to the coffee shops, and consequently, substrate is fed back into the system. However, since the microorganism concentration in the bed decreased during the shutdown, the substrate concentration in the outlet increases rapidly during the initial weeks to reach high values close to 650 g m^{-3}, thereby affecting the efficiency of

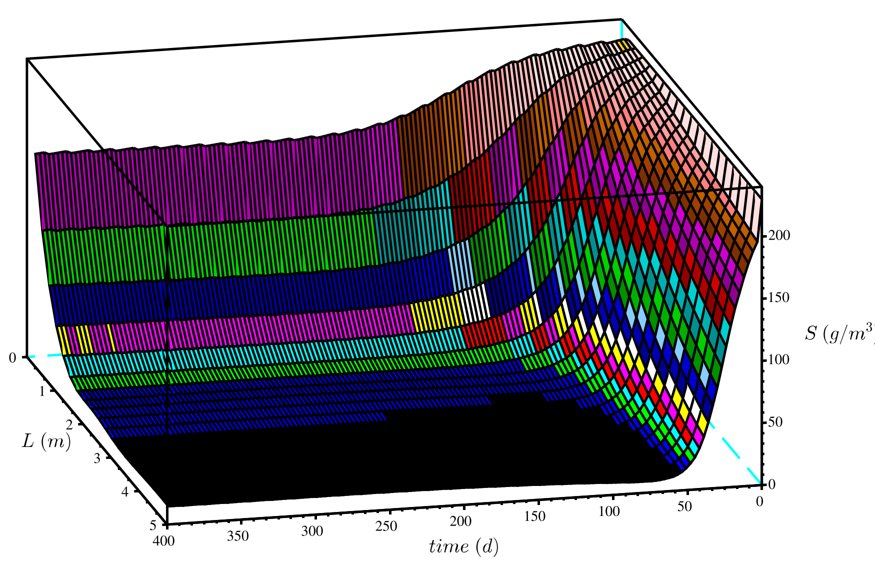

Fig. 6. Evolution over time and longitudinal position of the substrate concentration.

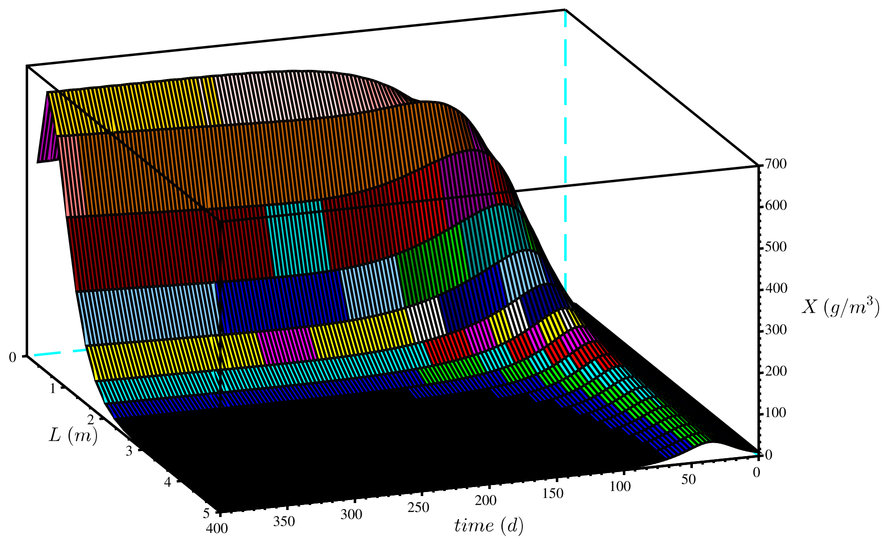

Fig. 7. Evolution over time and longitudinal position of the microorganism concentration.

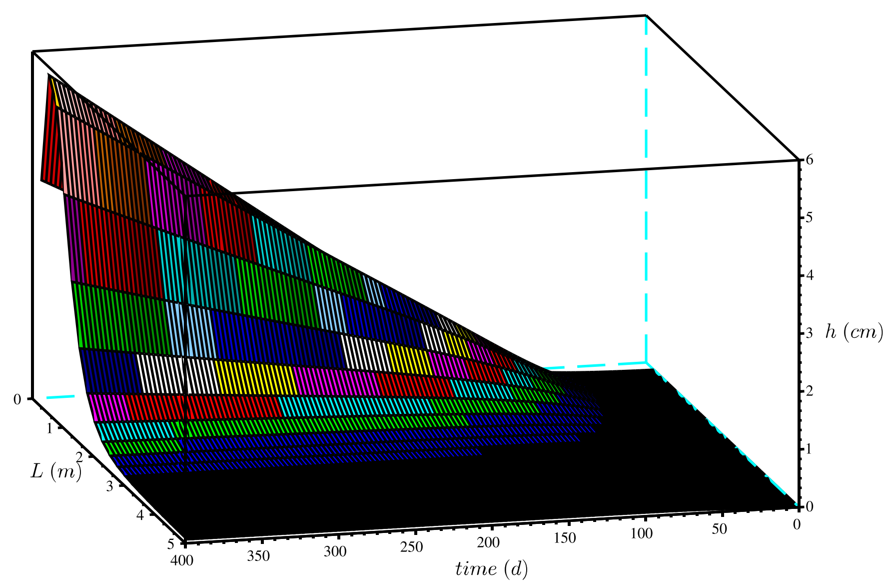

Fig. 8. Evolution over time and longitudinal position of the height of the sludge layer in the gravel bed.

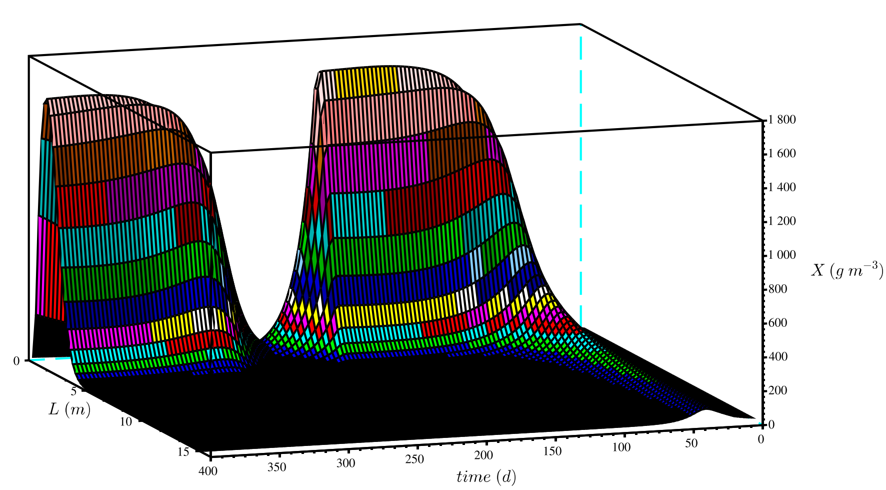

Fig. 9. Evolution over time and longitudinal position of the microorganism concentration during the holiday shutdown.

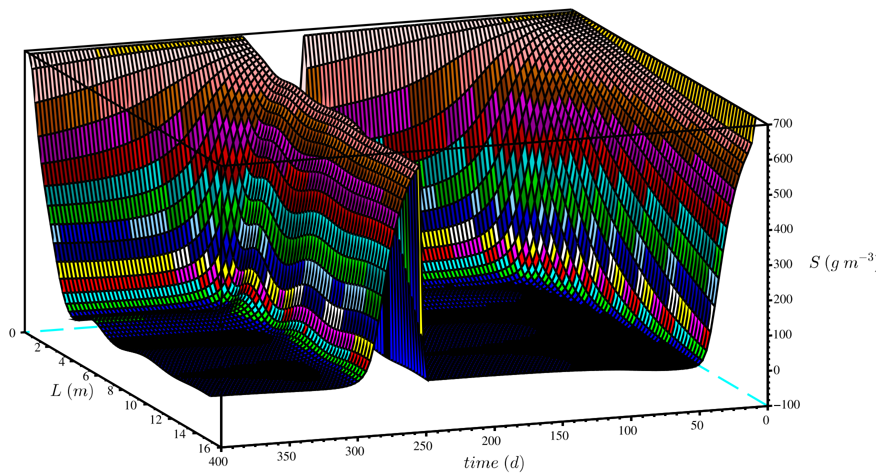

Fig. 10. Evolution over time and longitudinal position of the substrate concentration during the holiday shutdown.

the facility. The presence of substrate nutrients then activates bacterial proliferation, as can be seen in Fig. 9, and consequently, the purification capacity of the bed recovers over a period of six to eight weeks, to give contamination levels in the outlet comparable to those observed prior to shutdown, and the efficiency is raised above 96%. It is noteworthy that according to the results foreseen by the model, the slight reduction in the concentration of microorganisms in the section closest to the inlet of the wastewater after the shutdown foreseen by the model (Fig. 9) does not affect the good performance of the constructed wetland, since following stabilisation, the substrate concentration at the outlet returns to the same values reached prior to the shutdown.

In tropical countries, the rainy season leads to a considerable alteration of the wetland operating conditions, not only due to the increase in flow, but also due to dilution of the organic load. Although the effect of climatic events on the performance of water disinfection system [59] and wastewater treatment plants [60] has been previously discussed in the literature, there is a lack of knowledge regarding their effect on the performance of constructed wetland. Thus, to anticipate the effect of this meteorological phenomenon on the wetland performance, the entry of an additional flow of rainwater (i.e., without an organic load) from the surface of the constructed wetland was simulated, and as a result, the flow through the bed was found to increase longitudinally. In this simulation, it must be considered that the additional contribution of diluted wastewater directly accesses the gravel bed without passing through the bioactive grease trap. It should be noted here that this simulated system is the same as that proposed for the previous simulation, which is based on that studied by Bolaños and González [57], and is located on a Salvadoran university campus. The average daily precipitation in this region in the rainy season (i.e., from May to October) is close to 240 mm, which is equivalent to an incoming flow of $10\ \mathrm{L\,m^{-2}\,h^{-1}}$. For the simulation, it was considered that the rainy season begins after 200 d, when the steady state has been reached and the concentration profiles of the substrate and the microorganisms in the bed are stable. In Fig. 11, it can be seen that the beginning of the rainy season initially causes a moderate decrease in the concentration of microorganisms in the bed (likely due to dilution), and that in the following weeks, the bed adapts the bacterial population to the new flow conditions and the available substrate. As a result, in the following rainy months, a slight but continued decrease in this parameter is foreseen. When the dry season returns after 180 d, the concentration of microorganisms increases rapidly in the section closest to the wastewater entrance as a consequence of an increase in the substrate concentration, although as can be seen from Fig. 9, the maximum level was slightly lower than the value foreseen by the model for the period before the start of the rainy season.

As previously mentioned, the entry of rainwater into the constructed wetland causes dilution of the nutrient concentration in the bed (Fig. 12). However, contrary to our observations at the restart following the holiday shutdown, the arrival of the dry season does not substantially alter the good performance of the installation, and although a slight increase in the substrate concentration is observed, the values are very similar to those foreseen by the model before the beginning of the

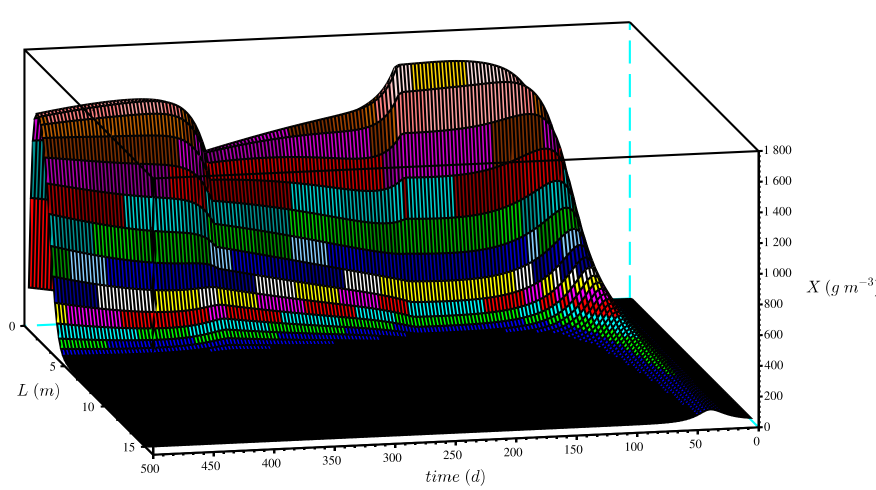

Fig. 11. Evolution over time and longitudinal position of the microorganism concentration during the rainy season.

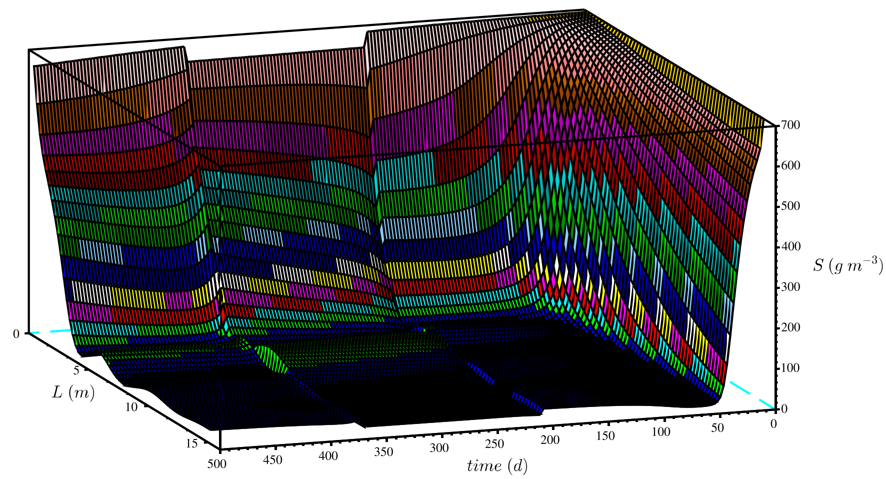

Fig. 12. Evolution over time and longitudinal position of the substrate concentration during the rainy season.

rainy season. These results agree with those obtained by Masi et al. [32], who carried out a two-year performance evaluation of the performances of four different constructed wetland treatment systems established to treat wastewater effluent from tourist activities, i.e., with a high variability in the water consumption and the wastewater flow depending on the season and the weather. They concluded that constructed wetlands are robust and relatively resistant to peak flows and loads.

Finally, the differences in the behaviour of the wetland in the two simulations was attributed to the fact that in this second case, the precipitation dilutes but does not substantially reduce the bacterial population of the bed. As a result, when recovering the conditions prior to the alteration, the bed exhibits a sufficient biological activity to rapidly adapt to the slight increase in the substrate concentration. Dilution of the substrate due to rainfall, which is foreseen throughout the bed, in fact involves a reduction in the substrate concentration at the outlet, which causes a slight increase in the efficiency of the wetland during the rainy months (Fig. 13).

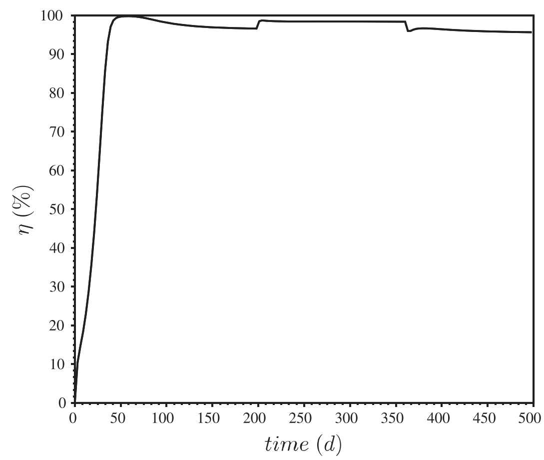

Fig. 13. Evolution over time of the substrate removal efficiency during the rainy season.

5. Conclusions

A rigorous mathematical model has been proposed to describe the dynamic behaviour of horizontal subsurface constructed wetlands containing a bioactive grease trap. This model considers the mass balances of the substrate and the microorganisms, in addition to the degradation kinetics of the biological processes, the life cycle of the microorganisms, and their horizontal and vertical transport processes. The former (i.e., horizontal transport) guarantees the propagation and maintenance of the microbial colony in all sections of the bed, while the latter (i.e., vertical transport) causes the collapse of the facility by sedimentation. The tuning of this model was completed by setting values for all parameters to ensure that the developed simulation tool allows the simulation of real or projected facilities. The model foresees start-up times close to three months and depuration efficiencies above 90%. These values are in accordance with those measured in operating facilities and published in the literature. This new simulation tool can also be used to analyse the evolution of unmeasurable parameters in operating facilities and to study the effects of modifying operating parameters. It is therefore able to anticipate the response of the system, to establish stabilisation measures in case of occasional disturbances, and also to predict the future behaviour of projected facilities. Thus, during the ordinary start-up, the model foresees an increase in the bacterial population in the entrance section, which reduces the supply of substrate to the subsequent sections and slightly decreases the efficiency after the maximum reached during the third month of operation. Furthermore, the simulation of a six-week shutdown allowed anticipation of the system response to the holiday period. More specifically, the model foresees that under these conditions, the microbial population cannot proliferate and is greatly affected by the death microbial rate, which significantly affects the efficiency of the wetland. In contrast, the arrival of the rainy season does not significantly affect the wetland performance, since the substrate concentration in the outlet is reduced slightly due to dilution, and as a result, the efficiency increases.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to thank the technicians of ADES Santa Marta and the School of Chemical Engineering and Food Engineering from the Faculty of Engineering and Architecture of the University of El Salvador for their help and for providing the information required to carry out this work. Leire García and Mikel Manso wish to thank the Development Cooperation Office of the University of the Basque Country UPV/EHU for the financial aid provided to travel to El Salvador. Engineering Without Borders - Basque Country wish to thank the County Council of Biscay (projects DESA/0027/2017, DESA/0024/2019 and SUBV/COOP/SENS/0012/2019) and the Bilbao Council (projects 2019-

017085 and 2020-015220) for their financial support.

References

[1] U. Nations, Water and sanitation, URL, https://www.un.org/sustainabledevelopment/en/water-and-sanitation/.
[2] U. Nations, Sustainable Development Goal 6 - Synthesis Report 2018 on Water And Sanitation, URL, UN-Water, United Nations, New York, USA, 2018, https://www.unwater.org/app/uploads/2018/12/SDG6_SynthesisReport2018_WaterandSanitation_04122018.pdf.
[3] M. Al-Obaidi, C. Kara-Zaitri, I. Mutjaba, Wastewater treatment by reverse osmosis process, CRC Press, 2020 https://www.routledge.com/Wastewater-Treatment-by-Reverse-Osmosis-Process/Al-Obaidi-Kara-Zaitri-Mujtaba/p/book/9780367819347.
[4] A. Abdelhay, S.G. Abunaser, Modeling and economic analysis of greywater treatment in rural areas in Jordan using a novel vertical-flow constructed wetland, Environ. Manag. 67 (2021) 477–488, https://doi.org/10.1007/s00267-020-01349-7.
[5] S.G. Abunaser, A. Abdelhay, Performance of a novel vertical flow constructed wetland for greywater treatment in rural areas in Jordan, 0 (0, in: Environmental Technology, Taylor & Francis, 2020, pp. 1–11, https://doi.org/10.1080/09593330.2020.1841832. _eprint.
[6] S. Arden, X. Ma, Constructed wetlands for greywater recycle and reuse: a review, Sci. Total Environ. 630 (2018) 587–599, https://doi.org/10.1016/j.scitotenv.2018.02.218, https://www.sciencedirect.com/science/article/pii/S004896971830617X.
[7] F. Boano, A. Caruso, E. Costamagna, L. Ridolfi, S. Fiore, F. Demichelis, A. Galvão, J. Pisoeiro, A. Rizzo, F. Masi, A review of nature-based solutions for greywater treatment: applications, hydraulic design, and environmental benefits, Sci. Total Environ. 711 (2020), 134731, https://doi.org/10.1016/j.scitotenv.2019.134731 https://www.sciencedirect.com/science/article/pii/S0048969719347229.
[8] H.S. Fowdar, B.E. Hatt, P. Breen, P.L.M. Cook, A. Deletic, Designing living walls for greywater treatment, Water Res. 110 (2017) 218–232, https://doi.org/10.1016/j.watres.2016.12.018, https://www.sciencedirect.com/science/article/pii/S0043135416309538.
[9] D.M. Ghaitidak, K.D. Yadav, Characteristics and treatment of greywater—a review, Environ. Sci. Pollut. Res. 20 (5) (2013) 2795–2809, https://doi.org/10.1007/s11356-013-1533-0.
[10] F. Li, K. Wichmann, R. Otterpohl, Review of the technological approaches for grey water treatment and reuses, Sci. Total Environ. 407 (11) (2009) 3439–3449, https://doi.org/10.1016/j.scitotenv.2009.02.004, https://www.sciencedirect.com/science/article/pii/S0048969709001594.
[11] C. Santasmasas, M. Rovira, F. Clarens, C. Valderrama, Grey water reclamation by decentralized MBR prototype, Resour. Conserv. Recycl. 72 (2013) 102–107, https://doi.org/10.1016/j.resconrec.2013.01.004, https://www.sciencedirect.com/science/article/pii/S0921344913000050.
[12] P. Andreo-Martínez, N. García-Martínez, J. Quesada-Medina, L. Almela, Domestic wastewaters reuse reclaimed by an improved horizontal subsurface-flow constructed wetland: a case study in the southeast of Spain, Bioresour. Technol. 233 (2017) 236–246, https://doi.org/10.1016/j.biortech.2017.02.123.
[13] M.C. Collivignarelli, M.Carnevale Miino, F.H. Gomez, V. Torretta, E.C. Rada, S. Sorlini, Horizontal flow constructed wetland for greywater treatment and reuse: an experimental case, number: 7, in: International Journal of Environmental Research and Public Health 17 (7), Multidisciplinary Digital Publishing Institute, 2020, https://doi.org/10.3390/ijerph17072317. URL https://www.mdpi.com/1660-4601/17/7/2317.
[14] F. Masi, A. Rizzo, M. Regelsberger, The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm, J. Environ. Manag. 216 (2018) 275–284, https://doi.org/10.1016/j.jenvman.2017.11.086. URL https://www.sciencedirect.com/science/article/pii/S0301479717311611.
[15] R. Liu, Y. Zhao, L. Doherty, Y. Hu, X. Hao, A review of incorporation of constructed wetland with other treatment processes, Chem. Eng. J. 279 (2015) 220–230, https://doi.org/10.1016/j.cej.2015.05.023, https://www.sciencedirect.com/science/article/pii/S1385894715006749.
[16] S. Borzooei, Y. Amerlinck, D. Panepinto, S. Abolfathi, I. Nopens, G. Scibilia, L. Meucci, M.C. Zanetti, Energy optimization of a wastewater treatment plant based on energy audit data: small investment with high return, Environ. Sci. Pollut. Res. 27 (15) (2020) 17972–17985, https://doi.org/10.1007/s11356-020-08277-3.
[17] S. Borzooei, G.H.B. Miranda, S. Abolfathi, G. Scibilia, L. Meucci, M.C. Zanetti, Application of unsupervised learning and process simulation for energy optimization of a WWTP under various weather conditions, Water Sci. Technol. 81 (8) (2020) 1541–1551, https://doi.org/10.2166/wst.2020.220.
[18] J.García Serrano, A.Corzo Hernández, Depuración con Humedales Construidos. Guía Práctica de Diseño, Construcción y Explotación de Sistemas de Humedales de Flujo Subsuperficial, Universidad Politécnica de Cataluña, Barcelona, ES, 2008. URL http://hdl.handle.net/2117/2474.
[19] O. Delgadillo, A. Camacho, L.F. Pérez, M. Andrade, Depuración de aguas residuales por medio de humedales artificiales, Serie Técnica, URL, Centro Andino para la Gestión y Uso del Agua, Cochabamba (Bolivia), 2010. https://core.ac.uk/download/pdf/48017573.pdf.
[20] A.K. Thalla, C.P. Devatha, K. Anagh, E. Sony, Performance evaluation of horizontal and vertical flow constructed wetlands as tertiary treatment option for secondary effluents, Appl. Water Sci. 9 (6) (2019) 147, https://doi.org/10.1007/s13201-019-1014-9.
[21] J. García, J.G. Serrano, J. Morató, J.M. Bayona, Nuevos criterios para el diseño y operación de humedales construidos: una alternativa de bajo coste para el tratamiento de aguas residuales, Ediciones CPET, Centro de Publicaciones de Campus Nord, 2004.
[22] J. García, D.P.L. Rousseau, J. Morató, E. Lesage, V. Matamoros, J.M. Bayona, Contaminant removal processes in subsurface-flow constructed wetlands: a review, in: Critical Reviews in Environmental Science and Technology 40 (7), Taylor & Francis, 2010, pp. 561–661, https://doi.org/10.1080/10643380802471076. _eprint.
[23] J. Laaffat, N. Ouazzani, L. Mandi, The evaluation of potential purification of a horizontal subsurface flow constructed wetland treating greywater in semi-arid environment, Process Saf. Environ. Prot. 95 (2015) 86–92, https://doi.org/10.1016/j.psep.2015.02.016, https://www.sciencedirect.com/science/article/pii/S0957582015000397.
[24] A.K. Kivaisi, The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review, Ecol. Eng. 16 (4) (2001) 545–560, https://doi.org/10.1016/S0925-8574(00)00113-0, https://www.sciencedirect.com/science/article/pii/S0925857400001130.
[25] R. Pérez-Salazar, C. Mora-Aparicio, C. Alfaro-Chinchilla, J. Sasa-Marín, C. Scholz, J.A. Rodríguez-Corrales, Biogardens as constructed wetlands in tropical climate: a case study in the central pacific coast of Costa Rica, Sci. Total Environ. 658 (2019) 1023–1028, https://doi.org/10.1016/j.scitotenv.2018.12.259, https://www.sciencedirect.com/science/article/pii/S0048969718351325.
[26] S. Dehestaniathar, S. Nesari, S. Borzooei, S. Abolfathi, Application of natural biodegradable fiber as biofilm medium and carbon source in DEnitrifying AMmonium OXidation (DEAMOX) process for nitrogen removal from wastewater, J. Taiwan Inst. Chem. Eng. 119 (2021) 108–114, https://doi.org/10.1016/j.jtice.2021.01.030, https://www.sciencedirect.com/science/article/pii/S1876107021000559.
[27] C. An, G. Huang, Y. Yao, S. Zhao, Emerging usage of electrocoagulation technology for oil removal from wastewater: a review, Sci. Total Environ. 579 (2017) 537–556, https://doi.org/10.1016/j.scitotenv.2016.11.062, https://www.sciencedirect.com/science/article/pii/S0048969716325013.
[28] A.Y. Arellano, E.R. Sánchez, Master's thesis, URL, Universidad Nacional Autónoma de México, Facultad de Ingeniería, Ciudad de México, México, 2017, http://132.248.52.100:8080/xmlui/bitstream/handle/132.248.52.100/14522/Propuesta%20de%20mejora%20de%20dise%c3%b1o%20de%20una%20trampa%20de%20grasa%20para%20restaurantes.pdf?sequence=1.
[29] K.-E. Jaeger, M.T. Reetz, Microbial lipases form versatile tools for biotechnology, Trends Biotechnol. 16 (9) (1998) 396–403, https://doi.org/10.1016/S0167-7799(98)01195-0, https://www.sciencedirect.com/science/article/pii/S0167779998011950.
[30] H.-S. Wu, M.-J. Tsai, Kinetics of tributyrin hydrolysis by lipase, Enzym. Microb. Technol. 35 (6) (2004) 488–493, https://doi.org/10.1016/j.enzmictec.2004.08.002, https://www.sciencedirect.com/science/article/pii/S0141022904002145.
[31] K. Ágnes Kis, S. Laczi, G. Zsíros, K.Perei Rákhely, Biodegradation of animal fats and vegetable oils by Rhodococcus erythropolis pr4, Int. Biodeterior. Biodegradation 105 (2015) 114–119, https://doi.org/10.1016/j.ibiod.2015.08.015, https://www.sciencedirect.com/science/article/pii/S0964830515300706, https://www.sciencedirect.com/science/article/pii/S0964830515300706.
[32] F. Masi, N. Martinuzzi, R. Bresciani, L. Giovannelli, G. Conte, Tolerance to hydraulic and organic load fluctuations in constructed wetlands, Water Sci. Technol. 56 (3) (2007) 39–48, https://doi.org/10.2166/wst.2007.507.
[33] J.B. da Silva, P.J.A. de Oliveira, M. Árpád Boncz, P. Loureiro Paulo, A modified constructed wetland system for greywater treatment, Desalin. Water Treat. 91 (2017) 31–39, https://doi.org/10.5004/dwt.2017.20849, http://www.deswater.com/DWT_abstracts/vol_91/91_2017_31.pdf, http://www.deswater.com/DWT_abstracts/vol_91/91_2017_31.pdf.
[34] G.M.P.R. Weerakoon, K.B.S.N. Jinadasa, J. Manatunge, B. Wijesiri, A. Goonetilleke, Kinetic modelling and performance evaluation of vertical subsurface flow constructed wetlands in tropics, J.Water Process Eng. 38 (2020), 101539, https://doi.org/10.1016/j.jwpe.2020.101539 https://www.sciencedirect.com/science/article/pii/S2214714420304177.
[35] R. Kadlec, S. Wallace, Treatment Wetlands, 2nd Edition, CRC Press, Boca Raton, Florida, 2009. URL https://www.routledge.com/Treatment-Wetlands/Kadlec-Wallace/p/book/9781566705264.
[36] R.H. Kadlec, The inadequacy of first-order treatment wetland models, Ecol. Eng. 15 (1) (2000) 105–119, https://doi.org/10.1016/S0925-8574(99)00039-7, https://www.sciencedirect.com/science/article/pii/S0925857499000397.
[37] N.A. Mohammed, Z.Z. Ismail, Prediction of pollutants removal from cheese industry wastewater in constructed wetland by artificial neural network, Int. J. Environ. Sci. Technol. (Nov. 2021), https://doi.org/10.1007/s13762-021-03805-1.
[38] A.G. Ferreira, A.C. Borges, A.P. Rosa, Comparison of first-order kinetic models for sewage treatment in horizontal subsurface-flow constructed wetlands, in: Environmental Technology 42 (28), Taylor & Francis, 2021, pp. 4511–4518, https://doi.org/10.1080/09593330.2020.1769741. _eprint.
[39] K. Chan, W. Chu, Modeling the reaction kinetics of Fenton's process on the removal of atrazine, Chemosphere 51 (4) (2003) 305–311, https://doi.org/10.1016/S0045-6535(02)00812-3, https://www.sciencedirect.com/science/article/pii/S0045653502008123.
[40] E. Dittrich, M. Klincsik, D. Somfai, A. Dolgos-Kovács, T. Kiss, A. Szekeres, Application of divided convective-dispersive transport model to simulate variability of conservative transport processes inside a planted horizontal subsurface flow constructed wetland, Environ. Sci. Pollut. Res. 28 (13) (2021) 15966–15994, https://doi.org/10.1007/s11356-020-10965-z.

[41] R. Samsó, J. García, P. Molle, N. Forquet, Modelling bioclogging in variably saturated porous media and the interactions between surface/subsurface flows: application to constructed wetlands, J. Environ. Manag. 165 (2016) 271–279, https://doi.org/10.1016/j.jenvman.2015.09.045, https://www.sciencedirect.com/science/article/pii/S0301479715302978.
[42] C. Yuan, T. Huang, X. Zhao, Y. Zhao, Numerical models of subsurface flow constructed wetlands: review and future development, number: 8, in: Sustainability 12 (8), Multidisciplinary Digital Publishing Institute, 2020, https://doi.org/10.3390/su12083498. URL https://www.mdpi.com/2071-1050/12/8/3498.
[43] S. Saktaweewong, P. Phinyocheep, C. Ulmer, E. Marie, A. Durand, P. Inprakhon, Lipase activity in biphasic media: why interfacial area is a significant parameter? J. Mol. Catal. B Enzym. 70 (1) (2011) 8–16, https://doi.org/10.1016/j.molcatb.2011.01.013, https://www.sciencedirect.com/science/article/pii/S1381117711000385.
[44] S. Al-Zuhair, K.B. Ramachandran, M. Hasan, Investigation of the specific interfacial area of a palm oil–water system, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/jctb.1039, J. Chem. Technol. Biotechnol. 79 (7) (2004) 706–710, https://doi.org/10.1002/jctb.1039. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/jctb.1039.
[45] S.-W. Tsai, G.-H. Wu, C.-L. Chiang, Kinetics of enzymatic hydrolysis of olive oil in biphasic organic-aqueous systems, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/bit.260380710, Biotechnol. Bioeng. 38 (7) (1991) 761–766, https://doi.org/10.1002/bit.260380710. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/bit.260380710.
[46] S. Al-Zuhair, M. Hasan, K.B. Ramachandran, Kinetics of the enzymatic hydrolysis of palm oil by lipase, Process Biochem. 38 (8) (2003) 1155–1163, https://doi.org/10.1016/S0032-9592(02)00279-0, https://www.sciencedirect.com/science/article/pii/S0032959202002790.
[47] S.-W. Tsai, C.-S. Chang, Kinetics of lipase-catalyzed hydrolysis of lipids in biphasic organic—aqueous systems, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/jctb.280570209, J. Chem. Technol. Biotechnol. 57 (2) (1993) 147–154, https://doi.org/10.1002/jctb.280570209. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/jctb.280570209.
[48] J. Laaffat, F. Aziz, N. Ouazzani, L. Mandi, Biotechnological approach of greywater treatment and reuse for landscape irrigation in small communities, Saudi J.Biol.Sci. 26 (1) (2019) 83–90, https://doi.org/10.1016/j.sjbs.2017.01.006, https://www.sciencedirect.com/science/article/pii/S1319562X17300062.
[49] M. Oteng-Peprah, M.A. Acheampong, N.K. deVries, Greywater characteristics, treatment systems, reuse strategies and user perception—a review, Water Air Soil Pollut. 229 (8) (2018) 255, https://doi.org/10.1007/s11270-018-3909-8.
[50] A. Gross, O. Shmueli, Z. Ronen, E. Raveh, Recycled vertical flow constructed wetland (RVFCW)—a novel method of recycling greywater for irrigation in small communities and households, Chemosphere 66 (5) (2007) 916–923, https://doi.org/10.1016/j.chemosphere.2006.06.006, https://www.sciencedirect.com/science/article/pii/S0045653506007442.
[51] X. Nan, S. Lavrnić, A. Toscano, Potential of constructed wetland treatment systems for agricultural wastewater reuse under the EU framework, J. Environ. Manag. 275 (2020), 111219, https://doi.org/10.1016/j.jenvman.2020.111219 https://www.sciencedirect.com/science/article/pii/S0301479720311440.
[52] D. López, A.M. Leiva, W. Arismendi, G. Vidal, Influence of design and operational parameters on the pathogens reduction in constructed wetland under the climate change scenario, Rev. Environ. Sci. Biotechnol. 18 (1) (2019) 101–125, https://doi.org/10.1007/s11157-019-09493-1.
[53] C.N. Shillington, C.M. Cianfrani, S. Hews, Evaluating the performance of a decentralized graywater treatment system in a living building at Hampshire College, Amherst, MA, USA, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/wer.1251, Water Environ. Res. 92 (2) (2020) 291–301, https://doi.org/10.1002/wer.1251. URL http://onlinelibrary.wiley.com/doi/abs/10.1002/wer.1251.
[54] A. Nema, K.D. Yadav, R.A. Christian, Sustainability and performance analysis of constructed wetland for treatment of greywater in batch process, in: International Journal of Phytoremediation 22 (6), Taylor & Francis, 2020, pp. 644–652, https://doi.org/10.1080/15226514.2019.1701983. _eprint.
[55] S. Vanitha, Study on suitability of single and hybrid constructed wetland for treating sewage for a small community, in: IOP Conference Series: Materials Science And Engineering 955, IOP Publishing, 2020, https://doi.org/10.1088/1757-899X/955/1/012094.
[56] S. Moncada-Corrales, Evaluación del diseño de una biojardinera de flujo subsuperficial para el tratamiento de aguas grises en Zapote, San José, Master's thesis, Instituto Tecnologico de Costa Rica, Escuela de Química, Cartago, Costa Rica, 2011. URL https://hdl.handle.net/2238/2874.
[57] C.M.Bolaños Calderón, D.B.González Serrano, Evaluación de la eficiencia de tratamiento de aguas grises mediante la comparación de un humedal artificial con un método fisicoquímico en los comedores de la Universidad de El Salvador, Master's thesis, Universidad de El Salvador, Escuela de Ingeniería Química e Ingeniería de Alimentos, San Salvador, El Salvador, 2020. URL http://ri.ues.edu.sv/id/eprint/20805/.
[58] S.C. Reed, R.W. Crites, E.J. Middlebrooks, Natural Systems for Waste Management And Treatment, McGraw-Hill, New York, 1994 section: pages cm.URL.
[59] D. Goodarzi, S. Abolfathi, S. Borzooei, Modelling solute transport in water disinfection systems: effects of temperature gradient on the hydraulic and disinfection efficiency of serpentine chlorine contact tanks, J.Water Process Eng. 37 (2020), 101411, https://doi.org/10.1016/j.jwpe.2020.101411 https://www.sciencedirect.com/science/article/pii/S2214714420302890.
[60] S. Borzooei, R. Teegavarapu, S. Abolfathi, Y. Amerlinck, I. Nopens, M.C. Zanetti, Data mining application in assessment of weather-based influent scenarios for a WWTP: getting the most out of plant historical data, Water Air Soil Pollut. 230 (1) (2018) 5, https://doi.org/10.1007/s11270-018-4053-1.