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Green wall for greywater treatment: literature review and wall design

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Abstract

This study presents the development of an outdoor greywater treating green wall by adapting a commercially available system, identifying which native swiss wild plant species can be implemented and examining how operational conditions (substrate and irrigation method) influence nutrient removal from synthetic light greywater. The experiment was conducted over a 2 months' time period located in a greenhouse at the ZHAW Wädenswil, in Switzerland. A total of nine plant species, three substrates (Vulkaponic; Vulkaponic plus biochar; perlite plus coco peat) and two irrigation methods (drip irrigation; top-down irrigation) were tested. The synthetic GW was recirculated and renewed weekly.

The results showed that swiss wild plant species can successfully adapt to greywater, only one out of nine species (*N. officinale*) didn't adapt to the system. The expected differences in treatment efficiency have been confirmed by the wider range of observed removal rates between the different substrates. Vulkaponic (chemical oxygen demand, COD, 74-76%, biochemical oxygen demand, BOD, 46-53%), Vulkaponic plus biochar (COD 77-83%, BOD 56-58%) perlite plus coco peat (COD 27-35%, BOD 58-61%), denoting higher treatment potentialities for COD with the Vulkaponic based substrates and for BOD with the perlite coco peat mixture. Overall the drip irrigation method was better for plant growth, but slightly worse for the COD and BOD removal efficiency.

Key words: green walls, greywater reuse, greywater treatment, synthetic greywater, vertical gardens, green technology, water treatment, Nature based solutions (NBS), swiss wild plants. Examining

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1 Introduction

"Green building" or "green architecture" is used to mean the strategic application of plants and an integrative examination of the climatic, energy and technical aspects of such measures in building planning (Pfoser et al., 2016)

In urban ecosystems, the greening of buildings offers a huge potential for improvement at various levels (people, buildings, infrastructures, biodiversity, micro-climate, etc.) and can occur in various forms, such as vertical and roof greening.

In particular, green facades can play an important role as an urban climate buffer, not only by reducing the heat island effect, but also by improving air quality, sound and heat insulation, energy- and water-saving and aesthetics.

Owing to the worldwide increase in urbanisation together with the frequency of extreme weather events, there is growing pressure on sewage and drinking-water systems, and an increasingly urgent need for treatment and recycling of processed waters. Nature based solutions (NBS) could help to alleviate some of these problems. Currently, constructed wetlands and biofilters are the most frequently researched NBS in water treatment (Fowdar et al., 2017; Gross et al., 2007). However, in cities there is often a high demand on horizontal space, therefore it is challenging to find sufficient place for constructed wetlands.

The use of greywater instead of fresh water for green infrastructures irrigation offers a great potential, especially for countries with a drier climate. This means that at the same time wastewater could be recycled and freshwater consumption reduced.

The various studies cited in the next paragraph show that there has been an increase in the development of green building designs for water treatment and wastewater reduction, among which green facades have been especially investigated for their wastewater treatment potential.

In Melbourne, Fowdar et al. (2017) designed a biofilter to investigate greywater treatment in living walls by nonclimbing and climbing plant species using sand both as a filter medium as well as the substrate for plant growth. Also in Melbourne, Prodanovic et al. (2019) developed a compartmental green wall for treating light greywater, using a commercially available system filled with a mix of perlite and coco coir and planted it with 13 different plant species. Masi et al. (2016) developed a green wall in Pune (India) using three different substrates [LECA® (expanded clay); LECA with sand; LECA with coconut fibres] and tested them for wastewater (WW) treatment efficiency. Gattringer et al. (2016) developed an indoor/outdoor constructed wetland for treating the shower and lavatory greywater of the Hotel Samba in Girona (Spain), combining sub-surface horizontal water flow with stage-wise vertical flow, using the VertECO system from alchemia-nova.

Although nowadays there are different green facades systems commercially available: from a complete living wall from ‘Vertiko GmbH (Germany) to the smaller modular NatureUp! from GARDENA (Germany), they are often not suited for greywater treatment because (a) the irrigation system is not designed for greywater, (b) the substrate volume is too small to provide sufficient attachment area for microorganisms, and (c) current vertical plantings are not, or not sufficiently, suitable for the process, as they often have stricter habitat requirements. For example, pH and nutrient levels are both decisive for the survival of some plant species. Hence it is often common practice to add fertiliser or a pH regulator to the irrigation medium, whereas greywater would not necessarily meet the same requirements.

The objectives of this study are therefore:

(I) to select and adapt a commercially available modular green facade system for the use of domestic grey water for plant irrigation, and treatment.

(II) to select native wild plant species and test them for their suitability for growth in the selected substrates when irrigated with greywater.

(III) to define which substrate type and which irrigation mode is most suitable for a greywater treatment wall.

To investigate this, a prototype will be built with a combination of nine different plant species, three different substrates and two forms of irrigation.

1.1 Plant species

One of the central variables for a green wall system design are the plant species. They perform ecosystem services and characterise the aesthetic. In addition, they determine, along with their habitat requirements, the structures and the growing medium that must be implemented (or vice versa). Irrigation with greywater adds a whole new dimension, as not every plant is adapted for wastewater irrigation or can tolerate the presence of chemical compounds in the irrigation medium. This reduces the available pool of species and varieties that can be used in green facades treating greywater. Among other things, the purpose of this study is to observe and evaluate the plants that have not yet been tested in such experimental conditions and if possible, to identify suitable species for future studies or green walls designs.

It is therefore important to keep track of the species that have been proved viable for WW treatment (Table 1), and to also search for additional species to use in green walls dedicated to greywater treatment.

Table 1: Plant species implemented in green facades for GW treatment

(Fowdar et al., 2017)		(Masi et al.,2016)	(Prodanovic et al, 2019)	
Vitis vinifera	*Phormium spp.*	*Abelia sp.*	*Carex appressa*	*Liriope muscari*
Billardiera scandens	*Phragmites australis*	*Wedelia sp.*	*Nadina domestica*	*Patersonia occidentalis*
Canna lilies	*Strelitzia nicolai*	*Portulaca sp.*	*Antirrhinum majus*	*Nasturtium officinale*
Carex appressa	*Strelitzia reginae*	*Alternenthera sp.*	*Ophiopogon japonicus*	*Myoporum parvifolium*
Lonicera japonica		*Duranta sp.*	*Agapanthus praecox*	*Dianella tasmanica*
Pandorea jasminoides		*Hemigraphis sp.*	*Nephrolepis obliterata*	*Phomium tenax*
Parthenocissus tricuspidata			*Viola tricolor*	

Both Fowdar et al. (2017) and Prodanovic et al. (2019) measured nutrient removal efficiency from greywater by each specific plant species.

Fowdar et al. (2017) implemented 11 ornamental plants, both climbing and non-climbing based on their ability to tolerate water-logged conditions, a high nutrient environment and elevated salinity. After one operational year, it was observed, that most of the plant species were effective for nitrogen removal (>80%), whereas only *Carex appressa* and *Canna lilies* were effective in the phosphorus removal.

Prodanovic et al. (2019) implemented 13 plant species, also using 12 ornamental plants and one wetland plant (*Carex* sp.). After one year in operation it was observed that plant type could impact nitrogen removal. In fact, *Carex appressa, Nephrolepis obliterata, Dianella tasmanica, Agapanthus praecox, Liriope muscari, Phormium tenax* and *Myoporum parvifolium* were found to be good nitrogen removers, whereas *C. appressa* and *N. obliterata* capable of removing on average 98% of nitrogen, were identified as the best performing plants. For phosphorus removal there was a higher variation across plant species, but *C. appressa* and *N. obliterata* were again consistently the two best performing plants.

In both studies a wetland plant was implemented for greywater treatment, namely *Carex apppressa,* and in both cases it was proved and confirmed to be the best performing nitrogen and phosphorus remover among all others. On the basis of that result, it was decided also to implement in this study a native wetland plant of the genus *Carex.*

Masi et al. (2016) implemented six ornamental plant geni, but instead of measuring the plants' nutrient removal efficiency, the study focused on the treating efficiency of the different growing media. There was no direct correlation between the given nutrient removal data and the plant species used. It is still interesting though to note which species were used in that study (Table 1).

1.2 Substrates

Substrates are also decisive for the design of a green wall system. Their weight is important, as both the static and structural load-bearing capacity of a facade could vary greatly depending on the construction method and building. Accordingly, lightweight substrates like perlite, expanded clay or rockwool among others are usually preferred. Table 2 lists some substrates, that were used for wastewater treatment in green walls.

Table 2: Substrates for wastewater treatment [a(Prodanovic et al., 2017); b((Farhan et al., 2017)]

Name	pH[b]	AFP[b]-air filled porosity(%)	Porosity (%)[a]	BD[a]-bulk density (g/cm^3)	Source
Coco peat	6	13	80	0.08	(Prodanovic et al., 2017)
Rockwool	8	13	96	0.85	(Prodanovic et al., 2017)
Fyto-foam	-	-	99	0.0176	(Prodanovic et al., 2017)
Grow stone	7	-	88	0.202	(Prodanovic et al., 2017)
Expanded clay	7	-	80	0.429	(Prodanovic et al., 2017)
Vermiculite	7	-	94	0.103	(Prodanovic et al., 2017)
Perlite	7	30	75	0.1	(Prodanovic et al., 2017)
River sand	Varies	-	35	1.6	(Prodanovic et al., 2017)
Leca-Coconut fibers		-	-	-	(Masi et al., 2016)
Leca Sand		-	-	-	(Masi et al., 2016)
Biochar		25	72-74	1.87	(Dalahmeh et al. 2019)

Masi et al. (2016) tested three LECA mixtures, namely LECA, LECA plus sand and LECA plus coconut fibres to improve the green wall treatment performance. The outcome showed a lower COD removal efficiency for the first mixture than for the other two. In fact, the removal rates for LECA-coconut of the order of 14–86% and 7–80% for LECA-sand were better than LECA alone, with a removal rate of 16–20%. With the two better configurations they achieved an effluent quality that under the Indian legal specifications could be reused for flushing toilets.

In another study on the water treatment capacity of lightweight substrates, Perlite and LECA as mineral substrates and coco peat as an organic substrate were identified as the best (Prodanovic et al., 2017).

Plant-based biochar has increasingly been recommended and studied both as a plant growing medium (GM) and a filtering medium. For example, Schulz et al. (2013), added up to 50% of biochar, produced in a charcoal kiln from beech wood, to other substrates, and observed that the higher the biochar amount, the more the plant growth and soil fertility of the GM could be raised. Nemati et al. (2015) found that biochar can both reduce nutrient leaching and increase the cation-exchange capacity (CEC) and pH in the GM. Moreover, both the good nutrient- and water-retention capacity of biochar, in addition to its similarity with other aggregates such as perlite and expanded clay, were also mentioned (Nemati et al., 2015; Steiner & Harttung, 2014). Therefore, biochar could be recommended as a possible additive for substrates.

The choice of substrates for this experiment was based upon the various outcomes of these studies.

2 Material and methods

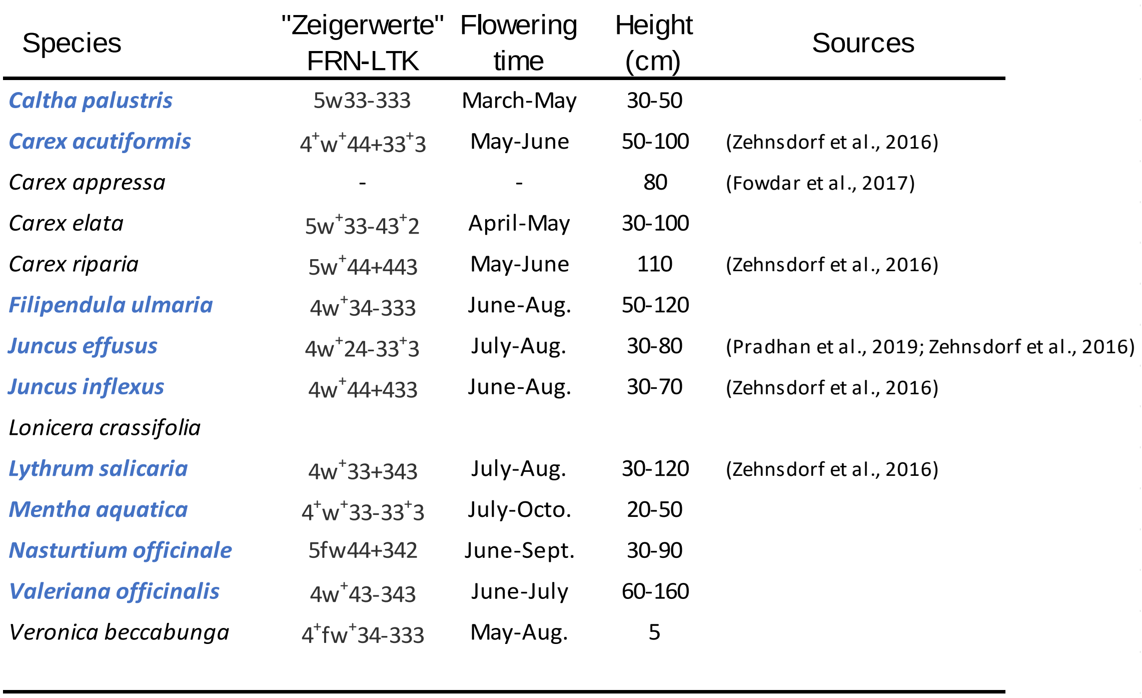
2.1 Experimental design: plant species

The plant species for planting the green wall were selected based on the selection criteria of indicator values (“Zeigerwerte”, Landolt et al., 2010), habitat, flowering time (Lauber et al., 2018) and wastewater treatment function.

While *Carex*, *Juncus* and *Lythrum* had already been used in other studies (Fowdar et al., 2017; Zehnsdorf et al., 2016), other plants were selected that best met both the technical and aesthetic requirements of this study. The choice fell on those plants that would have had a better chance of thriving in the experimental design. For this green facade it was decided to implement native plants when possible.

According to these criteria, 14 species were identified, 9 of which were selected for the final design (shown in blue, Table 3). Depending on the size of the experimental design, the other species could also have been implemented.

Table 3: Possible plant species for the system design. The ones in blue are the species selected for this study



Species	"Zeigerwerte" FRN-LTK	Flowering time	Height (cm)	Sources
Caltha palustris	5w33-333	March-May	30-50	
Carex acutiformis	4$^+$w$^+$44+33$^+$3	May-June	50-100	(Zehnsdorf et al., 2016)
Carex appressa	-	-	80	(Fowdar et al., 2017)
Carex elata	5w$^+$33-43$^+$2	April-May	30-100	
Carex riparia	5w$^+$44+443	May-June	110	(Zehnsdorf et al., 2016)
Filipendula ulmaria	4w$^+$34-333	June-Aug.	50-120	
Juncus effusus	4w$^+$24-33$^+$3	July-Aug.	30-80	(Pradhan et al., 2019; Zehnsdorf et al., 2016)
Juncus inflexus	4w$^+$44+433	June-Aug.	30-70	(Zehnsdorf et al., 2016)
Lonicera crassifolia				
Lythrum salicaria	4w$^+$33+343	July-Aug.	30-120	(Zehnsdorf et al., 2016)
Mentha aquatica	4$^+$w$^+$33-33$^+$3	July-Octo.	20-50	
Nasturtium officinale	5fw44+342	June-Sept.	30-90	
Valeriana officinalis	4w$^+$43-343	June-July	60-160	
Veronica beccabunga	4$^+$fw$^+$34-333	May-Aug.	5	

The ecological indicator values consist of two main groups, soil factors and climate factors, which each consist of three criteria. FRN-LTK: moisture number, reaction number, nutrient number, light number, temperature number, climate number(Landolt et al., 2010). Table 4 sets out the legend for the values.

Table 4: Legend of the ecological indicator values (FRN-LTK)

(F) moisture number	**(R)** reaction number
from 1 (very dry) to 5 (flooded or under water) w moisture moderately changing (+/- 1-2) w^{+} moisture strongly changing (more than +/- 2)	from 1 (pH 2.5-5.5) to 5 (pH 6.5-8.5)
(L) light number	**(T)** temperature number
from 1 (very shady) to 5 (very bright)	from 1 (alpin and nival) to 5 (very warm-collinous)
(N) nutrient number,	**(K)** climate number
from 1 (very low nutrient) to 5 (high nutrient to over-fertilized)	1 oceanic 2 suboceanic 3 suboceanic to subcontinental 4 subcontinental 5 continental

2.2 Experimental design: substrates

Since this study is also about identifying a plant-substrate combination that would both thrive with greywater irrigation and achieve a certain level of water treatment, after literature research, substrates were selected that could be used as both a plant growing and a filtering medium.

Özer & Dede (2018) and Prodanovic et al. (2017) suggested that perlite is the most suitable mineral substrate. However, based on practical experience of Erich Stutz (ZHAW Wädenswil, CH), perlite would be more likely to suffer from severe chemical and physical corrosion within approx. 2 years, leading to a loss of structural stability and to clogging. Erich Stutz recommended Vulkaponic, a pure mineral mixture of pumice and high-quality zeolites produced by KLANZ Systeme (Germany). Vulkaponic is light and particularly suitable for indoor planting in pots as well as for water-bearing systems(Vulkaponic, 2019). It shares many advantageous properties with perlite and can better endure long-term chemical and physical corrosion. A similar argument was made for the organic substrate; since coco peat decomposes relatively quickly and could lead to clogging the more stable biochar would be preferred as the organic substrate. Nevertheless, both organic substrates were used in the green wall design, for comparison purposes.

In conclusion, three suitable substrates mixtures were selected. The first is 100% Vulkaponic, while the second and the third consist respectively of 75% Vulkaponic, 25% plant-based Biochar (Verora GmbH, Switzerland) and 75% Perlite (RICOTER Erdaufbereitung AG, Switzerland) 25% Coco peat (ökohum GmbH, Switzerland) (Table 5).

Table 5: Properties of substrate aggregates used in in this study

Name	pH	(AFP) air filled	Porosity (%)	(BD) bulk density (g/cm^3)	Source
Coco peat	6	13	80	0.08	(Prodanovic et al., 2017)
Perlite	7	30	75	0.1	(Prodanovic et al., 2017)
Vulkaponik	7	81	35		(Klanz GmbH,Switzerland)
Biochar	8.8	-	-	0.22	(Verora GmbH, Switzerland)

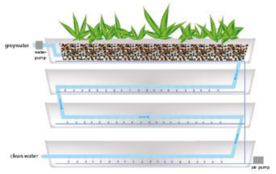
2.3 Experimental design: modular system selection

Most green facades are either modular or surface systems, the latter usually consisting of a growing medium, an encapsulating textile layer (Vliess) and a metal frame. It was decided that a modular system would be best suited for the purpose of this study, because a single modular unit is easier to replace if it malfunctions and it allows a flexible design according to the desired size.

Several modular systems, that can be found on the Swiss market, were assessed in terms of modularity, price and available space for root growth (Table 6).

Table 6: List of green wall modular systems available on the Swiss market

System (source)	No	Photo	Price (CHF)	Plant modularity (units)
"Minigarden Vertical" (vegandthecity.ch, 2019)	1		78	3x3
"NatureUP!" (Gardena, 2019)	2		65	3x3
"Nature Vertikale Garten-Pflanzwand Startset 2 " (vidaxl.ch, 2019)	3		70	4x3

”Pflanzelement zur Wandbefestigung ” (Manufactum, 2019)	4		117	9
”Vertikaler Garten Stahl verzinkt˝ (Manufactum, 2019)	5		169	4
“vertECO®” (alchemia-nova, 2019)	6		NA	3x1
“VersiWall” (Femox GmbH, 2019)	7		NA	33

Regarding the factors ''available root space'' and ''price'' (Table 5), options 3, 4, 5 and 7 (considering also the weight for No 7) seemed to be unsuitable. Moreover, vertECO® by alchemia-nova is sold as a ready planted product, which restricts the desired design freedom for the system. It also lacks modular plant units, which would simplify both the evaluation and the planting of each specimen in a single unit.

The very similar Options 1 and 2 seemed to be the best systems, as they have both approximately the same available volume and can be both mounted free-standing or on a wall.

NatureUP! by manufacturer Gardena met the space, installation and aesthetic requirements and was chosen for this study (Figure 1).

One set consists of three parts. The principal horizontal element (x3), which can house up to three plants each, the separation (3x) and the collection (1x) layers. There are three main elements, providing a total of nine openings for housing plants. Moreover, several sets can be stacked one on top of another as desired.

Figure 1: NatureUP! : the dimensions of each set are 65(width) x 15 (depth) x 55(height) cm with a surface area of 0.097 m^2

2.4 Experimental Design

The NatureUP! green wall system was modified with two adapted irrigation systems (drip and top-down irrigation). The green wall has a compartmental design composed of 18 sets, with every set having 3x3 plant openings. Each main element of a set contains about 11 litres of substrate volume, totalling 33 l per set; it has three horizontally connected openings, whereas vertically it’s divided by the collection layers, which directs the excess irrigation medium to the ground layer, where it is collected. Three vertically stacked sets with the same substrate and irrigation system formed one design configuration. One design configuration has about 100 l substrate volume and 0.29 m^2 surface area.

Figure 2: Sets horizontal elements after being planted and filled with the substrates. From top to bottom: Perlite/Coco, Vulkaponic, Vulkaponic/Biochar

This experiment tested two different irrigation systems, three substrate media and synthetic greywater, making a total of 18 sets and six design configurations. With A and B were defined the two irrigation methods: respectively Drip and Top-down. Each set was planted randomly with nine plant species (Figure 3).

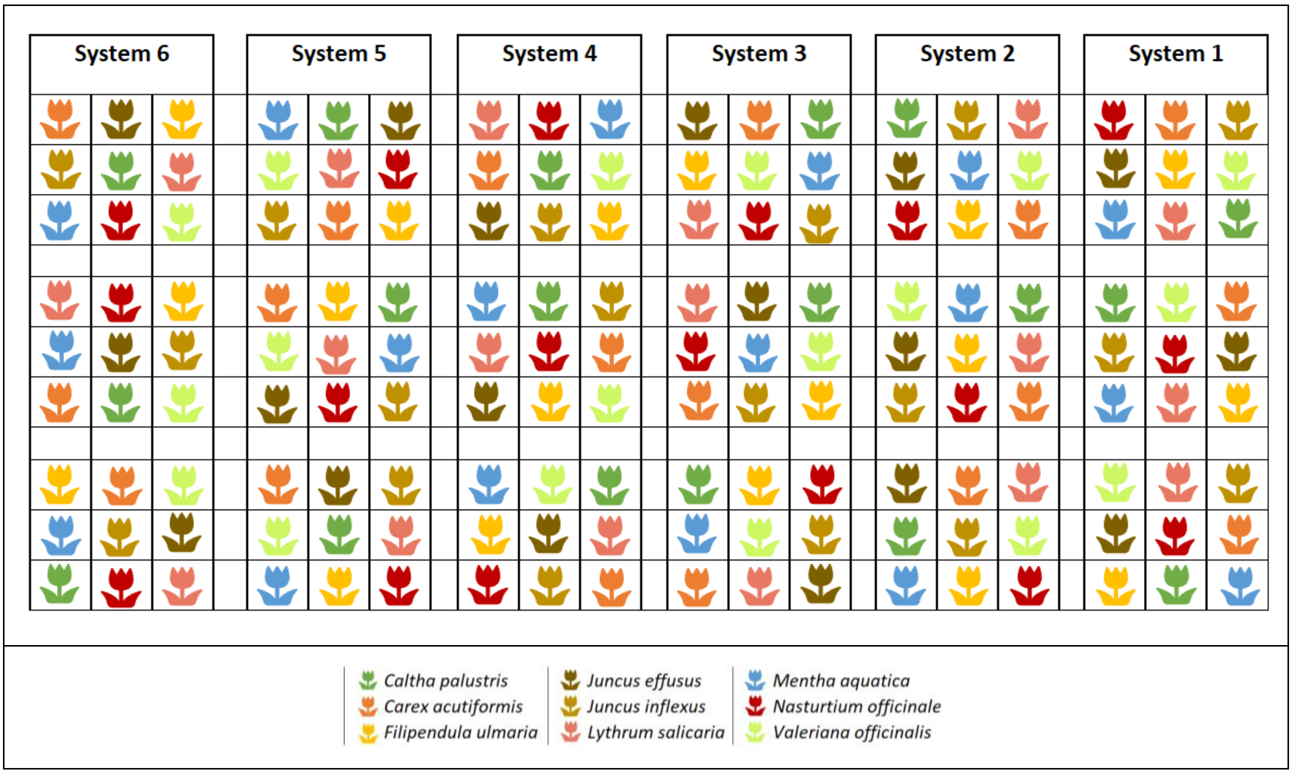


Figure 3: Positioning of the nine plant species in the green wall. The positioning was randomized for each element that was planted with the 9 species

In order to install a top-down irrigation system (B), three basic elements were connected to one another. This was achieved by drilling six holes in each layer and sealing the former collection holes/openings with silicone.

The green wall was set up in a greenhouse tunnel, which provided natural sunshine, but prevented rainfall from entering the system and in diluting the irrigation-medium samples. The temperature in the tunnel was recorded using two EL-USB 2+ (Logger for temperature and humidity).

Table 7 gives an overview of the factors, that were tested within this experiment. The aim of this study was to determine how the various design configurations together with the synthetic greywater were affecting the plants, and the greywater treatment performance of the green wall systems.

Table 7: Experimental factors and variables investigated in this study

Factor	**Variables**		
Plant species	*Carex acutiformis*	*Caltha palustris*	*Filipendula ulmaria.*
	Juncus effusus	*Juncus inflexus*	*Lythrum salicaria*
	Mentha aquatica	*Nasturtium officinale*	*Valeriana officinalis*
Irrigation	Drip -irrigation (A) Top-down (B)		
Growing media	Vulkaponic Vulkaponik and plant-based Biochar; Mix (75/25 %) Perlite and coco peat; Mix (75/25 %)		

A total of 21 individuals per species were sourced from a local nursery (Wildstaudengärtnerei, Patricia Willi, Switzerland), 18 of which were planted in the different configurations, while the others were held in reserve.

The synthetic greywater (GW) was created by mixing 11 ml of detergent ("Baby Laundry Detergent" I ATTITUDE) with 58 l of drinking water in 60 L tanks. For the establishment period fish tank water was added to the mix in order to favour a biofilm development in the system. For the experimental period, after each 7 days cycle, the GW in the tanks was renewed by leaving 8 l of the old GW (for the biofilm development) and mixing it with 50 l drinking water and with the detergent. The synthetic greywater was designed to mimic the effluent generated by a washing machine and it was used firstly due to the high volume requirements and secondly to ensure consistent composition and nutrient concentration of the inflow. The GW was then recirculated for 7 days.

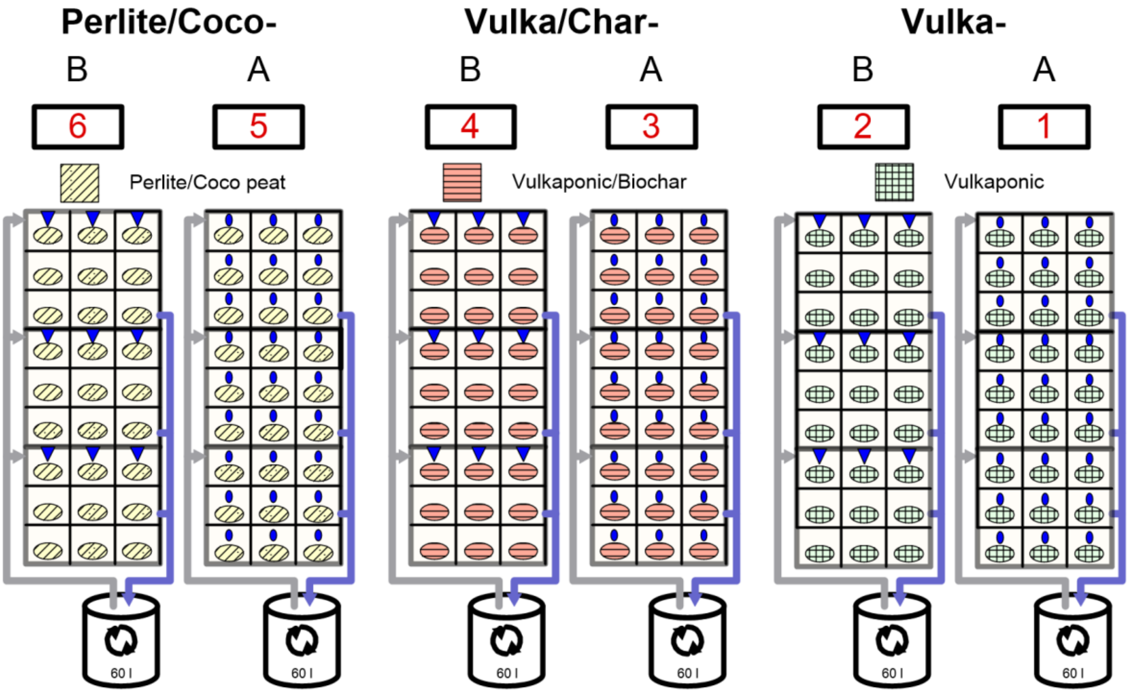


Figure 4: Green wall system design

Figure 5: Green wall after the establishment period, on May 16, 2019. All specimens seemed to have adapted well to the greywater irrigation.

2.5 Operation

After the start-up of the system on May 2, 2019, following a two-week establishment period, the green wall system was monitored until June 21, 2019. The system was dosed every day with synthetic greywater.

Each day approx. 100 l were passed through each system over 4 hours (from 8 to 10 a.m. and from 3 to 5 p.m.). The dosing volume was determined on the basis of the total volume of each configuration. While both the hydraulic retention time (HRT) and irrigation time (IT) were set at 1 day and 4 hours respectively, the average hydraulic loading rate (HLR) was 340 l*m^{-2}*d^{-1} (see Table 8 and 9).

Table 8: Parameters equations of the constructed wetland. HRT; HLR; OLR.

Parameters	**Equation**	**Explanation of variables**
Hydraulic retention time (HRT) [days] or [hours]	$HRT = \frac{V}{\theta}$	V = Volume of the system (m^3) θ = Feeding rate, inflow (m^3/day)
Hydraulic loading rate (HLR) [L m^{-2} d^{-1}] or [m^3 m^{-2} d^{-1}] or [m d^{-1}]	$HLR = \frac{\theta}{A}$	A = Infiltration area of the system [m^2]
Organic loading rate (OLR) [g m^{-2} d^{-1}] either g COD or g BOD$_5$	$OLR = \frac{\theta * conc_{COD}}{A}$	$conc_{COD}$ = the concentration of COD (or BOD) measured in the inflow [g m^{-3}]]

Table 9: Parameters of the six systems and of the different greywaters.

System	***Description***	**Volume** (l)	**Inflow** (l/h)	**Irrigation time** (h)	**HRT** (d)	**Feeding rate (θ)** (l /d)	**HLR** (l/m^2*d)
1	100% Vulcaponic	100	27.5	4	0.9	110.2	380
2	100% Vulcaponic	100	22.9	4	1.1	91.4	315
3	75% Vulcaponic, 25% Biochar	100	28.3	4	0.9	113.0	390
4	75% Vulcaponic, 25% Biochar	100	22.9	4	1.1	91.4	315
5	75% Perlite, 25% Coco-Peat	100	21.6	4	1.2	86.4	298
6	75% Perlite, 25% Coco-Peat	100	24.7	4	1.0	98.6	340
	Mean **(+/- 20%)**	**100**	**24.6**	**4**	**1.0**	**98.5**	**339.7**

raw GW	200 µL Detergent/ 1 L Drinkwater		
new GW	58 L fresh mixed GW		
old GW	1 Week old GW		
A (m^2)	infiltration area per System	0.29	m2

A total of four samplings were conducted, to assess nutrient removal performance. The outflow samples were collected directly from the blue tanks in 1 l glass bottles. Part of the samples was filtered through 0.45 µm filter, and analysed for ammonium (NH_4), nitrate (NO_3) and ortho phosphate (PO_4P) with a Spectrophotometer for water analysis (DR3900 HACH). The unfiltered samples were analysed for turbidity (2100Q Portable Turbidimeter), for COD (DR3900 HACH), whereas oxygen (O_2), electroconductivity (EC), Oxidation-Reduction Potential (ORP) and pH were measured with a portable parallel analyser (HQ40D Portable Multi Meter).

The greywater that was recirculated for 7 days was analysed for BOD_5 with the OxiTop®-System.

In order to assess the vitality of the plant species, on May 25, 2019 and June 18, 2019 the vitality status, was tested with a DUALEX Scientific (ForceA, France), a hand-tool leaf clip combining the use of fluorescence and light transmission. Some species (*Juncus effusus, Juncus inflexus* and *Nasturtium officinale*) had too small leaves to be measured, therefore only six species were tested. Three leaves were measured per plant. Values were read off for chlorophyll, flavonols and NBI (Nitrogen Balance Index), the Chlorophyll/Flavonols ratio (related to Nitrogen/Carbon allocation), which is directly proportional to plant vitality.

3 Results

3.1 Greenhouse temperature and humidity

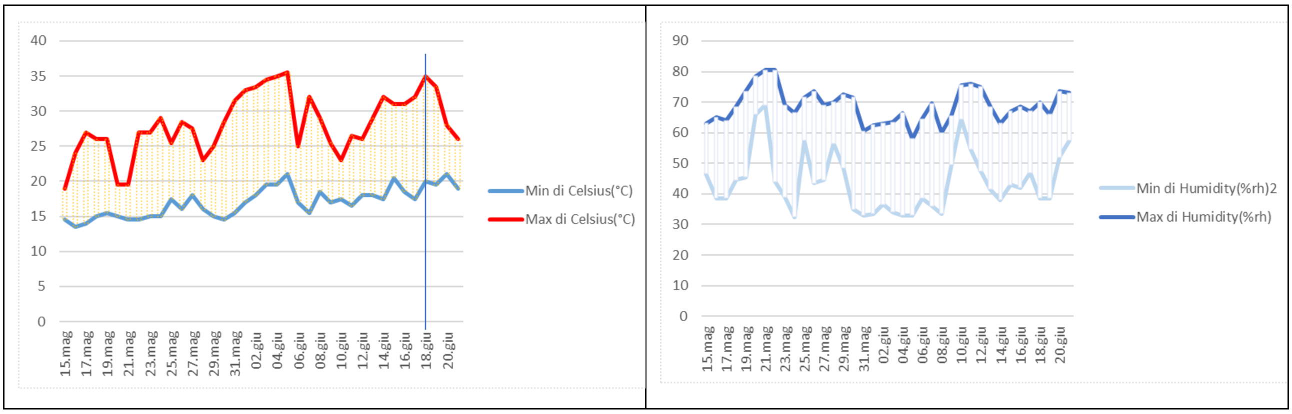


Figure 6: daily temperature and humidity recorded in the greenhouse during the experimental period with the EL-USB 2+ Logger

Figure 6 shows that there were two distinctive temperatures peak, which reached 35 C° on May 5, 2019 and on June 18, 2019. The min. temperatures remained overall above 14 C°.

3.2 COD & BOD$_5$ removal efficiency

Table 10: Greywater typologies and characteristics in this study

System	Typology	O_2 (mg/L)	EC (µs/cm)	Redox ORP (mV)	pH	Turbidity (NTU)	COD (mg/L)	BOD$_5$ (mg/L)	NH4-N (mg/L)	NO3-N (mg/L)	PO4-P (mg/L)	Source
synthetic GW of this study	raw	**7.72**	**410**	**251.5**	**8.0**	**10.20**	**95.7**	**30.0**	**0.030**	**1.33**	**0.003**	Balducci, 2019
	mixed	**7.35**	**389**	**217.5**	**7.8**	**7.63**	**74.9**	**-**	**0.025**	**1.11**	**0.037**	Balducci, 2019
Typical values	washing machine	-	-		9.3 - 10	14 - 296	375.0	48 - 682	-	0.4 - 0.6	4.0	(Ackermann et al., 2010)
	whole household	-	-	-	6.1 - 8.4	-	495 - 623	41 - 194	-	-	0.6 - 7.4	

The nutrient removal performances of the system are given as the difference between the concentrations of the standardized raw GW and the 7-day old recirculated GW (see Appendix A). For PO_4-P had to be used the concentration of the mixed GW, since the concentration was quite higher due to the addition of fish tank water in the establishment period (Table 10).

Table 10 shows that the prepared synthetic greywater was quite light in terms of concentrations compared with typical greywater, as the one used in this study is only mimicking a washing machine effluent and not the whole household greywater. The usually more contaminated greywater fractions, i.e. from kitchens and washbasins etc., are not simulated in this study.

BOD$_5$ and COD of synthetic greywater were at 30 and 95 mg.l^{-1} respectively. The hydraulic loading rate (HLR) and the organic loading rate resulted on average in 340 l.m^{-2}.d^{-1}, and 33 (COD) and 10.34 g.m^{-2}.d^{-1} (BOD$_5$) with an infiltration area of 0.29 m^2 for each system (Tables 9 and 10).

For the results interpretation system 1 to 6 will be respectively referred to as: Vulka-A (System 1); Vulka-B (System 2); Vulka/Char-A (System 3); Vulka/Char-B (System 4); Perlite/Coco-A (System 5); Perlite/Coco-B (System 6).

Table 11: Removal efficiency for COD and BOD of the green wall systems during 7 days.

System	1	2	3	4	5	6
Substrate	Vulka	Vulka	Vulka/Char	Vulka/Char	Perlite/Coco	Perlite/Coco
Irrigation	drip (A)	top-down (B)	drip (A)	top-down (B)	drip (A)	top-down (B)
			COD removal efficiency (%)			
Average	74.1	76.4	77.7	82.5	34.9	27.2
Min	70.5	72.5	72.3	79.7	22.0	15.3
Max	80.0	80.6	82.8	84.7	48.7	41.7
No. Days	7	7	7	7	7	7
No. Samples	4	4	4	4	4	4
			BOD$_5$ removal efficency (%)			
Average	46.3	53.3	56.3	58.1	58.1	60.9
Min	34.0	39.7	41.7	45.3	49.0	49.0
Max	58.7	68.0	64.3	66.0	62.3	68.0
No. Days	7	7	7	7	7	7
No. Samples	4	4	4	4	4	4

The analysis of COD and BOD$_5$ removal efficiencies for the six different systems is given in table 11. For COD, Perlite/Coco-A and Perlite/Coco-B have the lowest average removal efficiency, reaching respectively only 34.9% and 27.2%, while Vulka/Char-B and Vulka/Char-A instead have the highest removal rates with respectively 82.5% and 77.7%. The systems Vulka-A and Vulka-B have also a good average removal reaching 74.1% and 76.4%.

This considerable difference could probably be explained with the washing in of organic substances from the coco peat in the effluent. A hint was the strong brown colouring of all the collected effluent samples from these systems.

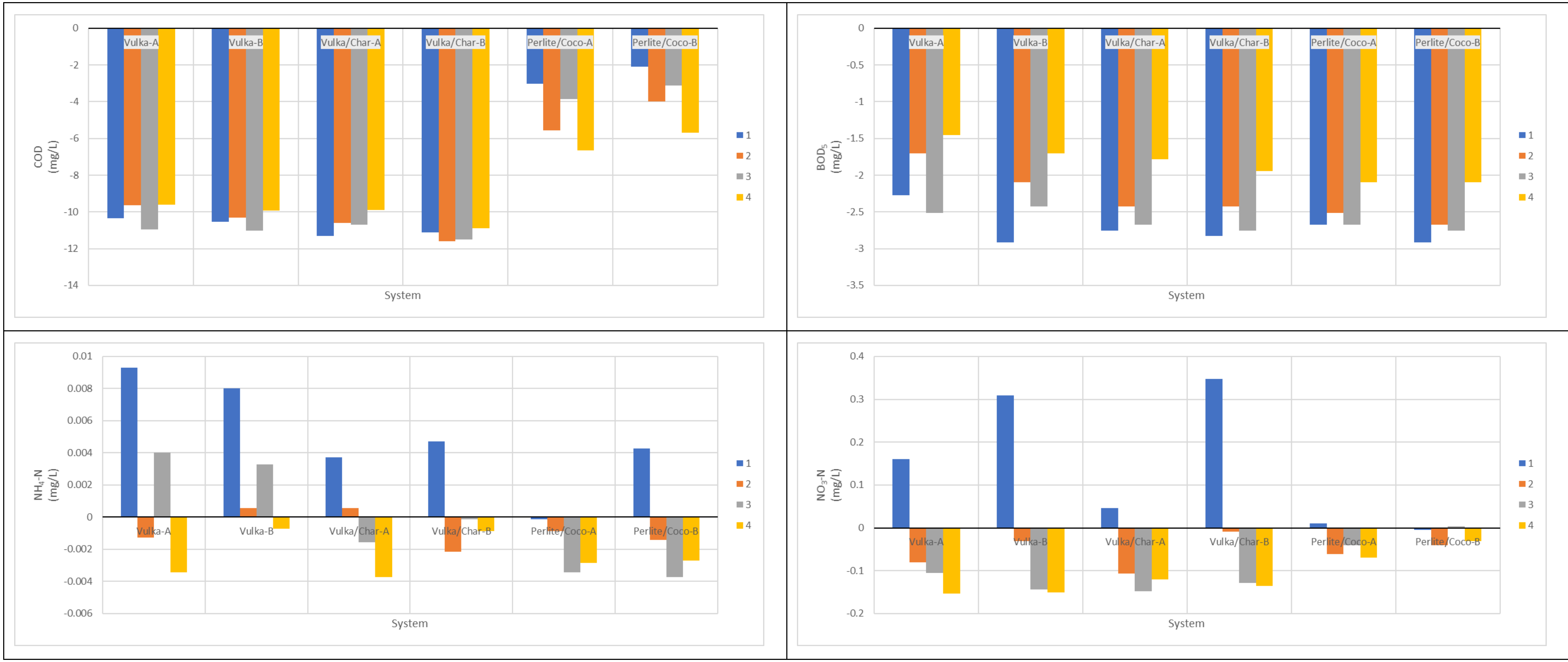
In all the systems with Vulkaponic was reached a relatively good COD removal, which could hint to a better aeration of the substrate, which could have led to better chemical reactions in the growing medium. Still must be taken in consideration, that the removal could be in the most part be driven by the filtration process. It seems, that the systems with the top-down irrigation had slightly higher removal rates. This difference between the two irrigations methods, that can also be observed in the BOD$_5$ removal, could be explained by the distance that the GW has to pass on its passage through the medium. With the top-down method the GW is fed on top of each set and as a result it undergoes a longer medium filtration process as its counterpart.

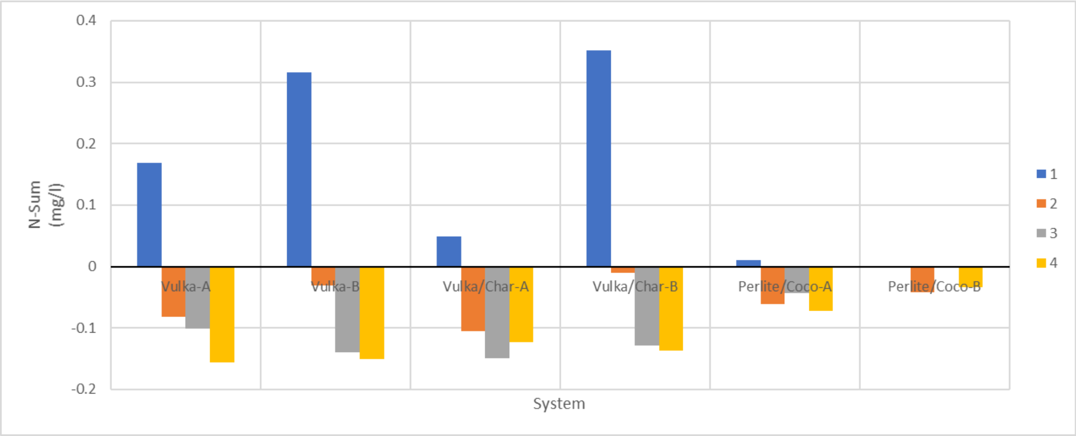
For the BOD_5 organic removal efficiency, is presented almost an opposite scenario. While in this case the removal rates between the systems are more homogenous, the average values range between 46.3% and 60.9 %, whereas Perlite/Coco-A and Perlite/Coco-B have the highest removal rates with 58.8% and 60.9%.

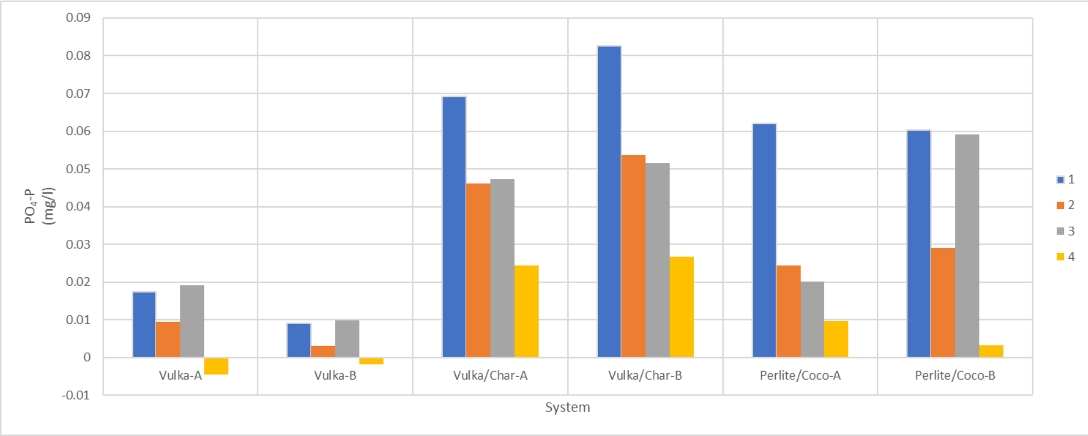
If taking in consideration only the systems whit the same irrigation type: namely drip irrigation for Vulka-A, Vulka/Char-A, Perlite/Coco-A and top-down irrigation for Vulka-B, Vulka/Char-B, Perlite/Coco-B, this comparison confirms the improvement of the performances driven by the different substrates. Indeed, the COD average removal efficiency for drip irrigation is at its highest with both Vulkaponic mixtures and at its lowest for perlite with coco peat. Whereas for BOD_5 removal, the Vulka/Char and the Perlite/Coco substrates had the highest rates. These removals could hint to a more successful biofilm development in the Perlite/Coco mixture than in the other substrates.

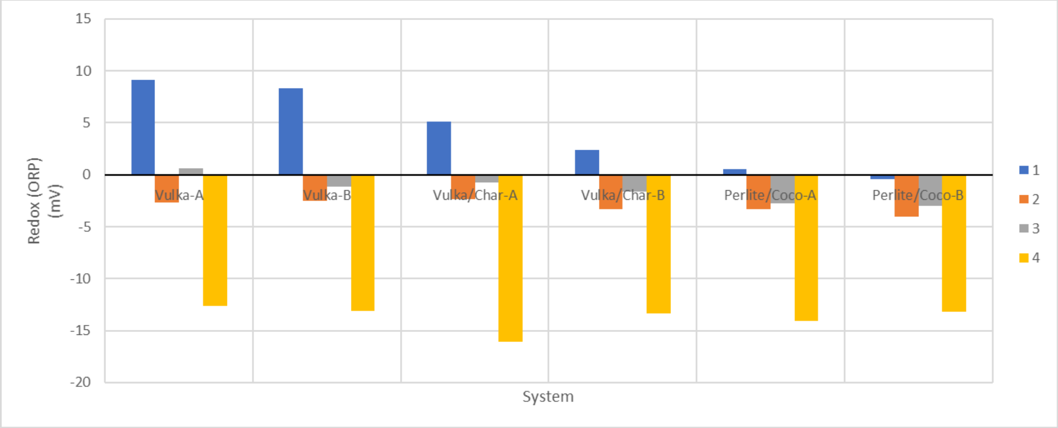
3.3 System performance

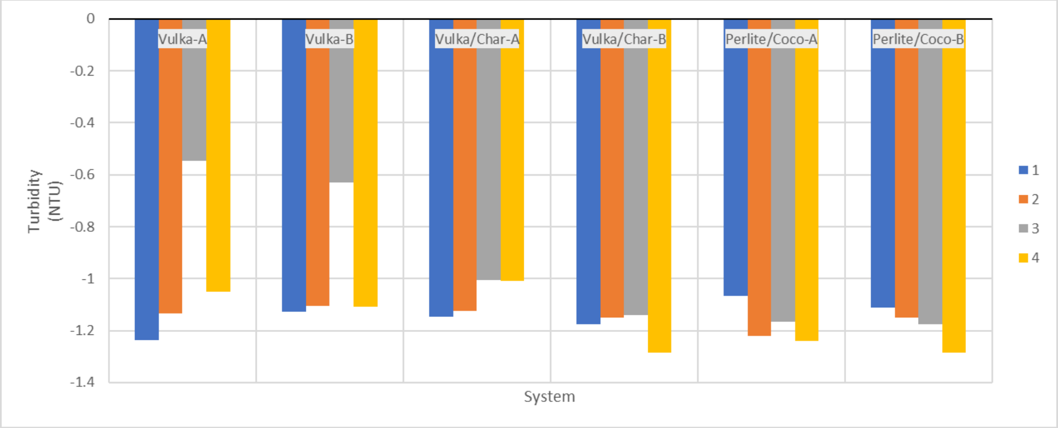
The average daily change in the system performances (nutrient and parameter removal and increase) of the six systems are given in Figure 7.




N-Sum
(mg/l)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
Vulka-A
Vulka-B
Vulka/Char-A
Vulka/Char-B
Perlite/Coco-A
Perlite/Coco-B
System
1
2
3
4


PO4-P
(mg/l)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
Vulka-A
Vulka-B
Vulka/Char-A
Vulka/Char-B
Perlite/Coco-A
Perlite/Coco-B
System
1
2
3
4


Redox (ORP)
(mV)
15
10
5
0
-5
-10
-15
-20
Vulka-A
Vulka-B
Vulka/Char-A
Vulka/Char-B
Perlite/Coco-A
Perlite/Coco-B
System
1
2
3
4


Turbidity
(NTU)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Vulka-A
Vulka-B
Vulka/Char-A
Vulka/Char-B
Perlite/Coco-A
Perlite/Coco-B
System
1
2
3
4

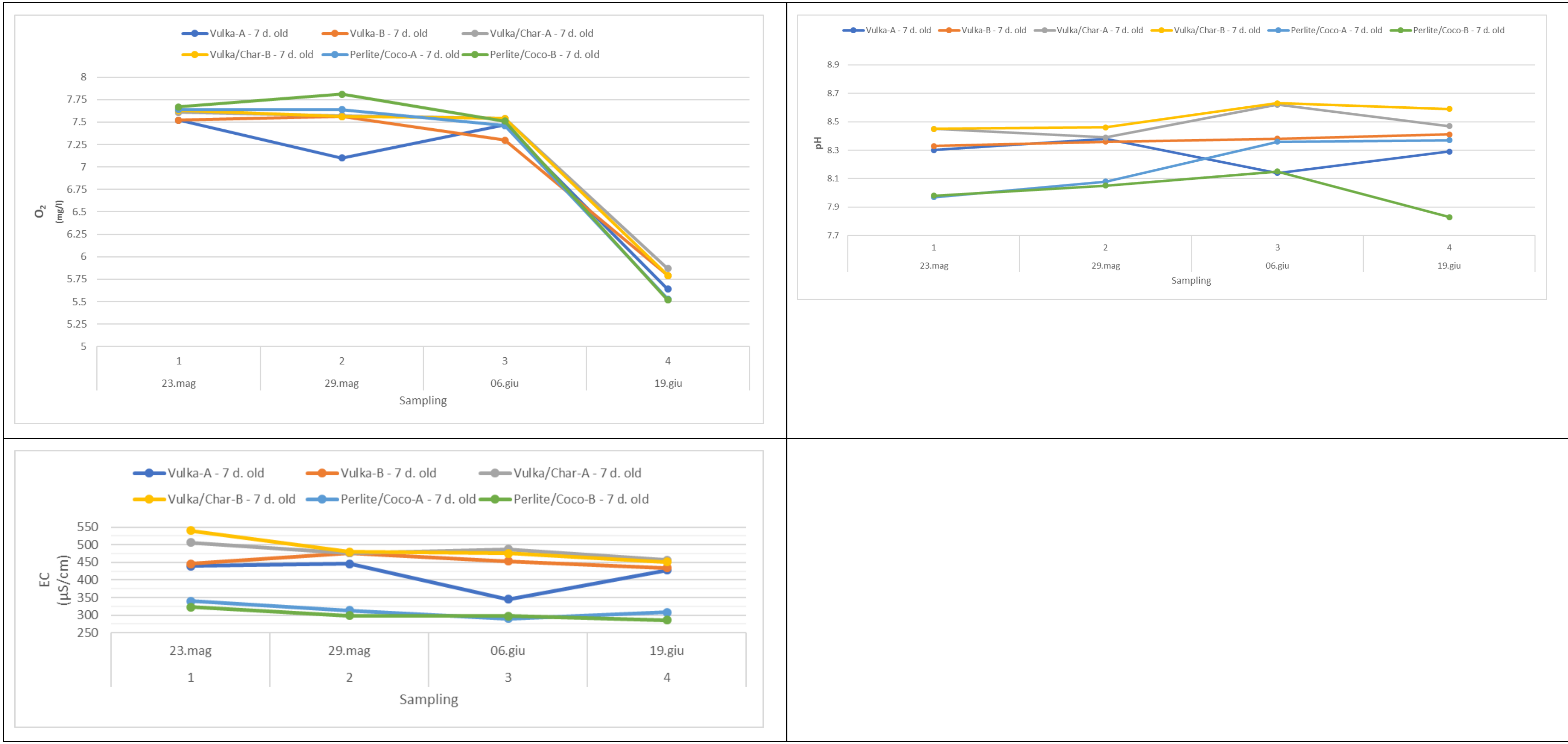


Figure 7: Performance of the green wall greywater treatment systems. Representation of the average daily change in concentrations of the 6 systems for all 4 samplings.

In figure 7 is again shown that Perlite/Coco-A and Perlite/Coco-B had the lowest COD removal with an average daily removal of only 4.8 and 3.7 $mg.l^{-1}.d^{-1}$respectively, while the others were in the range of 10.1 - 11.3 $mg.l^{-1}.d^{-1}$.

Conversely, daily BOD_5 removal is more uniform across all the systems with average values ranging between 2.0 and 2.6 $mg.l^{-1}.d^{-1}$.

While in samplings 2 to 4, in an average of 0.02 (Perlite/Coco-B) and 0.12 (Vulka/Char-A) $mg.l^{-1}.d^{-1}$ of nitrate was removed daily, for sampling 1 there was an increase in nitrate across all the systems. Nitrate could have initially been washed in the GW from the substrates and later been absorbed by the plants. The high variability across the systems is still to be taken in consideration, since, for Vulka/Char-A, Perlite/Coco-A, Perlite/Coco-B, there was almost no change in the concentrations (the increase was slightly above 0.05 $mg.l^{-1}.d^{-1}$) between influent and effluent, while for Vulka-A, Vulka-B, Vulka/Char-B it was well above 0.1 $mg.l^{-1}.d^{-1}$. Although both the removal and increase of nitrate were consequential across all the systems, there is a distinctive difference between those filled with the perlite coco peat and those with Vulkaponic.

The picture for ammonium is more heterogeneous. All systems but Perlite/Coco-A went first above and then below the influent concentration. Vulka-A seems to have an increase in samplings 1 and 3 and a removal on 2 and 4. Vulka-B had an increase in sampling 1 to 3 and then a removal on the last one, and so on. But it appears, that ammonium concentrations generally increased in the first weeks, maybe due to leaching of the substrates or the plants, and then decreased in the later ones, as the plants may have started to slowly assimilate it.

Nitrate and ammonium were summed together (N-Sum) and represented also in Figure 7 as daily removal rates. The chart is very similar to the nitrate-one. Vulka-A, Vulka-B and Vulka/Char-B had after the first week the strongest nitrogen increase, while together with Vulka/char-A they achieved a nitrogen removal in the following weeks. Perlite/Coco-A and Perlite/Coco-B had almost no increase and had very low removal rates (under 0.05 $mg.l^{-1}.d^{-1}$) so that the nitrogen concentrations changed only slightly from the influent.

Ortho-phosphate concentrations increased in all systems over all four samplings. Vulka-A and Vulka-B had the lowest increase, averaging around 0.02 and 0.01 $mg.l^{-1}.d^{-1}$ respectively, while being the only systems able to remove it in sampling 4. From Vulka/Char-A to Perlite/Coco-B there was a remarkable increase ranging between 0.65 and 0.87 $mg.l^{-1}.d^{-1}$ on the first sampling and then slowly decreased to between 0.08 and 0.032 $mg.l^{-1}.d^{-1}$. Mixing the first Week GW with the 8 litres recirculated GW from the establishment period (fish tank water was added, so it likely had very high PO_4-P concentrations) could have initially increased the concentrations in the systems, which gradually decreased with time hinting to a plant absorption. The initial difference could also hint to an ortho-phosphate leaching from system 3 to 6 in the irrigation medium.

Turbidity declined distinctively in all systems from a 10.20 NTU of the GW to an average value of 3 NTU.

Overall, the concentrations of O_2 starting from the influent concentration of 7.72 $mg.l^{-1}$, decreased significantly only on the fourth sampling, ranging between 5.52 and 5.87 $mg.l^{-1}$, while remaining above 7 $mg.l^{-1}$ in samplings 1 to 3. The drop in dissolved O_2 could have been caused by higher temperatures. Indeed, there was a temperature peak on June 18, 2019 reaching 35 C^o. Still it can't be explained, why on June 4, 2019, there was no visible change in dissolved O_2, despite having almost the same temperature peak (Figure 6).

The pH, starting from 8 for the fresh GW, fluctuated between 7.8 and 8.6. The systems with the same substrate started in the first sampling with the same pH value, namely 8.3 (Vulka), 8.45 (Vulka/Char) and 7.98 (Perlite/Coco) and then differed in the following weeks. Vulka-B had the smallest increment in pH starting from 8.33 and ending with 8.41. Of all systems its pH changed the least. On sampling 4 Perlite/Coco-B had the lowest pH (7.83) while Vulka/Char-B had the highest pH value (8.59). This result confirms the statement from Nemati et al. (2015) that biochar would have increased the pH of the system.

The electroconductivity (EC) results show that the systems with Vulkaponik started (sampling 1) and ended (sampling 4) with higher values than those with Perlite/Coco. In sampling 4 they ranged between 428 - 456 µS/cm and 286 - 308 µS/cm respectively.

3.4 Visual comparison

From figure 8 and 9 can be observed that initially there was a satisfactory plant growth throughout the whole living wall. Almost all species appeared to thrive within the different systems and to grow with no apparent problems with the light greywater irrigation. Nonetheless starting from the third week, the species *Nasturtium officinale*, after it bloomed, showed signs of stress as yellowish and dry leaves and by the end of the fifth week several specimens seemed to have died. The death of the species could be explained by the fact that the species didn't adapt well to the system and by its inherent shorter life cycle. In either way is clear that *Nasturtium officinale* would not be suited for such a system. Beside *Nasturtium officinale*, all species seemed vital and had visible growth. *Valeriana officinalis*, *Lythrum salicaria* and both *Juncus* species had good growth and a satisfying flowering. Generally, the plants became less green and more yellowish, also confirmed by the lower chlorophyll amount in the leaves on June 21, 2019 and as a result also a lower NBI (vitality) (see next chapter).

Figure 8: Photograph of the living wall systems on May 16, 2019(above) and June 21, 2019 (below). From right to left System 1 to 6.

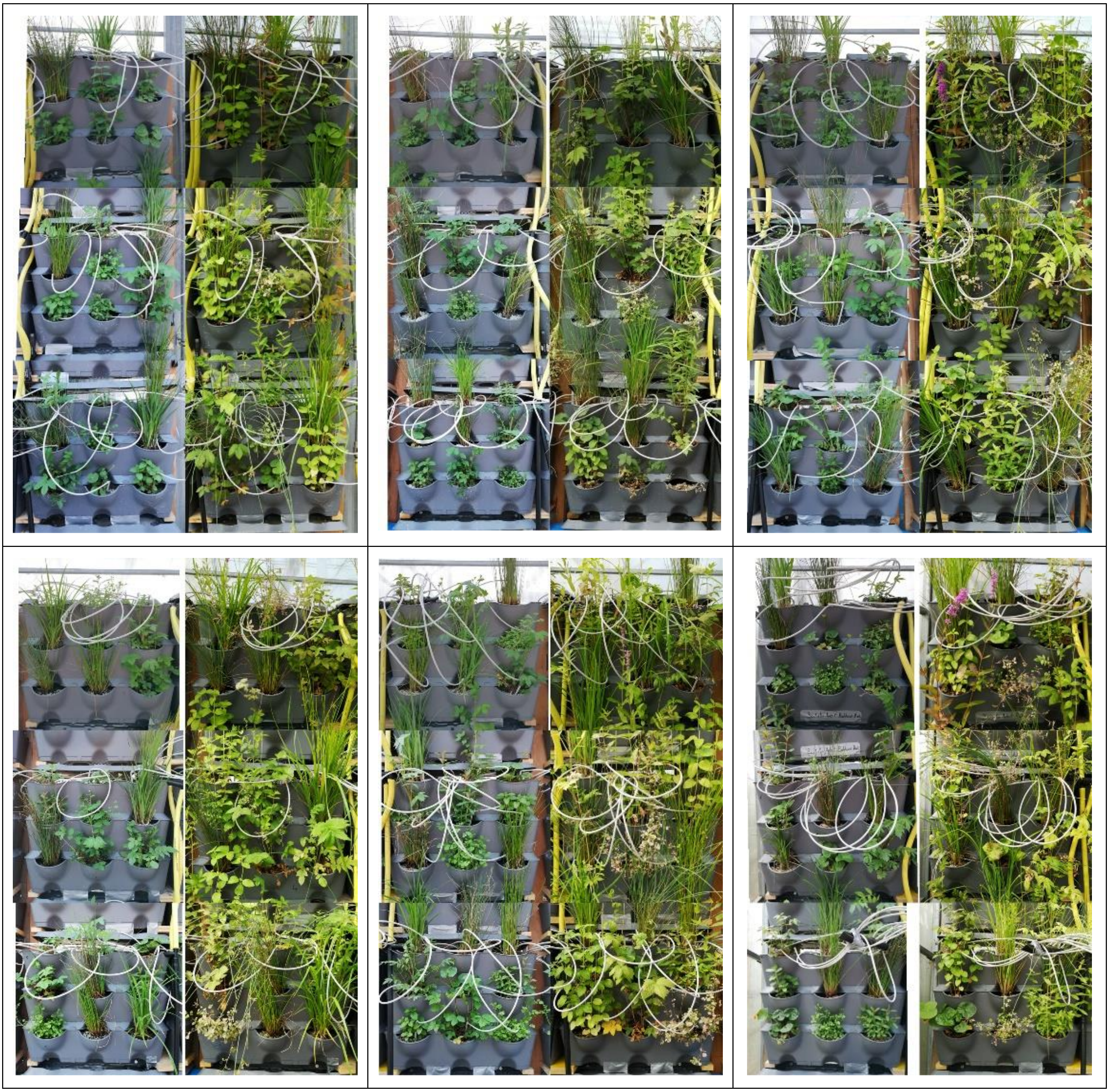


Figure 9: From left to right. Above: System 1 to 3, below: System 4 to 6

3.5 Dualex-Analysis

Chlorophyll can be used as a nitrogen status indicator, because it is an essential element in photosynthetic protein synthesis and flavonols are generated when plants are under N deficiency stress. As the NBI is the the chlorophyll/flavonols ratio, the higher the NBI value the bigger is the chlorophyll amount and the more vital the plant can be interpreted (Muñoz-Huerta et al., 2013).

This way the NBI can be directly understood as a plant vitality parameter. In the following chapters the values of the six tested species are represented as the average values of the three specimen of each system.

Almost every plant showed a lower vitality in terms of a lower NBI index after 50 days. This can be probably be explained by the normal life cycle development and also by the flowering of many plants, which normally means the redirection of part of the nutrients from the leaves to the flower. That is why there is no comparison of the vitality between the two samplings periods.

The plant vitality is also used to find out, if there is a correlation and a significant difference between the plant species growing in different growing media, at different heights and with different irrigations.

3.5.1 Height-NBI Index correlation

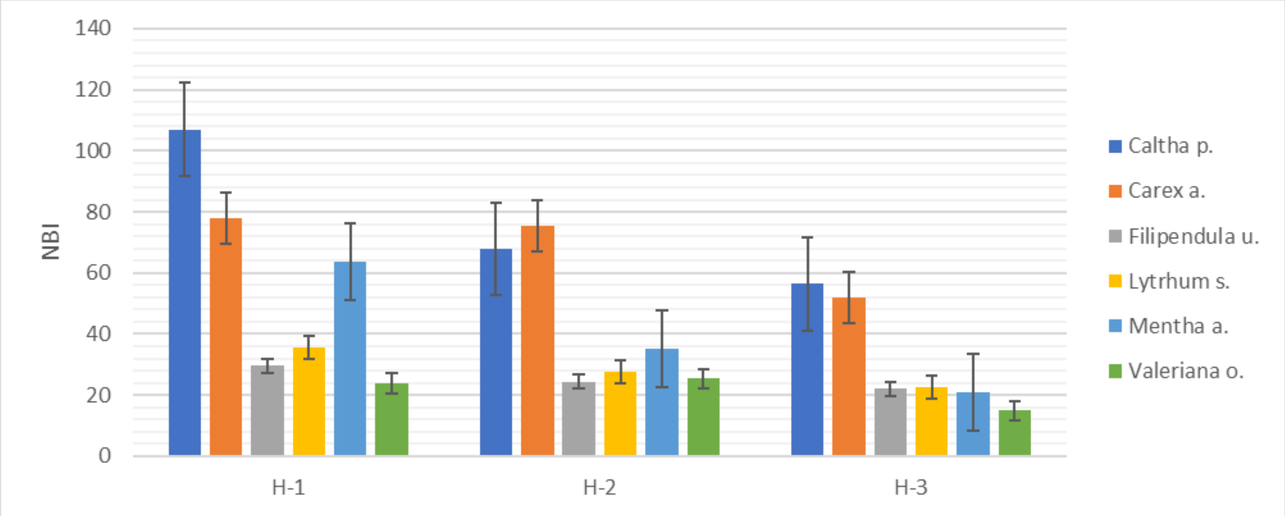


Figure 10: Average NBI values of six plant species (standard error bars) depending on the heights of the sets within the entire system, where they were planted. H-1 denotes the sets in the lower row, H-2 the sets in the middle and H-3 the sets on the top row.

For the genus *Filipendula, Lythrum*, and *Valeriana* there is no distinctive difference between the heights. *Caltha* and *Mentha* showed higher vitality values when planted low (H-1). *Carex* had a good vitality on both the lower rows but a decrease in the top one (Figure 10). Other factors to be taken in consideration that may affect plant vitality are that the top rows are exposed to more sunlight, and hence also to the higher temperatures, that may collect in the top of the greenhouse.

3.5.2 Irrigation mode

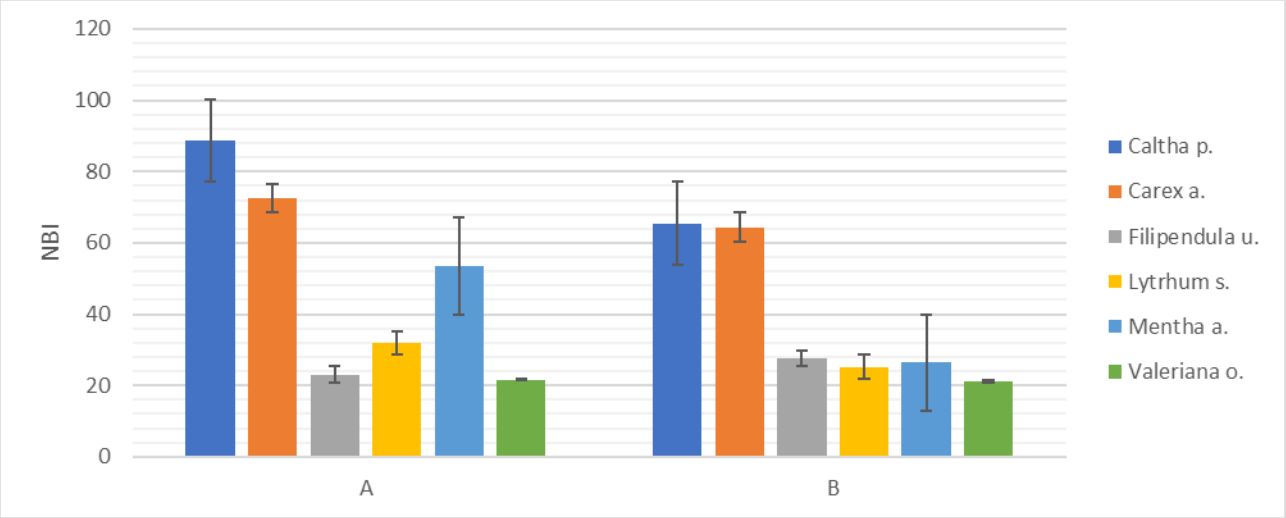


Figure 11: Average NBI values of six plant species (standard error bars) in dependence of the different irrigation types (A: drip; B: top-down).

Genus *Caltha* and Mentha, showed higher NBI values with the drip irrigation (Figure 11). Other species did not show a response to different irrigation.

3.5.3 Growing Media

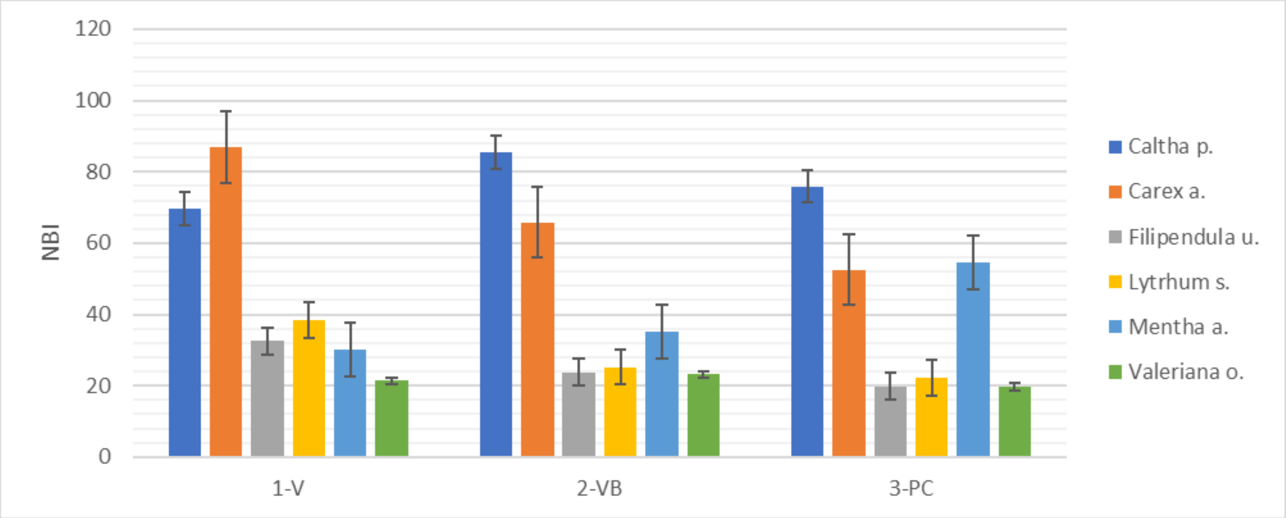


Figure 12: Average NBI values of six plant species (standard error bars) in dependence of the different substrates: Vulkaponic (1-V); Vulkaponic-Biochar (2-VB); Perlite-Coco peat (3-PC).

From figure 12 can be extrapolated, in which substrates the plant species seemed to grow best. The 100% Vulkaponic was preferred by *Carex acutiformis, Filipendula ulmaria and Lythrum salicaria*. *Caltha palustris* had the best vitality values growing in the Vulkaponic/Biochar substrate, while *Mentha aquatica* grew at best in the perlite/coco peat (3-PC). *Valeriana officinalis* didn't seem to have a distinctive vitality difference between the different media.

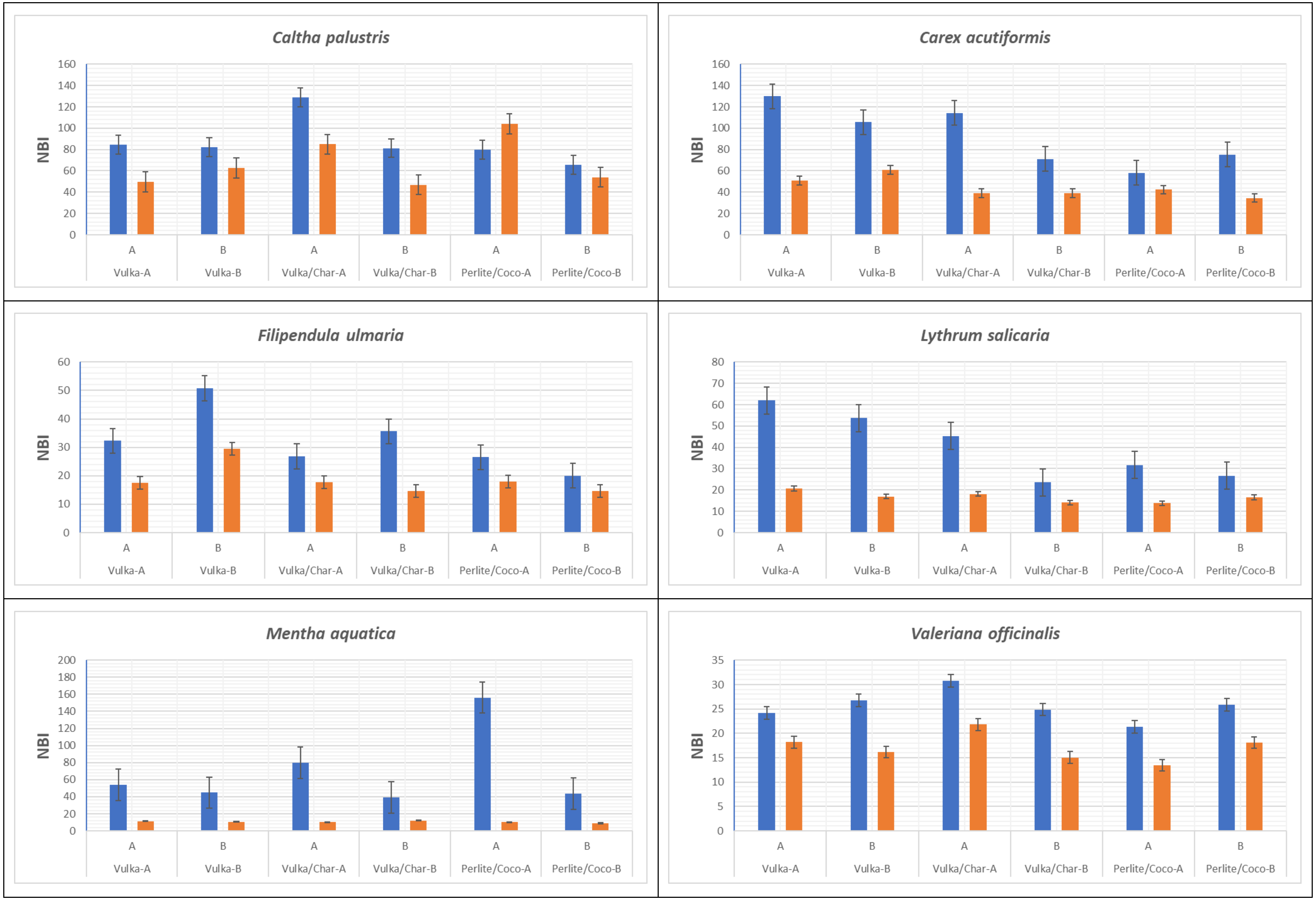


Figure 13: Average NBI index values (standard error bars) of six plant species grouped by irrigation method (A: drip; B:top-down) and by system (1-6) . In blue is the data from May 25, 2019 and in red from June 18, 2019.

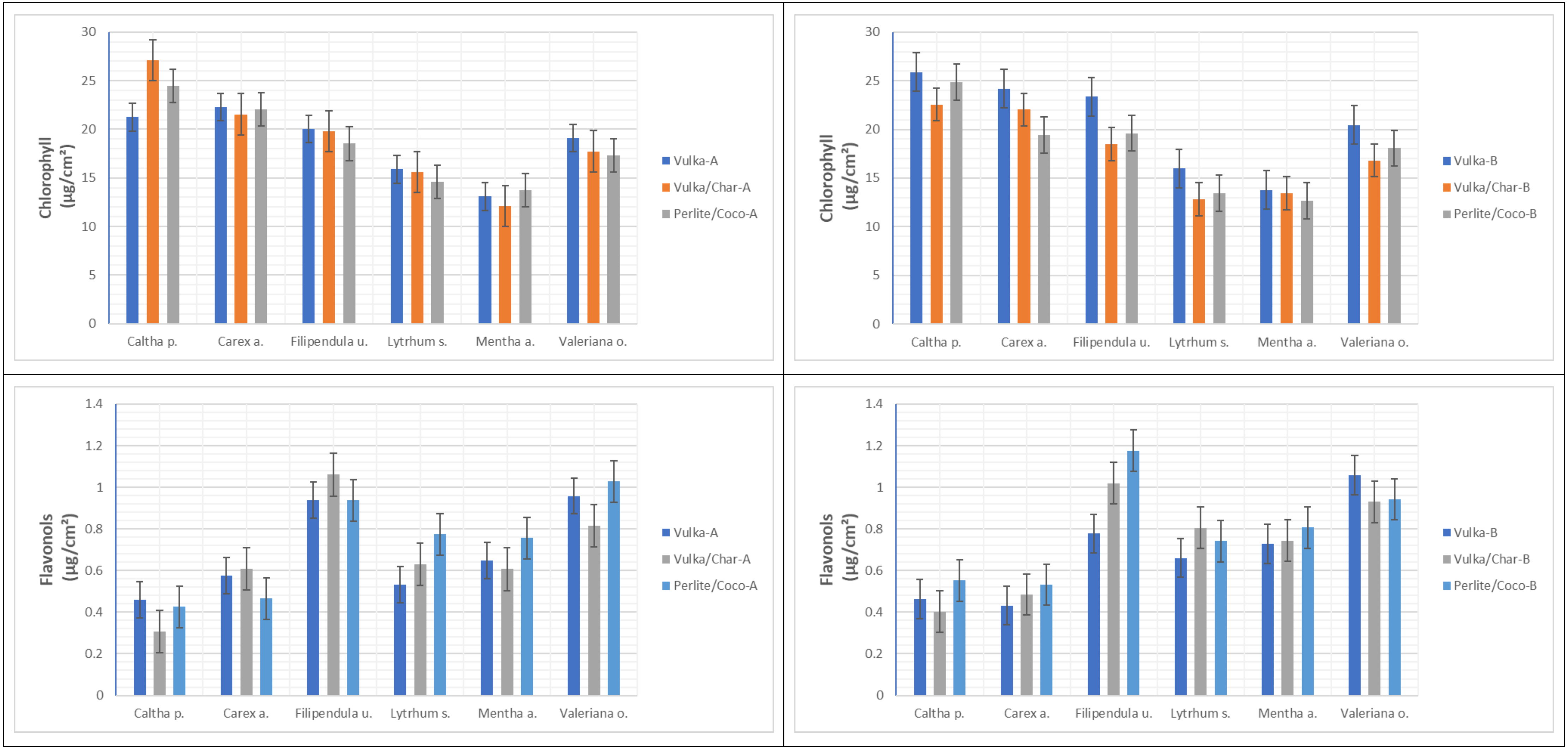


Figure 14: Average Chlorophyll and flavonols concentrations (standard error bars) of the six species, grouped by substrate and divided per irrigation method (A: drip; B:top-down).

3.5.4 Caltha palustris

Figure 13 and 14 show, that *Caltha palustris* specimens were initially at their most vital in Vulka/Char-A with the drip irrigation, as there was probably more available water and nutrients in the GM. With an approx. 40 points lower NBI, the others showed no distinctive difference among one another having almost all around 80 points.

The second measurement shows a different picture, as Vulka/Char-A now has the second-best vitality value, while Perlite/Coco-A (drip irrigation; perlite coco peat) has the highest one.

Vulka-B, Vulka/Char-A and Perlite/Coco-B had the highest chlorophyll value (better nitrogen uptake), while the Vulka/Char-A system had the lowest flavonols concentration (lower N-deficiency stress).

3.5.5 Carex acutiformis

The species *Carex acutiformis* seems to do very well in the beginning in Vulka-A, Vulka/Char-A and Vulka-B, while exhibiting lower vitality values in Perlite/Coco-A, Vulka/Char-B and Perlite/Coco-B. In the later measurement, Vulka-A and Vulka-B still had the highest vitality in relation to the others, while Vulka/Char-A to Perlite/Coco-B show lower values. It seems, that the *Carex acutiformis* may prefer the Vulkaponic based substrates and a direct drip irrigation, as both showed higher values than top-down.

Vulka-B with 24 $\mu g.cm^{-2}$ and the drip irrigated systems(-A) right below with around 21 $\mu g.cm^{-2}$ had the highest chlorophyll amount. *Carex acutiformis* had the lowest flavonols concentration in the Vulka-B system with 0.5 $\mu g.cm^{-2}$.

3.5.6 Filipendula ulmaria

The species *Filipendula ulmaria*, seems to do best in Vulka-B in both periods. In the beginning it has a medium vitality in Vulka-A and Vulka/Char-B. In the later measurement the differences between the values seems to be less substantial. It seems that for *Filipendula u.* the substrate has played a major role, as it prefers the Vulkaponic based substrate above all others and also grows better with top-down irrigation.

Vulka-B had with 23 $\mu g.cm^{-2}$ the highest chlorophyll concentration, and with 0.8 $\mu g.cm^{-2}$ the lowest flavonols amount.

3.5.7 Lythrum salicaria

From the first measurement it would seem, that *Lythrum salicaria* distinctly prefers the 100% Vulkaponic substrate and drip irrigation, as “A” shows overall higher values. The same could be extrapolated from the second measurement, although the differences between the substrates are very slight.

Vulka-A and Vulka-B had with 16 µg.cm^{-2} the highest chlorophyll concentration, while Lythrum salicaria had the lowest flavonols amount in the Vulka-A and in the Vulka/Char-A systems with respectively 0.55 and 0.8 µg.cm^{-2}.

3.5.8 Mentha aquatica

At first, Mentha aquatica too seems to have grown very well in the perlite coco-peat substrate and with drip irrigation. This difference seems to disappear over time, however, as in the second measurement, there is little or none difference in NBI index depending on the different substrates and the different irrigation methods. Vulka-B, Vulka/Char-B and Perlite/Coco-A with each around 14 µg.cm^{-2} reached the highest chlorophyll concentrations. The lowest flavonols amount was in the Vulka-A and Vulka/Char-A systems with approx. 0.6 µg.cm^{-2}.

3.5.9 Valeriana officinalis

For *Valeriana officinalis* the pattern is more heterogeneous. The Vulkaponic and the perlite coco peat substrates give higher vitality values with top-down irrigation, while drip irrigation is preferred with the Vulkaponic biochar substrate. Overall it seems, that *Valeriana* has grown best in Vulka/Char-A. Vulka-B reached with 20 µg.cm^{-2} the highest chlorophyll concentration. The lowest flavonols amount was in the Vulka/Char-A system with 0.8 µg.cm^{-2}.

4 Discussion

The values of this study were compared to the ones of other systems in Table 12

Table 12: Green wall systems comparison

System comparison

System	A (infiltration area) [m2]	V (substrate volume) [m3]	HRT [days]	HLR $[m^3/m^{2*}d]$	OLR $[g/m^{2*}d]$	Reference
Samba Hotel, Spain	7.2-7.5 m^2	2 m^3	1 – 1.9	0.10 – 0.19	16 – 34 (COD)	Gattringer,Ignasi Rodriguez-Roda et al., 2016 (pers. comm)
Pune, India	0.72 m^2	0.072 m^3	0.29 – 0.58	0.173 – 0.347	10 – 20 (COD)	Masi et al., 2016
ZHAW Wädenswil, Switzerland	0.29 m^2	0.1 m^3	1	0.34	26-33 (COD)	Balducci et al., 2019
					10.34 (BOD)	Balducci et al., 2019
Melbourne, Australia	0.045 m^2	0.043 m^3	2	0.0025	99.3 (BOD)	Fowdar et al., 2017
	0.045 m^2	0.036 m^3	2	0.0025	83.2 (BOD)	Fowdar et al., 2017
Melbourne, Australia	0.04	0.018 m^3	-	0.03	-	Prodanovic et al., 2019

To be taken in consideration is, that all other studies did not recirculate the GW. This could be a main reason for performance differences between the different systems.

Gattringer et al. (2016) had a similar OLR (COD) in the range of 16-34 $g.m^{-2}.d^{-1}$ to the system in Pune and to our study but had by far the biggest surface area and medium volume of all systems. Compared to our study Masi et al. (2016) had almost the same volume, a similar HLR, double the surface area but half the HRT.

In Melbourne Fowdar et al. (2017) had less medium volume a longer HRT and a very low HLR under 0.0025 $m^3.m^{-2}d^{-1}$, but very high OLR (BOD) in the range of 83-99 $g.m^{-2}.d^{-1}$, while in our study we measured an OLR (BOD) of only 10.34 $g.m^{-2}.d^{-1}$. They did use sand, which is a good filtering medium, which would not have been suited for our modular system due to the weight. They were able to reach a 97% BOD removal efficiency with all biofilter configurations.

In the Samba Hotel they were able to achieve with the vertECO system from alchemia-nova using expanded clay for both COD and BOD a very high removal efficiency around 96% and 97% respectively. While Masi et al. (2016) also used expanded clay in three different forms (LECA; LECA with coconut fibres; LECA with sand) they reached way lower removal efficiencies. In the substrate order they had for COD approx. 18%, 53% and 42% and for BOD 24%, 53% and 44%.

In our study we were able to reach an average COD removal of around 80% (+/- 5%) with the four Vulkaponic systems, while with the perlite coco mix, we reached only around 30%. For BOD we reached with all six systems a removal of approx. 50% (+/- 10%).

Despite having similar system parameters like Masi et al. (2016), we were able to remove COD and BOD more efficiently. Although we did instead recirculate the GW for seven days, we could still deduce that our system design and our substrates has been relatively efficient in removing COD and BOD.

Instead compared to Gattringer et al. (2016), we did reach around 20% lower removal performances for COD and around 40% for BOD, but we also did have 24 times less surface area and 27 times less medium volume. Nonetheless the 1 m^3 GW fed into the vertECO system wasn't recirculated and they were able to reach the reported removal rates with only one cycle. They also aerated the medium in order to improve removal and the symbiosis of roots and microorganisms. Taking all these factors in consideration, it appears that the vertECO system in Spain is indeed more efficient.

Taking inspiration from it, it could be possible to increase the removal performances of our system by increasing the medium volume, which would mean for future studies adding a fourth or also a fifth NatureUP! set per system.

Prodanovic et al. (2019) also had smaller surface areas and medium volumes, as well as an HLR of 0.03 $m^3.m^{-2}d^{-1}$. They had very low TP removal rates, around 20% in the first operational month but then improved to around 60% afterwards. For TN they almost had the whole time a removal above 70%.

Fowdar et al. (2017) had both high and low TN removal performances depending on the plant species. For example, *Carex appressa* had a 90% and *Phragmites australis* a 7% removal rate. The same was for TP removals also depending on the plant species but with lower maximal performance values (around 80%).

We had in the first week in all six systems an increment in the N-Sum concentrations. In the following weeks system 1 to 3 had an average N removal rate around 60%, while the two systems with the perlite coco mix had only around 30% and 13% removal. Prodanovic et al. (2019) did use a similar perlite coco mix (ratio 2:1) and had half the medium volume but compared to our study, system 5 and 6 (Perlite/Coco) could still reach higher removal rates. In our systems there was almost no phosphate removal rather an increment through the whole operational period, probably due to substrate leaching in the irrigation medium.

Despite having different designs and parameters than the other studies, it appears that our system should be improved the most for TP and TN as well as for BOD removal (by improving the biofilm development), whereas the COD removal, though still not excellent, would only need a smaller adjustment.

5 Conclusions

Exploring different green wall system combinations, treating synthetic light greywater, provided a better understanding of how nutrient removal and vegetation performance is affected by the operating conditions. The overall results point to a successful adaptation of the NatureUP! modular system for greywater treatment. While there are significant design differences (media, and water irrigation method) between the six green wall systems, the findings of this work suggest, that the Vulkaponic substrate mixtures achieved the best COD average removal efficiency (approx. 80%). Higher rates were especially achieved with the top-down irrigation, whereas the perlite coco peat substrate in Perlite/Coco-A and Perlite/Coco-B, had with both irrigation methods significantly lower performances for COD, while achieved for BOD the best removal performance. Perlite/Coco-A and Perlite/Coco-B also had the lowest daily nitrate removal. Vulka-A and Vulka-B had better Ortho-phosphate values, showing the lowest increment among the systems.

The treated water had on average 21.4 $mg.l^{-1}$ COD and 14 $mg.l^{-1}$ BOD for the four Vulkaponic systems and 66 $mg.l^{-1}$ COD and 12 $mg.l^{-1}$ BOD for the two Perlite/Coco systems. For example our treated water would be allowed to be percolated in Darmstadt (Germany), being the set limits for COD and BOD respectively at 80 $mg.l^{-1}$ and at 15 $mg.l^{-1}$ (Fachvereinigung für Betriebs- und & Regenwassernutzung e.V., Darmstadt April, 2005), while they would still be too high in Germany (BOD set below 5 $mg.l^{-1}$) for toilet flushing reuse (Nolde, 2000).

Though there is still room for improvement, as seen in the discussion the removal performances were lower compared to other studies, it's confirmed, that if designed correctly green walls planted with native swiss wild plants can be effectively used for greywater treatment and irrigation.

These functions could be promising additional services provided by green walls, which are already being adopted principally for aesthetic purposes, and also for various auxiliary benefits such as air filtration (O_2 production and carbon storage), thermal insulation of buildings, and reduction of noise pollution.

Eight out of the nine plant species used in this study were found to adapt successfully. Indeed, it was found that *Nasturtium officinale* having a shorter life cycle it's not suited for this type of living wall. Height and irrigation seem to only play an important role in affecting plant vitality upon *Caltha palustris* and *Mentha aquatica*, which both had better values in the lower rows, where there was more shading from other plants, and where they were irrigated with the drip irrigation.

The drip irrigation method was better for the plant growth, but slightly worse for the COD and BOD removal efficiency. Overall the plants planted in the Vulkaponic had a better nitrogen uptake as well higher chlorophyll levels in the leaves and less flavonols. Especially the plants growing in the Vulkaponic substrate with the top-down irrigation showed the best values.

In this study the plants were planted one above the other (due to the NatureUP! set configuration), which caused some self-shadowing. For future studies the design of the green wall could be improved (also aesthetically) by placing the plants alternated. It would be also interesting to test this living wall, firstly by flowing the GW only one time through the system instead of recirculating it, and secondly by adding an additional configuration to compare the performance between planted and unplanted systems, in order to better assess the daily removal and treatment performance of the living wall.

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Appendix A. Supplementary data

Performances of the raw GW and of the samples after a 7 day recirculation

Sampling	System	Typology	O_2 (mg/L)	EC (µs/cm)	Redox ORP (mV)	pH	Trübung (NTU)	COD (mg/L)	BOD_5 (mg/L)	NH4-N (mg/L)	NO_3-N (mg/L)	PO4-P (mg/L)	N-Sum (mg/L)
0	**GW**	**raw**	**7.72**	**410**	**251.5**	**8.0**	**10.20**	**95.7**	**30.0**	**0.030**	**1.33**	**0.003**	**1.360**
1	Vulka-A	**7 d. old**	7.52	440	315.7	8.3	1.54	23.2	14.1	0.095	2.45	0.159	2.545
1	Vulka-B	**7 d. old**	7.52	446	309.7	8.3	2.31	21.9	9.6	0.086	3.49	0.101	3.576
1	Vulka/Char-A	**7 d. old**	7.61	506	287.1	8.5	2.18	16.5	10.7	0.056	1.65	0.522	1.706
1	Vulka/Char-B	**7 d. old**	7.63	540	268.0	8.5	1.96	17.8	10.2	0.063	3.76	0.615	3.823
1	Perlite/Coco-A	**7 d. old**	7.64	340	255.5	8.0	2.73	74.6	11.3	0.029	1.40	0.471	1.429
1	Perlite/Coco-B	**7 d. old**	7.67	323	248.3	8.0	2.43	81.1	9.6	0.060	1.30	0.460	1.36
2	Vulka-A	**7 d. old**	7.10	446	232.9	8.4	2.26	28.2	18.1	0.021	0.76	0.103	0.785
2	Vulka-B	**7 d. old**	7.56	477	234.2	8.4	2.47	23.5	15.3	0.034	1.11	0.058	1.144
2	Vulka/Char-A	**7 d. old**	7.57	477	235.3	8.4	2.33	21.4	13.0	0.034	0.59	0.360	0.619
2	Vulka/Char-B	**7 d. old**	7.56	480	228.2	8.5	2.15	14.6	13.0	0.015	1.27	0.413	1.285
2	Perlite/Coco-A	**7 d. old**	7.64	313	228.3	8.1	1.66	56.8	12.4	0.024	0.90	0.208	0.928
2	Perlite/Coco-B	**7 d. old**	7.81	299	223.1	8.1	2.16	67.8	11.3	0.020	1.05	0.240	1.07
3	Vulka-A	**7 d. old**	7.47	345	256.1	8.1	6.38	19.1	12.4	0.058	0.59	0.171	0.65
3	Vulka-B	**7 d. old**	7.30	453	243.6	8.4	5.79	18.6	13.0	0.053	0.33	0.106	0.379
3	Vulka/Char-A	**7 d. old**	7.54	487	246.3	8.6	3.16	20.9	11.3	0.019	0.29	0.369	0.311
3	Vulka/Char-B	**7 d. old**	7.54	475	240.3	8.6	2.22	15.3	10.7	0.029	0.43	0.398	0.46
3	Perlite/Coco-A	**7 d. old**	7.46	290	232.0	8.4	2.04	68.7	11.3	0.006	1.05	0.178	1.056
3	Perlite/Coco-B	**7 d. old**	7.51	298	230.6	8.2	1.97	73.9	10.7	0.004	1.35	0.451	1.354
4	Vulka-A	**7 d. old**	5.64	428	163.2	8.3	2.84	28.5	19.8	0.006	0.256	0.005	0.262
4	Vulka-B	**7 d. old**	5.79	434	159.8	8.4	2.44	26.3	18.1	0.025	0.276	0.025	0.301
4	Vulka/Char-A	**7 d. old**	5.87	456	138.9	8.5	3.14	26.5	17.5	0.004	0.492	0.208	0.496
4	Vulka/Char-B	**7 d. old**	5.79	451	158.1	8.6	1.21	19.4	16.4	0.024	0.379	0.224	0.403

Dualex Sampling 25 May, 2019: average value for chlorophyll, flavonols, NBI for each specimen

Caltha palustris				**Carex acutiformis**				**Filipendula ulmaria**				**Lythrum salicaria**				**Mentha aquatica**				**Valeriana officinalis**			
specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI
1	25.5	0.3676	147.3	1	18.9	0.1942	238.4	1	21.5	0.5756	38.1	1	18.3	0.2752	67.0	1	15.3	0.510333	29.8	1	22.7	0.894133	25.8
2	23.7	0.369083	63.8	2	22.8	0.225733	111.1	2	22.1	0.7504	30.9	2	14.4	0.3294	47.0	2	16.1	0.166267	97.6	2	23.2	0.906267	27.5
3	22.5	0.533267	42.2	3	27.3	0.702717	40.3	3	18.7	0.933067	27.9	3	20.4	0.286467	72.1	3	18.1	0.535733	34.3	3	22.7	1.1894	19.3
4	34.6	0.472167	72.0	4	25.4	0.6348	49.8	4	25.6	0.333467	91.6	4	19.3	0.4498	44.3	4	17.4	0.277133	65.0	4	28.0	1.0027	31.7
5	25.2	0.700067	69.6	5	26.0	0.3402	97.5	5	24.1	0.7888	31.6	5	22.4	0.312333	97.7	5	17.4	0.544483	32.3	5	26.6	0.8676	31.7
6	32.0	0.316733	105.6	6	30.4	0.263433	169.8	6	19.5	0.737483	29.0	6	14.6	0.779267	19.0	6	16.7	0.488267	36.9	6	22.6	1.359333	17.1
7	35.0	0.247133	151.0	7	25.9	0.1184	238.1	7	17.7	1.0042	19.1	7	16.1	0.305267	66.2	7	17.4	0.186067	95.9	7	19.8	0.7996	27.2
8	28.2	0.241133	160.0	8	25.4	0.318583	83.8	8	24.6	0.7532	41.8	8	15.0	0.532467	28.7	8	15.9	0.161467	115.3	8	23.9	0.477	49.9
9	29.4	0.4524	75.7	9	19.7	0.943867	21.0	9	21.0	1.095667	19.6	9	18.0	0.448333	41.2	9	12.1	0.521267	27.6	9	18.8	1.2374	15.3
10	25.6	0.269267	104.2	10	26.8	0.581733	48.6	10	16.8	0.954333	19.5	10	15.0	0.4398	34.2	10	17.3	0.357467	50.5	10	18.7	0.711867	27.7
11	22.5	0.392267	60.4	11	23.2	0.318067	90.5	11	21.2	1.025333	20.8	11	14.8	0.5754	26.4	11	14.2	0.669933	29.8	11	20.5	0.9576	26.6
12	24.9	0.342267	79.1	12	23.2	0.33	74.1	12	19.7	0.448333	66.6	12	10.1	0.993	10.3	12	17.8	0.487467	36.7	12	20.5	1.029667	20.4
13	26.5	0.2702	128.1	13	21.5	0.435533	50.1	13	19.9	0.58665	34.4	13	16.4	0.3598	48.9	13	17.2	0.048533	382.3	13	20.9	0.9952	21.6
14	28.8	0.557533	55.3	14	22.5	0.363867	61.7	14	19.1	0.792867	25.1	14	17.4	0.8402	20.7	14	17.0	0.4166	61.2	14	23.0	0.983933	24.2
15	27.4	0.51015	55.9	15	21.4	0.351533	62.8	15	21.0	1.0404	20.0	15	15.5	0.615867	25.3	15	17.6	0.737617	25.1	15	22.0	1.228933	18.0
16	30.5	0.563533	65.2	16	21.4	0.265467	88.3	16	24.8	1.196533	20.6	16	14.0	0.358733	40.3	16	17.9	0.36565	66.7	16	20.3	0.9642	22.5
17	32.3	0.3618	96.9	17	23.5	0.258867	93.9	17	24.5	1.000667	24.5	17	14.4	0.874133	16.3	17	14.4	0.680733	21.7	17	22.9	0.647933	35.6
18	25.8	0.747267	35.2	18	19.9	0.634983	43.6	18	18.0	1.215	15.0	18	12.7	0.575733	23.3	18	14.6	0.419467	41.7	18	21.7	1.516267	19.4

Dualex Sampling June 18, 2019: average value for chlorophyll, flavonols, NBI for each specimen

Caltha palustris				**Carex acutiformis**				**Filipendula ulmaria**				**Lythrum salicaria**				**Mentha aquatica**				**Valeriana officinalis**			
specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI	specimen	Chl	Flav	NBI
1	22.5	0.469867	81.2	1	19.1	0.656933	31.5	1	20.0	0.975733	20.5	1	13.2	0.7474	23.4	1	9.5	1.033067	9.5	1	16.7	0.8626	19.3
2	17.8	0.496383	37.2	2	21.7	0.54035	99.6	2	20.1	1.1732	17.1	2	15.5	0.7074	22.4	2	10.5	0.783333	13.2	2	15.6	0.680933	23.7
3	15.7	0.523667	30.3	3	23.9	1.134733	21.4	3	17.8	1.216533	14.7	3	13.6	0.842333	16.3	3	8.9	0.863467	11.3	3	13.8	1.216183	11.5
4	21.5	0.259733	88.0	4	19.1	0.632467	31.9	4	27.7	0.593067	48.5	4	15.5	0.717667	22.7	4	9.4	0.874667	10.8	4	22.2	0.850733	26.7
5	20.2	0.592133	50.2	5	21.1	0.379533	59.8	5	22.2	1.1436	19.6	5	10.9	0.738533	14.4	5	11.3	0.945	11.9	5	13.3	0.956467	14.0
6	21.9	0.441067	49.6	6	23.1	0.34	91.3	6	21.2	1.066467	20.2	6	13.2	0.9656	13.6	6	10.4	1.239083	9.0	6	10.2	1.320367	7.8
7	22.7	0.207533	110.7	7	20.7	0.694417	36.5	7	20.5	1.030733	23.6	7	14.4	0.7364	19.6	7	9.1	0.826733	11.0	7	16.3	0.587889	31.1
8	23.2	0.3574	68.8	8	18.8	0.334667	65.2	8	18.8	1.015067	18.6	8	16.2	0.830556	19.7	8	9.3	0.801133	11.8	8	14.3	0.632511	22.7
9	24.2	0.331967	75.4	9	18.8	1.2436	15.1	9	16.3	1.464717	11.1	9	14.0	0.931933	14.9	9	8.7	1.142733	7.8	9	13.4	1.161467	11.6
10	22.9	0.4596	49.9	10	20.1	0.663822	30.2	10	14.7	1.228933	12.1	10	15.5	0.775356	20.7	10	12.5	0.702072	18.7	10	14.0	0.8938	15.9
11	18.1	0.559667	33.3	11	22.2	0.406383	56.3	11	22.8	1.377567	16.6	11	12.1	0.9586	12.7	11	10.7	1.003417	10.7	11	15.8	0.970578	17.9
12	21.5	0.3912	57.7	12	16.7	0.608783	30.5	12	15.7	1.081067	15.4	12	9.5	1.090867	8.7	12	8.1	1.2436	7.0	12	11.3	1.014933	11.3
13	21.5	0.173267	223.5	13	23.9	0.5128	46.8	13	12.6	1.164267	10.9	13	12.8	0.8065	16.0	13	10.9	0.808267	14.0	13	11.9	0.863733	15.1
14	21.3	0.532	45.5	14	23.1	0.5368	43.2	14	20.9	0.794	28.7	14	14.4	1.067	13.5	14	9.8	1.075667	9.2	14	12.9	0.9486	13.6
15	21.5	0.507533	43.2	15	20.0	0.5948	37.0	15	17.6	1.245533	14.2	15	11.2	0.9518	11.9	15	9.9	1.450467	6.8	15	13.1	1.153867	11.6
16	26.7	0.6378	61.5	16	17.1	0.527983	44.4	16	17.8	1.184156	17.1	16	12.7	0.605622	22.3	16	9.9	0.9178	11.0	16	14.9	0.696733	22.1
17	14.7	0.242733	73.1	17	17.8	0.456867	43.3	17	18.5	1.1408	16.5	17	12.2	1.058867	12.3	17	9.9	1.2694	7.9	17	12.3	0.761367	16.7

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Bachelor Thesis

Green wall for greywater treatment: wall design and literature review

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Bachelor in Natural Resource Sciences
Specialization in Urban Ecosystems

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Introduction

This study presents the development of an outdoor greywater treating green wall by adapting a commercially available system, identifying which native swiss wild plant species can be implemented and examining how operational conditions (substrate and irrigation method) influence nutrient removal from synthetic light greywater.

The experiment was conducted over a 2 months' time period located in a greenhouse at the ZHAW Wädenswil, in Switzerland. A total of nine plant species, three substrates (Vulkaponic; Vulkaponic plus biochar; perlite plus coco peat) and two irrigation methods (drip irrigation; top-down irrigation) were tested. The synthetic GW was recirculated and renewed weekly.

Objektives

(I) to select and adapt a commercially available modular green facade system for the use of domestic grey water for the plant irrigation, and treatment.
(II) to select native wild plant species and test them for their suitability for growth in the selected substrates when irrigated with greywater.
(III) to discover which substrate type and which irrigation mode are most suitable for a greywater treatment wall.

Method and experimental design

The green wall set NatureUP! (figure 2) was adapted to two irrigation systems: drip and top-down irrigation. The green wall had a compartmental design composed by 18 sets, with every set having 3x3 plant openings. Three vertically stacked sets with the same substrate and irrigation system formed one design configuration, each had a volume of 0.1 m³ and 0.29 m² surface area.

This experiment tested 9 plant species, two different irrigation systems, three substrate media and synthetic greywater, making a total of six design configurations. The synthetic greywater (GW) was created by mixing 11 ml of detergent ("Baby Laundry Detergent" I ATTITUDE) with 50 l drinking water and 8 l of the previously recirculated GW.

After a two-week establishment period, the green wall system was monitored from May 15, 2019 until June 21, 2019. Each day approx. 100 L GW were passed through each system over 4 hours. Hydraulic retention time (HRT) and irrigation time (IT) were fixed respectively at 1 day and at 4 hours, the average hydraulic loading rate (HLR) was 340 $l*m^{-2}*d^{-1}$. The GW was recirculated and weekly renewed.

Figure 2: Start of the green wall system on May 16, 2019.
NatureUP! Set from Gradena(germany)

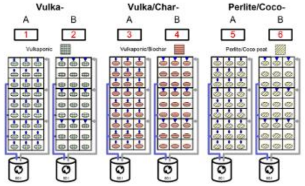


Figure 1: Green wall system design. (created with Vectorworks von A. Balducci)

Table 1: Experimental factors and variables investigated in this study

Factor	Variables		
Plant species	*acutiformis*	*Caltha palustris*	*Filipendula ulmaria*
	Juncus effusus	*Juncus inflexus*	*Lythrum salicaria*
	Mentha aquatica	*Nasturtium officinale*	*Valeriana officinalis*
Irrigation	Drip-irrigation (A) Top-down (B)		
Growing media	Vulkaponic Vulkaponik and plant-based Biochar; Mix (75/25 %) Perlite and coco peat; Mix (75/25 %)		
Greywater	synthetic wash machine Greywater (11 ml Solvent/ 58 l Drinkwater)		

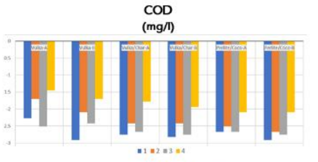
Table 2: Experimental factors and operational conditions of the study.

For each system					
Volume (m³)	Inflow (l/h)	Irrigation time (h)	HRT (d)	θ (l /d)	HLR (l/m²*d)
0.1	24.6	4	1.0	98.5	339.7

raw GW 200 µL Detergent/ 1 L Drinkwater
new GW 58 L fresh mixed GW

A total of four samplings were conducted, to assess nutrient removal performance. The outflow samples were tested with a Spectrophotometer for chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), ammonium (NH_4-N), nitrate (NO_3-N) and ortho phosphate (PO_4-P). Turbidity dissolved oxygen (O_2), electroconductivity (EC), oxidation reduction potential (ORP) and pH were measured as well. The vitality of 6 plant species was assessed with a DUALEX Scientific (ForceA, France), a leaf clip hand-tool combining the use of fluorescence and light transmission.

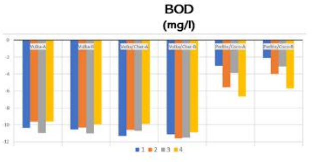
Results – Nutrient performance



COD removal efficiency

	Vulka-A (%)	Vulka-B (%)	Vulka/Char-A (%)	Vulka/Char-B (%)	Perlite/Coco-A (%)	Perlite/Coco-B (%)
Mean	74.1	76.4	77.7	82.5	34.9	27.2
Min	70.5	72.5	72.3	79.7	22.0	15.3
Max	80.0	80.6	82.8	84.7	48.7	41.7
No. Days	7	7	7	7	7	7
No. Samples	4	4	4	4	4	4

Figure 3: Representation of the COD removal performances and the average daily change in concentrations of the 6 systems for all 4 samplings.



BOD_5 removal efficency

	Vulka-A (%)	Vulka-B (%)	Vulka/Char-A (%)	Vulka/Char-B (%)	Perlite/Coco-A (%)	Perlite/Coco-B (%)
Mean	46.3	53.3	56.3	58.1	58.1	60.9
Min	34.0	39.7	41.7	45.3	49.0	49.0
Max	58.7	68.0	64.3	66.0	62.3	68.0
No. Days	7	7	7	7	7	7
No. Samples	4	4	4	4	4	4

Figure 4: Representation of the BOD removal performances and the average daily change in concentrations of the 6 systems for all 4 samplings.

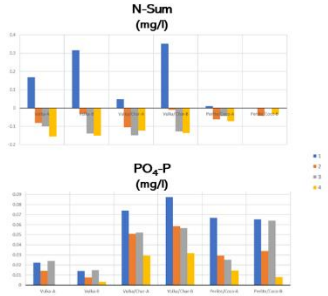


Figure 5: Representation of the average daily change in concentrations for PO_4-P and N-Sum (NH_4-N + NO_3-N) of the 6 systems for all 4 samplings.

Results – Vitality performance (Dualex)

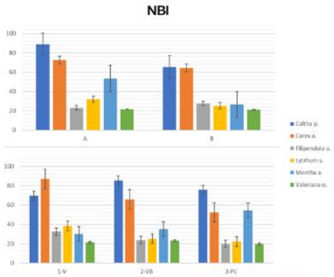


Figure 6: Average NBI index values (standard error bars) of six plant species grouped by irrigation method (A: drip; B:top-down) and by system (1-6). In blue is the data from May 25, 2019 and in red from June 18, 2019.

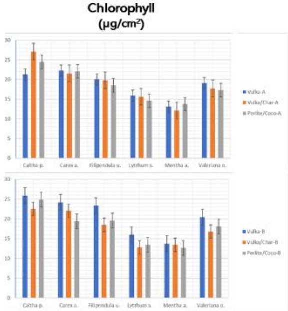


Figure 7: Average chlorophyll concentrations (standard error bars) of the six species, grouped by substrate and divided per irrigation method (A: drip; B:top-down).

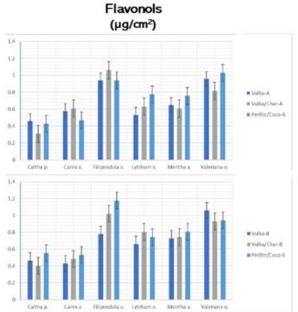


Figure 8: Average flavonols concentrations (standard error bars) of the six species, grouped by substrate and divided per irrigation method (A: drip; B:top-down).

Conclusions

The overall results point to a successful adaptation of the modular system NatureUP! and of the plant species for the greywater treatment . The findings of this work suggest, that the systems with the Vulkaponic substrate mixtures reached the best COD and nitrogen average removal efficiency (approx. 80% for COD and 56% for nitrogen).

Figure 9: End of the experimental period on June 21, 2019.

Perlite/Coco-A and Perlite/Coco-B did have significantly lower performances, approx. 30% for COD and 21% for nitrogen, but of all systems had the best BOD removal efficiency, Turbidity dissolved oxygen (O_2), electroconductivity (EC), oxidation reduction potential (ORP) and pH were measured as well. The vitality of 6 plant species was assessed with a DUALEX Scientific (ForceA, France), a leaf clip hand-tool combining the use of fluorescence and light transmission.

During the experimental period eight out of nine plant species used in this study were found to have successfully adapted. Only *Nasturtium officinale* was not suited for this living wall. Overall the plants growing in the Vulkaponic had a better nitrogen uptake as well higher chlorophyll amounts in the leaves and less N-deficiency stress.

Irrigation method and height seem to only have affected significantly the plant vitality of *Caltha palustris* and *Mentha aquatica*, which thrived better in the lower rows with the drip irrigation.
Between the two methods the drip irrigation appears to be better for plant growth, but slightly worse for COD and BOD removal efficiency.

For future studies the design of the green wall could be improved (also aesthetically) by placing the plants alternated. It would be also interesting to test this living wall, firstly by flowing the GW only one time through the system instead of recirculating it, and secondly by adding an additional system to compare the performance between planted and unplanted systems, in order to better assess the daily removal and treatment performance of the living wall