"WETWALL" — an innovative design concept for the treatment of wastewater at an urban scale

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ABSTRACT

Rising temperatures, increasing food demand and scarcity of water and land resources highlight the importance of promoting the sustainable expansion of agriculture to our urban environment, while preserving water resources. Treating urban wastewaters, such as greywater and hydroponic wastewater, may represent a strategic point for the implementation of urban farming, ensuring food security, reducing pressures on water resources and promoting climate change mitigation. The WETWALL design concept proposes a unique ecotechnology for secondary wastewater treatment at an urban scale, which brings the novelty of a modular living wall hybrid flow. This concept is based on the integration of two established nature-based solutions/ecomimetic designs: constructed wetlands and a modular living walls. First presented is an overview about the state of the art in the scope of living walls treating wastewater, in order to identify the main design aspects related to the performance of such systems, which mainly concerns the removal of nitrates and phosphates. Second, the WETWALL design concept is presented. A scheme regarding the selection of the main components, such as plants and substrate, is proposed, and potential structure developments and operation strategies are discussed. In addition, considering the scope of integrating the circular economy with the design process, potential interactions between this technology and the urban environment are discussed. The main goal of this article is to substantiate the potential of the WETWALL design concept as an innovative wastewater treatment at an urban scale.

Keywords: Wastewater; Circular economy; Living wall; Constructed wetland; Nature-based solutions

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1. Background

The development of modern society has led to an exponential urbanization and exploitation of natural capital, causing significant pressures on the availability and quality of natural resources, especially water [1]. Urbanization has a significant impact on the quality of freshwater, and the reduction of urban groundwater supplies. According to Ren et al. [2], "rapid urbanization corresponds with rapid degradation of water quality." In this regard, greywaters (water from several uses such as, bath, hand washing, kitchen sinks and others), representing about one-third of domestic wastewaters, are also considered as an important source of pollution, containing high levels of several contaminants, especially, phosphorus and nitrogen [3,4].

On the other hand, considering future threats related to the exponential increment of food demand, scarcity of local resources such as water and land, and climate change, the adoption of soilless agriculture has been proposed as a sustainable alternative to produce food at an urban scale [5–10]. According to Komisar et al. [10], "Reconnecting cities to their food systems is now emerging as one of the core components of the design of more sustainable urban settlements." In this regard, hydroponic systems can be applied in buildings, which can improve supply chains while reducing transport distance and time of storage [8]. However, several authors have shown that soilless crop production can represent an important source of diffuse pollution, since the wastewater of these systems have a high concentration of nitrates and phosphorus and is normally drained and discharged to the environment [11–14].

According to Rockström et al. [15], humanity has already transgressed planetary boundaries in relation to changes on the global nitrogen (N) cycle. The inputs of reactive nitrogen, mainly caused by the production of chemical fertilizers (chemical fixation – Haber–Bosch process), are greater than the environmental capacity to remove reactive nitrogen though the denitrification process. This leads to an accumulation of nitrates (NO_3^-) in water and nitrous oxide in the air (N_2O), a process called the nitrogen cascade effect [15–18]. On the other hand, anthropogenic input of phosphorus into the environment is mainly caused by agriculture through the application of chemical fertilizers, households and industries in the form of detergents [19]. The accumulation of reactive nitrogen and phosphorus may cause several environmental damages such as pollution of groundwater, eutrophication of surface waters, decrease of biodiversity and changes in terrestrial, aquatic and marine systems [15,19,20].

Therefore, technologies, which can promote the treatment and reuse of urban wastewaters such as greywater and effluents from soilless crop, may play an important role for the preservation of water resources, mitigation of climate change and promoting a sustainable development of agriculture into the urban environment. According to European Environment Agency [21] and Malik et al. [22], treating and promoting the safe reuse of wastewater on a global scale represents a crucial strategy to ensure an efficient use of water resources and decreasing the competition with drinking water supply.

In this scope, ecomimetic designs (ED) and nature-based solution (NBS) have been considered as a promising strategies for climate change mitigation. ED and NBS, replicates features of natural systems to integrate ecosystem services into the human environment, and thus promote an efficient use of natural resources, a human well-being and a socially inclusive green growth [23,24]. According to Blok and Gremmen [25], "By using the same design principles as natural entities and systems, and by modelling our technological design on natural principles, biomimicry adheres to a bio-inclusive ethics that enables us to resituate our technological design within the ecological limits of the biosphere."

Regarding this, constructed wetlands (CWs), a technology based on the replication of biological, chemical and physical processes occurring in natural wetlands have been used throughout the world to treat several types of wastewater. This technology has been efficiently applied for the treatment of greywaters [3,26] and hydroponic wastewaters [11,12,13]. On the other hand, living walls (LWs), as part of an innovative green infrastructure, could provide multiple functions at a urban scale, related to climate change mitigation. Among these functions are the reduction of environment temperatures and the urban heat island effect [27], energy savings [28,29] and improvement of carbon sequestration [30,31].

Moreover, in the face of future threats such as the reduction of land availability and the exponential growth of expected population, NBS, which can take advantage of vertical spaces, can represent a sustainable strategy in the scope of the decentralization of wastewater treatments and climate change mitigation. In addition, several authors have been showing that the implementation of natural ecosystems in vertical spaces of urban environments could represent an important factor in the context of urban resilience [32–34]. Therefore, unlike CWs, which demands great land area, the LWs can be implemented in empty spaces of building walls and facades and can undertake the function of wastewater treatment, improve air quality, to help the mitigation of climate change.

It is well known that microbial degradation, adsorption, plant uptake, sedimentation and precipitation are among the main processes responsible for pollutants removal in CW [35,36]. These processes can be intrinsically related to the substrate by favouring adsorption, providing suitable conditions for biofilm growth to promote microorganism mediated degradation and (nitrification–denitrification) precipitation of phosphorus (Ca, Mg, Fe and Al). Additionally, the presence of plants can enhance nutrient uptake and the water flow can affect the oxygen conditions in the structures, which consequently influences the microbial degradation and precipitation processes. The essential elements of CWs, such as the interaction among substrate, plants, biofilm and water flow also take a place in LWs. Therefore, the WETWALL design concept, by integrating these two technologies (CWs and LWs), could have an interesting role as a wastewater treatment technology. In addition, the treatment of urban wastewaters by LWs may help overcome the biggest limitation related to the implementation of this type of system: the high water consumption.

This article presents a theoretical discussion on the innovation presented by the WETWALL design concept in the scope of urban wastewater treatments. Therefore, this paper presents an overview about LWs treating wastewaters

in order to determine the main design parameters and its relation with system performance, especially regarding the removal of nitrogen and phosphorus. Then, the WETWALL design concept is presented in four parts. First, a selection of plant species and substrates to be used. Second, the structure developments are discussed to develop a modular LW hybrid flow, based on the background of a CW hybrid flow. Third, operation strategies such as water recirculation (treatment cycles) and intermittent flow are presented. Fourth, to integrate circular economy into the design process, potential interactions between the WETWALL and the urban environment are presented and discussed. To the best of our knowledge, there is no information within the scientific literature about a design of a modular LW hybrid flow to enhance the removal of nitrogen and phosphates from urban wastewaters.

2. State of the art

Modular LWs can be defined as "elements with a specific dimension, which include the growing media where plants can grow. Each element is supported by a complementary structure or fixed directly on the vertical surface" [37]. Modular LWs typology is an appropriate structure for wastewater treatment. The structure allows contact between roots, substrate and water, which are key conditions to provide pollutants removal through plant uptake, substrate adsorption and microbiological degradation. In addition, modular LWs are known as widespread system, mainly because of their easy maintenance, their adaptability to different facades, adaptation to different species and for being environmentally efficient in reducing energy demand, mainly by thermal insulation [37–40]. In this regard, all previous research on the scope of wastewater treatments used modular typology. However, the different studies present a wide variety of structures, substrates, plants and operational factors.

Most of the researchers are focused in LWs performance regarding the treatment of greywaters. There are few studies studying and validating the reuse of wastewater to irrigate LWs [41] or even integrating LWs with other treatment systems [42,43]. For example, Elmasry and Haggag [41] proposed recycling greywater at a school building, using this water as an irrigation source for LWs. Cameron [42] proposed an integrated system combining a subsurface flow CW, LW and green roof in order to treat greywater. However, no specific sampling was performed in order to assess the contribution of the LWs for the removal of contaminants in this system. Emeric [43] proposed an integrated household greywater system, which combines one initial storage treatment, a LW and filter chambers. The LW was responsible for 24% of nitrate removal and 44% of orthophosphate removal and the global efficiency on phosphorus removal reached 95%.

Sakkas [44] proposed a LW for the treatment of greywater based on the replication of a vertical subsurface flow CW. The LW was composed by vertical sections (0.57 m) connected to each other. Each section was divided in a merging zone (0.07 m), which is the space for the plant growth, a root zone (0.30 m) filled with expanded clay aggregates and a drainage layer (0.20 m) filled up with foam glass gravel.

No data about the practical validation of this system was presented related to pollutants removal. However, the author suggested that the proposed LW could treat 0.105 m^3/d of domestic greywater on a facade of 4.2 m^2.

Even though the integrated system seems to be a promising alternative, it was decided to focus this overview on wastewater treatments based on LWs systems validated with practical experimentation. In this regard, it was noticed that a couple of authors based the LW design on similar biological wastewater treatments, such as intermittent biological filter [45] or CWs and storm biofilters [46]. Considering the lack of information in this field, the background provided by such references is important to establish the main parameters, which may be used for the improvement of the LWs design for wastewater treatment. On the other hand, a couple of authors focused the design on the development of a LWs concept for the treatment of wastewater and tested variables such as filter media, plants and biofilm [47,48]. Furthermore, to understand the influence of design parameters on the removal of nitrates and phosphates and to determine patterns in this matter, the overview is presented in the next section.

2.1. Living walls as wastewater treatments

Svete [45] developed a system, which is mainly based on the adaptation of an intermittent underground biological filter to become a vegetated wall structure for treating greywater. The biggest challenge was the reduction of surface area in comparison with conventional treatment, which can lead to a limitation on the removal of pollutants. Typical intermittent biological filters have larger surface area than filter depth, which is the opposite of the LW structure, which has bigger filter depth than surface area. To overcome this limitation, the author, as a reference, used design parameters such as aeration and hydraulic retention time. The author design is mainly based on the hypothesis that enhancing the aeration and increasing the retention time may help to overcome the issue of limited surface area. Hence, the design proposes the implementation of low volume doses and sequentially feeding, to increase retention time and to avoid saturated zones in the filter profile.

The module was filled with lightweight expanded clay aggregates and a drainage section on the bottom was implemented to promote effective drainage. The module was divided in three sections: section A, containing substrates without contact with the atmosphere, enclosed in a plastic liner and plywood walls; sections B and C, where the substrate is in contact with the atmosphere, enclosed by a polyester/PVC geotextile grid and supported by a steel grid. Only section C had plants and all the sections received the same flow frequency and volume doses. Regarding total phosphorus (TP) and total nitrogen (TN) removal, no variations were observed between the sections A, B and C. In fact, Svete [45] suggests that the diffusion of oxygen from the atmosphere may not significantly influence the aeration of the system and consequently did not influence the nitrification process.

The results showed high removal of TP and TN, in comparison with the expected treatment performance for biological greywater filters in Norway, ranging in the

sections, respectively, between 69%–71% and 31%–34%. According to Svete [45], the high removal of TP may be associated to the adsorption capacity of the expanded clay. However, a pattern of nitrate accumulation at 1 m depth was also evident for all the sections. According to the author, "this is most likely due to suppression of nitrification at the surface of the filter caused by high organic loading." These results may also suggest that the structure design and operation factors, such as volume dose and frequency of application, lead to limited saturated conditions in the filter bed. This may have a reduced denitrification in the system, promoting the accumulation of nitrates and increasing the nitrification process among depth layers. In addition, the system showed high efficiency at removing BOD_5 (95%–98%), which perhaps limited the availability of organic carbon needed for denitrification. This lack of organic carbon availability also may be related to the fact that the filter media is not organic and the exudates of plants roots were not sufficient.

Fowdar et al. [46] used the background of wetlands and storm biological filters as a reference for the LW design. The structure designed was mainly based on a planted vertical biological filter (Ø 240 mm columns) filled with substrates (washed sand, coarse sand and gravel), where the greywater percolates vertically. Moreover, Fowdar et al. [46] proposed a design, which integrates a saturation zone in the bottom of the structure in order to improve the removal of nitrates by denitrification, a fact which was the biggest limitation of Svete [45] design, according to the results mentioned above. The saturation zone proposed by Fowdar et al. [46] was created by elevating the outlet pipe at 0.16 m and using panels in the bottom of the cylindrical structure, instead of an outlet pipe at 0.30 m and layers of washed sand with carbon, course sand and gravel, which is normally used for stormwater biological filters.

This publication is the first research, which combines different design parameters such as vegetation (climber and non-climbers), saturation zones (standard of stormwater biofiltration and novel design), inflow concentrations (standard and 2× standard) and operation factors such as loading rates (0.11 m/d and low 0.055 m/d) and dose–frequency (five times per week and a resting period of 2.5 weeks). In addition, the author made infiltration rate tests in order to access the hydraulic performance of the system.

The results showed high biochemical oxygen demand (BOD) removal (96%–99%) for all experimental configurations, however, some treatments showed low removal of TN. For example, *Phragmites australis* and *Strelitzia reginae* presented TN removal of 7% and 23%, respectively, lower than the non-vegetated treatment (control 36%). The lower performance of *P. australis* was related to the attachment of aphids. *S. reginae* showed lower development under the system conditions. This result may suggest that the removal by process not related to uptake, such as, adsorption and microbiological degradation are important in these systems. Moreover, plant health and adaptation to the system conditions may influence in its ability on up taking contaminants.

Additionally, it was observed that both species and the non-vegetated treatment showed an accumulation of NO_x, suggesting that the denitrification was limited. The denitrification efficiency depends on the presence of denitrifying bacteria, carbon availability and under anoxic conditions.

In this sense, two aspects should be highlighted. First, the only carbon source was provided by wastewater, a fact which associated with a high removal of BOD may lead to a limited availability of organic carbon for denitrification. Second, the author suggests a preferential degradation of organic matter in the upper layers and low availability of organic carbon in the bottom-saturated layers where the denitrification is expected to happen. Therefore, the allocation of organic substrate in the saturated layer could help to solve the lack of organic carbon required to complete the denitrification process.

The TP removal (%) was lower than TN removal (%), regardless of the configurations used, mainly due to the low capacity of sand on adsorbing phosphorus, a lower phosphorus than nitrogen plant uptake, the release of organic phosphorus from exudates and solid particles of roots and the fact that adsorption of phosphorus is usually temporary. Both, the saturated zone designed by Fowdar et al. [46] and the standard saturated zone showed good results at removing nitrogen and phosphorus. However, Fowdar et al. [46], concluded that the design with the novel saturated zone seemed to be more aerobic than the design with standard saturated zone, as the concentration of NH_4–N in the effluent was always lower in the novel design.

In relation to the system operation, some configurations using a low hydraulic loading rate (HLR) increased TN and TP removal, which according to Fowdar et al. [46] indicates that increasing retention time promotes further processing of the nutrients. Moreover, ambient temperature influences the infiltration rates, being lower during colder months compared with warmer months. The author attributed this behavior mainly to the effect of temperature on water viscosity. Moreover, the infiltration rates were also increased by the implementation of one rest period of 2.5 weeks, mainly because of the reduction of substrate moisture and the reestablishment of the macropores structure. According to Kadlec and Wallace [49] and Knowles et al. [50], resting intervals between loading periods are necessary in order to control the accumulation of solids and to avoid clogging problems.

Masi et al. [47] proposed the use of a vertical LW for the treatment of greywater in a building. The design consists in 6 pots for each column and 12 pots in a row (12 × 6 pots matrix) planted with several plant species. The greywater collected from the building feeds the vertical garden though perforated pipes and the water flow is carried by gravity to the bottom, where it is collected and reused for garden irrigation. The author compared the influence of coconut and sand, both mixed with light expanded clay aggregates (LECA) on the removal of pollutants.

The LECA with coconut and LECA with sand treatments showed a NH_4^+–N removal of 19.4% and 70%, respectively. However, a significant increase of total Kjeldahl nitrogen was also observed in the effluent of coconut treatment, which was probably related to the release of organic nitrogen from the substrate. In addition, the retention time of LECA with coconut was approximately three times bigger than LECA with sand, fact which besides favoring the release of organic compounds also may increase saturation among layers, and limit nitrification. On the other hand, the sand treatment showed a higher removal of NH_4^+–N, fact which may be related to lower input of organic nitrogen, once the substrate is mineral,

and the aerobic conditions favoured by the use of sand which has higher hydraulic conductivity than coconut. These results highlight the importance of considering the allocation of an appropriate substrate during the design process. In other words, if the main goal of the system is to increase the removal of NH_4^+–N, one alternative could be just to use mineral substrates, design structures and operation strategies capable of improving the aeration of the system. No results on nitrates or phosphorus were discussed in this paper.

Wolcott et al. [48] proposes the design of a modular LW to treat wastewater from beverage manufacturers. The modules were made by aluminum panels (0.61 m × 0.61 m × 0.1 m). Each module was divided in 24 small cells (0.1 m × 0.15 m × 0.1 m) made by packets of fiber-glass and filled with substrate. This author compared the performance on the following scenarios: substrate only (S), substrate with plants (S + P), substrate with biofilm (S + B) and substrate with plants and biofilm (S + P + B). The substrate used was recycled glass beads. The modules were continually fed with wastewater with the same flow rate in all scenarios resulting in a 354 m/d HLR. The HLR proposed by this author was much higher than Fowdar et al. [46] recommendation of 0.055 m/d and HLR used by Svete [45], which was 0.67 m/d. According to Wolcott et al. [48], the increment in the HLR could be achieved by treatment length increase, which could favourably affect detention time. However, no data validated this hypothesis.

The scenarios S and S+P+B showed, respectively, highest (28%) and lowest (12%) removal of phosphorus. These results highlight that the removal of phosphorus was mainly related to substrate adsorption. Indeed, a strong limitation on phosphorus removal was directly associated with the development of biofilm due to the loss of specific surface for adsorption. The removal of TN after 24 h varied between 25% and 56% for, S + P + B and S + B, respectively. According to the author, the plants uptake did not seem to play an important role in the removal of nitrogen for this experiment. No data about nitrates and ammonium concentrations were discussed.

2.2. Main research achievements

The previous results highlight the importance of optimizing removal processes by (i) selection of appropriate substrates as well as its placement in the system, (ii) sustainable hydraulic design and (iii) setting the most favorable operation strategies.

Considering that LWs are supposed to run all over the year, it is important to consider strategies to avoid the loss of hydraulic conductivity among the filter bed to ensure the long term sustainability of the system. The clogging of porous media is mainly caused by suspended solids (mineral and organic), accumulation of organic matter (biofilm) and chemical precipitation [50,51]. In this sense, physical properties of the porous media may play an important role, which regards reducing the problem of clogging and losses in hydraulic conductivity. According to Kadlec and Wallace [49] and Knowles et al. [50], particle diameter, distribution, shape, arrangement and bed total porosity are important parameters, which regard the influence of porous media on the hydraulic conductivity of the system. Therefore, the selection of a proper particle size may play an important role, to ensure the systems hydraulic conductivity.

Smaller particle sizes may favour the development of higher biofilm quantity due to the larger available surface and are more effective in regards of the interception of suspended solids with narrower pore diameters [50]. On the other hand, grain size and hydraulic conductivity increase proportionally, the larger the grain size, the higher the hydraulic conductivity (Fig. 2.20 in [49]). Therefore, substrates with larger granulometry may avoid hydraulic conductivity loss over time or at least maintain it. However, the use of bigger particle sizes can also lead to a reduction of the adsorption properties of the material, less biofilm surface area and lower retention time. Therefore, the particle size of the substrate must be taken into account to find the best balance between suitable hydraulics and increased biofilm activity and consequent removal processes.

Considering that the adsorption is a temporary and saturated process, the use of substrates to optimize phosphorus removal by precipitation with Fe, Al, Mg and Ca may be an alternative to overcome the losses of adsorption implied by using bigger particle sizes. On the other hand, a couple of designs showed limited TN removal, mainly related to the denitrification process, suggesting the absence of appropriate anoxic condition and/or availability or organic carbon. Therefore, another strategy to be considered is selecting filter media, not just by its ability to adsorb pollutants but, at the same time, by its ability on providing organic carbon and allocating it to the proper places for enhancing denitrification. Therefore, the use of a mixture of organic and mineral materials rich in Ca, Fe Al and Mg to enhance denitrification of nitrogen and precipitation of phosphorus, may be considered as a viable alternative to increase the range of removal process in the system. However, according to Masi et al. [47] results, the use of organic substrate may lead to an increase of total Kjeldahl nitrogen. Therefore, studies on the combination of organic and mineral substrates, assessment of proper particle size and its allocation in the system may be an interesting line of research, which relates to enhancing removal of nitrogen and phosphates and reducing issues related to losses on hydraulic conductivity.

On the other hand, Svete [45] highlights that one of the main concerns related to the performance of these treatments is the lower area available in comparison with other conventional wastewater treatments. This author applied 0.360 m³/d and the module occupied a vertical area of approximately 2.34 m². On the other hand, Fowdar et al. [46] applied 0.0025 m³/d (considering HLR of 0.055 m/d) and the module occupied a vertical area of 0.192 m². Thus, the relation between hydraulic load and vertical area occupied is 0.153 m³/m²/d [45] and 0.013 m³/m²/d [46]. However, the system proposed by Fowdar et al. [46] showed a maximum TN removal of 92% while Svete [45] system showed a TN removal ranging 31%–34%. Therefore, it is possible to conclude that the assessment of optimum HLRs may play an important role concerning taking maximum advantage of the vertical space available on urban facades.

Regarding the plants used, Table 1 shows different species that have been used, such as ornamental flowers and climbers [46], agricultural species [45] and ornamentals [47,48]. However, none of the authors described the methodology used for plant selection. According to Raji et al. [28],

Table 1
Main design parameters and results on nitrogen and phosphorus removal provided by LWs wastewater treatments

	Authors			
	Svete [45]	Fowdar et al. [46]	Masi et al. [47]	Wolcott et al. [48]
Wastewater	Greywater	Greywater	Greywater	Brewery wastewater
Irrigation	Drip irrigation: spray nozzles and timer		Drip irrigation: timer-based solenoid valve and perforated pipe	Drip irrigation: perforated pipe (gravity flow)
Plants	Lettuce, marigolds	*Strelitzia nicolai, Phormium* spp. Canna *lilies, Strelitzia reginae, Lonicera japonica, Carex appressa, Phragmites australis, Vitis vinifera, Parthenocissus tricuspidata, Pandorea jasminoides, Billardiera scandens*	*Abelia, Wedelia, Portulaca, Alternanthera, Duranta, Hemigraphis*	*Golden pothos, Epipremnum aureum*
Substrate	Lightweight expanded clay	Sand, coarse sand, gravel	Coconut shell, light expanded clay, sand	Lightweight expanded clay and recycled glass beads
Operational factors	D: 0.36 m³/d HLR: 0.67 m/d RT (NaCl): 29,880 s	D: standard 0.005 m³/d Low 0.0025 m³/d HLR: standard (0.1 m/d) low (0.055 m/d) HRT: standard = 172,800 s Low: 345,600 s IR: 626.4–2,170.8 m/s		HLR: 354 m/d
Ranges of N removal[a]	NO_3^-: 0.2–6.2 mg/L TN: 31%–34%	TN: 7%–92% NO_x: 0.001–4.20 mg/L NH_3^+: 0.001–0.35 mg/L	NH_4^+-N: 1–1.9 mg/L TKN: 5–7.3 mg/L	TN: 25%–56%
Ranges of P removal[a]	TP (aeration sections): 95%–98%	TP: 7%–85% FRP: 8%–87%		TP: 12%–28%

[a]Removal percentage (%) or concentration in the effluent (mg/L). D: doses; HLR: hydraulic loading rate; HRT: hydraulic retention time; RT: retention time using tracer; IR: infiltration rate; TN: total nitrogen; TKN: total Kjeldahl nitrogen; NO_x: nitrites and nitrates; TP: total phosphorus and FRP: filterable reactive phosphorus.

LWs can support a large variety of plants, such as ferns, small shrubs and perennial flowers but ornamental species were usually utilized. However, recently the use of native plants has been recommended because of the biodiversity value assigned. Moreover, the use of native species can be an environmentally friendly choice mainly for its adaptation related to weather conditions and capacity of reconciling anthropogenic development and natural environment.

All the information discussed above leads to four main concerns in the field of designing LWs optimized for nitrogen and phosphorus removal from wastewaters. First, how to ensure desired unsaturated and saturated conditions required for both nitrification and denitrification processes. Second, how to enhance nitrogen removal by microbiological means without reducing phosphorus removal by adsorption. Third, how to ensure enough carbon availability to complete denitrification requirements and fourth, how to overcome the issue related with the reduced area available for this kind of treatment.

In this regard, the WETWALL design concept first aims to ensure appropriate conditions for nitrification and denitrification through the development of structures, which replicate the CW hybrid flow in a modular LW structure: a novel concept of modular LW hybrid flow, which is separated in two independent structures. Second, the WETWALL design concept proposes a methodology for plant and substrate selection and allocation, in order to ensure system efficiency at removing nitrogen and phosphorus. Third, the WETWALL concept design proposes an innovative water recirculation approach, which besides ensuring an intermittently flow, also increases the retention time through the establishment of treatment cycles; which may be an alternative to overcome the issue related to reduction of treatment area in comparison with conventional treatments.

3. WETWALL design

There is no terminology to define lLWs as wastewater treatment. Therefore, the terminology of WETWALL was proposed, since the design concept is mainly based on the combination of a constructed WETland hybrid flow

with a modular living WALL structure, creating an innovative modular LW hybrid flow. The design proposed by Fowdar et al. [46], intend to promote anoxic and aerobic conditions as well. However, the author design aims to promote these different conditions in the same structure by elevating the outlet and creating a saturated layer at the bottom of the vertical pipe used as a support for plants and substrate. For the best of our knowledge there is no similar LW, in the scope of wastewater treatment that integrates two separated types of treatment in a modular LW.

In addition, to the best of our knowledge, a design concept for LWs treating wastewaters, which proposes a selection methodology for plants and substrates, as well the integration of circular economy principles into the design process, does not exist in the current literature. Therefore, in this section, the methodology to select plants and substrates, the modular LW hybrid flow, the operation strategies and the integration of circular economy principles into the design concept, are presented and described.

3.1. Plant selection

The plants can play an important role in the scope of LWs treating wastewaters not just by direct pollutant uptake or promoting microbial activity, but also in ensuring the acceptation and implementation of this kind of technology in urban areas. However, due to the novelty of this research field, there is no methodology available to select the plants. Most of the authors used ornamental [46–48] or crop species [45] in their works. However, no parameters of selection were discussed. Therefore, the WETWALL design concept brings several prerogatives for the selection of plants, which mainly takes into account three key aspects: adaptation to the system, ecosystem services and social acceptance.

Moreover, the results of Wang et al. [52] suggest that the use of three to four different plant species in CWs may increase the removal of TN in wastewater. In addition, the use of more than one species may avoid issues related to pests and phytodiseases, once increases the biodiversity of the system. Therefore, the WETWALL design concept proposes the selection of a minimum of three native species according to the following prerogatives (Table 2):

(a) *Adaptation*: A candidate species must be adaptable to the system conditions such as weather, high moisture, limited space for root development (modular structure), high solar incidence and high concentrations of contaminants (salts, nitrates, phosphates among others – depending

on the type of wastewater to be treated). Species must be resistant or not susceptible to existing diseases and plagues in the implementation area.

(b) *Ecosystem services*: The species must be capable of providing ecosystem services such as uptake of contaminants and high evapotranspiration rates, to ensure high performance in cleaning the water and providing the cooling effect. Moreover, the ability of the species, regarding the reduction of greenhouse gases in the atmosphere, must be taken into account to increase air quality and reduce the greenhouse effects.

(c) *Social acceptance*: Considering the acceptance of society, the species selected should provide a social benefit, for example medicinal properties, agriculture value and good aesthetic appearance. The use of agricultural species can be an option, however, restrictions and legislation related to the irrigation of crops with wastewater must be considered. Indeed, species with a good aesthetic appearance provide welfare and acceptance, fact which is important considering large scale acceptance and implementation.

It is expected that plant selection success will depend on the information available and on the number of prerogatives filled (Table 2). The A and B prerogatives are related to the system performance, treating water and providing thermal insulation. The C prerogative aims to promote the integration of technology with the urban environment, anticipating possible issues regarding social acceptance. In addition, the C prerogative brings the circular economy principle of connecting production chains. However, in this particular case, connecting a wastewater treatment (WETWALL design concept) with other production chains, such as food sector, pharmaceutical and landscape industry.

3.2. Substrate selection

The selection of appropriate substrates and their location in the system is fundamental to guarantee the efficiency of wastewater treatments based on the replication of natural processes. Growing media for modular LWs systems is usually based on a mixture of lightweight substrate with granular material [37] while the commonly used filter media in CWs are sand and gravel [53]. In the scope of LWs treating wastewater, most authors [45–48] have been using substrates such as gravel, sand and lightweight expanded clay, which are materials frequently used in similar biological treatments such as biological filters

Table 2
WETWALL design concept – prerogatives for the selection of native species

(a) Adaptation	(b) Ecosystem services	(c) Social acceptance
Adaptable to weather changes	High uptake of nitrates and phosphates	Medicinal plants
Tolerant to high moisture	High evapotranspiration	Agriculture species
Tolerant to high solar radiation	Carbon sequestration	Aesthetics appearance
Restricted roots grown		
Tolerant to high concentrations of contaminants		
Resistance to diseases and plagues		

and CWs. However, considering the novelty of this field, it is important to establish adequate criteria for appropriate filter media selection, to ensure system hydraulic operation and pollutant removal efficiency.

The main requirements of LWs, regarding substrates, are related to light weightiness, water retention and capacity to support plant growth. The substrate, besides being support for plant growth, must be lightweight in order to reduce the total weight of the structure and to facilitate the implementation in external facades. Finally, the water retention capacity plays an important role for plants maintaining and incrementing the cooling effect by water evaporation. On the other hand, substrates ability on pollutants removal from wastewater is mainly related to exchange, adsorption, precipitation and complexation [35]. However, in the scope of CWs, usually the selection of substrates must prioritize good hydraulic behaviour and adsorption ability, in order to avoid clogging and enhancing pollutants removal by adsorption [54].

In the scope of LW for wastewater treatment, Sakkas [44] suggested the use of expanded clay aggregate (ECA) and glass foam gravel as substrate based on the following criteria: high water treatment efficiency, low weight/bulk density, low environmental burden and good structural behaviour. However, that selection is contradictory, since the production of ECA demands high energy, which leads to a high environmental burden and not much is known about the adsorption properties of recycled foam glass gravel. Prodanovic et al. [55] selected organic and mineral materials based on physical and chemical properties such as weight, water retention, capacity for nutrients adsorption, porosity, sustainability and local availability. However, none of the papers discussed in the state of the art proposes selection criteria, they only deal about the features of the substrate selected or describe the parameters used [45 -48]. None of the authors considered the parameters such as organic carbon, Fe, Al, Mg and Ca in the selection procedure. Considering that, the adsorption of materials usually reduces with time [53], and that uptake varies according to species and physiologic stages, these features can play an important role at providing conditions to increase the

range of removal processes, such as denitrification and phosphorus precipitation.

The removal of nitrogen is mainly performed by microorganisms through denitrification and microbiological degradation, processes which are highly dependent on anoxic conditions and organic carbon availability [36,56]. Moreover, taking CW as a reference, it is possible to predict that the precipitation and adsorption of phosphorus are higher under saturated conditions because of the low fluctuation in redox potential [35]. Therefore, the selection of materials rich in Fe, Al, Mg, Ca and organic carbon and its allocation under anoxic zones could increase phosphorous removal by precipitation and nitrogen removal by microbiological degradation (denitrification) in LWs systems.

In addition, the reuse of waste/by-products as filter media is an alternative to reduce cost, minimize extraction of non-renewable raw materials, promote energy saving and reduce the generation of waste and CO_2 emissions [57,58]. A couple of authors proposed the use of waste materials as substrates in LWs for wastewater treatments [47,48], however, not as a part of the selection process, where the substrate needs to fulfil a series of parameters in a certain order. In that sense, the WETWALL design concept proposes a selection, which is mainly based on selecting local waste/by-products, with good hydraulic conductivity, light weightiness, high adsorption of contaminants, potential to release organic carbon and rich in Fe, Al, Ca and Mg. Water retention capacity was not considered, since the design concept suggests water recirculation as an alternative to overcome the limitation regarding the area available (facades). More details about the water recirculation proposed by the design concept will be discussed in section 3.4.

However, the selection of a material, which can fit in all the criteria mentioned above, was not considered feasible. Therefore, the selection process is focused in selecting one organic filter media to ensure organic carbon availability so that the denitrification process takes place and one mineral filter media to potentiate the adsorption and precipitation of phosphorus. Considering the information mentioned above, the selection process is based on three stages (Table 3).

Table 3
WETWALL design concept – stages and parameters suggested for the selection of filter media

Selection stages	Parameters	Selection parameters	
		Filter media A	Filter media B
(a)	Waste origin	Organic	Mineral
	Lightweight	Yes	Yes
	Pollutants	NO	NO
	Diameter	$1 < \varnothing < 20$	$1 < \varnothing < 20$
	Energy and CO_2 embodied	Lowest	Lowest
(b) and (c)	Infiltration rate (mm/h) or hydraulic conductivity (m/s)	Highest	Highest
	Organic carbon (C:N)	Minimum 2:1	
	Fe, Al, Ca and Mg (mg/g)		Highest
	Adsorption of NO_3^-–N[a]	Highest	Highest
	Adsorption of PO_4^{3-}–P[a]	Highest	Highest

[a]Flexible parameters: Filter media A and B does not necessarily need to fulfil both parameters at the same time.

(a) *Pre-selection*: List of potential waste materials or byproducts available in the implementation area, considering the following criteria: organic and mineral materials, light weightiness, free of pollutants (heavy metals, pesticides and herbicides, among others), low energy and CO_2 emissions embodied. Recommended particle size: 1–20 mm (adapted from [54]). The allocation of filter media is done considering the goal for each designed water flow, in order to ensure appropriate conditions for nitrogen and phosphorus removal. The allocation of filter media will be discussed in sections 3.3.1 and 3.3.2.

(b) *Materials characterization*: The characterization can be done based on available literature information or laboratory analysis. The main parameters suggested are hydraulics (hydraulic conductivity m/s or infiltration rate mm/h), concentration of Fe, Al, Ca and Mg, C:N ratio and adsorption ability (NO_3–N, PO_4^{3-}–P).

(c) *Final selection*: The goal is to select materials by comparison, considering the following parameters: good hydraulic behaviour, capable to release organic carbon and to enhance precipitation of phosphorus and high adsorption of nitrates and phosphates. The comparison must be between materials with same origin (mineral or organic). First, regarding the hydraulic operation, organic and mineral materials with the highest infiltration rate (mm/h) or hydraulic conductivity (m/s) should be selected in order to reduce risk of clogging and reduce maintenance costs. With regards to phosphorus removal by precipitation, the concentration of Fe, Al Ca, Mg of mineral materials should be the highest as well. In order to select a material with potential on releasing organic carbon, the C:N ratio should be considered. The recommended C:N ratios may vary depending on the type of system, type of wastewater and organic source. For example, Hang et al. [59] recommended C:N ratios of at least 4:5 and 1.8:3.0 for CWs and bioreactor, respectively. Park et al. [14] results showed the maximum removal of nitrogen at 2:1 ratio. Considering the novelty of LWs in the scope of treating wastewater, materials with a minimum C:N ratio of 2:1 is suggested. Regarding the removal of contaminants by adsorption, the comparison should select organic and mineral materials with highest adsorption of nitrates and phosphates. However, it is important to highlight that these are flexible parameters. The material with the highest adsorption of nitrates may not be the material with highest phosphates adsorption. Therefore, each filter media organic and mineral, must fulfil at least one of the flexible parameters (adsorption of NO_3–N and/or PO_4^{3-}-P) as long as the other material fulfill the remaining flexible parameters.

3.3. Innovative living wall hybrid flow

Hydroponic wastewater and greywaters have different characteristics (Table 4). On one hand, hydroponic wastewater has high concentrations of nitrates and ammonium and low organic matter while greywaters have a high concentration of organic matter and phosphates and a low concentration of nitrates. Therefore, in order to design a LW, which can cope with a bigger range of urban wastewater types, a hybrid flow is proposed. The design is mainly based on the prerogatives of a CWs subsurface hybrid flow.

Hybrid systems include the advantage of combining horizontal flow (HF) and vertical flow (VF), providing different redox environments, which can significantly improve the conditions needed for nitrification and denitrification processes, adsorption and precipitation of phosphorus and removal of organic matter. The VF bring aerobic conditions needed to remove ammonia–N by nitrification/volatilization and BOD_5 by bacterial oxidation, while HF bring anaerobic conditions which increases the removal of nitrogen and phosphorus, through denitrification and precipitation [35,56]. According to Vymazal [35] HF systems have higher potential to promote adsorption and precipitation of phosphorus because of the low fluctuation in redox potential (anaerobic conditions) while the aerobic conditions of VF systems may cause desorption and release of phosphorus.

Therefore, the main goal of the LW hybrid flow is the enhancement of aerobic conditions of VF and anoxic conditions through the HF, in order to enhance the contaminants removal from urban wastewater such as, greywaters and hydroponic wastewaters. For the treatment of greywater, the VF aims to remove BOD5 (biological oxidation), while the HF aims to remove phosphates (precipitations and adsorption).

On the other hand, for the treatment of hydroponic wastewater, the VF aims to remove ammonium, while the HF aims to remove nitrates (denitrification) and phosphates (precipitations and adsorption). It is important to highlight that the proposed hybrid flow is a design concept based mainly on the oxygen conditions. However, other aspects such as, pH, biofilm and temperature, among others, may influence the removal process as well.

Table 4
Typical composition of hydroponic wastewater and greywaters (adapted from 4, 11–14, 60–63)

Compounds	Hydroponic wastewater		Greywater	
	Minimum	Maximum	Minimum	Maximum
	mg/L			
NO_3^-–N	10	414	0	6.3
NH_4^+–N	0.8	36	0.002	25
PO_4^{3-}–P	0.8	60	1	170
BOD	9	12	5	890

NO_3^-–N: nitrate–nitrogen; NH_4^+–N: ammonia–nitrogen; PO_4^{3-}–P: phosphate–phosphorus and BOD: biological oxygen demand.

3.3.1. Subsurface vertical flow

Subsurface VF consists of a planted bed filled with porous media, where the wastewater flows vertically [56,64]. Several methods have been proposed in order to improve the aeration of subsurface flow [65,66]. However, artificial aeration usually requires energy inputs and additional costs [65]. Therefore, in the WETWALL concept, the vertical subsurface flow was designed to enhance the aeration of the bed during the gravity drainage to tackle the removal of BOD_5, the nitrification of ammonium and the plants uptake (nitrogen and phosphorus). The main considered assumptions were the following ones (Fig. 1):

(a) *Vertical drainage* (Fig. 1 – a_1 and a_2): The inlet (Fig. 1 – a_1) and outlet (Fig. 1 – a_2) are located at different levels in order to promote vertical drainage.

(b) *Irrigation and overflow control* (Fig. 1 – b_1 and b_2): Drip irrigation is recommended in order to provide a homogeneous distribution of the flow among time and to avoid saturation on the first layers of substrate. The VF can be feed by compensate drippers or perforated pipe. The main advantage of using compensate drippers is the constant flow rate, however, the dripper can be easily clogged by solids particles, fact which will depend on the type of wastewater to be treated and on the secondary treatment used to remove total solids (Fig. 1 – b_1). Also, compensate dripper requires a minimum water pressure, fact which may be a limitation if the system is operating by gravity flow. On the other hand, the flow rate of perforated pipes varies according to the hydraulic head, however, clogging is not such a big concern. Therefore, the type of drip irrigation will depend on two main aspects: the presence
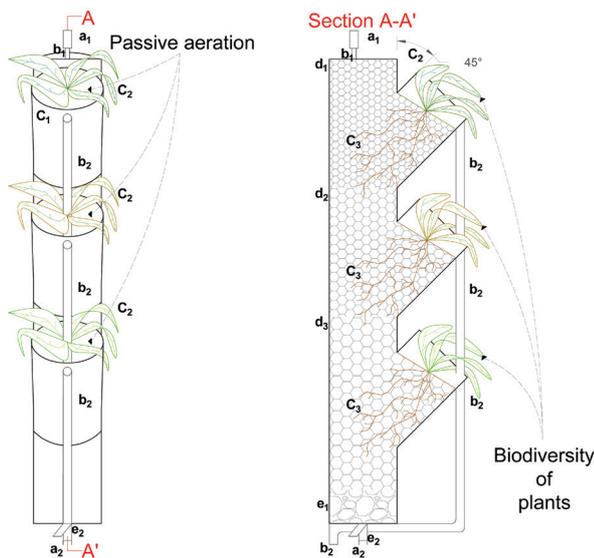
or absence of previous treatment to remove total solids and if the system will work by gravity flow or under pressured flow. A cascade overflow control is allocated along the VF in order to avoid saturated layers and to collect the overflow in cases of extreme rainfall (Fig. 1 – b_2). The overflow is discharged to a water reservoir.

(c) *Main structure features* (Fig. 1 – c_1, c_2 and c_3): The main structure of the VF is a filter column built from a cylindrical pipe (Fig. 1 – c_1). Additional pipes installed at 45° in order to support the plants and promote a passive diffusion of oxygen to the filter bed (Fig. 1 – c_2). Moreover, the distribution of plants among the column aims to enhance the contact of roots with the wastewater and facilitate the uptake of contaminants (Fig. 1 – c_3).

(d) *Filter media allocation* (Fig. 1 – d_1, d_2 and d_3): Since the main goal of VF is to reduce the organic load by oxidative processes and increase nitrification process, it is suggested that the use of mineral substrates to avoid the increment of organic load by the substrate. The mineral filter media is allocated all over the VF (Fig. 1 – d_1, d_2 and d_3). It is recommended to use three particle sizes distributed in three layers in order to enhance retention time and avoid saturation of the upper layers. The length of each layer will depend on the height of the treatment column. The substrate in the upper layers must have a smaller particle size than the lower layers.

(e) *Water collection and system maintenance* (Fig. 1 – e_1 and e_2): This drainage layer aims to avoid clogging and favours the gravity flow (Fig. 1 – e_1). The use of gravel with diameter ranging from 10 to 16 mm it is suggested. An external filter is allocated in the bottom in order to reduce the flow of sediments to the next treatment stage and to facilitate the maintenance of the system (Fig. 1 – e_2). This filter can be easily removed in case of system maintenance. It is expected that the reduction of the sediments flow will also reduce the potential of clogging (coming inlet zone).

3.3.2. Subsurface horizontal flow

In subsurface HF, the wastewater pass through substrate and go under the surface of the bed in a horizontal path, until it reaches the outlet zone, where it is collected for further recirculation or discharge [36]. Therefore, the WETWALL horizontal subsurface flow is designed to provide anoxic conditions among the filter bed and, therefore, enhance the removal of nitrogen by denitrification and phosphorus by precipitation. The main compounds and structures are explained below (Fig. 2):

(a) *Main structure functions* (Fig. 2 – a_1, a_2, a_3 and a_4): The main structure of the HF is cylindrical with a slope of 1% (Fig. 2). The inlet position is higher than the outlet (Fig. 2 – a_2). Therefore, besides providing anoxic conditions at a certain height, the design also gives a margin for water rise by capillarity, while avoiding dead zones. Moreover, there is a water level control, which is located at the same height as the inlet, to avoid overflow in case of rainfall (Fig. 2 – a_3). The plants are located all over the bed in order to increase the uptake of contaminants, mainly by ensuring the contact of roots with the subsurface water flow (Fig. 2 – a_4).

Fig. 1. WETWALL – vertical flow design. (a) Vertical drainage (a_1: inlet; a_2: outlet). (b) Irrigation and overflow control (b_1: drip irrigation – compensate drippers; b_2: cascade water level control). (c) Main structure features (c_1: filter column; c_2: plants support and passive aeration; c_3: roots contact with filter media and water). (d) Filter media allocation (d_1, d_2 and d_3: layers of mineral substrate). (e) Water collection and system maintenance (e_1: drainage layer; e_2: external filter).
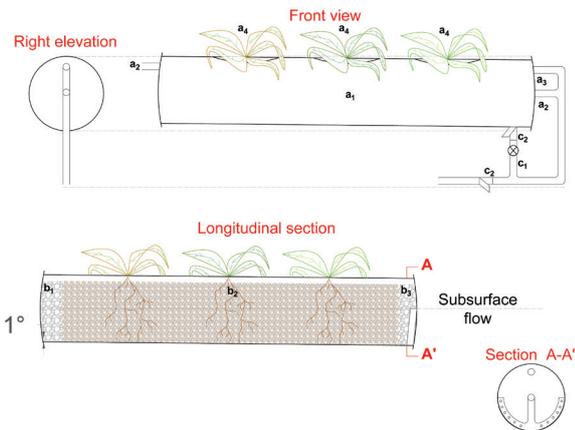
Fig. 2. WETWALL – horizontal flow design. (a) Main structure functions (a_1: main structure; a_2: inlet and outlet; a_3: water level control; a_4: plants location). (b) Filter media location (b_1: inlet layer – gravel; b_2: Mixture of mineral and organic media (1:1); b_3: outlet layer – gravel). (c) Water collection and system maintenance (Section A-A': water collection pipe; c_1: drainage; c_2: external filters).

(b) *Filter media allocation* (Fig. 2 – b_1, b_2 and b_3): The allocation of the substrates is divided into three main layers. Usually, in CWs HF, the clogging of the inlet area causes a great reduction of hydraulic conductivity [49]. Therefore, the design suggests the implementation of an inlet layer (Fig. 2 – b_1) filled with gravel (10 mm < Ø < 16 mm) in order to minimize inlet clogging effects. On the other hand, HFs require large amounts of organic carbon to promote denitrification and at the same time are quite efficient for the adsorption and precipitation of phosphorus [35]. Therefore, a layer composed by a mixture (1:1) of mineral media rich in Fe, Al, Ca and Mg with organic media (Fig. 2 – b_2) is proposed. In addition, as the WETWALL design concept aims to increase microbiological degradation of nitrogen and precipitation of phosphorus, fact which may lead to accumulation of solid particles, an outlet layer filled with gravel (10 mm < Ø < 16 mm) is proposed (Fig. 2 – b_3).

(c) *Water collection and system drainage* (Fig. 2 – c_1 and c_2): The wastewater is collected by an inverted T-pipe perforated, which is allocated at the end of the HF (Fig. 2 – section A-A'). A drainage pipe is located at the bottom of the HF, in order to facilitate the system's full drainage in case of maintenance (Fig. 2 – c_1). External filters are suggested in order to facilitate the maintenance and as well avoid clogging by reducing the sediments flow through treatment cycles (Fig. 2 – c_2).

3.4. Operations strategies and challenges

The implementation of NBS, such as CWs, is unfeasible at urban scale, mainly because of its large area requirement [64]. In this regard, the WETWALL design concept aims to give the urban environment a NBS, which can undertake available spaces of facades. However, one of the main concerns related to the efficiency of LWs treating wastewater at an urban scale, is the limited area available for its implementation. While the implementation of similar treatments, such as CWs, demands large areas, the blank spaces of vertical facades are limited.

Therefore, the WETWALL design concept proposes the recirculation of water in order to enhance the removal of nutrients through increasing the contact time between wastewater and the treatment surface. According to Wu et al. [64] water recirculation in VFs and hybrid CWs enhances the interactions between pollutants and microorganisms, which can increase treatment performance, as well as reducing the area requirement. However, the energy spent for pumping can be a limitation. Therefore, the use of two tanks (lower and upper) is proposed in order to minimize the operating time of the pump and save energy during the water recirculation. The pump only works the necessary time to raise the water to the upper tank and remains off until all the water flows through the system by gravity and a new water cycle starts.

On the other hand, VF CW must be intermittently fed to promote the drainage and diffusion of oxygen into the bed, providing suitable conditions for the nitrification process [36]. The intermittent flow is ensured by the establishment of "resting periods" between cycles of treatment to ensure the full drainage and passive aeration of the VF bed.

In addition, an integrated overflow control is proposed in order to facilitate the collection of rainwater. The overflow control of both, vertical and horizontal treatments (sections 3.3.1 and 3.3.2), are connected to the lower reservoir. The rainwater collected can be stored for further reuses.

Moreover, the WETWALL design concept brings the possibility of performing different configurations of water recirculation, which may play an important role, especially considering the adaptation of the system to different types of urban wastewater and different pollutant loads. Treatments using separate structures which can be combined differently were not found in the literature. All the papers discussed in the state of the art present one single main structure where the wastewater is treated. In this regard, the WETWALL design concept, can run as a hybrid flow (Fig. 3 – VF-HF, HF-VF, VF-HF and HF-VF) or just VF (Fig. 3 – VF) or just HF (Fig. 3 – HF).

However, a couple considerations regarding the WETWALL operation are important. First, it is expected that the number of treatment cycles will influence the treatment performance, once the contact time between wastewater and treatment surface increases. Second, the hydraulic load will influence the number of viable treatment cycles per day. Considering a constant flow rate (compensate drippers), the treatment cycles will be as long as the hydraulic load increases. Hence, accessing the optimum flow rate and hydraulic load is important to adapt the system to real scale, where a certain amount of wastewater is produced per day. Third, different resting periods between cycles may influence the system efficiency as well, mainly regarding the aeration of the VF. Fourth, it is expected that the number of treatment cycles needed will be as higher as loading rates of contaminants increases. Fifth, the hydraulic conductivity of the system will decrease with time affecting the retention time, fact which may influence treatment efficiency as well. Sixth, it is expected that the treatment configuration (Fig. 3), as well as the number of modules will vary in accordance to the wastewater features (pollutant loading) and the hydraulic load.

Horizontal Flow (HF)

Vertical Flow (VF)

Hybrid Flow (HF - VF)

Hybrid Flow (VF - HF)

Hybrid Flow (HF-VF and VF-HF)
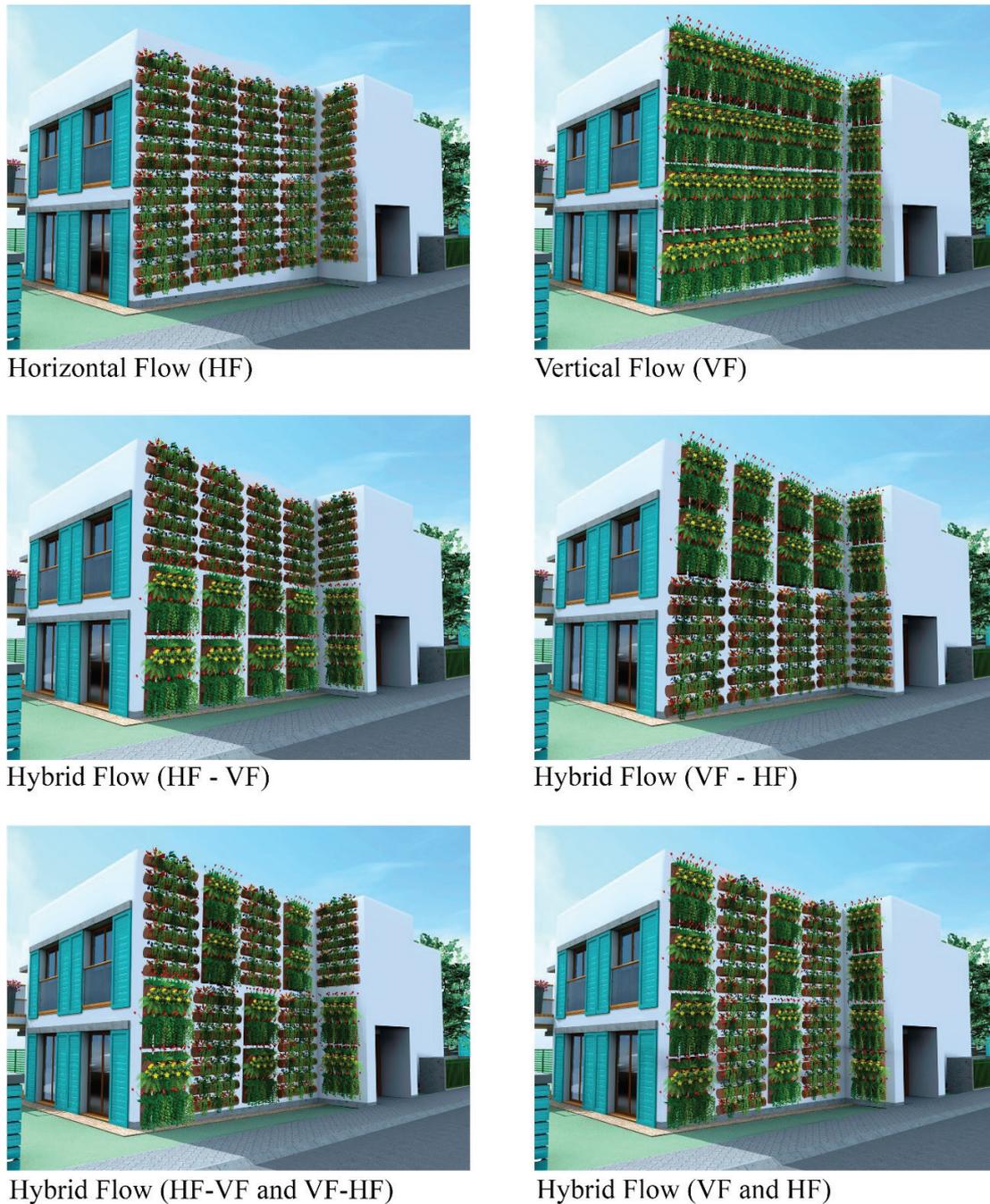

Hybrid Flow (VF and HF)

Fig. 3. The WETWALL design concept – possible treatment configurations.

Therefore, to ensure the validation of the WETWALL design concept and its implementations at real scale, further research on the relation between treatment configurations (Fig. 3), number of cycles, hydraulic load, hydraulic conductivity, resting periods and pollutant loadings is needed.

3.5. WETWALL and circular economy

In general, the production model currently widely used is based on the concept of "take-make-dispose" or "linear" model, in which the reuse of materials is not a concern, since the economic efficiency is achieved by using raw resources and exploiting natural environments [67,68]. Currently, the concept of linear production has been questioned, in order to rethink the optimization of waste management, through the integration of production chains.

In 2012, the European commission published a manifesto about resource use-efficiency, which stated as following: "In a world with growing pressures on resources and the environment, the EU has no choice but to go for the transition

to a resource efficient and ultimately regenerative circular economy" [69]. In this sense, the development of systems based on the principles of circular economy (reuse, recycling and reducing), plays an important role regarding the promotion of the efficient use of resources, reducing environmental costs, conserving raw materials, mitigating global warming, reducing greenhouse emissions and providing energy savings [57,68].

It is important to highlight that integrating technological development and the circular economy is more than just reusing materials. Moreover, considering the scope of water treatment designs, the initiatives are mainly focused on the efficiency of technological features and system performances. Technologies are developed primarily as individual systems and no account is taken for the interaction between them and the operating environment where they are introduced.

LWs provide a number of benefits; environmental, economic and social. Not just for the buildings, but also for all urban areas. Several authors have been showing the positive impact of promoting the reconciliation of the urban environment and natural habitats, with regards to promoting biodiversity, increasing the resilience ability of the cities and climate change mitigation [24,33,34]. The potential interactions between green technologies and the environment may represent an important role, regarding closing the "cycle" and promoting a sustainable technological development. Therefore, it was considered as part of the design process, the determination of possible interactions between the technology and the urban environment. Therefore, four main interactions are discussed below (Fig. 4):

(a) *Reusing wastewater → recycling water and nutrients* (Fig. 4 – a): Irrigating with wastewater a LW may overcome the biggest limitation, concerning the implementation of these green technologies at an urban scale: high water demand. An important step regarding social acceptance and integrating natural habitats into urban environment. Moreover, the treatment and reuse of wastewaters "in situ" promotes a sustainable recycling of water and nutrients (N and P) and the decentralization of water treatment. At the same time that the contaminants will be transformed and stored in the system (uptake of plants, adsorption of substrates and microbiological degradation), the water treated can be reused in accordance with international water quality standards. According to European Environment Agency [21], reusing wastewater is an important strategy to increase the efficient use of water resources and to decrease the use of drinking water for activities that do not demand drinking quality standards.

(b) *Reusing waste materials → recycling organic fertilizer* (Fig. 4 – b): The selection of local waste/by-products as filter media (section 3.2) aims to integrate local production chains, to reduce waste generation and withdrawal of raw materials. The reuse/recycling of local materials are important strategies with regards to minimizing extraction of non-renewable raw materials, promoting energy saving, reducing waste and CO_2 emissions and, therefore, promoting climate change mitigation [57,58,70]. The research of Manso and Castro-Gomes [37] shows that several authors have been using natural/recycled
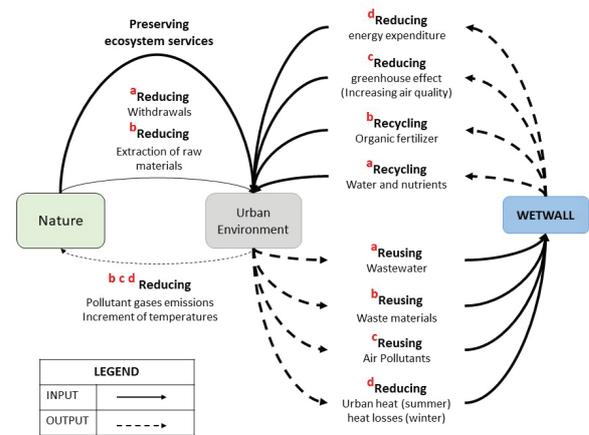

Fig. 4. Integration of circular economy principles of reusing, recycling and reducing into the design process. The letters are in accordance with the interactions discussed previously in this section.

materials and integrating water recovery systems in order to provide a sustainable implementation of this kind of technology at an urban scale. The WETWALL design concept suggests the recovery and further reuse of nutrients (wastewaters). The substrates and plants can be reused as fertilizer for local urban crops, creating short distances between the provider (WETWALL) and consumers (local agriculture). Recovering these nutrients, reusing them instead of keep producing, can be a sustainable way to reduce the impacts caused by the production of chemical fertilizers and by their accumulation in the environment. Moreover, giving a new application to the "waste" generated by the treatment besides reducing the economic costs by subsidising maintenance costs also may encourage technology acceptance. However, it should be considered that depending on the wastewater treated, the presence of contaminants such as pesticides, heavy metals and pathogens, might represent a challenge on reusing this material as fertilizer.

(c) *Reusing air pollutants → providing air quality → reducing greenhouse effect* (Fig. 4 – c): According to Szulejko et al. [71], the highest level of global warming was achieved in 2015, mainly due to the increment of greenhouse gases emissions. In this regard, LWs are able to create a new profile of urban areas in accordance to nature, improving air quality, mainly through reducing pollutant levels, absorbing fine dust particles and increasing atmospheric oxygen [30,40]. The research developed by Marchi et al. [30] provided evidence of carbon sequestration promoted by LWs. The author's results showed that "CO_2 uptake by plant biomass of 0.44 – 3.18 kg CO_2 eqm–2 of vertical garden per year." Therefore, the WETWALL design concept aims to promote the reuse of pollutant gases, in order to improve air quality and reduce the greenhouse effect. However, it is important to highlight that the performance of such system is intrinsically related to the capacity of plants at up taking CO_2 and others pollutants.

(d) *Reducing urban heat (summer)/heat losses (winter) → reducing energy expenditure* (Fig. 4 – d): LWs as a part of innovative

green infrastructure can provide multiple functions in the scope of thermal maintenance and energy savings [29,31,72]. Vertical greening systems are efficient at providing cooling and heating effects on the building's surface, which can significantly increase energy savings for buildings and the urban environment. The evapotranspiration of plants and substrate provides the cooling effect on the building's surface, which is very important during summer. The reduction of indoor temperatures during summer leads to a reduction in the use of air conditioning and increases energy savings [28]. Results of Stec et al. [73] showed that the use of certain plants inside a facade cavity can reduce energy requirement for air-conditioning systems by 20%. On the other hand, during winter the surface covered by the plants can work as an external insulation layer and avoid heat loss. Results from Tudiwer and Korjenic [39] suggest the use of the greening system on building facades, leads to a lower heat demand during winter. However, it is important to highlight that each greening system has different performances regarding cooling and heating effects. Evaporation rates (pants and substrates), thermal features of the structure materials, orientation and weather conditions are important factors regarding the thermal performance of LWs.

4. Conclusions

Currently, the number of studies on the performance of LWs treating urban wastewater has been increasing. Mainly because of their potential for decentralizing wastewater treatments and their properties that can provide thermal insulation, both facts which may have a positive impact on climate change adaptation. However, it was observed that a wide diversity related to design parameters for LWs, such as structures, operational factors, plants and substrates, are hindering the establishment of standards. Indeed, operational factors such as HLRs and retention time seem to be dependent on each design. Hence, the assessment of optimum operational factors is crucial to ensure high pollutants removal and an efficient use of vertical spaces.

The removal of nitrogen and phosphorus in these systems are mainly related to microbiological degradation, plant uptake and filter media adsorption. In this sense, it was noticed that the development of biofilm is an advantage for nitrogen removal by microbiological process. On the other hand, the biofilm development was also associated with the decrease in the adsorption of phosphorus. This fact highlights the importance of selecting the appropriate substrates and plants, as well as their allocation, in order to ensure optimum conditions for adsorption, microbiological degradation and plant uptake. Some systems showed limitations on the nitrogen removal, related to low availability of carbon and/or limitation on saturated or unsaturated conditions. Therefore, the design should favour the requirements for microbiological degradation of nitrogen, which are aerobic for nitrification and anoxic conditions with availability of organic carbon for denitrification.

In this regard, the WETWALL design concept proposes a novel design in the scope of LWs as wastewater treatment, which brings a modular LW hybrid flow that is mainly based on the integration of CWs hybrid flow into a modular modular LW structure. This design aims to provide saturated and unsaturated conditions (two separated structures), in order to enhance nitrification and denitrification. Furthermore, a selection procedure of plants and substrates, which aims to enhance the removal of contaminants, good thermal and hydraulic performances and social acceptance, is proposed. The selection of substrates highlights the importance of selecting organic and mineral materials, in order to provide sustainable conditions for denitrification and precipitation of phosphorus. The allocation and proportion of these materials in the system can be as important as selecting the appropriate materials. Moreover, it is suggested that water recirculation, in accordance with an intermittent flow, could be an alternative to overcome the issue related with the area available to the treatment.

The WETWALL can be adapted to different urban environments, since it is modular and the species and substrates are selected in accordance with the implementation area. Moreover, the design concept proposed in this article highlights the importance of taking into account the potential interactions between the technology and the urban environment. The relevance of WETWALL designing concept, regarding climate mitigation, is fomented by the sustainable reconciliation between technological development and natural habitats proposed mainly through the replication of natural processes and reusing resources such as water, nutrients, materials and energy. This article was a theoretical discussion on the innovation proposed by the WETWALL design concept, however, further research on its validation and adaptation to real scale is needed.

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