Artículo original

Chemistry applications to wastewater treatment: case studies in Mexico and Cuba

Aplicaciones de la química al tratamiento de aguas residuales: casos de estudio en México y Cuba

E.R. Bazúa-Rueda[1]

M. Bernal-González[1]

María Irene Cano-Rodríguez[2]

M.C Durán-Domínguez-de-Bazúa[1]*

B. Espinosa-Aquino[3]

R.S. García-Gómez[1]

J.A. Herrera-Cárdenas[4]

U. Kappelmeyer[5]

A.E. Navarro-Frómeta[4]

L.I. Ramírez-Burgos[5]

N.J. Ruiz-Cárdenas[6]

M.G. Salinas-Juárez[7]

Irina Salgado-Bernal[8]

S.A. Sánchez-Tovar[9]

J.A. Solís-Fuentes[10]

[1]Facultad de Química, UNAM, Ciudad de México, México

[2]División de Ciencias Naturales y Exactas, Universidad de Guanajuato, México

[3]Instituto de Ciencias, Benemérita Universidad Autónoma de Puebla, Puebla, México

[4]Universidad Tecnológica de Izúcar de Matamoros, Puebla, México

[5]Centre for Environmental Research, Leipzig, Germany

[6]Colegio de Ciencias y Humanidades Plantel Sur, UNAM, México

[7]Facultad de Estudios Profesionales Zaragoza, UNAM, Ciudad de México, México

[8]Facultad de Biología, Universidad de La Habana, La Habana, Cuba

[9]TECNOBRIO, SA de CV, Lauro Villar, México

[10]Instituto de Ciencias Básicas, Universidad Veracruzana, Xalapa, Veracruz, México.

*Autor para la correspondencia. correo electrónico: mcduran@unam.mx

ABSTRACT

The authors had an academic meeting to face the challenge to provide clean water and to dispose of wastewaters once treated to reduce pollution impacts and to recycle the treated effluent. Chemistry plays a substantial role to the solution of removing pollutants since chemical reactions are crucial to increase the final quality of the treated effluents. A viable option might be the installation of units using the artificial wetlands technology. There microbial consortia carry these chemical reactions. Two case studies were considered, Mexico and Cuba. An example of the use of artificial wetlands to solve the lack of sanitation facilities for Mexico City's Tlalpan section is given using as example two prototype plants located near this neighbourhood so that climate conditions will not interfere in the chemical reactions. The equivalent is given for a zone Havana City considering the Almendares river and the environmental impact on it.

Keywords: wastewater, artificial wetlands, case studies Mexico and Havana Cities, chemistry applications.

RESUMEN

Los autores tuvieron una reunión académica para enfrentar el reto de tener agua limpia y tratar las aguas residuales, para reducir su impacto, reciclándolas. La química juega un rol sustantivo para la reducción de estos contaminantes, ya que las reacciones químicas son cruciales para mejorar la calidad final de los efluentes tratados. Estas reacciones químicas las realizan consorcios microbianos en la rizosfera de los humedales artificiales, por lo que una opción viable es instalarlos. Desde esta óptica se consideraron dos casos de estudio, México y Cuba. Se ejemplifica el uso de los humedales artificiales para resolver los problemas de Tlalpan en la Ciudad de México, usando una planta prototipo ubicada cerca de esta zona, para que el clima no interfiera en las reacciones químicas. El equivalente para Cuba es una zona del río Almendares, de La Habana y su impacto ambiental.

Palabras clave: aguas residuales, humedales artificiales, casos de estudio Ciudades de México y La Habana, aplicaciones de la química.

Recibido: 22/7/2018

Aprobado: 22/1/2019

Introduction

Wastewater is a threat to urban communities. Artificial or constructed wetlands (AW or CW) are systems emulating the same chemical processes that take place in the natural wetlands, in order to remove pollutants, particularly those dissolved in the water, trying to avoid its sending to natural ecosystems.(1) Nowadays, artificial wetlands are an excellent option for developing economies urban cities for the depuration of its wastewaters, either coming from small suburbs with scarcity of funds (2,3) or for more affluent communities, since this technology solves the same kind of problems.

In some cases a support media may be included to provide a surface for the formation of microbial biofilms and to maintain the hydrophytes vertical.(4) The systems may operate according to its water flow, either vertical or horizontal. Also, water may flow on the surface or some distance under the support media, and the AW are named superficial or sub-superficial. When horizontal and vertical AW are combined, they are called hybrid systems and the main aspect of these new versions is to improve its efficiency reducing the necessary area per equivalent inhabitant, that is one of the limiting factors of these systems.[5-7]

Depending upon the characteristics of the microbial community present, the system may remove from water heavy metals [8-11] or organic matter [12] and organics toxic.[13-15] The aquatic plants play a crucial role thanks to photosynthesis in the daytime [16-18], as well as removing nitrogen.[19-21]

An international group of researchers has joined efforts to implement these artificial wetlands, both in small communities and small neighbourhoods within big urbanizations. One of the examples was to support communities to build their own systems, as well as to build demonstration facilities located in Mexico City at the end of the XX Century. One is still in a suburb called Coyoacán, in a Vivarium with a horizontal sub-superficial flow, and a second one with a vertical sub-superficial flow at the University City grounds. The second one has been moved to a senior high school belonging to UNAM, also in the University City, changing its flow to horizontal. The present installation has as a main aim to create an environmentally conscious mind among the young students (between 15 al 18 years old), as well as to be a prototype to be followed by other UNAM installations.[22]

The group has extended the research activities to the South Eastern region of Mexico to serve the population of a small community near the city of Puebla.[23] In the same Mexican state, there are some pilot installations in the region of Izúcar de Matamoros.[24-25] A hybrid artificial system is to be built in the neighbourhood of San Martín Alchichica, near Izúcar de Matamoros. The community of San Martin Alchichica has provisions for growing up to 2000 inhabitants approximately. The *Universidad Tecnológica de Izúcar de Matamoros* has been carrying out research with different types of artificial wetlands since 2002.[24-25]

As the cost of these systems is much lower than the traditional WWTP, the case of Santa María Coatepec El Seco, Puebla, Mexico [23] was taken as example. The additional benefits of using gravity to receive the waste waters reduces or even eliminates the costs not only of equipment but in operation and maintenance. In this case, considering the appropriation of the technology by the community, when their inhabitants participate in its construction, starting-up, and operation through communal work is an added value.

The objective, for the two case studies presented here, is to solve the threats in Mexico City and Havana City due to polluted water, using artificial wetlands as a key point considering the fact that urban neighbourhoods confront the same type of problems than rural communities, such as the two examples mentioned above from the state of Puebla, Mexico, and that are applicable to any country.

Development (methodology)

Case of study: Mexico City

Mexico City is located in what it used to be a series of interconnected lakes.[26] As human populations started inhabiting the area, constructions were held to separate salty marshes from the rest of them, on the Nezahualcóyotl time, 14th century (figures 1a-b, 2a).[27]

Fig. 1a. Simulation of the Mexico City Basin in 1519 (based on CONAGUA) [31]

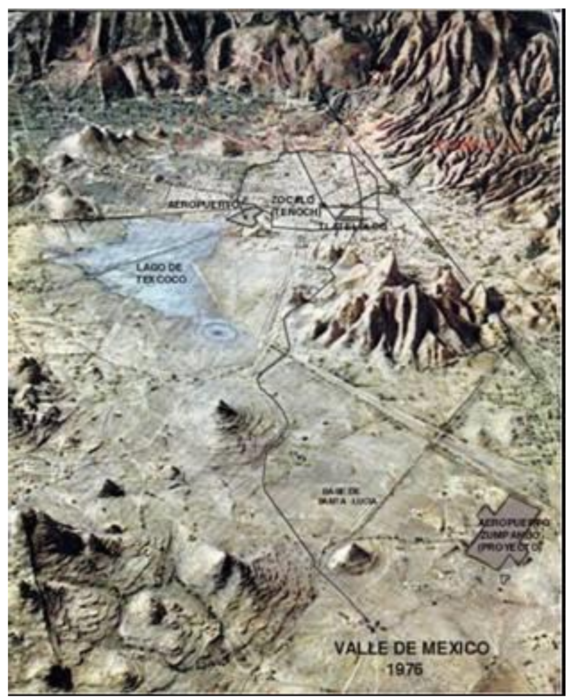

Fig. 1b. Ecocide after 1521 conquest to 1976 (455 years later) [31]

Presently, the ecocide caused after the Spanish conquest of the Aztec empire, made a valley of that basin, losing all the ecological characteristics that sustained the life of an estimated population of 10 million people that were quickly decimated by diseases, hunger, and violent death (figure 2b).[26-28]

A vivid example of this ecocide was presented in the first chapter of a recent book on artificial or constructed wetlands [1] showing that badly treated wastewaters dumped in the remains of the Xochimilco Lake need not really traditional wastewater treatment plants, WWTP, to restore the quality of the water used to refill it, but artificial wetlands, AW.[29]

On the other hand, drinking water has to be pumped in from the Michoacán and Mexico states to provide it to the population, roughly the same as in the Aztec times before the conquest, nine millions.[30] As the volume pumped is insufficient, subterranean water from aquifers and springs is used, creating its over exploitation.[31] Consequently, the city is sinking at a very high rate.[31]

There are areas of Mexico City that have no drinking water facilities and water has to be provided using cistern tank trucks, colloquially known in Mexico as “pipas”.

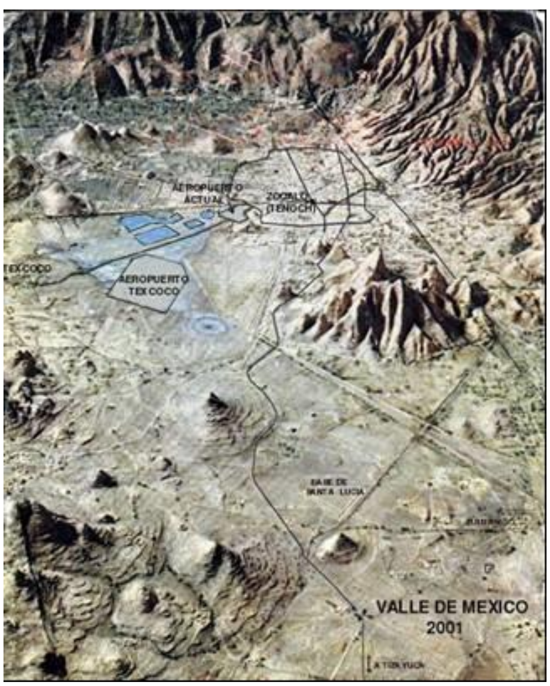

Fig. 2a. Ecocide from 1976 to 2001 (only 25 years more) [26]

Fig. 2b. Location of Mexico City limits within the valley -black line- [26]

The figure 3 presents some data from the official *Instituto Nacional de Estadística y Geografía*, *INEGI* [32], that although are almost 20 years old only depict the huge problem. It is clear that the Tlalpan municipality or county (*alcaldía* in Spanish) suffers from this problem. It is precisely the place that traditionally had most springs and rivers. Unfortunately, during these five centuries due to the logging and invasion of this land located in the southern part of Mexico City to build households, especially for low and very low income people, the area is no longer receiving the rain water and storing it in the subsoil. These households have no drinking water network due to the geographical conditions of the *Ajusco* area, with an altitude of 3,930 m (deep slopes from the *Sierra Ajusco-Chichinautzin* volcanic mountain ranges, figure 2b).[26]

Tlalpan inhabitants dispose of their wastewaters directly to the ground, that is from volcanic origin, giving place to the mixing of the wastewaters with the subterranean aquifers polluting all the water sources.[32] INEGI statistics [32] indicate that, for the particular case of Tlalpan is the third place in problems of sanitation. The sad first two places are for Alvaro Obregón and Magdalena Contreras municipalities (*alcaldías*), west of Tlalpan (figure 4).

The last but not least important problem of Mexico City Metropolitan Area, MCMA is that it is located in a seismic area.[33-36] Very slight earthquakes occur every day that only the devices of the Mexico's National Seismological Service can appreciate. As the whole water network for drinking water and for wastewaters is subterranean the joint surfaces of the piping systems become leaky and release the vital liquid in the case of drinking water piping, and the not so clean wastewaters too. Sadly, these leaks cannot be easily observed. The losses of drinking water due to these leaks are quite considerable. Some estimates indicate that they might be up to 30% of the total flow.[30]

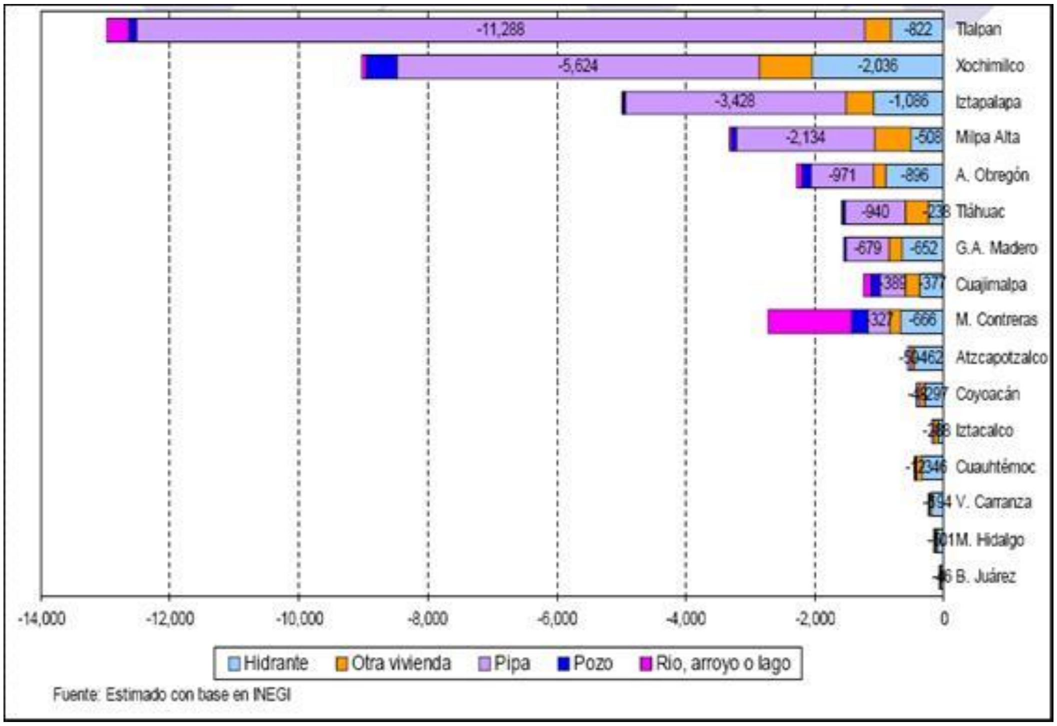

Fig. 3. Deficit of drinking water in Mexico City households: Tlalpan municipality with 822 households receiving drinking water from street hydrants, 11,288 from cistern tank trucks or "pipas", and non depicted is the hugely reduced number of households that have a well or take it from a creek since there no rivers anymore and even less lakes.(37)

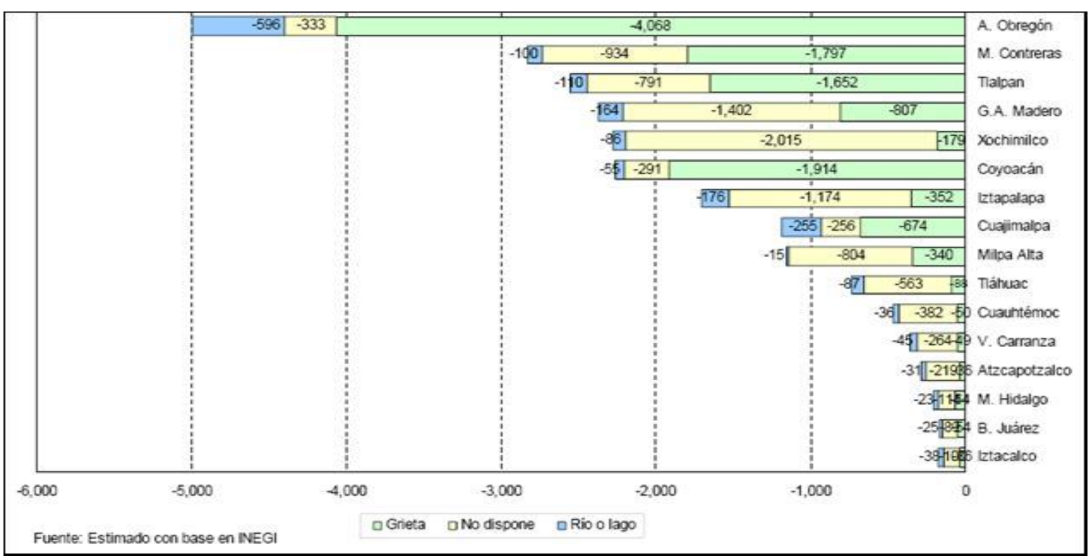

Fig. 4. Number of households with deficit of sewage systems: The Tlalpan municipality has 1,652 households dumping wastewaters to creases or cracks (*grietas* in Spanish), 791 just put outside of their homes in the street, and 110 to former bed rivers or bed lakes.(37)

Considering the solution of using artificial wetlands to avoid polluting aquifers with wastewaters of these 2,553 households in the next paragraphs there are some chemical data to support it.

Solutions for the case of mexico city´s tlalpan municipality with drinking water supply deficit and water sewage treatment systems deficit

As mentioned in an international presentation: [(29)]

“First of all, awareness of the problem is the first step to be considered. The majority of the inhabitants of Mexico City are not conscious that they are all part of the problem but also of the solution. Most of them simply expect to receive drinking water from the local government, preferably free of charge and of good quality. Also, the majority completely ignore the costs associated to bring water to the Mexico City Metropolitan Area, MCMA. These costs are not only monetary but ecological and social since several basins in the states of Michoacán and Mexico have being deprived of their clean water.[(30)] ... On the other side, the water of the rivers that originally were to be discharged to the Pacific Ocean is now used in the MCMA, loaded with enormous amounts of pollutants ranging from organic matter from households but also with toxic pollutants from the industrial large area located in this former basin, plus those of hospitals, and other numerous services, and sent to the state of Hidalgo where it has been used to irrigate large cultivation areas, the so called Valley of Mixquiahuala, and then finally discharged in the Gulf of Mexico.[(31)]”

The problem is certainly hard. Drinking water should be provided at prices in accordance with the effort to obtain it but, at the same time, being a public and human right to have clean water it is rather difficult to establish just prices for those persons that can pay it and to those that cannot. Also, if the population acquires the sensitivity to understand this issue, the inhabitants of Mexico City Metropolitan Area will be able to use this vital liquid in a sensible manner. Besides, the minimization of wastewaters dumping and its mixing with the rain water has become a very important issue, particularly with climate change phenomena that increase the intensity of rainfall in Mexico City due to meteorological problems in both coasts, the Pacific Ocean one and the Gulf of Mexico and the Atlantic one (Caribbean Sea) requiring that the whole population be aware of the effects of the use of chemical products to enhance body and clothing visual characteristics (shampoos, lotions, rinsing liquids, etc.), or to have in the refrigerator or in the kitchen food items for a very long time that should contain preservation chemical compounds.

The figure 5 presents a very simple diagram of the transformation of the pollutants present in the wastewaters into innocuous materials. It is clear that the biochemical methods are environmentally friendlier than the chemical ones that need reagents to precipitate the pollutants in order to separate them from the water as solid materials. The organisms, either microbial communities or micro- and macrophytes, are the reagents, the reactors, and the products, and can be efficiently used in this context.[34] In figure 6, a scheme of a horizontal sub-surface flow artificial wetland system with *Phragmites australis* as the macrophyte is shown.[34] It is clear that an impermeable membrane (made of a geotextile material or with natural clays) to isolate wastewater from the surrounding environment is required. It also includes a settling tank as a primary treatment. A secondary tank collects treated wastewater (effluent) with a hose that controls the flooding height within the reactor.[34] The by-products from primary treatment together with the excess biomass may be further treated obtaining a solid material (compost). These might be used as a fuel, recovering the ashes as stable pollutants to be disposed of in an ecological manner.[35] Three prototype artificial wetlands systems have been designed, constructed, started-up, and operated by UNAM authors (figures 7a,b,c).

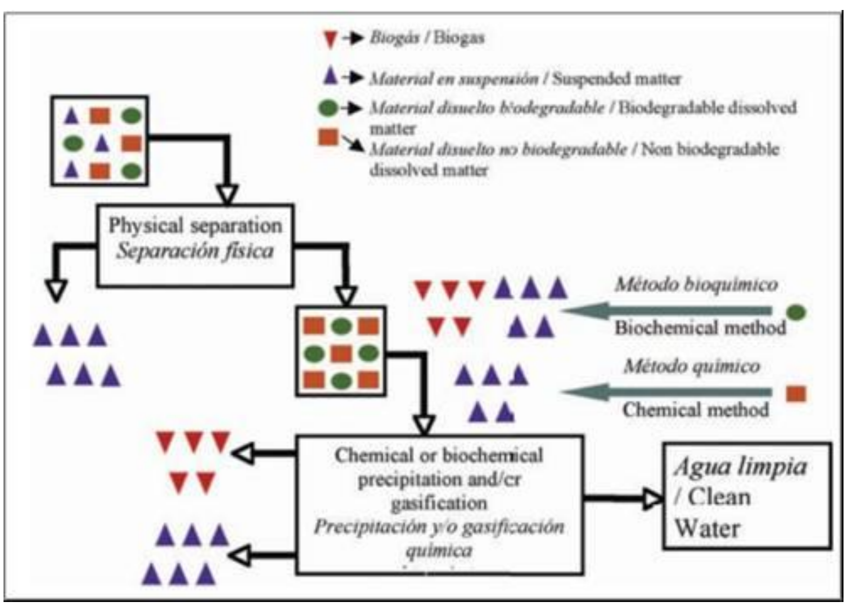

Fig. 5. Scheme diagram for a wastewater treatment system [34]

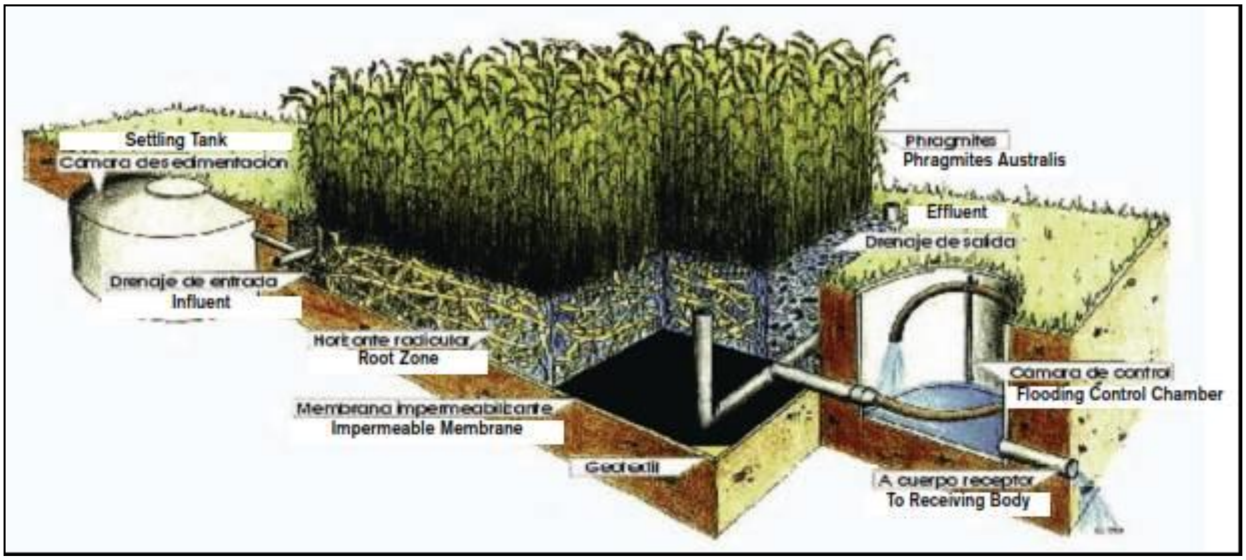

Fig. 6. Horizontal sub-surface flow artificial wetland system with an impermeable membrane (including a geotextile material) to isolate wastewater from the surrounding environment. It includes a settling tank as a primary treatment, and a secondary tank to collect treated wastewater (effluent) with a hose that controls the flooding height within the reactor [34]

Fig. 7a. UNAM Coyoacán Vivarium subsuperficial horizontal flow artificial wetland [23]

Fig. 7b. UNAM Cultural Zone subsuperficial descending vertical flow artificial wetland [23]

Fig. 7c. UNAM CCH Sur subsuperficial horizontal flow artificial wetland [25,26]

Two of them still remain and are a good example of how resilience politics may become useful to overcome the problems of small nuclei of population even in megacities such as Mexico City. Its design follows the chemical characteristics of the wastewaters being received and the desired treated effluents should comply with the official acts.

As an example of the expected values of the wastewaters and treated effluents (Figures 8a,b, Table 1) some data collected from the experimental phase of the subsuperficial descending vertical flow artificial wetland located at UNAM Cultural Zone [(23)] are presented.

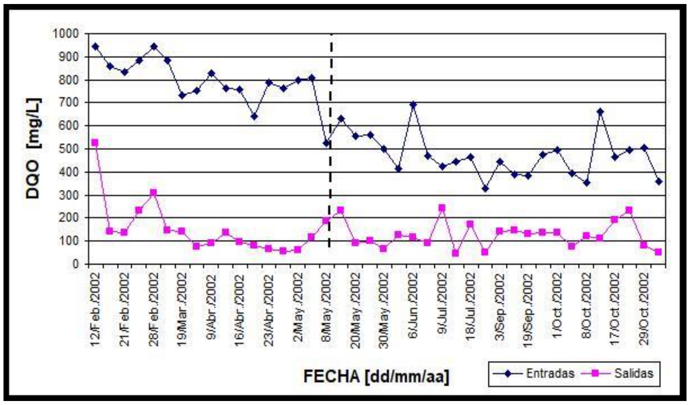

Fig.8a. Behavior of total chemical oxygen demand data from February until October (data are weekly average values for daily measurements) [(23)]

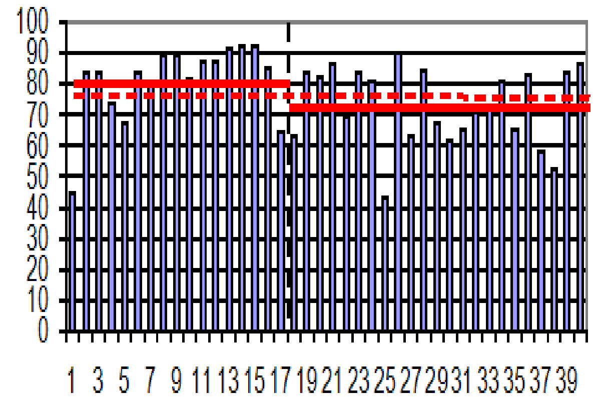

Fig. 8b. Removal efficiencies during these two different hydraulic residence times [(23)]

Data show the differences between two hydraulic residence times (4.8 versus 5.4 days)[1]. The interesting feature is the relative homogeneity of the effluent values for chemical oxygen demand: 450 L d^{-1} with HRT of 4.8 d, obtaining 80% COD_{total} removal *versus* 400 L d^{-1} with HRT of 5.4 d, and 73% COD_{total} removal. The difference observed for the COD_{total} influent data may be due to the rainy season, since statistical analyses ($p<0.05$) do not indicate statistical differences with an average of 77% COD_{tot} removal. In Table 1 some other experimental data for the artificial wetland exemplified are presented, such as temperature, pH value, electric conductivity, total chemical oxygen demand, helminth eggs, fecal coliform organisms, and *Salmonella* spp. (using three different media).

Although data indicate a good performance, concerning international acts, microbiological data are not considered in the first two Mexican acts, one for wastewater dumped into national sources of water and soils [(36)], and the second one listed for treated wastewater to be reused.[(37)] For microbiological parameters and helminth eggs these are not considered except for biosolids or sludges.[(38)] Also, the three of them do not consider chemical oxygen demand but only the first one

[1] This contribution uses the decimal point (scientific notation)

considers biochemical oxygen demand, and when toxic substances are present this value is not reliable. For this reason, in the UNAM experimental analyses only chemical oxygen demand is taken into account.

This second artificial wetland was substituted by the third one, due to the construction of buildings for the UNAM graduate programs in the site where it was located. Figure 7c depicts this relatively newer prototype installed in another UNAM institution. Its interesting feature is that it receives wastewaters not only from sanitary facilities but from the laboratories for experimental teaching of chemistry, biology, and physics. Its results are quite interesting as Table 2 shows the effect of the chemicals on wastewater that impair the performance of the wetland to remove coliforms and helminth eggs complying only with its use without direct contact.(27)

Table 1-Comparison among physical, chemical, and microbiological parameters obtained in the subsuperficial descending vertical flow artificial wetland using the pertinent Mexican acts[1]

PARAMETER	**Average value for the artificial wetland**		**DOF (1996)** [36] **(a)**		**DOF (1997)** [37] **(b)**	**(c)**	**DOF (2002)** [38] **(d)**
	Influent	Effluent	Monthly average value	Daily average value	Monthly average value	Daily average value	A, B
T [°C]	23.4	19.8	40	40	NA	NA	NA
Value of pH	7.31	7.14	NA	NA	NA	NA	NA
Electric conductivity, EC [µmho cm^{-1}]	2090	1926	NA	NA	NA	NA	NA
Dissolved oxygen, OD [mg/L]	0.47	1.83	NA	NA	NA	NA	NA
COD_{tot} [mg/L]	610	138	NA	NA	NA	NA	NA
Helminth eggs [number/L treated wastewater]	6	1	NA	NA	NA	NA	≤1, ≤10 [number/g db]
Fecal Coliform Organisms [MPN/100 mL]	$1.01x10^4$ = 10,100	$2.006x10^1$ = 20	NA	NA	240	1000	<1000 [MPN/g db]
***Salmonella* spp. in SS Agar [CFU/mL]**	$128x10^3$ = 128,000	Not present	NA	NA	NA	NA	< 3 [MPN/g db]
***Salmonella* spp. in XLD Agar [CFU /mL]**	$187x10^3$ = 187,000	$1.0x10^2$ = 100	NA	NA	NA	NA	ND
***Salmonella* spp. in MacConkey Agar [CFU /mL]**	$186x10^3$ = 186,000	Not present	NA	NA	NA	NA	ND

ND = Not determined, NA = Not applicable

MPN = Most probable number and CFU = Colonies forming units [39], SS Agar = Salmonella-Shigella Agar, XLD Agar = Xylose-Lysine-Desoxycholate Agar, MacConkey agar (MAC) was the first solid differential media to be formulated which was developed at 20th century by Alfred Theodore MacConkey**.** MacConkey agar is a selective and differential media used for the isolation and differentiation of non-fastidious gram-negative rods, particularly members of the family Enterobacteriaceae and the genus *Pseudomonas*

(a) Use in irrigation (rural areas)

(b) Services to people with direct contact

(c) Services to people with indirect or occasional contact

(d) Allowed maximum limit of biosolids and sludges (A: Urban use without direct contact with people during its application; B: Urban use with direct contact with people during its application) (db = dry basis)

Table 2- Comparison among microbiological parameters obtained in the newer subsuperficial horizontal flow artificial wetland using the pertinent Mexican act (37,39) (data average from 12 samples taken along 7 months)[1]

	Use without direct contact with people during its application	**Use with direct contact with people during its application**	**Influent data**	**Effluent data**
Fecal coliform organisms [MPN/100 mL]	**1,000**	240	2375.0±8.300	**965.0±4.5**
Helminth eggs [number/L treated wastewater]	**5**	1	3.925±0.072	**2.80±0.13 ≅ 3**

Concluding remarks for the México City's example: Tlalpan

The installation's costs of an artificial wetland system for a household may range from 3-6 times the minimal wages monthly salary.(40)

These costs, for most family dwellings in Tlalpan, are unaffordable since they cannot save money to build them. In these cases, the government should help them acquiring the materials and the people should give their hand labour to construct the systems so that they really become involved with them. In this way they will appreciate the effort and will start having this awareness of the problem and how to solve it.

The majority of the inhabitants of Mexico City that are not conscious that they are all part of the problem will become part of the solution.

Again using the material of a previous presentation: (29)

In parallel, the social groups in each "*colonia*" (a division within the political territorial area in Mexico City) should start step by step bringing out a solution, especially those that are lucky to have drinking water and sanitation:

(a) every time there is a leak detected from the subterranean areas where the network systems are located to have the care of disinterring it for avoiding further leakages caused by the telluric daily movements, especially with the drinking water;

(b) for the sewage, every time a leak is detected, to start up the segregation or separation of rain water from sewage with two different types of piping, and with this solution greatly reducing the flow rate and encouraging the reuse of rain water for irrigation of green areas and the filling out again of river beds, channels, lakes, ponds, fountains, etc., for recovering the beauty of the city and tempering again the climate [(41)]; and

(c) the sending of the separated wastewaters to environmentally friendly systems such as rotating biological reactors coupled with artificial wetlands for apartment building complexes whereas for horizontal building complexes and small private households the proposed hybrid systems would be the pertinent solution.[(6,24,25)]

Case of study: havana city

The following material was presented in RESURBE III [(29)] and has not been published:

Presently, around the world 750 millions of people have no access to drinking water enough for daily consumption and 2,500[1] million cannot enjoy sanitation basic facilities for water used.[(42)] Multiple causes contribute to this situation. Among them, the pollution of aquatic ecosystems that have suffered an ever increasing damage in its quality, mainly due to the discharges of household, industrial, and derived of the agricultural and livestock keeping activities.[(43)]

This problem concerns not only to the countries in development but also to those already developed since their companies tend to migrate their enterprises and businesses to those countries considering that pollution protection laws and norms are laxer than those in their home countries and that pollution will never reach them.

For Cuba, this is the present case, being one of the most stringent environmental problems the dumping of wastewaters to water bodies and ecosystems in general either untreated or with deficient treatments.[44-46]

This fact is clearly observed in some important surface water bodies such as the Almendares river, pertaining to the hydrographic basin of Almendares-Vento, La Habana, Cuba (figures 9a, b).

This basin possesses a total surface of 402.02 km², where the Almendares river is the most important one and reaches an extension of 49.8 km where more than 570,000 inhabitants live. Around 70 polluted sources of different origins discharge their wastewaters to the river, estimating the existence of high levels of chemical pollutants there [47], as well as microbiological sources of pollution. Studies carried out in this ecosystem have shown elevated contents of organic matter, ammonium compounds, phosphates, polycyclic aromatic hydrocarbons and some heavy metals, as a consequence of these discharges.[44,46,48] The chemical oxygen demand values, COD, a commonly used parameter to measure global pollutants in water or wastewater, exceed in approximately ten-fold the reference values of the Cuban norms. The phosphates concentrations (0 a 4 ppm) and ammonium compounds (1 a 12 ppm) in some occasions are very near to the limits established. The concentrations of some heavy metals are high, for example, for Pb (II) (2.86-73.29 $\mu g.L^{-1}$) and Cr (VI) (0.14-0.20 $\mu g.L^{-1}$), and for Cd (II) (0.12-0.81 $\mu g.L^{-1}$).[44]

Fig 9a. The Almendares river as it crosses Havana City [44]

Fig. 9b. Almendares river. Image source: https://commons.wikimedia.org/wiki/File:Metropolitan_Park_of_Havana.jpg

According to these data it can be said that the main course of the Almendares River shows a critical hygienic – sanitary situation. In Cuba, due to its condition of a country with a developing economy, there is a high deficit of maintenance and attention to the operation of the wastewater treatment facilities. This situation increases its inefficiency for the wastewaters treatment.[49]

Thus, some options should be considered to solve this urgent problem. That is, low cost and ingenious solutions to appropriately deal with the pollution of the wastewaters. One of these options is precisely the use of artificial or constructed wetlands.

Artificial or constructed wetlands, as mentioned in the preceding paragraphs are those that simulate the operation of the natural wetlands. These engineered systems are designed and constructed to use the natural processes implicated in the symbiotic interactions between living organisms and its abiotic environment for recycling the so called wastes or pollutants present in the water, that for those organisms (micro- and macro-phytes, microbial communities) are really resources. As it was said at the beginning of this document, these systems were created to take advantage of the processes occurring in nature but in a more controlled environment.[4,50,51]

Microorganisms are a fundamental part of the correct functioning of these systems, since these are the limiting step for the efficient removal of pollutants: they contribute to the degradation of the organic matter and to the removal and transformation of the nitrogen and phosphorus compounds present in the wastewaters.[17,52,54] Among the various advantages of this technology are the very low costs of construction (even more if they are built with collective work, known in Mexico as *tequio* or *tequiotl*, a Nahuatl or Aztec word for collective tasks to improve the community) starting-up, operation, and maintenance, compared with the conventional physical, chemical, and biological systems. It is an effective and safe technology for the treatment and recycling of water especially if they are properly operated and maintained. It is simple and highly efficient operation warrants the removal of pollutants.[54,58] These are aspects that strengthen its use as an option for the treatment of wastewaters especially where land is not expensive.[59]

Additionally, they can be constructed in small communities or by the neighbours of localities immersed in the big cities where traditional wastewaters treatment facilities are not feasible such as the case of many big cities in the world.[60,61] They can also be built *in situ* where wastewaters are being produced and maintenance may be carried out by personnel relatively untrained,[61,63] Besides, the environmental impact, such as noise, odour, etc., is very low and they are quite well integrated to the environment. Furthermore, there has been a strong approach to improve its performance to reduce the total area needed for its construction, one of its main limitations, especially in the urban areas. One of these strategies is directed towards bio-augmentation. Bio-augmentation or “seeding” consists in la addition of highly specialized and concentrated microbial populations of pure strains or consortia, to a specific contaminated site.[64,65]

This technique is considered suitable for those sites that do not possess enough microbial cells or when the native population does not present the metabolic capabilities and necessary characteristics for the proper interaction with the compounds to be removed. [65] The most common options used with this strategy are the addition of pre-adapted pure bacterial strains, the addition of pre-adapted consortia, the introduction of genetically modified bacteria, and the incorporation of genes relevant to the efficient interaction with the specific pollutant, through a vector, to be transferred to the indigenous microorganisms.[66] In spite of the many elements to be considered and that some contradictory results from different research groups are to be found, bio-augmentation represents one of the best options to improve the operation of the artificial wetlands [65], mainly due to the specialization and selectivity of the inoculated microorganisms since process efficiency depends upon the biological agents.[67] Thus, the search for competent microorganisms for its application in each specific site or given pollutant is probably one of the interesting approaches in the present moment to enhance the use of artificial wetlands.[65]

This is precisely one of the subjects that the Group for Microbial Treatment of Wastewaters of the Faculty of Biology at the *Universidad de La Habana* (*Grupo de Tratamiento Microbiano de Aguas Residuales de la Facultad de Biología*). It is done in cooperation with the *UNAM Facultad de Química*. The main objective is to study the internal functioning of the artificial wetlands to be applicable in communities, as well as enterprises, and other needed areas such as mine sites, etc.

One of the results reached was the isolation and selection of bacterial strains, some with the potentiality to remove organic matter, ammonium, phosphates, and others with the capacity to remove heavy metals such as cadmium, chrome, mercury, and lead.[9,10,12,13] With these selected bacteria consortia were designed to bio-augment the metals removal efficiency in lab scale reactors simulating artificial wetlands resulting in an increased removal of the selected pollutants as well as the removal of organic matter, nitrogen, and phosphorus. These results may be used to reduce the surface area needed in heavily built households in big cities improving its operation as is the case of the Almendares river basin. Near the Almendares river there are some identified communities that require treatment systems for its wastewaters. Most of them comprise around 2000 inhabitants. Thus, the application of these environmentally friendly approaches is just what it is needed. As a surplus of the treatment system based on artificial wetlands, the treated effluents might be used not only for the sanitary facilities but also for the now so popular urban agriculture. Besides, the self-employment among the community may become a status of pride to be cooperating to improve the quality of the river basin and even to use it for touristic purposes. All these actions constitute resilient responses of the inhabitants towards its living standards improvement (figures 10, 11).

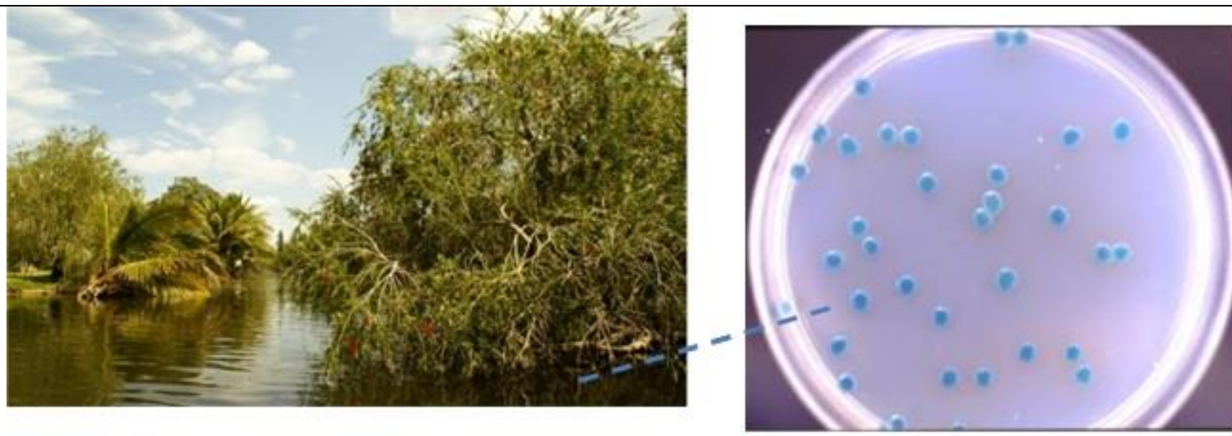

Fig. 10. Metalo-tolerant microorganisms isolated from the Almendares River to enhance artificial wetlands performance [9,10,12,13]

Fig.11. The luxurious vegetation in the Almendares riverbed.

Concluding remarks for the case study of havana city

The subsequent bioaugmentation with the consortium of CWs at laboratory scale allowed 100%, greater than 70 and 55% removal of organic matter, ammonium, and phosphate, respectively.[(68)] Also removals over 95, 80 and 50% for lead, mercury and chromium, respectively, were obtained.

Conclusions

The use of artificial or constructed wetlands for rural communities as well as for suburban areas where nowadays the construction of sewage systems is not only too costly but full of problems associated with already built streets and avenues, as well as type of soil and other construction constrains, is a very promising solution.

Authors hope that this approach becomes a useful tool for sanitation solutions not only in Mexico and Cuba but all over the world.

Acknowledgements

The authors acknowledge the generous financial and logistic support of *UNAM*'s *Dirección General de Cooperación e Internacionalización* to the new *Red sobre el Uso de Humedales Artificiales para Reducir la Vulnerabilidad de las Comunidades con Escasez de Agua* / Network on the use of artificial wetlands to reduce the vulnerability of communities with water scarcity (February 2015-January 2016), a pioneer university program with social outcome. They also acknowledge the valuable support for their academic activities from Mr. David Navarrete, from the Mayor's office at Izúcar de Matamoros, Puebla, Mexico. The rest of the authors warmly thank Mrs. Dr. en Ing. Marisela Bernal-González for kindly providing part of her didactic visual material that she carefully prepared for her graduate course "*Tratamiento de agua y aguas residuales*" (Treatment of water and wastewaters) of the Master's Programs in Chemical Engineering and Environmental Engineering at UNAM, Mexico.

References

1. GARCÍA-LUNA, V. J., BERNAL-GONZÁLEZ, M., GARCÍA-JIMÉNEZ, F. A., DURÁN-DOMÍNGUEZ-de-BAZÚA, M.d.C. "Xochimilco, Mexico, a natural wetland or an artificial one?". In: Durán-Domínguez-de-Bazúa M.d.C. (Mexico), Navarro-Frómeta A.E. (Mexico), Bayona Termens J.M. (Spain) (Eds.). *Artificial & Constructed Wetlands: A Suitable Technology for Sustainable Water Management*. Boca Raton: CRC Press, 2018, Chapter 1, pp. 1-24. ISBN-10: 1138739189. ISBN-13: 978-1138739185 https://www.taylorfrancis.com/books/e/9781315184265/chapters/10.1201/9781315184265-1

2. KADLEC, R. H., WALLACE, S. D. *Treatment Wetlands.* 2nd Ed. CRC Press, Boca Raton, U.S, 2009. 1016 p. ISBN: 978-1-56670-526-4

3. VYMAZAL, J. "Constructed wetlands for wastewater treatment". *Water*, 2010, 2, 530-549. https://doi.org/10.3390/w2030530

4. GARCÍA, J., CORZO, A. *Depuración con humedales construidos, Guía práctica de diseño, construcción y explotación de sistemas de humedales de flujo subsuperficial*. Departamento de Ingeniería Hidráulica, Marítima y Ambiental. Universidad Politécnica de Catalunya, España, 2008. pp. 2-10. http://humedales-construidos-wetlands.fr/wp-content/uploads/2015/11/JGarcia_and_ACorzo.pdf

5. ÁVILA, C., GARFÍ, M., GARCÍA, J. "Three-stage hybrid constructed wetland system for wastewater treatment and reuse in warm climate regions". *Ecol. Eng*. 2013, 61, 43-49. https://doi.org/10.1016/j.ecoleng.2013.09.048

6. VYMAZAL, J. "The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: a review of a recent development". *Water Research.* 2013, **47**(14), 4795-4811. https://doi.org/10.1016/j.watres.2013.05.029

7. ZURITA, F., WHITE, J. R. "Comparative study of three two-stage hybrid ecological wastewater treatment systems for producing high nutrient, reclaimed water for irrigation reuse in developing countries". *Water*, 2014, 6, 213-228. https://doi.org/10.3390/w6020213

8. AMÁBILIS-SOSA, L. E., SIEBE, Ch., MOELLER-CHÁVEZ, G., DURÁN-DOMÍNGUEZ-de-BAZÚA, M. C. "Remoción de mercurio por *Phragmites australis* empleada como barrera biológica en humedales artificiales inoculados con cepas tolerantes a metales pesados". *Revista Internacional de Contaminación Ambiental*. 2016, **32**(1), 47-53. http://www.redalyc.org/articulo.oa?id=37045275004

9. AMÁBILIS-SOSA, L. E., SIEBE, Ch., MOELLER-CHÁVEZ, G., DURÁN-DOMÍNGUEZ-de-BAZÚA, M. C. “Accumulation and distribution of lead and chromium in laboratory-scale constructed wetlands inoculated with metal-tolerant bacteria”. *International Journal of Phytoremediation*. 2015, **17**(11), 1090-1096. https://doi.org/10.1080/15226514.2015.1021953

10. PANIZZA-de-LEÓN, A., CARRILLO-GONZÁLEZ, R., BERNAL-GONZÁLEZ, M., VACA-MIER, M., DURÁN-DOMÍNGUEZ-de-BAZÚA, C. “Exploration of the ability of *Coleus blumei* to accumulate aluminum”. *International Journal of Phytoremediation*. 2011, **13**(5), 421-433. DOI: 10.1080/15226514.2010.483263

11. SALGADO-BERNAL, I., CARBALLO-VALDÉS, M. E., MARTÍNEZ-SARDIÑAS, A., CRUZ-ARIAS, M., DURÁN-DOMÍNGUEZ, C. “Interacción de aislados bacterianos rizosféricos con metales de importancia ambiental”. *Revista Tecnología y Ciencias del Agua*. 2012a, **3**(3), 83-95. http://www.scielo.org.mx/pdf/tca/v3n3/v3n3a6.pdf

12. SALGADO-BERNAL, I., DURÁN-DOMÍNGUEZ, C., CRUZ-ARIAS, M., CARBALLO-VALDÉS, M. E., MARTÍNEZ-SARDIÑAS, A. “Bacterias rizosféricas con potencialidades fisiológicas para eliminar materia orgánica de aguas residuales”. *Revista Internacional de Contaminación Ambiental*. 2012b, **28**(1), 17-26. http://www.scielo.org.mx/pdf/rica/v28n1/v28n1a2.pdf

13. CHEN, Z. B., KAPPELMEYER, U., KUSCHK, P. Benzene removal in laboratory scale model wetland under different electron acceptor conditions treating sulfate-rich wastewater. In *Advances in environmental technologies III. Selected, peer reviewed papers from the 2014 3rd International Conference on Energy and Environmental Protection (ICEEP 2014)*. Wang, A., Li, X., Wang, X., Zhao, J., (Eds.). *April 26-28, 2014, Xi'an, China. Advanced Materials Research, 955-959.* Trans Tech Publications, Durnten-Zurich, pp. 2083-2086. https://doi.org/10.4028/www.scientific.net/AMR.955-959.2083

14. MARTÍNEZ-LAVANCHY, P. M., CHEN, Z., LÜNSMANN, V., MARIN-CEVADA, V., VILCHEZ-VARGAS, R., PIEPER, D. H., REICHE, N., KAPPELMEYER, U., IMPARATO, V., JUNCA, H., NIJENHUIS, I., MÜLLER, J. A., KUSCHK, P., HEIPIEPER, H. J. “Microbial toluene removal in hypoxic model constructed wetlands occurs predominantly via the ring monooxygenation pathway”. *Applied Environmental Microbiology.* 2015, **81**(18), 6241-6252. DOI: 10.1128/AEM.01822-15

15. SCHULTZE-NOBRE, L., WIESSNER, A., WANG, D., BARTSCH, C., KAPPELMEYER, U., PASCHKE, H., MATTUSCH, J., KUSCHK, P. “Removal of dimethylphenols from an artificial wastewater in a laboratory-

scale wetland system planted with *Juncus effuses". Ecology and Engineering.* 2015, 80, 151-155. https://doi.org/10.1016/j.ecoleng.2014.11.056

16. GUIDO-ZÁRATE, A., BUITRÓN, G., MIJAYLOVA-NACHEVA, P., DURÁN-de-BAZÚA, C. "Behavior of redox potentials in artificial wetlands models: A tool for controlling its efficiency". In *Communicating current research and educational topics and trends in applied microbiology*. Méndez-Vilas. A. (Ed.). Badajoz: Formatex Series, 2007, pp. 59-60, Vol. 1: ISBN-13:978-84-611-9421-6. Vol. 2. ISBN-13: 978-84-611-9423-0.

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.589.7943&rep=rep1&type=pdf

17. SOTO-ESQUIVEL, M. G., GUIDO-ZÁRATE, A., GUZMÁN-AGUIRRE, S., MEJÍA-CHÁVEZ, A. G., GARCÍA-GÓMEZ, R. S., HUANOSTA, T., PADRÓN-LÓPEZ, R. M., RODRÍGUEZ-MONROY, J., MIJAYLOVA-NACHEVA, P., BUITRÓN-MÉNDEZ, G., DURÁN-de-BAZÚA, C. "Algunos aspectos interesantes de sistemas de humedales a escala de laboratorio y de banco en México". *Revista Química Central de la Facultad de Ciencias Químicas (Ecuador)*. 2013, **3**(2), 53-65. http://revistadigital.uce.edu.ec/index.php/QUIMICA/article/view/1206

18. SOTO-ESQUIVEL, M. G., GUZMÁN-AGUIRRE, S., MEJÍA-CHÁVEZ, A. G., GARCÍA-GÓMEZ, R. S., DURÁN-de-BAZÚA, C. "Efecto de la presencia de hidrofitas (*Typha latifolia*) sobre los potenciales redox (reducción-oxidación) en columnas empacadas a escala de laboratorio / *Effect of hydrophytes (Typha latifolia) presence on the redox potentials (reduction-oxidation) in lab scale packed columns"*. *Tecnología Ciencia y Educación (IMIQ)*. 2009, **24**(1), 5-11. http://www.redalyc.org/service/redalyc/downloadPdf/48212169003

19. COBAN, O., KUSCHK, P., KAPPELMEYER, U., SPOTT, O., MARTIENSSEN, M., JETTEN, M. S. M., KNOELLER, K. "Nitrogen transforming community in a horizontal subsurface-flow constructed wetland". *Water Research.* 2015, 74, 203-212. https://doi.org/10.1016/j.watres.2015.02.018

20. DURÁN-de-BAZÚA, C., GUIDO-ZÁRATE, A., HUANOSTA, T., PADRÓN-LÓPEZ, R. M., RODRÍGUEZ-MONROY, J. "Artificial wetlands performance: nitrogen removal". *Water Science and Technology*, 2008, **58**(7), 1357-1360. DOI: 10.2166/wst.2008.350

21. ORDUÑA-BUSTAMANTE, M. A., VACA-MIER, M., ESCALANTE-ESTRADA, J. A., DURÁN-DOMÍNGUEZ-de-BAZÚA, C. "Nitrogen and potassium variation on contaminant removal for a vertical subsurface

flow lab scale constructed wetland". *Bioresource Technology*. 2011, 102, 7745-7754. https://doi.org/10.1016/j.biortech.2011.06.005

22. BORREGO-SARÁCHAGA, N.G. "Estudio de la calidad del agua en un sistema de humedales artificiales a nivel prototipo que recibe aguas residuales de un plantel educativo". Professional Thesis (Chemical Engineering). UNAM, Facultad de Química. Mexico City, Mexico, 2015. 132.248.9.195/ptd2015/agosto/0732926/Index.html

23. SECUNDINO-SÁNCHEZ, O., AMÁBILIS-SOSA, L. E., GONZÁLEZ-FLORES, E., DURÁN-DOMÍNGUEZ-de-BAZÚA, M.d.C. "Diseño de un humedal artificial subsuperficial de flujo horizontal para el tratamiento de agua residual en Santa María Coatepec El Seco, Puebla, México/ *Design of a horizontal subsurface flow artificial wetland for treatment of wastewater in Santa Maria Coatepec El Seco, Puebla, Mexico*". In *Libro electrónico de trabajos selectos/Electronic Book of Selected Papers VIII Minisimposio Internacional sobre Remoción de Contaminantes de Agua, Atmósfera y Suelo*. DURÁN-de-BAZÚA, M.d.C., PADRÓN-LÓPEZ, R.M., BERNAL-GONZÁLEZ, M., GARCÍA-GÓMEZ, R.S., RAMÍREZ-BURGOS, L.I. (Eds.). Villahermosa: RACAM-AMCATH-DACB Universidad Juárez Autónoma de Tabasco-LIQAyQA, FQ, UNAM, 2014, pp. 185-196, ISSN 2448-6116. Premio a la MEJOR contribución en cartel de la Mesa Redonda de AGUA Y AGUAS RESIDUALES. http://www.ambiental.unam.mx/albunimagenes/Libro-e-Book%20Mems-Procs%20VIII%20MSIRCAAS-8th%20IMSRCWAS%2023-28Jun2014.pdf

24. NAVARRO, A., MORALES, L., SÁNCHEZ, J., MONTOYA, J., HERRERA, J. Depuración terciaria de aguas residuales municipales con humedales híbridos: una experiencia piloto. In Memorias del VII Seminario Internacional de Gestión Ambiental y II Seminario de Ciencias Ambientales. SUE Caribe, 2014. pp. 72-78. ISBN 978-958-9244-64-7. Santa Marta, Colombia. Oct. 10-12.

25. NAVARRO, F. A. E., MORALES, M. L., SÁNCHEZ, M. J. & MONTOYA, R. J. I. "Humedales híbridos para la remoción de microcontaminantes orgánicos de aguas residuales municipales". *Revista Latinoamericana el Ambiente y las Ciencias*. 2015, **6**(Número Especial), 86-90. ISSN: 2310-2799

26. CONAGUA. Programa de sustentabilidad hídrica de la cuenca del Valle de México. In Tribuna del agua. Semana temática 5. Servicio de agua potable y saneamiento. Expo Agua, Zaragoza, España, 2008a. Web Page: https://www.zaragoza.es/contenidos/medioambiente/cajaAzul/Semana5.pdf

27. DELGADO, J., SUÁREZ, M. "Ciudad de México ¿Ciudad sustentable?" *Ciencia*. 2014, **65**(4), 20-27. https://www.amc.edu.mx/revistaciencia/images/revista/65_4/PDF/MexicoCS.pdf

28. DÍAZ-DEL-CASTILLO, B. Historia verdadera de la conquista de la Nueva España. 1568. http://www.historiadelnuevomundo.com/docs/Conquista-Nueva-Espana-Bernal-Diaz-del-Castillo.pdf

29. DURÁN-DOMÍNGUEZ-de-BAZÚA, María-del-Carmen, SALGADO-BERNAL, Irina, NAVARRO-FROMETA, A. Enrique, KAPPELMEYER, Uwe, ESPINOSA-AQUINO, Beatriz, RUIZ-CARDENAS, N. José, BERNAL-GONZALEZ, Marisela, GARCIA-GOMEZ, Rolando Salvador, RAMIREZ-BURGOS, Landy Irene, ARREGUIN-ROJAS, Agustín. Polluted water threats to urban resilience: Case studies in Mexico and Havana Cities. Presented at RESURBE III, INTERNATIONAL CONFERENCE ON URBAN AND REGIONAL RESILIENCE, Empowering Local Communities for Local Action. RECNET, UNESCO. UNAM, Facultad de Arquitectura. Mexico City, Mexico, 2016. http://lcn.pascalobservatory.org/pascalnow/pascal-activities/events/resurbe-iii-international-conference-urban-resilience-17-20-february

30. CONAGUA. Efecto en el servicio de agua potable de la Ciudad de México con motivo de la suspensión parcial en el suministro del Sistema Cutzamala. 2010, Web Page: http://www.conagua.gob .mx/CONAGUA07/Noticias/SGP-2-14Web.pdf.

31. CONAGUA. Planta de tratamiento de aguas residuales. Municipio de Atotonilco de Tula Estado de Hidalgo, 2008b. http://www.conagua.gob.mx/conagua07/contenido/Documentos/MEMORIAS%20DOCUMENTALES /Memoria%20Documental%20Planta%20de%20tratamiento%20de%20agus%20residuales%20de%20 Atotonilco.pdf

32. INEGI. Panorama sociodemográfico del Distrito Federal, 2010. Web Page: http://www.inegi.org.mx/prod_serv/contenidos/espanol/bvinegi/productos/censos/poblacion/2010/ panora_socio/df/panorama_df.pdf

33. SSN. Servicio Sismológico Nacional. 2014. Web Page: http://www.ssn.unam.mx/

34. DURÁN-DOMÍNGUEZ-de-BAZÚA, M. C. "Artificial Wetlands: Pre-Columbian Inheritance for the Depuration of Polluted Water. Applications to the Sugarcane and Ethyl Alcohol Industry / *Humedales artificiales: Herencia prehispánica para la depuración de aguas contaminadas. Aplicaciones a la industria azucarera-alcoholera"*. *Sugar Journal*. 2011, 74(7), 10-21. http://www.SugarJournal.com

35. GAITÁN-ZAMORA, N. A., DURÁN-de-BAZÚA, M. C. Ecotoxicological evaluation of compost obtained from vegetable wastes of artificial wetlands and primary sludges in a laboratory scale / Evaluación ecotoxicológica de composta producida con residuos vegetales de humedales artificiales y lodos

primarios a escala de laboratorio. In *Proceedings of the 2006 Fourth International Minisymposium on Removal of Contaminants from Wastewaters, Atmosphere, and Soils*. Durán-de-Bazúa, C. & Ramírez Burgos, L.I. (eds.). Compact Disc (e-book). Pp. 93-104. PIQAyQA, Facultad de Química, UNAM. México D.F. México. November 8-11, 2006. http://www.ambiental.unam.mx/albunimagenes/IV%20Mini-SProcs-Mems8-11Nov2006.pdf

36. DOF. Norma Oficial Mexicana NOM-001-SEMARNAT-1996. Diario Oficial de la Federación. Estados Unidos Mexicanos. 1996. https://www.profepa.gob.mx/innovaportal/file/3290/1/nom-001-semarnat-1996.pdf

37. DOF. Norma Oficial Mexicana NOM-003-SEMARNAT-1997. Diario Oficial de la Federación. Estados Unidos Mexicanos. 1997. https://www.profepa.gob.mx/innovaportal/file/3297/1/nom-003-semarnat-1997.pdf

38. DOF. Norma Oficial Mexicana NOM-004-SEMARNAT-2002. Diario Oficial de la Federación. Estados Unidos Mexicanos. 2002. http://legismex.mty.itesm.mx/normas/ecol/semarnat004.pdf

39. GRONEWOLD, A.D., WOLPERT, R.L. "Modeling the relationship between most probable number (MPN) and colony-forming unit (CFU) estimates of fecal coliform concentration". *Water Research*. 2008, **42**(13), 3327-3334. https://doi.org/10.1016/j.watres.2008.04.011. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.220.2828&rep=rep1&type=pdf

40. SÁNCHEZ-TOVAR, S.A. TERRABRIO, S.A. de C.V. Mexico City, Mexico. Personal communication. In Somos agua 2: Humedales. Una tecnología que nos ayuda a tratar el agua residual (la que ya utilizamos), para proteger el ambiente: Humedales artificiales o construidos. 2018. www.aguanet.com.mx

41. MOLINA, M. "Expansión urbana y cambio climático". *Ciencia*. 2014, **65**(4), 10-13. https://www.amc.edu.mx/revistaciencia/images/revista/65_4/PDF/ExpansionUrbana.pdf

42. WHO/UNICEF.. Progress on drinking-water, sanitation and hygiene 2000-2017: Special focus on inequalities. UNICEF, World Health Organization. Geneva, Switzerland, 2019. https://www.who.int/water_sanitation_health/publications/jmp-report-2019/en/

43. SALDÍVAR, A. "México, la economía del desarrollo insustentable". *Mundo Siglo XXI, Revista del Centro de Investigaciones Económicas Administrativas y Sociales del Instituto Politécnico Nacional*.

2005, 1, 51-49. https://repositorio.flacsoandes.edu.ec/xmlui/bitstream/handle/10469/7417/REXTN-MS01-03-Saldivar.pdf?sequence=1&isAllowed=y

44. CARBALLO, M. E, HEYDRICH, M., ROJAS, N., SALGADO, I., ROMEU, B., MANZANO, A. M., LARREA, J., DOMÍNGUEZ, O., MARTÍNEZ, A., SÁNCHEZ, M. I., CRUZ, M., GUERRA, G., ROJAS, M. & RAMOS, M. “Impact of microbial and chemical pollution in Cuban freshwater ecosystems: strategies for environmental recovery”. *Biotecnología Aplicada*. 2011, 28, 276-279. https://elfosscientiae.cigb.edu.cu/PDFs/Biotecnol%20Apl/2011/28/4/BA002804RP276-279.pdf

45. MARTÍNEZ, Armando, CRUZ, Mario, VERANES, Oiris, CARBALLO, María Elena, SALGADO, Irina, OLIVARES, Susana, LIMA, Lázaro, RODRÍGUEZ, Danae. “Resistencia a antibióticos y a metales pesados en bacterias aisladas del río Almendares”. Revista CENIC. Ciencias Biológicas [en linea], 2010, 41 <http://www.redalyc.org/articulo.oa?id=181220509038> ISSN: 0253-5688

46. OLIVARES-RIEUMONT, S., LIMA, L., De-la-ROSA, D., GRAHAM, D. W., COLUMBIE, I., SANTANA, J. L., SÁNCHEZ, M. J. “Water hyacinths (*Eichhornia crassipes*) as indicators of heavy metal impact of a large landfill on the Almendares river near Havana, Cuba”. *Bull Environ. Contam. Toxicol*., 2007, **79**(6), 583-587. DOI https://doi.org/10.1007/s00128-007-9305-5

47. LIMA, L., OLIVARES, S., COLUMBIE, I., De-la-ROSA, D., GIL, R. “Niveles de plomo, zinc, cadmio y cobre en el Río Almendares, Ciudad Habana, Cuba”. *Rev. Int. Contam. Ambient.*, 2005, **21**(3), 115-124. http://www.scielo.org.mx/pdf/rica/v21n3/0188-4999-rica-21-03-115.pdf

48. SANTANA-ROMERO, J. L., VALDÉS-CALLADO, M., OLIVARES-RIEUMONT, S., LIMA-CAZORLA, L. “Determinación de hidrocarburos aromáticos policíclicos ligeros en aguas superficiales de los ríos Almendares y Luyanó en La Habana”. *Revista CENIC. Ciencias Químicas*. 2012, 43, 1-7. http://www.redalyc.org/articulo.oa?id=181628775002

49. PÉREZ, M. M., DOMÍNGUEZ, E. R., MARTÍNEZ, P., LÓPEZ, M. E., GONZÁLEZ, Y. M., MONTEAGUDO, M. “Eficiencia de diferentes sustratos de filtros de suelo plantados en la depuración de aguas residuales domésticas”. *Revista CENIC Ciencias Biológicas*. 2009, **40**(3), 181-185. https://revista.cnic.edu.cu/revistaCB/sites/default/files/articulos/Articulo%20No%206%20B43%20-%2008%20pp181-185.pdf

50. DIPU, S., KUMAR, A. A. & GNANA THANGA, V. S. “Phytoremediation of dairy effluent by constructed wetland technology”. *Environmentalist*. 2011, 31, 263-278.

https://www.researchgate.net/profile/Dipu_S2/publication/289522261_Phytoremediation_of_dairy_effluent_by_constructed_wetland_technology/links/568e486908aeaa1481aff19f/Phytoremediation-of-dairy-effluent-by-constructed-wetland-technology.pdf

51. VYMAZAL, J. "Removal of nutrients in various types of constructed wetlands". *Science of the Total Environment.* 2007, 380, 48-65. https://reader.elsevier.com/reader/sd/pii/S0048969706007212?token=960CDF740A99D8562A6E7C3CB3B99A1591643F7AE7E9B6FC2929A50D7C1B069BE1A8ED0CAD330DD608C88746ADEA913C

52. CHAUDHRY, Q., BLOM-ZANDSTRA, M., GUPTA, S., JONER, E. J. "Utilising the synergy between plants and rhizosphere microorganisms to enhance breakdown of organic pollutants in the environment". *Environmental Science and Pollution Research*, 2005, **12**(1), 34-48. http://agris.fao.org/agris-search/search.do?recordID=NL2012007610

53. FAULWETTER, J. L., GAGNON, V., SUNDBERG, C., CHAZARENC, F., BURR, M. D., BRISSON, J., CAMPERA, A. K., STEIN, O. R. "Microbial processes influencing performance of treatment wetlands: A review". *Ecological Engineering*. 2009, 35, 987-1004. doi.org/10.1016/j.ecoleng.2008.12.030

54. ROMERO-AGUILAR, M., COLÍN-CRUZ, A., SÁNCHEZ-SALINAS, E., ORTIZ-HERNÁNDEZ, M. L. "Tratamiento de aguas residuales por un sistema piloto de humedales artificiales: evaluación de la remoción de la carga orgánica". *Rev. Int. Contam. Ambient*. 2009, **25**(3), 157-167. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0188-49992009000300004

55. CASELLES-OSORIO, A., VILLAFAÑE, P., CABALLERO, V., MANZANO, Y. "Efficiency of mesocosm-scale constructed wetland systems for treatment of sanitary wastewater under tropical conditions". *Water Air Soil Pollut*. 2011, 220, 161-171. DOI: 10.1007/s11270-011-0743-7

56. CHEN, H. "Surface-flow constructed treatment wetlands for pollutant removal: applications and perspectives". *Wetlands*. 2011, 31, 805-814. DOI: 10.1007/s13157-011-0186-3

57. CURIA, A. C., KOPPE, J. C., COSTA, J., FÉRIS, L. A., GERBER, W. D. "Application of pilot-scale-constructed wetland as tertiary treatment system of wastewater for phosphorus and nitrogen removal". *Water Air Soil Pollut*. 2011, 218, 131-143. https://*doi*.org/10.1007/s11270-010-0629-0

58. GAGNON, V., MALTAIS-LANDRY, G., PUIGAGUT, J., CHAZARENC, F., BRISSON, J. "Treatment of hydroponics wastewater using constructed wetlands in winter conditions". *Water Air Soil Pollut*. 2010, 212, 483-490. DOI: 10.1007/s11270-010-0362-8

59. KAYRANLI, B., SCHOLZ, M., MUSTAFA, A., HOFMANN, O., HARRINGTON, R. "Performance evaluation of integrated constructed wetlands treating domestic wastewater". *Water Air Soil Pollut*. 2010, 210, 435-451. DOI: 10.2175/106143016X14504669767814

60. BABATUNDE, A. O., ZHAO, Y. Q., O'NEILL, M., O'SULLIVAN, B. "Constructed wetlands for environmental pollution control: A review of developments, research and practice in Ireland". *Environment International.* 2008, **34**(1), 116-126. https://researchrepository.ucd.ie/handle/10197/3142

61. CHUNG, A. K. C., WUB, Y., TAM, N. F. Y., WONG, M. H. "Nitrogen and phosphate mass balance in a sub-surface flow constructed wetland for treating municipal wastewater". *Ecological Engineering.* 2008, 32, 81-89. https://doi.org/10.1016/j.ecoleng.2007.09.007

62. KASEVA, M. E. "Performance of a sub-surface flow constructed wetland in polishing pre-treated wastewater - a tropical case study". *Water Research*. 2004, 38, 681-687. DOI: 10.1016/j.watres.2003.10.041

63. SOLANO, M. L., SORIANO, P., CHIRIA, M. P. "Constructed wetlands as sustainable solution for wastewater treatment in small villages". *Biosyst. Eng*. 2004, 87, 109-118. DOI: 10.1016/j.biosystemseng.2003.10.005

64. CERQUEIRA, V. S., HOLLENBACH, E. B., MABONI, F., CAMARGO, F. A. O, PERALBA, M. C. R., BENTO, F. M. "Bioprospection and selection of bacteria isolated from environments contaminated with petrochemical residues for application in bioremediation". *World Journal of Microbiology and Biotechnology*. 2012, **28(3**), 1203-1222. DOI: 10.1007/s11274-011-0923-z

65. TYAGI, M., Da-FONSECA, M., De-CARVALHO, C. 2011. "Bioaugmentation and biostimulation strategies to improve the effectiveness of bioremediation processes". *Biodegradation*. 2012, 22, 231-241. DOI 10.1007/s10532-010-9394-4

66. EL FANTROUSSI, S. & AGATHOS, S.N. "Is bioaugmentation a feasible strategy for pollutant removal and site remediation?" *Current Opinion in Microbiology.* 2005, 8, 268-275. https://doi.org/10.1016/j.mib.2005.04.011

67. HAMDI, H., BENZARTI, S., MANUSADZIANAS, L., AOYAMA, I. & JEDIDI N. "Bioaugmentation and biostimulation effects on PAH dissipation and soil ecotoxicity under controlled conditions". *Soil Biol. Biochem*. 2007, 39, 1926-1935. doi:10.1016/j.soilbio.2007.02.008

68. SALGADO, I., CÁRCAMO, H., CARBALLO, M.E., CRUZ, M., DURÁN, M.C. “Domestic wastewater treatment by constructed wetlands enhanced with bioremediating rhizobacteria”. *Environ. Sci. Pollut. Res*. 2017. DOI 10.1007/s11356-017-9505-4.