

Removing water-relevant substances from green roof and façade runoff via decentralized granular activated carbon filtration – a pilot scale study

Élimination de substances liées à l'eau provenant des toitures végétalisées et des façades grâce à une filtration décentralisée par charbon actif granulaire – une étude à l'échelle pilote

Daniel Nieß & Brigitte Helmreich

Chair of Urban Water Systems Engineering, Technical University of Munich

daniel.niess@tum.de & b.helmreich@tum.de

RÉSUMÉ

Les toitures végétalisées (TV) sont de plus en plus utilisées dans les zones urbaines pour atténuer les effets du changement climatique, favoriser la biodiversité et réduire les pics de chaleur et de ruissellement. Cependant, les ruissellements des TV peuvent contenir des nutriments, des métaux et des pesticides provenant des substrats, des barrières anti-racines et des peintures de façade. Ces substances peuvent détériorer les écosystèmes aquatiques. Cette étude examine l'efficacité d'un filtre décentralisé à charbon actif granulé (CAG) pour l'élimination des pesticides et des nutriments issus du ruissellement des TV. Des tests en laboratoire ont évalué onze types de CAG et leurs mélanges, notamment avec de l'hydroxyde de fer, de la calcite et des copeaux de fer, dans des conditions contrôlées. Le CAG le plus performant a montré une rétention élevée des pesticides (jusqu'à 98 %) et une forte élimination du phosphate (>99 %), bien que l'élimination du carbone organique dissous reste limitée. Un système pilote a été installé sur une toiture extensive de 1 000 m². Durant un mois, neuf événements pluvieux ont été suivis à l'aide de systèmes automatisés de mesure et d'échantillonnage. Les résultats montrent des efficacités d'élimination du Mecoprop variant entre 27 % et 84 %, influencées par les périodes sèches successives et la quantité de précipitations. Ces résultats démontrent le potentiel de la filtration décentralisée par CAG pour réduire la pollution du ruissellement des TV et pour promouvoir une gestion durable des eaux urbaines.

ABSTRACT

Green roofs (GRs) are increasingly being applied in urban areas to mitigate the effects of climate change, enhance biodiversity, and reduce heat and stormwater runoff peaks. However, GRs runoff may contain nutrients, metals, and pesticides originating from substrates, root barrier layers, and façade paints. These substances may deteriorate aquatic ecosystems. This study examines the effectiveness of a decentralized granular activated carbon (GAC) filter in removing pesticides and nutrients from GR runoff. Laboratory batch experiments tested eleven GAC types and mixtures, including those with iron hydroxide, calcite, and iron shavings, under controlled conditions. The best-performing GAC achieved high pesticide retention (up to 98%) and strong phosphate removal (>99%), though DOC removal was limited. A pilot system was installed at the runoff of a 1,000 m² extensive GR. The monitoring of the first nine rain events using automated flow and sampling systems show Mecoprop removal efficiencies ranging from 27% to 84%, influenced by consecutive dry weather days and the volume of rainfall. The findings highlight the potential of decentralized GAC filtration to reduce pollutants in GRs runoff, supporting sustainable urban water management. However, the treatment system must be improved.

KEYWORDS

(pesticides, rainfall characteristics, stormwater treatment, technical scale, urban green infrastructure)

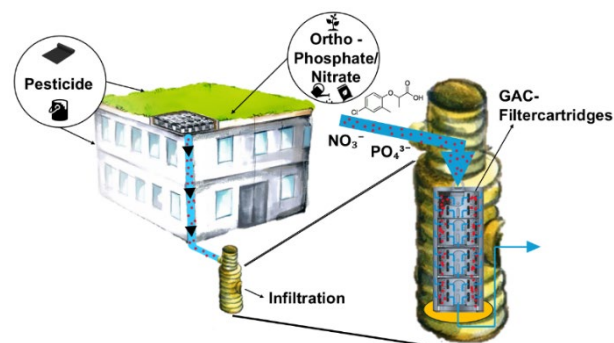
1 INTRODUCTION

Green roofs (GRs) serve as an important tool to mitigate climate change in urban areas (Brendel et al., 2025). They increase evapotranspiration, influence the microclimate by lowering the surrounding air temperature, increase biodiversity, and can help minimize peak flows during heavy rain to mitigate the effects of extreme weather phenomena (Zölch et al., 2017).

Even though the positive effects outweigh the negative, there are some downsides to GRs. Their runoff contains multiple water-relevant substances that may deteriorate the quality of water bodies and negatively impact aquatic life (Ouellet et al., 2021). It is essential to remove these substances before runoff is discharged into surface water bodies or infiltrated into groundwater bodies (Cristiano et al., 2021).

The sources of water-relevant substances are the substrates and root barrier layers on GRs, as well as the paints from façades. As each GR must be equipped with a root barrier layer, which protects the building from damage caused by the roots. These root barriers are often bitumen sheets that contain pesticides, such as Mecoprop (MCPP). Other pesticides, such as Diuron and Terbutryn, are used as fungicides and algaecides in façade paints. These pesticides can impact the endocrine systems of aquatic life to the point of endangering their survival and potentially leading to extinction (Meftaul et al., 2020). While non-chemical alternatives are available on the market, their use is still limited due to higher costs and more challenging handling required by their stiffness. Therefore, chemical root barriers remain state-of-the-art in GRs.

As there are different types of GRs, the substrates can vary in their composition. Standard materials are expanded shale or clay, lava, pumice, brick chippings, and green compost, which can naturally contain water-relevant substances. We found that some of these materials emit high concentrations of water-relevant substances, including nitrate, orthophosphate, and heavy metals such as copper and vanadium. Especially green compost is needed in these substrates, as it contains essential nutrients, such as nitrates and phosphates, for plant survival (Czemieli Berntsson, 2010). Unfortunately, the nutrients are often quickly released from the substrate, necessitating additional fertilization. Both actions pose a threat to aquatic life.



Our decentralized, granular activated carbon filter was tested for its ability to remove nutrients and pesticides in

Figure 1: Pesticides and nutrients coming from extensive green roof runoff are removed in granular activated carbon filter (adapted from Fränkische Rohrwerke Gebr. Kirchner GmbH & CO. KG, Optigrün International AG(2025))

laboratory batch and column setups. After successfully passing all laboratory tests, the system is now being tested in a pilot-scale setup with a 1000m² extensive GR (Figure 1). This setup should not only provide us with information about the removal of water-relevant substances but also enlarge the knowledge about GR runoff behavior during different precipitation events (Osawa et al., 2025).

2 METHODS

2.1 Preliminary laboratory tests

After conducting a literature review, we concluded that pesticides should be our focus. They pose a high risk to aquatic life and are not effectively removed by existing filters, which were primarily designed for removing nutrients and heavy metals. Therefore, we first focused on materials that can remove pesticides, with the aim of further improving our filter by adding different materials to tackle other water-relevant substances.

In a two-step batch testing process, eleven GAC types were evaluated for their ability to retain pesticides. In the

initial phase of filter substrate development, a series of batch tests was conducted to evaluate the retention of pesticides and biocides. The tests involved a comparison of eleven GACs from five distinct manufacturers. As posited by Spahr et al. (2022), varying quantities of adsorbent (5, 20, and 40 mg of GAC) were preconditioned with 200 ml of deionized water for a period of 24 hours on an orbital shaker at 150 rpm. Subsequently, a pesticide/biocide mixture containing 200 µg/L each of Diuron, MCP, and Terbutryn were added. Following a seven-day period, samples were collected for the analysis of pesticides and biocides.

The best-performing GAC was then tested alone and in mixtures with iron hydroxide, calcite, and iron shavings to assess retention of a more complex water matrix including pesticides, nutrients, and DOC. Tests were conducted with increasing material quantities of 1, 2, and 5 g of the mixtures, which were used and tested in a batch experiment. After 24 hours of preconditioning with deionised water, 5 g/L of nitrate, 2 g/L of phosphate, and 200 mg/L of DOC were added to the 500 µg/L pesticide mixture. After a further 24 hours on the orbital shaker, samples were taken for analysis of the pesticide, nutrients (DIN EN ISO 10304-1), and DOC (EN 1484).

2.2 Pilot scale study

In early June 2025, we installed a decentralized, granular activated carbon filter at GR, featuring a bitumen membrane. Our setup includes an electromagnetic flow meter (Krohne IFM5080 DN40) to measure the flow rate and two autosamplers (WaterSam WS 316 MS3) to sample the inflow and outflow of our filter unit. We also installed a weather station (METER ATMOS 41W) on the extensive GR to monitor parameters such as precipitation.

The 1,000 m² GR drains into our filter setup via the flow meter and then into the filter shaft. When the flow rate reaches 1 L/min for 30 seconds, the autosamplers automatically trigger and collect a 100-mL sample for every 200 L that passes through the flow meter. The sampling tubes are positioned close to the inflow and outflow of the filter unit. If the flow rate falls below 1 L/min for 30 seconds, the event stops automatically.

Rain events can be sampled in mixed mode to produce composite samples or in fractionated mode to produce fractionated samples. Composite samples can be analyzed cost-efficiently to determine the percentage removal of each rain event. Fractionated samples provide a more detailed picture of the removal process at different flow rates. They can also demonstrate first-flush effects or changes in runoff concentration during a rain event.

We also aim to investigate the runoff behavior of extensive GRs and the factors that influence changing runoff concentrations. To achieve this, we will combine and analyze datasets from the weather station, flow meter, and autosampler. According to the literature, the expected influencing factors on runoff concentration are higher temperatures, which increase diffusion rates for substances in the substrates and bitumen sheets; consecutive dry weather days, which lead to more severe first-flush effects due to longer diffusion times; and the amount of precipitation, which leads to dilution effects during heavy precipitation events. Additionally, increased flow rates result in shorter contact times within the filter unit, leading to a decrease in removal efficiency.

3 RESULTS

3.1 Laboratory batch tests

Results showed that most GACs effectively retained pesticides, especially at higher dosages. One GAC type (HPC) demonstrated excellent performance even at low quantities. In the second test phase, all filter mixtures showed high retention of pesticides. Nutrient retention, however, varied: nitrate was moderately retained, with an average retention of 57%, whereas pure GAC achieved up to 98% retention. Phosphate retention was consistently high across all mixtures, often exceeding 99%. However, DOC retention was generally low, with a maximum of 35%.

Due to its strong overall performance, particularly in retaining both organic and inorganic pollutants, the pure GAC material was selected for further testing in a pilot-scale treatment system.

3.2 Pilot scale study

After one month of installing the decentralized granular activated carbon filter, we recorded 14 rain events with daily precipitation exceeding 1 mm. Only 9 of them were sufficiently large to trigger the automatic sampler (>1 L/min for 30 seconds). The results in Figure 2 show the MCP concentration in µg/L in the inflow and outflow of the filter. The inflow and outflow concentrations range from a minimum of 1.5 µg/L and 0.7 µg/L on 15 June to

a maximum of 34.7 $\mu\text{g/L}$ and 21.3 $\mu\text{g/L}$ on 4 July, respectively. The removal ranges from a minimum of 27 % on 23 June up to 84 % on 4 June. As we expect consecutive dry weather days and daily precipitation to play a significant role in influencing the MCPP release, we have also included them in Figure 2. The consecutive dry weather days lead to an increase in MCPP concentration, as MCPP can diffuse from within the treated bitumen membrane to the top and is directly available (Erich & Baukh, 2016). A higher precipitation volume leads to a decrease in the MCPP concentration due to dilution of the composite sample. To mitigate this influence and gain a better understanding of the leaching dynamics of the extensive GR, we will adopt a fractionated sampling approach to observe effects such as first flushes (Osawa et al., 2025).

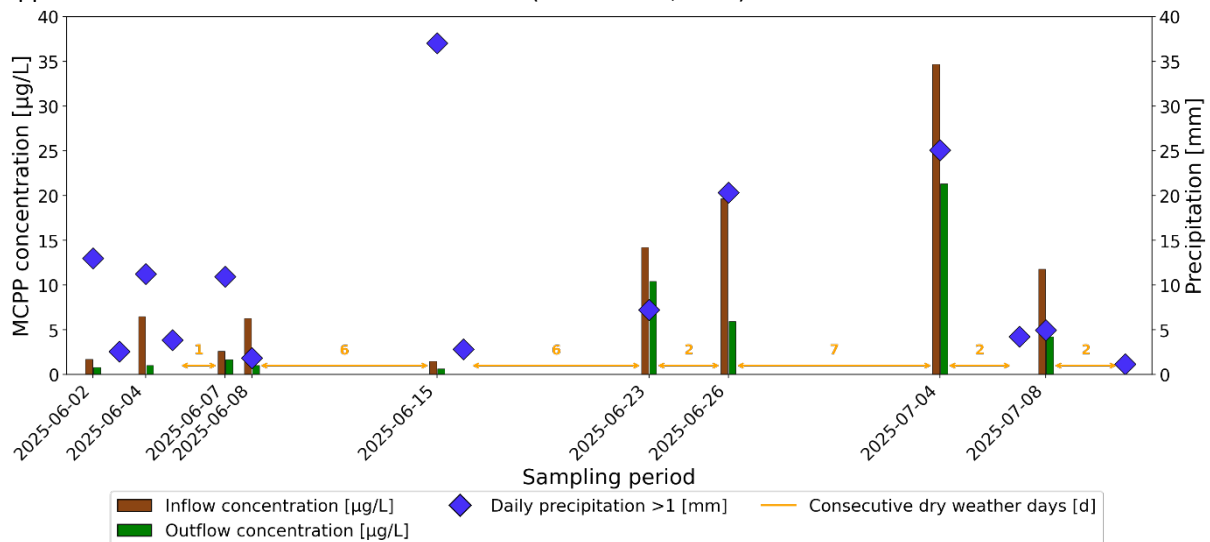


Figure 2: Daily precipitation > 1 [mm] (blue diamonds), consecutive dry weather days (precipitation < 1 mm) as yellow arrows with numbers indicating the number of days, and MCPP concentration in [$\mu\text{g/L}$] from composite samples of inflow (brown bar) and outflow (green bar) from decentralized granular activated carbon filter. Left Y-axis shows MCPP concentration in $\mu\text{g/L}$; Right Y-axis shows daily precipitation in mm; X-axis shows the sampling period of composite samples.

The results indicate that the retention of MCPP needs to be improved. Therefore, the system will be closely examined, and possible improvements, such as prolonging the contact time, will be further tested.

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