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Experimental analysis to assess the hydrological efficiency and the nutrient leaching behavior of a new green wall system

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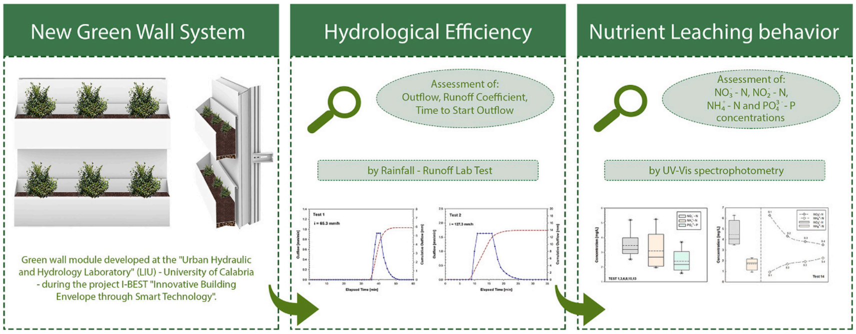
HIGHLIGHTS

- Development of an innovative green wall system for urban stormwater management
- The new green wall panel presents good rainfall retention capacity.
- Fertilizer use strongly increases the nitrate concentration in the green wall panel outflow.
- In normal operational conditions, the concentrations of nitrogen and phosphorous in the green wall panel outflow are very low.

GRAPHICAL ABSTRACT



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ABSTRACT

Green Walls represent a sustainable solution to mitigate the effects due to climate change and urbanization. However, although they have been widely investigated in different fields of science, studies on the potential of these systems to manage urban stormwater are still few. Moreover, even if these systems provide multiple benefits, as other nature-based solutions, they leach nutrients due to growing media, decomposed vegetation, and the possibility of fertilizer use. In this regard, several studies have evaluated the nutrient concentrations in the runoff from green roofs, while studies that have analyzed the nutrient-leaching behavior of green walls are still limited. To bridge these scientific gaps, this study presents experimental findings on the hydrological efficiency and nutrient-leaching behavior of an innovative modular living wall system. Some rainfall-runoff tests were carried out to assess the hydrological response of a new green wall system in retaining stormwater. To evaluate the concentration of the nutrients, the collected outflow was analyzed by spectrophotometer UV–visible. The findings show that the developed green wall panel presents good retention capacity by considering different simulated rainfalls and varying the initial soil moisture conditions. The results in terms of nutrient concentrations highlight that the vegetation life cycle and the fertilizer uses affect the quality of the water released from the green wall panel. The concentration of the analyzed nutrients is influenced by the simulated rainfall's hydrological characteristics and the days between the planting phase and the test. However, the overall results show that the concentrations of each analyzed nutrient are low, except after the fertilizer use, highlighting that the choice of vegetation that does not need external nutrients should be preferred during the design of a green wall.

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1. Introduction

Urbanization and climate change led to a drastic change in the hydrological cycle with more considerable surface runoff. The existing drainage systems cannot manage this increased runoff, making cities vulnerable to flooding that risks human life, economic assets, and the environment (Miller and Hutchins, 2017; Pumo et al., 2017; Sohn et al., 2020).

In this context, Nature-based Solutions (NbS) are sustainable systems to manage stormwater in urban areas whose primary purpose is to reproduce natural processes to filter, infiltrate, evaporate, store, and detain runoff close to its source (Kozak et al., 2020). The most common benefits of NbS are urban flooding risk mitigation, urban heat island effects reduction, water quality restoration, air quality improvement, enhancement of biodiversity, and many others (Ávila-Hernández et al., 2023; Boano et al., 2020; Emilsson and Ode Sang, 2017; Kabisch et al., 2016; Pirouz et al., 2020; Ávila-Hernández et al., 2023; Vojinovic et al., 2021; Viecco et al., 2021).

The green wall system is one of these sustainable solutions able to increase the green area in urban spaces, achieving several benefits at multiple scales. These systems can be classified into two macro-categories: Green Facades (direct or indirect) and Living Walls (continuous or modular) (Manso and Castro-Gomes, 2015). As reported in several studies (Baran and Gültekin, 2018; Manso and Castro-Gomes, 2015; Palermo and Turco, 2020), the main technical differences between Green Facades (GFs) and Living Walls (LWs) can be summarized as follow. The GFs, which represent the traditional green wall system, are characterized by few elements and low technology; they are light, easy to install, and support the natural development of plants (generally climbing plants) on the wall surface (direct GF) or by a supporting system (indirect GF). While the Living Walls (LWs), which represent a recent innovation of the GFs, can allow rapid vegetation development on high buildings, and they can use a wide variety of plants. More in detail, the continuous LWs consist of different layers supported by a base panel that can be directly attached to a supporting structure. These systems are usually characterized by lightweight and absorbent screens, as a fabric layer (i.e., felt), for the plants' growth and are generally based on hydroponic techniques. While the modular LWs are pre-vegetated panels and the plants grow in supporting elements such as vessels, trays, flexible bags, and planter tiles; the growing media consists of a substrate (organic and/or inorganic) with good retention capacity; while the irrigation system is usually installed between the panels. By this analysis, carried out on the main design features between these types of GW systems, it emerges that although LWs require much more materials than the GFs with higher installation costs, they are easier to maintain.

The different features (such as foliage thickness, water content, properties of the materials, and the possible presence of air cavities between the layers) that characterized LWs and GFs can affect cooling and insulating properties, as well it is possible to considerably decrease the rate of heat that can be re-radiated by facades and other hard surfaces by the evapotranspiration and shading due to the plants (Ottelé et al., 2011). In this regard, as obtained by Victorero et al. (2015), it is possible to achieve a significant reduction of wall surfaces temperatures by implementing living walls, and, thus, mitigate urban heat island effect; therefore, as reported in Akbari and Kolokotsa (2016), these technologies can be considered as climate change mitigation strategies. The beneficial performances of these systems in thermal or energy issues were also analyzed in several studies (Andric et al., 2020; Daemei et al., 2021; Kenai et al., 2021; Koch et al., 2020). Additionally to these aspects, GWs have already been investigated as greywater treatment systems (Addo-Bankas et al., 2021; Boano et al., 2021), as a strategy to improve the air in urban cities (Paull et al., 2021; Ysebaert et al., 2021), and mitigate noise pollution (Attal et al., 2021; Shushunova et al., 2022).

Although GW systems present the same hydrological processes that occur in other NbSs, (such as green roofs), studies on their efficiency in managing stormwater close to the source are still limited. In a study (Ostendorf et al., 2011), the authors analyzed the stormwater retention capabilities of circular green wall systems. The experimental site at the SIUE (Southern Illinois University Edwardsville) campus consisted of eighteen green wall systems, five planted systems, and one unplanted control system, both replicated three times. The authors have found no significant differences in stormwater runoff volume and runoff reduction between the different treatment systems for the whole study period. In contrast, they have found differences in runoff reduction between the systems for individual months (September 2010, May 2011, and June 2011) by highlighting the importance of species selection to maximize the environmental benefits of green retaining walls. Overall, all treatment systems have retained >75 % of the total rainfall from October 2010 to June 2011. Another study (Kew et al., 2014) assessed the ability of green walls to retain stormwater runoff by developing eight green wall systems on two existing courtyard walls (four green wall systems on the northeast facing and the other four on the southwest facing); to simulate the stormwater from a roof by using local rainfall data, cisterns, and drip irrigation systems were used. The findings showed that green walls could retain a significant amount of stormwater; on average, during the monitoring campaign of five months, the systems have retained about 10.4 L of water a day; the green wall systems on the southeast-facing retained an average of 11.2 L of water a day, while that one on the northwest-facing an average of 9.5 L. Based on the achieved results, the authors have concluded that green walls linked to a cistern were able to manage a consistent amount of first-flush stormwater comparable to green roofs. Finally, the study by Lau and Mah (2018) investigated the hydrological effectiveness of a green wall system by modeling it as a portion of the urban drainage system. More in detail, the authors have used the Environmental Protection Agency's (EPA) Stormwater Management Model (SWMM) 5.1 with the bioretention cell interface to simulate the green wall systems by modeling four scenarios according to different conditions (soil types, average recurrence interval - ARI, storm duration) and by considering design and observed rainfalls. In all scenarios with the synthesized rainfalls, a runoff reduction of more than half was obtained (more in detail 55 % when one-year ARI and 5 min storms were considered); similarly, the scenario with observed rainfall data showed a runoff reduction by half. Thus, the model proposed in this study showed that a green wall might effectively be used as an urban drainage system to reduce surface runoff. Overall, even if these few studies have analyzed the suitability of green wall systems for stormwater management, they have not evaluated their hydrological efficiency by experimental laboratory campaigns.

Despite the nature-based solutions present several benefits, due to the presence of growing media and plants, they can also release nutrients that, discharged into the sewer system during rainfall events or irrigation processes, could be a source of pollutants for the receiving water bodies. As reported in some studies (Akther et al., 2021; Kuoppamäki and Lehvävirta, 2016; Speak et al., 2014), the concentrations of phosphorus and nitrogen in runoff from nature-based solutions such as green roofs can be substantial. This phenomenon can be further amplified by fertilizers (Emilsson et al., 2007), generally used to ensure a constant supply of plant nutrients. Thus, since nitrogen (N) and phosphorus (P) leach to downstream aquatic ecosystems can contribute to eutrophication phenomena (Buffam and Mitchell, 2015), the nutrients leaching from these green infrastructures under different boundary conditions should be carefully considered. As discussed by (Akther et al., 2021), N (especially NO_3^-–N) is leached quicker than P; this occurs because N presents higher mobility in the soil than P, and it is highly susceptible to leaching from the growing media due to its negligible interaction with the soil. While the less mobility of PO_4^{3-}–P in most growing media is due to precipitation, adsorption to the soil of organic and mineral particles, and immobilization by microorganisms. Moreover, as reported by (Li and Babcock, 2014), most of the N found in the runoff from green infrastructure is NO_3^-–N and NH_4^+–N, both inorganic forms of nitrogen soluble and with different degrees of mobility in the soil. Nitrate nitrogen, negatively charged, generally is repelled by negatively charged soil particles (except in the case of acidic soils); it diffuses quickly through soils and can easily leach out. Ammonium nitrogen, positively charged, tends to be bound to and adsorbed by soil particles, with slow diffusion in the soil. Focusing on these two forms of nitrogen, several Redox transformations can occur in soil. Ammonium nitrogen can be: absorbed by plants and the soil through the assimilation and immobilization process, respectively; oxidized to nitrate through the nitrification process; and transformed into ammonia. Nitrate nitrogen can be: absorbed by plants (assimilation) and by soil organisms (immobilization), transported by the percolation waters through the leaching process, and transformed into molecular nitrogen by denitrification (Buffam and Mitchell, 2015; Masoni and Ercoli, 2010).

Based on these phenomena occurring in the growing media, some studies have investigated the nutrient-leaching behavior of green infrastructures. The study by van Seters et al. (2009) analyzed the benefits of green roof implementation regarding rainwater treatment. It highlighted that the concentration of phosphorus and nitrogen in the discharged water from a green roof is higher than in conventional techniques. Another study (Akther et al., 2021) assessed the concentrations of leached nutrients of an extensive green roof by simulating laboratory rainfall events of different intensities and durations. This study showed that nutrient leaching decreases with the water percolation processes in the substrate. It has also demonstrated that the primary source of nutrients, gradually washed away by water, is due to the growing media and only secondarily to the presence of plants and that nitrogen is the nutrient that leaches more rapidly than phosphorus. The experimental study by Zhang et al. (2018b) analyzed the nutrients leaching from six types of substrate soils for an extensive green roof. The results have remarked as the use of growing media rich in nitrogen and phosphorous (as peat) amplifies the pollution processes of the discharged water due to the nutrients leaching, especially in the initial phase of the rainfall event. In another study (Teemusk and Mander, 2007), the authors conducted a short-term quantitative and qualitative analysis of a green roof by considering rainfall events with different intensities and durations. They obtained that the lower the water flow speed into the substrate, the higher the total nitrogen concentrations, ammoniacal nitrogen, nitric nitrogen, and organic material. While the concentration of total phosphorus and phosphate had an opposite behavior, i.e., it increased proportionally to the green roof outflow. Finally, the study by Emilsson et al. (2007) focused on the polluting effects of fertilization on urban wastewater, showing that conventional fertilizers should be avoided if the runoff from the green roof is not suitably treated and that plants with lower nutrient supply requirements (such as succulent ones) should be preferred over flowering plants. Thus, according to the studies (Akther et al., 2021, 2020), several factors, including growing media composition and thickness, vegetation type, maintenance activities (as fertilizer use), age of the installation, and hydrometeorological condition (cumulative precipitation/inflow, temperature, and antecedent soil moisture) affect the leaching nutrient behavior from this type of infrastructures. This literature analysis revealed that several studies had assessed the nutrient-leaching behavior of green roofs, while similar studies on green wall systems are still limited.

Therefore, to bridge the scientific gaps, both in water quantity and quality analysis for green wall systems, an innovative modular green wall system, previouslydeveloped at the “Urban Hydraulic and Hydrology Laboratory” (LIU) at the University of Calabria during the project “Innovative Building Envelope through Smart Technology (I-Best)”, was tested. The new green wall system was studied to achieve the following main research objectives: (i) to assess the hydrological efficiency of the new system by an experimental campaign; (ii) to evaluate the nutrient leaching concerning nitrogen cycle and phosphorous.

2. Material and methods

2.1. The green wall panel experimental set-up

A new green wall panel (Fig. 1) was previously developed at the “Urban Hydraulic and Hydrology Laboratory” (LIU) of the Department of Civil Engineering (DINCI – University of Calabria) during Project I-BEST.

As shown in Fig. 1, it is a 100 cm × 100 cm panel with two boxes for the plants’ growth. Each box has a height of 16 cm, length of 100 cm, and width of 14.5 cm and presents the same stratigraphy consisting of (i) a surface layer vegetated with plants; (ii) a soil substrate with a depth of 12 cm; (iii) a filter layer (geotextile with high permeability) to prevent the fine soil particles from moving into the underlying layer; (iv) a drainage layer in clay pebbles with a depth of around 2 cm. Ten drainage holes at the bottom of each box guarantee the discharge flow, and an overflow hole in each box avoids surface runoff.

The soil substrate comprises 70 % “Irish Peat” and 30 % Perlite. This mixture of soils was selected after experimental investigations on the soil hydraulic parameters, evaluated by the HYPROP® device. The soil sample was packed on a 250 mL sample ring, compacted, vibrated, fully saturated, and finally placed on the HYPROP® device. Two vertical tension shafts, located at different levels of the sample, have estimated the water tension. While the average water content was determined according to the mass change and evaluated by measuring the weighing of the sample in real time, the medial tension value was determined as the mean value recorded by the two tensiometers. At the end of the experiment, the dry weight was measured. Finally, the measurement outcomes allowed the definition by points of the soil water retention curve. To fit the analytical hydraulic models already present in the literature, for defining the hydraulic parameters of the medium, the soil water retention curve data were processed by the HYPROP-FIT software (Pertassek et al., 2015). Based on the Unimodal Van Genucthen-Mualem model (Genuchten, 1980), the residual and the saturated water contents, θr and θs [$cm^3\ cm^{-3}$], the fitting parameters of the soil water retention curve (SWRC), α [cm^{-1}] and n [−], the unsaturated hydraulic conductivity Ks [$cm\ min^{-1}$], and the tortuosity of the medium l [−] were measured. More details on the methodology used to define the SWRC of the chosen soil substrate are reported in the study by Turco et al. (2022).

While about vegetation, native species and plants suited for well-drained soils and characterized by a high drought tolerance were preferred. Thus, the following species were selected for the green wall panel tested in the Laboratory: Dianthus, Crassulaceae, and Sedum Palmeri.

The GW panel’s hydrological effectiveness and nutrient-leaching behavior were assessed by developing the experimental system, shown in Fig. 1, to reproduce a series of rainfall-runoff tests in the laboratory environment. The precipitation was reproduced using a rainfall simulator of ten sprinklers delivering water pumped from a storage tank. Constant rainfall intensity was delivered from the top of the green wall panel. The outflow from the bottom outlet of the green wall panel was measured by a tipping-bucket MTX device with a factory resolution of 0.2 mm. This device was pre-calibrated in the Laboratory, and the specific rain collection area was considered during the measurements. A Frequency Domain Reflectometry (FDR) probe WaterScout SMEC was used to measure the volumetric water content in the middle of the soil substrate layer. The inflow, outflow, and water content were logged by a specific acquisition system made of NI modules, personal computer, and measurement software with a time step of 1 min.

2.2. Data analysis

2.2.1. Water quantity analysis

To analyze the hydrological performances of the green wall panel, thirty-two tests with different rainfall characteristics were simulated in the Laboratory. The design of the rainfall events was based on the

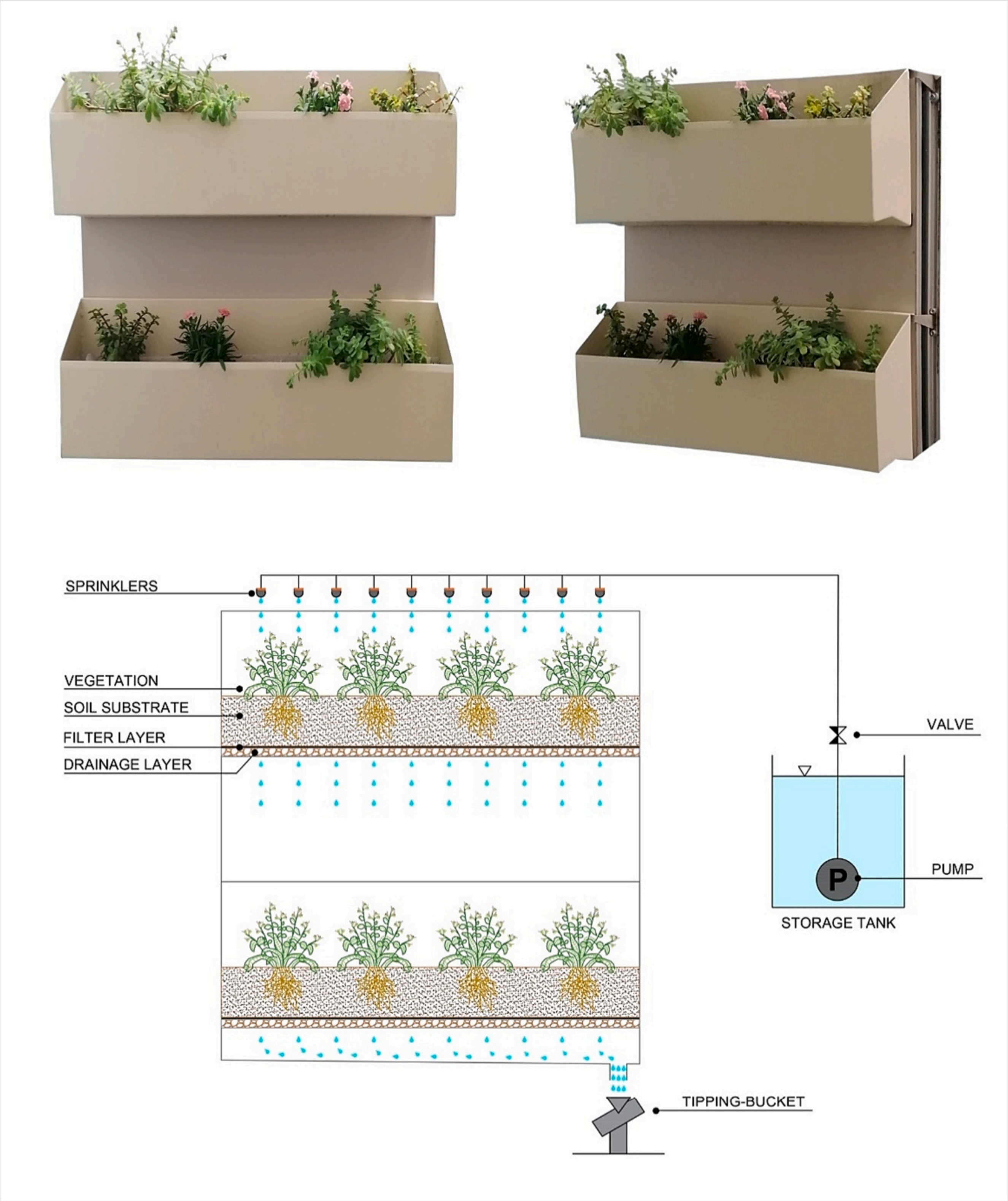

Fig. 1. Two live images of the green wall panel tested in the Urban Hydraulic and Hydrology Laboratory (LIU) (upper side); a schematic of the experimental set-up developed in the Laboratory (lower side).

following assumptions: (i) only constant rainfall intensities were simulated; (ii) since sub-hourly precipitations are the most critical in urban areas (Carbone et al., 2015), all rainfall events had a duration <40 min; (iii) the variation range of the rainfall intensities (15.3 mm/h ÷ 210.2 mm/h) was selected based on other experimental studies (Carbone et al., 2014; Palla et al., 2010; Turco et al., 2017) and to cover a wide range of precipitation; (iv) each test was carried out by considering an inter-event dry period of at least 6 h, in agreement with other studies (Palermo et al., 2019; Stovin et al., 2012; Voyde et al., 2010). Thus, the simulated constant rainfall intensities were reproduced by considering

Table 1

Characteristics of the rainfall events (I - total Inflow; D - rainfall Duration, i - constant intensity) the initial soil Volumetric Water Content (VWC), total Outflow (O), and the hydrological performance indexes Runoff Coefficient (RC) and Time to Start Outflow (TSO) resulting from laboratory tests.

Test	I [mm]	D [min]	i [mm/h]	VWC [%]	O [mm]	RC [%]	TSO [min]
1	41.4	38	65.3	1.7	5.9	14.2	35.0
2	27.6	13	127.3	7.8	13.9	50.3	9.0
3	32.7	20	98.1	6.6	16.9	51.7	11.0
4	29.6	20	88.7	7.9	22.3	75.5	4.0
5	16.2	15	64.6	7.9	7.7	47.9	10.0
6	6.3	20	18.9	8.1	2.3	36.3	14.0
7	4.3	17	15.3	6.5	0.0	0.0	–
8	27.6	10	165.5	7.7	14.4	52.3	7.0
9	35.0	10	210.2	8.3	21.9	62.6	4.0
10	31.5	10	189.1	9.1	23.2	73.5	4.0
11	19.3	15	77.2	9.3	11.4	58.9	7.0
12	11.0	10	66.2	10.9	9.0	81.6	6.0
13	34.7	15	138.7	8.5	18.9	54.6	8.0
14	13.8	15	55.2	10.5	9.5	68.9	9.0
15	11.4	10	68.6	10.5	7.4	64.9	5.0
16	31.1	25	74.7	6.6	5.3	17.1	23.0
17	23.6	15	94.6	10.1	12.8	54.0	10.0
18	20.1	15	80.4	9	5.4	27.1	13.0
19	25.6	15	102.3	5	3.4	13.3	15.0
20	17.2	10	103.4	8.7	5.3	30.7	10.0
21	33.6	10	201.7	7.5	13.6	40.5	7.0
22	10.6	15	42.6	–	0.0	0.0	–
23	37.0	20	111.1	–	7.4	20.0	16.0
24	35.1	20	105.3	8.7	12.8	36.5	14.0
25	23.7	25	56.8	9.5	5.4	22.7	22.0
26	31.5	15	126.1	2.1	7.6	24.1	10.0
27	27.2	30	54.3	–	7.2	26.5	21.0
28	27.6	15	110.3	–	11.4	41.3	9.0
29	13.8	20	41.4	–	4.9	35.5	12.0
30	24.8	20	74.5	–	8.4	33.8	12.0
31	27.6	20	82.8	–	12.3	44.6	11.0
32	27.6	10	165.5	–	19.9	72.1	8.0
Min	4.3	10.0	15.3	1.7	0.0; [a]2.3	0.0: [a]13.3	4.0
Max	41.4	38.0	210.2	10.9	23.2; [a]23.2	81.6; [a]81.6	35.0
Mean	24.4	16.8	96.2	7.9	10.2; [a]10.9	41.7; [a]44.4	11.5
Median	27.4	15.0	85.7	8.2	8.7; [a]9.3	40.9: [a]43.0	10.0
St. deviation	9.4	6.3	48.6	2.3	6.2; [a]5.9	21.5; [a]19.6	6.7

– Missing data because the acquisition system did not save them.

[a] Values obtained by excluding the rainfall events that have not produced outflow from the green wall.

different combinations of total inflow and duration. More details about the thirty-two simulated rainfall events (total inflow, rainfall duration, rainfall intensity) are displayed in Table 1. Moreover, to assess the influence of the initial soil volumetric water content (VWC) on the retention behavior of the green wall panel , some tests were carried out by considering very similar constant rainfall intensities with different VWC. For instance, events 1 and 5 (in Table 1) present a rainfall intensity of around 65.0 mm/h and volumetric water content at the beginning of the test of 1.7 % and 7.9 %, respectively; similarly, for events 2 and 26, or 19 and 20.

For each simulated rainfall event, the outflow from the green wall panel was measured using the previously described tipping bucket. Moreover, to consider the systematic mechanic errors due to this device, according to the study by Lanza and Stagi (2002) and Molini et al. (2005), the following power law was considered:

$$I_a = \alpha I_r^{\beta} \tag{1}$$

where I_a is the actual intensity, I_r is the recorded intensity by the gauge, and α and β are the calibration parameters, as reported in Lanza and Stagi (2002) for an MTX device are 0.759 and 1.076, respectively.

Then, the runoff coefficient and the time to start outflow were analyzed on an event scale as hydrological performance indexes to determine the green wall hydraulic efficiency.

More in detail, the *Runoff Coefficient* (RC) was estimated as the percentage ratio between the total Outflow (O) and the total inflow (I):

$$RC(\%) = \frac{O}{I} \bullet 100 \tag{2}$$

While the *Time to Start Outflow* (TSO) was determined, according to the study carried out on green roofs (Stovin et al., 2012), as the time difference between the start of simulated precipitation (t_{0*}) and the time at which the total outflow (t_O) > 0.01 mm:

$$TSO(min) = t_{O>0.01mm} - t_{0*} \tag{3}$$

Finally, to statistically identify the most influencing parameters on the hydrological efficiency of the specific green wall panel, similar to other studies on nature-based solutions (Ferrans et al., 2018; Garofalo et al., 2016; Nawaz et al., 2015; Stovin et al., 2012), a regression analysis was performed. This type of statistical analysis assesses the existing relationship of a collection of independent variables to a single dependent variable. In this study, the rainfall intensity (i), the total inflow (I), the rainfall duration (D), and the soil volumetric water content (VWC) were selected as independent variables; while the outflow (O), the runoff coefficient (RC), and the time to start outflow (TSO) were considered each per time as the dependent variable. Initially, similar to (Stovin et al., 2012), scatter plots and regression analysis on a single parameter were carried out to identify predictive parameters expected to be most influential. Then a compressive multiple regression analysis was conducted for each dependent variable (outflow, runoff coefficient, and time to start outflow) using forward and backward stepwise regression. Some preliminary checks were carried out, principally based on correlation indexes analysis, significance tests evaluation, and assessment of possible multicollinearity concerns. More in detail, the Variance Inflation Factor (VIF), which measures the correlation between the independent variables in a regression model, was estimated to detect possible multicollinearity between the variables. These regression analyses were performed systematically to ensure that the generated equations presented the highest possible R^2, and non-significant terms were removed from the model. In this regard, to analyze the significance of each regression coefficient, a *t*-test was used, and a *p*-value of 0.05 was considered. While R^2 coefficient was evaluated to define how closely the regression line fits the data, and F-test (significant at $p = 0.05$) was determined to estimate the overall significance of the obtained equation.

2.2.2. Water quality analysis

The outflow from the test bed was sampled and analyzed to assess the nutrient-leaching behavior of the specific green wall panel. To evaluate the influence of some parameters (rainfall hydrological characteristics, soil moisture condition, period occurring between the planting phase and the test, and days after the fertilizer use) on the nutrient leaching of the green wall panel, eighteen tests were selected from the whole dataset reported in Table 1.

More in detail, the water quality monitoring campaign was split into different phases as described below. The first phase consisted of the experimental analysis carried out on the green wall panel with vegetation; it started 28 days after the first planting phase and ended after 71 days. The second phase was performed to analyze the nutrient-leaching behavior when only decaying plants were in the green wall panel, and it was executed 180 days after the plants were installed for the first time in the boxes. Finally, a third phase was carried out after a second planting phase, around nine months after the first one. Furthermore, the fertilizer effect on the nutrient-leaching behavior was also investigated in this last phase.

From the whole dataset composed of eighteen tests, the water sample was collected at the end of each event for fifteen tests, and the quality analysis was made on the mixed total outflow. While to evaluate the nutrient leaching behavior during the same rainfall event, for the remaining three events, the outflow from the green wall panel was collected at four different times during the discharge, and then the water quality analysis was performed for each discrete sample. More in detail, the three rainfall events considered for this last analysis (tests 11, 14 and 17) presented: a rainfall duration of 15 min; a rainfall intensity of 77.2 mm/h, 55.2 mm/h, and 94.6 mm/h, respectively; a time to start outflow of 7, 9, and 10 min, respectively; an estimated total outflow time ranging between 21 and 25 min. The sampling carried out during the same rainfall event followed this procedure: four discrete samples were collected from each test during the outflow hydrograph; the first sample was collected at the beginning of the outflow from the green wall panel; the collection time of each sample depended by the amount of water needed for the quality analysis, and this time was also affected by the outflow velocity; the time between the end of sampling and the next one was around 4 min.

The concentration of three N forms (nitrate $\left(NO_3^-\text{–}N\right)$, nitrite $\left(NO_2^-\text{–}N\right)$, ammonium $\left(NH_4^+\text{–}N\right)$), and one P form (orthophosphate ($PO_4^{3-}\text{–}P$)) in each sample were determined by Ultraviolet-Visible (UV–Vis) spectrophotometry by considering the standard methods as reported in APAT CNR IRSA (2003). Each nutrient concentration (C) was defined using the following calibration curves (which correlate the measured Absorbance – A with C) obtained before starting the analysis on the outflow discharged from the green wall panel.

$$\mathbf{NO_3^-\text{–}N}\rightarrow A = 0.2752 \bullet C + 0.0277; R^2 = 0.9971 \tag{4}$$

$$\mathbf{NO_2^-\text{–}N}\rightarrow A = 6.9596 \bullet C + 0.0074; R^2 = 0.9999 \tag{5}$$

$$\mathbf{NH_4^+\text{–}N}\rightarrow A = 2.1355 \bullet C - 0.0111; R^2 = 0.9999 \tag{6}$$

$$\mathbf{PO_4^{3-}\text{–}P}\rightarrow A = 2.7192 \bullet C + 0.0017; R^2 = 0.9999 \tag{7}$$

Then by the standard methods, the concentrations of the considered nutrients in the different dilutions of each collected sample were measured and finally averaged.

Moreover, the initial content of the nutrients in the growing media was measured using the saturation soil extraction method. The results showed a concentration (mean ± standard deviation) of 1.795 ± 0.364 mg/L, 0.118 ± 0.004 mg/L, 2.848 ± 0.296 mg/L, and 3.627 ± 0.185 mg/L of $NO_3^-\text{–}N$, $NO_2^-\text{–}N$, $NH_4^+\text{–}N$, and $PO_4^{3-}\text{–}P$, respectively.

Finally, a correlation analysis using Pearson's coefficient (denoted by r) was performed. This analysis was carried out to statistically investigate the parameters most strongly associated with the nutrient concentrations in the outflow collected from the specific green wall module. Pearson's correlation coefficient, as reported in the study (Ratner, 2009), measures the strength of the linear correlation between two variables, and it ranges between the values −1 (perfect negative correlation) and + 1 (perfect positive correlation). In this range of interval: $r \approx 0$ indicates no linear relationship; $0 < r < 0.3$ $(0 < r < -0.3)$ reflects a weak positive (negative) linear correlation; $0.3 < r < 0.7$ $(-0.3 < r < -0.7)$ testifies a moderate positive (negative) linear correlation; $0.7 < r < 1$ $(-0.7 < r < -1)$ indicates a strong positive (negative) linear correlation. In this study, the concentration of the three nitrogen forms (nitrate, nitrite, and ammonium) and of the orthophosphate were considered each time as the dependent variable, while the rainfall features (inflow, intensity, duration), the volumetric water content in the soil , the days between the planting phase and tests, and the days after the fertilizer use as the independent variables. In addition, since for small samples, it is possible to obtain a high correlation coefficient that is not significant, it was necessary to evaluate both the r coefficient and the *p*-value.

3. Results and discussion

3.1. Green wall panel hydrological effectiveness

The total outflow from the green panel and the hydrological indexes were analyzed on an event scale. Thus, Table 1 shows for each event the hydrological characteristics (I - total Inflow; D – rainfall Duration, i – constant rainfall intensity), the initial soil Volumetric Water Content (VWC), and the results in terms of total Outflow (O), Runoff Coefficient (RC), and Time to Start Outflow (TSO) . TSO was evaluated for all rainfall events, excluding tests 7 and 22 which did not produce outflow. Table 1 also exhibits the variation range (minimum and maximum value), the mean, the median, and the standard deviation for each parameter, considering that two simulated rainfall events (test 7 and test 22) have not produced outflow from the green wall module.

By observing the findings in Table 1, the RC presents a high variability, ranging from 0 % to 81.6 %, with a mean value of 41.7 % and a standard deviation of 21.5 %, considering the whole dataset. While when events 7 and 22, which have not produced outflow from the green wall panel, are excluded, the RC ranges from 13.3 % to 81.6 % with a mean value of 44.4 % and a standard deviation of 19.6 %, and the TSO ranges from 4 min to 35 min, with a mean value of 11.5 min and a standard deviation of 6.7 min. Overall, these findings highlight the good response of the specific green wall system under different precipitations but simultaneously confirm how the initial soil moisture condition strongly influences the RC and the delay to start the outflow. For example, by comparing three rainfall events with similar intensities, such as Test 1 ($i = 65.3$ mm/h), Test 5 ($i = 64.6$ mm/h), and Test 12 ($i = 66.2$ mm/h), the RC values are 14.2 %, 47.9 %, and 81.6 %, respectively. Similarly, for Test 2 and Test 26, which present a higher similar intensity (127.3 mm/h and 126.1 mm/h, respectively), different runoff coefficients (50.3 % and 24.1 %, respectively) were obtained. These differences in the findings, although similar intensities, can be explained by observing in Table 1 the volumetric water content at the beginning of each event, which affects the soil retention capacity of the green wall panel. A similar conclusion can also be achieved by observing the results regarding the time to start outflow (TSO) index; higher delay, given similar rainfall intensity or inflow depth, is associated with the initial volumetric water content in the growing media.

Moreover, the different behavior of the green wall panel under similar rainfall intensities could also be justified by the potential preferential flow pathways that the root systems could have created through the soil. In this regard, as reported in other studies (Chen et al., 2023; Getter et al., 2007; Zhang et al., 2018a), the increasing free air space in the substrate due to macropores and well-developed channels created by root systems, might increase water flux via preferential flow paths affecting the retention capacity of the green infrastructure and resulting in a quicker initial runoff.

The findings shown in Table 1 reveal the good retention capacity of the analyzed green wall panel, and they are promising if compared to the results obtained for other nature-based solutions, especially green roof systems, investigated in the literature. For instance, in a previous study (Palermo et al., 2019) carried out by considering one-year monitoring data of an extensive green roof located at the University of Calabria, a mean surface runoff coefficient of around 50 % was found for rainfall events with precipitation depth >8 mm. Furthermore, the mean runoff coefficient of the green wall panel falls in the range obtained in another study (Garofalo et al., 2016), where the results of several literature studies on green roofs carried out under different climate conditions were compared.

Finally, to statistically investigate the significance of the hydrological parameters, a regression analysis was carried out using the data in Table 1. The regression analysis results are summarized in Table 2, where the F-test of overall significance (significant at $p = 0.05$) and the t-statistics (significant at p = 0.05), displayed in the same order as the parameters in the equation, are shown. By observing Table 2, Eq. (8) correlates the outflow with the total inflow, while Eq. (9) was defined by adding the rainfall duration as an additional parameter, showing that both variables (I and D) affect the green wall panel outflow response. Eq. (11) highlights as the total inflow and the initial soil volumetric water content influence the total outflow from the green wall panel. Eq. (12) shows how the variables considered (I, VWC, and i) can affect the outflow. While in Eq. (10), the only correlation is between rainfall intensity and outflow. These results confirm as all of the considered hydrological features (I, D, I, and VWC) can affect the outflow from the green wall system with different grades of significance. While by applying the regression analysis considering as dependent variables the runoff coefficient (RC), Eqs. (13), (14), (15), and (16) were found. Analyzing these regression equations emerges as rainfall intensity, duration, and volumetric water content in the soil substrate at the beginning of the events are the most influential parameters on the runoff coefficient. Eqs. (17), (18), (19), (20), and (21) were obtained when the time to start outflow (TSO) was the dependent variable. These equations exhibit the correlation between the hydrological parameters (I, i, D, and VWC) and the TSO index. Finally, Eqs. (15) and (20) demonstrate as the soil volumetric water content at the begging of the test can affect the runoff coefficient and the delay to start outflow from the green wall system by confirming, as previously discussed, by comparing rainfall events with similar intensity. While Eqs. (16) and (21) highlight the influence of rainfall intensity and the volumetric water content on the runoff coefficient and time to start outflow.

3.2. Nutrient leaching behavior of the green wall panel

This section shows the results obtained during the experimental analysis of the green wall's nutrient-leaching behavior. The findings are summarized in different Tables based on the organization of the monitoring campaign discussed in Section 2.2.2. More in detail, the concentrations of NO_3^-–N, NO_2^-–N, NH_4^+–N, PO_4^{3-}–P measured in the samples collected at the end of 15 rainfall events reproduced in the Laboratory are reported in Tables 3, 5, and 6. While, to better understand the nutrient-leaching behavior during a simulated rainfall event, Table 4 shows the concentration of nutrients in the samples collected at different times during the discharge outflow for tests 11, 14, and 17. To analyzed the parameters involved in this analysis (inflow, rainfall intensity, rainfall duration, volumetric water content) it must refer to Table 1 by considering the test number reported in all tables of this section.

Table 2
Multiple linear regression analysis (i - rainfall intensity; I – total Inflow; D – rainfall Duration; VWC – Volumetric Water Content; O – total Outflow; RC – Runoff Coefficient; TSO – Time to Start Outflow).

Regression equation		R^2_{adg}	F-test	n. obs.	t-Statistics
$O = 1.194 + 0.371\,I$	(8)	0.29	13.87	*	$0.458^{NS}; 3.725$
$O = 7.563 + 0.463\,I - 0.512\,D$	(9)	0.53	18.78	*	$2.874; 5.510; -4.064$
$O = 1.038 + 0.096\,i$	(10)	0.55	38.46	*	$0.624^{NS}; 6.202$
$O = -16.055 + 0.547\,I + 1.708\,VWC$	(11)	0.58	16.66	***	$-3.187; 5.545; 3.968$
$O = -13.186 + 0.345\,I + 1.350\,VWC + 0.049\,i$	(12)	0.64	14.59	***	$-2.726; 2.639; 3.136; 2.157$
$RC = 69.960 - 1.684\,D$	(13)	0.21	9.48	*	$7.129; -3.078$
$RC = 24.496 - 0.178\,i$	(14)	0.13	5.79	*	$3.067; 2.407$
$RC = -2.615 + 5.952\,VWC$	(15)	0.36	13.84	***	$-0.200^{NS}; 3.721$
$RC = -17.975 + 0.143\,i + 6.087\,VWC$	(16)	0.45	10.45	***	$-1.283^{NS}; 2.172; 4.110$
$TSO = -3.553 + 0.894\,D$	(17)	0.77	98.62	**	$-2.184; 9.931$
$TSO = 17.974 - 0.064\,i$	(18)	0.18	7.36	**	$6.867; -2.713$
$TSO = 8.890 - 0.129\,i + 0.613\,I$	(19)	0.61	23.34	**	$3.654; -6.437; 5.599$
$TSO = 24.461 - 1.679\,VWC$	(20)	0.26	8.74	****	$5.229; -2.957$
$TSO = 33.052 - 0.072\,i - 1.820\,VWC$	(21)	0.49	11.59	****	$7.029; -3.238; -3.845$

NS - not significant.
[*] n. of observations = 32 (all tests).
[**] n. of observations = 30 (tests which have produced outflow).
[***] n. of observations = 24 (tests with VWC data).
[****] n. of observations = 23 (tests with VWC data that have produced outflow).

Table 3

Concentrations (mean ± standard deviation) of NO_3^-–N, NO_2^-–N, NH_4^+–N, PO_4^{3-}–P in the samples collected at the end of six simulated rainfall events with different hydrological characteristics.

Test	Post-plant. [d]	i [mm/h]	NO_3^-–N [mg/L]	NO_2^-–N [mg/L]	NH_4^+–N [mg/L]	PO_4^{3-}–P [mg/L]
1	28	65.3	3.264 ± 0.332	0.016 ± 0.003	5.254 ± 0.225	3.698 ± 0.187
3	33	98.1	2.531 ± 0.357	0.012 ± 0.003	3.885 ± 0.056	2.359 ± 0.097
6	36	18.9	5.202 ± 0.288	0.014 ± 0.004	2.093 ± 0.054	2.838 ± 0.153
8	41	165.5	3.583 ± 0.294	0.016 ± 0.003	3.207 ± 0.168	1.998 ± 0.060
10	46	189.1	3.051 ± 0.293	0.007 ± 0.004	2.142 ± 0.052	1.592 ± 0.045
13	55	138.7	3.123 ± 0.295	0.010 ± 0.004	1.973 ± 0.061	1.876 ± 0.210
Min			2.531	0.007	1.973	1.592
Max			5.202	0.016	5.254	3.698
Mean			3.459	0.013	3.092	2.394

Table 4

Concentrations (mean ± standard deviation) of NO_3^-–N, NO_2^-–N, NH_4^+–N, PO_4^{3-}–P in the samples (1, 2, 3, 4) collected at a different time of the outflow discharged from the green wall module for each of the three considered tests (11, 14, 17).

Test	Post-plant. [d]	i [mm/h]	Sample	NO_3^-–N [mg/L]	NO_2^-–N [mg/L]	NH_4^+–N [mg/L]	PO_4^{3-}–P [mg/L]
11	49	77.2	1	5.722 ± 0.693	0.011 ± 0.004	1.734 ± 0.075	2.212 ± 0.010
			2	2.886 ± 0.344	0.012 ± 0.002	2.265 ± 0.067	1.770 ± 0.037
			3	2.405 ± 0.359	0.010 ± 0.004	2.359 ± 0.081	1.699 ± 0.010
			4	2.563 ± 0.229	0.014 ± 0.004	2.389 ± 0.073	1.740 ± 0.015
14	56	55.2	1	6.276 ± 0.248	0.008 ± 0.004	0.929 ± 0.032	2.066 ± 0.036
			2	4.318 ± 0.276	0.009 ± 0.004	1.687 ± 0.017	1.899 ± 0.018
			3	3.805 ± 0.366	0.010 ± 0.004	1.915 ± 0.019	1.804 ± 0.030
			4	3.503 ± 0.264	0.012 ± 0.004	2.253 ± 0.035	1.947 ± 0.024
17	71	94.6	1	5.910 ± 0.231	0.013 ± 0.005	1.307 ± 0.035	1.529 ± 0.018
			2	3.974 ± 0.363	0.012 ± 0.004	1.604 ± 0.069	1.486 ± 0.012
			3	3.725 ± 0.374	0.014 ± 0.003	1.937 ± 0.060	1.521 ± 0.053
			4	3.699 ± 0.293	0.014 ± 0.004	2.026 ± 0.055	1.562 ± 0.050

Table 5

Concentrations (mean ± standard deviation) of NO_3^-–N, NO_2^-–N, NH_4^+–N, PO_4^{3-}–P in the samples collected at the end of three simulated rainfall events with different hydrological characteristics and with decomposed plants.

Test	Post-plant. [d]	i [mm/h]	NO_3^-–N [mg/L]	NO_2^-–N [mg/L]	NH_4^+–N [mg/L]	PO_4^{3-}–P [mg/L]
24	180	105.3	15.331 ± 1.608	0.007 ± 0.004	0.246 ± 0.039	0.883 ± 0.025
25	193	56.8	20.324 ± 0.541	0.015 ± 0.003	1.694 ± 0.314	3.177 ± 0.458
26	243	126.1	9.799 ± 1.465	0.005 ± 0.002	0.553 ± 0.032	1.648 ± 0.551
Min			9.799	0.005	0.246	0.883
Max			20.324	0.015	1.694	3.177
Mean			15.151	0.009	0.831	1.903

Table 3 displays the results regarding nutrient concentration in the samples collected for 27 days. The findings in this table concern the samples collected 28 days after the vegetation was planted until 55 days. Before this analysis, the green wall panel has been only irrigated. Thus, to better understand the system's leaching behavior and consider the turnover of the plants, which were also exposed to specific conditions due to the other rainfall-runoff laboratory tests analysis, the table also shows the days between the planting phase and each test. The results in Table 3 exhibit average values of the concentration of NO_3^-–N and NH_4^+–N range from 2.53 mg/L to 5.20 mg/L and from 1.97 mg/L to 5.25 mg/L, respectively; while the concentration of NO_2^-–N is very low, with average values <0.016 mg/L. The concentration of PO_4^{3-}–P varies from 1.59 mg/L to 3.70 mg/L, considering the average value. These outcomes highlight that the concentrations in the outflow from the green wall panel can be affected by the rainfall characteristics and the days between the test and the planting phase. In this regard, it is possible to observe that the highest nitrate value was obtained during the rainfall event with the lowest rainfall intensity and total inflow (test 6). Therefore, lower speed into the substrate resulted in higher concentrations of nitric nitrogen in agreement with (Teemusk and Mander, 2007).

As previously described, Table 4 shows the concentration of the nutrients in the samples collected at different times during the discharge outflow from the green wall panel for tests 11, 14, and 17. Four samples (1, 2, 3, and 4) at different times were collected and analyzed for each test. From Table 4 emerges that for the three analyzed rainfall events with different intensities (77.2 mm/h, 55.2 mm/h, and 94.6 mm/h), the same behavior occurred: a decrease of NO_3^-–N concentration and an increase of NH_4^+–N concentration during the outflow from the green wall panel. Moreover, a higher value of nitrate concentration than ammonium concentration during the initial phase was also observed.

While Table 5 shows the results regarding nutrient concentrations measured during a second phase, carried out after 109 days from the end of test 17. In the period between the first phase of the water quality monitoring campaign (Tables 3 and 4) and the second one (Table 5), the green wall panel was tested only for water quantity analysis. During this second phase, three tests were conducted to assess the nutrient-leaching behavior when only decaying vegetation was in the boxes, i.e., when the physical breakup of the plants into smaller pieces occurred and the process of decomposing organic matter started. As reported in the study (Berg and Staaf, 1981), the chemical composition of the fallen litter governed the decomposition process, and, thus, the release of nutrients, that for the nitrogen can be distinguished into three phases (rapid release of initially leachable nitrogen in litter, accumulation and final release phase). In this regard, the concentration values in Table 5 demonstrate a high increase in the samples' nitrate concentration by confirming that the processes occurring in the soil can change the concentration of this nitrogen form. In this regard, by observing the values of nitrate concentration in Tables 3 and 5 for rainfall intensity with comparable order of magnitude, it is possible to observe a considerable increase; for instance, test 1 in Table 3 ($i = 65.3$ mm/h) and test 25 in Table 5 ($i = 56.8$ mm/h) present a nitrate concentration of 3.3 mg/L and 20.3 mg/L, respectively; similarly for test 13 in Table 3 ($i = 138.7$ mm/h) and test 26 inTable 5 ($i = 126.1$ mm/h), the concentrations of nitrate nitrogen are of 3.1 mg/L and 9.8 mg/L, respectively. Moreover, as in the previous phases, the highest concentration value was observed for the rainfall event with lower intensity and inflow volume (test 25).

The results obtained from the quality analysis by considering the total outflow volume collected at the end of the rainfall events (data in Tables 3 and 5), were used to perform the correlation analysis by the Pearson coefficient. This analysis show a very strong correlation between the "days post planting phase" and the concentration of NO_3^-–N ($r = 0.822$, t-test $= 3.814$, p-value $= 0.007$), between the "days post planting phase" and the concentration of NH_4^+–N ($r = -0.753$, t-test $= -3.030$, p-value $= 0.019$), and between the "rainfall duration" and the concentration of PO_4^{3-}–P ($r = +0.736$, t-test $= 2.872$, p-value $= 0.024$). These findings confirm as the phenomena occurring in the soil substrate over the days, principally due to the interaction of plants and soil, can strongly affect the nutrient-leaching behavior of the green wall system. More in detail, it was possible to observe a negative strong correlation with the ammonium nitrogen and a positive strong correlation with the nitrate nitrogen. Furthermore, a strong positive correlation was observed between the duration of the rainfall event and the phosphate concentration in the total outflow from the green wall. While the results for the other correlation analyses, carried out between the different nutrient concentrations, here investigated, and the other independent variables (volumetric water content, inflow, intensity, duration) are not shown because although the Pearson coefficients for most of them were considerable, the p-values were not verified.

Finally, Table 6 displays the findings after a second planting phase, when only the vegetation was replaced in the same growing media; this phase occurred around nine months after the first plants' placement. In this case, the first test (test 27 in Table 6) was carried out one week after the new plants' installation. As reported in the methodology section, this monitoring campaign examines the fertilizer's influence on the green wall's nutrient-leaching behavior. Before starting this analysis, the concentration of the nutrients in the fertilizer used for the tests was determined by the UV–Vis spectrophotometer. Values in Table 6

Table 6
Concentrations (mean ± standard deviation) of NO_3^-–N, NO_2^-–N, NH_4^+–N, PO_4^{3-}–P in the samples collected at the end of six simulated rainfall events with different hydrological characteristics during 47 days after the second planting phase and by considering fertilizer use.

Test	Post-fertig. [d]	i [mm/h]	NO_3^-–N [mg/L]	NO_2^-–N [mg/L]	NH_4^+–N [mg/L]	PO_4^{3-}–P [mg/L]
27	[a]	54.3	29.469 ± 0.222	0.010 ± 0.003	1.342 ± 0.143	2.653 ± 0.251
28	5	110.3	47.873 ± 6.638	0.186 ± 0.012	5.308 ± 0.109	2.918 ± 0.202
29	7	41.4	42.533 ± 5.990	0.006 ± 0.005	2.651 ± 0.129	2.576 ± 0.097
30	20	74.5	25.451 ± 1.985	0.005 ± 0.003	0.181 ± 0.027	1.231 ± 0.088
31	26	82.8	24.596 ± 3.649	0.006 ± 0.004	0.071 ± 0.006	1.587 ± 0.218
32	32	165.5	21.747 ± 5.949	0.003 ± 0.003	0.102 ± 0.011	2.237 ± 0.134
Min		41.4	21.747	0.003	0.071	1.231
Max		165.5	47.873	0.186	5.308	2.918
Mean		88.1	31.945	0.036	1.609	2.200

[a] Test 27 is the first test carried out after the new planting phase; after this test, the green wall panel was fertigated, and then test 28 was carried out.

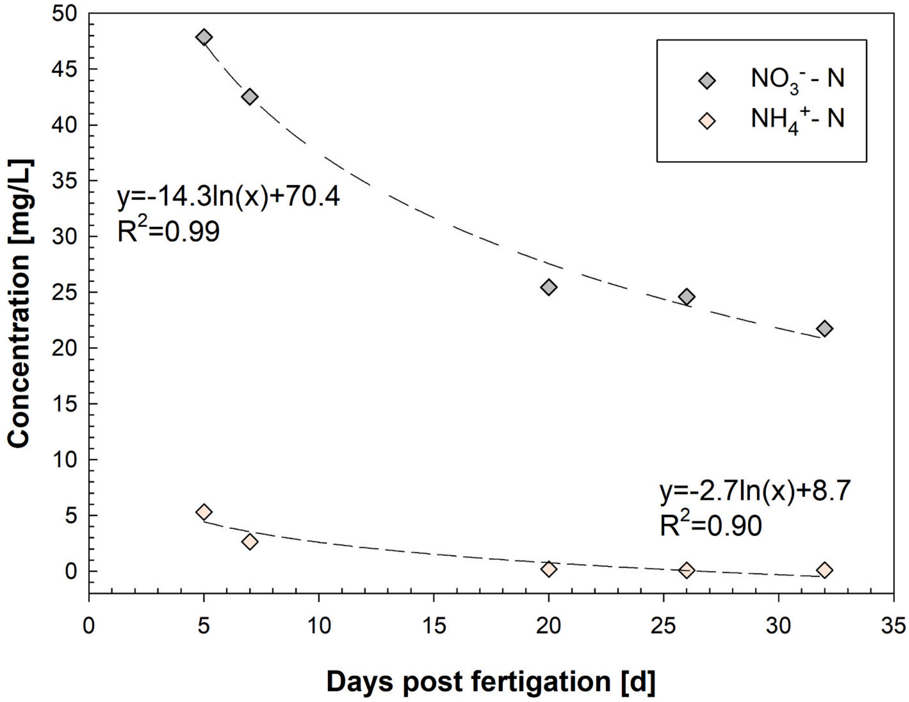

Fig. 2. Concentrations of NO_3^-–N and NH_4^+–N measured in the samples collected at the end of tests 28, 29, 30, 31, and 32 (in Table 6) vs. the days occurring after fertilizer use and related Regression plots.

highlight that the new planting phase and fertilizer use affected the nutrient concentration value. The higher value of nitrate concentration (29.5 mg/L) in test 27, which occurred before the application of fertilizer, was principally due to the new planting phase, which was made after around nine months from the first one and the vegetation was installed, like in a regular maintenance activity, in the same boxes without removing the existing soil substrate. Therefore, the results, as previously described might also be affected by the decaying materials of the previous planting phase. Moreover, fertilizer strongly influenced the nitrate concentration in the outflow released from the green wall panel. For the first two tests (28 and 29) after fertigation, values of >40 mg/L were obtained, and only after 20 days from fertigation the nitrate value was under 30 mg/L. Then, with the passing of days from fertigation, it is possible to observe a decreasing trend in the concentration of nutrients. This finding was also confirmed by the correlation analysis between the two nitrogen forms, added by the fertilizer (nitrate and ammonium nitrogen), and the days after the fertigation. The results obtained from this analysis showed a strong negative correlation between the "days post **fertigation**" and the concentration of NO_3^-–N ($r = -0.962$, t-test $= -6.100$, p-value $= 0.009$), and the "days post **fertigation**" and the concentration of NH_4^+–N ($r = -0.879$, t-test $= -3.198$, p-value $= 0.049$).

A similar conclusion emerges by considering Fig. 2, which displays the trend of nitrate and ammonium nitrogen concentrations after fertilizer use. In both cases, the scatter plots presented a logarithm behavior.

Overall, these results were also affected by the new vegetation, but this analysis highlights that fertilizer use should be considered carefully. Based on these outcomes, in agreement with the study by Emilsson et al. (2007), conventional fertilizers should not be used if the runoff of these green infrastructures is not adequately treated. Therefore, plants that have low nutrient needs (like succulent plants) should be preferred to flowering plants.

4. Conclusions

In this study, the hydrological efficiency and the nutrient leaching behavior of a new green wall system developed in the "Urban Hydraulic and Hydrology Laboratory" (LIU) at the Department of Civil Engineering (University of Calabria) are investigated.

The findings showed that the developed green wall panel has good retention capacity with an average value of the runoff coefficient (RC) of around 42 % when all the rainfall events are considered, while the average value of the time to start outflow (TSO), obtained by considering only the rainfall events which produced discharge from the test bed, is around 12 min. Both these indexes are strongly affected by the hydrological features of the simulated precipitation and by the volumetric water content in the soil at the beginning of the test. These findings can be confirmed by observing the significance of these parameters in the equations obtained through the multiple linear regression analysis.

The following main results emerged by observing the green wall panel's nutrient-leaching behavior. Nitrogen, which presents high mobility than phosphorous, is leached quicker. During the same monitoring phase, the highest nitrate values were obtained during the rainfall events with the lowest rainfall intensity and total inflow volume. Moreover, during the same rainfall event, it was observed a decrease in nitrate concentration and a slight increase in ammonium concentration. All the measured concentrations of nitrogen and phosphorous in the outflow from the green wall panel were very low except for some tests carried out after fertilization. Fertilizer use strongly increases the nitrate concentration in the outflow released from the green wall module, thus should be preferred plants with low nutrient supply requirements or follow other simple tricks (use of fertilizer with slow release and similar).

In conclusion, this new green wall system can be considered a suitable sustainable strategy for urban stormwater management regarding hydrological efficiency and low nutrient leaching in normal operational conditions.

Declaration of competing interest

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

Data availability

All relevant data are includedin the manuscript.

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