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Enhancing Urban Water Quality with Green Infrastructure – A Study in Guadalupe, Nuevo Leon, Mexico

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ABSTRACT

Green roofs and living walls are effective tools for addressing water management challenges in urban environments. These green infrastructure elements can mitigate rainwater runoff, reduce water contamination, and support more sustainable flow regulation. They also contribute to temperature regulation and provide habitat support for urban wildlife. Careful plant selection can maximize the positive impact of green infrastructure, reducing pollution levels and improving water quality in densely populated urban areas with extreme weather conditions. The research presented in this article raises awareness about potential challenges and risks associated with green infrastructure, such as pollutant release. Understanding the factors that influence water quality enables improved management practices and sustainable urban planning. The article also identifies various plant species with remarkable contaminant retention capabilities, particularly several metals such as calcium and sodium. These findings propose the design of effective green infrastructure solutions. This study confirms that green infrastructure effectively filters pollutants from precipitation water, making it suitable for injection into underground water wells. Overall, the research provides valuable scientific insights for urban water management, fostering eco-friendly and resilient cities in semi-arid climates.

Keywords: Green infrastructure, urban water management, contaminant retention, rainwater runoff, sustainable urban development.

INTRODUCTION

The rapid expansion of urban areas has led to the loss of green spaces within cities and their surroundings, including forests, grasslands, and agricultural lands, resulting in significant environmental challenges. Among them, the substantial increase in rainwater runoff, increasing water contamination, the decline of groundwater recharge, and the escalation of watershed erosion stands out as critical issues (Antrop, 2004). Addressing these challenges has become a pressing concern, necessitating effective solutions to mitigate adverse impacts and foster more sustainable urban development.

In this context, green roofs and living walls have emerged as promising alternatives to tackle the water management challenges in urban environments. These green infrastructure (GI) elements act as drainage layers to release excess water and substrates housing vegetation species that aid in conserving and filtering rainwater, which can carry various types of contaminants (Mentens et al., 2006).

Researchers like Czemiel (2010) have extensively explored the role of green roofs in urban drainage and the quality of runoff water, identifying factors influencing their performance and emphasizing the need for long-term investigations. While rainwater is generally perceived as clean, scientific studies have demonstrated its potential to carry significant amounts of contaminants, including heavy metals and pathogenic microorganisms (Czemiel, 2010).

One of the key benefits of green roofs with vegetation is their remarkable ability to substantially reduce rainwater runoff in urban areas by enhancing water retention and promoting more sustainable flow regulation (VanWoert et al., 2005). Furthermore, it has been highlighted that these green systems contribute to temperature regulation, mitigate the urban heat island effect, and support urban habitats (Oberndofer et al., 2007).

In 2022, Appiotti et al. demonstrated that vegetation can effectively retain air pollutants through interception, absorption, deposition, and bioaccumulation. The retention capacity of vegetation depends on factors such as plant species, growth stage, type of pollutant, and environmental conditions. The study emphasized the need for further research to fully comprehend the mechanisms behind pollutant retention by vegetation and to devise effective strategies for utilizing vegetation to mitigate air pollution (Appiotti et al., 2022).

In densely populated cities such as Barcelona, the significance of green roofs has been emphasized, with spatial models identifying priority areas and optimal design types to maximize ecosystem services provided (Langemeyer et al., 2020). Moreover, the role of green roofs in mitigating pollution in urban environments, by filtering airborne contaminants, sequestering carbon, and improving water quality, has been underscored, directly benefiting human health (Rowe, 2010; Abanto-Bazán, et.al. 2023).

Nevertheless, it is acknowledged that the use of green roofs and living walls may pose certain challenges. Concerns arise from the potential release of pollutants into the water, originating from soil, plants, and fertilizers, necessitating careful consideration (VanWoert et al., 2005). As a result, the quality of water from GI largely depends on various characteristics, including substrate layer thickness and composition, vegetation type, drainage, age, and maintenance of the infrastructure, as well as the local surroundings in which it is implemented.

Another important aspect of GI it is their capability to improve the air quality. In their 2022 study, Sorribas et al. examined 12 urban gardens in Spain and observed variations in the ability of plant species to retain heavy metals. They found that species like *Hedera helix* and *Salix spp*. were more effective in this regard compared to others, such as *Poaceae* and *Pinus spp.* The study concluded that urban gardens with plants capable of accumulating heavy metals could serve as a valuable strategy to mitigate the environmental impact of these pollutants. (Sorribas-de-Vega et al., 2022). Abdel-Fattah et al. (2021) studied heavy metal retention by urban trees in Cairo, Egypt. They found that certain species, like *Eucalyptus* and *Acacia*, accumulate high levels of heavy metals in their leaves. Trees may thus play a crucial role in urban heavy metal retention, making planting metal-accumulating species a viable strategy to mitigate environmental impact (Abdel-Fattah et al., 2021). Martínez-Martínez et al. (2021) studied vegetation's particle retention. They identified four mechanisms: interception, deposition, wet deposition, and bioaccumulation. Retention varies with plant species, growth stage, particle type, and environmental conditions. Further research is needed to comprehend these mechanisms and devise pollution mitigation strategies using vegetation (Martínez-Martínez et al., 2021).

Vegetation retains air pollutants through interception, absorption, deposition, and bioaccumulation. Retention varies with species, growth stage, pollutant type, and environment. More research needed to understand mechanisms and develop air pollution mitigation strategies (Awasthi et al., 2021). Amon several studied species, the most promising have been *Eichhornia crassipes* because its suitable morphological and anatomical features for water quality improvement. Its leaves and roots with high surface area-to-volume ratio efficiently absorb nutrients and pollutants. The leaves contain abundant chloroplasts for photosynthesis, and the roots house bacteria that degrade pollutants (Mathew & Thomas, 2016). *Eichhornia crassipes* impacts tropical urban reservoirs. Its dense mats decrease water transparency and oxygen levels. The plant releases nutrients, leading to reservoir eutrophication. Management strategies needed to control spread and improve water quality (Carvalho et al., 2015). *Eichhornia crassipes* effectively retains nutrients and heavy metals. Leaves and roots accumulate nitrogen, phosphorus, lead, cadmium, and chromium. It can serve as a biosorbent to remove pollutants from water bodies and treat wastewater, rainwater, and aquaculture systems (Oliveira et al., 2014).

Eichhornia crassipes efficiently removes heavy metals from water. It accumulates high concentrations without toxicity. Suitable for treating wastewater, rainwater, and aquaculture systems (da Silva et al., 2013). *Eichhornia crassipes* can improve tropical reservoirs by reducing transparency and releasing nutrients. Proper management is crucial to avoid negative impacts. Leaves and roots accumulate nutrients and heavy metals, offering potential for water quality improvement with effective management (Alves et al., 2012).

In the specific case of metal retentions, is reported that GI effectively removes sodium from rainwater (Chen et al., 2021; Wang et al. 2022). For this application, bioretention cells were most effective, followed by vegetated swales and rain gardens concluding that vegetation type also influenced sodium removal capacity, being the salt-tolerant plants more effective for this purpose (Wang et al., 2022).

In other work, Zhang et al. (2020) reviewed literature on GI for rainwater sodium remotion. In this work is reported that effectiveness depends on GI type, soil, vegetation, and runoff sodium concentration (Zhang et al., 2020).

This work aims to investigate the effectiveness of green roofs and living walls for metal remotion like calcium and sodium in urban environments and their impact on water quality; the presence of calcium and sodium in rainwater can be influenced by atmospheric sources, including emissions from human activities and natural processes. This investigation is essential for understanding the impact of contributing activities on the local environment. Analyzing calcium and sodium presence in rainwater gains significance within the context of climate change and atmospheric pollution. Anthropogenic activities, like road dust resuspension, limestone exploitation, construction industry, fossil fuels emissions, and others, release these elements into the atmosphere attributed to the large number of cars and infrastructure growth carried out in Guadalupe and surroundings municipalities. The correlation between these elements and atmospheric sources prompts crucial future research, unraveling their impact on the environment, interplaying with climate change and pollution. Fossil fuel emissions, exemplified by refineries and automotive emissions, accentuate the importance of targeted investigation. The insights gained hold potential to drive effective mitigation strategies and inform policies for sustainable urban environmental management. Such comprehension facilitates an understanding of the synergistic effects on ecosystems and water quality within urban settings. The study will conduct an exhaustive literature review (Oberndofer et al., 2007) to examine benefits, challenges, and propose recommendations for sustainable integration into urban environment. The research seeks to contribute to scientific knowledge and inform sustainable public policies and urban planning for cities with semiarid climate conditions.

MATERIALS AND METHODS

Study area

Guadalupe is a city situated in the northeastern state of Nuevo León, Mexico, and is a part of the Monterrey Metropolitan Area. It is geographically positioned at a latitude of 25.6792 and a longitude of -100.235, specifically at 25°40’45” North latitude and 100°14’6” West longitude. The city’s elevation stands at 490 meters above sea level. In this region, the prevalent climate classification according to Köppen and Geiger is BSh, characterizing a warm semi-arid climate with an average annual temperature of 22.1°C and an average annual precipitation of 640 mm, with most of the rainfall occurring during September.

Within the study area, there exists an air quality monitoring station named “La Pastora,” strategically located in the southeastern region. This station is capable of measuring particulate matter suspended in the air with an aerodynamic diameter equal to or less than 10 micrometers (μm). These fine particles are of significant concern due to their ability to deeply penetrate the human respiratory system upon inhalation, leading to potential adverse health effects, particularly on the respiratory and cardiovascular systems, commonly referred to as PM10 (Tian et al., 2019). Over the past decade (2010–2019), the “La Pastora” monitoring station has consistently recorded an average PM10 concentration of 53.44 μg/m^3.

The “La Pastora” monitoring station is surrounded by a diverse urban landscape, including residential areas, recreational parks, green spaces, and heavily trafficked urban roads. As part of the ongoing research project, an experimental analysis station was thoughtfully installed within the municipality of Guadalupe. This station is situated atop a residential house, positioned at an elevation of 4 meters above ground level, in an area devoid of tall buildings, and surrounded by neighboring houses of comparable height.

Metal remotion assays

In this study, a prototype GI analysis station was established to investigate the performance of different plants species in enhancing water quality. The station consisted of individual units measuring 0.3 m by 0.3 m per species. Each unit was designed with three distinct layers: a geotextile layer, a gravel layer, and a surface substrate layer. Four plant species were carefully selected for this experiment, including *Aptenia cordiflora*, *Sedum reflexum*, *Trachelospermum jasminoides*, and *Lavandula angustifolia*. Furthermore, a submerged hybrid flow-type prototype wetland was integrated into the system to complete the analysis station. This wetland unit was constructed with polyethylene material and measured 0.9 m in length by 0.4 m in width, housing the *Eichhornia crassipes* species.

The primary focus of this investigation lies in analyzing the water originating from precipitation and subsequently processed by the three GI prototypes. A comparative assessment will be conducted to examine the discrepancies between the contaminants identified in the air, as studied previously by our research group (Abanto-Bazan et al., 2023) and those present in the water after traversing the different layers of the experimental system. By doing so, it was able to elucidate the specific species that exhibit exceptional contaminant filtering capabilities.

Rainwater sampling

Sampling methods for water analysis are critical to ensuring that the results are representative of the water being sampled. Researchers can guarantee that the findings of their water quality analyses are accurate and reliable by following carefully designed protocols. This is important for a variety of reasons, including monitoring water quality. It is also important to properly preserve water samples to prevent the degradation of the samples before analysis (Kumar et al., 2009; Suliman et al., 2008; Thompson et al., 2007).

Grab samples were collected from the pipes of three different types of GI: green roofs, living walls, and a wetland. The water samples were collected in clean, plastic containers. The samples were collected in the morning and were stored at ≈ 4 ^{o}C until analysis. Six samples were collected from each type of GI, and one sample was collected from direct rainwater as a blank. All samples were collected by triplicate in 0.25-L high-density polyethylene bottles. Samples and blanks were preserved by adding concentrated nitric acid until the pH was less than 2.

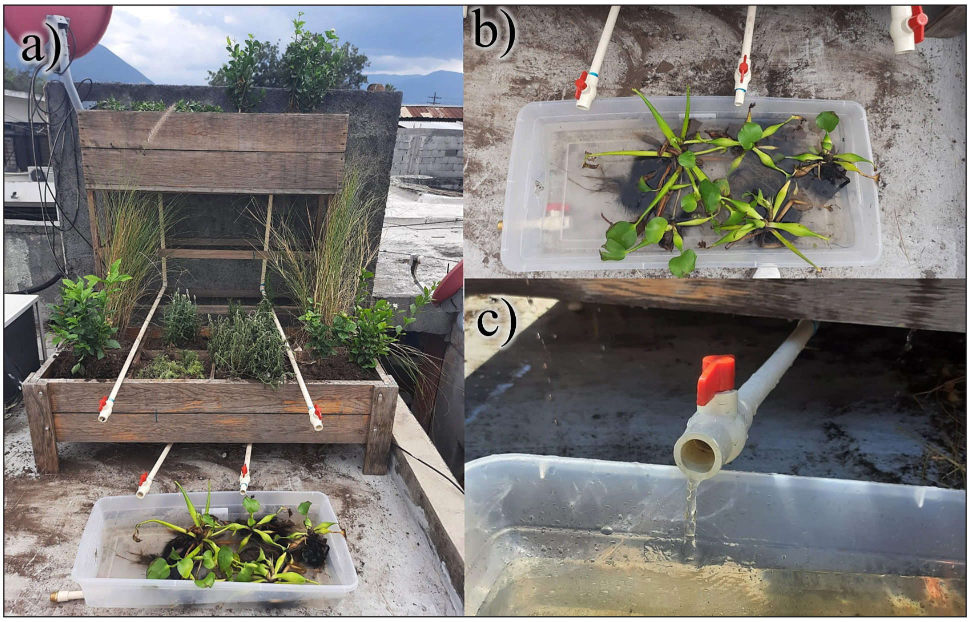

Fig. 1: a) Complete green infrastructure prototype (roof, wall, and wetland), b) wetland prototype, c) water excreted towards the wetland prototype

Metal analysis

Before the analysis, acid digestion treatment was applied to all samples. Samples were filtered through a 0.45-µm pore membrane. Then, 0.05 L of sample was measured in triplicate in 30-mL glass vials. Concentrated nitric acid (0.003 L) was added to each vial, and the vials were covered with watch glasses and heated to 90°C. The samples were evaporated to almost dry, and then 0.01 L of hydrochloric acid (1:1) was added. The vials were heated for an additional 15 minutes to redissolve any precipitates that could formed. Finally, 0.015 L of water was added to each vial, and the samples were diluted to a final volume of 0.1 L.

After the chemical digestion, the concentrations of Sodium, Calcium and Cooper were measured by atomic absorption spectroscopy (AAS), calibrated using standard solutions of each metal. After the preparation of the standards, both standard and samples were analyzed by using GBC 932AAA atomic absorption spectrometer. This procedure was carried out in a total of two sampling rounds.

RESULTS

Building upon previous results on PM_{10} reported previously by our research group (Abanto-Bazan et al. 2023), it was identified two types of retained elements: those most abundant and those most harmful to water quality. Calcium was found to be the most prevalent element in the plant species, its presence could be related to dust particles originating from the soil or materials transformed by industrial activities, such as limestone exploitation on the outskirts of the urban area (Reyes et al., 2016).

According to AAS analysis, direct rainwater samples showed a concentration of 0.11 $g{\cdot}L^{-1}$ of calcium and 0.64 $g{\cdot}L^{-1}$of sodium. These concentrations were lower than those found in the elements obtained by the five plant species but higher than the concentration in the *Eichhornia crassipes* species as it is shown in Figure 2. This different in metal concentrations suggests that *Eichhornia crassipes* contributes to the retention of metals coming from rainwater indicating that this plant can be proposed to purify metals present in rainwater, as shown in the following Figure 2.

On the other hand, Figure 3 shows the average concentration of two sampling rounds of calcium obtained of sample from different plant species analyzed in this work. The sample with the highest calcium concentration originates from the *Sedum reflexum* species (1.51 $g{\cdot}L^{-1}$), while the one with the lowest concentration comes from the *Eichhornia crassipes* species (0.078 $g{\cdot}L^{-1}$). This variation could be mainly attributed to differences in the morphology of these species; the former has a smooth structure that facilitates particle transport

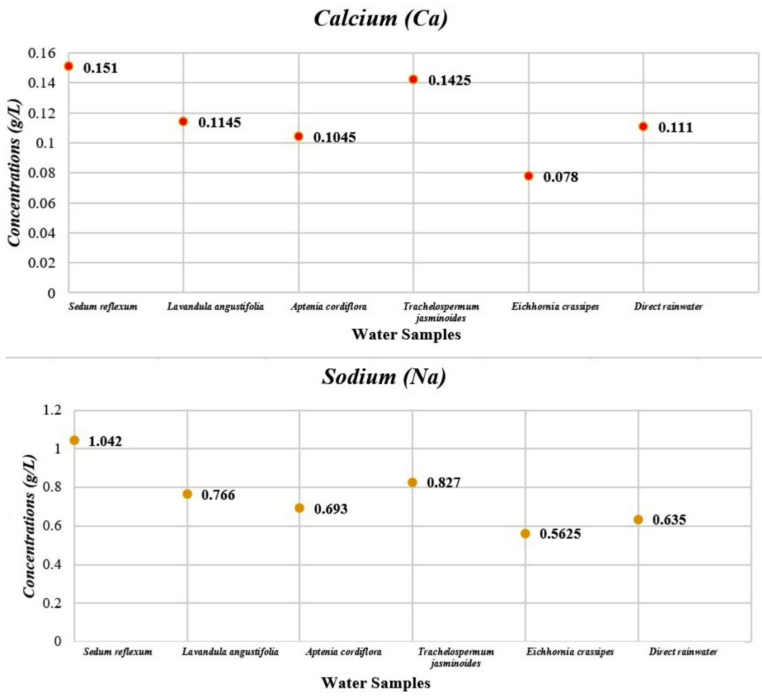

Fig. 2 Metal concentration analyzed in rainwater as function of plant species

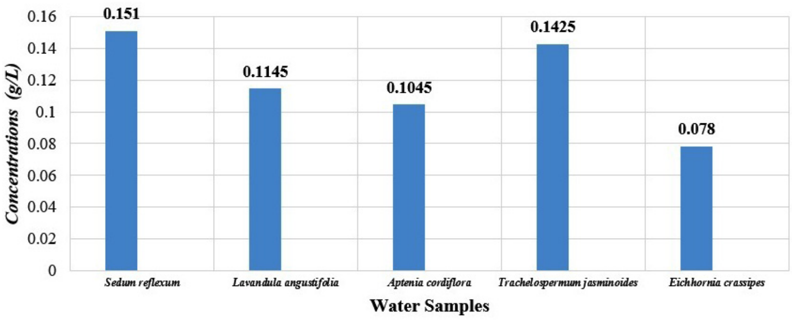

Fig. 3. Average of the calcium concentration obtained in rainwater samples measured in this work

by rainwater, whereas the latter, as mentioned before, possesses an irregular and porous structure (Mathew & Thomas, 2016), which would exhibit a better particle retention function and prevent the presence of calcium in the water.

In the case of copper, due to its very low concentration identified in samples (below the detection limit 0.4356 $mg \cdot L^{-1}$), The copper concentration was not calculated. This result indicates minimal presence of this element in the water resulting from the GI. Plant species may play a crucial role in copper particle retention, particularly *Eichhornia crassipes*, which demonstrated a strong adsorption capacity in the biomass of its roots. Further investigation of this metal could be addressed in future studies.

On the other hand, Figure 4 shows the concentration of sodium obtained from the sample of rainwater, being the highest amount of this element *Sedum reflexum* species (1.04 $g \cdot L^{-1}$) and the sample with the lowest concentration was *Eichhornia crassipes* (0.56 $g \cdot L^{-1}$). As mentioned above, the differences in morphology cause the species to act in a certain way, in this case; As with calcium, the sodium particles had a very similar behavior, adhering to the leaves with a branched structure and trichomes; opposite case to the species of smooth structure that present greater amounts of concentration in the water.

Furthermore, Figure 5 shows the particle transport behavior of the analyzed elements in plant species, with three consecutive sampling points visible. In species with a smooth structure (*Sedum reflexum* and *Aptenia cordiflora*), the highest calcium concentration was found in the second sample, indicating initial retention of particles, followed by easier dragging and subsequent decrease in concentration. On the other hand, *Trachelospermum jasminoides* showed almost complete dragging of particles during the initial sampling moment, as they do not adhere well to its smooth surface, lacking trichomes.

Lavandula angustifolia, however, demonstrated gradual retention due to its branched structure and the presence of trichomes on its surface, making it more difficult for particles to be dragged initially. *Eichhornia crassipes*, present in the wetland prototype, exhibited the lowest concentrations of calcium and sodium. Additionally, its irregular structure favored particle retention, and its roots played a crucial role in water decontamination, as particles strongly adhered to the root biomass (Muchanyereyi et al., 2016) leading to low levels of the studied elements in the water. This plant species could be utilized to absorb pollutants in water, not only on its surface but also within the biomass of its roots.

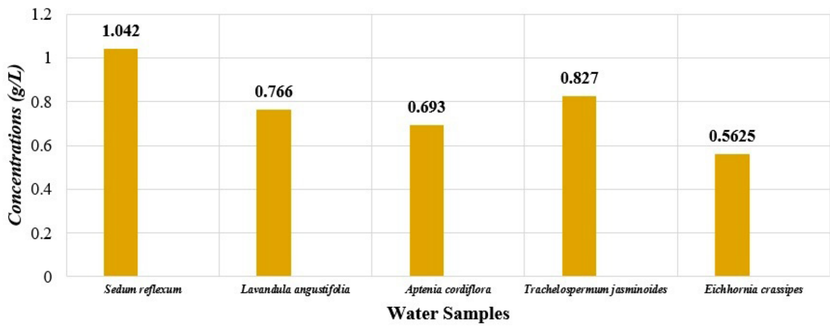

Fig. 4. Concentration of sodium identified in rainwater samples analyzed in this work

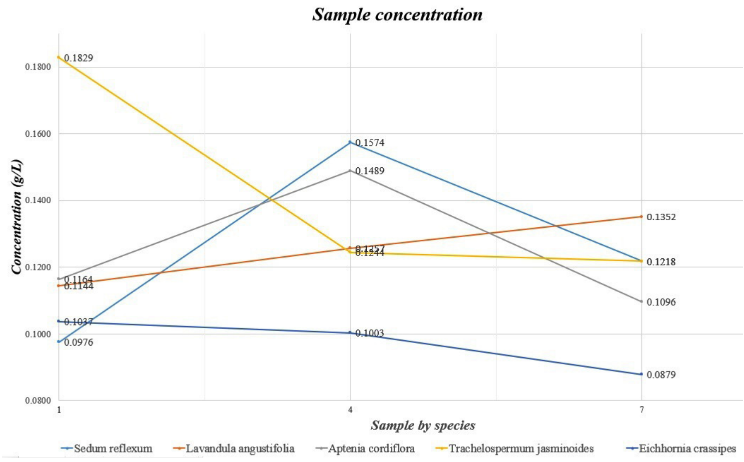

Fig. 5. Calcium particle transport

DISCUSSION

The research project aligns with previous studies in three ways. In the first way, plant species vary in their pollutant retention ability. On the second way, retention depends on factors like species, growth stage, pollutant type, and environment. Finally in the third way, vegetation plays a crucial role in pollutant retention, suggesting planting pollutant-accumulating species can mitigate environmental impact.

The research project differs from previous studies in several aspects. In this work, calcium was the predominant element, while heavy metals were emphasized in earlier studies. This discrepancy may be due to varied research methods and contaminant focus. The project used a mixed approach with field and laboratory analysis, while previous studies relied solely on field investigations for contaminant retention. The research project's calcium retention analysis aligns with prior studies. The *Eichhornia crassipes* efficiently absorbs nutrients and pollutants due to its high surface-to-volume ratio. This is attributed to the abundant chloroplasts in its leaves, facilitating photosynthesis. Additionally, the research project's results confirm the low calcium concentration in *Eichhornia crassipes* leaves, consistent with previous studies showing its calcium removal ability.

Results align with previous studies, showing that GI effectively removes sodium from rainwater. Sodium removal efficiency depends on vegetation type, with salt-tolerant plants more effective. *Sedum reflexum*, with a branched structure and trichomes, removes more sodium than *Eichhornia crassipes* with a smooth structure, consistent with previous findings on the impact of plant morphology on sodium removal.

Furthermore, there is no evidence of bioaccumulation in plant species in this work, likely because the study focused on specific pollutants. Other contaminants, such as heavy metals, might have higher bioaccumulation potential, but they were not prioritized in this study. Discrepancies exist between our study and previous ones. *Eichhornia crassipes* has less calcium than *Sedum reflexum*, but both remove calcium from the water. Differences in sampling and analysis methods may explain variations in particle retention efficiency. Sodium results showed discrepancies with previous studies. *Sedum reflexum* removed more sodium than bioretention cells in contrast to Wang et al. (2022). This difference may be due to the study and analysis methods used. The prototype test station conditions likely improved sodium removal for *Sedum reflexum*. Additionally, this project did not investigate sodium bioaccumulation in *Sedum reflexum*, unlike some previous studies. Bioaccumulation was not considered as an analysis variable in this study.

CONCLUSIONS

1. The research conducted in this scientific article highlights the significance of green roofs and living walls as effective tools to address water management challenges in urban environments. These green infrastructure elements play a crucial role in mitigating rainwater runoff, reducing water contamination, and supporting more sustainable flow regulation. They also contribute to temperature regulation,

mitigating the urban heat island effect, and providing habitat support for urban wildlife.

2. Careful selection of suitable plant species can maximize their positive impact in green infrastructure, improving water quality in densely populated urban areas with extreme weather conditions and reducing pollution levels.
3. Importantly, the research raises awareness about the potential challenges and risks associated with green infrastructure, such as the release of pollutants from soil, plants, and fertilizers. By identifying and understanding the factors influencing water quality in Green Infrastructure systems, this study enables the development of improved management practices and more sustainable urban planning.
4. The study emphasizes the importance to identify various plant species with remarkable contaminant retention capabilities, particularly in relation to calcium and sodium. This knowledge can be leveraged to design and implement effective Green Infrastructure solutions in urban areas, ultimately improving water quality and enhancing urban ecosystem services.
5. Considering these findings, is recommended that a more profound exploration of adaptable plant species from northern Mexico be undertaken, capitalizing on their potential to purify particles stemming from industrial, limestone, and mobile source pollution. The exemplar *Eichhornia crassipes* specimens showcased remarkable proficiency in retaining calcium, copper, and sodium, underscoring their possible remarkable phytoremediation capacity within wetland ecosystems. The intrinsic morphological structure and root retention of this species augments pollutant removal efficacy, thereby enabling effective water purification and the potential for injection into subterranean aquifers. This presents a promising field for future scientific inquiry and practical implementation of environmentally beneficial strategies. On the other hand, *Lavandula angustifolia* and *Aptenia cordiflora* samples had lower calcium concentrations, while *Sedum reflexum* and *Trachelospermum jasminoides* had higher concentrations due to their morphological structure, promoting particle adherence to leaves. Further research is needed to optimize the use of these plant species for phytoremediation. This research should focus on factors such as the plant's growth rate, tolerance to pollutants, and ability to remove specific contaminants.
6. Studied plant species effectively filter pollutants through precipitation water. Water exiting the system through the wetland contains 0.078 $g{\cdot}L^{-1}$of Calcium, 0.56 $g{\cdot}L^{-1}$of Sodium, and is below the Copper detection limit, meeting criteria for soft water per NOM 127 SSA1 1994 Environmental Health, suitable for injection into underground water wells, where this Green Infrastructure is designed.
7. Overall, the research contributes valuable scientific insights to the field of urban water management, demonstrating the positive impact of green roofs and living walls on water quality in urban environments with a semi-arid climate. The findings have implications for the design of sustainable public policies and urban planning strategies to create more resilient and eco-friendly cities.

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