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Review

Review of emerging contaminants in green stormwater infrastructure: Antibiotic resistance genes, microplastics, tire wear particles, PFAS, and temperature

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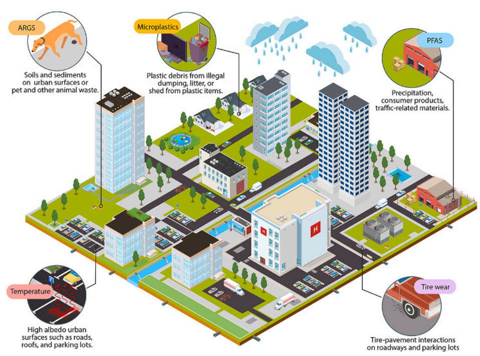
HIGHLIGHTS

- Green stormwater infrastructure is subject to emerging stormwater contaminants.
- These include ARGs, microplastics, tire-wear particles, PFAS, and temperature.
- Common removal mechanisms include filtration, sorption, and biogeochemical processes.
- Risk of accumulation in GSI and best practices for removal need further research.

GRAPHICAL ABSTRACT



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ABSTRACT

Green stormwater infrastructure is a growing management approach to capturing, infiltrating, and treating runoff at the source. However, there are several emerging contaminants for which green stormwater infrastructure has not been explicitly designed to mitigate and for which removal mechanisms are not yet well defined. This is an issue, as there is a growing understanding of the impact of emerging contaminants on human and environmental health. This paper presents a review of five emerging contaminants – antibiotic resistance genes, microplastics, tire wear particles, PFAS, and temperature – and seeks to improve our understanding of how green stormwater infrastructure is impacted by and can be designed to mitigate these emerging contaminants. To do so, we present a review of the source and transport of these contaminants to green stormwater infrastructure, specific treatment mechanisms within green infrastructure, and design considerations of green stormwater infrastructure that could lead to their removal. In addition, common removal mechanisms across these contaminants and limitations of green infrastructure for contaminant mitigation are discussed. Finally, we present future research directions that can help to advance the use of green infrastructure as a first line of defense for downstream water bodies against emerging contaminants of concern.

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1. Introduction

Green stormwater infrastructure (GSI) is a growing practice of managing stormwater by capturing, infiltrating, and treating stormwater runoff at the source (Clary et al., 2020). GSI – also known as low impact development or blue-green infrastructure – also has co-benefits including connecting green spaces, heat stress reduction, sustainable resource management, increased biodiversity, and air quality improvements, among others (Choi et al., 2021; Davies et al., 2015; Rivera and Hendricks, 2022; Wendel et al., 2011). In many cases, GSI is primarily designed to reduce flooding by decreasing stormwater runoff volumes and peak flow rates; however, they are also designed to remove stormwater pollutants through processes such as settling, filtration, adsorption, and biotransformation of contaminants.

While GSI has broad contaminant mitigation potential, the regulatory criteria for which it is designed are limited to only a handful of pollutants. For example, within the US, state and municipal GSI regulations are largely limited to total suspended solids (TSS) mitigation, with few regulatory entities requiring total phosphorus (TP) and/or total nitrogen (TN) mitigation (Naughton et al., 2021). While these goals provide attainable and flexible stormwater management criteria, they do not target other contaminants. In addition, these regulations lend themselves to a "one size fits all" approach when it comes to GSI design, resulting in repeated designs installed throughout watersheds (Taguchi et al., 2020).

The limited regulatory focus on primary contaminants and a "one size fits all" approach may not be appropriate for removing other contaminants of concern (Taguchi et al., 2020). For example, removal of TSS largely focuses on removing large particles through either sedimentation or filtration. However, these processes are ineffective at removing solid contaminants with a high buoyancy or those that are dissolved (Spahr et al., 2020). Monitoring studies demonstrate evidence of this relationship, with total dissolved solids and dissolved phosphorus concentrations either not reduced or increasing from the influent to effluent for many GSI practices (Clary et al., 2020). It is therefore possible that by simply meeting regulations as written, GSI is designed and constructed with a bias towards removing particulate contaminants or those contaminants that are easily filtered or adsorbed with standard GSI media.

Despite this potential disconnect, there is growing and robust research demonstrating that GSI can be designed to remove a broad range of contaminants. This includes modifications such as soil amendments that can promote adsorption and transformation of dissolved contaminants (Ali and Pickering, 2023). In doing so, GSI has been shown to reduce concentrations of TP (30–99 %), TKN (0–60 %), total coliforms (5–65 %), metals (up to 99 %), and chemical oxygen demand (79–84 %) (Clar et al., 2015; Jarrett, 2022; MassDEP, 2008; MPCA, 2022; Rossman and Huber, 2016; Wurochekke et al., 2015). For example, engineered GSI media promoting cation-exchange, specific adsorption, coprecipitation, and organic complexation has been shown to remove >90 % of heavy metal concentrations (Malaviya and Singh, 2016; Szota et al., 2015). Furthermore, GSI media engineered for adsorption, phosphorus content, and specific chemical fixation removed between 70 and 85 % of total phosphorus concentrations while binding orthophosphates (e.g., biologically available phosphorus species) (Wadzuk et al., 2021). Also, GSI amended with a carbon substrate (e.g., woodchips) has been shown to reduce nitrate concentrations by 87 % (Yang, 2010). GSI engineered to maximize adsorption can also reduce fecal coliform (69–92 %), pathogen (55–100 %), and *Escherichia coli* (*E. coli)* (71 %) concentrations by promoting pathogen die off (Hunt et al., 2008). In addition to reductions in the concentration of contaminants, infiltration of stormwater runoff in GSI can result in significant load reductions to downstream waterbodies. Therefore, while the focus of regulations may be on a limited number of primary contaminants, there are potential mechanisms or modifications to GSI that can remove other contaminants of concern.

The ability of GSI to further treat existing and emerging contaminants of concern is important for addressing current and emerging water quality issues. This is a challenge, however, because many emerging contaminants contain unique physiochemical properties that may make them more difficult to remove within GSI than traditional legacy pollutants (e.g., TSS, phosphorus, and nitrogen). Therefore, this review focuses on 5 emerging contaminants – antibiotic resistance genes (ARGs), microplastics, tire wear particles, PFAS, and temperature (Fig. 1) – due to emerging recognition of their impact on environmental contamination, as well as their physicochemical properties that make them unique compared to legacy pollutants. Together, these five emerging contaminants represent different classes of pollutants including biological, particulate, and chemical contaminants, as well as physical properties of stormwater runoff.

As a biological contaminant, ARGs have been found in stormwater runoff at levels comparable to wastewater effluent (O'Malley et al., 2021), and represent a significant threat to human health; as in 2019 alone, 1.27 million deaths were attributed to bacterial resistant infections, making antibiotic resistance the leading cause of death around the world (Murray et al., 2022). Antibiotic resistant bacteria (ARB) that harbor ARGs may present unique challenges for GSI such as limiting the biogeochemical processes, survival, and diversity of beneficial soil bacterial communities and vegetation (Gold et al., 2018; Shea and Moser, 2008). Their removal is complex and therefore may rely on cellular defense and competition mechanisms, cellular nutrient uptake mechanisms, and charge, among others (Gold et al., 2018; Shea and Moser, 2008).

Emerging particulate pollutants, such as microplastics and tire wear particles, are growing in recognition due to their abundance in stormwater (Knight et al., 2020) (CSWB, 2022) and their subsequent acute toxicity from their chemical compounds to aquatic species (Tian et al., 2021) (Corcoran, 2022; Pramanik et al., 2020). Microplastics and tire wear particles have physical and chemical properties that are different from suspended solids, such as sediment and organic debris, typically found in stormwater. Microplastics and tire wear particles have low densities that may prevent them from settling (Koutnik et al., 2022b; Lange et al., 2021), and unique morphologies and surface characteristics that may sorb other pollutants (Cherniak et al., 2022; Corcoran, 2022; Pramanik et al., 2020; Rochman et al., 2022). Furthermore, each can leach other pollutants that have been found to be toxic to aquatic biota (Corcoran, 2022; Pramanik et al., 2020).

Emerging chemical pollutants, such as PFAS or *Per-* and polyfluoroalkyl substances, are growing in their recognition as a class of emerging contaminant that can have a significant detrimental impact to environmental and human health (Gaines et al., 2023; Lyu et al., 2022; Rayne and Forest, 2009). In fact, in August 2022 the U.S. Environmental Protection Agency proposed a new rule that would designate PFAS as hazardous substances because they "may present a substantial danger to human health or welfare or the environment" (Blackman, 2022). Not only do they pose a threat, but their removal is challenging as PFAS are hydrophobic and sustain in the environment for years due to their unique morphologies and complex chemical compositions causing slow degradation (Gaines et al., 2023; Lyu et al., 2022; Rayne and Forest, 2009).

Finally, physical properties of stormwater runoff, such as temperature, are of emerging concern. With global air temperatures rising and rapid urbanization occurring in cities, a subsequent increase in runoff temperatures has created hydrologic urban heat islands that are a serious threat to aquatic health (Zahn et al., 2021). Physical properties of the runoff, such as temperature, cannot be removed with a mass transfer and rely on the heat exchange between the runoff and surface and subsurface interactions. Therefore, GSI characteristics and processes that mitigate temperature are unique and include thermodynamic fluxes, heat capacity, heat storage, and thermal conductivity, among others (Campbell and Norman, 1998; de Vries, 1975; Jaynes, 1998; Tamai, 1998).

It is important to consider how GSI can serve as a first line of defense to treat these contaminants and what impact the contaminants may have on GSI itself. To that end, the objective of this review is to identify the sources of emerging contaminants, their transport to GSI, treatment processes specific to their removal, and specific design criteria of GSI that should be considered. In this study we define GSI as infrastructure that captures, infiltrates, and treats stormwater with an engineered media at site-level. This includes practices such as bioretention, bioswales, rain gardens, permeable pavements, green roofs, and constructed wetlands. However, this excludes those practices that do not capture, infiltrate, and treat runoff such as wet or dry ponds, underground detention structures, and rain barrels. Furthermore, in this review we have restricted our discussion to five emerging contaminants: ARGs, microplastics, tire wear particles, PFAS, and temperature because of their presence in urban stormwater runoff, emerging threat to human and environmental health, and unique physiochemical properties (Pamuru et al., 2022). While the list of emerging contaminants in stormwater is numerous, for the purpose of being thorough in our discussion of each contaminant, this review will restrict our focus to five that we believe are of increasing importance. In addition, there are numerous review papers that focus on urban contaminant sources and transport (Müller et al., 2020), emerging contaminants in stormwater runoff (Saifur and Gardner, 2021; Spahr et al., 2020), the performance of GSI designs (Clary et al., 2020; Eckart et al., 2017; Okaikue-Woodi et al., 2020), and their unintended consequences (Taguchi et al., 2020); however, there is a lack of review papers that consider how these emerging contaminants of concern (ARGs, microplastics, tire wear particles, PFAS, and temperature) can both be treated by and impact GSI. Because these contaminants are emerging in recognition and importance, in many cases, there is limited research focused on their impact on GSI. Therefore, in our discussion we make recommendations by pulling from other disciplines such as environmental genetics, chemistry, hydrology, water resources engineering, ecology, biology, and physics.

The following sections focus on individual contaminants and describe (1) the background of the contaminant and its potential sources in urban watersheds, (2) treatment processes for the contaminant within GSI, (3) potential GSI design considerations to remove the contaminant, and (4) a summary of the broader importance of the contaminant within GSI. Finally, we provide a discussion and perspectives on the future of GSI in context of emerging contaminants. Ultimately, this paper seeks to improve the understanding of how GSI can serve as a first line of defense against emerging stormwater contaminants to protect human and environmental health.

2. Antibiotic resistance genes (ARGs)

2.1. Background

Soil environments have diverse microbial communities that serve many functions, including carbon and nutrient cycling, organic matter decomposition, primary productivity, and climate regulation (Delgado-Baquerizo et al., 2016; Geyer et al., 2017). A specific function that has borne out of the stress of anthropogenic pollution is antibiotic resistance (Cantón et al., 2011). Antibiotic resistance is a defense mechanism that bacteria can develop or acquire to resist the lethal effects of antibiotics

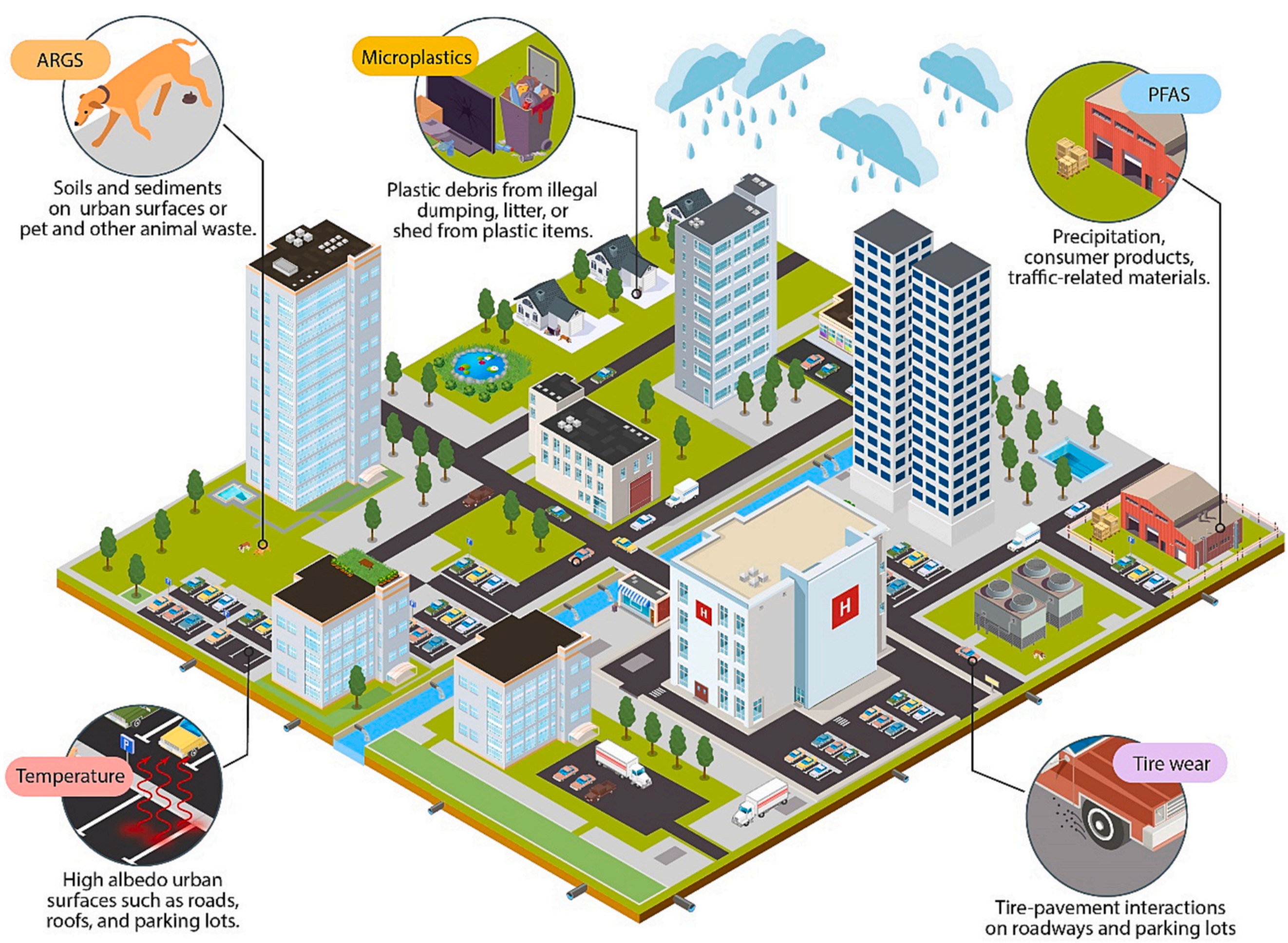

Fig. 1. Illustration of the sources of emerging contaminants in the urban environment.

and other antimicrobial compounds. Antibiotic resistance originates in the environment, preceding the use of antibiotics by humans. However, the crisis we see today is due in part to the excessive use of antibiotics by humans and for animals (D'Costa et al., 2011; Kraemer et al., 2019). The use of antibiotics by humans has led to an expansion of antibiotic resistance beyond the environment and to clinical bacteria (Wright, 2010). As a result, antibiotic resistance has become a modern public health crisis.

Antibiotics are becoming less effective for the treatment of bacterial infections (D'Costa et al., 2011). Consequently, there has been a severe increase in the number of infections and fatalities caused by ARB. In 2019 alone, 1.27 million deaths were attributed to bacterial resistant infections making antibiotic resistance the leading cause of death around the world (Murray et al., 2022). If actions are not taken to address this threat, an interagency coordination group on antimicrobial resistance projected that 10 million deaths per year will stem from antibiotic resistant infections by 2050 (IACG, 2016). Antibiotic resistance also has a significant financial impact. Antibiotic resistance is estimated to cost the United States $55 billion per year, through associated medical costs and loss in productivity (Dadgostar, 2019). By 2050, resistant-tuberculosis infections alone are expected to cost the world $16.7 trillion (Dadgostar, 2019).

Human actions such as the over-prescription of antibiotics for minor ailments, the prolific use of antibiotics for livestock, and subsequent antibiotic discharge into the environment are partly responsible for the rise in antibiotic resistance. The Center for Disease Control found that approximately 30 % of antibiotic prescriptions are unnecessary, equating to 47 million prescriptions per year (Fleming-Dutra et al., 2016). This is primarily because antibiotics are regularly prescribed for respiratory conditions, such as the common cold, bronchitis, and sinus and ear infections, that are caused by viruses, which are not affected by antibiotics (Fleming-Dutra et al., 2016). Besides the excessive use of antibiotics by humans, roughly 80 % of the antibiotics sold in the United States are sold for use in animals (Martin et al., 2015). The use of medically important antibiotics by humans and for animals has demonstrated causal evidence that antibiotic use in the agricultural sector is exacerbating antibiotic resistance in the clinic (Witte, 1998). The emerging concern for fighting antibiotic resistance is the connection between antibiotic resistance in the environment and human health.

Antibiotic resistance is considered ubiquitous in the environment but is exacerbated in places with diverse bacterial communities and pronounced anthropogenic pollution (Finley et al., 2013; Tello et al., 2012). Anthropogenic contaminants are considered selective pressures for antibiotic resistance, meaning they can exert a pressure on microbial growth and trigger adaptive responses by the community (Kunhikannan et al., 2021). For example, antibiotics, antimicrobial compounds, heavy metals, pesticides, biocides, and nutrients are known selecting agents (Imran et al., 2019; Zhuang et al., 2021). An increase in the abundance of selective pressures is known to accelerate horizontal gene transfer (HGT) thereby diversifying the overall resistome (i.e., the entirety of genetic elements conferring resistance in an environment) and increasing the risk of ARG dissemination to human pathogens (Baker-Austin et al., 2006; Sundin and Bender, 1996). Wastewater treatment plants (WWTPs) and agricultural waste have been documented to contain excessive selective pressures, and thus have been extensively researched as a source and reservoir for ARGs (Allen et al., 2010; Witte, 2000; Zhao et al., 2019). Urban stormwater runoff is also a source of selective pressures and ARGs into the environment; however, stormwater has not been as comprehensively researched as WWTPs and the agricultural sector in regard to ARGs (Burch et al., 2022). Identified sources of ARGs in stormwater include fecal contamination from combined sewer overflows, illicit discharges of wastewater, and sanitary sewer leaks (Hamilton et al., 2020). Moreover, stormwater can entrain ARGs from soils, sediments, and pet waste as it travels over impervious surfaces and into urban streams (Almakki et al., 2019). In addition, stormwater can be a vector for selective pressures, particularly nutrients, pesticides, and metals. The transport of these contaminants can have a detrimental impact on downstream water quality (Feraud and Holden, 2021; Hamilton et al., 2020).

Stormwater has been a recent source of increased research for the presence of antibiotic resistance due to the co-occurrence of ARGs and selecting anthropogenic contaminants (Hamilton et al., 2020). Research has confirmed an abundant amount of ARGs in stormwater and elucidated that stormwater can transport these resistance elements into downstream environments (e.g., rivers, lakes, reservoirs) (Garner et al., 2017; Lee et al., 2020; O'Malley et al., 2023; Zhang et al., 2016) To mitigate the impact of stormwater on downstream water bodies, GSI has been installed to improve the quantity and quality of urban runoff (Fowdar et al., 2022; McFarland et al., 2019). Moreover, GSI presents the opportunity to treat stormwater where it falls, minimizing the flow of antibiotic resistance elements and other contaminants to a central location (O'Malley et al., 2022b). Since there is evidence that stormwater is a vector for the transport of resistance elements, it is likely that ARGs are transported to GSI and are potentially accumulating in the soils.

2.2. Treatment processes

Antibiotic resistance is considered ubiquitous in the environment. Therefore, soils will still contain ARGs regardless of the amount of urban stormwater input (Finley et al., 2013). However, stormwater runoff can transport a diverse and abundant composition of ARGs into GSI, altering the resistome of GSI soils from the baseline community. Elevated concentrations of the *sul*1 ARG, a gene that confers resistance to sulfonamide antibiotics, have been reported in GSI bioswale and bioretention systems in comparison to native soils (Hung et al., 2022). In Fig. 2, the relative concentrations of ARGs quantified in various soil environments are presented. The abundance of ARGs in GSI is greater than those found in native soils and are not statistically different ($p > 0.05$, Student *t*-test) from those of other soils described besides the fruit treatment amendment. GSI systems accumulate ARGs from stormwater primarily by adsorption and filtration mechanisms. Moreover, the accumulation in soils can cause HGT for the development of more resistant bacteria (Sorinolu et al., 2021).

In a lab-scale study, bioretention cells were shown to have the ability to remove ARGs from stormwater up to a 5-log removal efficiency (Zuo et al., 2022b). The optimized conditions for this removal were an 8:2 sand to soil ratio, a hydraulic loading rate of 0.044 $cm^3\ cm^{-2}\ min^{-1}$, and a 150-mm submerged area depth (Zuo et al., 2022b). Moreover, the ARGs were revealed to be primarily removed in the topsoil layer (0–5 cm) by adsorption. A more intensive field-scale study corroborated these findings and observed that a biofilter was able to reduce the concentration of the ARGs *sul*1 and *erm*B in stormwater by 0.9 and 2.5-log units, respectively (Rugh et al., 2022). The results of these studies suggest GSI systems can be engineered to remove and accumulate ARGs in the top layer of soil via adsorption (Rugh et al., 2022; Zuo et al., 2022b) and straining (Li et al., 2021), however, more research is needed to determine how different soil properties and hydrologic conditions impact ARG adsorption over time (Hung et al., 2022). Research on other soil environments demonstrates soil texture plays a critical role in ARG adsorption. The accumulation of ARGs in irrigated soils was most influenced by the clay content of the soil; one gram of clay particles was found to absorb up to 200 mg of extracellular DNA (eDNA), DNA located outside of cell membranes (Gardner and Gunsch, 2017; Seyoum et al., 2021). ARGs have an affinity to bind to soil particles, thus ARGs can also accumulate in GSI systems by filtration of soil particles from urban runoff. Analysis of particle size distribution found ARGs predominantly absorb to particles <75 μm on account of strong adsorption capacity (Zuo et al., 2022c). Therefore, it is evident that GSI can be designed to enhance ARG retention from stormwater. However, there is a risk of ARG propagation when diverse ARGs are accumulated together.

A potential consequence of GSI removing ARGs from stormwater is

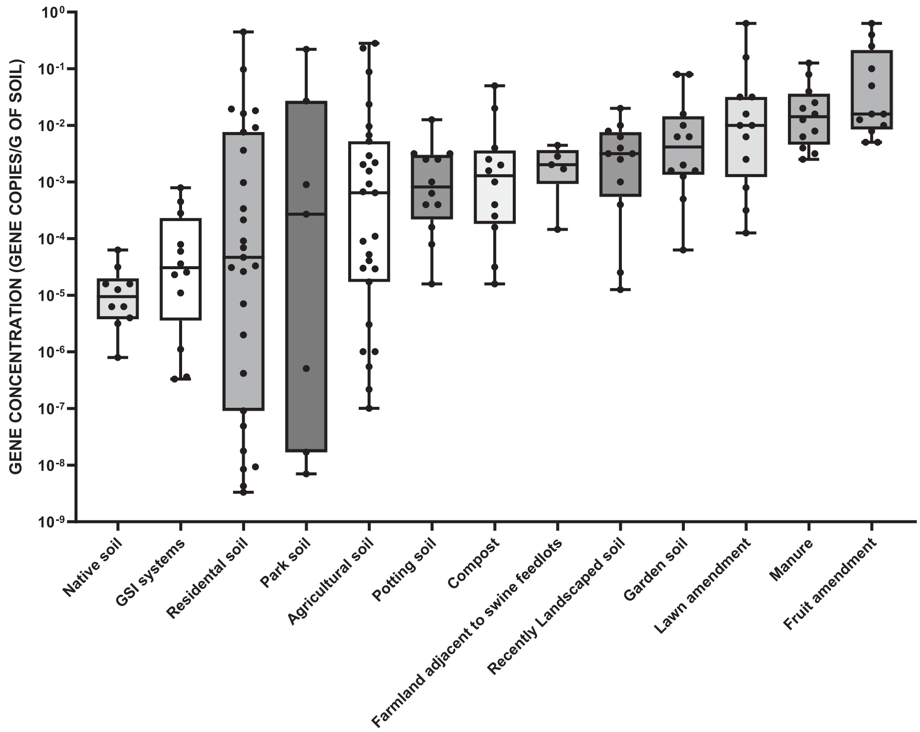

Fig. 2. Relative concentrations of ARGs quantified in various soil environment categories, including native soil [USA, CA] (Cira et al., 2021), GSI [USA, CA] (Hung et al., 2022), residential soil [Australia] (Knapp et al., 2017), park soils [USA, CA] (Echeverria-Palencia et al., 2017), agricultural soil [China] (Sun et al., 2020), potting soil [USA, CA] (Cira et al., 2021), compost [USA, CA] (Cira et al., 2021), farmland adjacent to swine feedlot [China] (Wu et al., 2010), recently landscaped soil [USA, CA] (Cira et al., 2021), garden soil [USA, CA] (Cira et al., 2021), lawn amendment [USA, CA] (Cira et al., 2021), manure [USA, CA] (Cira et al., 2021), and fruit amendment treatment [USA, CA] (Cira et al., 2021). An ordinary one-way ANOVA with Tukey's posthoc test was conducted to determine statistically significant differences ($p < 0.05$) between the GSI data and all other soil environments.

the accumulation potential of a high abundance of ARGs in the soils, with the possibility of gene transfer between indigenous and exogenous soil bacterial communities. HGT is the mechanism by which bacteria can acquire ARGs. Three mechanisms of HGT have been identified: (1) conjugation, (2) transduction, and (3) transformation (Levy, 1989; Von Wintersdorff et al., 2016). Conjugation is gene transfer by cell-to-cell connection, transduction is transfer facilitated by bacteriophages, and transformation is the uptake and integration of eDNA from the environment (Thomas and Nielsen, 2005). HGT can have an impact on the evolution of microbial communities including pathogenic bacteria, via ARGs, virulence factors or other diverse biological functions which can be encoded on horizontally transferred genes (Juhas, 2015; Lopatkin et al., 2016). HGT can also be triggered when stress is placed on a bacterial cell; in the presence of antibiotic pollution the rate of HGT has been found to increase (Jutkina et al., 2018). Heavy metals have also been found to dramatically increase the rate of HGT (Yang et al., 2017; Zhang et al., 2018). GSI has not been specifically evaluated for its ability to exert selective pressures and increase the rate of gene acquisition. However, HGT is likely occurring in GSI soils as heavy metals are abundant in stormwater runoff and have been found to accumulate in GSI soils (Hung et al., 2022).

The long-term fate of ARGs in GSI soils has yet to be investigated, but research of other soil-based environments has indicated the fate of ARGs can vary dramatically. In general, microbial communities can be highly dependent on environmental factors such as sunlight photolysis/inactivation, nutrient/carbon source deficiency, contaminant (e.g., metal) stress, temperature, pH, and oxygen. Therefore, it can be assumed that the fate of ARGs in GSI will be unique to the individual system. Moreover, as GSI systems are constructed to infiltrate large volumes of runoff, an additional fate of ARGs could be they are flushed out of the systems. ARGs in a soil column experiment following a simulated rainfall event responded differently in their vertical transport and distribution; some ARGs remained concentrated in the topsoil while others were found to migrate into the bottom layers of the column (Joy et al., 2013). There are also additional factors that can increase the rate of ARG desorption in GSI including an increase in the volume of stormwater relative to the soil volume, an increase in stormwater temperature, and decrease in pH (Zuo et al., 2022a). As such, a likely fate of ARGs in GSI is desorption and vertical transport.

2.3. Design consideration

Maintaining a healthy microbial community is essential for GSI function (Gill et al., 2017, 2020). Functional genes specific to carbon sequestration, nitrogen cycling, and contaminant degradation have been reported in GSI systems, and in comparison to non-engineered soils, GSI contain a compositionally distinct and more diverse bacterial community (Gill et al., 2017). However, GSI design can impact microbial diversity in GSI systems, limiting or enhancing the metabolic functionality of the community (Gill et al., 2020; Lundholm, 2015). For instance, higher microbial diversity and activity has been found in GSI with a higher percentage of silt and clay particles in comparison to sandy soils (Deeb et al., 2018; Zhang et al., 2007). Design features can also impact the response of the microbial community to perturbations and influxes of foreign chemical and biological contaminants. For example, smaller systems as well as systems with a larger drainage area can be more sensitive to external influences. It has been observed that the size of the GSI system is positively correlated with microbial biomass, carbon and nitrogen content, and microbial respiration (Deeb et al., 2018; Joyner et al., 2019; Li et al., 2021; Lundholm, 2015). Moreover, high microbial diversity can be a barrier to the spread of antibiotic resistance (Chen et al., 2019). In a soil environment amended with manure containing ARGs, the diversity of the indigenous microbial community directly affected the ARG abundance, with low diversity allowing for the invasion and dissemination of ARGs from the manure (Chen et al., 2019). To manage ARGs in GSI, promoting microbial diversity could assist in limiting the development of resistant bacteria. Other design considerations to mitigate the downstream transport of ARGs from GSI can include using clay-based media that has a high adsorption capacity to remove ARGs from stormwater. Inclusively, remediation actions targeting the top layer of GSI could potentially remove the majority of ARGs deposited and limit vertical and downstream migration of ARGs into connected environments.

To narrow down sites considered for maintenance and mitigation efforts, GSI with excessive selecting agents (e.g., metals), significant anthropogenic contaminant source inputs, and GSI with connections to greater human activity and health risks should be considered. Considering these site characteristics will enable identification of probable ARG hotspots without technical and expensive ARG quantification methods (i.e., qPCR) and resistomes characterization (i.e., metagenomic sequencing).

Media and amendments have been investigated for the management of ARGs in soil environments. Biochar has been explored extensively as an amendment in agricultural fields. Biochar has been found to adsorb antibiotics and heavy metals, thus reducing selective pressures on bacterial communities for the transfer of ARGs (Cui et al., 2018). Bamboo biochar was reported to reduce ARG abundances in soil by 44 %, and limit the accumulation of ARGs in plant leaves and roots (Duan et al., 2017). However, biochar did not reduce the concentration of the mobile genetic element *intI*1 (Duan et al., 2017). Biochar, in addition to reducing the concentration of ARGs in the bulk soil, can inhibit HGT of ARGs and limit the vertical transport of ARGs in soil (Fang et al., 2022; Qiu et al., 2021). Transformation of ARGs was reduced by up to 90 % with 8 mg mL^{-1} of the 700 °C rice straw biochar (Fang et al., 2022). Moreover, the reduction in the vertical transport of ARGs was found to extend to both intracellular ARGs and extracellular ARGs but efficiency varied by gene (Qiu et al., 2021). When the application of biochar was examined over time the reduction of ARG concentrations was maintained for 30-days (Cui et al., 2018). At day 60, abundances of ARGs were significantly higher than the control field with no biochar added (Cui et al., 2018). As a result, biochar presents promising results for the management of ARGs in soil environments, however, further research is needed to understand the long-term efficiency. To overcome the limitations of biochar additives, co-application of biochar with other soil amendments has been explored. Biochar with polyvalent phage therapy, struvite, and pyroligneous acid has been reported (Wang et al., 2022; Zheng et al., 2021b). Such applications individually and in combination with biochar also present encouraging results for the mitigation of ARGs.

2.4. Summary

The public health crisis of antibiotic resistance is fueled by the overuse and misuse of antibiotics in humans and animals, and this has led to a significant increase in the deaths and hospitalizations due to antibiotic resistant infections. Management of this crisis will require cross disciplinary actions as antibiotic resistance expands beyond the clinic and extends into different environmental compartments. The identification of increased concentrations of ARGs in stormwater presents the opportunity to use stormwater infrastructure, such as GSI, to mitigate the dissemination of ARGs in the environment (O'Malley et al., 2022a). GSI can remove ARGs from stormwater via filtration and adsorption and it has been exemplified that a five-log reduction is achievable under specific hydraulic and soil conditions (Zuo et al., 2022b). Additional design factors such as system size, plants, and soil texture could be manipulated to enhance the removal of ARGs (Zuo et al., 2022b). However, there is very limited research investigating these design factors in the field and additional design considerations can be made to control antibiotic resistance in GSI. Other potential research directions could include comparing GSI (e.g., bioretention, permeable pavements, rain gardens) elucidating how different design factors of such systems influence soil microbial community and resistomes. A further necessary consideration is the potential for the accumulation of ARGs in GSI soils that propagate resistance. The propagation of ARGs in GSI is likely due to selective agent, notably heavy metals, which can accumulate in GSI along with ARGs. Further research should explore this possibility and risks associated with using GSI to manage this public health crisis.

3. Microplastics

3.1. Background

Plastic waste is a legacy contaminant that has been an environmental concern for several decades and its presence in the environment is continuing to grow. For example, the US is one of the largest contributors of plastic waste in the world (Law et al., 2020; Sedlak, 2017), with the annual amount entering coastal environments increasing more than five times between 2010 and 2016 (Law et al., 2020). The increased use of plastics is an emerging concern due to the transformation of larger plastic waste into microplastics that are created via mechanical, biological, and chemical weathering processes. As plastic waste breaks down forming microplastics, the particles and chemicals become more biologically available and digestible for humans and organisms, thereby presenting a significant risk to human and ecological health (Corcoran, 2022). Microplastics were first classified as an emerging environmental contaminant of concern in 2007, and five years later microbeads were found in wastewater receiving surface waters; prompting elevated health concerns and water treatment design assessments (Sedlak, 2017). Microplastics are defined as particles 1 μm - 5 mm in size created for human uses (e.g., textile manufacturing, packaging, cosmetic creation, etc.) and can be categorized based on shape, chemical composition, and hazard potential (Danopoulos et al., 2020; Miller et al., 2021; Smyth et al., 2021). Common microplastics found in stormwater include rubbery particles, fibers, fiber bundles, films, foams, fragments, gels, glassy fragments, spheres, and suds (Cherniak et al., 2022; Pramanik et al., 2020; Rochman et al., 2022).

People are largely exposed to microplastics via breathing, drinking, and eating. Drinking water is a point of microplastic exposure due to stormwater effluent acting as a vector of microplastics from land surfaces to drinking water sources. Microplastic exposure through tap water can be great, with the highest daily consumption from tap drinking water ranging from 1260 particles in European adults to 40 particles in North American adults (Danopoulos et al., 2020). This is concerning as the daily World Health Organization recommendations for tap water intake is 4000 microplastic particles annually (Cox et al., 2019). The higher microplastic consumption from tap water in Europe are believed to coincide with less developed plastic waste management practices increasing more plastic waste leaching into surrounding drinking water sources (Danopoulos et al., 2020). However, even these values may underestimate the high range of microplastic intake through drinking water because it does not include those without treated drinking water access (Danopoulos et al., 2020).

This exposure to microplastics can cause serious health effects to humans. Microplastics (<1.5 μm in size) can accumulate in the body if consumed regularly and infiltrate past digestive tract tissues and into vital organs (Danopoulos et al., 2020). When microplastics are broken down in the gut, compounds, additives and adsorbed toxins can cause oxidative stress, cancer, tissue damage, chronic inflammation, airway diseases and genotoxicity (Poma et al., 2019; Prata, 2018; Schirinzi et al., 2017; Wang et al., 2018; Wright and Kelly, 2017). Other emerging contaminants that may be associated with or adsorbed to microplastics include endocrine disruptors, phthalates, plasticizers, per-and polyfluoroalkyl substances (PFAS) and tire wear compounds (An et al., 2020; Kontrick, 2018; Scott et al., 2021; Ye et al., 2020). Although knowledge on the abundance and risks of microplastics is growing, there is still limited data on microplastics' short and long-term health effects

(Thompson, 2015). To date, microplastics' health risks are thought to be primarily dependent on consumption rate, toxicity, shape, size, solubility and structure (Schirinzi et al., 2017; Schmidt et al., 2013; Wang et al., 2018).

Microplastics also pose risks to aquatic ecology as they are ubiquitous in aquatic environments and can bioaccumulate up food chains (Elizalde-Velázquez and Gómez-Oliván, 2021). Documented ecological effects on aquatic organisms include neurotoxicity, embryotoxicity, and behavioral changes (Chen et al., 2017; Elizalde-Velázquez and Gómez-Oliván, 2021; Yin et al., 2018). Specific examples include lazy swimming and feeding behavior of fish exposed to microplastics, and increased neurotransmitter stimulation leading to paralysis and even death (Chen et al., 2017; Elizalde-Velázquez and Gómez-Oliván, 2021). Feeding behaviors makes some fish more prone to microplastic bioaccumulation, with those that feed on a wide range of prey more susceptible to consuming microplastics compared to fish that selectively feed (Elizalde-Velázquez and Gómez-Oliván, 2021; Renzi et al., 2019). Despite these examples, the breadth of knowledge regarding factors which influence the transport and breakdown of microplastics into and within aquatic environments is limited (Elizalde-Velázquez and Gómez-Oliván, 2021).

Stormwater acts as a vector of microplastics into aquatic environments through their mobilization from land surfaces during runoff events. Microplastics accumulate on land surfaces via degradation of tires, road dust, artificial turf, plastic garbage and packaging materials, among other pathways (Pramanik et al., 2020; Sutton, 2019). Personal items can also directly leach microplastics including clothing, yard decor and dryer lint (Sutton, 2019). Nearby land applications with mulch, fertilizers and pesticides can also introduce microplastics to stormwater runoff (Koutnik et al., 2022b). If these sources are exposed on urban surfaces, they can be mobilized in urban stormwater runoff and reach downstream water bodies.

Because GSI captures and treats direct runoff, these systems have been shown to have greater concentrations compared to stormwater outfalls (Boni et al., 2022). Therefore, the source, transport, and treatment of microplastics in GSI are important to consider. Beyond direct runoff, there may be other sources of microplastics in GSI, such as GSI filter linings that can leach microplastics (Mbachu et al., 2022). Atmospheric deposition can further introduce microplastics onto GSI itself, and has yet to be definitively compared to microplastics' concentrations introduced to GSI via stormwater runoff, although the amount may be equally significant (Koutnik et al., 2022b). Regardless of the source, it is important to understand the mechanisms that drive the transport and removal of microplastic in GSI, and how the accumulation of microplastics in GSI may influence GSI function.

3.2. Treatment processes

GSI mechanisms for removing microplastics include filtration, settling, and biotransformation. Most GSI are designed to capture and infiltrate stormwater runoff into the ground; however, filtration of microplastics within the GSI media may prevent significant infiltration of the particles. For example, microplastics in a bioretention were found to decrease exponentially below the first 5 cm of GSI surfaces (Koutnik et al., 2022b), and the first 3 cm of biofilters have been shown to remove (90 %) of microplastics from stormwater influent (Koutnik et al., 2022a), demonstrating limited groundwater leaching potential. Due to filtration, urban bioretention basins have been observed to have microplastic concentrations as great as 704 particles/L at varying soil depths and at the inlet and outlet, where rubbery tire particles and fibers compose the greatest percentage of microplastics (Gilbreath et al., 2019; Smyth et al., 2021; Werbowski et al., 2021). Plastics slightly larger than microplastics termed mesoplastics (5–10 mm in size) have also been observed to dramatically decrease between a bioretention inlet and outlet due to filtration of the particles, indicating that particle size may play a role in the filtration capacity of a system (Mbachu et al., 2022). While filtration removes these contaminants from downstream water bodies, the accumulation of mesoplastics and microplastics may impact GSI function through clogging of the media pores (Mbachu et al., 2022).

Settling is also a possible removal mechanism as many GSI practices have forebays or design components in which ponding occurs; however, the density and buoyancy of most microplastics may prevent their settling (Koutnik et al., 2022b). In order for microplastics to settle, the particles likely need to be heavier than water or >80 μm in size (Skumlien Furuseth and Støhle Rødland, 2020). This can also be observed in comparative monitoring studies between those that primarily rely on filtration versus settling. Practices that rely on filtration and infiltration have demonstrated significant removal of microplastics with bioretention systems have shown to remove between (84 %–90 %) of microplastics from stormwater influent (Gilbreath et al., 2019; Smyth et al., 2021; Stang et al., 2022) and rain gardens demonstrated 99 % removal of microplastics from stormwater influent (Werbowski et al., 2021). However, constructed wetlands, which rely heavily on settling of contaminants, have been shown to remove only 55 % of microplastics, which may be due to the reliance on particle settling or limited filtration by design (Stang et al., 2022).

Biotransformation of compounds leached from microplastics may also provide additional removal of contaminants of concern derived from microplastics. Microplastics can leach trace organic compounds (e.g., polychlorinated biphenyls [PCBs], polycyclic aromatic hydrocarbons [PAHs], and PFAS) into stormwater (Meng et al., 2023b; Santana-Viera et al., 2021). The removal of trace organic compounds by GSI may be performed with bioremediation techniques (e.g., biochemical transformation) with vegetation, fungi or soil microbes (Saifur and Gardner, 2021), however, the potential for microplastic chemical compounds to be adsorbed largely depends on pH and particle surface charge (McDougall et al., 2022).

The study of microplastic removal in GSI is limited; therefore, there may be other applications that are more mature for which specific approaches to removal of microplastics can be better understood. One of those is water treatment plant design, where the removal of microplastic has been extensively studied. Table 1 illustrates removal processes and technologies which could have the potential to be adapted to GSI based on literature. Of the removal processes, infiltration and filtration demonstrate the greatest microplastic removal potential for GSI (e.g., dual sand microfiltration, rapid sand filtration, microfiber catchers, sand trapping, super-wettable anticorrosive surfaces, and micro/nanomotors) (Liu et al., 2021). Soil amendments could also facilitate further microplastic removal efficiency by GSI (e.g., adding granular activated carbon, inorganic-organic silica gels, anthracite, magnetic carbon nanotubes, super-wettable anticorrosive surfaces, micro/nanomotors, mealworms, or seaweed/seagrasses).

These treatment processes may also be impacted by the physical characteristics of the microplastics, or the specific environmental conditions of the GSI. For example, microplastic removal in GSI has been shown to have efficiency ranges dependent upon microplastic physical characteristics (e.g., shape, size, polymer type) in stormwater (Liu et al., 2021). In terms of environmental conditions, temperature fluctuations may have an impact on mobilization as freeze-thaw cycles could cause microplastics to mobilize deeper into GSI compared to dry-wet cycles (Koutnik et al., 2022a). In addition, it is unclear what impact antecedent dry days may have, as some studies have found no correlation between antecedent dry days and microplastics' concentrations in a bioretention basin (Boni et al., 2022), while others have found a positive correlation between dry days and concentrations in GSI (Smyth et al., 2021). Similarly, rainfall intensity has been shown to have a negative relationship with microplastic accumulation, suggesting dilution due to greater rainfall volumes (Boni et al., 2022), as well as a positive relationship perhaps due to greater mobilization (Smyth et al., 2021). Therefore, there is an opportunity for improving our understanding surrounding the mechanisms that drive mobilization and transport of microplastic in urban stormwater runoff.

Table 1
Microplastic removal processes, treatment materials/methods and their efficiency range applicable for GSI application.

Removal process	Treatment material or method	Microplastics removal efficiency	Source
Infiltration	Anthracite and Sand	29–44 %	(Wang et al., 2020a)
	Biochar (grain size from 5 mm to 50 mm)	93 %	(Pankkonen, 2020)
	Bioretention Depressions (sand, silt and clay covered with mulch/ vegetation)	84 %	(Smyth et al., 2021; Stang et al., 2022)
	Granular Activated Carbon	57–61 %	(Wang et al., 2020a)
	Sand (grain size from 0.8 mm to 1.2 mm)	96 %	(Pankkonen, 2020)
	Straining with Coarse Sand	99 %	(Valenca et al., 2020)
Filtration	Aluminosilicate Filters	>96 %	(M. Shen et al., 2021)
	Biochar Filters	95 %	(Wang et al., 2020b)
	Biofilters	79 %	(Liu et al., 2021)
	Cloth Disc Filters (pore size 10 μm)	40 %	(Talvitie et al., 2017)
	Cloth Disc Filters (pore size 20 μm)	99 %	(Talvitie et al., 2017)
	Leachate Ultrafiltration Membrane	75 %	(Zhang et al., 2021)
	Membrane Disc Filters	79 %	(Hidayaturrahman and Lee, 2019)
	Polyester Mesh Disc Filters (pore size 18 μm)	~90 %	(Simon et al., 2019)
	Superhydrophobic 304 Stainless Steel Mesh	99 %	(Rius-Ayra et al., 2021)
Sedimentation	Sedimentation as a part of full-scale water treatment	52 %	(Cherniak et al., 2022)
	Treatment Train with Gross Pollutant Traps	70 % - Virtually All	(Lange et al., 2021)
Manufactured amendment contact	Aerogels	83–97 %	(Rius-Ayra and Llorca-Isern, 2021)
	Anticorrosion Non-Fluorinated Superhydrophobic Aluminum or Coating	99–100 %	(Rius-Ayra et al., 2021; Rius-Ayra and Llorca-Isern, 2021; Ye et al., 2021)
	Iron-Oxide Nanoparticles	90–100 %	(Zeng et al., 2022)
	Magnetic Carbon Nanotubes	80 %	(Martin et al., 2022)
Natural amendment contact	Biodegradation of MPs with Mealworms	81–90 % (Polylactic acid conversion rate)	(Yang et al., 2015)
	Phytoremediation with Seagrasses/ Seaweeds	Limited Research	(Goss et al., 2018; Masiá et al., 2020)

3.3. Design considerations

For a typical bioretention system, designs for microplastic removal should consider the soil characteristics of the media, the expected physical characteristics of incoming microplastic pollution, and how these impact specific removal mechanisms. In regard to soil, replacing media with sand can increase pore size and hydraulic conductivity (Tirpak et al., 2021) and decrease the clogging potential of the soil with microplastics. This alteration can promote smaller sized microplastics infiltrating deeper into GSI and prevent settling on the surface that may lead to washout and resuspension (Tirpak et al., 2021). Despite sand promoting smaller sized microplastic infiltration, it can also break down plastic microfibers and promote plastic leaching from GSI due to greater particle mobility through media (Cohen and Radian, 2022). GSI with materials that promote infiltration without increasing latent microplastic concentrations at deeper depths, will foster long-term benefits (Koutnik et al., 2022b). Other conditions of the soil (e.g., root structure, worm burrowing activity, age of media) also affect the hydraulics and filtration of the system, especially between the first 3 cm and 7.5 cm of media where most microplastics are located (Koutnik et al., 2022a). In addition, if microplastics accumulate in the top layers of the soil, the roots of vegetation may be affected by the leaching of chemicals affecting biochemical processes (Koutnik et al., 2022b).

Regular and routine maintenance of soil media (e.g., replacing the surface media every 7 years) has been shown to improve the removal of microplastics and other emerging contaminants (such as PCBs), as well as increase the long-term microplastic removal effectiveness by GSI (Gilbreath et al., 2019; Koutnik et al., 2022a). Promoting better infiltration of microplastics and removal efficiency with regular soil replacement reduces the need for more frequent labor to reestablish old media and amend GSI with more expensive solutions over time (e.g., end of pipe filtration construction or additional soil amendments). However, microplastic accumulation in GSI media should be the primary removal objective as greater infiltration can lead to microfibers leaching in GSI effluent (Cohen and Radian, 2022). Treating soil media that has accumulated plastics can be conducted with pyrolysis or biochemical methods (i.e., phytoremediation, microbial degradation or photodegradation) although the full potential of these methods is not yet fully known (Zhao and Zhang, 2023).

GSI designs for microplastic mitigation should also consider how their unique physical properties influence their hydraulic transport through GSI. Size is an important consideration as microplastics pass through pollutant traps while larger sized mesoplastics are retained and accumulate (Mbachu et al., 2022). This accumulation of mesoplastics can affect long-term GSI function (e.g., clogging) and eventually leach microplastics. If the leaching of microplastics becomes a concern, evaluating possibilities of amending GSI with easily replaceable media material may be an additional consideration. In addition, practices that rely on settling are not ideal for removing fibrous microplastics and other low-density microplastics due to particle buoyancy affecting washout tendencies (Stang et al., 2022). Microplastic settling can cause a variety of risks if they are not properly managed as settled microplastics can become resuspended during "first flush" events, affecting water quality (Koutnik et al., 2022b). Adsorbed microplastics could even resuspend in the wind and affect air quality (Koutnik et al., 2022b).

Furthermore, designs to remove microplastics should consider the extent to which weathering, physicochemical characteristics, and other environmental characteristics have on microplastics in GSI. For example, environmental exposure to UV radiation, biodegradation, chemical oxidation, and physical abrasion could lead to changes in physiochemical properties that affect the sorption behavior or microplastics (Jahnke et al., 2017; Liu et al., 2020) and increase particle mobility (Koutnik et al., 2022b). Weathering and UV radiation can lead to increased surface area and oxygen containing groups that increase adsorption of other pollutants such as metals (Wang et al., 2020a). Other environmental factors may also impact the sorption capacity of microplastics, such as the presence of natural organic matter that may compete for sorption sites (Shen et al., 2018), or salinity from road salt runoff that could decrease the sorption of microplastics (Liu et al., 2019). In addition, weathering of microplastics retained in GSI media can decrease their hydrophobic properties and alter their surface charge (Liu et al., 2020), leading to an increase in mobility through GSI media during intermittent flows (Gao et al., 2021).

In addition to the GSI itself, there are other design considerations for the catchments that drain to GSI that could help with microplastic removal. For example, design of a curb and gutter system that contains pre-treatment steps such as straining, filtration or reduced flow mechanisms (e.g., baffles or weirs), could promote further settling and removal of microplastics within GSI (Steiner et al., 2020). These design considerations can potentially improve microplastic mitigation by GSI and reduce microplastic transport to downstream water bodies, thereby providing further protections to human and environmental health.

3.4. Summary

The use and disposal of plastics by humans has accelerated microplastic accumulation in the environment, much of which gets transported to water bodies through stormwater runoff. GSI is a stormwater treatment technology that has the potential to remove microplastic contaminants through infiltration, filtration, accumulation, and biotransformation. While the study of microplastics in GSI is in its infancy, some microplastic mitigation technologies from more mature domains such as wastewater treatment may be scaled down or applied to GSI. A growing knowledge of the health effects of microplastics and their accelerated presence in the environment highlights the critical need for mitigation technologies such as GSI. To that end, future research focused on defining microplastic fate and transport across environmental conditions and in interaction with other stormwater contaminants is crucial to design stormwater infrastructure to mitigate microplastics alongside other stormwater contaminants.

4. Tire wear particles

4.1. Background

Tire wear particles originate from wear of vehicle tires on pavements and are estimated to be the most dominant source of synthetic polymer-based material in the environment (Baensch-Baltruschat et al., 2020) and a major source of metals (Goonetilleke et al., 2017). They are also a rich source of toxic compounds including acetanilide, bicyclic amines, methoxymethylmelamines, and N,N′-disubstituted phenylenediamine tire (Johannessen et al., 2021; Rauert et al., 2020). They are ubiquitous in the environment; in Europe it is estimated that about 1.3 million metric tons of tire wear are generated on roads per year (Wagner et al., 2018). These particles are transported to urban surface waters through stormwater runoff where they can have negative consequences for aquatic species. Despite their extent in the environment and potential impact on aquatic organisms, their effects on aquatic and human health has only recently been explored and is an emerging contaminant of concern (Knight et al., 2020).

Tire wear particles in urban waters pose ecotoxicological threats to aquatic species and human health through their physical and chemical effects (e.g., Fig. 3). Ingestion of tire wear particles by aquatic species can cause physical effects such as a reduction in food intake due to the volume that tire wear particles occupy in the stomach or toxic chemical effects due to leaching within the digestive tract (Baensch-Baltruschat et al., 2020). Due to these effects, the chronic toxicity levels of tire wear particles (TWP) for several aquatic species range between 10 and 3600 TWP/L (Wagner et al., 2018). Perhaps more threatening are compounds from tire wear particles that can have acutely toxic effects on aquatic biota. For example, tire wear particles have been shown to result in the mortality of adult coho salmon (>50 %) due the transformation of the chemicals *N*-phenyl-N′-(1,3-dimethylbutyl)-*p*- phenylenediamine (6-PPD) quinone from tire-derived leachate (McIntyre et al., 2021; Tian et al., 2021). In terms of human health, tire wear particles may pose the most risk through inhalation (Kreider et al., 2020) as tire wear particles suspended in the air accounts for up to 11 % of PM10 air contaminants (Baensch-Baltruschat et al., 2020). They also may pose risk through their bioaccumulation up the food chain, but their impact on human health through the food chain is largely unknown (De-la-Torre, 2020; Rubio-Armendáriz et al., 2022).

Tire wear particles are derived from interactions between vehicles and pavements in the urban environment. Main determinants of tire wear particles include automobile weight, tire size, tire quantity, tire quality, road roughness, driving distance, and traffic density (Luo et al., 2021). For example, tire wear particles in gully pot sediments has been shown to range from 1 mg TWP/g in streets with the lowest traffic density to 150 mg TWP/g in streets with the highest traffic density (Mengistu et al., 2021). Urban stormwater runoff is the main vector of transport of tire wear particles to aquatic environments, and tire wear particles have been found to make up 40 %–85 % of the total microplastics within urban stormwater runoff (Järlskog et al., 2020; Werbowski et al., 2021). Tire wear particles discharged from stormwater outfalls have been shown to decrease in concentration downstream as the runoff is diluted with streamflow (Knight et al., 2020); however, even in downstream estuaries, where dilution may occur, tire wear particles were found to make up 17 % of the total microplastics (Leads and Weinstein, 2019).

GSI is a growing practice to treat roadside runoff and is therefore important to consider in context of tire wear particle mitigation. Since GSI is designed to capture and treat stormwater runoff at a site-level, the concentrations of tire wear particles in GSI may be higher than other stormwater infrastructure that treat or convey runoff at larger spatial scales. In addition, the main mass fraction of tire wear in runoff have been found to be lower (<50 μm) than those in roadside dust (>100 μm) (Klöckner et al., 2020). Others have found tens to several hundred times more mass fraction for small tire wear particles (≥20 μm) than larger particles (≥100 μm) in stormwater runoff (Järlskog et al., 2020), likely due to their ability to be suspended during runoff events. The presence of higher concentrations and lower mass fractions of tire wear could have implications for tire wear particle mitigation.

4.2. Treatment processes

While studies on tire wear particles and compounds in GSI are limited, there are several mechanisms that could contribute to the physical removal of tire wear particles or biotransformation of tire wear compounds in GSI. Like other particulate contaminants, tire wear particles can be physically removed through filtration in GSI media and infiltration into the subsurface. Beyond physical removal of tire wear

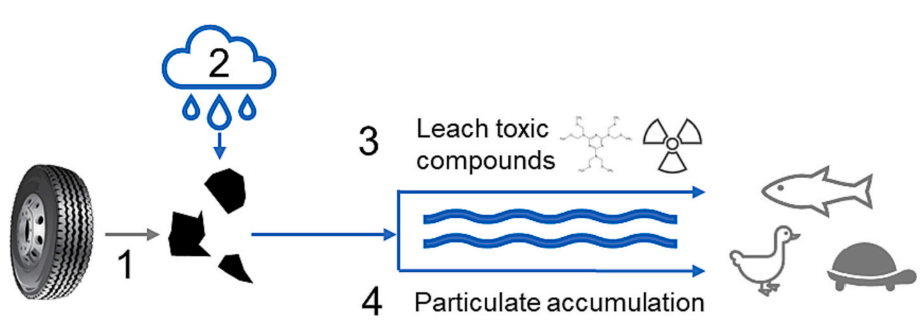

Fig. 3. Tire wear particles originate from tire wear on pavements (1) that are then washed off the pavement surfaces during rainfall-runoff events (2). Tire wear particles are a threat to aquatic species through the leaching of toxic compounds (3) or particulate accumulation in the gastrointestinal tract (4).

particles, there are other compounds of concern for which additional removal processes, such as biotransformation, could mitigate the presence of toxic compounds. The discussion below highlights emerging research on these mechanisms for removing tire wear particles in GSI.

Filtration and sedimentation are the main mechanisms for physically removing particulate contaminants in GSI. However, like other microplastics, tire wear particles have a density close to the density of water; therefore, sedimentation is unlikely to lead to their removal in urban stormwater practices that are designed to have short hydraulic residence times. For example, in a study of a green infrastructure treatment train it was found that a bioretention and non-vegetated sand filter both removed >70 % of tire wear particles, while a gross pollutant trap designed to settle particles resulted in non-significant removal (Lange et al., 2021). Similarly, it has been observed that tire wear particles are lower in the outlet than the inlet of bioretention due to physical filtration of the particles in bioretention media (Smyth et al., 2021).

Toxic compounds of concern in tire wear particles can also be removed through biotransformation. While biotransformation for removing dissolved organic nitrogen and metals in GSI is well researched, there are limited studies on biotransformation to remove other compounds from tire wear particles that are toxic to aquatic species. One example is that of white rot fungus, which has been shown to remove the tire wear compound concentrations acetanilide and hexamethoxymethylmelamine (HMMM) by 82 % and 70 %, respectively (Wiener and Lefevre, 2022). This finding suggests that GSI such as bioretention could be augmented with fungi in their media to enhance removal of tire wear compounds within the system. Other leachates of concern from tire wear particles include zinc, lead, cadmmium, and other toxic metals, as well as organic compounds that cause toxicity to aquatic organisms (Wik et al., 2009). One treatment process for toxic metals could include volatilization if they form a volatile metal-organic compound with microbial reactions (Clary et al., 2020). Others may be removed through bioaccumulation through plant uptake that is dependent upon plant density and type and hydraulic residence time (Johnson et al., 2003; Sun and Davis, 2007).

As tire wear particles persist in GSI, aging may change their properties through microbial degradation or mechanical stress. However, because the main components of tire wear particles are rubber (synthetic and natural) and carbon, it is likely they degrade slowly and persist within GSI. This persistence may also lead to GSI as a source of tire wear leachate where compounds from tire wear particles are released into the aqueous phase. Tire wear particles have been shown to have a high desorption capacity for heavy metal ions, which could be a threat to downstream aquatic organisms (Fan et al., 2021). A mechanistic understanding of these processes for an individual GSI practice is difficult to define as leaching likely depends upon several factors including tire wear particle chemical makeup varying among tire models, hydraulic and hydrochemical properties of stormwater runoff, and physiochemical properties of GSI media.

Furthermore, the persistence of tire wear particles in GSI could have adverse effects on the soil microbiota, fauna, and plants themselves. For example, low concentrations of tire wear particles negatively affect plant growth, likely due to metals such as zinc leaching from tire wear particles (Ding et al., 2022). In addition, tire wear compounds can alter important biogeochemical soil parameters such as bulk density and soil aeration, introduce a carbon source changing resource availability, and increase the soil pH affecting decomposer activity and composition (Leifheit et al., 2022). Leachates from tire wear particles have also been shown to disrupt the mutualism between microbial and plant growth in biological systems (O'Brien et al., 2022). Therefore, an accumulation of tire wear particles within GSI may lead to adverse consequences for soil health and plants.

4.3. Design considerations

Due to filtration as the main mechanism of physical removal, designs of GSI may focus on the minimum pore size within the system prescribed a mix of bioretention media (i.e., sand, soil, and clay percentages) that must be used. If removal of tire wear particles is a priority, a focus on pore sizes that would remove anticipated sizes of tire wear particles may be important; however, this may be offset by drawdown or hydraulic requirements of the system that dictate a minimum pore size. This consideration may also impact the type of GSI that is considered for filtration of tire wear particles. For example, many permeable pavers are installed upon a mix of sand and crushed aggregate with larger pore sizes than soil and vegetation based GSI (Rasmussen et al., 2023). Therefore, permeable pavers may not be as effective at removing tire wear particles; however, to the authors' knowledge there are no existing studies on the removal of tire wear particles within permeable pavers.

Beyond physical filtration, abiotic sorption of tire wear compounds through soil amendments could provide removal of toxic contaminants of concern. This could include amendments such as biochar, that has been shown to cause effective sorption of heavy metals, which could leach from tire wear particles (Biswal et al., 2022). Furthermore, where metal leachates are a concern, the introduction of an amendment such as struvite could immobilize metals within the media (Moragaspitiya et al., 2020). However, to date there is limited research on the fundamental physio-chemical properties of tire wear particles (e.g., density, size distribution in runoff, or surface charge) that are necessary for understanding the best approaches for abiotic removal of tire wear compounds (Wagner et al., 2018). Finally, biological uptake or transformation of tire wear particles through bacteria, plants, or fungi could provide further removal. While there is emerging research on the impact of soil amendments on biological transformation (Wiener and Lefevre, 2022), transformation processes are complex and further research is necessary to elucidate the factors that drive uptake and transformation of toxic contaminants of concern derived from tire wear particles.

Additionally, there may be certain ineffective design components of GSI for removing tire wear particles. As discussed, tire wear particles have a density that is close to water, therefore contaminant mitigation measures which rely on settling of contaminants may not effectively remove tire wear particles due to the relatively short hydraulic residence time of GSI. During large runoff events, these systems could even flush out tire wear particles leading to higher concentrations downstream than would have otherwise not been observed. Therefore, structures that rely on settling (e.g., dry ponds, wet ponds, or underground detention structures) or GSI components such as settling basins, may not be effective at reducing concentrations or loads of tire wear particles in receiving waters.

While to date there are no studies on the maintenance and operational aspects of GSI with respect to tire wear particles, there are several general actions which could be considered. Maintenance considerations for tire wear particles would be like other contaminants that accumulate within soil media or within GSI vegetation. If tire wear particles accumulate within the media, clogging might occur resulting in the need to remove and replace the soil media over time. Similarly, for any of the leachates that are removed through plant uptake, GSI plants could be removed as part of an annual maintenance schedule.

4.4. Summary

Tire wear particles are an emerging stormwater contaminant of concern due to their impact on environmental and human health. Stormwater runoff is the main vector of this contaminant into the aquatic environment and as such, roadside GSI can serve as a primary treatment device for tire wear particles. Their removal is primarily influenced by filtration and infiltration; however, certain toxic compounds of concerns that may leach from tire wear particles could be removed through adsorption or biological transformation. Due to their low density, GSI design components that rely on settling may be ineffective at tire wear particle removal. However, there is a paucity of research on the mechanisms of removal of tire wear particles and their associated toxic compounds. Therefore, future research focused on GSI design parameters including filtration mechanisms and soil amendments, that could promote sorption or biological transformation, are needed. This research would provide a better understanding of how GSI can effectively serve as a first line of defense against tire wear pollution in aquatic environments.

5. Per- and polyfluoroalkyl substances (PFAS)

5.1. Background

Per- and polyfluoroalkyl substances, more commonly known as PFAS, are a class of anthropogenic chemicals that encompass over 7800 structurally different compounds (De Silva et al., 2021). The strong C—F bonds in these compounds gives rise to unique properties such as high thermal and chemical stability as well as hydrophobic and lipophobic properties (Lenka et al., 2021). Due to these extraordinary combination of properties, these compounds are being used in almost all industrial and consumer products such as in fire-fighting foams, textiles, electronics, cosmetics, pharmaceuticals, and consumer packaging, as well as in some lesser known compounds such as evaporation retardants used for soil remediations (Glüge et al., 2020). Due to the persistent nature of PFAS as a result of aforementioned properties they become 'forever chemicals' once they enter ecosystems and bioaccumulate (Chow et al., 2021; Wanninayake, 2021). PFAS were first used in products during the 1940's and their use exponentially increased due to its wide applicability; however, the adverse and toxic nature of these chemicals were only acknowledged in the early 2000's (Brennan et al., 2021) and is still not fully understood.

PFAS have been found in various concentrations in all ecosystems. Surface water (Podder et al., 2021), municipal drinking water (Domingo and Nadal, 2019), bottled water (Chow et al., 2021), oceanic air (Yamazaki et al., 2021), soils (Mahinroosta and Senevirathna, 2020), and even the food we eat (Ghisi et al., 2019) are contaminated with PFAS. A survey in Germany conducted on PFAS detection in children and adolescents during 2014 to 2017 found that 100 % of the 1109 blood samples tested positive for PFAS (Duffek et al., 2020). Furthermore, recent global long-term studies on breast milk have shown that while long-chain PFAS compounds that are being phased out of production declined in breastmilk samples from 1996 to 2009, new short-chain PFAS alternatives are increasing (Zheng et al., 2021a).

While it has been established that these short-chain compounds are toxic, the health implications of the numerous PFAS compounds are still unknown. Therefore, they have been named as a category of emergent contaminants (Wickham and Shriver, 2021). Most of the toxicological data currently available for PFAS are limited to a few compounds, mainly PFOA (perfluoro-octanoic acid) and PFOS (perfluoro-octane sulfonate) (Fenton et al., 2021), which are long-chain "legacy" compounds being phased out of products (Brennan et al., 2021). Both laboratory and community medical studies have found direct links between PFAS and human health conditions. Some of these include reduced immune response, thyroid functions, liver and kidney diseases, cancer, and adverse reproductive and developmental outcomes (Anderko and Pennea, 2020; Fenton et al., 2021; Kirk et al., 2018; Sunderland et al., 2018). The comparative health impact of newer alternative short-chain PFAS compounds are unclear, with some showing weaker associations with health impairments (Pierozan et al., 2022) and others demonstrating similar (Pelch et al., 2019) or greater toxicity (Wang et al., 2019).

Given the large human health implications of PFAS in the environment, it is important to understand their source and transport through ecosystems to reduce exposure to both humans and fauna. PFAS enter the urban environment primarily through solid-waste and wastewater management cycles. In Florida, the main sources of PFAS to the environment are through landfills, wastewater treatment plants, and aqueous film forming foams such as fire retardants (Cui et al., 2020). Furthermore, point source pollution from industrial sites, such as 3 M production facilities and textile factories, as well as institutions that use PFAS heavy products (i.e., military facilities) have resulted in highly contaminated sites (Renfrew and Pearson, 2021). Once PFAS enter an ecosystem, they integrate into soil, water, and air transport cycles due to a lack of both PFAS specific treatment and the high stability of PFAS in nature (Stoiber et al., 2020).

Within the urban environment, surfaces are contaminated with PFAS due to atmospheric deposition, leachate from solid waste, and traffic-related materials. An analysis of street sweepings in various Florida urban cities has detected up to 37 types of PFAS compounds and a maximum PFAS concentration of 41.24 ng g^{-1} (Ahmadireskety et al., 2021). In Albany, NY, field measurements of surface runoff have shown PFAS concentrations up to 81.8 ng/L (Kim and Kannan, 2007) and in Saskatoon, Canada, PFAS have been detected in surface runoff with an average concentration of 9 ng/L (Codling et al., 2020). There is evidence that this is largely driven by stormwater runoff as first flush PFAS concentrations measured in a watershed in Yokohama, Japan revealed that the contaminant concentrations are 2–3.4 times higher than average surface flow concentrations. Therefore, due to the presence of PFAS in stormwater runoff, green infrastructure may serve as a critical step in PFAS accumulation or removal, as it is designed to capture and treat direct surface runoff from urban areas.

5.2. Treatment processes

Determining the extent to which GSI can remove PFAS from the environment is important; however, to date no studies have assessed PFAS accumulation, transportation, and treatment through GSI. This is a critical gap as (1) PFAS are present in the entire water cycle, including stormwater runoff (Kurwadkar et al., 2022), and (2) GSI is growing in adoption as an initial treatment step in removing stormwater contaminants. Throughout the last two decades, many studies and reviews have focused on methods to remove PFAS from wastewater treatment systems and polluted soils, including through adsorption, chemical oxidation, biological and physical degradation, and filtration (Lenka et al., 2021; Mahinroosta and Senevirathna, 2020; Wanninayake, 2021). However, they are focused largely on highly concentrated outlets such as water treatment plants and contaminated landfills, and while some approaches may be appropriate, their applicability to concentrations present in stormwater runoff are unclear. To this end, the following section presents possible treatment methods in GSI to remove PFAS from stormwater runoff including adsorption, filtration, microbial degradation, and bioaccumulation.

Adsorption is perhaps the most economically viable PFAS capture method through soil amendments such as granular activated carbon (Mahinroosta and Senevirathna, 2020). However, PFAS compound structural variabilities cause different PFAS species to have different levels of absorptivity, making this type of removal challenging for all types of PFAS species. For example, long-chain PFAS adsorb to granular activated carbon at a greater rate than short-chain compounds (Gagliano et al., 2020). Furthermore, PFAS compounds have low dissociation constants meaning they easily dissolve in water while reducing the ability of adsorbents to capture and retain these compounds (Zhang et al., 2019). The pH of stormwater plays a crucial role in the ability of granular activated carbon to capture PFAS as well. As pH increases, the electrostatic repulsive forces increase between granular activated carbon and PFAS reducing absorptivity and increasing solubility of PFAS (Mahinroosta and Senevirathna, 2020). Therefore, granular activated carbon is effective at low pH levels; however, urban stormwater usually has a basic pH due to contaminants it picks up which adversely affects the applicability of granular activated carbon in GSI. In addition, in field conditions stormwater consists of many other contaminants that impact the ability of PFAS to adsorb. Inorganic cations such as Ca^{2+} and Na^{+} and organic compounds compete for adsorbent space and have been shown to inhibit PFAS adsorption (Gagliano et al., 2020).

Another process to remove PFAS from stormwater is bioaccumulation and phytouptake (Arslan and Gamal El-Din, 2021). Constructed wetlands with three wetland plants, *Juncus kraussii*, *Baumea articulata,* and *Phragmites australis*, accumulated PFOA and PFOS over a 28-day period in notable concentrations (Awad et al., 2022). Adding aeration within wetland systems has been shown to remove 80 % of PFOS concentrations within 7 h, with 95 % removal in two weeks, likely due to an increase in microbial action (Zhang and Liang, 2020). Phytouptake can also remove PFAS, but removal processes are slow with a field study estimating that it would take 48,000 years with phytouptake from spruce trees to achieve a target removal for a land contaminated with fire training from an airport (Gobelius et al., 2017). Furthermore, phytouptake does not degrade the contaminant into harmless compounds, therefore this method needs to be combined with a PFAS destruction technique such as incineration of the plant material. Most GSI such as bioswales, wetlands, and green roofs include a plant component and therefore bioaccumulation and phytouptake have potential to play a role in PFAS removal. To that end, research should be done to assess the ability of plantings to accumulate PFAS and degrade PFAS through secondary methods.

Other removal mechanisms present in GSI that may be more difficult in removing PFAS include filtration and biological degradation. Filtration technologies such as reverse osmosis and nanofiltration have been shown to be successful at capturing PFAS (Arias Espana et al., 2015); however, they need additional treatment to regenerate filters and completely degrade contaminants and may not be applicable in the context of GSI due to their need for higher pressures. In addition, biological degradation may be challenging due to the highly stable C—F bonds in PFAS compounds, precluding microbes from effectively oxidizing them. Although laboratory studies have found biological degradation of some limited PFAS compounds (Garg et al., 2021), they are done under laboratory conditions with the use of enzymes and catalysts that may not be present in GSI. Additionally, many PFAS compounds may be toxic to bacteria (Fitzgerald et al., 2018), limiting the ability for microbial communities to degrade PFAS.

5.3. Design considerations

To the authors knowledge, at the time of this writing few studies have evaluated the PFAS mitigation potential of GSI (Pritchard et al., 2023); therefore, design considerations for PFAS reduction or capture through GSI should consider the uncertainty associated with designing for an emerging contaminant for which there is little basic or applied research in the field. Compounding this is the fact that concentrations of PFAS in runoff are lower than those in landfills and the outlet of wastewater treatment plants for which most research on removal has focused. However, given these limitations there are a few design considerations that could be implemented to remove or prevent PFAS contamination in GSI including increasing adsorption potential using soil amendment, bioaccumulation through plantings, and geotextile liners to prevent groundwater infiltration.

The first design consideration could be the use of soil amendments that increase the ability of the soil to adsorb PFAS. Laboratory studies found that 1 % of activated biochar amendment in specific soils can remove >96 % of PFAS concentrations in contaminated soils (Silvani et al., 2019). However, as mentioned before, PFAS adsorption depends on many environmental conditions such as pH, the presence of other contaminants, and PFAS concentrations. Furthermore, long term adsorption potential should be tested since biochar in GSI soils cannot be reactivated frequently and could be a long-term maintenance cost.

Another design could be the implementation of specific GSI vegetation that could contribute to PFAS reduction through bioaccumulation. In wetland studies, it has been found that PFAS removal improves with greater root biomass, surface area, growth rate, and shallow root distribution (Chen et al., 2012). Therefore, green infrastructure designs may consider planting that can optimize root biomass, growth, and distribution for PFAS removal. However, if these plants are successfully utilized in removing PFAS from runoff, they may need to be remediated, such as through incineration, which would be another added maintenance and operations costs.

Finally, the use of geotextiles and membranes to prevent infiltration of PFAS into the subsoil and redirect runoff into the sewer systems could be a potential technique to prevent groundwater contamination. However, this modification will negate the use of GSI as an infiltration practice. Furthermore, modifying GSI with filtration membranes would not remove PFAS from water bodies unless the GSI is within a combined sewer system and adequate removal methods are present at the downstream wastewater treatment plant.

5.4. Summary

PFAS are a highly stable class of compounds known as a forever chemical that pollutes all stages of the water cycle. Due to their inherent stability in nature, it has become harder to find methods to mitigate them in the urban environment. Green infrastructure has become an integral part of the urban stormwater cycle and could be a potential intervention site to capture and reduce PFAS contamination. Potential removal mechanisms include adsorption using soil amendments such as biochar, bioaccumulation and phyto-uptake through green infrastructure plantings, and prevention of groundwater contamination through impermeable liners. However, given the dearth of research on PFAS removal in green infrastructure, research is needed to determine the most effective removal mechanisms and potential designs of GSI that can promote PFAS capture or removal.

6. Temperature

6.1. Background

During rainfall events in urban centers, stormwater runoff is routed to stormwater control measures via urban surfaces, the properties of which can alter stormwater runoff temperature (Herb et al., 2009a; Omidvar et al., 2018; Thompson et al., 2008; van Buren et al., 2000). Thermally polluted urban runoff can subsequently cause stream temperatures to surpass threshold temperatures, resulting in sublethal and lethal effects to downstream ecosystems (Beitinger et al., 2000; Nelson and Palmer, 1998; Zeiger and Hubbart, 2015). These effects are only expected to increase with increasing population and urban development compounded by rising global temperatures (Pachauri and Reisinger, 2007). It is therefore critical to understand how we can best mitigate thermal pollution to urban water bodies in order to protect aquatic ecosystems.

Thermal pollution in urban water bodies is an effect of the urban heat island, where higher temperatures are observed in an urban population center relative to a parallel, undeveloped land area (Oke, 1982). The primary causes of the urban heat island are the prevalence of low albedo surfaces (i.e., the proportion of solar radiation reflected by a surface), low evapotranspiration rates, and anthropogenic heat production (Akbari et al., 1992; Jones et al., 2012; Stone et al., 2010). Low albedo surfaces reflect less solar radiation, leading to higher surface temperatures due to increased solar radiation absorbance. The heat generated and sustained from these surfaces increases energy demands to cool buildings, further increasing the temperature of urban centers (Akbari et al., 1992). The combination of urban surfaces and reduced vegetation create steep temperature gradients between densely populated urban centers and their surroundings, with urban areas containing higher temperatures (Trlica et al., 2017; Wang et al., 2016). The same causes of the urban heat island have direct impacts on the temperature of urban runoff, resulting in hydrologic urban heat islands where urban streams have comparatively higher baseflow temperatures and are subject to greater temperature surges from stormwater runoff (Zahn et al., 2021).

Thermally polluted runoff causes direct and indirect effects to downstream waterways. Streams rely on a temperature regime to directly regulate important ecosystem processes, such as migration patterns, reproduction, growth, immune responses, and competitive ability (Armour, 1991). For freshwater bodies, typical upper-level thresholds for cold water, cool water, and warm water ecosystems are 22 °C, 29 °C, and 30 °C, respectively (Armour, 1991; Hathaway et al., 2016; Jones et al., 2012), above which temperature begins to limit ecosystem success. Specifically, this could include lethal effects to cold-water fish species and sub-lethal effects to non-cold water fish species. For example, sharp and sustained temperature changes due to urban runoff from upstream impervious surfaces can impede the growth of younger fish populations (Beitinger et al., 2000; Nelson and Palmer, 1998; Zeiger and Hubbart, 2015).

In addition, temperature can alter reaction rates, causing imbalance in important regulating nutrients and compounds. For example, dissolved oxygen (DO) concentrations are directly related to water temperature, but the effects of altered DO levels cause indirect effects to ecosystems. Streams subject to warm urban runoff may contain lower concentrations of DO impacting respiration and algal production (Butcher, 1995). However, the degree to which temperature impacts DO concentrations can vary as temperature is one of many factors that affect DO solubility, thereby making direct causality difficult (Harvey et al., 2011; Matthews and Berg, 1997). Beyond DO, metal toxicity to aquatic life has been observed to increase with rising temperatures (Davies et al., 1986).

As discussed, the potential harms of thermal pollution in stormwater runoff are well known; however, temperature as a contaminant has received less attention than others in management strategies to mitigate non-point source runoff. GSI provides a unique management strategy with several mechanisms for reducing the heat of urban runoff. With a proliferation of GSI to reduce both runoff quantity and other contaminants, it is therefore important to understand how these systems may also be able to reduce the impact of thermal pollution, which is a complex and unique contaminant.

6.2. Treatment processes

There are several heat transfer mechanisms within green stormwater infrastructure that may influence the reduction of runoff temperatures. Unlike other contaminants, temperature is a physical property of matter, meaning typical filtration removal mechanisms cannot be used to mitigate excess runoff temperature. The temperature of a substance is a measure of the average random kinetic energy of the substance's molecules (Campbell and Norman, 1998), and energy can be transported between substances via a variety of pathways, such as conduction, convection, radiation, and latent heat of vaporization (Campbell and Norman, 1998; de Vries, 1975). As illustrated in Fig. 4, conduction, advection, and latent heat of vaporization offer the most direct pathways to cooling in the context of urban infiltration (de Vries, 1975).

Runoff temperature pollution can be mitigated through exposure to a cooler media, through a timed release, or infiltration, all of which maximize advective and conductive heat transfer processes. During initial infiltration, heat transfer is dominated by mass movement (advection) (Jaynes, 1998; Wieranga and de Wit, 1970). As infiltration speed slows, heat transfer is equally governed by thermal equilibration (conduction) and mass movement (Jaynes, 1998; Wierenga et al., 1970). After some time, when water movement is reduced, conduction acts as the primary driver of heat transfer and there is a reduced rate of mass transfer between soil layers (Jaynes, 1998; Wierenga et al., 1970).

Because heat can be transferred during infiltration through soil media via conduction and advection, the physical parameters of soil relevant to the heat transfer processes are important controls. Volumetric heat capacity and thermal conductivity are the most relevant physical parameters in the context of heat transfer mechanisms, controlling the rate of conduction and advection in a substrate (de Vries, 1975). For example, lower hydraulic conductivity decreases infiltration speeds, lowering the time for advective heat transfer and increasing conductive heat transfer. In addition, the soil parameters influence the volumetric heat capacity, which is a composite value of the different substances that make up the soil, considering the composite volumetric heat capacity of all the fractions of a solid, water, and air (de Vries, 1975). The composite volumetric heat capacity expresses the amount of energy required to change one cubic meter by one degree of absolute temperature. In this way, understanding which solids are present, the mass percentage of those solids, and moisture conditions of soil is necessary to predict how resilient the media is to absorbing energy.

1. Water inflow from precipitation
2. Thermally polluted urban runoff enters GSI
3. Intercepted precipitation equilibrates and evapotranspirates via green roofs
4. Warm water infiltrates into GSI
5. Retained water equilibrates with soils and loses energy
6. Water released at GSI outfall to downstream ecosystems
7. Infiltrated water enters aquifers
8. Latent moisture is removed to the plants and atmosphere

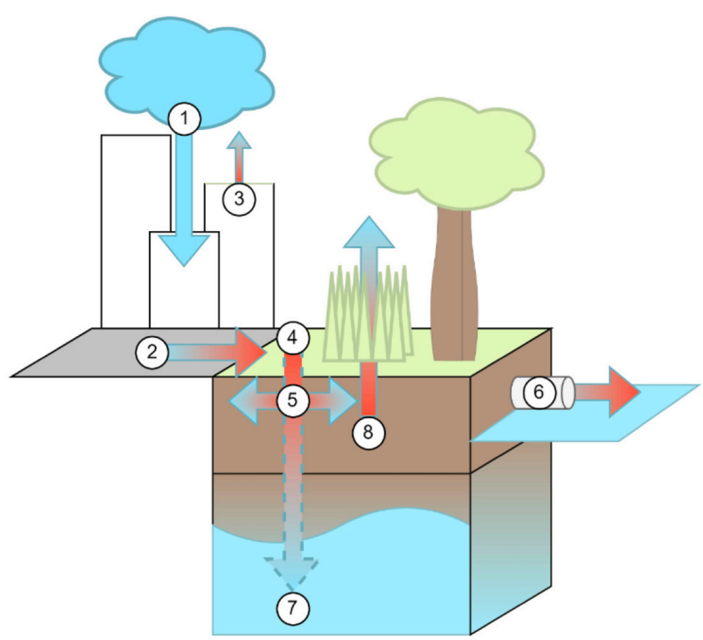

Fig. 4. Illustration of the heat flux in stormwater runoff as it is routed through green stormwater infrastructure.

In addition, the degree to which the soil is saturated, and the rate of infiltration can influence temperature reductions. In general, as the moisture fraction increases within a soil media, thermal conductivity increases since water is more thermally conductive than air (de Vries, 1975). The addition of water to the soil media will displace the presence of air voids between soil grains, increasing the transfer of energy between soil grains (de Vries, 1975). For both volumetric heat capacity and thermal conductivity, the variation of physical parameters with depth should also be considered (Wierenga et al., 1970). Finally, a media's hydraulic conductivity controls the rate and depth water will infiltrate (de Vries, 1975; Lu et al., 2003; Wierenga et al., 1970) and therefore will influence advective and convective heat transfer processes dependent on infiltration rates.

Timed release is another GSI function where thermally polluted runoff is routed through a controlled outlet that is sized to distribute the volume and subsequent thermal load across a longer period. Thermal load, or heat export, is defined as the total heat export over a period (Herb et al., 2009b). By reducing the rate and volume of runoff, timed release impacts how the total thermal load is distributed from GSI to a downstream waterway and can minimize the impact of temperature spikes. If a GSI feature has minimal thermal reduction but reduces the flowrate by extending the effluent over a longer period, the overall thermal load might compare to that of a non-urban system due to the polluted runoff distributed over a longer period. The timed release of urban runoff has been shown to reduce the number of days for which downstream temperatures increased by 28 days (1° F increase), 24 days (2 °C increase), and 5 days (4 °C increase); however, doing so increased the duration of the 1° and 2 °C temperature change by 5.3 and 0.1 h, respectively (Herb et al., 2009b). Therefore, this highlights the potential tradeoff of decreasing sudden and dramatic pulses in temperature for longer timed-release discharges that, although lower in temperature, are released over a longer period of time.

In terms of downstream impacts, infiltration provides the most direct benefit by eliminating polluted runoff and using the subsurface as a heat sink. The relative impact of surface runoff temperatures to aquifers compared to other contaminants is minimal as large volumes of water are needed to substantially increase soil temperatures. For example, in saturated soils temperatures ranged from 4.1 °C to 21.6 °C within the first 13 cm, but remained constant at a depth of 60 cm (Lu et al., 2003; Wierenga et al., 1970). This is because as warmer water infiltrates deeper, advective heat transfer slows and conductive heat transfer processes take over. Bulk fluid motion comes to a halt as the water equilibrates to soil temperature and the soil temperature returns to the annual regime.

Finally, evapotranspiration may also have an influence on the heat exchange involved in urban stormwater runoff when considering time scales larger than a storm event. In the context of GSI, the most relevant process is evaporation from the soil surface and root uptake of water (which eventually manifests into transpiration) (Tamai, 1998). Soil depth and meteorological factors such as net radiation, air pressure, windspeed, and the rate of change of the saturation vapor pressure versus temperature are factors in the magnitude of the evaporation flux; evaporation acts in the topmost soil layers, with most evaporation occurring under 20 mm (Heitman et al., 2010; Novak, 2010; Philip, 1957; Tamai, 1998). Meanwhile, transpiration is dependent upon root uptake of water, which decreases with depth, and varies with plants and climate (Daly et al., 2012; Tamai, 1998). Together, evaporation and transpiration influence the latent heat flux, which can makes up about 15 % more of the heat budget in a natural area (Tamai, 1998).

6.3. Design considerations

There are several design considerations that may impact the extent to which GSI reduces the thermal loads of stormwater runoff including infiltration rate, conductivity, media depth, underdrain sizing, and plantings that influence shading and evapotranspiration. Attention should be placed on the physical parameters controlling infiltration to maximize infiltrated volumes, via high volumetric heat capacity, thermal conductivity, hydraulic conductivity, and hydraulic permeability parameters. To that end, GSI should be unlined to encourage infiltration of runoff. However, like any design decision, this should be implemented while mindfully and carefully considering how this would affect mitigation of other contaminants. Within the GSI itself, media with high volumetric heat capacity and thermal conductivity allow faster and greater amounts of heat transfer. Volumetric heat capacity is relatively constant between soils, but thermal conductivity varies depending on soil water content (de Vries, 1975). Similarly, soils that have high hydrologic conductivity and permeability (such as coarse or sandy soils) will have higher infiltration rates, ultimately reducing directly discharged runoff volumes (DNR, 2017; Jones et al., 2009). Like other contaminants, consideration should be made for how thermal loads that are infiltrated impact groundwater aquifers and the subsurface urban heat island (Foulquier et al., 2009). However, research suggests infiltration is a lesser contributor to the subsurface urban heat island in comparison to other anthropogenic heat fluxes, such as district heating networks, heat pumps, underground utilities, and buildings (Benz et al., 2015; Foulquier et al., 2009).

In addition, media depth will have a direct impact on the advective and conductive heat transfer processes. A system with soil shallower than 90 cm may not allow enough infiltration time and distance to cool runoff sufficiently (Graves, 1998; Jones et al., 2009). To that end, the depth of the underdrain will influence the effluent temperature from GSI, with underdrains at lower depths producing lower temperatures due to the longer infiltration distance for heat transfer (Jones et al., 2009). Finally, beyond promoting infiltration and heat exchange in the GSI media, underdrains should be sized to optimize the thermal load of the effluent, taking catchment size, downstream temperatures, storm size, and basin size into account.

Plantings within the GSI and contributing watershed could have an impact on runoff temperatures through the shading they provide. For example, a parking lot with no tree shade was found to release higher median runoff temperatures to stormwater control measures (SCMs) (by 0.3 °C) and higher maximum runoff temperatures to SCMs (by 3.2 °C) when compared to a parking lot with tree shade (Jones et al., 2009). In addition, detention basins with increased exposed and unshaded surfaces have been shown to produce warmer effluent temperatures (Herb et al., 2009b; Jones et al., 2012). Besides shading, plantings within GSI provide latent heat transfer through evaporation and transpiration. Therefore, deliberate designs could maximize these benefits within GSI, although this may result in increased routine maintenance to care for plants.

6.4. Summary

Thermally polluted urban runoff can cause stream temperatures to surpass threshold temperatures, causing sublethal and lethal effects to aquatic wildlife and altering biochemical equilibriums. Low albedo surfaces, low evapotranspiration rates, and anthropogenic heat production drive the urban heat island, increasing energy transferred to urban runoff during precipitation events. GSI offers pathways for reducing the temperature of stormwater runoff. Fundamentally, GSI could potentially disperse and remove heightened temperatures from urban runoff via retention, timed release, evapotranspiration, and infiltration. However, implementation of these strategies will need to consider how the removed energy impacts other ecosystems or equilibriums (such as surface vegetation, urban atmosphere, and aquifers). Design strategies should prioritize infiltration via media with high volumetric heat capacity, thermal and hydraulic conductivity, and hydraulic permeability to rapidly infiltrate runoff. These parameters should also be combined with controlled release that lowers the thermal load while not leading to overflow. Increased evapotranspiration, while not directly contributing to mitigation of temperature pollution during storm events, can remove runoff before reaching outfalls and mitigate overall temperature pollution through evapotranspiration removal. More research is needed to understand the magnitude of thermally polluted infiltration in the context of aquifers and the subsurface urban heat island. Research on accurate modeling of evapotranspiration is also needed to promote an accurate and generalizable approach to evapotranspitation estimation.

7. Discussion

7.1. Common removal mechanisms

The emerging contaminants reviewed in this paper fall within four classes – biological, particulate, chemical, and physical properties – for which there are common removal mechanisms in GSI that largely fall within three categories (1) filtration and sedimentation, (2) sorption and other physicochemical processes, and (3) biological (Table 2). These common mechanisms each have advantages and limitations for removing the different classes of emerging pollutants within GSI as discussed in the following paragraphs.

Filtration of stormwater through the GSI media can physically remove particulate pollutants such as microplastics, tire wear particles, and sediment-bound ARGs, and in many cases has been found to be the dominant removal process for these emerging particulate pollutants in GSI. However, filtration of these emerging contaminants is limited by the characteristics of the stormwater media, as well as the properties of the stormwater particulates. Filtration of microplastics and tire wear particles in GSI is largely dependent upon the size of the incoming particulates and that of the pores in the media that serve to strain the pollutants (Koutnik et al., 2022a; Lange et al., 2021). Unlike sediment particles, microplastics and tire wear particles possess unique shapes, structures, and conductivities (Ampomah, 2020; Clary et al., 2020; Ebrahimian et al., 2020), which may also affect their ability to bypass filters and infiltrate through GSI media. Similarly, for biological contaminants such as ARGs that are bound to particulates, filtration can provide a mechanism for retaining those ARGs within the GSI media.

Sedimentation, on the other hand, may not effectively remove synthetic particulates such as microplastics and tire wear particles. This is because tire wear particles and microplastics have densities close to that of water which makes them buoyant (Stang et al., 2022). Therefore, these particles may not settle in sedimentation forebays absent of long hydraulic residence times (Lange et al., 2021). Designs of GSI must therefore consider if critical settling velocities of synthetic particulates and hydraulic residence times in GSI design will promote their sedimentation. Furthermore, for PFAS, ARGs, and temperature, it is unclear if designs that focus on settling will have a substantial impact on removal. Ultimately, filtration and sedimentation mechanisms have varying potential to remove particulates such as microplastics, tire wear particles, and particulate-bound contaminants, but may not affect other biological or chemical contaminants.

Sorption and other physicochemical processes (e.g., ion exchange and oxidation-reduction reactions) are removal mechanisms that have potential to remove biological and chemical contaminants such as ARGs (Hunt et al., 2008; Zuo et al., 2022b), PFAS (Gagliano et al., 2020; Silvani et al., 2019), and chemical compounds leached from plastics (Koutnik et al., 2022b). Nonpolar ARGs (Christou et al., 2017), microplastics (Padervand et al., 2020), tire wear particles (Huang et al., 2023), and PFAS (Cai et al., 2022) can be adsorbed quickly as these contaminants are hydrophobic and tend to have an affinity towards hydrophobic media pores or to adsorb into amendment compounds. Additionally, as the size of microplastics (Padervand et al., 2020) and length of PFAS (Cai et al., 2022) increase so does their adsorption due to larger binding surfaces for adsorption to occur. To this end, ARGs have been found to be removed in GSI primarily from adsorption (Zuo et al., 2022b) and oxidation-reduction reactions (Zhao et al., 2021), which increases with soft (kaolinite) soil texture and greater soil clay content (Gardner and Gunsch, 2017; Seyoum et al., 2021). In addition, adsorption and oxidation-reduction reactions are primary removal mechanisms for PFAS and some microplastics and tire wear compounds, (Douna and Yousefi, 2023; Gagliano et al., 2020; Huang et al., 2023; Padervand et al., 2020; Silvani et al., 2019). These processes can be promoted through soil amendments such as granular activated carbon and biochar (Biswal et al., 2022; Mahinroosta and Senevirathna, 2020) or metals (Douna and Yousefi, 2023; Valencia et al., 2019). Developing a soil

Table 2
Common removal mechanisms.

Class	Contaminant(s)	Removal mechanisms	Contaminant considerations	GSI component considerations	Selected sources
Biological	ARGs	Filtration	Particulate size	Media size, soil texture, and conductivity	(Christou et al., 2017; Zuo et al., 2022b)
		Sorption and physicochemical processes	Size and polarity/hydrophobicity	pH, conductivity, media composition, soil amendments, soil texture, and soil clay content	
Particulate	Tire wear particles and microplastics	Filtration	Size, density, shape, composition, and structure	Media size, soil freeze-thaw cycles, and conductivity	(Ampomah, 2020; Clary et al., 2020; Ebrahimian et al., 2020; Koutnik et al., 2022a; Lange et al., 2021; Padervand et al., 2020; Stang et al., 2022)
		Sedimentation	Size, density, and critical settling velocity	Hydraulic residence time	(Koutnik et al., 2022a; Lange et al., 2021)
		Sorption and physicochemical processes	Particle size/structure, biproduct and chemical composition/structure, and polarity/hydrophobicity	Conductivity, media composition, soil amendments, and porosity	(Gagliano et al., 2020; Huang et al., 2023; Padervand et al., 2020)
		Biological		Soil ecology and saturation, nutrient availability, pH, oxygen/metal/amendment concentrations, and submerged zones	(Johnson et al., 2003, Koutnik et al., 2022a; Meng et al., 2023a; Padervand et al., 2020; Saifur and Gardner, 2023)
Chemical	PFAS	Sorption and physicochemical processes	Chemical chain length, chemical composition/structure, and polarity/hydrophobicity	Conductivity, pH, media composition, and soil amendments	(Cai et al., 2022; Douna and Yousefi, 2023; Gagliano et al., 2020; Silvani et al., 2019)
		Biological		Soil ecology and saturation, nutrient availability, pH, oxygen/metal/amendment concentrations, and submerged zones	(Douna and Yousefi, 2023; Johnson et al., 2003, Koutnik et al., 2022a; Meng et al., 2023a; Saifur and Gardner, 2023)
Physical	Temperature	Biological/heat exchange	Thermal conductivity, specific heat capacity, flow rate, and heat fluxes	Plant shading, infiltration rate, media depth, and hydraulic conductivity	(DNR, 2017; Ebrahimian et al., 2020; Herb et al., 2009a,b; Jones et al., 2009; Jones et al., 2012; Tamai, 1998)

media mix that contains both clay content for ARGs adsorption, as well as amendments that can adsorb PFAS, microplastics, and tire wear compounds, could leverage sorption for the removal of these contaminants based on their unique characteristics (e.g., particle size and structure, compound structure, chemical composition, and conductivity). The future use of engineered medias within GSI for sorption will ultimately depend on further findings regarding the removal capacities of media, their cost-effectiveness of implementation and maintenance, and their associated leaching risks.

Lastly, there are several common biological removal mechanisms that have the potential to remove several emerging contaminants. For example, vegetation within GSI can break down and assimilate plastic waste chemicals by biogeochemical activity, and therefore may be a cheap and efficient way to remove plastic waste biproducts from stormwater (Koutnik et al., 2022b). Vegetation within GIS can also reduce effluent temperatures by promoting latent heat transfer and reducing surface temperatures (Herb et al., 2009b; Jones et al., 2012; Tamai, 1998). In addition, microplastics, tire wear particles, and ARGs can be removed through processes such as biotransformation, volatilization, and chemo-transformation breaking down contaminants (Johnson et al., 2003; Koutnik et al., 2022b; Saifur and Gardner, 2023). For example, bacteria *B. cereus* and *P. putida* grow as the concentration of tire wear particles increases suggesting these species can mineralize, transform, and utilize the compounds to sustain growth (Saifur and Gardner, 2023) These processes are best facilitated when specific chemicals are available for biogeochemical processes to occur. Breaking down plastics into specific chemicals for bacteria to degrade is largely a three-step process consisting of bacteria colonizing upon plastic, enzymes depolymerizing plastic particulates into compounds or chemicals, and soil bacteria utilizing these depolymerized biproducts (Meng et al., 2023a). Designing media based on soil ecology capable of facilitating these steps is crucial for plastic waste degradation. Examples of how to promote more efficient soil ecology to facilitate these processes includes maintaining suitable environmental conditions for probiotic microorganisms (e.g., pH, saturation levels, oxygen concentrations, heavy metal concentrations, or other limiting nutrient concentrations), creating submerged zones at specific media depths, and utilizing soil amendments to promote soil productivity and biodiversity.

7.2. Limitations of GSI for removal of emerging contaminants

Despite the potential of GSI to serve as a first line of defense for downstream water bodies, there are limitations to the extent to which GSI can be used remove these emerging contaminants. This includes the economic costs of design components (soil amendments, soil depth, plantings, etc.), tradeoffs between removal mechanisms, and increased maintenance and operational needs. First, changes to the design of GSI often come at an economic cost, which are likely weighed against the benefits provided. For example, amending soils with costly products such as biochar, activated alumina, or others may not be economically feasible on a scale that would make an impact to downstream water bodies. Furthermore, increasing the depth of an underdrain to facilitate greater filtration or heat conduction adds additional costs to the excavation and materials of the GSI.

Secondly, tradeoffs may exist between GSI design components for removal of a specific contaminant and its ability to effectively remove other contaminants. For example, amendments targeting the breakdown of tire wear particles or microplastics may negatively affect ARG removal, as tire wear particles and microplastics have an abundance of heavy metals, which can promote ARG transfer (Zhao et al., 2023). There may also be tradeoffs on the hydraulic conditions, with smaller GSI media pore sizes promoting greater removal of particulates and increasing the residence time for adsorption and heat conduction, yet also reducing the infiltration rates and requiring more frequent amendment removal to ensure proper GSI drawdown times. Furthermore, removal processes are also impacted by the intermittent flow rates inherent in stormwater runoff, with larger events producing greater hydraulic head and velocities in the GSI that may impact filtration or sorption processes, resuspend pollutants, or bypass the GSI entirely through overflow structures.

In addition, regulations focused solely on the removal of particulate pollutants may be a practical barrier to implementing GSI that can remove these emerging stormwater pollutants. However, there may be regulatory indicators from other water sectors that provide insights into the potential levels of removal required for stormwater. For example, in the past two years there have been several efforts to regulate emerging contaminants in municipal drinking water for microplastics (CSWB, 2022) and PFAS (US EPA, 2023). In September 2022, California enacted the world's first requirements to monitor and report the concentrations of microplastics drinking water (CSWB, 2022). Furthermore, a proposed federal law aims to regulate six PFAS chemicals by the end of 2023 in municipal drinking water to 4.0 ppt or 1 on the Hazard Index based on the type of PFAS (US EPA, 2023). As regulations in drinking water for monitoring, reporting, and removing emerging contaminants become enacted they can help to frame similar regulations for stormwater and mitigation goals for GSI.

Finally, accumulation of contaminants within GSI may lead to more frequent maintenance and operational needs. The removal of contaminants and their accumulation may require the vegetation and soils to be remediated more often when the limit of their removal capacity is reached. When this limit is reached, soil clogging or leaching of contaminants could degrade the ability of the GSI to effectively mitigate contaminants. In addition, there is an unknown risk that the flushing of contaminants during extreme rainfall events may have on mobilizing accumulated contaminants, causing downstream pulses that are greater than would have otherwise been observed. For example, ARGs can desorb from particles with increased stormwater volume which can cause ARGs to leach (Zuo et al., 2022b). Therefore, evaluating contaminant loading and accumulation rates in conjunction with soil and plant remediation requirements is crucial for effective long-term maintenance of GSI.

7.3. Future research directions

Given the emerging nature of the contaminants in this study, there are several research directions that are needed to gain a better understanding of the fate and transport of these emerging contaminants through GSI and the most effective removal mechanisms. First, for PFAS, microplastics, and tire wear particles, physical and biological mechanisms (e.g., filtration, adsorption, and biotransformation) have perhaps the greatest potential to remove these contaminants. Therefore, research on the ability of soil amendments (e.g., biochar, fungi, carbon, etc.), biological uptake from plants, and biological transformation are needed to more clearly define the extent and conditions under which these mechanisms can further remove contaminants. Doing so is synergistic with growing and robust research for evaluating the ability of these processes to remove legacy contaminants such as nutrients and metals. Secondly, it is important to gain a better understanding of what selective pressures within GSI contribute to the horizontal gene transfer of ARGs, or how design factors (system size, plant types, soil texture, etc.) can be manipulated to enhance the removal of ARGs. Finally, there is a need to understand how these contaminants interact together within GSI to either advance or prevent removal mechanisms. For example, the presence of microplastics can be a stressor that promotes ARG transfer (Zeng et al., 2022) and higher temperatures of stormwater runoff in GSI may facilitate the degradation of tire wear particles, microplastics, or PFAS in stormwater, impeding the efficiency of treatment mechanisms.

8. Conclusion

GSI is a growing stormwater management approach to capturing, infiltrating, and treating runoff at the source. However, there are several emerging contaminants for which mitigation efforts are not yet well defined including ARGs, microplastics, tire wear particles, PFAS, and runoff temperature. This paper presents a review of the source of these contaminants, potential treatment mechanisms in GSI, and design considerations for better removal by GSI. A growing research body has demonstrated the negative impacts of these contaminants to human and environmental health, highlighting the need to mitigate these contaminants from stormwater runoff. While many existing treatment mechanisms of GSI hold potential to remove these contaminants, the precise approaches and engineering designs to do so are unclear. This review highlights several common removal mechanisms – filtration, sorption and other physicochemical processes, and biological processes – that could lead to their removal. However, to facilitate removal, consideration must be given to these contaminants' unique physiochemical properties, environmental conditions, and design of GSI. To reach this goal, GSI designs can be improved by classifying the properties of emerging contaminants within stormwater influent and developing treatment processes that are both tailored to and maximize the range of pollutants that can be removed. To this end, future research is needed to clarify the mechanisms and relationships between removal processes and these contaminant properties in GSI, as well as the potential risk to their concentration and accumulation in GSI systems. Doing so will help improve our understanding of how to best use GSI as a first line of defense against emerging contaminants in stormwater runoff.

CRediT authorship contribution statement

Benjamin Bodus: Conceptualization, Writing – original draft, Writing – review & editing, Methodology. **Kassidy O'Malley:** Conceptualization, Writing – original draft. **Greg Dieter:** Conceptualization, Writing – original draft. **Charitha Gunawardana:** Conceptualization, Writing – original draft. **Walter McDonald:** Supervision, Project administration, Conceptualization, Writing – original draft, Writing – review & editing, Methodology.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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