Building-Integrated Indoor Vertical Ecosystem for Treatment and Recycling of Greywater

This article describes the reduction of fresh water consumption with an integrated greywater treatment system in buildings based on the functionality of a natural ecosystem.

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Abstract

The Vertical Ecosystem is a greywater purification system based on indoor constructed wetlands with cascading set-up that combines sub-surface horizontal water flow with stage wise vertical flow. A test unit with three levels of plant containers installed at the laboratory of alchemia-nova has been tested under conditions that simulate greywater pollution levels of tourist facilities. This Vertical Ecosystem supports the reduction of drinking water by providing an aesthetically appealing indoors solution utilising plants and their rhizosphere. The investigated plant species function in symbiosis with rhizosphere microorganisms providing water-cleaning abilities. Special focus lies on practical considerations regarding bottlenecks for market uptake of this concept. In relation to EU-legislations and recommendations the effluent of the Vertical Ecosystem can be used for toilet flushing, irrigation of private gardens, golf grounds, groundwater recharge and laundry, at the studied level of greywater pollution load and flow throughput.

Introduction

Constructed wetlands are well known to filter pollutants from water since the early 1950's (Seidel, 1961). These treatment systems use natural processes involving wetland vegetation, soils and their associated microorganism to improve water quality. Wetland plants offer proper conditions for microorganisms to live in the rhizosphere (Brix, 1987). Through a series of complex processes, these microorganisms transform and remove pollutants from the water (Vymazal, 1998; US EPA, 1999). The approach of reuse of treated greywater for applications with lower water quality requirements like toilet flushing, irrigation or groundwater recharge is not new. Due to the low contamination with pathogens compared to blackwater, the reuse of treated greywater becomes increasingly attractive (Li et al., 2009). With regard to innovative buildings, there are many integrated water management approaches (Nolde, 1999). In fact most plant-based wastewater treatment units are usually located outdoors. Often they are centralised and operated by companies or community services and infrastructure providers. Some efforts aim to treat greywater decentralised and on building sites, but these are all designed as outdoor solutions. Only a few horizontal indoor-constructed wetlands are known (Starkl et al., 2005; Weissenbacher et al., 2009).

Due to space limitations vertical Greenwalls (vertical greening elements) are already known as an architectural

Technical data:

Laboratory scale plant-based greywater treatment

- size 1 m (w) x 3 m (l) x 2,8 m (h)
- indoor, semi-indoor, in 3 cascading stages
- 0,5 m^3 volume rhizosphere
- forced air oxygenation of the rhizosphere
- flow rate 0,3-0,5 m^3/d, semi-continuous
- storage puffer tank
- pollution abatement: COD from > 300 mg O_2/L to < 10 mg O_2/L,
- BOD from > 200 mg O_2/L to < 5 mg O_2/L
- Energy requirement: 2,7 kWh/m^3 of treated greywater without artificial lighting

gardening structure (Carpenter, 2008; Timur and Karaca, 2008). These living walls or greenroofs are often used to reduce overall temperature of the building, improve air quality, buffer noise or are used for urban gardening, but mostly for aesthetic purposes. The combination of both, a vertical constructed wetland integrated in an indoor approach of a building, is new. This Vertical Ecosystem (VertECO) will solve the problem of reducing the consumption of drinking water by providing a technological solution based on plants. It will be tied into the greywater treatment cycles of the building and will support significant potable water savings by reusing water flows on site, e.g. for flushing toilets. This ecosystem technology is based on subsurface water flow through the root zone of plants (Seidel, 1965; Vymazal, 2011). The investigated plant species function in symbiosis with rhizosphere specific microorganisms providing intrinsic water cleaning abilities and will demonstrate that there are no negative odours or microbial impacts on the air or water treated by the system (Nolde, 1999). In fact, it will help to remove VOC`s (volatile organic compounds) from the ambient air (Wolverton et al., 1989), and also will demonstrate that this plant based water treatment technology is applicable to buildings in regions of all climate conditions. Particularly in Mediterranean countries or regions with an arid climate, water resources are limited and unequally distributed in space and time. As an educational side benefit, it will demonstrate tangibly the importance of wetland ecosystem services in relation to clean water for the planet and humanity.

The main demonstration site of the Vertical Ecosystem is Samba Hotel, a representative hotel chain located in Lloret de Mar, Girona, Spain. It is a large resort with 441 air-conditioned rooms, green areas and exterior pools, conference rooms, bar and restaurant. It is certified by EMAS and ISO 14001.

For this technology, a wide range of applications might be possible like public or private households, office buildings, commercial buildings, train stations, hotels, restaurants, airports, as well as for industrial end users like food processing industries or other industries (Vymazal, 2008).

Material and methods

The laboratory scale plant-based greywater treatment unit imitates real life conditions of a demonstration site located in a hotel at the Costa Brava in Spain. This unit is monitored for cleaning performance, microbiological factors, chemical pollutants, reliability, maintenance and energy demands. For the constructed plant based wetland a vertical stage wise set-up has been used combined with a sub-surface horizontal water flow. The laboratory small-scale wetland consists of three floors (Figure 1), connected by water tubes. A pump, with time controlled operation, feeds (grey)water from a buffer tank into the top floor. Water flows in a sub-surface horizontal manner, meandering through the rhizosphere and pushed down to the next floors by gravity. In order to improve the aerobic symbiosis (Stottmeister et al., 2003) of roots and microorganisms, air is continuously injected through perforated hoses at the bottom of the plant containers into the water. As an additional side-benefit, air-pollutants are also removed from the air through this ventilation system. Many harmful air-pollutants are known to be metabolised by microorganisms in the root zone (Wolverton et al., 1989). To ensure the largest possible area for the colonization of microorganisms, inorganic substrates with a large surface area (e.g. expanded clay) are most suitable (Kickuth, 1969; Geller et al., 1990). The substrate must also be stable, not biodegradable over time, so that it does not break up and clog any pipes. The investigated plant species are specifically suitable for this indoor constructed wetland system and have some decorative qualities (figure 1). With sensors from S::can (UV-VIS spectrometry, ion selective electrodes) and Thermo Scientific (electrochemical and ion selective electrodes) following chemical parameters are tested either online (continuously) or in situ (directly):

- organics: chemical oxygen demand (COD), biological oxygen demand (BOD), total organic carbon (TOC) dissolved organic carbon (DOC)

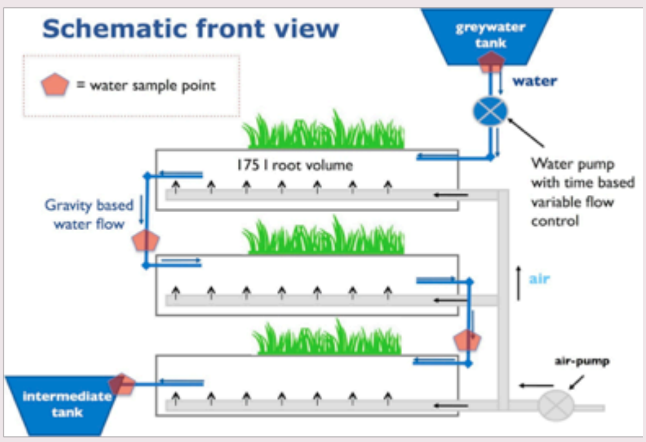

Figure 1: Vertical Ecosystem - laboratory test unit (left) schematic front view of the Vertical Ecosystem (right)

- nutrients: total nitrogen bound (TN_b), nitrate (NO_{3-}), nitrite (NO_{2-}), ammonium (NH_{4+}), total phosphorus (PO_4^{3-}), sulphate (SO_4^{2-}), sulphite (SO_3^{2-}), sulphide (H_2S), chlorine total (Cl_2)
- suspended matter: total suspended solids (TSS), turbidity
- on-site: pH, temperature, dissolved oxygen (DO) and conductivity
- surfactants: anionic, cationic and nonionic

For analysis of microbiological and pharmaceutical parameters, external laboratories were commissioned.

A water sampling campaign was done in June 2014 by a project consortium partner in the SAMBA hotel to get preliminary water quantity and quality data. Composite samples from the different streams were analysed for standard chemical parameters and some micro pollutants (pharmaceutical compounds). The sampling points at the hotel, relevant to the indoor constructed wetland technology are shower water, greywater tank and laundry effluent. Synthetic greywater that imitates the quality of the expected flows at the demonstration site was used for the laboratory experiments, Synthetic greywater is mixed using hygiene products (like soaps, shower gel, shampoo, conditioner, tooth gel, deodorant, cosmetics, body lotion), lavatory cleaning products, dust from a vacuum cleaner, citric acid to adjust pH, curing salts. Washing machine effluent was also prepared at the laboratory of alchemia-nova in Vienna. The salts are added to increase the electrical conductivity parameter and simulate a higher salt content as seems to be the case at the hotel in Spain, as well as to provide some nitrates to the mixture. The hotel located on the Mediterranean shore uses tap water that comes partially from desalination plants or groundwater, which seem to have a higher base salt content than the drinking water in Vienna, which comes mostly from natural springs in the close alps. The water flow is regulated so that a volume of 250 to 300 L/day is pumped through the laboratory small-scale test wetland. To obtain a higher cleaning performance, a longer retention time of the water in the treatment unit is desirable (Vymazal, 2011). For this reason, the water is pumped intermittently through the treatment plant. More than 90 plants (marsh plants, graminoids, tropical and subtropical plants) in different combinations were tested. These plants must satisfy following requirements: grow in inorganic, hydroponic-like substrates, tolerate the pollution load of greywater, thrive under limited amounts of light, show positive water cleaning interactions and have decorative value. The effluent from the Vertical Ecosystem was analysed for water quality defining parameters and compared to the initial values from the synthetic greywater to allow a performance appraisal.

Results and discussion

Table 1 compares values of key water quality parameters (reference values for pollution loads) for the synthetic greywater mixed at the laboratory in Vienna for test purposes and the values for the final outflow from the Vertical Ecosystem unit after the water has been treated. These values are averaged and condensed from a period of 9 months of tests with the unit at different greywater loads. Pollution abatement and water cleaning performance is considerable.

Table 1: Synthetic greywater (inflow), effluent water after treatment

Parameter	Unit	simulated greywater GW Tank	effluent after treatment cleared water
COD	mg O_2/L	336	8.9
BOD_5	mg O_2/L	238	3
TOC	mg C/L	122	3.9
DOC	mg C/L	109	2.8
TNb	mg N/L	2	0.3
NO_3-N	mg N/L	0.8	0.1
NO_2-N	mg N/L	0.089	<0.003
NO_4-N	mg N/L	0.04	<0.03
TSS	mg/L	46.9	4.61
Turbidity	NTU	43.9	0.3
pH		5.83	7.22
DO	% Sat	81.83	90.8
Conductivity	µS/cm	431.4	423.1
Surfactant anionic	mg/L	57	0.3
Surfactant cationic	mg/L	<0.2	<0.2
Surfactant nonionic	mg/L	1	<0.2

For a better insight, the average values at each sampling point for selected parameters are presented next. COD and BOD are very important in order to assess the cleaning performance of the system. Our sampling points are the greywater tanks with the synthetic mixture, after 175 L rhizosphere (1st floor), after 350 L rhizosphere (2nd floor) and after 525 L rhizosphere (3rd floor) (Figure 2). Drastic reductions in the COD and BOD parameters are obtained after the first cleaning stage, then this decrease levels off in an approximately logarithmic manner and at values of about 8,9 mg O_2/L for COD and 3 mg O_2/L for BOD. Further decreases do not seem practical anymore for a reasonable size (=root area) of the unit. Similar conclusions can be drawn for TOC and DOC (Figure 2). Odour levels throughout these tests remained within acceptable limits, though this may be a bit subjective. The emanated smell could be characterised as half way between fresh air and wet earth smell.

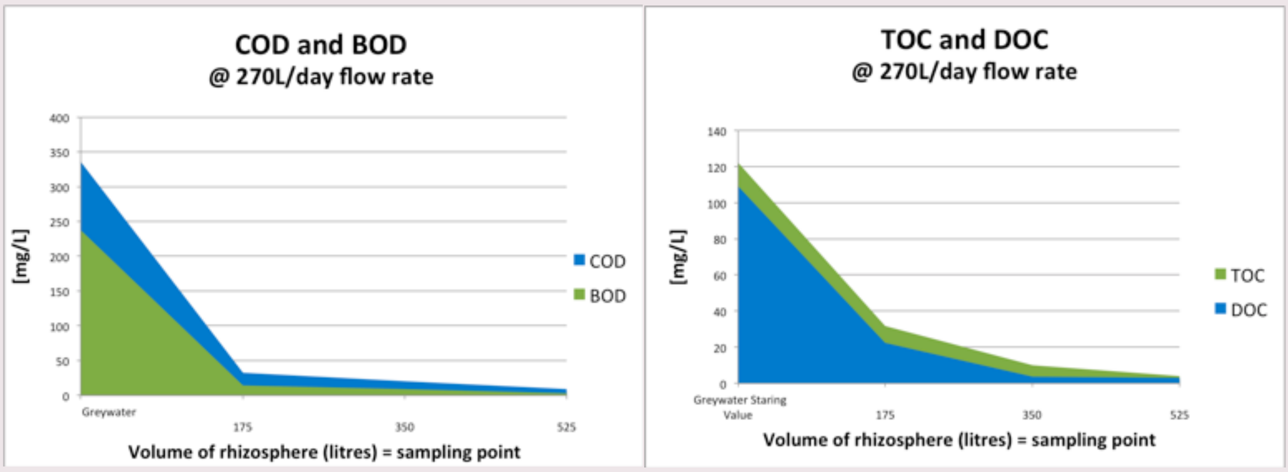

Figure 2: Cleaning performance of the Vertical Ecosystem for COD and BOD (left) and TOC and DOC (right).

Influent concentrations of nitrogen compounds have been very low (Table 1). Effluent concentrations of nitrogen compounds are close to or below the limit of detection. No accumulation of organic nitrogen during degradation of organic matter can be observed.

The turbidity decreases continuously from stage to stage, whereas for the TSS parameter the highest cleaning performance takes place in the first stage (Figure 3). Turbidity is an important parameter for water reuse. For most water reuses there are guidelines for groundwater recharge or irrigation of maximum 2 NTU established by law. After treatment with the Vertical Ecosystem the turbidity decreases with a value of 0,3 NTU, obviously below these guidelines.

The parameter of conductivity is one that does not evidence a satisfactory behaviour in the Vertical Ecosystem. The conductivity of the effluent water is as high or even slightly higher than the conductivity of the influent greywater (Table 1). Some conductivity increases can be attributed to the breaking up of pollutants into smaller polar components like acids. The higher unwanted salt insertion though seems to derive from the substrate itself. This indicates that some of the substrate components used have a high anorganic salt content, which is not washed out in a short time. This motivated the substitution of the initial substrate and also a search for plant species that would be adequate to grow in the unit and also extract and accumulate salts in their tissue.

Surfactants were also analysed in several experiments. There are high amounts of anionic surfactants in the greywater tank, while cationic and non-ionic surfactants where extremely low in the common greywater test mixture. Anionic surfactants have a negative charged head. Common types include e.g. sodium lauryl sulphate that is present in almost any common off the shelf soap, shampoo, shower gel etc. A satisfactory cleaning performance is achieved. According to our results, with an initial value of 57 mg/L in the influent only 0.3 mg/L are detectable at the effluent of the test unit.

For microbiological analysis (Escherichia coli and intestinal Enterococci) the test greywater was spiked at rather high levels of the studied microorganisms (E. coli at 6.77 x 10^5, c.f.u., Enterococci at 3.33 x 10^3). Although there is a remarkable reduction in the count of these potentially harmful microorganisms (down to 7,5 x 10^3 and <10 respectively), *E. coli* count could not

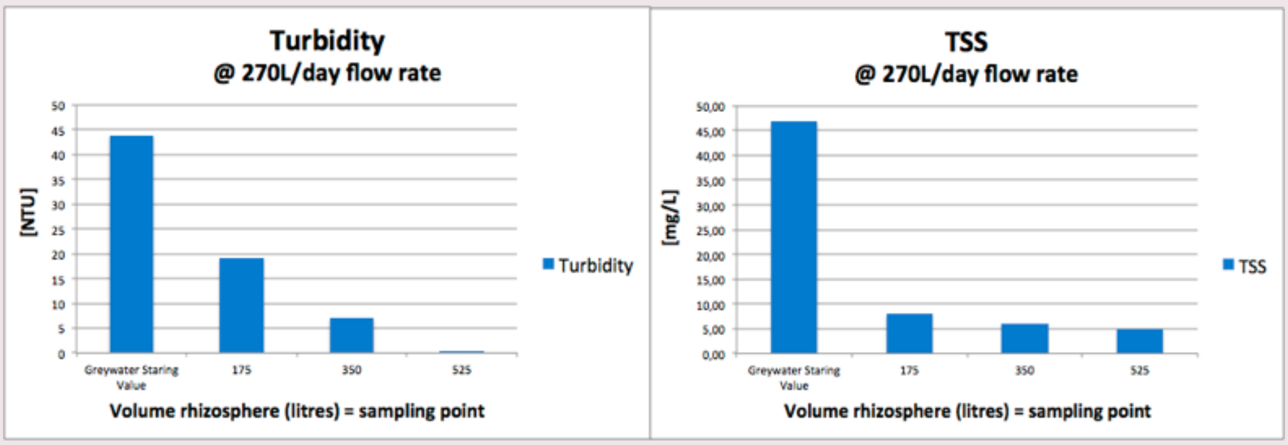

Figure 3: Cleaning performance of the Vertical Ecosystem for Turbidity (left) and TSS (right).

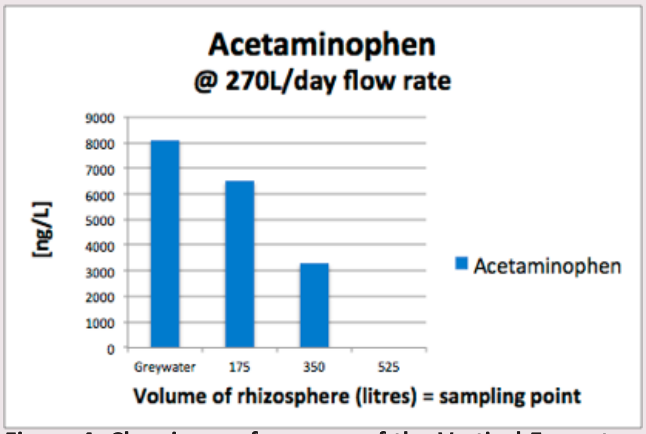

Figure 4: Cleaning performance of the Vertical Ecosystem (Acetaminophen)

be reduced to a desirable level of 0 given the water throughput of the test set-up. Since the reference data of microbiological pollution load from the water at the hotel demonstration site in Spain showed hardly any noticeable germ count, no further microbiological tests were performed.

For pharmaceutical tests a common painkiller (acetaminophen) was selected as test parameter. Initial mixture was 16 mg pill powder from the drug store preparation "Mexalen rapid, 500 mg" in 500 L greywater tank (Figure 4). With an initial concentration of about 8000 ng/L in the greywater, acetaminophen was not detectable (with a detection limit of 50 ng/L) in the effluent of the unit. However, these tests have just begun, repetitions, confirmation and metabolite analyses are needed. Initial results are definitely very encouraging.

Tests with higher chlorinated greywater were performed. To the mentioned recipe, 2 g of commercial swimming-pool chlorine were added to an approx. 450 L greywater tank. Results in the measurements did not show any great deviations in the cleaning performance of the unit and most parameters evidenced similar results as in non-chlorinated test tanks. Tests with laundry water from washing machines were also carried out, using two different kinds of detergents (one that claims to be more environmentally friendly and one that is just a standard detergent with colour enhancers). These experiments are still ongoing and data is still being collected, so no definitive conclusions can be offered. Preliminary results indicate that the cleaning performance of the unit is still very satisfactory. Nevertheless, the detergent perfumes in the laundry cleaning formulations are so strong, that the whole Vertical Ecosystems emanates these perfumes quite strongly, so that an indoor cleaning of laundry effluents seems not feasible, at least not in living quarters.

In the meantime more than 90 plants were tested in different combinations in a combined effort between Radtke Biotechnik and alchemia-nova. 15 species like marsh plants (Typha, Iris,…), graminoids (Carex, Cyperus,…), tropical and subtropical plants (Ficus, Spathiphyllum,…) were selected for use at the demonstration site, as they provided the best results.

Conclusions and outlook

Based on Table 1, a considerable cleaning performance of water was achieved by the Vertical Ecosystem. In relation to Spanish/EU legislations, preliminary results seem to indicate that the effluent of the Vertical Ecosystem can be used for applications with lower water quality requirements like toilet flushing, irrigation of private garden, golf irrigation, groundwater recharge and laundry, at the given load of greywater pollution and flow rate input of approximately 1 litre of greywater per litre of root volume per day (Table 2). Microbiological tests for key indicator species are still pending, but the target water streams at the demonstrations site at the hotel did not show any problems with microbiological load, probably because those water streams get chlorinated quite intensely.

Regarding physicochemical parameters the indoor Vertical Ecosystem performed remarkably well. It needs

Table 2: Pertinent regulatory guidelines for water quality for on-site recycled water compared to the results from the Vertical Ecosystem unit

			Potential Re-uses of VertECO effluent					
				Groundwater recharge		Irrigation		
	Simulated greywater effluent	Water effluent after VertECO	Laundry	Direct injection	Localized ground percolation	Private garden irrigation	Golf irrigation	Toilet flushing
European Directive			91/271/EC	91/271/EC	91/271/EC	91/271/EC	91/271/EC	91/271/EC
Spanish Legislations				RD 1620/2007	RD 1620/2007	RD 1620/2007	RD 1620/2007	RD 1620/2007
COD (mg/L)	336	8,9	125			125	125	
BOD_5 (mg/L)	238	3	25			25	25	
TSS (mg/L)	46,9	5	< 60	10	35	10	20	10
Conductivity (µS/cm)	287,83	423				6000	6000	
Nitrate (mg/L)	0,8	0,1		25	25			
Turbidity NTU	43,9	0,3		2		2	10	2

to be pointed out, that quite often the smell emanated from the unit would quite often be the limiting factor for acceptance of use, even if the chemical and physical parameters of the effluent water are well within range of acceptable limits. So the matter of smell will often define how much polluted water can be discharged into the unit in a given time frame, not the effluent water quality.

Further steps will be the optimisation and modification of the laboratory unit to better resemble the demo version and to increase the flow rate. Several tests at different pollution loads and with varying amounts of water flow per day will also be done, with the aim of achieving a mathematical model, which allows for theoretical simulations and calculations of Vertical Ecosystem unit sizes in relation to pollution load and expected greywater quantities. The Vertical Ecosystem can be scaled quite easily to accommodate different water cleaning demands, yet highly polluted large water flows will be a challenge for indoor treatment, especially considering the limiting factor of space and odour.

For the demEAUmed project, the incorporation of advanced monitoring and control systems and a decision support tool will ultimately define the best water management solutions for different specific practical cases by means of a database built upon the considered technological solutions. The Vertical Ecosystem and the data gained from concluded and on-going tests is an important part of this decision support tool.

The demEAUmed project

The project demEAUmed („Demonstrating integrated innovative technologies for an optimal and safe closed water cycle in Mediterranean tourist facilities", www.demeaumed.eu) demonstrates and promotes innovative technologies for an optimal and safe closed water cycle in Euro-Mediterranean tourist facilities. A resort placed in Catalonia, Spain, is considered the DEMO site, where a representative part of all inlet and outlet water flows will be characterised, treated with proper innovative technologies, and reused to reduce overall tap water consumption and the carbon footprint of water management through an integrated approach at demonstration level. Using alternative water sources, such as treated groundwater, treated rainwater or the reuse of treated greywaters and/or wastewaters within the resort will result in the reduction of fresh water consumption in hotel installations and the establishment of green and recreational areas. An exhaustive environmental and socio-economic assessment will be developed, an advanced monitoring and control systems and a decision support tool will be also implemented to define the best water management system.

demEAUmed will face two key challenges: the importance of tourism economy and the characteristics of water scarcity of the area. The project will be a critical platform for promoting the use of sustainable and innovative technologies in other Euro-Mediterranean tourist facilities not at last also in the light of the global tourism market. Finally, demEAUmed will also contribute to attain the main goals of European Innovation Partnership on waters: water reuse and recycling, water and wastewater treatment, including recovery of resources and the water-energy nexus ().

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