

ABSTRACT

Title of Thesis: UTILIZING GREEN WALLS FOR IN-SITU GREYWATER TREATMENT

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Agricultural industrialization in the 21st century has presented acute strains on freshwater globally, and population growth has driven modern farming practices towards the overuse of already scarce water resources. This coupled with the increased popularity of water-intensive green infrastructure has led to the focus of this project: integrating greywater recycling through vegetated walls to minimize freshwater use and promote sustainable wastewater management. By selecting wetland species accustomed to a saturated environment, we designed walls that were well suited to absorbing the varied contaminants of greywater, which was modeled after effluent from sources like laundry machines, showers, and dishwashers. We evaluated the treatment performance of the walls through the U.S. Environmental Protection Agency (EPA) and Maryland Department of the Environment (MDE) guidelines for pH, turbidity, total organic carbon (TOC/NPOC), total nitrogen (TN), chemical oxygen demand (COD), and plant health was monitored through qualitative metrics. The development of green walls with region-specific native plants may allow for greater accessibility in communities local to Maryland, and may be used in future applications of green infrastructure planning.

UTILIZING GREEN WALLS FOR IN-SITU GREYWATER TREATMENT

by

TEAM VERDANT

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List of Abbreviations

BOD	- Biological Oxygen Demand
COD	- Chemical Oxygen Demand
DO	- Dissolved Oxygen
EPA	- Environmental Protection Agency
LCP	- Light Compensation Point
LECA	- Lightweight Expanded Clay Aggregate
LED	- Light-emitting Diode
LW	- Living Wall
MDE	- Maryland Department of the Environment
NATA	- National Association of Testing Authorities, Australia
NPOC	- Non-purgeable Organic Carbon
NTU	- Nephelometric Turbidity Units
PAR	- Photoactive Radiation
PPFD	- Photosynthetic Photon Flux Density
PPM	- Parts Per Million
SCG	- Spent Coffee Grounds
TOC	- Total Organic Carbon
TN	- Total Nitrogen
TP	- Total Phosphorus
TSS	- Total Suspended Solids
UHI	- Urban Heat Island
UV	- Ultraviolet

Introduction

Water scarcity and its effects have created a crisis experienced worldwide. Linked to a global increase in food and energy consumption, many communities are now incapable of providing this vital resource to their residents – especially in crowded urban centers where inadequate sanitation makes the process even harder (WWF, n.d.). Globally, close to one billion people lack sufficient access to drinking water, and most water resources that do exist are subject to mismanagement due to overuse (Djehdian et al., 2019).

The ongoing water crisis is multifaceted, and diverse avenues and approaches will be needed to address weaknesses in water conservation. Team VERDANT's focus is one of these shortcomings, identified as inefficiency in wastewater treatment. Centralized wastewater treatment systems are costly to maintain, energy intensive, and require a lot of land. As it stands, these systems indiscriminately send all used domestic wastewater to a plant for chemical purification, even though the majority of used wastewater does not need to be treated to the same extent as sewage. Greywater is defined as wastewater with lower levels of pollution coming from sources like showers and washing machines (Masi et al., 2016), and it typically accounts for 65% of total domestic wastewater (Ghaitidak & Yadav, 2013). Separating greywater at the source would mean only the most polluted effluent water enters treatment facilities and wastewater generation is reduced: this could reduce the energy and land demands of treatment plants.

Greywater recycling schemes have been shown to achieve 10-50% savings on water usage (Pradhan et al., 2019a). By converting wastewater into re-purified non-potable water through less energy intensive mechanisms, it can be used for various purposes including irrigation, toilet flushing, and laundry (Boano et al., 2020). Decentralized source-separated

systems combined with reuse, such as the proposed greenwall-greywater recycling design, are cost-effective and ecologically conscious solutions: these designs require less land, energy, and have the potential to mitigate CO₂ emissions (Pradhan et al., 2019a).

Green walls can provide a system through which greywater is filtered and recycled for non-potable uses. These “self-sufficient vertical gardens” are attached to the exterior or interior of a building and receive water and nutrients from within vertical supports instead of the ground (Weinmaster, 2009). In recent years, the popularity of sustainable infrastructure has soared in response to the challenges of climate change, and green walls in particular offer a variety of environmental and social advantages to the communities that implement them. Energy savings and mitigating the urban heat island effect, stormwater management, protecting building exteriors, increasing property market values and promoting biodiversity and conservation are all green wall benefits (EPA, 2014). Specifically, indoor green walls improve air quality, reduce noise pollution, and promote the mental wellbeing of viewers. The advantages green walls provide in tandem with their high degree of customization (e.g., structural style, type of plant, and type of media used) set them apart as an innovative approach to sustainable filtration systems for greywater: greywater can be filtered and recycled through the green wall while the green wall receives the benefit of being irrigated by that greywater. In this system, a wall watered by greywater no longer requires copious amounts of potable freshwater to maintain.

Many studies have researched these green-wall-greywater filtration systems in different climates, contexts, designs, and with reference to different variables. Filtration improvements for existing designs of green walls are well documented in avenues including rainwater harvesting, growing media, artificial lighting, and more. Additionally, the ways in which green walls can be modified for dry regions has been considered in the past because they are so water intensive.

Existing literature also spans the scope of how different forms of green infrastructure compare to one another in urban heat mitigation, air purification, psychological benefits, and propensity for growth.

There is, however, an absence in findings related to specific characteristics of green walls that filter *greywater*. There is also minimal literature pertaining to the use of specific plants and their ability to contribute to the benefits of a green wall in greywater filtration, especially when it comes to using plants native to a particular region. A final key component that is relatively unexplored is the cost of implementing green walls, and the ways in which accessibility can be increased for those who would stand to benefit greatly from delocalized greywater purification.

The research focus of Team VERDANT, (Vegetated walls to Enable Reuse, Detoxification, And Natural Treatment of greywater), is as follows: *Utilizing green walls for in-situ treatment of greywater for non-potable reuse*. We evaluated the effectiveness of endemic plants and media in an indoor green wall for greywater filtration. Our standards were set through national EPA and local MDE water quality guidelines (for pH, TOC/NPOC, TN, COD and turbidity), and plant health was monitored through qualitative metrics as a baseline for designing a filtration mechanism that produces reusable water. Our goals were to reduce strain on local water resources and combat water scarcity through the use of non-potable water in areas where drinking water is non essential. This allows for greater availability of potable water for industries like food and energy production, in turn reducing obstacles to sustainability. Traditional centralized wastewater treatment fails to address increasing demands associated with population growth, including increased wastewater generation, climate change, and water scarcity (Pradhan et al., 2019a). However, with alternative methods of greywater recycling, and in particular those that invoke a green wall, enhanced conservation of water resources may be achieved.

Literature Review

Benefits of Green Walls

Green walls have the capacity to benefit sustainability and human health in a variety of ways, but the advantages a wall has are largely dependent on certain characteristics including location, size, and plants used. In the process of designing a vertical garden, our team investigated which features of a green wall are responsible for the benefits we want to optimize and in general what potential assets exist.

A core benefit of outdoor green walls is the mitigation of the urban heat island (UHI) effect in addition to energy savings both for the buildings with those living walls (LWs) and the buildings in the city as a whole. The EPA identifies the source of UHI effects as the result of sensible heating of building materials, which then dissipate over time into their surroundings (EPA, 2014). Urban areas tend to absorb more heat than their surrounding areas because of the modified impermeable surfaces, and increased temperatures have been linked to health detriments in urban residences- clearly any technology that combats this phenomenon is necessary and important.

An additional issue caused by UHI is “thermal pollution” identified by higher temperatures in stormwater run-off (Somers et al., 2013; Zeiger et al., 2015). The EPA recommends using green infrastructure and conservation of green spaces in urban landscapes to reduce increased temperatures on surfaces due to building/pavement materials and lack of shading. This class of run-off is particularly harmful given its propensity to disrupt the temperature of natural bodies of water that it mixes into. Indeed, warm stormwater runoff can

dramatically and quickly change the temperature of an aquatic ecosystem, which is stressful to the inhabitants (EPA, 2014).

Newer studies have suggested that low air flow across urban landscapes from surrounding rural and suburban areas is the cause of the worst conditions of UHI, allowing for a build up of warmed air due to various energy inputs (Gunawardena et al., 2017).

Evapotranspiration was identified early on as a mechanism by which green walls can reduce heat build-up by allowing heat to be absorbed into water which in turn evaporates and carries the heat energy away from the surface of the building. In droughts and other conditions that lead to high risk of water loss/lack of supply (e.g., extended or intense heat waves) plants will no longer actively transpire to conserve water by closing their stomata and by extension no longer participate in evapotranspiration (Gunawardena et al., 2017). The majority of water supplied to essentially all species of plants is used for transpiration, though the conditions/times in which those plants transpire differs and affects how green infrastructure may serve to mitigate UHI (Gunawardena et al., 2017).

Overall green spaces have been found to mitigate urban heat island intensity, a sentiment held in literature reviews and various articles on the topic, though studies on LWs in particular are less common (Gunawardena, 2017; Balany et al., 2020). There have been a number of case studies and other evidence to support their effectiveness for building or local temperature reduction, but currently their benefits when used in urban landscapes have been relatively underexplored (Davis et al., 2015; Radic et al., 2019).

Green spaces can help reduce the negative effects of the resulting extreme temperatures by helping regulate temperatures in urban ecosystems via evapotranspiration, deflection of heat, and increased surface roughness (Gill et al., 2007; Gunawardena et al., 2017). However, they

also contribute to higher humidities and act as heat sinks without proper design or in poor conditions (i.e., low air flow and lack of air-gaps or other insulating materials to prevent heat transfer from the green wall to the building or when dry during a drought/in winter), reducing thermal comfort and increasing the risks associated with UHI to public health (Widiastuti et al., 2020). Clearly, a consideration of climate is crucial to green wall success.

The indoor environment has been shown to be more negatively affected by green spaces under the previously discussed conditions, with up to 72.5% increase in relative humidity due to evapotranspiration with an indoor environment openly interfacing with a green wall (Widiastuti et al., 2020). While the heat-sink behavior and increases in humidity are a detriment compared to stronger insulators, which could be installed with lower costs, there is still a large advantage in implementing green spaces to curb UHI and for improved cooling and insulation, partly due to the other benefits they offer.

There have been studies demonstrating green walls cutting energy bills by figures as high as 30% due to their shading effects and the plants' ability to evapotranspire (Weinmaster, 2009). Evapotranspiration via vegetation in living walls and green roofs can lower summer temperatures by 1-5°C (Pradhan et al., 2019a) and evapotranspiration by green walls/lawns can lower indoor temperatures within a home by 1-3°C (Musy et al., 2017), showing strong benefits for building-scale cooling.

Green walls have the potential to outperform green roofs within thermal regulation, prompting an increased interest in researching green walls (Jim, 2015). This is due to green roofs acting as strong heat sinks, mitigating the benefits from evapotranspiration, and the limited spread of the benefits of green roofs (Musy et al., 2017). Shading and reflectivity are better provided by specialized building materials, often performing magnitudes above green space in

terms of achieving close to 100% reflectivity. (Gunawardena et al., 2017). Implementing green walls may significantly improve indoor comfort conditions and reduce energy costs (Radíc et al., 2019)

Another potential benefit of green walls is mitigating runoff and protecting water quality, which are increasingly common problems facing more urbanized communities. Urban surfaces, like roads, sidewalks, and pavement do not allow for proper drainage and permeation of precipitation. Consequently, when runoff flows over these impervious surfaces, pollutants in the runoff accumulate on their paths to sewage drains and may ultimately overwhelm water treatment plants (Weinmaster, 2009). This phenomenon is known as the “first flush” phenomenon, which is defined as the accumulation of air pollutants and other debris on paved surfaces in runoff (Ostendorf et al., 2011). Green walls have emerged as a potential solution in combating runoff and the consequences of “first flush”. When green walls are irrigated with or exposed to rainwater, pollution can be eliminated through the roots before the water reaches the ground (Weinmaster, 2009). Thus, green walls can potentially address urban hydrology challenges such as disruptions to natural infiltration, groundwater water recharge, and increased runoff linked to minimal and reduced vegetative and prevalence of impervious surfaces in urban areas (Ostendorf et al., 2011).

Green walls are also centers of biodiversity and conservation. Modern cities that have undergone rapid and intense urbanization have the unintended consequence of destroying complex biological habitats and natural, green surfaces (Weinmaster, 2009). Green walls help mitigate this; they provide mini ecosystems that are responsible for fostering homes for many different plant species and organisms (Weinmaster, 2009). Since green walls are

space-conservative, they are suitable green additions to crowded cities to promote biodiversity and sustainability.

Green walls have the added benefit of improving the indoor air quality of the surrounding area. Certain plants are very effective in improving air quality, which affects the health of the building occupants in a positive way (Weinmaster, 2009). Indoor green walls have potential to reduce allergens by filtering aerosols and other atmospheric particulates (Pradhan et al, 2019a). Plants commonly used in green wall designs do not produce large quantities of pollen, which is a common allergy concern for many. However, further studies are needed to assess the risk of bioaerosols and fungal spores from greywater-recycling indoor green walls.

A further advantage of green wall usage is its capacity to reduce noise pollution and mitigate indoor acoustics. Green walls insulate against outside noise and reduce sound penetration from urban noise pollution, dampening city sound and offering a more quiet, peaceful environment (Weinmaster, 2009). The reduction of disturbing, loud noises consequently improves the health and wellness of the residents in a green wall environment.

Indeed, green walls can ease human stress and provide intrinsic connections with nature in the busy city life. Studies in American and European universities have shown that viewing greenery induces positive emotions in people, increasing their levels of happiness and worker efficiency (Weinmaster, 2009). A study at Washington State University found that participants were less stressed and more productive in the presence of plants (Lohr et al., 1996, as cited in Weinmaster, 2009). Another study by the Norwegian Agricultural University discovered that the number of sick days workers took in an office with plants was lower than in a bare office (Fjeld et al., 1998, as cited in Weinmaster, 2009). Historically, access to green spaces has been linked to positive impacts on adolescents' mental health (Zhang et al., 2020). Increased exposure to green

spaces has been associated with improved attention, social support, school performance, and management of attention deficit hyperactivity disorder symptoms (Zhang et al., 2020). Yet, gaps still exist in terms of qualitatively and quantitatively assessing green spaces' ability to improve mental wellness (Zhang et al., 2020).

The scope of effect of green walls on human health, both mental and physical, is expansive. This green infrastructure also privileges the structure it lies on by protecting the building integrity. The buildings are protected against ultraviolet (UV) radiation, rain, wind, and precipitation (Weinmaster, 2009). Green walls reduce temperature fluctuations in buildings, which are largely responsible for the expansion and shrinking of building materials, causing cracks and other structural damages (Weinmaster, 2009). For example, they can enable temperature reductions between 2.5 and 6.1°C on sunny days (Cuce, 2017). This not only protects the building exterior but reduces energy used within the building (Cuce, 2017).

Thus far, green walls have been discussed in the context of their practical usages and applications. However, with the increase in popularity of sustainable, green spaces in cities, green walls offer unique marketing and economic opportunities. They have been found to increase property values of homes, offices, and business by up to 15 percent (Weinmaster, 2009). In retail and business settings, green walls even promote and increase customer visitation and participation (Weinmaster, 2009).

Overview of Greywater

Greywater Definition and Characteristics

Greywater is defined as any “wastewater from kitchen, bath, and laundry excluding wastewater from toilets” (Ghaitidak & Yadav, 2013). Greywater is further classified into two groups: light greywater and dark greywater (Ghaitidak & Yadav, 2013; Fowdar et al., 2017). Light greywater is characterized as “wastewater discharges from showers, baths and washing basins,” whereas dark greywater defined as more heavily polluted greywater and is typically discharged from laundry, dishwashers, and occasionally kitchen sinks (Ghaitidak & Yadav, 2013; Fowdar et al., 2017). The focus of our study involves using synthetic light greywater to irrigate our green wall. Synthetic light greywater is greywater artificially synthesized to simulate the quality of typical household light greywater and consists of a combination of personal care and cleaning products as well as analytical grade chemicals (Prodanovic et al., 2017).

Greywater characteristics can also be broken down into the following categories: physical, chemical and biological (Shaikh & Ahammed, 2020). Physical characteristics refer to temperature, turbidity, and total suspended solids, while chemical characteristics are pH, organic content, chemical oxygen demand (COD) concentration, biological oxygen demand (BOD) concentrations, total nitrogen (TN), total phosphorus (TP); however this is not an exhaustive list of parameters (Shaikh & Ahammed, 2020). Lastly, the biological side looks at the microbial content of the greywater which is measured and analyzed by the levels of total coliforms and fecal coliforms (Shaikh & Ahammed, 2020). Additional parameters to evaluate greywater quality may involve analyzing concentrations of organic micropollutants, heavy metals, and contaminants of emerging concern (Noutsopoulous et al., 2018).

Moreover, greywater characteristics depend on several factors like the season, the living habits and customs of the resident, the composition of the resident's personal care and cleaning products, and the geographical location of the resident (Boano et al., 2020; Shaikh & Ahammed, 2020). Additionally, greywater quality can also vary depending on the source. For example, greywater source from the laundry or kitchen is associated with higher levels of organic carbon, suspended solids, surfactants, and bacteria (Noutsopoulos et al., 2018; Shaikh & Ahammed, 2020). Common sources of pollutants in kitchen greywater from dishwasher appliances and other household amenities include detergents and cleaning products, food residues, oils, and fats thus making it a major source of phosphorus (Noutsopoulos et al., 2018; Shaikh & Ahammed, 2020).

Typically, bathroom and hand basin greywater contain body care products such as shampoo and soap, oral care products, hairs, skin, etc (Shaikh & Ahammed, 2020). Bacteria and chemicals are typically found in lower concentrations in bathroom greywater (Shaikh & Ahammed, 2020). Laundry greywater typically consists of various chemical pollutants from detergents, oils, solvents, clothing fibers (Shaikh & Ahammed, 2020). Pathogens, associated with unwashed clothes, are also commonly found in laundry greywater (Shaikh & Ahammed, 2020). Higher concentrations of heavy metals, phosphates, suspended solids, oxygen demand, and turbidity are also characteristic of laundry greywater (Shaikh & Ahammed, 2020).

Uses of Treated Non-Potable Greywater

Because it contains a lower concentration of pollutants than heavily polluted wastewater from toilets (i.e., blackwater) and is generated on a regular basis in households, greywater has been increasingly viewed as a promising water source for unrestricted non-potable water reuse. Non-potable water reuse refers to recycled water that is suitable for non drinking purposes,

whereas potable water is recycled water suitable for drinking purposes (Marks, 2006).

Unrestricted non-potable water reuse is applicable across agricultural, industrial, and household settings and refers to recycled water that is appropriate for purposes including crop irrigation, construction, providing water for cooling towers, and toilet flushing (Okun, 2000).

Greywater recycling systems for non-potable water reuse are becoming increasingly considered as viable solutions to help lessen the burden of using potable water for water intensive processes such as toilet flushing and agricultural irrigation. Irrigation is one of the largest consumers of water globally and accounts for 80-90% of total US water consumption (Center for Sustainable Systems, University of Michigan, 2023). Greywater recycling emerges as a water conserving strategy to address the high demands of agricultural irrigation and domestic water usage, with greywater recycling systems having an estimated potential water savings of about 9 to 46% (Boyjoo et al., 2013).

Design Considerations

Green Wall Construction

Green wall design consists of several components, but those that are crucial to identify upfront are as follows (Table 1):

Table 1. Summary of key components of green wall design identified by the team.

Location	Evaluate the benefits and requirements of an indoor vs. outdoor living wall
Wall Configuration	Design the orientation of plants and pots to promote vitality of the living wall and filtration efficiency
Lighting	Leverage light intensity for ideal plant health and growth conditions
Plant Selection	Identify plants tolerant to saturated or unsaturated conditions
Media Selection	Consider optimizing pollutant removal via water flow speed through particles of varying size

These design considerations were specifically examined in the literature in order to ensure Team Verdant’s wall design and orientation was consistent with successful practices for plant growth and filtration.

Indoor vs Outdoor Walls

In beginning with the *Location* consideration, the literature revealed that indoor green walls are easier to maintain because of their limited size and there is greater freedom in plant selection because weather is not a factor (Mustonen, 2017). There is also the added benefit of a localized ecosystem: outside walls require more maintenance in separating weeds that will grow within them (Almusaed et al., 2011).

Wall Configuration

In our exploration of possible orientations of a living wall, we found the “pot” and “block” configurations were the most widely implemented. Prodanovic et al. (2017) sought to

discern the optimal green wall design for greywater treatment, and in their study, a pot design allotted an individual media-filled pot to each plant, while in a block design, multiple plants were located in one large media-filled block (Prodanovic et al., 2017). To test effectiveness of water filtration, the greywater was tested for total suspended solids (TSS), nitrogen (TN), phosphorus (TP), chemical oxygen demand (COD), and *E.coli* before and after going through the green wall. Though similar in pollutant removal effectiveness, block designs were more resistant to drying out and pot designs were more resistant to clogging and could provide aeration, preventing bad smells (Prodanovic et al., 2017). Other studies found that pot designs are easier to replace, should a plant need to be taken out of the green wall (Prodanovic et al., 2020; Boano et al., 2020).

Lighting Configurations

Most studies of green walls for thermal regulation or air pollutant removal applications provide optimal or outdoor lighting, so lighting optimization is rarely a concern. For our purposes, however, Team Verdant seeks to address indoor lighting dynamics as applied to greywater filtration efficiency. This section of the literature review aims to explore adapting to minimal or insufficient natural lighting indoors. There are a few major factors to consider, one being that the lighting must maintain the appearance of a living wall (LW) if the wall is in view of building occupants. Utilizing grow lights is an immediate and generally sufficient solution, but is not failproof in maintaining a natural or healthy appearance of the living wall (Kaltsidi et al., 2020). For greywater filtration, aesthetics are of lesser importance overall as the wall is not purely decorative, which allows for the use of higher intensity lighting.

Lighting intensity is defined as the amount of light received by the wall at any given height (varies with angle and distance relative to light source at different locations on the wall). Most high intensity or conventional lighting solutions are unfavorable due to heat generated, lower efficiency, and adverse effects on aesthetics irrespective of plant growth (Kaltsidi et al., 2020), though this effect is reduced in LEDs as described below.

Type of light source can greatly impact the growth of a living wall. One large distinction is that between high intensity fluorescent/incandescent solutions and LED bulbs. LED lighting is more cost and energy effective and also offers greater control over light quality. LED lighting has already been studied extensively for agricultural applications, and the lower temperatures from usage of LED lighting results in a greatly reduced effect on plant water consumption (Yeh et al., 2009; Kaltsidi et al., 2020). This is because increased temperatures elevated the rate of evapotranspiration and evaporation (Egea, et al., 2014; Kaltsidi et al., 2020).

Higher light intensity is linked to higher removal efficiency of CO₂ in the 2021 study by Dominici and other researchers, where the highest carbon removal varied with angle under same intensity lighting, demonstrating the loss in light intensity caused by the lack of optimization of the orientation of the lighting (Dominici et al., 2021). In their analysis of the results, set-ups that used lights with angles greater than 45 degrees were ruled out as they showed drops in photosynthetic photon flux density (PPFD), which measures average photosynthetic photons received and thus quantifies lighting quality and efficiency (Dominici et al., 2021). Bulb brightness directly influences intensity: larger walls will naturally require higher brightness or greater number of bulbs to reach minimum intensity levels for plant growth as a result of less light diffusing to the edges. To combat this, light diffusion strategies need to be employed as excessive light intensity causes more harm than good: reducing plant health and/or plant

coverage near lamps increases and poor light distribution is aggravated as a result (Kaltsidi et al., 2020). With larger LWs, illuminance is greatly reduced, which suggests using panels with individual lights in order to uniformly light each panel from different angles.

Lighting optimization intersects with plant selection as sunlight requirements are plant-specific. Plants should be selected to be “shade-tolerant” to lower requirements for intensity and maintenance, though only if they maintain efficiency in filtering greywater. In addition to this, the literature shows the prevalence of overcompensation in lighting green walls due to the practice of measuring light input as lux levels and broad categorizations of sunlight requirements for plants (i.e., full sun, semi-shade, or full-shade) rather than the integral of photosynthetic light provided by a lighting solution over each day, optimized based on the measured growth levels achieved in testing such as the growth chamber testing conducted by Tan and other researchers (Tan et al., 2017). Tan et al. (2017) recommend basing lighting configuration selection on the availability of natural light for better energy efficiency and to avoid “inadequate” or “excessive” intensities of light via matching the experimentally determined light compensation point (LCP) of the plant to the daily photoactive radiation (PAR) provided to the plant, including example calculations of these parameters in this same article (Tan et al., 2017). All of these considerations have assisted Team Verdant in optimizing lighting for our unique LW goals.

Plant Selection

In most applications of green walls plants are chosen for their aesthetics. With the introduction of greywater filtration as the primary role of the green wall, the plants selected for

the green wall must satisfy certain requirements to ensure their survival and increase the efficiency of pollutant removal:

1. The plant must be able to tolerate water-logged conditions (Fowdar et al., 2017).
2. The plant must be able to grow in a high nutrient environment (Rysulova et al., 2017).
3. The plant must be able to tolerate elevated salinity conditions (Fowdar et al., 2017).

The degree to which each plant must abide by these conditions differs depending on its location in the green wall. For example, if greywater is dosed in a vertical flow system, it is expected that the layers towards the top will be more exposed to air than the bottom layers because gravity causes the water to saturate the lower levels more (Rysulova et al., 2017). . Therefore, it may be beneficial to use wetland plants at the top of the wall and less water-prone plants at the bottom. Heavy nutrient absorbing plants at the bottom may also be useful to catch any remaining nutrients in the water.

A variety of plant species may also be beneficial in the green wall. Greater biodiversity is known for its effects on improving water quality in environments, such as in natural streams and rivers (Cardinale, 2011). Numerous plant species in a green wall with varying capacities for pollutant removal, water tolerance, and salinity conditions may help increase the overall efficiency of the wall, using the bioecological concept of ‘self-organization for maximum power,’ where the whole system arises out of local interactions between small components of the system (Lahlou & Truffet, 2020).

In the study by Rysulova et al. (2017), the use of four evergreen species that fulfilled the above requirements was proposed: *Cotoneaster dammeri*, *Blechnum spicant*, *Carex oshimensis*, and *Ophiopogon planiscapus*, many of which are native to areas of Asia and Europe (Rysulova

et al., 2017). In the study by Pradhan et al. (2019b), common plants in the study location, the Middle East, were utilized, such as *Ruellia brittoniana* and *Al-ternanthera dentata*. Indeed, many of these studies utilize native plants of their locations to facilitate ease of access, construction, maintenance, lifespan, and future replication (Alliance for the Chesapeake Bay, 2013). They are accustomed to the local sun, soil, and climate. However, to our knowledge, there is no study on greywater filtration in green walls using plants native to the Maryland and Chesapeake Bay area climate.

Possible Maryland native plants which satisfy the above requirements and are thus suitable candidates for greywater filtration in the green wall include: *Carex stricta*, *Asclepias incarnata*, *Veronia noveboracensis*, *Panicum virgatum*, *Tradescantia virginiana*, *Peltandra virginica*, and *Juncus effusus*.

Media Selection

Media is of vital importance to the filtration of greywater in a green wall. Previous research reveals that media selection can have a greater impact on greywater recycling experiments in green walls than plant selection, which emphasizes the need for an appropriate media choice to facilitate pollutant removal (Pradhan et al., 2019b).

Plant media, as evaluated for use in the saturated conditions of a green wall, can be categorized as either hydraulically ‘fast,’ referring to materials where water is physically able to passing through easily, and hydraulically ‘slow,’ where the characteristics of the media prevent water from moving through at an accelerated rate. An evaluation of the strengths of each media classification by Prodanovic et al. (2017) found that use of hydraulically slow media resulted in a higher purification of greywater contaminants across the board, with approximately “90%, 50%,”

30%, 70% and 80% removal of total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD) and *Escherichia coli* (*E. coli*) respectively” (Prodanovic et al., 2017). Despite its heightened capacity for filtration, slow media was frequently clogged. Fast media, alternatively, had no clogging, although there were diminished purification benefits, “80%, 30%, 15%, 30% and 20% of TSS, TN, TP, COD and *E. coli* removal respectively” (Prodanovic et al., 2017). The findings of this study demonstrate that a slow/fast media cocktail is needed to obtain both desirable characteristics. Pradhan et al. (2019a) also endorses hybrid material mixtures to optimize media performance and in order to identify characteristics relevant to porosity, density, and interactions with pollutants (Pradhan et al., 2019a).

Prodanovic et al. (2017) approached the selection of a media mixture by selecting the most effective slow and fast media which it identified as coco coir and perlite. Coco coir is a type of growing medium made of fiber from coconut husk and perlite is a growing medium made from expanded volcanic glass (Prodanovic et al., 2017). Coco coir was heralded as the most effective stand-alone media for filtration overall, with biological mechanisms that helped remove TN and COD. Other articles similarly established coco coir as a very desirable media (Prodanovic et al., 2017). Coco coir outperforms sand and other media like spent coffee grounds (SCG), especially in contrast to the porous and hydraulically conductive lightweight expanded clay aggregate (LECA) media (Pradhan et al., 2020). When looking at the biological characteristics present in coir that set it apart, substrates play a large role in pollutant removal and water filtration. Other substances that in some ways emulate this characteristic are biochar and alum sludge, but these are less practical for use in a green wall (Addo-Bankas et al., 2021).

Perlite was a hydraulically fast media that effectively purified greywater without clogging in the study by Prodanovic et al. (2017). It largely implemented physicochemical processes for contaminant capture and optimized other desirable characteristics. Perlite is lightweight, allowing for easy mounting of a green wall and limiting the structure's propensity to collapse. Additionally, Prodanovic et al. (2017) finds perlite adheres to standards for the green wall's ability to support plant growth with respect to retaining water and nutrients (Prodanovic et al., 2017).

Despite the favorable reviews of a few select green wall media, the pollutant removal capabilities of modern lightweight media are still not as well understood compared to conventional natural growing mediums, namely soil and sand (Pradhan et al., 2019a). As a result, a gap exists concerning the performance of media mixtures under different GW loading and “drying conditions”, and the team must therefore be sensitive to performance results that vary from the literature (Prodanovic et al., 2017). Specifically, a lack of knowledge surrounding lightweight media materials' nutrient capacity, COD, microorganism uptake, response to greywater flow, and pollutant removal processes will all be considered by the team as we seek to optimize greywater purification. Previous biofiltration studies also highlight the importance of media quantity in greywater filtration. The height of available soil through which the water runs through should be 400-600 mm (Prodanovic et al., 2019).

Greywater Considerations for Green Walls

In the design of our greywater-recycling green wall, it is also important to consider the source and composition of greywater supplied to the wall. Specifically, understanding inflow greywater quality will help us better understand and develop ways to promote targeted pollutant

removal via the media and plants in the green wall. Several studies have explored greywater treatment performance of green walls using synthetic greywater. Typically, synthetic greywater has been employed by these studies to maintain consistent water quality and to meet high water demands for experimental green walls (Fowdar et al., 2017; Boano et al., 2020). Moreover, synthetic greywater recipes have been primarily aimed at replicating light greywater; light greywater is household greywater derived from bathroom showers, baths, and hand basins (Prodanovic et al., 2017). Light greywater has been preferred over kitchen and laundry greywater due to its lower levels of contamination; that is, light greywater has typically shown greater potential for non-potable reuse than other greywater types (Boano et al., 2021).

In general, synthetic greywater recipes have usually employed a mixture of analytical grade chemical products and commercial products to reproduce light greywater composition (Boano et al., 2020). Several studies have followed the same standard light greywater recipe first developed by the Commonwealth Scientific and Industrial Research Organization of Australia (Diaper et al., 2008). Each of these studies has modified this standard recipe to meet the goals of their respective experiments and to better reflect local greywater compositions by using local brands of household cleaning and hygiene products (Fowdar et al., 2017; Prodanovic et al., 2017, 2019; Pradhan et al., 2019; Boano et al. 2021). Fowdar et al. (2017) conducted a study in Melbourne, Australia on the greywater treatment capacity of a green wall composed of ornamental plant species by varying specific design and operational conditions (Fowdar et al., 2017). The group assessed the ability of their green wall to remove common pollutants from household bathroom greywater, preparing a synthetic greywater recipe using specific commercial brand personal care products found in Australia and chemical products.

Boano et al. (2021) investigated the performance of green walls when different additives were incorporated into the base filter media of a green wall (Boano et al., 2021). This team of researchers at the Polytechnic University of Turin in Italy was specifically interested in further understanding the impact of filter media on optimizing greywater treatment efficiency. Boano et al. (2021) chose both local Italian brands and analytical grade chemicals for their greywater recipe, modifying the Diaper et al. (2008) recipe to more accurately represent local Turin greywater (Boano et al., 2021). Moreover, Boano et al. (2021) accounted for microbiological contaminants by adding *Escherichia coli* (*E.coli*) tablets into their greywater batches (Boano et al., 2021). Similarly, Prodanovic et al. (2017) investigated filtration abilities of various media in unvegetated columns in treating synthetic greywater, which was modified from the synthetic greywater recipe developed by Diaper et al. (2008) (Prodanovic et al. 2017; Diaper et al., 2008). In their study investigating the role of plants and different operational conditions in treating light synthetic greywater from a green wall, Prodanovic et al. (2019) employed a recipe similar to their earlier study that was originally based on the Diaper et al. (2008) recipe. The Diaper et al. (2008) recipe was modified by Prodanovic et al. (2019) to include locally available brands of household and personal care products in Australia as well as secondary effluent from a local wastewater treatment facility near the university where the study was conducted (Prodanovic et al., 2019).

Although there have been several studies conducted in laboratory settings using synthetic greywater, these studies fall short in representing the significant variation inherent in real greywater and suggest a growing need for research on designing green walls irrigated by real greywater (Fowdar et al., 2017). Indeed, to address this shortcoming, there have been a few studies that have targeted real-world conditions by sourcing real greywater and untreated

wastewater (Wolcott et al., 2016; Dal Ferro et al., 2021). For instance, researchers at the University of Padova in Italy used real greywater from the university cafeteria kitchen sink to investigate the treatment performance of green walls (Dal Ferro et al., 2021). Kitchen greywater was selected due to its lower levels of contamination, ease of isolation from wastewater collection, and convenience due to accessibility to the campus's kitchen (Dal Ferro et al., 2021). Wolcott et al. explored the potential for green walls to treat wastewater from food and beverage companies by sourcing wastewater from a small local brewery (Wolcott et al., 2016).

Dosing Regime

Another important consideration for designing greywater-recycling green wall experiments is developing a dosing regime for supplying greywater to the green wall. Dosing regimes typically involve defining hydraulic loading rates, which are rates at which greywater is supplied to the green wall columns, and defining “resting” or “dying” periods when the wall receives no greywater (Pradhan et al., 2019b; Prodanovic et al., 2019). In order to develop a procedure to load walls with greywater, water requirements for selected green wall plants and characteristics of media, such as tendency to clog under hydraulic loading, should be well understood. It is estimated that plants typically require approximately 0.12 L of water per column per day in green walls, for an experimental column with an area of about 0.00785 m² (Prodanovic et al., 2017).

Furthermore, dosing regimes in the past have attempted to represent the times and frequency at which greywater is typically generated in households per day. By doing so, researchers have further explored the feasibility and applicability of greywater recycling green walls in homes. Several studies using synthetic greywater chose to dose green wall columns with greywater five days per week (Fowdar et al., 2017; Prodanovic et al., 2017, 2019). Prodanovic et

al. employed both “regular” and “accelerated” dosing periods with intermittent drying periods for their green wall column experiment (Prodanovic et al., 2017). Accelerated dosing periods involved supplying the green wall with a greater volume of greywater (approximately 9 L), while regular dosing periods involved supplying the wall with about 3 L. Additionally, the group attempted to replicate daily greywater production peaks by dosing twice per day, once in the morning and once in the afternoon (Prodanovic et al., 2017).

Similarly, Fowdar et al. (2017) employed “low flow rate” and “high flow rate” periods as well as “resting” or drying periods in their one-year long column study; low flow rate periods involved dosing each column with 2.5 L and high flow rate periods involved dosing each column with 5 L of greywater (Fowdar et al., 2017). Fowdar et al. (2017) chose to dose each column once per day based on their assumption that households tend to shower in the morning, and thus peak light greywater generation occurs primarily in the morning. Contrastingly, Boano et al. (2021) dosing procedure was based on simulating the estimated mean greywater daily production per capita of about 100 L/day common in developed countries as opposed to replicating typical peak greywater generation times in households (Boano et al., 2021). Thus, these studies suggest that dosing regimes should reflect real-world conditions for greywater generation in order to better understand the viability of residential greywater treatment via green walls.

Greywater Composition

In order to identify and understand the processes driving greywater pollutant removal by the green wall, common pollutants and characteristics of greywater must first be understood. Greywater composition is significantly impacted by several factors including users, geographical location, tap water quality, time of day, living habits and customs of residents among several

other factors (Diaper et al., 2008; Boano et al., 2020; Shaikh & Ahammed, 2020). For instance, residents in different countries may use local household cleaning and hygiene product brands with different compositions than ones from another country. Moreover, as previously stated, residential greywater quality also varies by source in the household; for instance, light greywater generated from bathroom sinks and showers typically contains lower levels of contaminants in comparison to that from laundry and kitchen sinks (Noutsopoulous et al., 2018, Shaikh & Ahammed, 2020). Thus, greywater quality varies based on various factors. While several studies have primarily targeted reproducing and analyzing outflowing light greywater, it should be noted that there has not been a general consensus for one specific set of water quality parameters to follow for analyzing greywater treatment by green walls.

Different studies have analyzed a different set of parameters to assess the greywater treatment performance of green walls; however, for the most part, these studies have analyzed similar parameters. For instance, Diaper et al. (2008) identifies several physicochemical and microbiological water quality parameters for developing synthetic greywater recipes (Diaper et al., 2008). Physicochemical parameters according to Diaper et al. (2008) include suspended solids, biological oxygen demand (BOD), temperature pH, turbidity, total phosphorus (TP), total nitrogen (TN), nitrate, nitrites, chemical oxygen demand (COD), total organic carbon (TOC), conductivity, boron concentrations, and the presence of several minerals. Microbial parameters included total coliforms, *E.coli*, and *F Enterococci* concentrations.

In the Prodanovic et al. (2019) experimental greywater-recycling green wall study, researchers analyzed greywater effluent for total nitrogen, ammonia (NH_3), oxidized nitrogen (NO_x), total dissolved nitrogen (TDN), total phosphorus (TDP) following NATA (National Association of Testing Authorities, Australia) standards (Prodanovic et al., 2019). Boano et al.

(2021) monitored the outflow greywater from their green walls for physical, chemical, and biological parameters. pH, electric conductivity, total suspended solids, dissolved oxygen, BOD, COD, nitrogen and phosphorus compounds, chlorides sulfates, anionic surfactants, and *E. coli* were among some of the parameters analyzed by the group (Boano et al., 2021). Team Verdant analyzed several of the common greywater quality parameters identified in previous studies, namely pH, turbidity, COD, TN, and NPOC/TOC. A summary of these select greywater quality parameters along with their target concentrations as identified by Prodanovoic et al. (2019) and literature values from studies by Ghaitidak and Yanav (2013), Eriksson et al. (2022), and Birks and Hills (2007) are presented in Table 2 (Ghaitidak & Yanav, 2013; Eriksson et al., 2022; Birks & Hills, 2007).

Table 2. Select synthetic light greywater characteristics from Prodanovic et al. (2019)

<i>Parameter</i>	<i>Target Concentration</i>	<i>Literature*</i>
pH	7.0	5 - 8.1
Turbidity (NTU)	50	20 - 375
Chemical Oxygen Demand COD (mg/L)	295	21 - 645
Total Nitrogen TN (mg/L)	5.5	0 - 23.3
TOC/NPOC (mg/L)	66	30 - 104

* Literature values representing synthetic light greywater quality as summarized by Prodanovic et al. (2019) and Prodanovic et al. (2020) based on literature values from Ghaitidak and Yanav (2013), Eriksson et al. (2022), Birks and Hills (2007).

Tested Greywater Quality Parameters

1. pH

According to the EPA, pH is an indicator for the acidic and basic nature of solutions (EPA, 2021a). It uses a scale of 1-14. Solutions with a pH below 7.0 are acidic; those above 7.0 are basic; 7.0 is neutral, which is the pH of distilled water. The pH scale is logarithmic such that every one-unit increase represents a ten-times increase in acidity (EPA, 2021a). pH is measured using electrochemical methods involving probes as well as colorimetric methods involving indicator solutions/papers (EPA, 2021a). In wastewater, pH can help indicate the presence of acidic/basic pollutants and can alter the chemical state of those pollutants within the water. In

this way, it can help identify water safe for human consumption or non-potable use and is an important indicator for water purification.

2. Turbidity

Turbidity, according to the EPA, is a measure of water clarity (EPA, 2021b). High turbidity in a sample leads to a cloudy/muddy appearance and low turbidity samples are relatively clear. Turbidity is measured using a turbidity meter through the process of nephelometry, which uses light scattering to determine the concentration of suspended particles in a solution (EPA, 2021b). The suspended solids that contribute to high turbidity can indicate the presence of pollutants in wastewater. Turbidity is therefore an important visual indicator for water purification; water for reuse purposes is expected to appear relatively clear.

3. Chemical Oxygen Demand (COD)

Chemical oxygen demand (COD) is a water quality parameter used to measure the amount of Dissolved Oxygen (DO) when organic matter is oxidized (CHEMetrics, n.d.). To test greywater for COD, greywater samples are added to vials containing sulfuric acid and potassium dichromate and digested for two hours. The catalyzed reaction then yields spectrophotometric results that can be read with a COD analyzer to determine the ppm concentration. We used a Hach DR900 Multiparameter Portable Colorimeter with capability for measuring COD to analyze our COD samples. COD is relevant in water purification since it provides a reference for how the wastewater will affect the surrounding environment when discharged (RealTech Water, 2017). Higher COD indicates larger amounts of oxidizable organic material in the water, which can reduce dissolved oxygen (DO) levels and lead to anaerobic conditions for aquatic life in

bodies of water (RealTech Water, 2017). Because non-potable water reuse often involves activities like car washing and irrigation, in which water can runoff into local lakes, ponds, and rivers, it is important to ensure low COD levels in water samples to avoid harmful effects on the surrounding environment.

4. Total Nitrogen (TN)

Total nitrogen (TN) is defined by the EPA as the “sum of total kjeldahl nitrogen (organic and reduced nitrogen), ammonia, and nitrate-nitrite” (EPA, 2009). Total nitrogen in our study was analyzed using a TOC-L Shimadzu Total Organic Carbon Analyzer with total nitrogen measurement capability, in the Inorganics Pollutants Lab. According to the EPA, a TN level between 2 to 6 mg/L-N falls in the “acceptable” range (EPA, 2009). Similar to COD, excess levels of nitrogen in water samples can lead to low levels of DO and anaerobic conditions for aquatic life in local bodies of water that intercept runoff from these water samples; thus, it is important implement a strict standard for TN levels in non-potable water reuse (EPA, 2009).

5. TOC/NPOC

Total organic carbon (TOC) and non-purgeable organic carbon (NPOC) both refer to the “total amount of carbon present as organic molecules” in water (Texas Commission of Environmental Quality, 2022). TOC and NPOC are measurements that require sample acidification to strip off CO₂ and measure its concentration (UMES, 2018). Specifically, organic carbon is oxidized so that carbon dioxide gas can be measured by the device, and this reading is identical for both TOC and NPOC when purgeable organic carbon (i.e., volatile carbon) that is readily removed from a sample, is minimal; this is the case for the light synthetic greywater in

this study. Use of a TOC-L Shimadzu Total Organic Carbon Analyzer analyzer requires a calibration curve of known carbon concentrations, and the integration of these readings provides an estimate for sample purity based on their location on the linear curve (EPA, 2005). Since organic compounds can harm local bodies of water in the environment, ensuring acceptable amounts of NPOC/TOC is necessary for water purification.

Greywater Effluent Standards for Non-Potable Reuse

The 2012 EPA guidelines highlight that individual greywater reuse systems are largely subject to state regulatory systems and laws. States that have provided specific regulations for greywater reuse include: Arizona, California, Connecticut, Colorado, Georgia, Montana, Nevada, New Mexico, New York, Massachusetts, Oregon, Texas, Utah, Washington, and Wyoming (US EPA, 2012). The EPA recommends referencing the *NSF/ANSI Standard 350 Onsite Residential and Commercial Water Reuse Treatment Systems* created in 2011 as a baseline for examining onsite, individual water treatment systems in both residential and commercial capacities (US EPA, 2012). The residential system classification is used for systems that use up to 1,500 gallons per day (US EPA, 2012). The NSF-/ANSI 350 outlines end-uses of purified water, including restricted urban water usage (e.g., toilet-flushing) and unrestricted outdoor urban usage (e.g., surface irrigation) (Table 3).

Table 3. Table from NSF/ANSI 350 Report (Bruursema, 2011). Class R refers to residential treatment systems and class C refers to commercial treatment systems. Maryland guideline legislation on greywater reuse only refers to BOD and TSS reduction to ~10 mg/l with disinfectant (Maryland Department of the Environment, 2020).

Parameter	Class R		Class C	
	Overall test average	Single sample maximum	Overall test average	Single sample maximum
CBOD ₅ (mg/L)	10	25	10	25
TSS (mg/L)	10	30	10	30
Turbidity (NTU)	5	10	2	5
E. coli ² (MPN/100 mL)	14	240	2.2	200
pH (SU)	6–9	NA ¹	6–9	NA
Storage vessel disinfection (mg/L) ³	≥0.5–≤2.5	NA	≥0.5–≤2.5	NA
Color	MR ⁴	NA	MR	NA
Odor	Non-offensive	NA	Non-offensive	NA
Oily film and foam	Non-detectable	Non-detectable	Non-detectable	Non-detectable
Energy consumption	MR	NA	MR	NA

¹ NA = Not applicable

² Calculated as geometric mean

³ As chlorine. Other disinfectants can be used.

⁴ MR = Measured and reported only

It is important to note that despite this EPA recommendation, individual state statutes and regulations and local building codes take precedence for greywater usage and evaluation (US EPA, 2012). In recent years, the state of Maryland has adopted legislation for general greywater reuse guidelines for residential areas, including bath, shower, and lavatory water and excluding toilet, kitchen sink, dishwasher, and laundry water (Maryland Department of the Environment, 2020). They also broadly refer to the NSF/ANSI 350 code for a few treatment parameters and approve reuse of greywater in areas of non-drip irrigation, drip irrigation, and toilet flushing in residential units (Maryland Department of the Environment, 2020). Due to the limited scope of Maryland guidelines on greywater reuse standards and the overall subjectivity of these standards throughout the United States, our team referenced a variety of sources to create a comprehensive,

conservative list of water reuse standards for non-potable usage after greywater filtration, following the example of the Class of 2019 Gemstone team, Team PURIFY (Alving et al., 2019). These references included other state standards, industry reports (Table 4 and Table 5), as well as the NSF/ANSI 350 code (Table 3).

Table 4. Condensed list of relevant pollutant parameters. pH, turbidity standards taken from the NSF/ANSI 350 code (Bruursema, 2011). TN standards taken from New Jersey, Arizona, and North Carolina regulations, following Team PURIFY’s example (Alving et al., 2019). COD values taken from upper tier limit of COD from Proteus Instruments’ standards for urban waste water treatment (Proteus Instruments, 2024). The 250 mg/L-750 mg/L range indicates primary/secondary effluent; 500-1200 mg/L indicates raw municipal sewage; 1000-50000 mg/L indicates contaminated industrial effluent (Proteus Instruments, 2024).

<i>Parameter</i>	<i>Target Concentration</i>
pH	6 - 9
Turbidity (NTU)	< 5
Chemical Oxygen Demand COD (mg/L)	250
Total Nitrogen TN (mg/L-N)	< 10

Table 5. TOC/NPOC removal standards as percentages (absolute values of TOC are not referenced in wastewater purification standards). TOC removal depends on alkalinity and becomes more difficult as alkalinity increases and TOC levels decrease. See pH to alkalinity conversion chart below. Table from TCEQ Guide on TOC (Texas Commission of Environmental Quality, 2022).

Raw Water TOC Ranges (mg/L)	Raw Water Alkalinity Ranges (mg/L as CaCO₃)		
	<i>0 to 60</i>	<i>> 60 to 120</i>	<i>> 120</i>
<i>2.0 ≤ TOC ≤ 4.0</i>	35.0%	25.0%	15.0%
<i>4.0 ≤ TOC ≤ 8.0</i>	45.0%	35.0%	25.0%
<i>TOC ≥ 8.0</i>	50.0%	40.0%	30.0%

Table 5 and 6 concern the removal standards for NPOC/TOC. The standard is not a baseline number; it is a percentage removal rate that must be met for successful purification. This removal rate depends on the alkalinity of the water, as NPOC/TOC removal becomes more difficult to remove as alkalinity increases and NPOC/TOC decreases. The percentages were developed based on the NPOC/TOC ‘treatability’ of different alkalinity-level waters, as outlined in the TCEQ Regulatory Guidance (Texas Commission of Environmental Quality, 2022). It is expected that the majority of the water samples collected in this experiment will be within the 0-60 alkalinity range with a TOC greater than 8, so the projected removal rate standard will be 50%.

Table 6. Conversions of pH to alkalinity in terms of calcium carbonate. This table can be used in reference to Table 5 to convert between pH values and alkalinity and determine relevant TOC/NPOC standard removal levels. Table from Team PURIFY's Thesis (Alving et al., 2019).

<u>pH to Alkalinity Conversions</u>			
pH	Alkalinity in ppm CaCO₃	pH	Alkalinity in ppm CaCO₃
6.5	3	7.3	20
6.6	4	7.4	25
6.7	5	7.5	31
6.8	6	7.6	38
6.9	8	7.7	50
7	10	7.8	60
7.1	12	7.9	80
7.2	15	8	100

Greywater Management and Storage for Green Walls

Designing effective storage systems and maintenance practices is critical for successful operation of self-sufficient greywater recycling-green wall systems. Poor management of these systems can potentially contribute to serious public health issues such as the spread of pathogens and illnesses (Dal Ferro et al., 2020). There have been several challenges due to greywater

storage in real greywater recycling systems (Domènech & Saurí, 2010). For instance, in residential buildings with greywater recycling systems in Barcelona, Spain, researchers found that greywater storage exceeded the recommended capacity of 1m³, thus resulting in greywater accumulation, organic matter buildup, and foul odor generation (Domènech & Saurí, 2010). For effective greywater recycling systems, greywater recirculation should be optimized and accumulation should be minimized. Further, the aforementioned consequences encountered in the study were associated with negatively impacting the public's acceptance of greywater recycling systems (Domènech & Saurí, 2010). That is, ensuring the safety of this technology is important in gaining the public's support and ultimately implementing green walls in real households. Additionally, accumulation of microbial contaminants in greywater storage tanks is another potential concern, as Allen et al. cautions that real greywater should be properly treated prior to storage (Allen et al., 2010).

In laboratory settings, several studies have aimed to address these concerns and provide suggestions for best management practices and designs. To address some of the potential challenges of greywater storage and maintenance in real-life applications, Prodanovic et al. (2017) suggests adopting a greywater pre-treatment procedure before irrigating green walls to prevent potential buildup of organic matter and subsequent clogging; the group further recommends using sedimentation tanks to store the greywater prior to application, where sedimentation or “settling” tanks are usually employed in wastewater treatment plants to allow solid organic matter to settle before further processing (Prodanovic et al., 2017; Boano et al., 2020). In a study employing green walls to treat real kitchen greywater, Dal Ferro et al. employed accumulation tanks to store greywater before application in the green walls and to promote sedimentation (Dal Ferro et al., 2021). The group also pre-treated greywater samples,

resulting in fewer microbial species and overall lower levels of microbial contaminants in outflow greywater; however, the group does not elaborate on the pretreatment method they employed (Dal Ferro et al., 2021). Currently, the impact of pre-treated greywater is not fully understood; however, several of these studies suggest pre-treatment is a potentially important maintenance consideration.

Several studies have also illuminated potential public health concerns surrounding effluent greywater and have prompted further discussion into additional post-treatment of greywater following treatment by green walls. In their investigation into the performance of various green wall wall media in unvegetated columns, Prodanovic et al. (2017) found that levels of *E.coli* in the treated greywater exceeded those outlined by the Environmental Protection Authority Victoria in Victoria, Australia. Consequently, the group suggests that implementing post-treatment disinfection systems is potentially key in meeting federal, state, and/or local water reuse criteria, especially for mitigating public health issues (Prodanovic et al., 2017).

Methodology

Research Question

Team VERDANT seeks to address the question:

*How effective is a green wall made of Maryland native plants (in particular, *Carex stricta*) in filtering greywater?*

Specifically, the wall will be evaluated on its ability to purify synthetic light greywater to standards for unrestricted non-potable reuse. Our goals are to reduce strain on local water resources and combat water scarcity by utilizing non-potable water in areas where drinking water is not essential so water can be conserved.

Hypothesis

Our green wall (composed of *Carex stricta* and a mixture of coco coir and perlite for the media) will effectively filter synthetic light greywater. Note that our use of the word “effective” refers to the ability of the water which has passed through the green wall to satisfy the U.S. EPA and Maryland Department of Environment (MDE) standards for non-potable water reuse for irrigation.

Design Considerations and Constraints

Green Wall Environment

The team chose to build an indoor green wall as opposed to an outdoor green wall. Indoor green walls are built on a smaller scale in order to fit their space, which makes maintenance easier. The indoor environment also allowed for better control of climate conditions.

Overall Setup of Green Wall

The green wall was located at the Cypress Students Competition Building on campus. A pot configuration was used to provide the wall with higher levels of aeration, prevent unpleasant smells, and avoid clogging. The pot configuration allowed easier mobility and movement of plants in the wall without disruption of the overall design. We utilized two adjacent metal wire racks (5 shelves, 48" x 18"x 63") with the pots spread out among the bottom three shelves to create a 3-pot vertical system. We tested ten trials (i.e., replicates) for each configuration (length: 10 pots, height: 3 pots) for a total of 30 pots in the green wall (Figure 1). The wall was run and tested with the plants chosen and then again with the media only as a control (Figure 2). A 50 gallon tank placed adjacent to the wall included a submersible pump that was hooked to a drip irrigation system to water the plants from above. Plastic collection bins were placed at the very bottom of each configuration to collect outflow greywater.

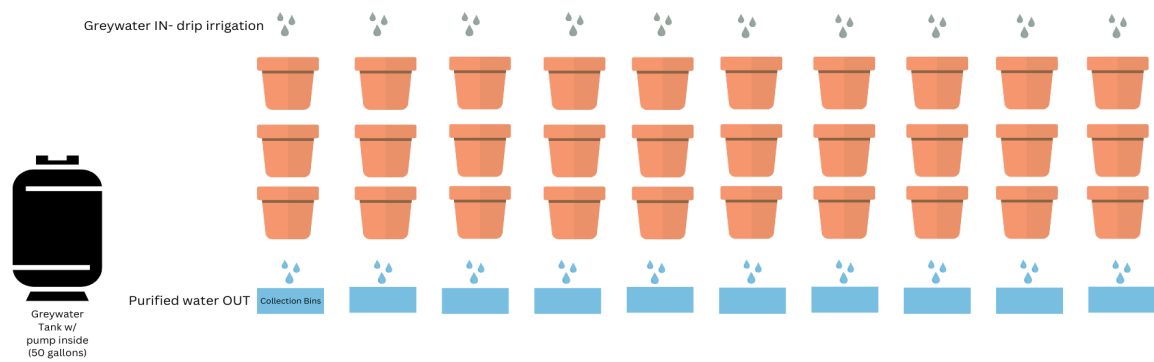


Figure 1. Schematic of 3-level vertical green wall and media wall design. Ten replicates/trials used to increase the amount of water samples analyzed for greater statistical power. 3-level configurations were used to fulfill soil height requirements for pollutant filtration (see ‘Media Selection’ below).

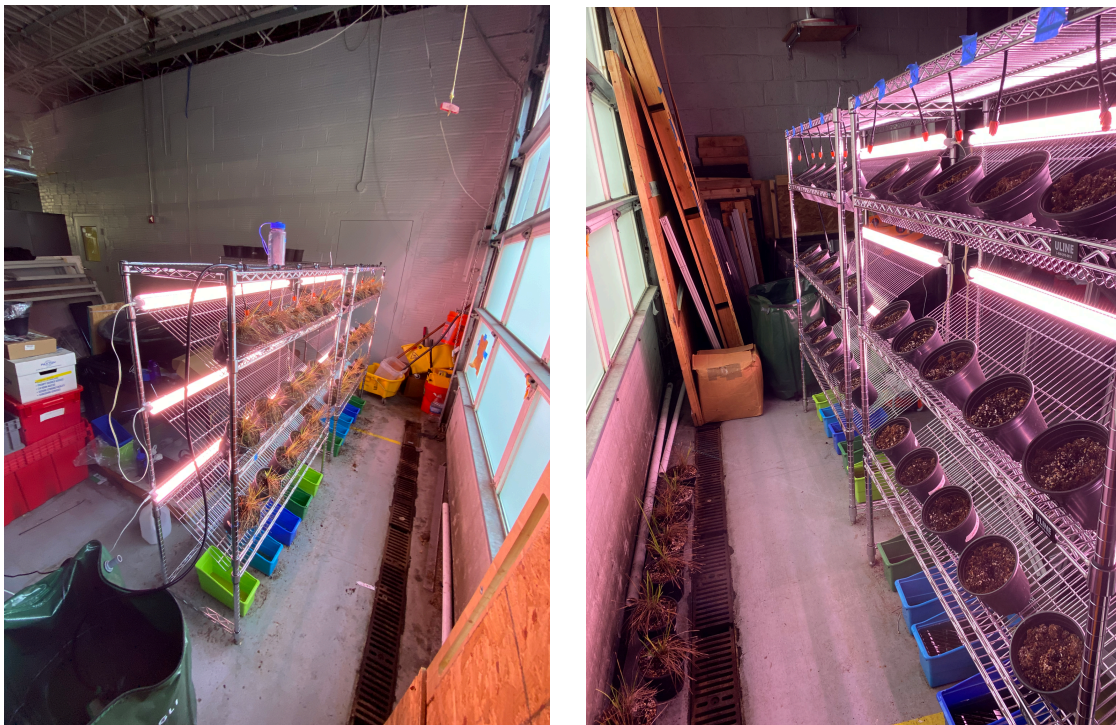


Figure 2: *Carex stricta* wall (left) and Media wall (right).



Figure 3. *Carex stricta* replicates 1 to 5 (left) and replicates 6 to 10 (right). Collection bins for sampling outflow greywater were placed under the lowest shelf of each replicate.

Media Selection

We used a mixture of coco coir and perlite for the media, which was a mixture of the most efficient slow and fast media determined by Prodanovic et al (2017) (Prodanovic et al., 2017). The coco coir was acquired in a brick form and then rehydrated to achieve a soil texture. Perlite was then mixed into the coco coir ratio according to a 1:2 ratio, as modeled in Prodanovic et al. (2019) (Prodanovic et al., 2019). To ensure the height of the media met biofiltration requirements (400-600mm of available soil), we used 5.3” deep pots to make the total cumulative height of media in the 3-pot system 15.9” (404mm).

Lighting Considerations for Green Wall

White LED lighting rods were used for the indoor green wall. Six lighting rods were used, one placed at each level on the shelf. The lights were controlled via wifi switch and turned on for 12 hours a day. There was also a minimal amount of natural lighting coming through a small window opposite of the green wall.

Plant Selection

We used *Carex stricta* (Tussock Sedge) as our Maryland native plant for the green wall. The plants were acquired as 5” deep plugs from a local nursery to ensure deep roots. The plants were repotted into 5.3” deep pots using the media mixture of coco coir and perlite. Table A details the characteristics of *Carex stricta* that made it a suitable choice for the green wall. Additional plant species, like *Juncus effusus* and *peltandra virginica*, were considered for use in the green wall in order to increase biodiversity and promote filtration; however, due to logistical concerns and time constraints, the team was not able to integrate these multiple plant species in the wall.

Table 7. *Carex stricta* Characteristics

Carex Stricta (Chesapeake Bay Native Plant Center, n.d.)	Name	Description	Water Conditions	Nutrient Capability	*Salt Tolerance
	<i>Carex stricta</i>	Tussock Sedge; 1-4 ft; blooms green flower in May-August, wetland plant (Chesapeake Bay Native Plant Center, n.d.)	High water-tolerance; flooded, moist, or wet soil (Chesapeake Bay Native Plant Center, n.d.)	Good at removal of nitrogen and phosphorous; tolerates nutrient-rich soil (Arboretum, 2010)	Low to none (Jersey-Friendly Yards, n.d)

*Salt tolerance is a metric to measure the relative tolerance of the plant to soil salinity (in comparison to other similar plant types of the same geographical region).

Greywater Composition and Quality

We synthesized our own synthetic light greywater by modifying the recipes used by Boano et al. (2021) and Prodanovic et al. (2019), both of which were adapted from the well-cited synthetic light greywater recipe by Diaper et al. (2008) (Boano et al., 2021; Prodanovic et al., 2019; Diaper et al., 2008). The greywater concentrate solution was produced in A. James Clark Hall Lab 1224. The ingredients shown in Table 8 were measured and added to a household kitchen blender for mixing at low speeds until a homogenous mixture formed. The concentrate solution was then added to the full 50 gallon water tank and mixed in thoroughly with tap water from the Cypress Building for even distribution. Chemicals used were a mixture of food, cosmetic and personal care products, and lab grade due to availability restrictions (Table 8).

Table 8. Synthetic light greywater recipe based on Boano et al. (2021), Prodanovic et al. (2019), and Diaper et al. (2008).

<i>Ingredient</i>	<i>Amount in 100L (g)</i>	<i>Product used</i>
Sunscreen	1.5	Banana Boat
Toothpaste	3.25	Colgate
Deodorant	1	Dove
Na ₂ SO ₄	3.5	Loudwolf - Food Grade
NaHCO ₃	2.5	Carolina- Lab Grade
Na ₂ HPO ₄	3.9	Eisen-Golden Laboratories- Food Grade
Clay	5	Kaolin Clay - Industrial Grade
Vegetable oil	0.7	Crisco
Shampoo/hand wash	72	Dove
Laundry detergent	15	Tide
Boric acid	0.14	Carolina- Lab Grade
Lactic acid	2.8	Talsen Chemicals - Cosmetic Grade

Greywater Dosing Regime

We decided to dose our wall with greywater everyday with no drying periods since our testing period was 20 consecutive days (10 days for the *Carex stricta* green wall and 10 days for the unvegetated media wall). We also wanted to test the effectiveness of our wall under

well-saturated conditions. The submersible pump inside the greywater tank was controlled via a wifi switch that was set to run for 40 minutes every morning during the testing period.

Greywater Irrigation System

Greywater was stored and discharged from a single 50 gallon tank adjacent to the green wall using a submersible pump connected to a drip irrigation system. One dripper was placed on top of each replicate (10 drippers total). Water flowed from the drippers to the first pot, through the mesh wire shelves into the second pot, then to the third, and finally, to the collection bins at the bottom. Samples of effluent greywater were collected from the collection bins using 32 oz plastic bottles and taken to the Inorganic Pollutants Research and Nutrient-Energy-Smart (NES) labs on campus for analysis.

Testing

The experiment was conducted in two separate phases: the green wall and the unvegetated media wall phases. After constructing our green wall set-up over the span of a few months with shelving, drip irrigation, a pump, and a tank, we assembled the *Carex stricta* pots in the wall. The *Carex stricta* were irrigated with tap water sourced from the Cypress Building for around 3 months to ensure that plant roots were well established in the media before commencing testing. The wall was run for 10 days, with 40 minutes of greywater inflow per day and no resting periods. In this way, we could test the immediate greywater purification capabilities of the green wall under extremely well-saturated conditions and a heavy water load. Greywater was made in a 50 gallon batch at the beginning of the testing period and was used up for the duration of the 10 days. Water sampling events took place on four separate occasions during the testing period for the green wall and unvegetated media wall phases, respectively.

Inflow and outflow greywater quality were sampled on 2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24 during the green wall phase; inflow and outflow greywater quality were sampled on 2024-Feb-27, 2024-Feb-29, 2024-Mar-04, and 2024-Mar-06 during the unvegetated media wall experimental phase. For each sampling event, we collected 500 mL of water from each collection bin and an additional sample from the greywater tank after mixing. Water samples were also taken from the original batch of greywater produced at the start of the testing period, as greywater concentrations are variable and can change over time. After the 10 days were completed for the green wall phase, we replaced the *Carex stricta* pots with our unvegetated control (i.e., the media-only pots), and repeated the same testing process for another 10-day period for the unvegetated media phase.

Water samples were tested for five parameters: pH, turbidity, COD, NPOC, and TN. These are common parameters used to quantify purification of wastewater. The machinery for these tests was also readily available to us from the Inorganic Pollutants Research and Nutrient-Energy-Smart (NES) labs on campus. pH was measured using a sympHony pH probe; turbidity was measured using a HACH 2100N turbidimeter; COD was measured using CHEMetrics COD vial kits, a digester block, and photometer from the lab; NPOC/TN were measured using a TOC-L Shimadzu Total Carbon Analyser.

pH and turbidity were tested immediately after water samples were collected. COD, NPOC, and TN were tested in batches a few days after water sampling events. Water samples for testing COD, NPOC, and TN were stored in the lab fridge to preserve the sample until testing was performed.

Results

Inflow Greywater Quality

Table 9. Synthetic light greywater quality for *Carex stricta* configuration collected from tank on 2024-Feb-16 and Media configuration collected from tank on 2024-Feb-27.

<i>Parameter</i>	<i>C. stricta Inflow</i>	<i>Media Inflow</i>
pH	6.52	7.05
Turbidity (NTU)	41.87	26.47
Chemical Oxygen Demand COD (mg/L)	454	643
Total Nitrogen TN (mg/L)	2.879	1.568
TOC/NPOC (mg/L)	143.1	98.72

Table 9 shows the synthetic light greywater quality for the *Carex stricta* inflow greywater collected on the first sampling event day (2024-Feb-16) for the 10 day testing period for the *Carex stricta* configuration and the synthetic light greywater quality for the media configuration inflow greywater collected on the first sampling event day for the 10 day testing period for the media configuration (Table 9). Two separate batches of greywater were prepared for the duration of the entire experiment: one batch for the 10 day *Carex stricta* testing period and one batch for the 10 day media testing period. This was primarily due to practical reasons accounting for the

space constraints of the Cypress space and our experimental timeline. Additionally, the same greywater recipe was used for both configurations; however, slight differences in preparation between batches may have contributed to the variation in inflow greywater quality between the two configurations.

In general, pH, turbidity, COD, and TN fall within their respective literature ranges for the *Carex stricta* configuration inflow greywater when comparing the inflow quality shown in Table 9 to the literature ranges and target concentrations of synthetic light greywater shown in Table 2. A notable exception is that the TOC/NPOC concentration for the *Carex stricta* configuration inflow exceeds the TOC/NPOC concentration range (30 - 104 mg/L) based on the literature by more than 30 mg/L. The *Carex stricta* inflow pH (6.52) is slightly more acidic than the expected target pH (7.0). Furthermore, inflow turbidity and TN for the *Carex stricta* configuration fall on the lower ends of the literature ranges while the inflow COD is generally towards the higher end for the literature range of synthetic light greywater COD. For the media configuration inflow greywater quality, pH, turbidity, COD, TOC/NPOC, and TN each fall within their respective literature ranges for synthetic light greywater quality (see Table 2). The inflow media pH (7.05) is closer to the target pH of synthetic light greywater (7.0), than the inflow *Carex stricta* pH. It is also worth noting that the inflow turbidity and TN values are on the lower end of the literature ranges for the media configuration inflow greywater; contrastingly, the inflow COD and TOC/NPOC tend toward the higher end of the literature ranges.

I. pH

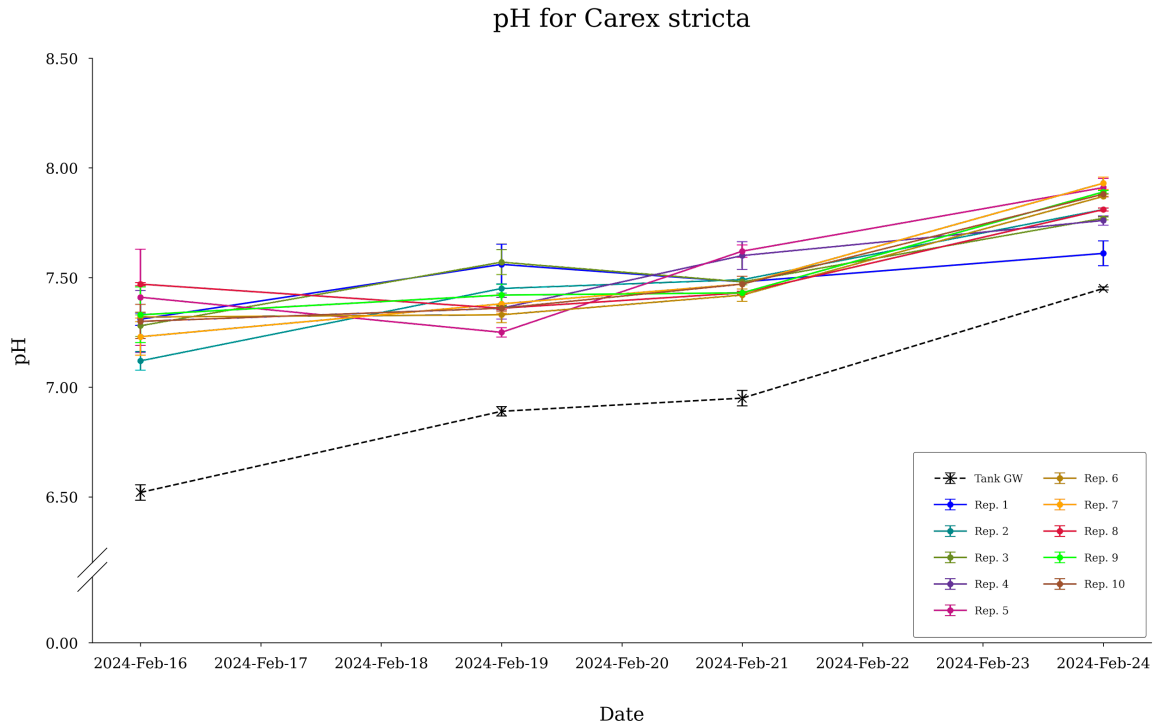


Figure 4 . Time series of mean pH for the 10 *Carex stricta* replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24). Error bars represent standard deviation of the measurements. Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between pH and sampling events.

The mean pH of measurements for each replicate (1 to 10) was computed and plotted for each respective sampling event (2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24) of the *Carex stricta* configuration (see Figure 4). Figure 4 shows a universal increase in mean pH from inflow to outflow, for each replicate, across each respective sampling event. Indeed, the smallest difference in pH occurs in the mean pH data for the final sampling event (February 24) between the inflow and replicate 1, where replicate 1 still has a higher pH than inflow. Generally, mean outflow pH values for *Carex stricta* fell within the range from about 7.20 to 7.90 across the four sampling events.

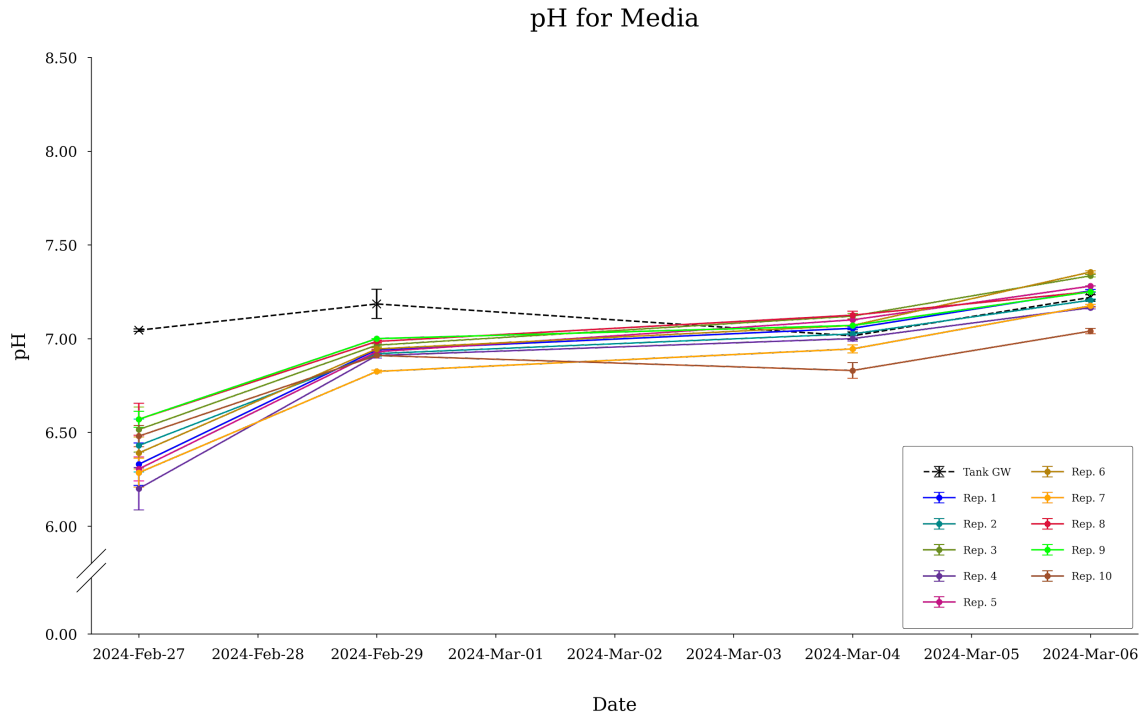


Figure 5. Time series of mean pH for the 10 Media replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-27, 2024-Feb-29, 2024-Mar-04, and 2024-Mar-06). Error bars represent standard deviation of the measurements. Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between pH and sampling events.

The mean pH of outflow measurements for each *Carex stricta* replicate (1 to 10) was computed and plotted for each respective sampling event (2024-Feb-27, 2024-Feb-29, 2024-Mar-04, and 2024-Mar-06) of the media configuration (see Figure 5). Figure 5 shows that each of the mean outflow pH of the 10 replicates on sampling events 1 and 2 (2024-Feb-27 and 2024-Feb-29, respectively) is lower than the inflow greywater sampled on those days, with pH values ranging from 6.20 to 7.0 across the replicates for those first two sampling events. For the third sampling event (2024-Mar-04), the mean outflow pH values of replicates 1, 2, 3, 5, 7, 8, and 9 are each higher than the inflow pH sampled that day with the mean outflow. Similarly, on

the final sampling event day for *Carex stricta* (2024-Mar-06), the mean outflow pH values of replicates 1, 3, 5, 6, 8 and 9 are each higher than the inflow pH whereas the mean outflow pH of replicates 2, 4, 7, and 10 are lower or nearly the same as the inflow pH sampled that day.

Figure 6 shows the mean outflow pH for *Carex stricta* is strictly higher than the outflow pH of media in all four sampling events. The mean outflow pH for *Carex stricta* was computed as the mean across all 10 replicates for each sampling event; the same approach was used to compute the mean outflow pH across the 10 replicates for each sampling event for the media configuration. Moreover, the mean outflow pH for *Carex stricta* is strictly higher than its corresponding inflow pH for each respective sampling event (Figure 6). On the other hand, the mean outflow pH for the media configuration is generally either less than or equal to its corresponding inflow pH for each respective sampling event. From this, *Carex stricta* seems to be associated with an increase in the pH of its outflow water, whereas the media is associated with a decrease in pH comparing outflow to inflow for each respective sampling event.

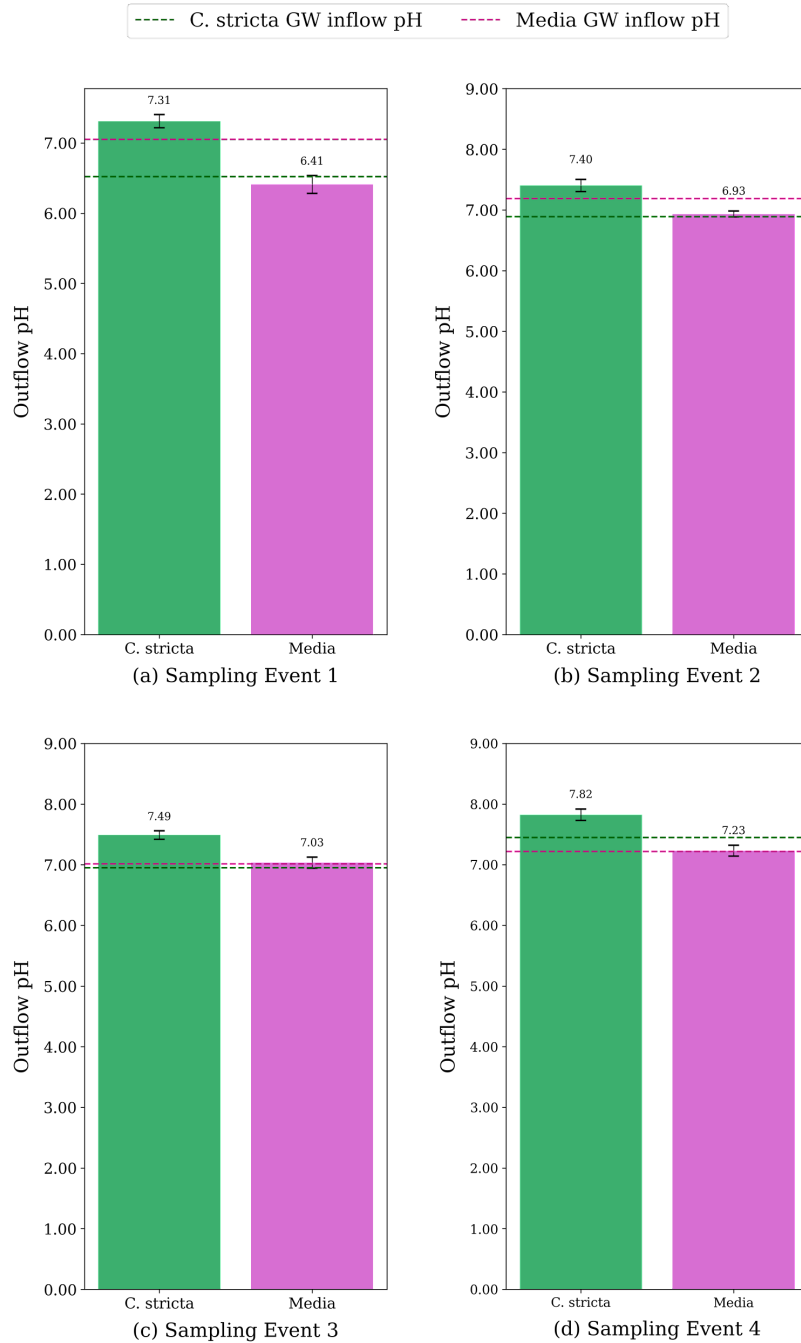


Figure 6. Mean outflow pH for *Carex stricta* (green) and media configurations (magenta) for the four respective sampling event days compared to respective inflow pH. Outflow pH of the *Carex stricta* replicates were collected and analyzed on the four sampling event days: 2024-Feb-16 (a), 2024-Feb-19 (b), 2024-Feb-21(c), and 2024-Feb-24 (d). Outflow pH of the media replicates were collected and analyzed on the four sampling event days: 2024-Feb-27 (a), 2024-Feb-29 (b), 2024-Mar-04 (c), and 2024-Mar-06 (d). Inflow pH for *Carex stricta* and media configuration are shown as dashed lines. Mean outflow pH of *Carex stricta* configuration and media configuration are labeled above each bar, respectively. Error bars represent standard deviation of the 10 replicates for each configuration.

II. Turbidity

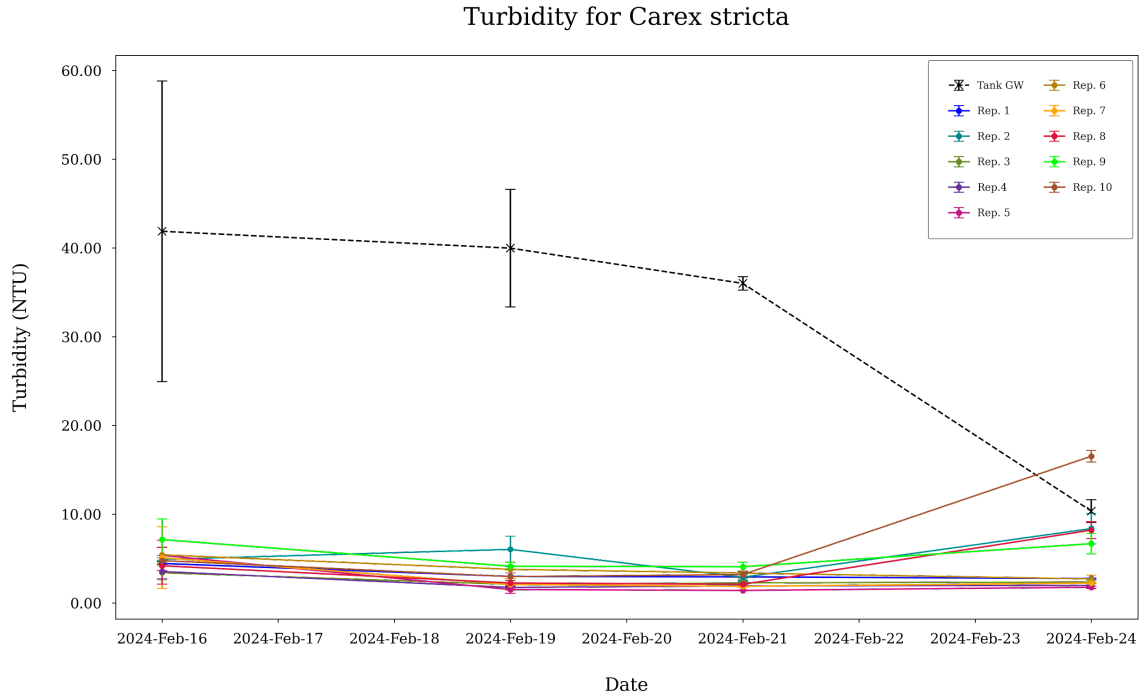


Figure 7. Time series of mean turbidity (NTU) for the 10 *Carex stricta* replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24). Error bars represent standard deviation of the measurements. Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between turbidity and sampling events.

In Figure 7, we can see a general decrease in mean turbidity between the inflow and outflow of each configuration for each sampling event for the *Carex stricta* configuration. Indeed, the first three test dates show similar values (Figure 7). On the last testing date for the *Carex stricta* configuration (2024-Feb-24), we see a lower mean turbidity value of the inflow water compared to the three previous sampling events (Figure 7). In particular, the mean turbidity of the inflow was 10.34 NTU for February 24 as opposed to the previous sampling event, where it was 36 NTU. Moreover, the mean turbidity of most of the replicates on the final

sampling event day (2024-Feb-24) was lower than the inflow turbidity sampled that day with the exception of replicate 10. Replicate 10 shows a higher turbidity value than the inflow turbidity on the final sampling event day; it is also worth noting that this is the highest mean outflow turbidity value for replicate 10 across the four sampling events, with the previous three sampling events showing considerably lower turbidity values.

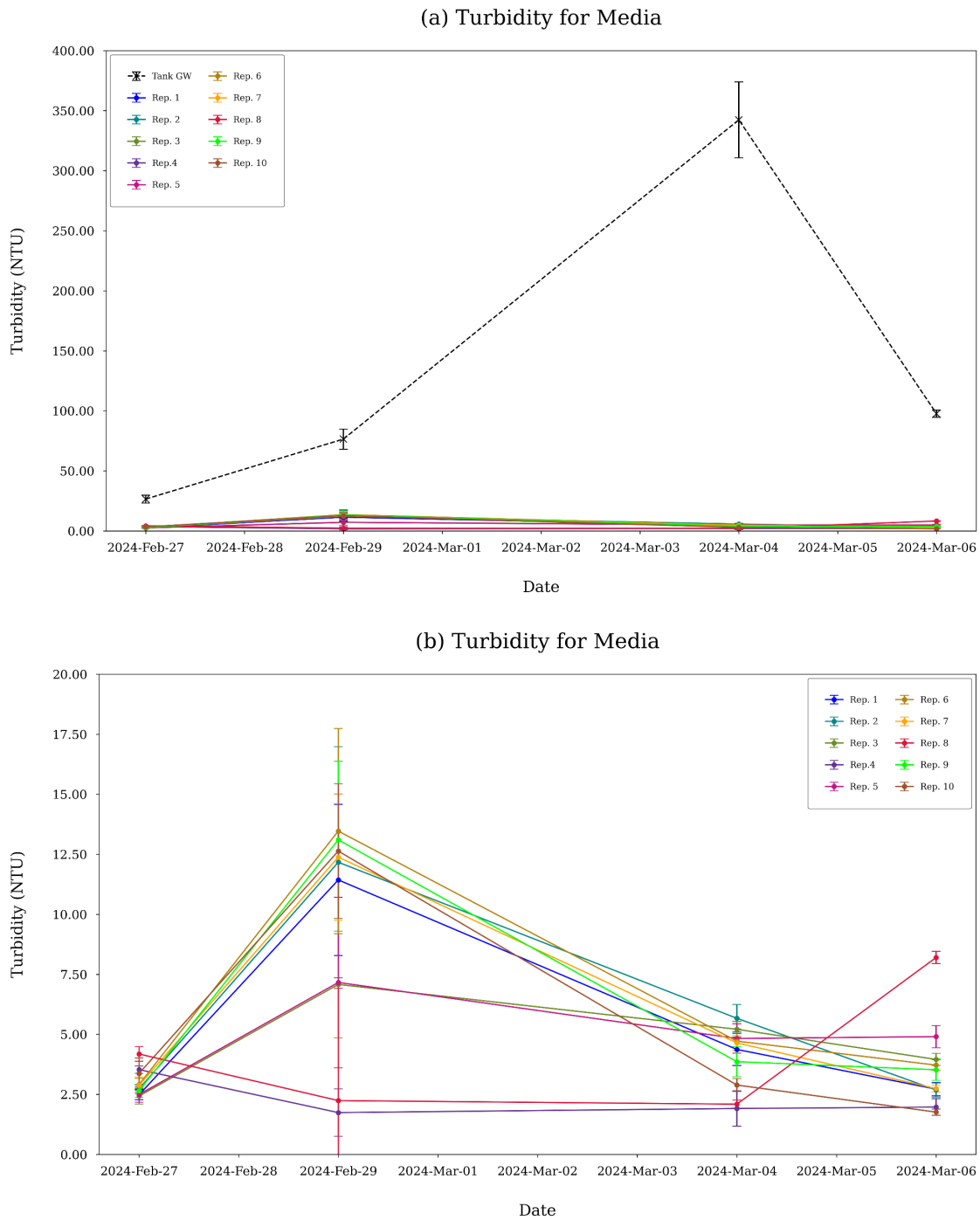


Figure 8. Time series of mean turbidity (NTU) for the 10 Media replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-27, 2024-Feb-29, 2024-Mar-04, and 2024-Mar-06) **(a)**. Time series of mean turbidity (NTU) for the 10 Media replicates **(b)** excluding the inflow. Error bars represent standard deviation of the measurements. Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between turbidity and sampling events.

For the media configuration, the mean outflow turbidity for all the replicates for each sampling event is lower than the inflow turbidity for each sampling event respectively (Figure 8a). The inflow turbidity across all four sampling events ranged from about 26.46 NTU to 342.33 NTU (Figure 8b). Figure 8b has been plotted to better visualize the mean outflow turbidity of each of the 10 replicates across all the sampling events. Figure 8b shows that there is a relatively larger degree of uncertainty associated with the mean outflow turbidity measurements for most of the replicates collected on the second sampling event (2024-Feb-29) compared to the other sampling events, as indicated by the error bars for several replicates for sampling event 2; this can possibly be attributed to difficulty with troubleshooting unstable readings in the turbidity meter on that day. For sampling event 2, Figure 8b shows that replicates 3, 4, 5, and 8 have noticeably lower turbidity values than the other six replicates. Generally, mean outflow turbidity values are similar for all 10 replicates in sampling events 1, 3, and 4; it is worth noting that Replicate 8 had a higher mean turbidity outflow measurement than the other nine replicates on the final sampling event day (Figure 8b).

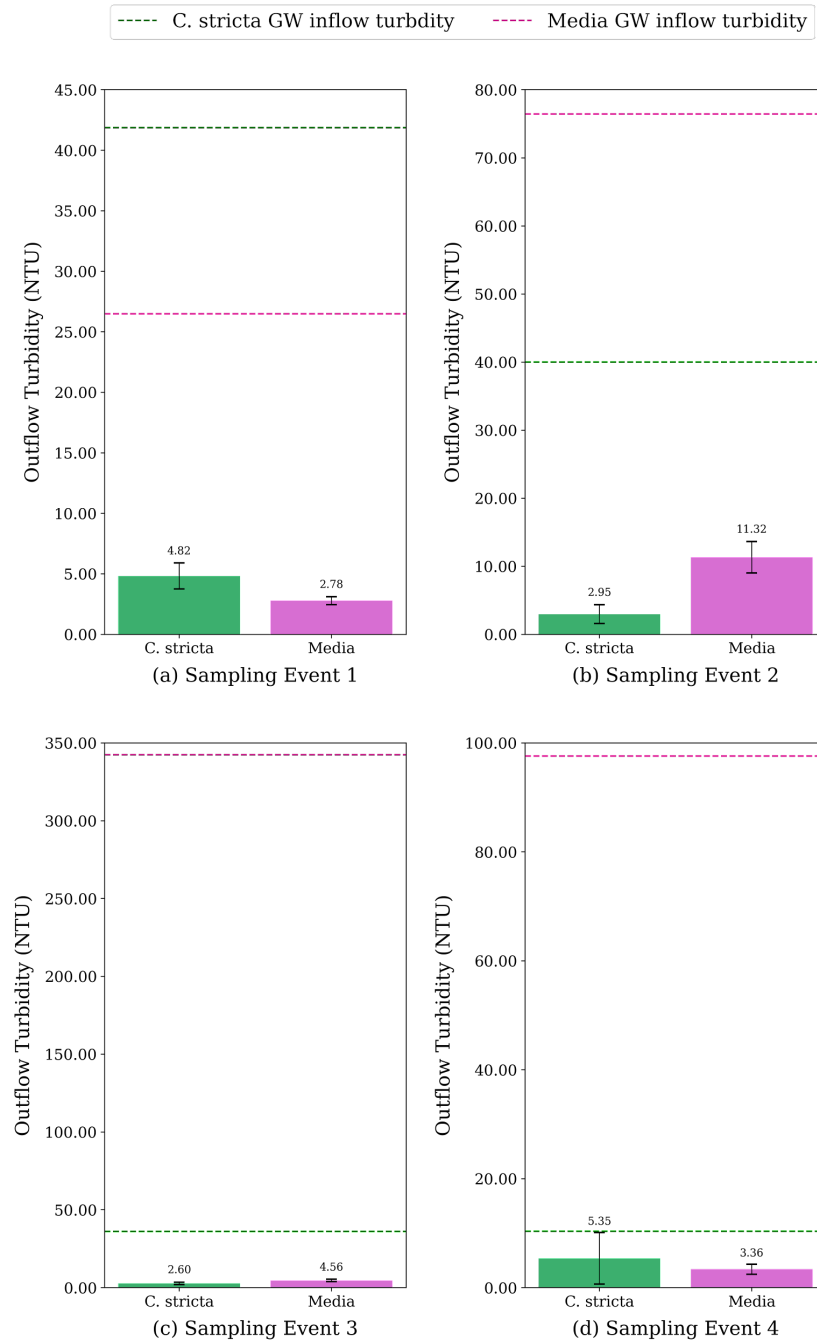


Figure 9. Mean outflow turbidity for *Carex stricta* (green) and media configuration (magenta) for the four respective sampling event days compared to respective inflow turbidity for each sampling event. Outflow turbidity of *Carex stricta* replicates were collected on the four sampling event days: 2024-Feb-16 (a), 2024-Feb-19 (b), 2024-Feb-21 (c), and 2024-Feb-24 (d). Outflow turbidity of the media replicates were collected on the four sampling event days: 2024-Feb-27 (a), 2024-Feb-29 (b), 2024-Mar-04 (c), and 2024-Mar-07 (d). Inflow turbidity for *Carex stricta* and media configuration are shown as dashed lines. Mean turbidity of *Carex stricta* configuration and media configuration are shown above each bar, respectively. Error bars represent standard deviation of the 10 replicates for each configuration.

Figure 9 shows the mean outflow turbidity for the *Carex stricta* and media configurations, which was computed by taking the mean across all 10 replicates for each sampling event for each configuration. Across all four sampling events, Figure 9 displays a decrease in turbidity between inflow and outflow of both the *Carex stricta* and media configurations. Indeed, the average disparity of the *Carex stricta* between its inflow and outflow is about 28.11 NTU, and for media, 130.19 NTU (note the potential outlier: the seemingly high media inflow turbidity on sampling event 3). However, it is not possible to conclude a trend in which (*Carex stricta* or media) leads to a higher turbidity or even difference in turbidity. For example, sampling event 1 shows a greater outflow turbidity of *Carex stricta* than media, but sampling event 2 shows the opposite (Figure 9). Additionally, sampling event 1 shows a larger disparity between the inflow and outflow turbidity of *Carex stricta* than media; however once again, day 2 shows the opposite. Therefore, our main conclusion is the overall decrease of turbidity in both *Carex stricta* and media between inflow and outflow for each sampling event.

III. COD

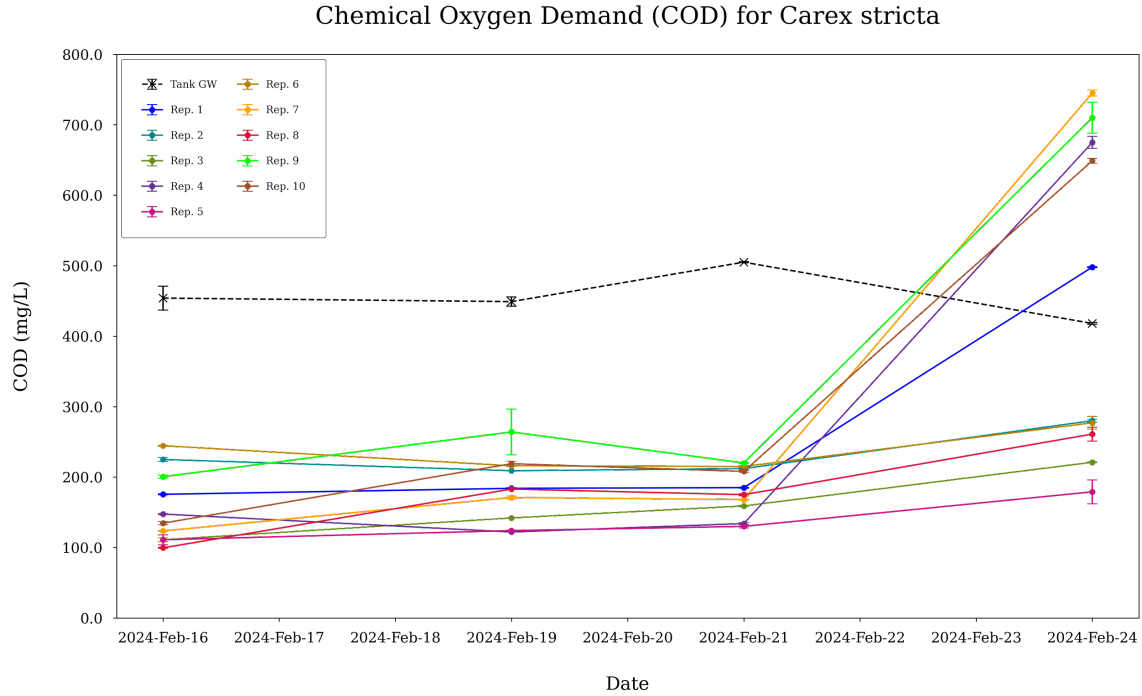


Figure 10. Time series of mean COD for the 10 *Carex stricta* replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24). Error bars represent standard deviation of the measurements. Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between COD and sampling events.

Figure 10 displays the general decrease in mean COD concentration for *Carex stricta* replicates between the inflow and outflow COD measurements for each respective sampling event. On the final sampling event day for the *Carex* configuration (2024-Feb-24), we observe an unusual overlap (compared to the first three sampling event days) where the COD of the inflow greywater falls between those of the 10 configurations. Interestingly, exactly 5 configurations (Replicates 1, 4, 7, 9, and 10) have COD levels higher than the inflow, and the other 5 (Replicates 2, 3, 5, 6, and 8) have COD levels lower than their inflow.

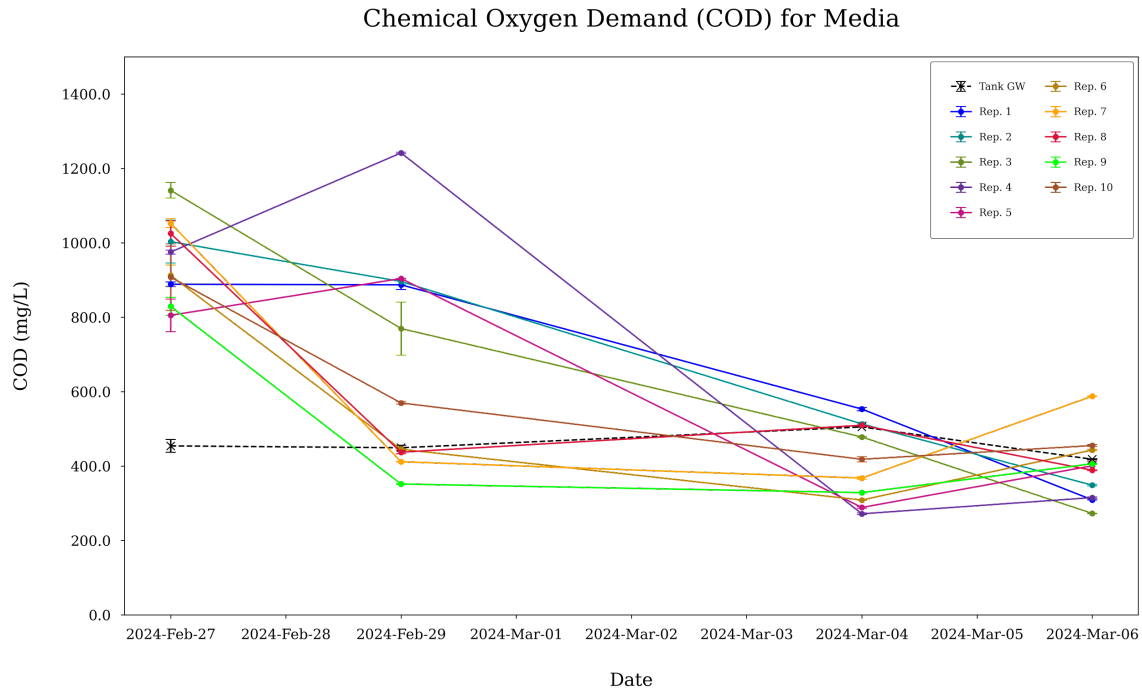


Figure 11. Time series of mean COD for the 10 Media replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-27, 2024-Feb-29, 2024-Mar-04, and 2024-Mar-06). Error bars represent standard deviation of the measurements. Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between COD and sampling events.

In general, the mean outflow COD of each of the 10 media replicates exceeded that of the inflow on the first sampling event day (2024-Feb-27) and the second sampling event day (2024-Feb-29), with the exception of replicates 6, 7, 8, 9 on event day 2 which had either slightly lower or nearly the same COD concentration as the inflow sampled that day (Figure 11). On sampling event day 3 (2024-Mar-04), mean outflow COD measurements for most replicates were lower than the inflow with the exceptions of replicates 1, 2, and 8. For the fourth and final sampling event day (2024-Mar-06), the mean outflow COD measurements for most of the replicates were less than or nearly the same as the inflow sampled that day; the exceptions are the outflow COD for replicates 6, 7, and 10 which all had slightly higher COD concentrations than the inflow.

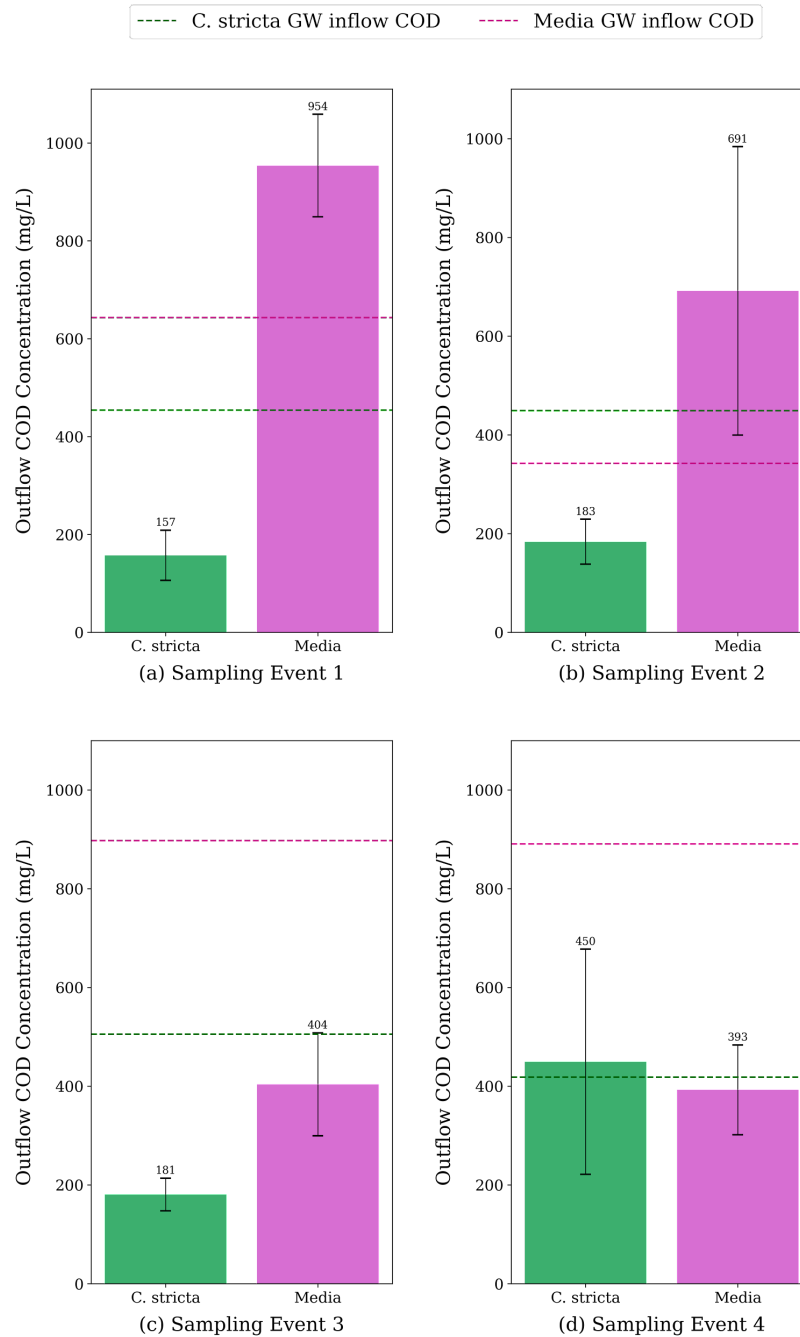


Figure 12. Mean outflow COD concentration (mg/L) for *Carex stricta* (green) and media configuration (magenta) for the four respective sampling event days compared to respective inflow COD. Outflow COD of *Carex stricta* replicates were collected on the sampling event days: 2024-Feb-16 (a), 2024-Feb-19 (b), 2024-Feb-21 (c), and 2024-Feb-24 (d). Outflow COD of the media replicates were collected on the four sampling event days: 2024-Feb-27 (a), 2024-Feb-29 (b), 2024-Mar-04 (c), and 2024-Mar-06 (d). Inflow COD for *Carex stricta* and media configuration are shown as dashed lines. Mean COD concentration of *Carex stricta* configuration and media configuration are shown above each bar, respectively. Error bars represent standard deviation of the 10 replicates for each configuration.

Sampling events 1, 2, and 3 show us that the media outflow has a higher mean COD concentration than that of *Carex stricta* (Figure 12). However, the difference between *Carex stricta* and media becomes smaller across sampling events 1 to 3. Moreover, in sampling event 4, we observe the opposite: the outflow of *Carex stricta* has a higher mean COD than that of media (although the difference is only 56.95 mg/L, much smaller than the difference in mean COD of outflow on day 1, which is 796.6 mg/L). There is a lack of consistency in differences between inflow and outflow of *Carex stricta* and media; on sampling event day 4, *Carex stricta* has a higher COD in its outflow than inflow, but media is the opposite. On day 1, *Carex stricta* has a higher COD in its inflow than outflow, and media shows the opposite. In general, we see mean outflow COD ranges from 157 to 183 mg/L for the first three sampling events for the *Carex stricta* configuration with the highest mean outflow COD of about 450 mg/L recorded on the final sampling event day. We can see that the mean outflow COD for the media configuration has a larger range of values from 393 to 954 mg/L across the four sampling events.

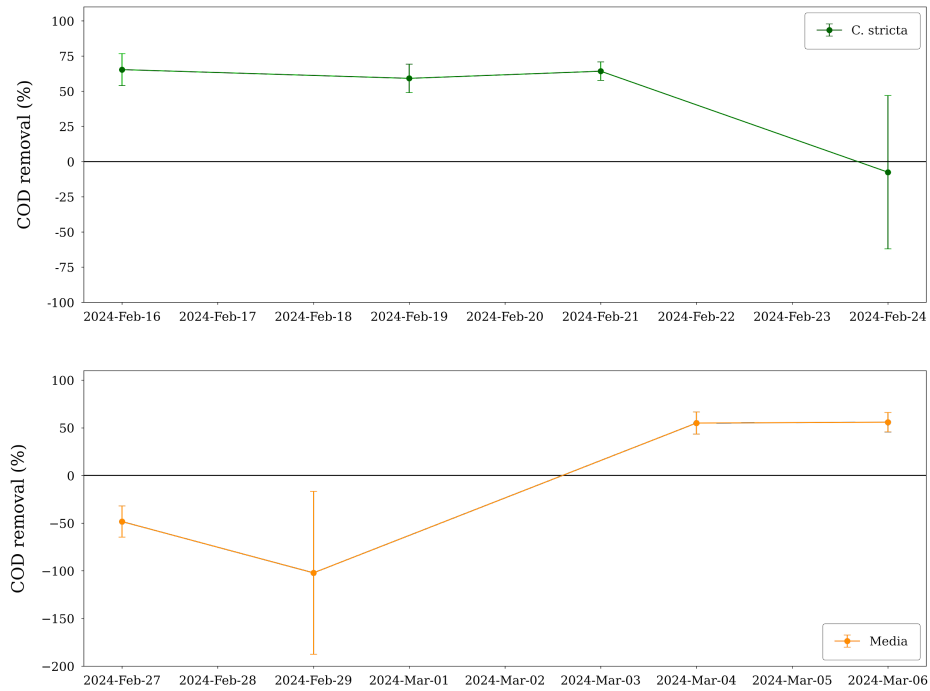


Figure 13. Mean COD removal across four sampling events for *Carex stricta* (green) and media (orange) configurations. Error bars represent standard deviations of the ten replicates for each configuration. Lines between each sampling event for both *Carex stricta* and media configurations have been added to improve visual clarity of each discrete value and do not represent linear trends between COD and sampling events.

COD removal was calculated as the difference between inflow and outflow COD concentration divided by the inflow concentration following the removal efficiency calculation used by Prodanovic et al. (2019). This same approach for calculating removal efficiency was used for NPOC and TN (Figures 17 and 21). Looking at the mean removal efficiencies of COD between *Carex stricta* and the media configurations in Figure 13, we observe that *Carex stricta* has a generally positive removal efficiency, meaning that in most cases, the outflow of *Carex stricta* has a lower COD level than its inflow. On day 4, we see a slightly negative removal rate indicating that the outflow COD concentration exceeded that of the inflow. By comparison, the

media shows a more drastic negative removal efficiencies, specifically on days 1 and 2, which are more negative than any of the removal efficiencies for *Carex stricta*.

IV. NPOC

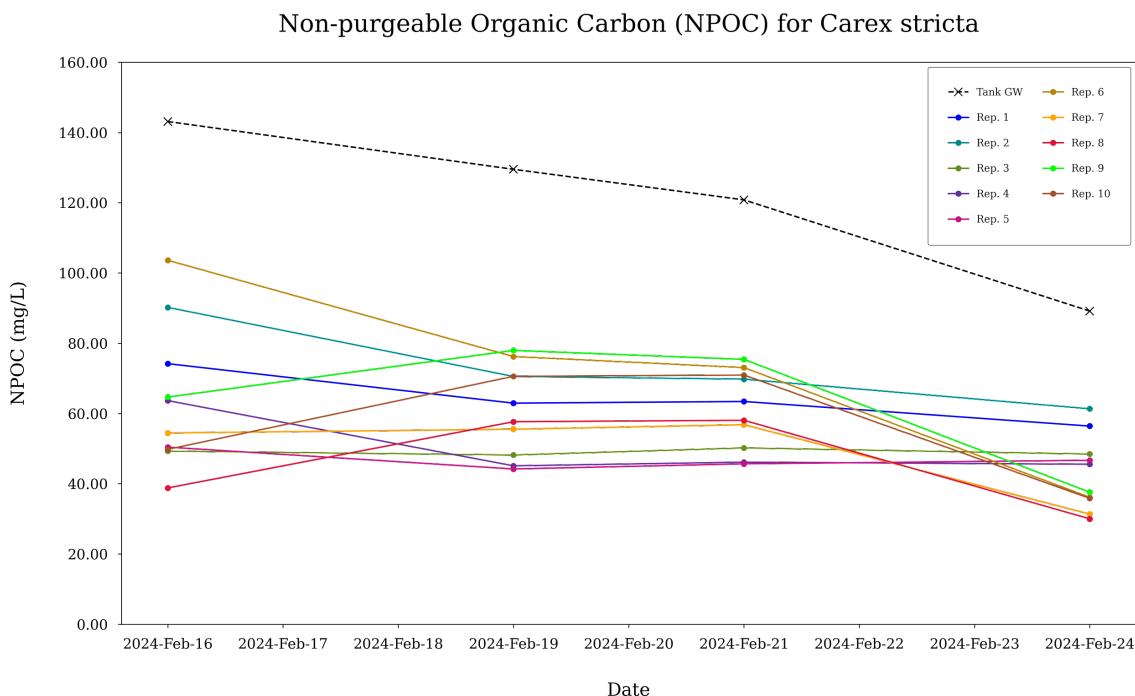


Figure 14. Time series of NPOC for the 10 *Carex stricta* replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24). Error bars are not shown because only one measurement per replicate for each configuration was taken. Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between NPOC and sampling events.

Overall, the outflow NPOC concentrations of the 10 *Carex stricta* replicates across all the four sampling event days were lower than the inflow for each respective sampling event day (Figure 14). It appears that the highest outflow NPOC concentrations were measured on the first sampling event day for several replicates, namely replicates 1, 2, 4, 5, and 6 (Figure 14). The

highest outflow concentrations Replicates 3, 7, 8, 9, 10 during the 10 day testing period were measured on sampling events 3 and 4. Contrastingly, it appears that the lowest outflow NPOC concentrations were observed on the final sampling event day for most of the *Carex stricta* replicates.

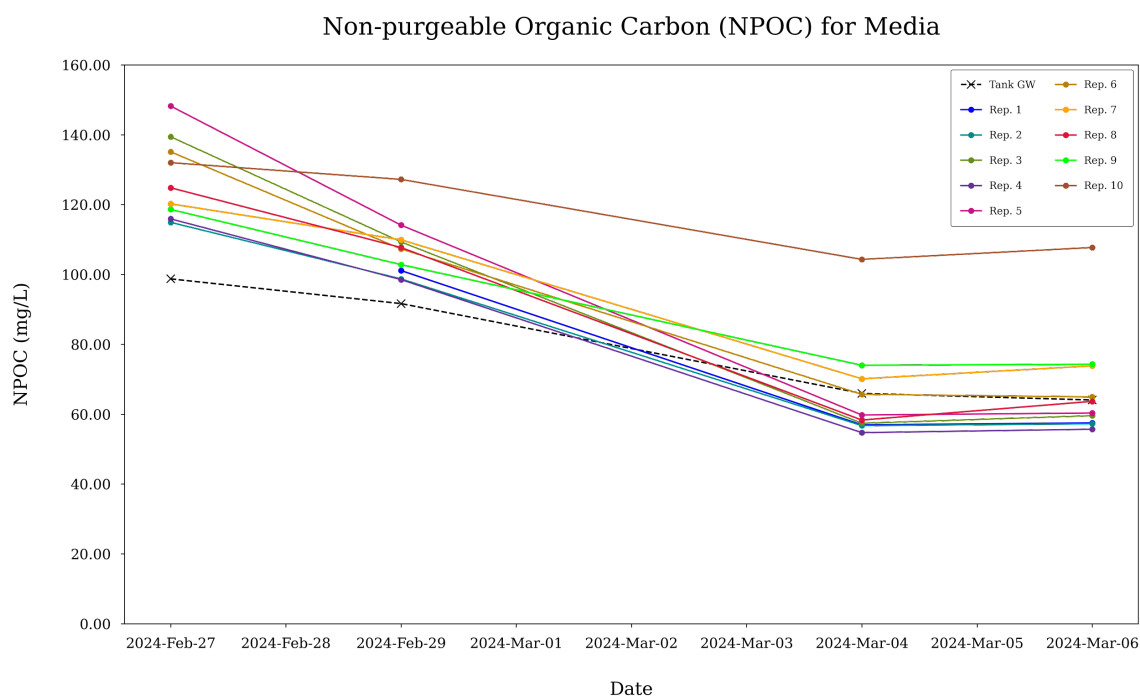


Figure 15. Time series of NPOC for the 10 Media replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-27, 2024-Feb-29, 2024-Mar-04, and 2024-Mar-06). Error bars are not shown because only one measurement per replicate for each configuration was taken. Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between NPOC and sampling events. Note that the NPOC measurement for replicate 1 for Media sampling event 1 (2024-Feb-27) was excluded due to an error in the analyzer reading.

Figure 15 shows that the outflow NPOC concentration for the 10 media replicates on the first two sampling event days (2024-Feb-27 and 2024-Feb-29) exceeds that of the inflow NPOC concentration for those respective sampling events. It appears that the highest inflow and outflow NPOC concentrations for each of the media replicates (excluding replicate 1 due to an error in

the analyzer reading) out of all the four sampling events were observed on the first sampling event day (2024-Feb-27), with the initial inflow NPOC concentration at a value of around 98.72 mg/L and values and outflow NPOC concentrations ranging from 114.9 to 148.2 mg/L that day. For sampling event 3 (2024-Mar-04), the outflow NPOC concentrations of the media replicates 6, 7, 9, and 10 exceeded or were nearly the same as that of the inflow observed that day. Similarly, for sampling event 4 (2024-Mar-06), the outflow NPOC concentrations of media replicates 6, 7, 8, 9, and 10 were higher than or nearly equal to the inflow NPOC concentration observed for that day. At the same time, the lowest inflow NPOC concentration was observed on the final sampling event day, with a concentration value of approximately 64.04 mg/L.

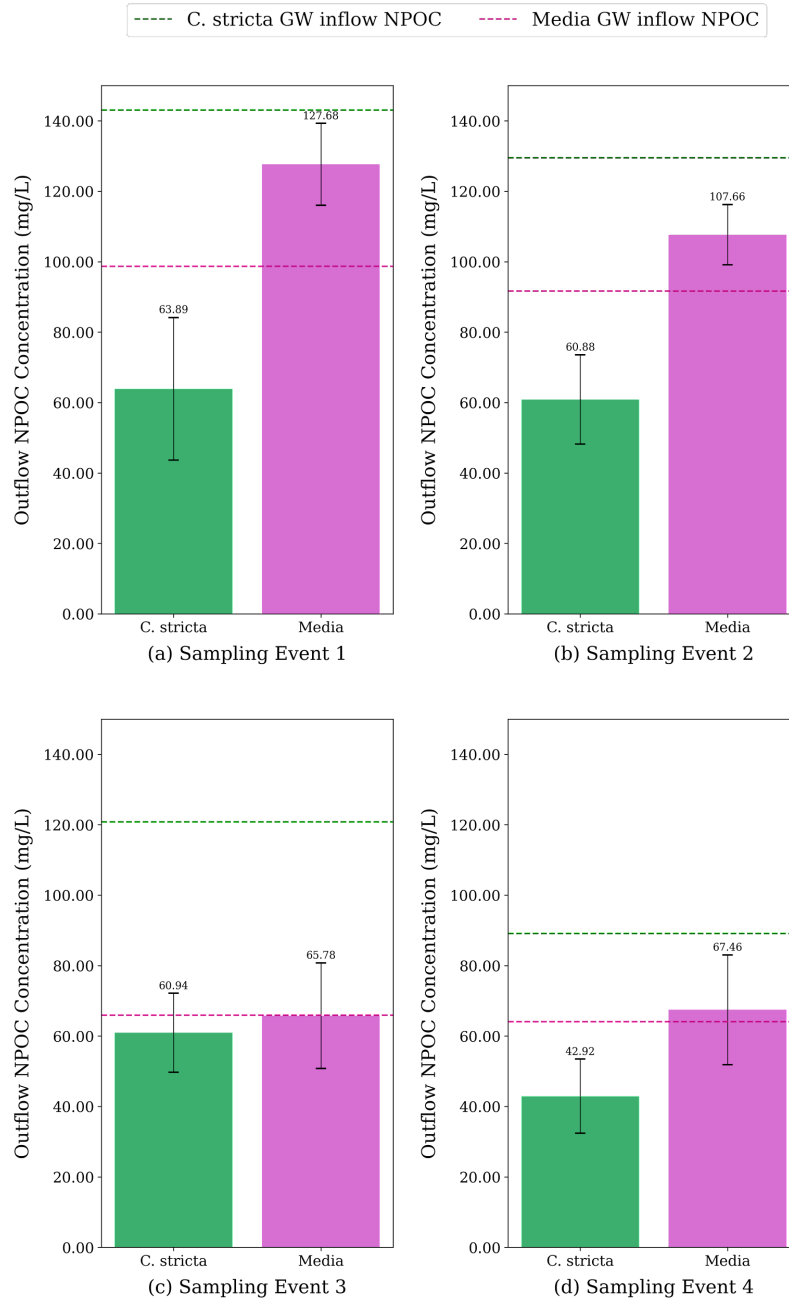


Figure 16. Mean outflow NPOC (mg/L) for *Carex stricta* (green) and media configuration (magenta) for the four respective sampling event days compared to respective inflow NPOC. Outflow NPOC of *Carex stricta* replicates were collected on the sampling event days: 2024-Feb-16 (a), 2024-Feb-19 (b), 2024-Feb-21 (c), and 2024-Feb-24 (d). Outflow NPOC of the media replicates were collected on the four sampling event days: 2024-Feb-27 (a), 2024-Feb-29 (b), 2024-Mar-04 (c), and 2024-Mar-06 (d). Inflow NPOC for *Carex stricta* and media configuration are shown above each bar, respectively. Mean NPOC concentration of *Carex stricta* configuration and media configuration are shown as dashed lines. Error bars represent standard deviation of the ten replicates for each configuration. Note that the NPOC measurement for replicate 1 for Media sampling event 1 collected on 2024-Feb-27 was excluded from the mean calculation due to an error in the analyzer reading.

For each of the four sampling events (2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24), the mean outflow NPOC concentration of the *Carex stricta* configuration is below that of the respective *Carex stricta* inflow (Figure 16). By comparison, the mean outflow NPOC concentrations of the media configuration exceeds the inflow NPOC concentrations for sampling events 1, 2, and 4; interestingly, the mean outflow NPOC concentration (65.78 mg/L) is nearly equal the inflow (65.93 mg/L) for sampling event 3 (2024-Mar-04). It can also be observed that the highest NPOC inflow concentration (143.10 mg/L) for the *Carex stricta* configuration was observed on the first sampling event day while the lowest NPOC inflow concentration (89.14 mg/L) for the *Carex stricta* configuration was observed on the final sampling event day; a similar pattern can be seen with the media configuration. Across the sampling events, the mean outflow NPOC concentration for the *Carex stricta* configuration shows a smaller range in values (42.92 to 63.89 mg/L) compared to the outflow NPOC concentration for the media configuration (65.58 to 127.68 mg/L).

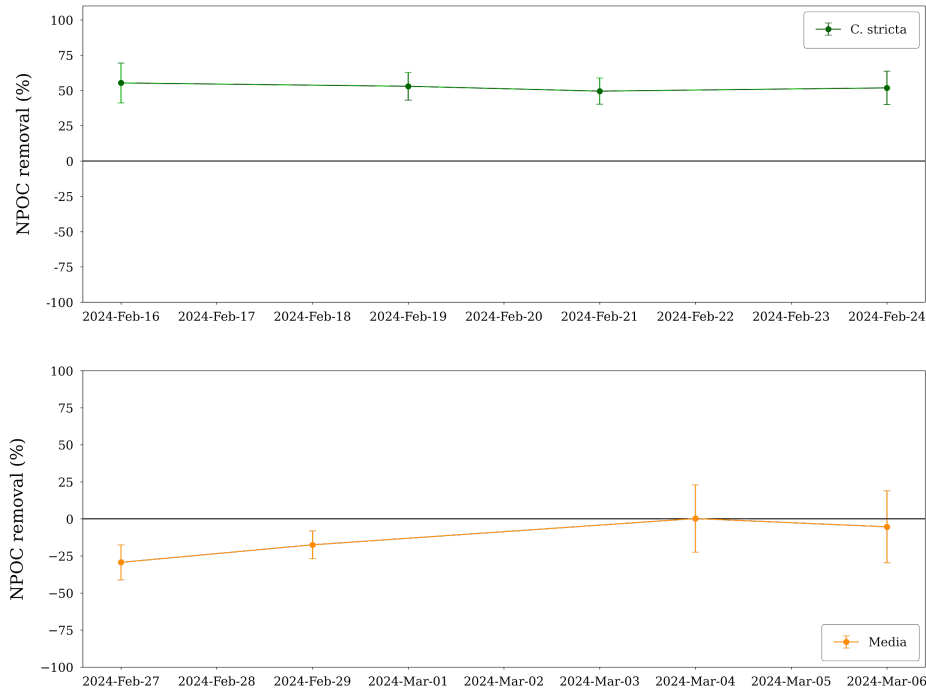


Figure 17. Mean NPOC removal across four sampling events for *Carex stricta* (green) and media (orange) configurations. Error bars represent standard deviations of the ten replicates for each configuration. Lines between each sampling event for both *Carex stricta* and media configurations have been added to improve visual clarity of each discrete value and do not represent linear trends between NPOC and sampling events. Note that the NPOC measurement replicate 1 for Media sampling event 1 collected on 2024-Feb-27 was excluded from the mean calculation due to an error in the analyzer reading.

Figure 17 shows the mean removal efficiencies of NPOC for the *Carex stricta* and the media configurations. We observe that the *Carex stricta* configuration has an overall positive removal efficiency of NPOC at around 50% for all the sampling events; that is, the outflow NPOC concentration for *Carex stricta*, on average, is lower than the inflow for each of the sampling event days (Figure 17). By comparison, the media configuration shows negative and nearly zero removal efficiencies over the four sampling event days. Negative removal efficiencies are observed for the first two sampling event days (2024-Feb-27 and 2024-Feb-29) for the media configuration, with values around -29.3% and -17.5% respectively; this indicates

that the outflow NPOC concentrations exceeded those of the inflow for those two days, respectively. For media sampling events 3 and 4 (2024-Mar-04 and 2024-Mar-06), the removal efficiencies of NPOC are approximately 0.2% and -5.3%, respectively.

V. TN

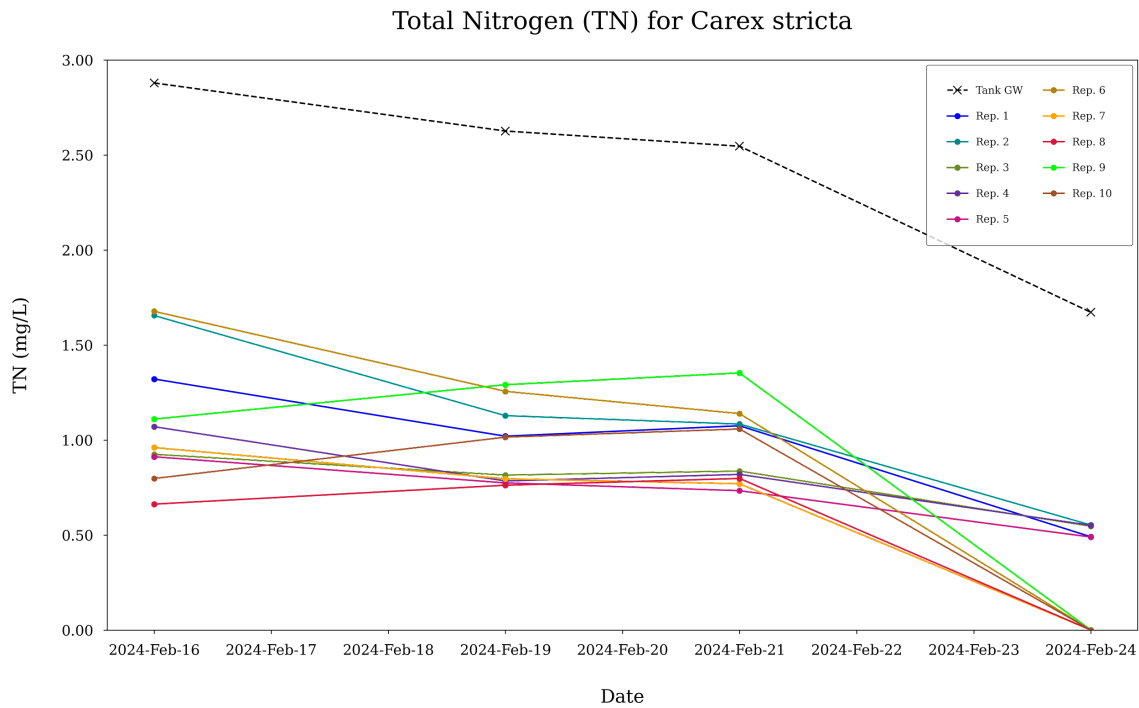


Figure 18. Time series of TN for the 10 *Carex stricta* replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24). Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between TN and sampling events. Error bars are not shown because only one measurement per replicate for each configuration was taken.

Overall, the outflow TN concentrations of the 10 *Carex stricta* replicates across all the four sampling event days were lower than the inflow for each respective sampling event day (Figure 18). It appears that the lowest outflow TN concentrations are observed on the final sampling event day for most of the replicates. It is also important to note that outflow TN concentration values for replicates 6, 7, 8, 9, and 10 were each approximated as 0.0000 mg/L due to their very small concentrations and our calibration curve; their original recorded values analyzed by the Shimadzu TOC analyzer were -0.5442, -0.6249, -0.6192, -0.3567, and -0.5597 mg/L respectively.

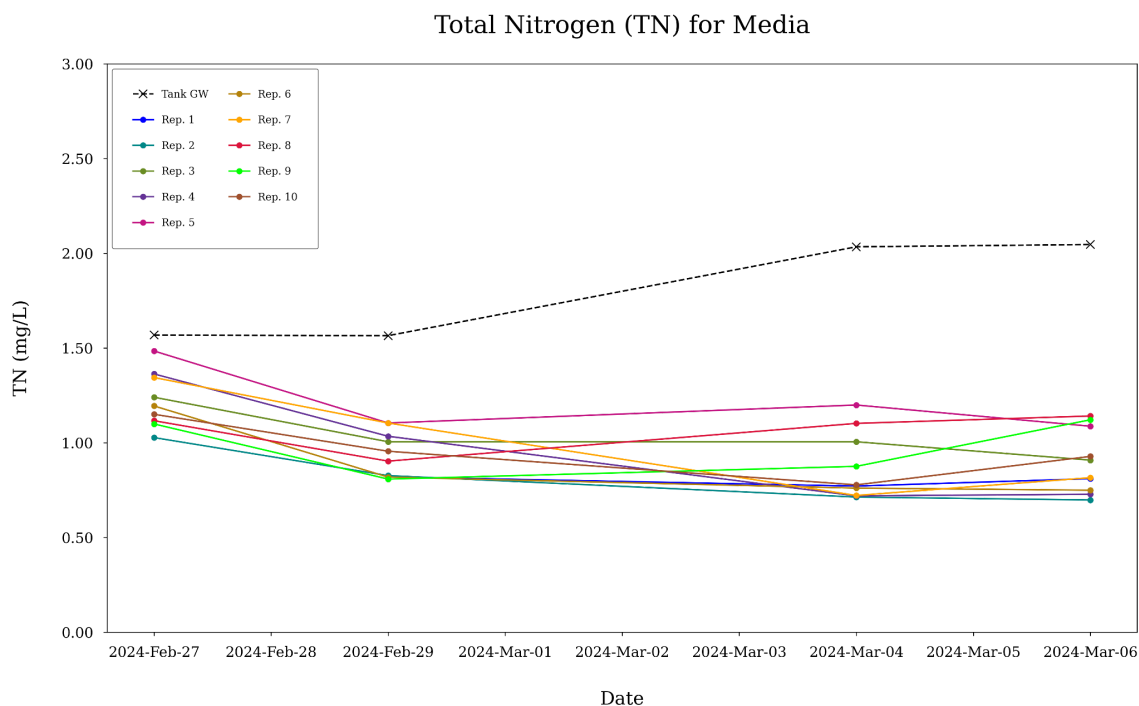


Figure 19. Time series of TN for the 10 Media replicates (Rep. 1 to Rep. 10) and inflow tank greywater (Tank GW) over the four sampling events (2024-Feb-27, 2024-Feb-29, 2024-Mar-04, and 2024-Mar-06). Lines between each sampling event have been added to improve visual clarity of each discrete value and do not represent linear trends between TN and sampling events. Note that the TN measurement for Replicate 1 for Media sampling event 1 (2024-Feb-27) was excluded due to an error in analyzer reading. Error bars are not shown because only one measurement per replicate for each configuration was taken.

For the 10 media replicates, we also see that outflow TN concentrations were lower than the inflow for each respective sampling event day (Figure 19). It should be noted that the TN measurement for replicate 1 for the media configuration was removed due to an error in the Shimadzu TOC analyzer. In general, it appears that the highest outflow TN concentrations for most of the replicates was observed on the first sampling event day (2024-Feb-27) with the exception of replicate 8, which saw its highest outflow TN concentration (1.141 mg/L) on the final sampling event day (2024-Mar-06). It also seems that the lowest outflow TN concentrations for most of the replicates was observed on the last two sampling event days.

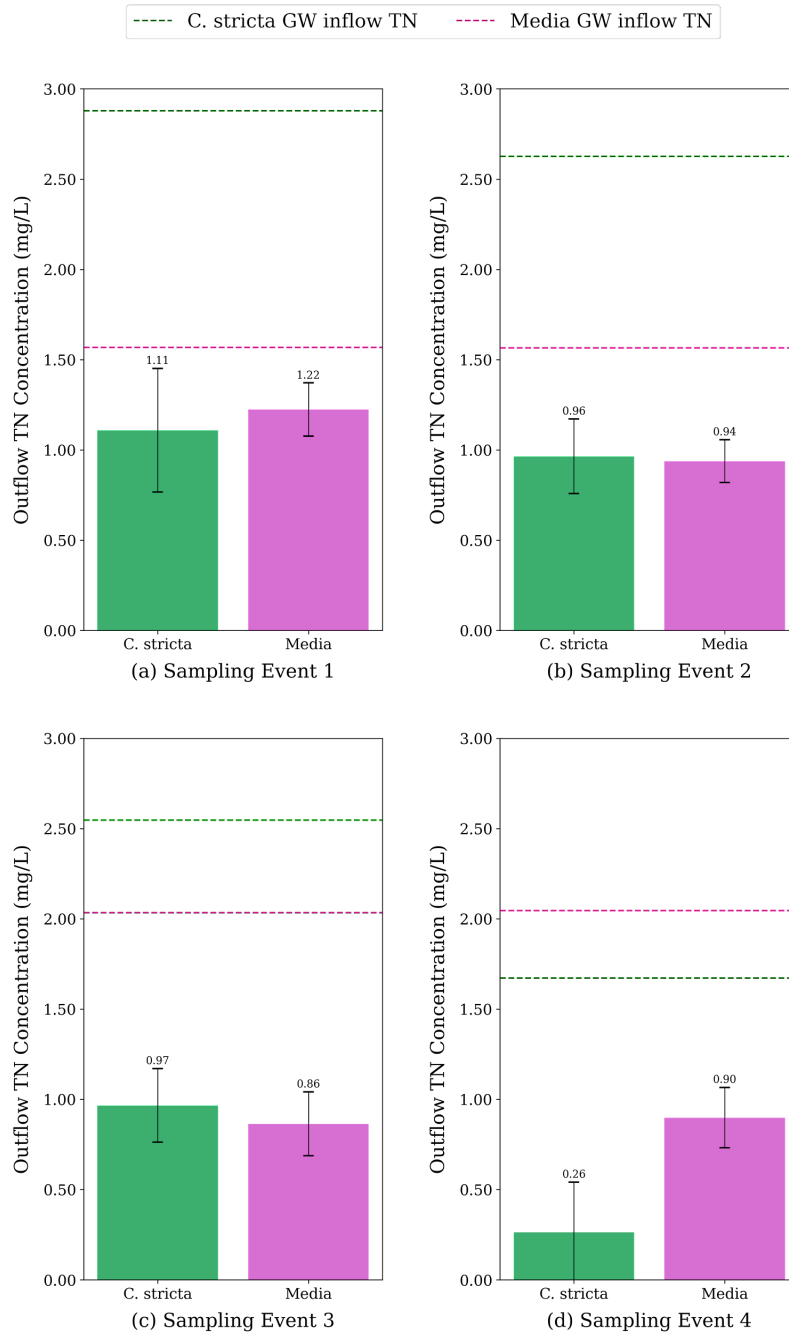


Figure 20. Mean outflow TN (mg/L) for *Carex stricta* (green) and media configuration (magenta) for the four respective sampling event days compared to respective inflow TN. Outflow TN of *Carex stricta* replicates were collected on the four sampling event days: 2024-Feb-16 (a), 2024-Feb-19 (b), 2024-Feb-21 (c), and 2024-Feb-24 (d). Outflow TN of the media replicates were collected on the four sampling event days: 2024-Feb-27 (a), 2024-Feb-29 (b), 2024-Mar-04 (c), and 2024-Mar-06 (d). Inflow TN for *Carex stricta* and media configuration are shown as dashed lines. Mean TN concentration of *Carex stricta* configuration and media configuration are shown above each bar, respectively. Error bars represent standard deviation of the 10 replicates for each configuration. Note that the TN measurement for replicate 1 for Media sampling event 1 collected on 2024-Feb-27 was excluded from the mean calculation due to an error in the analyzer reading.

For each of the four sampling events (2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24), the mean outflow TN concentration of the *Carex stricta* configuration is below that of the respective *Carex stricta* inflow (Figure 20). Similarly, the mean outflow TN concentration of the media configuration for each sampling event is lower than that of the media inflow, respectively. Overall, the mean outflow TN concentrations for both the *Carex stricta* and media configurations appear to be fairly similar in value for each of their respective sampling event days; across their four respective sampling events, the mean outflow TN concentration ranges from about 0.26 to 1.11 mg/L for *Carex stricta*, while the mean outflow TN concentration ranges from about 0.86 to 1.22 mg/L. It can also be observed that the highest TN inflow concentration (2.879 mg/L) for the *Carex stricta* configuration was observed on the first sampling event day while the lowest inflow TN concentration (1.672 mg/L) for the *Carex stricta* configuration was observed on the final sampling event day. By comparison, the lowest inflow TN concentration (1.565 mg/L) for the media configuration was observed on sampling event 2 whereas the highest (2.046 mg/L) was observed on sampling event 4.

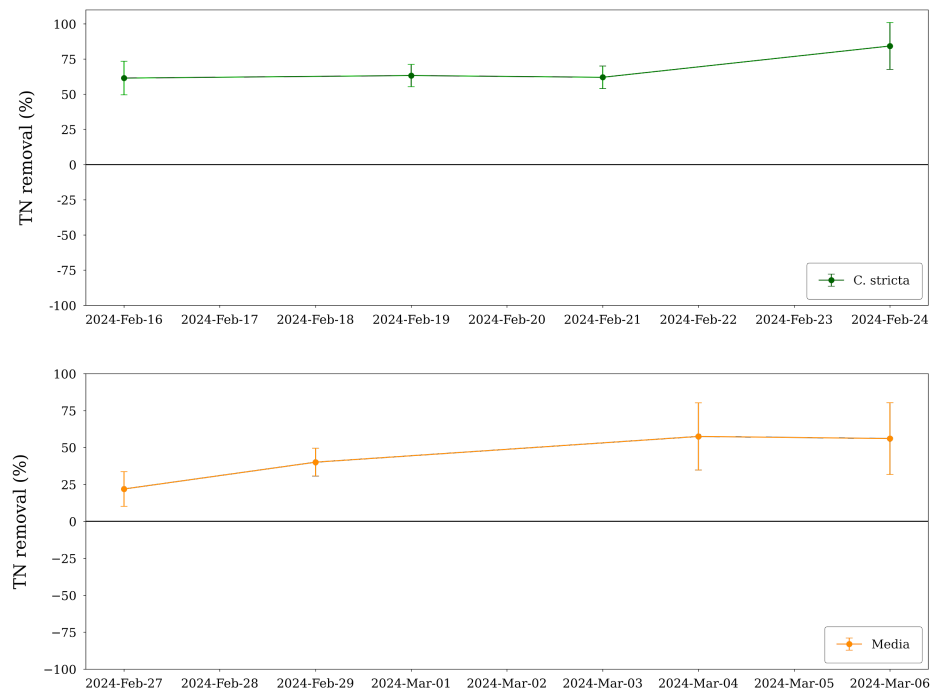


Figure 21. Mean TN removal across four sampling events for *Carex stricta* (green) and media (orange) configurations. Error bars represent standard deviations of the 10 replicates for each configuration. Lines between each sampling event for both *Carex stricta* and media configurations have been added to improve visual clarity of each discrete value and do not represent linear trends between TN and sampling events. Note that Replicate 1 for Media sampling event 1 (2024-Feb-27) was excluded from the mean calculation due to an error in the analyzer reading.

Figure 21 shows the mean removal efficiencies of TN for the *Carex stricta* and the media configurations. We observe that the *Carex stricta* configuration has positive removal efficiencies of TN, with values ranging from 61.5% to 84.3% NPOC removal across the four sampling events; that is, the outflow TN concentration for *Carex stricta*, on average, was lower than the inflow for each of the sampling event days (Figure 21). The media configuration also has positive removal efficiencies across the four sampling events, with removal efficiencies ranging from 21.9% to 57.5%. The lowest removal efficiency for the media configuration (21.9%) is observed on the first sampling event day (2024-Feb-27), while the highest (57.5%) is observed on the third sampling event (2024-Mar-04). For the *Carex stricta* configuration, the lowest

removal efficiency (61.5%) is observed on the first sampling event day (2024-Feb-16) while the highest removal efficiency (84.3%) is observed on the final sampling event day (2024-Feb-24). It should be noted that the positive removal efficiencies for all the sampling events of the media configuration are all lower than those for the *Carex stricta* configuration. Indeed, even the lowest removal (61.5%) efficiency observed for the *Carex stricta* configuration is greater than the maximum removal efficiency observed for the media configuration (57.5%).

Tables 10A-B shows a summary of the five tested greywater parameters and their respective changes from the inflow for the *Carex stricta* replicates averaged over the four sampling event days: 2024-Feb-16, 2024-Feb-19, 2024-Feb-21, and 2024-Feb-24 (Table 10A-B). Tables 11A-B shows a summary of the five tested greywater parameters and their respective changes for the media trial results averaged over the four sampling event days: 2024-Feb-27, 2024-Feb-29, 2024-Mar-04, and 2024-Mar-06 (Table 11A-B).

Table 10A. Plant trial results averaged over the four sampling event days for pH, turbidity, COD. Each change in pollutant measured is compared to the greywater intake and calculated individually before averaging. Δ COD was calculated through comparison to greywater results for each trial. The final average is taken over all replicates with standard deviation from each configurations' results.

Plant Trials	pH	ΔpH	Turbidity	ΔTurbidity	COD	ΔCOD (%)
Greywater (inflow)	6.95 $\pm$ 0.38	N/A	32.00 $\pm$ 14.6	N/A	407.9 $\pm$ 39.1	N/A
Replicate 1	7.49 $\pm$ 0.13	0.54 $\pm$ 0.27	3.27 $\pm$ 0.79	-28.77 $\pm$ 14.25	242.4 $\pm$ 207.9	-40.0 $\pm$ 51.4
Replicate 2	7.47 $\pm$ 0.28	0.52 $\pm$ 0.11	5.54 $\pm$ 2.29	-26.50 $\pm$ 16.44	349.2 $\pm$ 171.5	-13.1 $\pm$ 44.4
Replicate 3	7.53 $\pm$ 0.20	0.57 $\pm$ 0.19	2.52 $\pm$ 0.58	-29.53 $\pm$ 14.51	191.5 $\pm$ 54.1	-52.0 $\pm$ 16.4
Replicate 4	7.51 $\pm$ 0.21	0.55 $\pm$ 0.21	2.29 $\pm$ 0.83	-29.76 $\pm$ 14.39	296.9 $\pm$ 252.7	-27.4 $\pm$ 59.8
Replicate 5	7.55 $\pm$ 0.29	0.60 $\pm$ 0.24	2.51 $\pm$ 1.91	-29.54 $\pm$ 14.06	145.0 $\pm$ 28.1	-64.1 $\pm$ 8.0
Replicate 6	7.49 $\pm$ 0.26	0.53 $\pm$ 0.18	3.81 $\pm$ 1.15	-28.23 $\pm$ 13.84	308.9 $\pm$ 59.6	-23.0 $\pm$ 20.2
Replicate 7	7.50 $\pm$ 0.30	0.55 $\pm$ 0.11	2.82 $\pm$ 1.52	-29.23 $\pm$ 14.17	315.6 $\pm$ 288.5	-22.7 $\pm$ 68
Replicate 8	7.52 $\pm$ 0.20	0.57 $\pm$ 0.26	4.18 $\pm$ 2.84	-27.87 $\pm$ 17.24	198.4 $\pm$ 69.4	-50.4 $\pm$ 18.7
Replicate 9	7.52 $\pm$ 0.25	0.57 $\pm$ 0.17	5.50 $\pm$ 1.63	-26.55 $\pm$ 15.34	432.6 $\pm$ 209.7	7.6 $\pm$ 51.4
Replicate 10	7.50 $\pm$ 0.26	0.55 $\pm$ 0.16	6.86 $\pm$ 6.49	-25.19 $\pm$ 21.01	349.6 $\pm$ 215.8	-13.1 $\pm$ 52.0
Average	7.51$\pm$0.02	0.55$\pm$0.02	3.93$\pm$1.57	-28.12$\pm$1.57	283.0$\pm$91.2	-29.8$\pm$21.7

Table 10B. Plant trial results averaged over the four sampling event days for NPOC, TN. Each change in pollutant measured is compared to the greywater intake and calculated individually before averaging. The final average is taken over all replicates with standard deviation from each configurations' results.

Plant Trials	NPOC	ΔNPOC (%)	TN	ΔTN (%)
Greywater (inflow)	120.6 $\pm$ 22.9		2.43 $\pm$ 0.52	
Replicate 1	64.2 $\pm$ 7.4	46.0 $\pm$ 6.4	0.98 $\pm$ 0.35	60.9 $\pm$ 7.1
Replicate 2	73.0 $\pm$ 12.2	39.0 $\pm$ 6.3	1.10 $\pm$ 0.45	56.0 $\pm$ 10.1
Replicate 3	49.0 $\pm$ 0.9	58.1 $\pm$ 8.8	0.78 $\pm$ 0.16	67.8 $\pm$ 0.8
Replicate 4	50.1 $\pm$ 9.0	57.9 $\pm$ 7.2	0.81 $\pm$ 0.21	67.0 $\pm$ 3.0
Replicate 5	46.7 $\pm$ 2.7	60.1 $\pm$ 8.5	0.73 $\pm$ 0.18	70.2 $\pm$ 1.3
Replicate 6	72.2 $\pm$ 27.7	41.9 $\pm$ 13.2	1.02 $\pm$ 0.72	62.3 $\pm$ 25.8
Replicate 7	49.5 $\pm$ 12.2	59.2 $\pm$ 5.2	0.63 $\pm$ 0.43	76.5 $\pm$ 15.7
Replicate 8	46.1 $\pm$ 14.0	61.7 $\pm$ 9.7	0.56 $\pm$ 0.37	79.2 $\pm$ 14.3
Replicate 9	63.9 $\pm$ 18.5	47.5 $\pm$ 10.3	0.94 $\pm$ 0.63	64.8 $\pm$ 24.3
Replicate 10	56.8 $\pm$ 17.1	53.0 $\pm$ 11.4	0.72 $\pm$ 0.49	73.0 $\pm$ 18.9
Average	57.2 $\pm$ 7.9	52.4 $\pm$ 8.2	0.83 $\pm$ 0.18	67.8 $\pm$ 9.2

Table 11A. Media trial results averaged over the four sampling event days for pH, turbidity, COD. Each change in pollutant measured is compared to the greywater intake and calculated individually before averaging. Δ COD was calculated through comparison to greywater results for each trial. The final average is taken over all wall configurations and trials with standard deviation from each configurations' results.

Media Trials	pH	Δ pH	Turbidity	Δ Turbidity	COD	Δ COD (%)
Greywater (inflow)	7.11 $\pm$ 0.10		135.70 $\pm$ 140.94		693.3 $\pm$ 262.4	
Replicate 1	6.90 $\pm$ 0.40	-0.22 $\pm$ 0.36	5.24 $\pm$ 4.21	-130.45 $\pm$ 141.36	659.4 $\pm$ 281.9	23.5 $\pm$ 100.6
Replicate 2	6.90 $\pm$ 0.33	-0.22 $\pm$ 0.29	5.81 $\pm$ 4.46	-129.89 $\pm$ 140.90	690.1 $\pm$ 310.3	28.6 $\pm$ 102.7
Replicate 3	6.98 $\pm$ 0.35	-0.13 $\pm$ 0.31	4.67 $\pm$ 1.97	-131.03 $\pm$ 140.39	665.3 $\pm$ 377.1	21.6 $\pm$ 94.4
Replicate 4	6.82 $\pm$ 0.43	-0.30 $\pm$ 0.38	5.66 $\pm$ 3.71	-130.04 $\pm$ 141.29	700.8 $\pm$ 483.3	45.1 $\pm$ 155.7
Replicate 5	6.90 $\pm$ 0.43	-0.21 $\pm$ 0.38	4.85 $\pm$ 1.91	-130.85 $\pm$ 140.69	599.5 $\pm$ 300.7	16.7 $\pm$ 106.7
Replicate 6	6.94 $\pm$ 0.40	-0.18 $\pm$ 0.36	6.20 $\pm$ 4.90	-129.50 $\pm$ 141.70	527.1 $\pm$ 264.4	-11.0 $\pm$ 54.8
Replicate 7	6.81 $\pm$ 0.38	-0.31 $\pm$ 0.33	5.66 $\pm$ 4.56	-130.04 $\pm$ 141.47	604.8 $\pm$ 313.3	-2.3 $\pm$ 55.1
Replicate 8	6.98 $\pm$ 0.30	-0.14 $\pm$ 0.26	6.02 $\pm$ 4.52	-129.68 $\pm$ 141.63	590.0 $\pm$ 294.2	-3.1 $\pm$ 55.7
Replicate 9	6.97 $\pm$ 0.29	-0.14 $\pm$ 0.25	5.78 $\pm$ 4.91	-129.92 $\pm$ 141.98	478.8 $\pm$ 235.8	-21.5 $\pm$ 44.6
Replicate 10	6.82 $\pm$ 0.24	-0.30 $\pm$ 0.18	5.16 $\pm$ 5.02	-130.54 $\pm$ 142.41	587.5 $\pm$ 222.9	1.3 $\pm$ 61.5
Average	6.90$\pm$0.07	-0.21$\pm$0.07	5.51$\pm$0.50	-130.19$\pm$0.50	610.3$\pm$70.9	9.8$\pm$20.4

Table 11B. Media trial results averaged over the four sampling event days for NPOC, TN. Each change in pollutant measured is compared to the greywater intake and calculated individually before averaging. The final average is taken over all wall configurations and trials with standard deviation from each configurations' results.

Media Trials	NPOC	Δ NPOC (%)	TN	Δ TN (%)
Greywater (inflow)	80.1 $\pm$ 17.7		1.80 $\pm$ 0.27	
Replicate 1	71.8 $\pm$ 25.4	4.5 $\pm$ 13.0	0.80 $\pm$ 0.03	56.7 $\pm$ 7.9
Replicate 2	81.9 $\pm$ 29.5	0.1 $\pm$ 14.6	0.82 $\pm$ 0.14	53.1 $\pm$ 15.1
Replicate 3	91.4 $\pm$ 40.0	-10.1 $\pm$ 25.0	1.04 $\pm$ 0.14	40.7 $\pm$ 15.7
Replicate 4	81.2 $\pm$ 30.9	1.3 $\pm$ 16.5	0.96 $\pm$ 0.31	44.0 $\pm$ 25.2
Replicate 5	95.6 $\pm$ 43.4	-14.9 $\pm$ 28.0	1.22 $\pm$ 0.18	30.7 $\pm$ 18.4
Replicate 6	93.2 $\pm$ 34.2	-13.7 $\pm$ 17.3	0.88 $\pm$ 0.21	49.4 $\pm$ 18.5
Replicate 7	93.5 $\pm$ 25.3	-15.8 $\pm$ 6.9	1.00 $\pm$ 0.28	42.1 $\pm$ 24.2
Replicate 8	88.6 $\pm$ 32.7	-7.9 $\pm$ 17.2	1.07 $\pm$ 0.11	40.3 $\pm$ 7.8
Replicate 9	92.4 $\pm$ 22.1	-15.1 $\pm$ 3.8	0.98 $\pm$ 0.16	45.1 $\pm$ 11.3
Replicate 10	117.8 $\pm$ 13.8	-49.7 $\pm$ 16.2	0.95 $\pm$ 0.15	45.5 $\pm$ 15.8
Average	90.7 $\pm$ 12.0	-12.1 $\pm$ 15.2	0.97 $\pm$ 0.12	44.8 $\pm$ 7.3

The average pH across all testing days for the 10 *Carex stricta* replicates was 7.51 (Table 10A), while the average pH across all testing days for the ten media replicates was 6.90 (Table 11A). Both of these are within the target pH range of 6 - 9 for greywater reuse standards outlined in Table 4 previously. The average turbidity across all testing days for the 10 *Carex stricta* replicates was 3.93 NTU (Table 10A). The average turbidity across all testing days for the 10

media replicates was 5.51 NTU (Table 11A). Both turbidity parameters are below the 5 NTU standard shown previously in Table 4. The average COD across all testing days for the 10 *Carex stricta* replicates was 283 mg/L (Table 10A). The average COD across all testing days for the ten media replicates was 610 mg/L (Table 11A). Both COD averages for *Carex stricta* and media are above the target standard of 250 mg/L of COD. The average NPOC concentration across all four testing days for the 10 *Carex stricta* replicates was 57.2 mg/L-C (Table 10B), while that of the ten media replicates was 90.7 mg/L (Table 11B). Furthermore, the average TN concentration across all four testing days was 0.18 mg/L for the 10 *Carex stricta* replicates (Table 10B) and about 0.97 mg/L for the 10 media replicates (Table 11B).

Statistical Analysis

Estimates of the population means of the parameters were conducted for our trials, using t-test confidence intervals, and our analysis consisted of comparing the confidence interval ranges to the target pollutant levels (Table 12). This approach was selected as the target water quality parameter values are boundaries for meeting regulations for non-potable residential greywater reuse. If there is a reasonable potential that the true mean for a water quality parameter lies outside of the permissible range due to part of the confidence interval range exceeding the parameter limits: then it is no longer possible to reject the null hypothesis for at least some set of t-tests where the null hypothesis is that the value of the mean of the given parameter equals a value outside of the acceptable range, thus making the results either inconclusive or a full pass or “completely out-of-range” depending on the level of overlap with the target parameter levels. COD will be evaluated based upon the 250 mg/L figure being the lower limit for what is considered “polluted effluent” and as such will serve as our upper limit for the range of

acceptable COD values ($\text{COD} \leq 250 \text{ mg/L}$). For any measurements of concentration, negative values were rounded to zero or indicated as outliers in their accompanying data table.

Table 12. t-test confidence intervals.

T-test confidence intervals ($\alpha=0.95$) (n=40-extreme outliers*)					
	pH	Turbidity	COD (mg/L)	NPOC (removal %)	TN (mg/L-N)
<i>Carex stricta</i>	(7.4372,7.5748)	(3.0136,4.1992)	(166.58,200.88)	(48.863,56.011)	(0.6914,0.9599)
Media	(6.7986,7.0041)	(3.8622,5.9205)	(518.58,702.04)	(-17.41,-4.794)	(0.9127,1.042)

*See values for indicated outliers, identified using box plots for each data set (see Section IV. in Appendix). The t-intervals are meant to estimate the population mean for our two test groups, plants and media trials, and were generated using the above n and alpha. The NPOC was conducted as a removal rate as the target standards being compared to provided only the target NPOC removal rate %.

The target values for the water quality parameters are included in Tables 4 and 5. For the t-confidence intervals shown in Table 12, pH, turbidity, and TN ranges did not exceed the target pollutant values at any point for the plant trials (Table 12). This shows that the null hypothesis for any t-test indicating that the mean of these water quality parameters match any value outside the acceptable range would have to reject the null hypothesis given our significance level and respective degrees of freedoms. The results for COD and NPOC are inconclusive as there would be t-tests where there is not enough evidence to reject the null hypothesis that the true mean value is some value outside of the acceptable range, thus it is not possible to claim that they succeeded. The plants did not have any parameters “completely out-of-range” (i.e., have the full predicted range of the true mean of the parameter fall outside of the acceptable range). The media performed similarly for the pH and TN given that any t-test where the null hypothesis for

the true mean's value lies outside of the acceptable range would have the null hypothesis rejected. The turbidity t-confidence interval produced inconclusive results for the media trials, and the COD and NPOC were completely out-of-range.

The distinction between “completely out-of-range” and inconclusive is not in their conclusion, as both have the same interpretation for the purposes of determining if the level of a given water quality parameter in the outflow passes the standards listed. The distinction is to allow for screening of potential groups that may be evaluated for any less-extreme outliers in the case that their variance is determined to be abnormally high and a follow-up t-confidence interval may impact the conclusivity of this analysis with a potentially more accurate data set.

We were unable to perform t-tests and ANOVA testing of the different media and *Carex stricta* configurations primarily because data for various water quality parameters was not normally distributed and variances were not equal. The limited sample sizes for testing with each configuration (n=4 for 4 sampling events per configuration) also prevented our ability to work around having a worse fit to a normal distribution for each parameter to the lower degrees-of-freedom, for t-tests on a single configuration for meeting pollutant/water quality standards. This was a combination of small sample sizes and high variance, requiring the removal of outliers from the data set further lowering the size of n for any potential tests. We were able to make larger comparisons for pollutant removal across all configurations, however high variances and non-normality limited our ability to prove whether or not that the plants were successful in meeting reuse standards. Similarly, our comparison between *Carex stricta* and media trials was unsuccessful in proving more consistent filtration for individual configurations and successful across all configurations.

Plant Health (Qualitative)

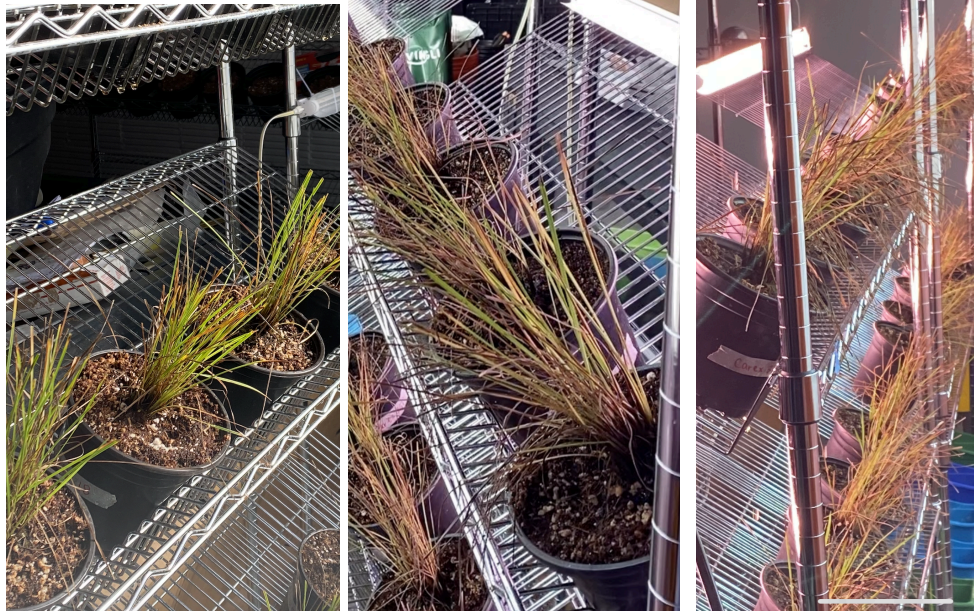


Figure 22: Plants after replanting into coco coir and perlite media, 3 months before testing period (15-Nov-2023) (left); two months before testing period (15-Dec-2023) (middle); 1 week before testing period (7-Feb-24) (right). Color differences can be attributed to lighting changes in photos as well as colder temperatures in green wall space, which led to some grass yellowing.

Throughout the period the wall was irrigated by greywater we wanted to monitor plant health via qualitative analysis. This allowed us to gauge the ability of the system to flourish when saturated with non potable water. Because this metric was decided on after experimentation had begun, there are fewer ‘before’ pictures included for direct comparison, but the following sections were considered notable in comparison to the original state of the plants.

New Growth



Figure 23: Small off-shoots of a plant unit after 10 days of greywater irrigation

New growth is an important indicator of plant health and can be defined by the growth of smaller, shorter green stalks from the base of the ‘parent’ plant. These are evidence that the plant has enough resources to reproduce and generate new propagations despite the influx of pollutants from the greywater irrigation.

Leaf Color

This project used *Carex stricta*, a Maryland endemic wetland grass that goes dormant when resources and sunlight are scarce (in the winter season). Dormancy can be seen when the leaves of a grass species assume a brown hue and begin to photosynthesize less. Even as the plants in the wall were given consistent water and light throughout the duration of this project, the temperature inside the testing space was decreasing gradually because testing occurred in the winter, so some browning of the leaves was unavoidable. The fact that the plants maintained the majority of their green-colored leaves under these conditions demonstrates that they benefited

from the consistent nutrients of the experiment and were being kept in a primarily non-dormant state.

Discussion

Summary

We compared the five parameters, pH, turbidity, COD, TN, NPOC for the plant and media walls to the overall standards for greywater reuse. Comparisons of the testing parameters to the non-potable standards outlined in Table 4 are shown in the tables below (see part III. in Appendix for numerical values/means computed and compared to standards). In Tables 13 and 14, the water outflow sample values were averaged over the 4 testing days for all 10 replicates and compared to the non-potable standards (e.g., the 4 values of pH for replicate 1 from testing days 1-4 were averaged); this mean was compared to the non-potable pH standard of 6-9 in order to determine success/failure. In Tables 15 and 16, the water samples were averaged over all 10 replicates for all 4 testing days (e.g. the 10 values of pH from all 10 replicates of day 1 were averaged and compared to the pH non-potable standard of 6-9). Comparisons to standards were solely based on the means computed and whether or not they were above/below the standards in Table 4. No statistical tests were used to validate these comparisons due to large differences in variance and the overall distribution of the data which violates normality.

Table 13: Comparing water outflow of *Carex stricta* to non-potable reuse standards for each testing parameter, by replicate. Water samples from each replicate are averaged across all 4 testing days. Green boxes indicate filtration success compared to standard, meaning the mean value of the parameter in the outflow was below the non-potable standard outlined in Table 4. Red boxes indicate failure to meet non-potable standards outlined in Table 4. Most replicates met non-potable standards for the majority of the water quality testing parameters. Replicates 3, 5, and 8 met non-potable standards across all 5 water quality testing parameters. pH and TN non-potable standards were met across all replicates.

	Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Rep. 7	Rep. 8	Rep. 9	Rep.10
pH										
Turbidity										
COD										
NPOC										
TN										

Table 14: Comparing water outflow of media to non-potable reuse standards for each testing parameter, by replicate. Water samples from each replicate are averaged across all 4 testing days. Green boxes indicate filtration success compared to standard, meaning the mean value of the parameter in the outflow was below the non-potable standard outlined in Table 4. Red boxes indicate failure to meet non-potable standards outlined in Table 4. Most replicates failed to meet non-potable standards for the majority of the water quality testing parameters. pH and TN non-potable standards were met across all replicates.

	Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Rep. 7	Rep. 8	Rep. 9	Rep.10
pH										
Turbidity										
COD										
NPOC										
TN										

Table 15: Comparing water outflow of *Carex stricta* to non-potable reuse standards for each testing parameter, by testing day. Water samples from each testing day are averaged across all 10 replicates. Green boxes indicate filtration success compared to standard, meaning the mean value of the parameter in the outflow was below the non-potable standard outlined in Table 4. Red boxes indicate failure to meet non-potable standards outlined in Table 4. Day 1 and 2 of plant testing yielded water outflow that met all non-potable water standards.

	Day 1	Day 2	Day 3	Day 4
pH				
Turbidity				
COD				
NPOC				
TN				

Table 16: Comparing water outflow of media to non-potable reuse standards for each testing parameter, by testing day. Water samples from each testing day are averaged across all 10 replicates. Green boxes indicate filtration success compared to standard, meaning the mean value of the parameter in the outflow was below the non-potable standard outlined in Table 4. Red boxes indicate failure to meet non-potable standards outlined in Table 4. No testing days yielded water outflow that consistently met non-potable standards.

	Day 1	Day 2	Day 3	Day 4
pH				
Turbidity				
COD				
NPOC				
TN				

A general analysis of the tables above shows that the *Carex stricta* wall met the non-potable standards outlined in Table 4 more often than the media wall, in both a comparison by replicates and a comparison by day. In Table 13, three replicates/walls (3, 5, and 8) met the non-potable standards across all five water quality testing parameters (Table 13). In contrast,

none of the media replicates met non-potable standards across all five water quality testing parameters (Table 14). Comparing the water samples by day also yields a similar conclusion: in Table 15 showing plant wall filtration, more green boxes are observed versus Table 16, which shows media wall filtration; this indicates that the plant wall consistently met more non-potable standards across all days than the media wall (Table 15 and Table 16).

The media wall failed to meet non-potable standards, especially for COD and NPOC. In fact, the media wall often produced a negative removal rate for NPOC, indicating higher levels of NPOC in the outflow versus the inflow (see Section III. in Appendix). A possible reason for this was the media actually adding more organic material to the water throughout the filtration process, especially since we used coco coir, a media composed of coconut husk (organic matter). COD in the media walls ranged from 400-950 mg/L across all 4 testing days, well above the 250 mg/L standard set for non-potable water reuse (see Section III. in Appendix). There were two days (day 1 and 2) of media testing where COD levels in the outflow water samples were actually higher than the inflow water samples (see Figure 13). The other two testing days had lower COD levels in the outflow versus the inflow water samples, but the levels measured were still consistently higher than the accepted non-potable reuse standard for COD. The COD values for the first two testing days may have been caused by delays in the COD water measurements (see 'Limitations' for further explanation). Overall however, the media was not as capable at removing COD to the non-potable standard level as the plants were.

pH and TN were consistently below the non-potable standard for both the media and *Carex stricta* walls. This occurrence is likely due to the fact that the initial greywater made by the team was already within the non-potable standards for pH and TN outlined in Table 4.

Despite this, the TN removal rate was still relatively high for both the *Carex stricta* and media wall (above 50% consistently for the *Carex stricta* wall and above 25% for the media wall), indicating that there was successful removal of TN, most significantly by the *Carex stricta* (see Figure 21).

Another conclusion that can be made from this experiment is the close relationship between flow rate and pollutant removal in the plant wall. The *Carex stricta* wall replicates (3, 5, & 8) which met all five water quality standards for non-potable reuse had a higher water inflow from the drippers in comparison to the other plant wall replicates (see ‘Limitations’ for further explanation). The *Carex stricta* walls that had higher water inflow performed better at pollutant filtration. In the media wall, this occurrence was not observed.

Additionally, the *Carex stricta* wall replicates that performed the best throughout the experiment included healthier plants, those with greener leaves and new growth observed at the roots. Plant health does seem to be related to water filtration capability, just as inflow rate may be. Furthermore, the team did not experience significant maintenance challenges for the green wall during experimentation; specifically, no clogging was experienced or foul odor was produced throughout the experiment. Since the irrigation system and lighting were automated, minimal contact was required with the green wall system except during water sampling days.

Limitations

The results may have been affected by several limitations throughout the experiment. Our testing period was relatively brief due to time constraints; we tested for a total of 20 days, with 8 water quality testing events in total. Other green wall studies varied in the length of their testing, ranging from a timeline of weeks to months, and others, a whole year (Prodanovic et al., 2019;

Fowdar et al., 2017). Testing for a longer period of time could have led to varying observations in water filtration and effectiveness of the green wall system. Testing throughout a longer duration could also help account for seasonal changes that affect plant health.

The Cypress Building where we built and managed the green wall was not completely temperature-controlled; while the building was insulated, it was subject to variations in temperature reflective of the outside temperature environment due to proximity to the garage door of the building. Thus, there was difficulty ensuring uniform temperature throughout the testing period and minimizing the effect of seasonal changes in climate on the *Carex stricta*. Testing began in the late-winter/early-spring with colder weathers, so the *Carex stricta* was not at optimal health; although the plant species is very cold-hardy, meaning it can survive through colder, harsher climates, increased performance and healthier leaves would likely have been observed during late-spring/early-summer periods. Due to time constraints, the *Carex stricta* was also given only around 2 months of growth before the testing began, which limited the plant from reaching full maturity.

Another limitation was the rate of drip irrigation across all ten configurations; the rate at which the water dripped onto the first layer of pots was not uniform, with some configurations flowing faster than others (most notably, configuration 8) and receiving a greater volume of water. While this variation was not significant, the team attempted to standardize the rate of water flow to the best of our ability but could not ensure exact results. We anticipate that this occurred principally as a result of some clogging in the drip nozzles due to the use of clay in the recipe. Other recipes that included clay powder agitated the mix for 10-25 hours (or overnight) in order to fully homogenize the mixture. Unfortunately due to our limited access to a mixing

system of that nature, our greywater needed to be manually stirred prior to each testing event, which could have created inconsistencies throughout the experiment overall.

The team also experienced challenges with the COD testing process. Standard protocol for COD testing in water recommends testing soon after the water sample is taken. We followed this procedure for the first 3 testing events (for the plants). However, due to an unforeseeable shipping delay in the vials needed for COD testing in the lab, we were inclined to store our water samples for 1-2 weeks while waiting for the new vials to complete COD testing for the remaining 5 testing events (one for *Carex stricta*, four for the media-only). The storing of the outflow water samples for this period of time may have affected the concentrations of pollutants in the water and skewed the COD results. For the testing days when water samples were stored for longer periods of time before analysis (Plant Test 4, Media Test 1, Media Test 2), the average COD removal rate was considerably lower (-7.54%, -48.3%, -102%, respectively) than testing days that involved almost-immediate COD analysis (Plant Test 1, Plant Test 2, Plant Test 3, Media Test 3, Media Test 4) with average COD removal rates of 65.4%, 59.2%, 64.2%, 55.0%, 55.9%, respectively. The transition to newer COD analysis vials may have also affected these results, despite being the same brand/type.

In the operation of the green wall irrigation system, the team observed deposition of larger media particles into the collection bins, the majority of which was runoff from the tops of the pots as they were irrigated. The excess media particles from runoff may have affected water pollutant concentrations, specifically organic material. The use of cheesecloth or other physical filtration objects could have been used at the bottom of the configuration to remove these larger particles from the collection bins.

The greywater tank was also mixed periodically since the contaminants (most notably, the powdered clay) settled onto the bottom, leading to a non-uniform concentration throughout the tank. Since the water pump removes water from the bottom of the tank, it would have displaced water that was of higher concentration than the water at the top of the tank. Therefore, our greywater inflow samples collected from the top of the tank may be unrepresentative of the actual greywater quality in the tank. Our greywater recipe also excluded *Escherichia coli* (*E. coli*) and other microbial contaminants due to limitations of our lab space and the Cypress Building space. Previous studies (e.g., Prodanovic et al., 2017; Fowdar et al., 2017; Boano et al., 2021), used microbial contaminants such as *Escherichia coli* in their greywater recipes as well as untreated secondary effluent sourced from their local sewage treatment plants, which more accurately reflects the typical compositions of light greywater. Water quality results would likely have varied with the addition of this into our greywater.

Our experiment solely investigated water filtration capabilities of one native Maryland plant: *Carex stricta*. While the results provide insight into the capabilities of this plant as a means for greywater filtration in a green wall structure, the experiment cannot be used to make general conclusions about the capabilities of all Maryland native plants for greywater filtration. In order to make these conclusions, a wider variety of Maryland plants needs to be analyzed, ideally, for a longer period of time. Using a more diverse set of plants in the green wall could also provide critical insight into the role of biodiversity in promoting greywater filtration.

Future Research

Future research in this subject area could involve testing a wider range of Maryland native plants with characteristics suitable for greywater filtration, such as *Juncus effusus*,

Peltandra virginica, *Panicum virgatum*, etc. Comparisons between plants and their filtration capabilities could be made to draw conclusions about the effectiveness of Maryland native plants and which specific species or combinations yield maximum efficiency. Maryland native plants could also be tested against standard ornamental green wall plants to examine their specific advantage in greywater filtration, if any.

Additionally, the usage of actual greywater in the green wall is an ambitious but necessary endeavor in this field, as the majority of research, including our own, constructed standard, artificial greywater for testing. However, greywater is unique in that it varies widely across regions depending on local human interactions with water sources, such as the type and frequency of products used and washed down the drains of sinks/showers. A standard greywater recipe does not cover all the nuances of greywater composition necessary to understand the full capacity of the wall for water purification.

Testing the green wall using real greywater has many future practical implications. For example, the greywater-green wall system could be modified experimentally to make it more viable for use in domestic scenes (e.g., home usage, in stores, malls, etc.). This would require modifications to the scale and overall structure of the wall as well as the addition of a water circulation system/storage to offload the filtered greywater for reuse later on.

Appendix

I. Equity Impact

The US Water Alliance, a non-profit organization that educates and supports sustainable and equitable water policies, defines three pillars of water equity: (1) Having access to safe, clean, affordable drinking water and wastewater services, (2) sharing the economic, social, and environmental benefits of water systems, and (3) having resilience in the face of droughts and other climate risks,” (US Water Alliance, n.d.). Our research into greywater recycling systems in green walls aims to help advance these goals of water equity. Filtering and recycling greywater through the green wall will provide affordable, reliable wastewater infrastructure to lower-income communities, allowing them to reuse their greywater for non-potable purposes: car washing, laundry, toilet flushing, etc. Furthermore, the accessibility of our green wall research will ensure that overlooked communities benefit from the traditionally exclusive social and economic perks of green walls, like improved mental well-being and higher property values.

This impact can be quantified when looking at the costs of a traditional wall in comparison to the design proposed in our project. The main differences between the two types are in irrigation, plant type and required lighting. Most green walls in use now utilize tropical plants for aesthetics such that they stay green year-round. But these plants require a simulated tropical environment: significant lighting and daily watering. Table 17 below shows how accessibility to green wall installation may be improved when endemic plants and greywater are used like Team Verdant proposes. The proposed green wall in Table 17 is estimated to save about \$70 compared to traditional green walls.

It is important to note that despite the theoretical cost savings present in the wall, our current prototype falls short of comprehensively addressing the needs of a fully-functioning residential green wall. As was mentioned in the discussion, a limitation of this study was the absence of testing with real greywater. This means that while it is possible to predict the response of the plant system to light greywater, it would be prudent to iterate wall designs with samples of actual (rather than lab-fabricated) greywater. In real greywater, bacterial loading would be a concern to monitor, because in this study's artificial greywater, *E. coli* was omitted. It is unlikely that without additional purification methods all bacterial contaminants will be eliminated from the water prior to reuse. Finally, the plumbing associated with rerouting greywater to a wall could range in complexity from extremely simple mechanisms (e.g., a collection bucket that is then manually added to a 'tank' that leads to the green wall plumbing) to highly complex (e.g., a new system of piping that connects to the wall itself). These could impose a high cost, but in spite of this, the cost overall would still be reduced from that of a traditional green wall. The savings associated with plant type, irrigation and watering, are significant ones, and any structural or plumbing costs would have been nonetheless included in the installation of a traditional green wall. The cost savings of the Verdant green wall design are therefore comparative in nature and can be further examined below (Table 17).

Table 17. Cost Analysis comparison of traditional green wall to modified system*

	Traditional Green Wall		Verdant Green Wall	
	Requirement	Notes	Requirement	Notes
Irrigation	<i>Potable</i> ¹ (+ \$10/year)	- Our wall used appx 6L/day → 180L/month (~ 50 gal) → ~ 600 gal/year	<i>Greywater</i> (Free)	- Potential cost to reroute greywater to wall system
Plant Type	<i>Tropical</i> ² (~ \$60)	- Tropical plants require daily irrigation	<i>MD Native</i> ³ (~ \$24)	- Readily available, more affordable - Aesthetics Tradeoff: plants go dormant during the winter
Lighting	<i>LEDs needed</i> ⁴ (~ \$30)	- Need to simulate tropical environment (full sun)	<i>Natural light</i> <i>acceptable</i>	- Plants are well-accustomed to MD conditions
Media	<i>Repotting is optional, cost varies</i>			
Construction	<i>Possible to use recycle materials**, cost varies</i>			
Final Cost Comparison***		Traditional: \$100 or more	Verdant: \$30 (Savings: \$70)	

* Costs in the table are for on the basis of 10 ft-sq wall area (~10 plants) ** Recycled materials include old wooden palettes, plastic bottles, etc (Khan, 2024) *** Comparison does not include variable costs of media or construction.

¹ Potable water costs for MD: <https://www.wsscwater.com/rates>

² Tropical plant costs: \$5 - \$20 per plant (fern), but median is ~ \$6:
<https://www.nativewildflowers.net/wholesale-ferns>

³ Team Verdant purchased 30 plants for ~ \$70 total

⁴ Team Verdant purchased one LED strip for \$30

II.TOC/TN Raw Data

Wall Type	Wall #	trial #	NPOC (mg/L)	TN (mg/L)	Δ NPOC (mg/L)	Δ TN (mg/L)
unfiltered greywater	NA	1	143.1	2.879	0	0
Plant	1	1	74.17	1.321	-68.93	-1.558
Plant	2	1	90.19	1.655	-52.91	-1.224
Plant	3	1	49.27	0.9249	-93.83	-1.9541
Plant	4	1	63.65	1.07	-79.45	-1.809
Plant	5	1	50.41	0.9118	-92.69	-1.9672
Plant	6	1	103.6	1.677	-39.5	-1.202
Plant	7	1	54.44	0.9602	-88.66	-1.9188
Plant	8	1	38.79	0.6626	-104.31	-2.2164
Plant	9	1	64.65	1.11	-78.45	-1.769
Plant	10	1	49.77	0.7974	-93.33	-2.0816
unfiltered greywater	NA	2	129.5	2.626	0	0
Plant	1	2	62.93	1.02	-66.57	-1.606
Plant	2	2	70.53	1.128	-58.97	-1.498
Plant	3	2	48.17	0.8152	-81.33	-1.8108
Plant	4	2	45.09	0.7844	-84.41	-1.8416
Plant	5	2	44.19	0.7743	-85.31	-1.8517
Plant	6	2	76.2	1.256	-53.3	-1.37
Plant	7	2	55.5	0.7957	-74	-1.8303
Plant	8	2	57.64	0.7621	-71.86	-1.8639
Plant	9	2	77.94	1.291	-51.56	-1.335
Plant	10	2	70.57	1.015	-58.93	-1.611
unfiltered greywater	NA	3	120.8	2.546	0	0
Plant	1	3	63.4	1.075	-57.4	-1.471
Plant	2	3	69.76	1.084	-51.04	-1.462
Plant	3	3	50.18	0.8366	-70.62	-1.7094
Plant	4	3	46.14	0.819	-74.66	-1.727
Plant	5	3	45.66	0.7332	-75.14	-1.8128

Plant	6	3	73.05	1.139	-47.75	-1.407
Plant	7	3	56.79	0.7698	-64.01	-1.7762
Plant	8	3	58.05	0.7977	-62.75	-1.7483
Plant	9	3	75.39	1.353	-45.41	-1.193
Plant	10	3	70.93	1.058	-49.87	-1.488
unfiltered greywater	NA	4	89.14	1.672	0	0
Plant	1	4	56.4	0.4906	-32.74	-1.1814
Plant	2	4	61.32	0.5524	-27.82	-1.1196
Plant	3	4	48.44	0.5463	-40.7	-1.1257
Plant	4	4	45.53	0.5508	-43.61	-1.1212
Plant	5	4	46.66	0.4894	-42.48	-1.1826
Plant	6	4	36.13	-0.5442	-53.01	-2.2162
Plant	7	4	31.34	-0.6249	-57.8	-2.2969
Plant	8	4	30	-0.6192	-59.14	-2.2912
Plant	9	4	37.57	-0.3567	-51.57	-2.0287
Plant	10	4	35.83	-0.5597	-53.31	-2.2317
unfiltered greywater	NA	1	98.72	1.568	0	0
Media only**	1	1	-1082	1.07	NA	NA
Media only	2	1	114.9	1.027	16.18	-0.541
Media only	3	1	139.4	1.24	40.68	-0.328
Media only	4	1	115.9	1.363	17.18	-0.205
Media only	5	1	148.2	1.484	49.48	-0.084
Media only	6	1	135.1	1.194	36.38	-0.374
Media only	7	1	120.2	1.344	21.48	-0.224
Media only	8	1	124.8	1.116	26.08	-0.452
Media only	9	1	118.6	1.099	19.88	-0.469
Media only	10	1	132	1.15	33.28	-0.418
unfiltered greywater	NA	2	91.64	1.565	0	0
Media only	1	2	101.1	0.82	9.46	-0.745
Media only	2	2	98.71	0.8263	7.07	-0.7387
Media only	3	2	109.3	1.005	17.66	-0.56

Media only	4	2	98.51	1.034	6.87	-0.531
Media only	5	2	114.1	1.104	22.46	-0.461
Media only	6	2	107.3	0.8185	15.66	-0.7465
Media only	7	2	109.9	1.104	18.26	-0.461
Media only	8	2	107.7	0.9028	16.06	-0.6622
Media only	9	2	102.8	0.808	11.16	-0.757
Media only	10	2	127.2	0.955	35.56	-0.61
unfiltered greywater	NA	3	65.93	2.034	0	0
Media only	1	3	56.92	0.771	-9.01	-1.263
Media only	2	3	56.7	0.7132	-9.23	-1.3208
Media only	3	3	57.38	1.005	-8.55	-1.029
Media only	4	3	54.7	0.7195	-11.23	-1.3145
Media only	5	3	59.75	1.199	-6.18	-0.835
Media only	6	3	65.66	0.7604	-0.27	-1.2736
Media only	7	3	70.11	0.7215	4.18	-1.3125
Media only	8	3	58.3	1.102	-7.63	-0.932
Media only	9	3	73.98	0.8752	8.05	-1.1588
Media only	10	3	104.3	0.7775	38.37	-1.2565
unfiltered greywater	NA	4	64.04	2.046	0	0
Media only	1	4	57.47	0.8103	-6.57	-1.2357
Media only	2	4	57.23	0.6977	-6.81	-1.3483
Media only	3	4	59.56	0.908	-4.48	-1.138
Media only	4	4	55.67	0.7278	-8.37	-1.3182
Media only	5	4	60.31	1.087	-3.73	-0.959
Media only	6	4	64.92	0.7493	0.88	-1.2967
Media only	7	4	73.81	0.8154	9.77	-1.2306
Media only	8	4	63.66	1.141	-0.38	-0.905
Media only	9	4	74.27	1.121	10.23	-0.925
Media only	10	4	107.7	0.9277	43.66	-1.1183
**Outliers to be excluded based on box plot error bar method						
The columns of delta values were calculated by subtracting the accompanying unfiltered greywater test parameter						

III. Mean Values of Water Quality Testing Parameters for Plant & Media Walls

*Green indicates met standard; Red indicates failed standard

CAREX STRICTA (values are averages across all 4 testing days w/standard deviation)																				
	Rep 1	stdev	Rep 2	stdev	Rep 3	stdev	Rep 4	stdev	Rep 5	stdev	Rep 6	stdev	Rep 7	stdev	Rep 8	stdev	Rep 9	stdev	Rep 10	stdev
pH	7.49	0.13	7.47	0.28	7.53	0.20	7.51	0.21	7.55	0.29	7.49	0.26	7.50	0.30	7.52	0.20	7.52	0.25	7.50	0.26
Turbid. (NTU)	3.27	0.79	5.55	2.29	2.52	0.59	2.29	0.83	2.51	1.91	3.81	1.15	2.82	1.52	4.18	2.85	5.50	1.63	6.86	6.50
COD (mg/L)	242.37	207.92	349.25	171.52	191.50	54.10	296.88	252.72	145.00	28.06	308.88	59.65	315.63	288.45	198.38	69.44	432.63	209.65	349.63	215.81
NPOC % removal (mg/L-C)	45.95	6.38	38.99	6.27	58.12	8.81	57.86	7.18	60.13	8.46	41.94	13.16	59.23	5.24	61.67	9.67	47.52	10.30	52.95	11.39
TN (mg/L)	0.98	0.35	1.10	0.45	0.78	0.16	0.81	0.21	0.73	0.18	1.02	0.72	0.63	0.43	0.56	0.37	0.94	0.63	0.72	0.49
MEDIA (values are averages across all 4 testing days w/standard deviation)																				
	Rep 1	stdev	Rep 2	stdev	Rep 3	stdev	Rep 4	stdev	Rep 5	stdev	Rep 6	stdev	Rep 7	stdev	Rep 8	stdev	Rep 9	stdev	Rep 10	stdev
pH	6.90	0.40	6.90	0.33	6.98	0.35	6.82	0.43	6.90	0.42	6.94	0.40	6.81	0.38	6.98	0.30	6.97	0.29	6.82	0.24
Turbid. (NTU)	5.25	4.21	5.81	4.46	4.67	1.97	5.66	3.71	4.85	1.91	6.20	4.90	5.66	4.56	6.02	4.53	5.78	4.91	5.16	5.02
COD (mg/L)	659.38	281.89	690.13	310.03	665.25	377.06	700.75	483.28	599.50	300.71	527.13	264.42	604.75	313.27	590.00	294.23	478.75	235.75	587.50	222.87
NPOC % removal (mg/L-C)	4.53	12.98	0.13	14.57	-10.13	25.01	1.30	16.46	-14.86	28.00	-13.73	17.31	-15.82	6.89	-7.94	17.19	-15.13	3.79	-49.72	16.21
TN (mg/L)	0.80	0.03	0.82	0.15	1.04	0.14	0.96	0.31	1.22	0.18	0.88	0.21	1.00	0.28	1.07	0.11	0.98	0.16	0.95	0.15

CAREX STRICTA (values are averages across all 10 replicates per day w/standard deviation)								
	Day 1	stdev	Day 2	stdev	Day 3	stdev	Day 4	stdev
pH	7.31	0.099	7.40	0.10	7.49	0.07	7.82	0.10
Turbid. (NTU)	4.818	1.07	3.00	1.38	2.60	0.82	5.36	4.72
COD (mg/L)	157.25	51.39	183.40	45.51	180.6	33.13	449.5	227.93
NPOC % removal (mg/L-C)	55.35	14.15	52.99	9.79	49.56	9.29	51.85	11.81
TN (mg/L)	1.11	0.34	0.96	0.21	0.97	0.20	0.26	0.28

MEDIA (values are averages across all 10 replicates per day w/standard deviation)								
	Day 1	stdev	Day 2	stdev	Day 3	stdev	Day 4	stdev
pH	6.41	0.13	6.93	0.05	7.03	0.09	7.23	0.09
Turbid. (NTU)	2.78	0.33	11.32	2.32	4.56	0.76	3.36	0.92
COD (mg/L)	953.85	104.67	691.25	292.16	403.60	104.31	392.55	90.71
NPOC % removal (mg/L-C)	-29.33	11.77	-17.48	9.36	0.23	22.70	-5.34	24.32
TN (mg/L)	1.21	0.15	0.94	0.12	0.86	0.18	0.90	0.17

IV. Box plots

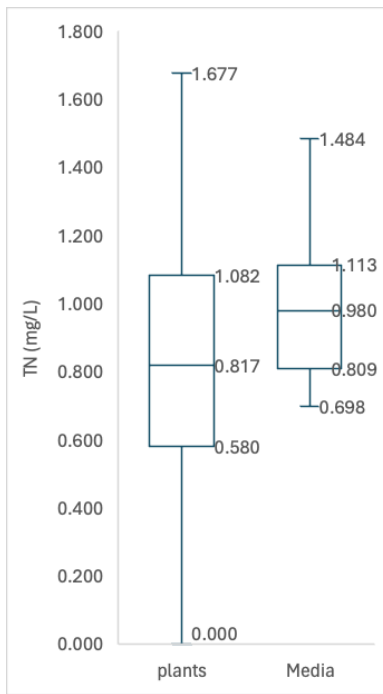


Figure 24a: Box plot for identification of outliers in TN data set for plants and media trails.

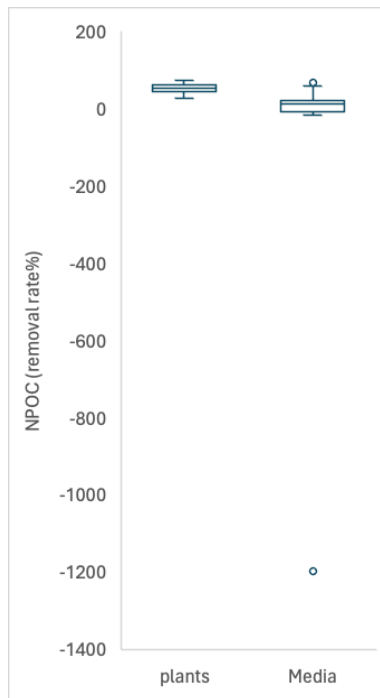


Figure 24b: Box plot for identification of outliers in NPOC data set for plants and media trails.

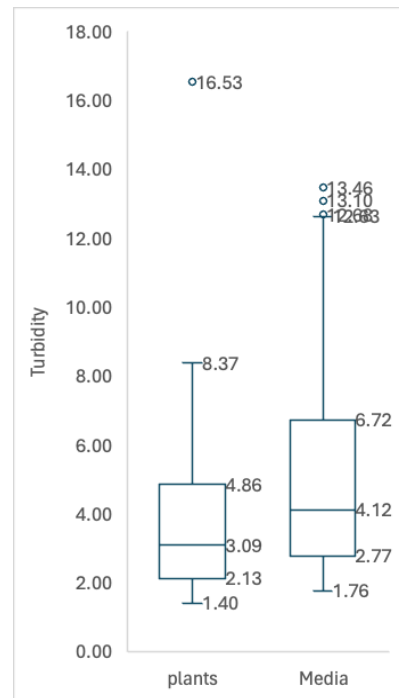


Figure 24c: Box plot for identification of outliers in turbidity data set for plants and media trails.

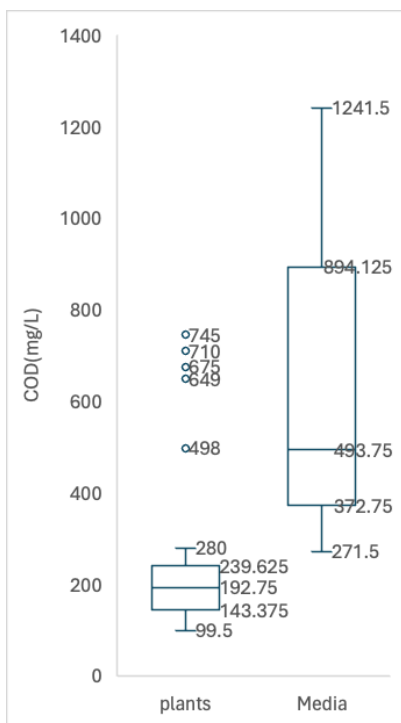


Figure 24d: Box plot for identification of outliers in COD data set for plants and media trails.

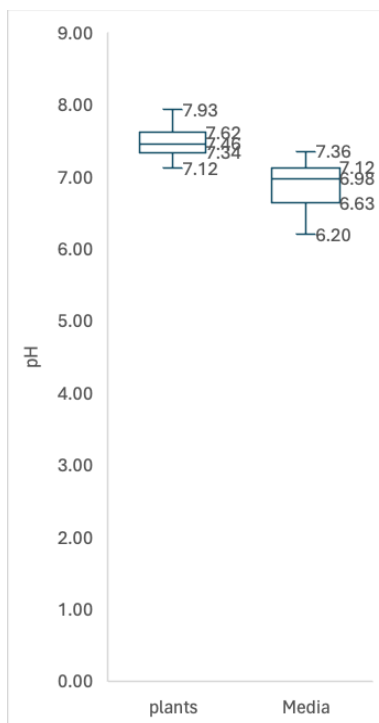


Figure 24e: Box plot for identification of outliers in pH data set for plants and media trails.

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