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The effects of multilayer blue-green roof on the runoff water quality

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ABSTRACT

In the context of climate changes, characterized by an increase of short but intense rainfall events and rise of the average temperature, the fast population growth and consequent urbanization require the implementation of innovative solutions to mitigate pluvial floods and, at the same time, reduce the water demand. Among the different nature-based solutions, multilayer blue-green roofs have been widely recognized for their high capacity of reducing runoff generation from rooftops, and their additional storage layer enables to collect water, which could be reused for different purposes. However, the quality of the collected water in a multilayer blue-green roof and the influence that the additional storage layer has on it have not been analysed yet. Following this knowledge gap, we investigated the potential benefits of a multilayer blue-green roof installed in Cagliari, with respect to a traditional roof. The outflow triggered by artificial irrigation and natural rainfall events was analysed, both from a quantitative and qualitative perspective. Results confirm the high contribution of multilayer blue-green roofs in mitigating runoff generation, which is however influenced by antecedent soil moisture and water level conditions. The outflow from the multilayer blue-green roof presents lower suspended solids and heavy metals concentrations than from a traditional roof. On the other hand, Carbon Oxigen Demand (COD) concentrations in the multilayer blue-green roof outflow exceed the limits defined by the Italian regulations (125 mg/l) for water discharge or reuse, partially due to the high residence time in the storage layer. Specific treatments could be planned to reuse the collected water for urban purposes.

1. Introduction

The fast population growth, that has characterized the last decades, is expected to continue in the future, enabling to reach 11.2 billion of people living on earth by 2100 [1]. Global water demand and urbanization are, hence, going to rapidly increase. At the same time, due to climate changes, the average annual temperature is rising [2], and rainfall events are becoming more intense but less frequent [3,4]. The consequences of climate changes are dual: (i) urban floods will become more frequent because of the increased soil imperviousness and (ii) available water resources are expected to be highly stressed and might not be enough to cover the global water demand. Several studies investigated the impacts that the combination of climate changes and population growth can have on urban

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floods and water demand increase [5–7]. Different structural and management strategies have been proposed to ensure flood risk mitigation [8–10] and a sufficient water supply [7,11–13].

Among the multiple climate change mitigation and adaptation measures proposed in the literature, green roofs have been largely investigated as nature-based solutions able to mitigate pluvial floods, totally or partially retaining the rainfall in the soil layer and, in the case of the multilayer blue-green roofs (MBGRs), also in the additional storage layer [14–21]. Indeed, thanks to the latter, MBGRs collect the water that percolates from the soil layer and store it; this increases the retention capacity of the green roof and makes the water available for possible reuses, with some hydraulic head on the ground level [22,23].

MBGRs have also shown multiple additional benefits for the sustainable development of resilient cities [24–26], especially if analysed following a Water-Energy-Food-Ecosystem nexus approach [27]. This tool can contribute to the thermal insulation of the building, reducing the costs of the energy consumption for the heating and cooling systems [28–30]. At the same time, it contrasts the urban heat islands effects, increasing the green areas and lowering the air temperature in the building surroundings [31–36], and it contribute to the CO_2 sequestration [37]. MBGRs can be used for the urban agriculture, providing a local food resource [38–41] and they provide additional aesthetic value, improving the quality of living in cities and having potential benefit on the physical and mental human health [42–45].

To exploit the benefits related to the potential water reuses, it is fundamental to know about the time variability of harvested water's quality. Different and contrasting findings and results are available in the literature for traditional green roofs, showing how this nature-based solutions can act both as a sink and a source of pollution for the rainwater [46–48]. Green roofs have been designed to exploit the soil porosity retaining pollutants and improving the water quality [49], however, in some cases, contaminants are released from the soil. Most of the analysis available in the literature focuses on the presence of nitrogen, phosphorous and heavy

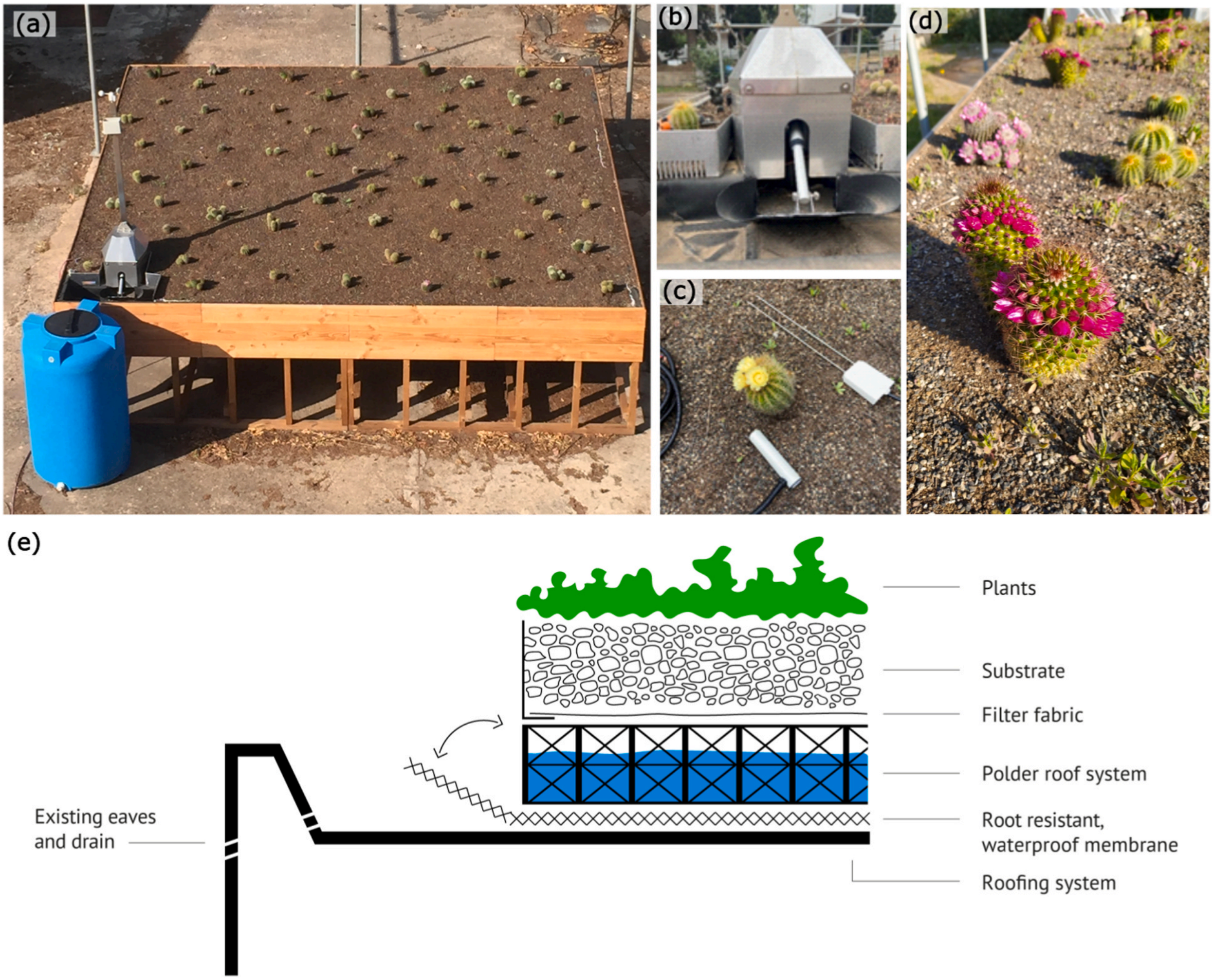

Fig. 1. Case study. (a) Multilayer blue-green roof prototype with the monitoring station to measure the climatic variables and rain barrel for the outflow. (b) Detail of the gate to manage the water storage layer. (c) Sensors installed to measure the water content variability in the soil layer. (d) Detail of the planted vegetation. (e) Schematic representation of multilayer MBGR, illustration modified from producer website: https://dakdokters.nl/en/polder-roofs/.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

metals in the green roof outflow [50], which is strongly influenced by the use of fertilizers and by the soil type. While phosphorous concentration is generally low in rainfall and its presence in the outflow is mostly due to the use of fertilizers, different analyses have shown contrasting results regarding nitrogen concentrations, highlighting how in some cases the soil layer can release the contaminant [51,52], and in other can retain it [53]. Among the heavy metals, the most investigated are Fe, Cu, Al, and Zn, which are generally retained by the soil layer [54,55].

Although several studies investigated the water quality from traditional green roofs, the potential of a MBGR for water reuse has not been explored yet. From a speculative point of view, traditional and MBGR may act in different ways on water quality dynamics because of the presence of the additional storage layer. The latter, in fact, could determine physical and biological processes, which in turn could strongly influence the water quality of the outflow. Only knowing the quality of the water will enable to identify the potential reuse of the outflow and, if needed, identify adequate treatments to meet the requirements requested by the European and Italian regulations.

Given the above premises, this work aims to investigate and test the potential benefits of a MBGR in terms of water collection and reuses, according to national and international regulations. We carried out field experiments on a MBGR prototype installed in Cagliari since June 2019 and on a traditional unaltered roof for comparisons, using irrigation and rainfall inputs and performing water quality analyses on the outflow. This work is a part of European Climate-KIC programme together with other three MBGR prototypes, produced by the Dutch company Metropolder, with the aim to investigate the potential impacts and benefits of this tool in the Mediterranean area [56].

The paper is structured as follows. Section 2 describes methodology followed in this work, starting from a presentation of the MBGR prototype located in Cagliari and the instruments installed to measure climatic variables and to monitor the eco-hydrological behaviour of this tool. In the same section, an overview of the experimental set up, of the laboratory analyses, and of the European and Italian regulations for the water reuse are introduced. Results are reported and discussed in Section 3, while Section 4 summarizes the main findings and conclusions and suggests possible future steps.

2. Methodology

This section describes the case study and the experimental set up to simulate artificial rainfall events and to evaluate the outflow quantity and quality. Finally, the last paragraph presents the actual national and international regulations for the water reuses.

2.1. Case study

The prototype of MBGR, installed in June 2019 as part of the EIT Climate-KIC Polder Roof Lab project, is located in the garden of the Faculty of Engineering and Architecture of the University of Cagliari, Italy (39.229096 N°, 9.109213 E°, Fig. 1a).

The MBGR is placed on a squared wooden structure (Fig. 1a), that ensures a 50 cm elevation from the ground. The surface of the prototype is 16 m^2 (4 m × 4 m) and is characterized by an 8 cm soil layer and a 10 cm storage layer, regulated with a remotely

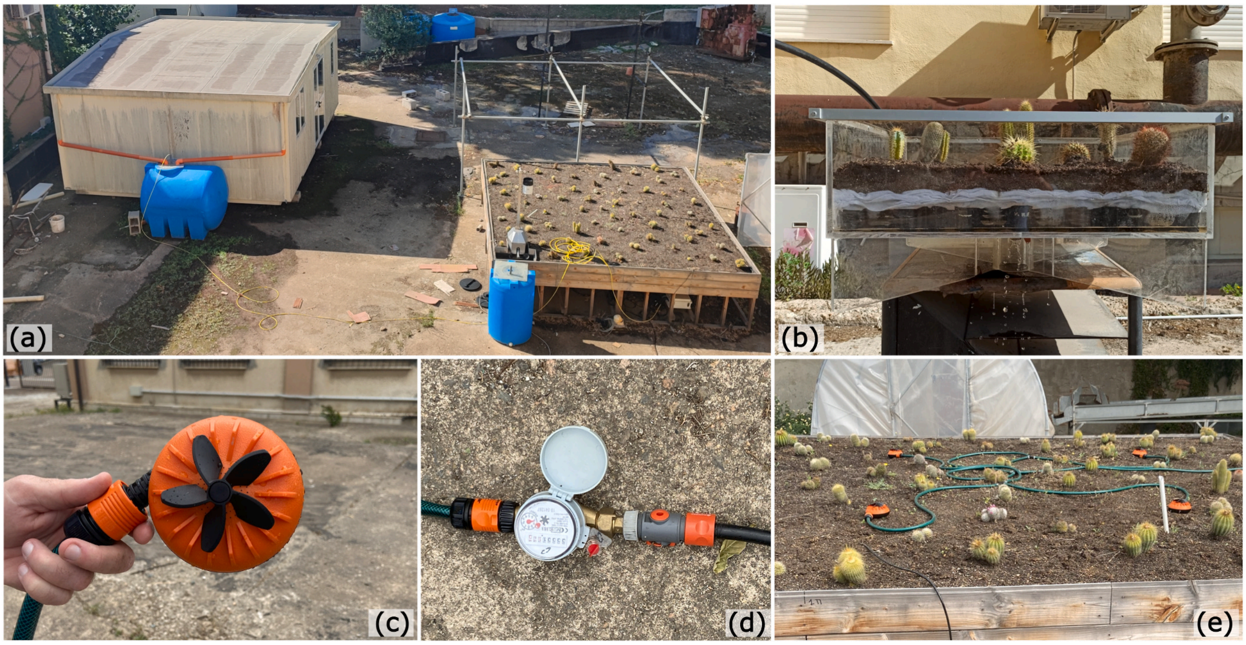

Fig. 2. Experimental set up: unaltered roof and MBGR (a) and TOY-GR (b). (c) Detail of the sprinklers used to simulate rainfall. (d) Detail of the flowmeter installed to measure the volume of water used as input. (e) MBGR equipped with sprinklers.

controlled gate (Fig. 1b). The soil has been classified as sand from a granulometric analysis. Common cactus plants (*Cactaceae,* Fig. 1d) have been installed on the MBGR, with the aim to investigate vegetation that do not need additional irrigation and could be representative of the native Sardinian species. This vegetation is characterised by Crassulacean Acid Metabolism (CAM), which shows a low evapotranspiration rate, due to the stomata closure during the day, but at the same time, it does not require any additional irrigation or maintenance to survive during the long arid summers, typical of the Mediterranean regions [57]. The substrate, used in the MBGR, is a commercial soil specific for cactaceae plants. A schematic representation of the multiple layers of the MBGR is illustrated in Fig. 1e.

The MBGR is equipped with a monitoring weather station, which enables to measure rainfall, wind speed and direction, air temperature and the water level and temperature in the storage layer. Four additional thermometers (MX2203, produced by HOBO) have been installed to measure the temperature in the soil, on the wooden structure (placed laterally, north face oriented) and below the MBGR (at two opposite corners). To better understand and estimate the water content dynamics in the soil layer, two soil moisture sensors (a CS650 Reflectometer and a Drill & Drop single sensor) have been placed at two opposite corners of the MBGR and connected to a datalogger to record soil moisture and temperature every 30 s (Fig. 1c). From the storage layer, the MBGR outflow is directed into a 350-l rain barrel, which has been equipped with a Baro-Diver®, to estimate the water level. Additional information about the MBGR prototype installed in Cagliari and about its retention capacity and thermal properties can be found in Ref. [56].

2.2. *Experimental set up*

The experimental set up, illustrated in Fig. 2, includes the MBGR prototype presented in Section 2 and a traditional unaltered roof (UN), located next to the MBGR and illustrated in Fig. 2a. The UN is a gabled roof of 20 m^2, covered with a tar cloth.

Both artificial and natural rainfall events have been considered. Six artificial events (3 for MBGR and 3 for UN), which guarantee an easier control of the sampling time, have been simulated during summer 2021, using clean water for irrigation. Similar weather conditions (i.e., air temperature, humidity, and absence of clouds) characterize the three artificial events. During these events, multiple samples have been collected, with the aim to evaluate how the water quality varies in time. Additionally, three natural events have been considered in Autumn 2021, to investigate the role of antecedent soil moisture conditions and the role of water quality input on the outflow. In this case, since the goal was different from the artificial events, only one sample has been collected. The quantitative description of both artificial and natural events is given in Table 1.

To simulate the rainfall events, four sprinklers, as the one shown in Fig. 2c, have been located on the MBGR and on the UN. These tools enable to reproduce an almost uniformly distributed rainfall over the MBGR or UN surface. For the MBGR, the sprinklers have been placed by dividing the total surface into four squares of 4 m^2 and putting one sprinkler in the centre of each one. Following this approach, we ensured an equal distribution of the artificial rainfall (Fig. 2e). For the UN, two sprinklers have been placed on each roof pitch and the outflow from only half roof was evaluated. The four sprinklers have been connected to the water supply system through a flowmeter (Fig. 2d) in between to measure the total volume of water used to simulate the rainfall.

Three samples of outflow have been collected with clean water bottles every 5 min for each artificial event. For the UN, the outflow delay with respect to artificial rainfall start is lower than 1 min, while, due to the retention capacity of the soil and storage layers, the MBGR requires more time before the outflow starts. Table 1 summarizes soil moisture and soil temperature initial conditions, input water volume and average intensity, as well as details on dates and duration of each experiment. It is worth noticing that all experiments have been carried out starting when the soil was completely dry, with a negligible water content. This ensures the same initial conditions for all the three artificial events on the MBGR. For each artificial event, a sample of water from the supply system, called "Zero.a", has been collected, analysed, and used as reference for samples collected from MBGR and UN roofs' outputs.

During the natural events, it was not possible to sample the beginning of the outflow, and consequently only one sample was collected from the receiving water tanks (Fig. 2a), thus representing the quality of the cumulated water during the event and mixed in

Table 1
Summary of the artificial and natural rainfall events.

	#	Date	ID	Start	End	*Total volume [l]*	*Average intensity [mm/h]*	Antecedent soil moisture [%]	Antecedent soil temperature [°C]
Artificial events	1	21/06/21	MBGR1.a	9:17	9:44	999	138	0.099	23.86
			UN1.a	10:34	10:51	186 (372/2)	66	–	–
	2	29/06/21	MBGR2.a	9:06	9:37	742	90	0.11	23.80
			UN2.a	10:05	10:18	136 (272/2)	63	–	–
	3	13/07/21	MBGR3.a	19:00	19:32	712	84	0.06	25.94
			UN3.a	19:52	20:03	117.5 (235/2)	66	–	–
Rainfall events	1	01/11/21	GR1.r	15:50	15:59	19.2	7.8	0.343	–
			UN1.r			11.7		–	–
	2	10/11/21	GR2.r	22:37	4:06	204.8	2.4	0.427	–
			UN2.r			127.6		–	–
	3	12/11/21	GR3.r	2:09	4:53	64	1.5	0.443	–
			UN3.r			41		–	–

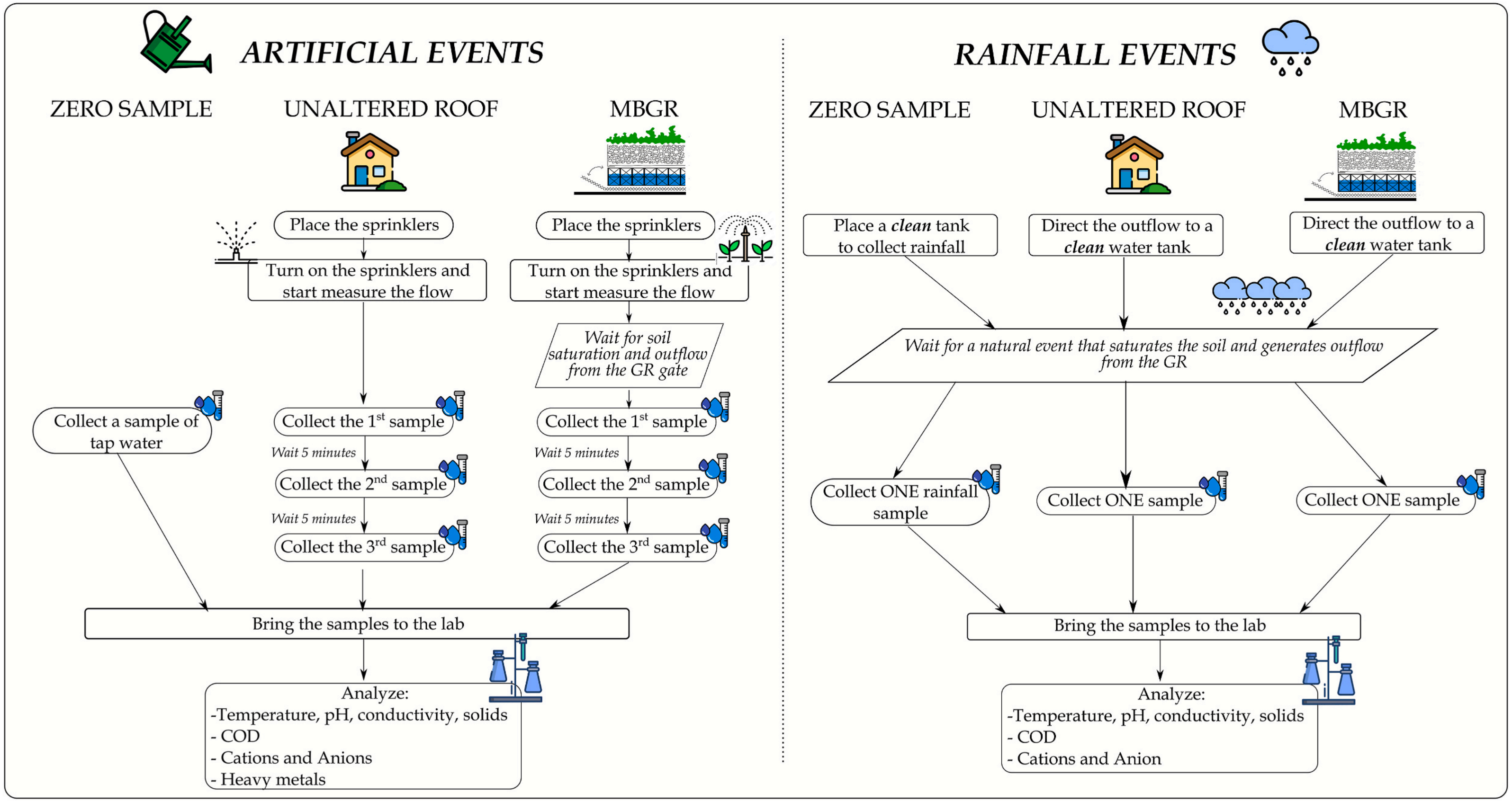

Fig. 3. Schematization of the developed experiments during artificial and rainfall events.

the rain barrel. For each natural event, the sample from the UN roof and from MBGR have been collected at the same time, limiting the sedimentation effects, and ensuring the same conditions for the two roofs. Between two subsequent experiments the tanks have been emptied and cleaned. Following the same approach also for natural events, a sample of rainwater, called "Zero.r" has been collected, analysed and used as reference for the outflow water quality analysis.

Fig. 3 schematize the methodology applied to develop the experiments for each scenario: different approaches are applied for artificial and rainfall events. In the first case, the main goal is to investigate the variability of the outflow quality in time, while for natural events the aim is to assess the average quality of the entire volume of collected water.

In addition to the experimental set up, a small Transparent Open laYered Green Roof (named TOY-GR) prototype has been used to better investigate on the influence of the additional storage layer on water quality, in particular on the Carbon Oxigen Demand (COD) dynamics. The TOY-GR, illustrated in Fig. 2b, consists of a plexiglass box of 0.7 m × 0.7 m and reproduces the characteristics of one module of MBGR: vegetation (Cactus), soil type and thickness (80 mm) and storage layer material and thickness (80 mm) are the same as the MBGR prototype. A small valve enables to manually reproduce the behaviour of the gate and to regulate the level in the storage layer. Thanks to the transparency of the plexiglass, the TOY-GR enables to easily visualize the flow dynamics in the soil and to better understand the retention capacity and the delay in outflow generation. The structure and the small dimensions allow to clean the storage layer, and consequently to investigate the influence of the sole soil substrate on the outflow water quality, and comparing the results with the MBGR outflow, to understand the impacts of the additional storage layer that cannot be regularly cleaned. In this study, the TOY-GR has been used specifically to investigate the impact of the additional storage layer on the COD concentration in the outflow. An artificial experiment on this small prototype has been conducted with tap water on September 18th, 2022, collecting 3 outflow samples, one every 5 min, and the COD concentration has been measured. In this way, we reproduced at small scale the artificial experiments on MBGR, focusing only on the role of the soil layer in governing the COD dynamics.

2.3. Maximum water retention capacity

Thanks to the two soil moisture sensors installed in the soil layer it was possible to observe the water content variability. Based on common soil definition, the maximum water retention capacity of the soil layer C_{MBGR}, defined as the maximum water depth that can be stored in the soil starting from dry conditions to leakage, can be estimated as:

$$C_{MBGR} = \left(s_{fc} - s_h\right) n Z_r \tag{1}$$

where s_{fc} and s_h are the field capacity and the hygroscopic point, respectively. The term ***nZr*** is the active soil layer depth, defined as the product of the porosity ***n*** and the soil depth ***Zr***, and it represents the space available in the soil to store water.

The commercial supplier classified the soil of the MBGR installed in Cagliari as loamy sand; following [58]; it is possible to assume a porosity of 0.43, a field capacity of 0.56 and an hygroscopic point of 0.14. The maximum water retention capacity C_{MBGR} is hence equal to about 14.5 mm. This threshold is expected to be the maximum rainfall water input that could be stored in the soil layer when the rainfall event occurs on dry soil. It is worth mentioning that MBGR could account also for additional water, that is the thickness of the additional layer.

2.4. Water quality analysis

The collected samples were immediately analysed or were stored for a few days at 4 °C. Total and volatile suspended solids (TSS, VSS), chemical oxygen demand (COD), ammonium nitrogen (NH_4^+), common cations and anions (chloride, sulphate, phosphate, nitrate) and metals were measured on collected samples. To evaluate the selected metal concentration (Cu, Zn, Fe, Al), a spike of sample collected was filtered at 0.45 μm and added with nitric acid (1 %). TSS and VSS were evaluated by filtering 250 ml of solution at 1.2 μm, and analysed according to Standard Methods [59]. Total COD was evaluated on solution filtered at 1.2 μm by spectrophotometric method (DR 2800 Lange, HACH, LCK 514). Ammonium nitrogen was measured on solution filtered at 0.45 μm by the spectrophotometric method, LCH LCK 304 (DR 2800 Lange, HACH). Common cations and anions concentration in 0.45 μm filtered solution were evaluated using ion chromatography (IC column AS14A, ICS90 Dionex). Elemental metal analysis on filtered and acidified samples was carried out by inductively coupled plasma ICP OES spectrometer (Optima 7000, PerkinElmer).

2.5. European and Italian regulations for water quality and minimum requirements for water reuse

To discuss on the quality of the outflow generated from a MBGR it is important to frame results on the policies and European and Italian regulations that define limits for the contaminants concentrations. At the European level, the Regulation (EU) 2020/741 of the European Parliament and of the council of 25 May 2020 sets the minimum requirements for water reuse. This regulation defines some guidelines that should be integrated at national level from 26 June 2023.

In Italy, the main reference for the water quality is the Legislative Decree 152/06 (D.Lgs 152/06), which regulates different aspects connected to the environmental protection, such as environmental assessment, water and soil protection, waste, air pollution and environmental damage. The D.Lgs. 152/06, in the Third Part, transposes the European Water Framework Directive 2000/60/EC [60] and the Directive 91/271/EEC concerning urban wastewater treatment. This regulation defines the requirements of contaminant concentrations that should be met by urban wastewater discharges. In particular, Annex 5 to the Third Part reports the contaminant concentrations that cannot be exceeded when discharging wastewater in the sewer system and in the water body. Regarding the parameters that are investigated in this study, the COD limits set as reference according to the national standards are equal to 500 mg/l for discharging in the sewer system and to 125 mg/l for discharging in the water body. The limits for the investigated heavy metals are reported in the Table 2.

Regarding the possibility of reusing wastewater, the Italian regulation refers to the Ministry Decree 185/2003 (DM 185/03), which defines the regulations for the reuse of domestic, urban and industrial wastewater, identifying the minimum required quality for each potential use. This regulation aims to improve the water resource management, limiting the pressure on the water supply system, the water abstraction from groundwater and from water bodies and the impacts on the hydrological cycle. Possible water reuses considered by the DM 185/03 are irrigation, for any crops, also for human and animal consumption, and for urban green spaces, urban uses, such as street cleaning, and industrial uses, such as fire prevention, cooling systems or washing. The regulation defines the contaminant concentration limits that the outflow from the Wastewater Treatment Plant needs to meet. The COD limit is set at 100 mg/l, while the heavy metals are reported in Table 2.

3. Results

3.1. Leakage dynamics

As described in section 3.1, to evaluate the MBGR performance in mitigating runoff generation, the soil moisture dynamics during artificial and natural events has been investigated. Fig. 4 illustrates for each artificial (upper subplots) and natural (lower subplots) event the rainfall time series (blue line, reverse secondary axis) and the related variation of the soil moisture (green line). The soil moisture is obtained as average of the recordings of the two installed sensors, described in Section 2, which are placed at two opposite corners. The field capacity (yellow line) and the hygroscopic point (orange line) for a sandy loam soil [58] are also plotted in Fig. 4. For artificial events, light blue vertical lines indicate the outflow start (solid line), which corresponds to the first sampling time, and when the other two samples have been collected (dashed lines). Before the events start, the soil moisture is close to the hygroscopic point, confirming the experimental hypothesis that the soil is dry. Then, when the artificial rainfall starts, the soil moisture consequently increases until it reaches a stable value, close to the field capacity: at this point, the leakage from the soil layer starts.

As calculated in Section 3.2, the expected maximum retention capacity of the soil layer of the MBGR is about 15 mm. Focusing on artificial experiments, the observed water depth that leads to leakages here varies between 13.36 mm and 16.08 mm: these values are associated to the amount of rainfall that could be entirely retained and stored in the soil. The measured soil moisture when leakage starts is slightly lower than s_{fc}: this is due to the fact that the soil moisture is recorded at point scale, and the measure does not take into account the presence of macropores and preferential flows. Notwithstanding with this little discrepancy, the experiments quantified the maximum amount of water that could be stored in the soil layer, taking into explicit account the role of soil heterogeneity.

On the other hand, the rainfall events that triggered leakage occurred on almost saturated soil. This situation demonstrates how the antecedent moisture condition are crucial in determining the retention capacity of the system. A traditional green roof produces outflow when the soil is saturated; the MBGR, even with a saturated soil, has a residual retention capacity in the additional layer, which depends on how this volume is managed.

3.2. Water quality

To evaluate the potential impact of the MBGR installation on the outflow water quality, several parameters have been investigated, for both artificial and natural rainfall events. Three samples have been collected during each artificial event, every 5 min from the incipient outflow, with the aim to investigate how the concentration varies with time. For natural rainfall events, instead, the outflow was directed to the rain barrel, and only one sample of it has been collected at the end of the event, thus representing average conditions. The rain barrel has been cleaned between each event to avoid contamination.

3.2.1. Temperature, pH, conductivity, total and volatile suspended solids

The first analysis, plotted in Fig. 5, focuses on basic parameters: temperature, pH, conductivity, total (TSS) and volatile suspended solids (VSS). Results are presented for both artificial (orange lines) and natural (blue lines) events.

Water temperature (Fig. 5a) has been measured only for artificial events when each sample was collected. For natural rainfall events, the sample was not collected immediately after the event, and for this reason the temperature was not considered significant and thus not measured. The first two artificial events have been held in the morning, when both unaltered roof and MBGR surfaces were exposed to direct sunlight, while the last experiment has been carried out in the evening. For this reason, the water temperature is higher during the first two artificial events. Observing the first sample from the unaltered roof during UN1.a, it is clear how the hot

Table 2
Maximum acceptable concentrations for heavy metals discharges to sewer and to receiving waters following the D.Lgs 152/06 and limit values for the wastewater treatment plant effluents following the DM 185/03.

		Aluminium [MG/L]	Copper [MG/L]	Iron [MG/L]	Zinc [MG/L]
D.Lgs. 152/06	Sewer system discharge	2	0.4	4	1
	Water body discharge	1	0.1	2	0.5
DM 185/03	Limits for agricultural reuse	1	1	2	0.5

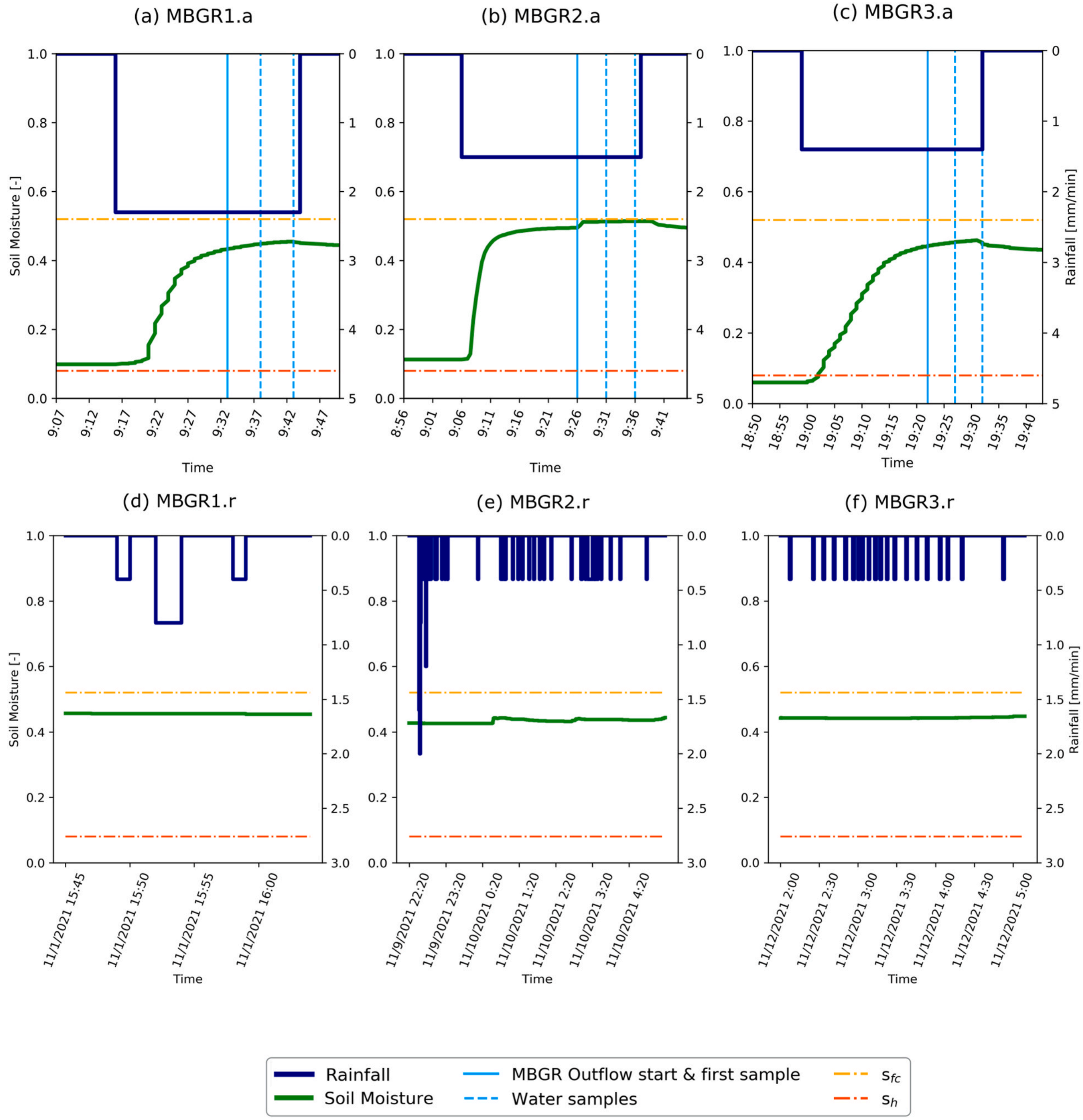

Fig. 4. Simulated rainfall and correspondent soil moisture. Dark and light orange dot-dashed lines represent s_h and s_{fc}, respectively. Light blue solid line indicates the starts of the outflow from the MGBR, which corresponds to the first sample. The other two samples are highlighted by the light blue dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

surface has a high impact on the outflow temperature, which reaches up to 32 °C during the first event. On the other hand, the MBGR showed a good mitigation of the water temperature for the first sample, and the capacity to maintain the outflow temperature almost constant.

The pH (Fig. 5b) measured in the Zero.a sample, corresponding to the artificial experiments, is equal to 7.6. The first collected sample of each artificial event, from both MBGR and UN, showed lower pH values (which vary between 7 and 7.4 and between 5.6 and 6.5, respectively) than the following samples and suggested that the UN outflow is more acidic than the MBGR one. From the second sample, however, an opposite trend is observed: while the MBGR outflow shows a little decrease of the pH (6.3–7.3), probably due to the soil which releases organic matter and soluble salts, the UN outflow is characterized by a pH higher than the first sample (7.4–7.9). During the natural events, on the other hand, pH is almost constant and the differences between the outflow from both roofs are

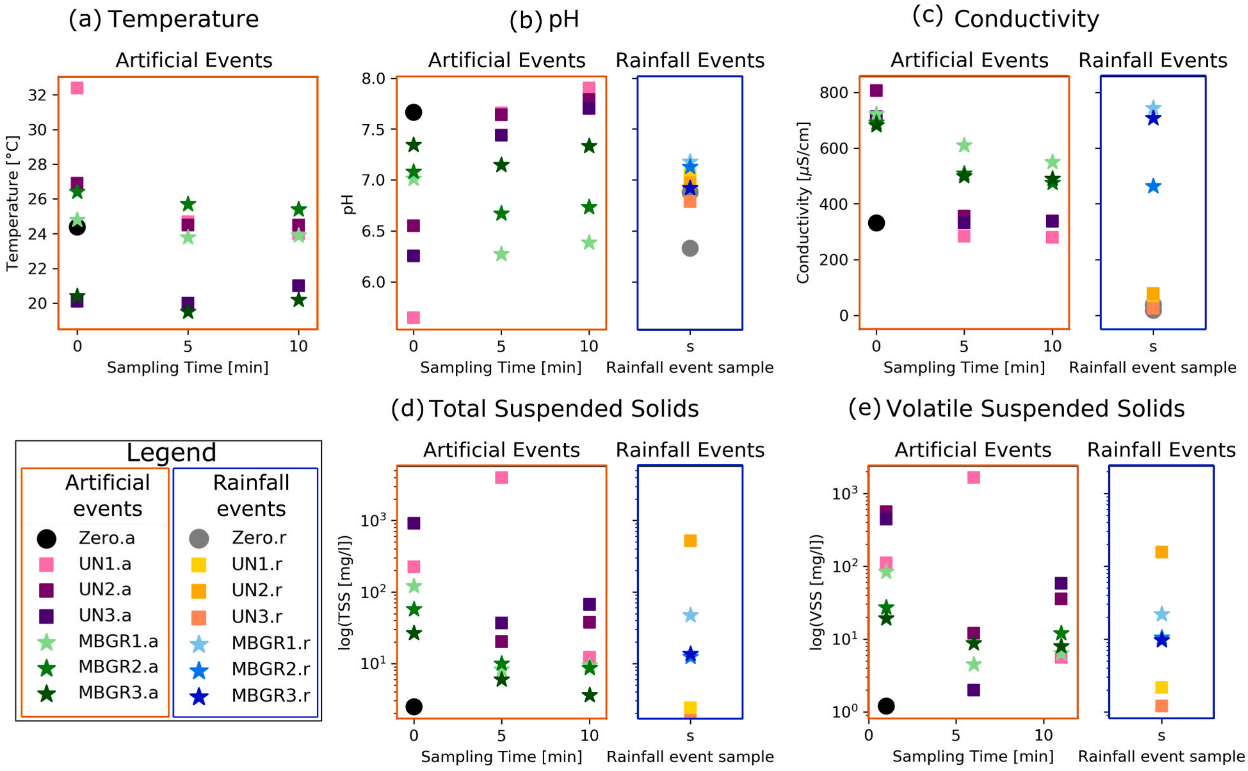

Fig. 5. Water quality results: (a)Temperature, (b) pH, (c) conductivity, (d) total suspended solids and (e) volatile suspended solids. Total and volatile suspended solid are plotted on a logarithmic scale. For each parameter, orange lines frame the samples from artificial events, while blue lines highlight results from natural events. Circles represent the Zero.a samples; squares indicate samples from the unaltered roof and stars illustrate the MBGR samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

negligible. All measured values, however, fall in the pH ranges defined in the National Regulations, which accept pH values between 6 and 9.5 for agricultural reuse.

Conductivity of the outflow is initially affected by both MBGR and unaltered roofs, being in the first sample almost double of the Zero.a sample (Fig. 5c). The conductivity decreases with time and already from the second sample the influence of the unaltered roof is negligible. On the other hand, a higher conductivity due to the MBGR presence persists over time. A similar situation is experienced during the natural events, where the conductivity of the rainfall and of the unaltered roof outflow is close to zero, while for the MBGR outflow varies between 450 μS/cm and 750 μS/cm. It is important to note that, although conductivity results to be increased by MBGR, sample values satisfy the requirements imposed by the National Regulation for the water reuse, being significantly lower than the limiting threshold of 3000 μS/cm.

The presence of TSS and VSS (Fig. 5d and e, in logarithmic scale) is negligible in the MBGR outflow, while it is observed in the unaltered roof outflow, especially in the first sample. This is caused by the presence of accumulated sediments over the roof during non-rainy periods. The high value of both TSS and VSS in the second sample of UN1.a sample is probably due to errors in the measurements or due to an accumulation effect and can be, hence, considered as outliers. Results suggest that MBGRs also present the advantage to release less TSS and VSS than unaltered roofs, and their installation should be hence evaluated. The MBGR presence enables to retain solid particles from the atmosphere; however, although the TSS concentrations from MBGR are lower than from unaltered roof, a filtration process is still required before considering potential water reuse, since the concentrations are above the 10 mg/l limit established by the DM 185/03.

3.2.2. Chemical oxygen demand (COD)

One of the most interesting parameters to investigate is the Chemical Oxygen Demand (COD), which represents a measure of the amount of oxygen consumed by the chemical oxidation of organic and inorganic compounds present in the water. High concentrations of COD often suggest high presence of organic substance, which can act as pollutant for the receiving waters and could lead to a reduction of the dissolved oxygen, which is necessary for the aquatic species.

In the analysis illustrated in Fig. 6, the COD measured during artificial and natural events is investigated in relation to the National Regulations, described in Section 3.4, which set a concentration limit of 125 mg/l for discharge in water bodies (D.Lgs 152/06) and of 100 mg/l for reuse in agriculture (DM 185/03).

Several studies showed how the COD concentration in the outflow from traditional green roofs is characterized by high variability

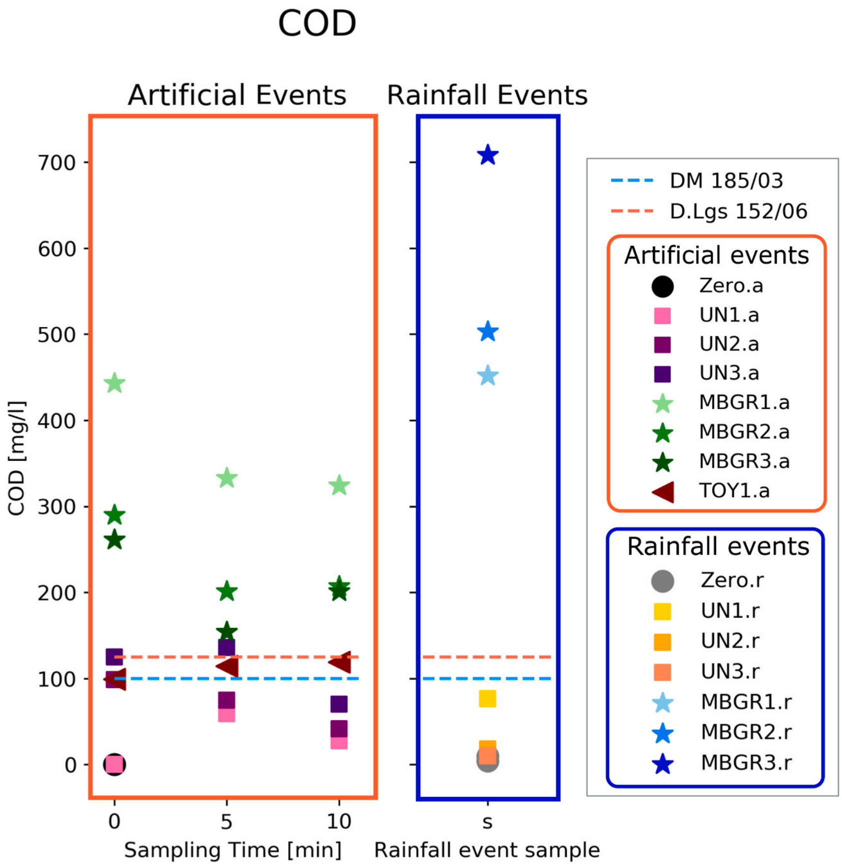

Fig. 6. Water quality results: COD.

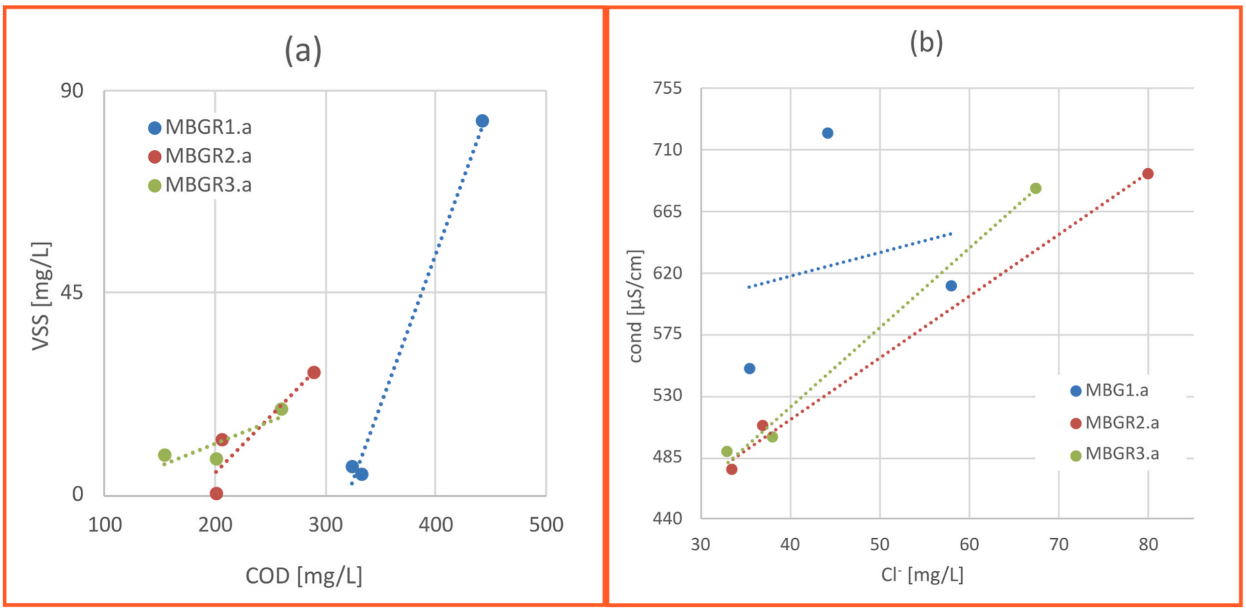

Fig. 7. (a)Scatterplot between COD concentration and VSS. (b) Scatterplot between Cl^- and conductivity.

[61] and it is strongly influenced by soil type and thickness [62], vegetation and rainfall intensity [63]. The COD concentration in the outflow from traditional green roofs varies between 10 mg/l and 200 mg/l [46,64–66].

COD concentrations observed in all samples of our experiments from MBGR present high values, generally higher than 200 mg/l for artificial events, and higher than 400 mg/l for natural events. These could be explained by two reasons. First, the commercial soil used for the substrate contains organic matter, and the soluble fractions could be easily released during the water percolation. Secondly, the additional storage layer, which cannot be regularly cleaned, collects solids and organic matter during time, and can be the ideal nest for larvae, insects, and other small animals.

With the aim to verify this hypothesis, we included in the analysis an additional experiment with the small prototype TOY-GR, which has the same soil and vegetation of the MBGR, but where the additional storage layer was regularly cleaned to preserve the outflow COD concentration from any influence due to dust or residuals. Results concerning the experiment with the TOY-GR, highlighted with dark red triangles in Fig. 6, show lower values than the ones from the MBGR. Observing the trends over time, the COD from MBGR presents a high peak in the first samples (330 mg/l – 443 mg/l) and decreases in the following two samples of each artificial event, until a final value (154 mg/l - 261 mg/l), while the COD concentrations in the outflow from the TOY-GR are almost constant (100 mg/l - 125 mg/l). The different trend of the COD concentrations in the outflow from MBGR and TOY-GR can, hence, be at least partially due to an accumulation of organic matter in the storage layer of the MBGR, which is washed out at the beginning of the outflow.

The COD concentration measured in the samples collected during the three artificial events increases with VSS concentration (Fig. 7a). Moreover, the measured water pH on MBGR leaching is around the neutrality (Fig. 5) during the artificial and real events and, in these conditions, humic and fulvic acids contained in soil can be solubilized into water, contributing to increase the COD values in a stable form, which is not harmful but rather beneficial to plants in case of irrigation reuse. In the same samples, as conductivity increases, Cl^- concentration shows the same behaviour (Fig. 7b).

3.2.3. Cations and anions

The analysis of the cations and anions focuses on the investigation of Ammonium, Sulphate, Nitrate, and Chlorine, as plotted in

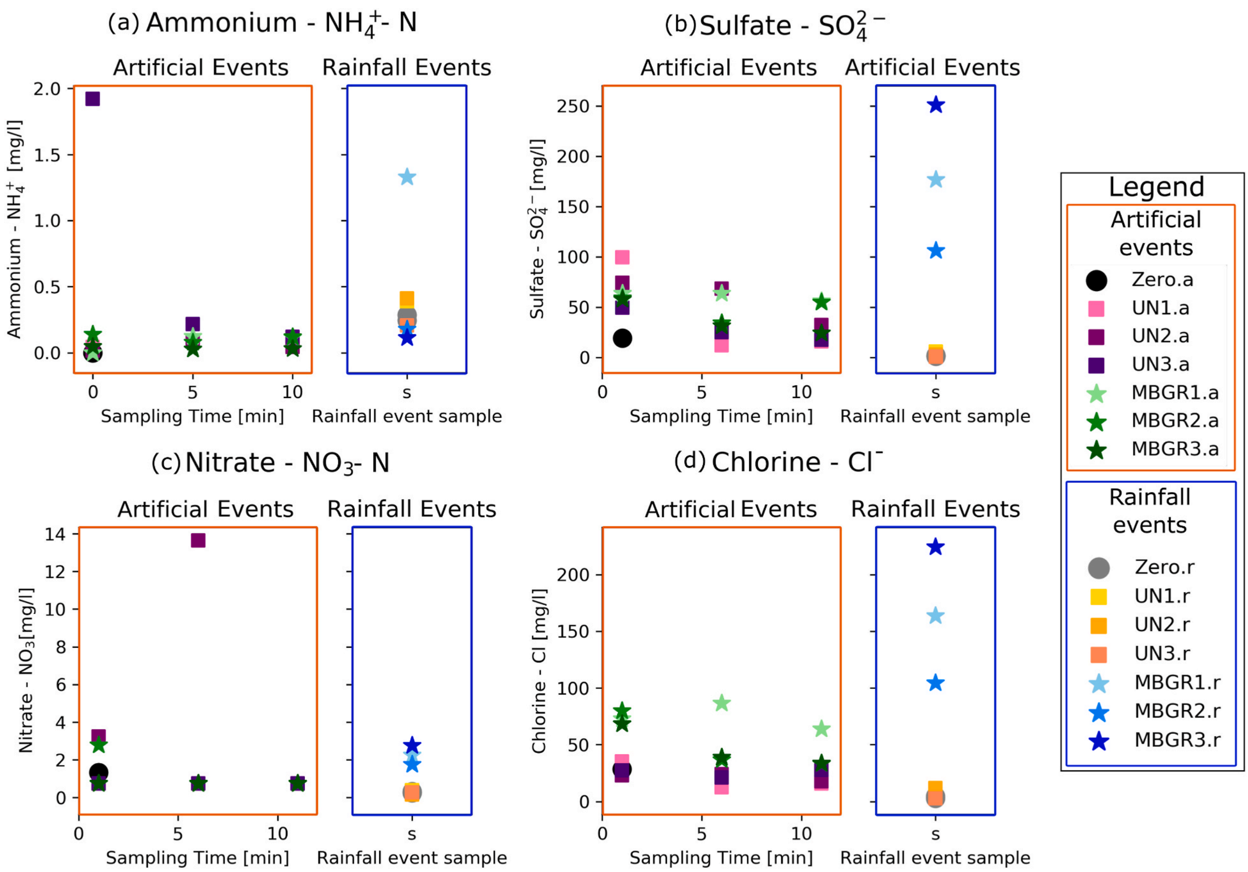

Fig. 8. Water quality results: Cations and Anions. (a) Ammonium, (b) Sulphate, (c) Nitrate and (d) Chlorine. For each parameter, orange lines frame samples from artificial events, while blue lines highlight results from natural events. Circles represent the Zero.a sample; squares indicate samples from the unaltered roof and stars illustrate the MBGR samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 8. Results are presented for both artificial (orange frame) and natural (blue frame) events.

The analyses of the Ammonium, illustrated in Fig. 8a, do not highlight significant differences between the unaltered roof and the MBGR outflow. The recorded ammonium concentration is lower than 0.4 mg/l for the artificial events and lower than 0.5 for the natural ones, except for two outliers, UN3.a (first sample) and MBGR1.r, which present high values (1.92 mg/l and 1.33 mg/l). Overall, recorded concentrations are lower than the limits imposed by the National Regulations, i.e., 2 mg/l threshold for reuse in agriculture (DM 185/03).

The presence of sulphate, plotted in Fig. 8b, tends to decrease during the artificial events, especially in the outflow from the unaltered roof. On the other hand, during the natural events the SO_4^{2-} concentration is particularly high in the outflow from MBGR, suggesting that the soil or the material that constitutes the storage layer release it in the water. In all samples, however, the SO_4^{2-} concentration is lower than the limit set for the reuse in agriculture (500 mg/l, DM 185/03).

Similar results are observed for nitrate concentrations, reported in Fig. 8c, which decrease in the outflow during the artificial events, but present values in the MBGR outflow during the natural events higher than the UN values.

Concerning chlorine (Fig. 8d), the MBGR structure releases it in the outflow, during both natural and artificial events. The concentrations recorded in the MBGR outflow during the natural events are, however, higher than during the artificial ones, ranging between 100 and 250 mg/l.

It is important to underline that for the MBGR prototype no fertilizer has been added, since the installed vegetation did not require it for growing in the local weather conditions. Other vegetation species, subjected to different climate conditions might need chemical fertilizers, which could determine an increase in the amount of nutrients released from the soil substrate.

3.2.4. *Heavy metals: aluminium, copper, iron, zinc*

Besides the presence of contaminants described in previous sections, we also investigated concentrations of heavy metals, which are particularly dangerous for the human health, and play a key role in the potential reuse of the stored water. Results, concerning Aluminium, Copper, Iron and Zinc, are plotted in Fig. 9 for the first artificial event, and compared to the limits defined by the National Regulation for the discharge in sewer systems and in natural water bodies (D.Lgs. 152/2006), and for the reuse in agriculture (DM 185/03). The presence of heavy metals has been tested for the first artificial event and, since the results showed very low concentrations in MBGR outflow, the analysis was not extended to the other events.

In contrast, high levels of Aluminum and Zinc were detected in unaltered roof outflow. Results shows concentrations exceeding the prescribed limit for discharging in sewer system (D.Lgs. 152/06, which imposes at maximum 2 mg Al/l and 1 mg Zn/l), have been measured in the first sample. Although the recorded values of Copper and Iron are below the limits defined by National Regulations for

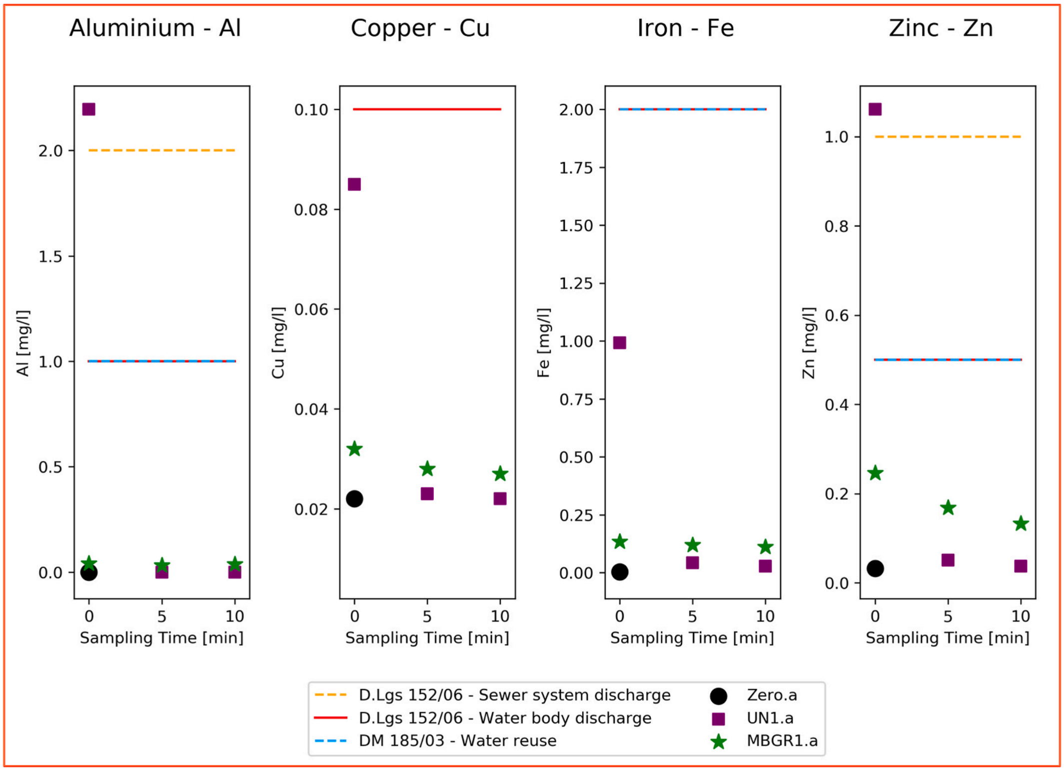

Fig. 9. Water quality results: heavy metals. Aluminium, Copper, Iron, Zinc. Circles represent the Zero.a samples, squares indicate samples from the unaltered roof and stars illustrate the MBGR samples.

discharge in water bodies and reuse in agriculture, the concentrations observed in the first sample from the unaltered roof are higher than the other samples. This is due to the fact that many contaminants, including heavy metals, accumulate on the roofs during dry periods and are immediately washed off with the first rainfall event. These results confirm the importance of separating the first part of the outflow generated from traditional roofs, which contains high contaminant concentrations and direct this fraction to specific treatments.

For Aluminum and Iron, the concentrations observed in the MBGR outflow are close to the Zero.a sample and do not vary in time, highlighting the fact that these elements are not released from the soil. The presence of MBGR, on the other hand, has an impact on the Copper and Zinc concentration in the generated outflow: contaminants are released from the soil or from accumulations in the additional water storage, especially at the beginning of the rainfall event. Concentrations are, however, low and meet the limits prescribed by the National Regulations for discharge in water bodies (D.Lgs. 152/06, 0.1 mg Cu/l and 0.5 mg Zn/l) and water reuse (DM 185/03 1 mg Cu/l and 0.5 mg Zn/l). Unlike the outflow from unaltered roof, the one from the MBGR prototype installed in Cagliari does not require treatment to remove heavy metals and can be directly reused for urban purposes, such as garden/parks irrigation.

4. Discussion

4.1. Traditional vs multilayer blue-green roofs

As already shown in multiple studies [22,56,67], MBGRs ensure a higher potential in reducing the runoff limitation from rooftops, thanks to the additional storage layer, providing a huge benefit for the city. Looking at the quality of the MBGR outflow, it is difficult to compare it with what is available in the literature for traditional green roofs, since there is not a common procedure and results are often contrasting. Green roofs can, in fact, act both as sink and source of pollutants [46], depending on soil type and thickness, vegetation, use of fertilizers etc. Overall, the results obtained for the MBGR are aligned with the ones available for traditional green roofs, except for the COD concentration. As mentioned in Section 3.2.2, the COD concentration in the outflow from traditional green roofs presents a high variability (from 10 mg/l to 200 mg/l [46,64–66]), due not only to the different characteristics, i.e., soil and vegetation types, soil thickness and use of fertilizers, but also due to different types of analysis that are approached in the laboratory. These values are confirmed by the artificial experiment carried out on the TOY-GR, where COD values in the range 100 mg/l - 125 mg/l have been observed. On the other hand, MBGR, showed higher COD values than traditional GR, with a concentration that varies between 154 mg/l and 443 mg/l for artificial events and presents values higher during natural rainfall. These differences can be explained by the presence of the additional storage layer, where organic matter accumulates during the dry periods and it is then flashed out with the outflow.

4.2. Advice for policymakers

Results presented in Section 3 confirm the high potential of MBGRs for a sustainable development of urban areas. MBGRs ensure a high reduction of the runoff generated during rainfall events and can hence be a powerful instrument to mitigate pluvial flood, especially if installed at large scale, using all the available and suitable roof of the city [68]. Although the presented study confirms the high retention capacity of the MBGR only in Mediterranean areas and does not investigate multiple case studies in different climates [21], presented how the retention capacity varies around the globe, dividing the different climate conditions into 5 classes, based on the rainfall and potential evapotranspiration annual patterns. From this study it is possible to derive the behaviour of this nature-based solution under different climatic conditions.

As already mentioned in the Introduction, the MBGR presents multiple benefits for the urban areas, also thanks to the additional storage layer, which can be used to collect water. Based on the analysis described in this study, the stored can be used mostly for irrigation of the MBGR itself or for small urban gardens. Promoting the self-irrigation of the MBGR should not be underestimated by stakeholders and policymakers: limited maintenance costs and effort is a key point increase the acceptability and interest of the society in this nature-based solution. Moreover, with additional treatments to reduce the COD concentration, the collected water could be used for multiple domestic non-drinkable purposes, limiting the urban request to the water supply system.

5. Conclusions and future directions

This work aimed to characterize the outflow from the multilayer blue-green roof (MBGR) prototype installed at the University of Cagliari (Italy), both in terms of quantity and quality, and compare it with the outflow from a traditional unaltered roof (UN). The outflow has been investigated during three artificial events, generated with an irrigation system, during Summer 2021, and three natural events, during Autumn 2021. Results confirm the high potential of this nature-based solution in mitigating the runoff generation, by accumulating a rainfall fraction in soil pores up to a maximum that has been here first theoretically hypothesized and then measured. Moreover, the importance of the antecedent soil moisture conditions for the retention capacity of the MBGRs has been highlighted by the fact that rainfall events occurring on saturated soil immediately generates leakage toward the additional storage layer.

Regarding the water quality, total and volatile suspended solids released in the water outflow by MBGR are lower than by UN roofs, as well as heavy metals concentrations. The MBGR advantage is particularly evident on the first sample collected in each artificial experiments, highlighting in contrast the importance of the treatment of runoff corresponding to the first minutes of rainfall events especially for UN roofs. In both cases, however, a filtration treatment is required before considering potential water reuses, such as irrigation. On the other hand, MBGR releases high COD concentrations, caused not only by the presence of the soil substrate, but also by the accumulation of organic matter in the additional storage layer, that is washed out with the outflow. Although the high values of COD concentrations measured in all samples, the MBGR outflow is suitable for being reused for garden irrigation, suggesting how the implementation of this tool and the consequent reuse of collected water could reduce the percentage of water directed to the wastewater treatment plant and support the sustainable urban development.

Results obtained in this study are, however, limited to one type of soil (classified as sand) and vegetation (Cactacee). Different vegetation, soil type and the potential use of fertilizer could strongly affect the quality of the MBGR outflow. For this reasons, multiple vegetation type and soil types and thickness should be evaluated in future studies.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Elena Cristiano: Visualization, Methodology, Conceptualization, Writing - original draft. **Alessandra Carucci:** Writing – review & editing, Supervision. **Martina Piredda:** Writing – review & editing, Methodology, Data curation. **Emma Dessì:** Data curation. **Salvatore Urru:** Data curation. **Roberto Deidda:** Writing – review & editing, Supervision. **Francesco Viola:** Writing – review & editing, Methodology, Conceptualization.

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.

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