BIORETENTION PLANTING DESIGN FOR POLLUTANT REMOVAL: BARRIERS AND BEST PRACTICES

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ABSTRACT

To address the urban stormwater quality impairment challenge, one type of green stormwater infrastructure (GSI) – bioretention, has gained increasing interest in practice due to its demonstrated hydrological and pollutant removal capabilities in both laboratory and field settings. Despite the well-studied hydrological benefits of bioretention, a critical knowledge gap exists in the role of vegetation contributing to bioretention pollutant removal. Existing research focuses primarily on plant survivability, aesthetics, and maintenance but remains insufficient to guide planting design and management to achieve multiple ecosystem benefits. To help bridge the gap between theory and practice and offer actionable recommendations for bioretention planting design for pollutant removal, we interviewed 15 experts with extensive GSI planting research, design, or nursery experiences. The three specific research objectives are to 1) understand the critical factors driving bioretention planting design decision-making and how professionals prioritize these factors to achieve different ecosystem benefits, 2) identify barriers to implementing designs for multiple benefits, including pollutant removal, and 3) synthesize design and management best practices. Qualitative data analysis software Nvivo was used for analyzing the transcripts with codes related to the factors, barriers, and best practices. Results show that aesthetics, plant survival, maintenance, and soil characteristics are currently the most critical considerations in bioretention planting design. Barriers such as knowledge gaps, lack of resources, lack of systems thinking and collaboration, and regulatory and law constraints all contribute to current designs' underperformance. Design and management best practices, such as understanding the site, designing for swift establishment and reduced maintenance, encouraging researcher-practitioner collaborations, investing in research of effective technologies, and creating publicly available, user-friendly, and reliable resources, can help address the inadequacies of current bioretention planting design.

Keywords

Bioretention Planting Design; Pollutant Removal; Design Considerations; Implementation Barriers; Best Practices

1 INTRODUCTION

Urban water bodies are "widely impaired" by excess nutrients and sediments from stormwater runoff despite efforts in stormwater management and control in surrounding watersheds (Shrestha, Hurley, & Wemple, 2018). Common harmful contaminants from impervious surfaces associated with urban development include total suspended solids, metals, nitrogen, phosphorous, pathogens, and hydrocarbons (Environmental Protection Agency, 1999; Shrestha et al., 2018). These pollutants are difficult to regulate and are considered one of today's most pressing water quality challenges (Shrestha et al., 2018). They not only threaten water quality in our natural systems but are also linked to chronic and acute illness from exposure through drinking water and physical contact (Gaffield, Goo, Richards, & Jackson, 2011).

In response to various urban water issues, including volume and quality impairment of stormwater released into receiving waters, bioretention systems have been implemented. Their initial use in the United States dates back to the early 1990s in Maryland. These systems are defined as "a landscape depression that consists of a surface ponding layer, vegetation, a soil layer, a storage layer, overflow structures, and an optional underdrain system" (Liu, Sample, Bell, & Guan, 2014). They are primarily designed to treat small (typically < 1 acre) contributing drainage areas (Center for Watershed Protection, 2020). With demonstrated pollutant removal capabilities in both laboratory and field studies (LeFevre et al., 2015), bioretention systems have received increasing attention in both research and practice. They are frequently designed as a phytotechnology, where the plant systems work with the soil media and utilize mechanisms of *phytodegradation*, *rhizodegradation,* and *phytovolatilization* to remove or, in some cases, completely degrade polluting compounds before they enter the sewer system (Kennen & Kirkwood, 2015).

More than 30 years of rapidly developing research and practice have generated a wealth of knowledge in bioretention functioning and best practices. However, a significant literature gap lies in understanding the system's pollutant removal mechanisms, especially the role of vegetation (Dagenoise, Brisson, & Fletcher, 2018; Muerdter, Wong, & LeFevre, 2018) and how its interactions with the media affect pollutant removal (Skorobogatov, He, Chu, Valeo, & van Duin, 2020). Although vegetation is widely recognized as a vital design component of bioretention, plant selection often focuses on survivorship, aesthetics, and sometimes regional native status (Muerdter et al., 2018). The contributions of vegetation to pollutant removal and hydrological functions are often overlooked (Muerdter et al., 2018).

Emerging research has shown that vegetation produces measurable hydrology and water quality benefits through intercepting precipitation, evapotranspiration, reducing erosion, maintaining soil media infiltration capacity, and influencing various pollutant removal processes (e.g., phytoextraction, in planta phytotransformation, and rhizosphere processes) (Muerdter et al., 2018). However, reported removal rates of common pollutants, e.g., total suspended solids (TSS), nitrogen (N), phosphorus (P), toxic metals, hydrocarbons, and pathogens, vary widely, ranging from nearly complete removal to net export (Muerdter et al., 2018). While the reduction of many heavy metals, sediment, and micropollutants (e.g., hydrocarbons and pesticides) is less affected by the plant palette and relies more on physio-chemical processes, the effectiveness of nutrient removal, especially nitrogen, can significantly hinge on species choices (Muerdter, Smith, & Davis, 2020; Payne et al., 2018). Choosing the right plants for targeted pollutants from a wide array of options is an enormous challenge, not only because information on pollutant-removal capabilities of different species under diverse environmental conditions remains limited, but also because findings can vary considerably across studies and sites and between the present and the future (Farrell et al., 2022; Payne et al., 2018). Therefore, transferable, mechanistic understandings of pollutant removal processes are critical research gaps requiring timely attention (Mehmood et al., 2021; Muerdter et al., 2018). As a result, novel approaches, such as using plant traits and species' natural distribution to guide bioretention planting design, have recently been proposed (Farrell et al., 2022; Payne et al., 2018). For example, plant traits such as extensive and fine root systems and high plant biomass have been suggested to critically affect nutrient removal. Besides pollutant removal mechanisms, additional significant areas of research needs include impacts of plant harvesting on pollutant uptake and vegetation impacts on emerging organic contaminants and metals (Dagenoise et al., 2018; Glaister, Fletcher, Cook, & Hatt, 2017; Muerdter et al., 2018).

Besides the research gaps above, a disconnect between research and practice, and therefore lack of planting design guidance, has also contributed to the lack of multi-functionality of many bioretention plantings (Hopman, 2018; Person et al., 2020; Rainer, 2017). Practitioners often struggle to find up-to-date scientific research essential for enhancing their strategies and designs, such as the types of pollutants that specific plants can absorb, species most effective in bioretention pollutant removal by regional ecology and climate, pollutant fate after on-site vegetation decline, and strategies to mitigate remaining contaminants. Our review of stormwater management manuals across the US shows a lack of planting design guidance in cities' general stormwater manuals, even for those with rigorous stormwater programs (e.g., Minneapolis, New York, and Seattle). Specialized manuals for planting guidance (e.g., Philadelphia Water Department's Green Stormwater Infrastructure Landscape Design Guidebook v4.0, 2020, and Department of Environmental Protection, Montgomery County, MD, 2020) are emerging but remain difficult to locate. Of the existing ones, most focus on guidelines regarding visibility, erosion control, ecological benefit, and aesthetics, and information on species recommendations is scattered. Some manuals mention types of pollutants found in the region and may suggest filtration systems or soil composition strategies to address the infiltration of pollutants. However, specific recommendations on how to use plants as a solution to water quality impairment remain scarce. In general, advanced knowledge on phytoremediating bioretention plants is scattered in scholarly publications [e.g., 20 Australian native species and two lawn grasses in Payne et al. (2018)] and extensive plant databases [e.g., the TRY plant trait database, Kattge et al. (2020)], not easily accessible for professionals. If advanced literature could be logically integrated into manuals, such as phytoremediating capabilities on plant lists and successful design strategies, planting design for bioretention systems could better achieve multiple ecosystem functions.

The literature review above suggested that pollutant removal has yet to become integral to bioretention planting design. The development of science on bioretention pollutant removal remains limited, and the application of effective pollutant removal strategies is constrained by the lack of horticultural knowledge and available resources for landscape manual creators and practitioners. Therefore, in this article, we address the following key research questions: 1) What are the guiding factors for practitioners when choosing plant species for bioretention facilities? 2) How can bioretention plantings be designed to maximize plant functionality in remediating stormwater pollutants beyond those currently pursued objectives such as survivorship, aesthetics, and regional native status?

2 RESEARCH OBJECTIVES

Our specific research objectives include: 1) to better understand the current critical factors driving bioretention planting design decision-making and how professionals prioritize these factors to achieve different ecosystem benefits, 2) to identify barriers to implementing designs that could achieve multiple benefits, including pollutant removal, and 3) to synthesize resources and design and management best practices for multiple benefits.

The findings will contribute to the academic understanding of bioretention system design and provide practical insights for landscape architects, engineers, and practitioners. The study will help bridge the gap between theory and practice by offering actionable recommendations for the planting design of bioretention systems that ultimately advance the effectiveness of these vital stormwater management systems.

3 METHODS

We conducted an expert interview to address the research question and objectives above. The interviews focused on obtaining information contributing to understanding the factors influencing bioretention planting design decision-making, barriers to implementing phytoremediating plants, and landscape design and management best practices for pollutant removal. More specifically, we used the snowball sampling technique (Yadav et al., 2019) to recruit 15 experts with extensive GSI planting research, design, or nursery experiences (Table 1). Experts were of diverse backgrounds and included stormwater manual creators, designers or practitioners, researchers, educators, and plant nursery experts. The interview instrument was approved by The Pennsylvania State University's Institutional Review Board (STUDY00013257) with no risks to participants.

Table 1. Interviewees' basic information.

	Type	Agency	Role
1	Researcher	Federal research agency	Researcher with environmental engineering expertise
2	Practitioner/manual creator	University (sustainable landscapes program)	Landscape architect; program manager
3	Practitioner	Multi-disciplinary environmental engineering firm	Landscape architect; ecologist
4	Practitioner	Nursery	President and CEO
5	Practitioner	Nursery	Marketing manager
6	Practitioner /researcher/educator	University	Plant science and landscape contracting professor
7	Practitioner	Multi-disciplinary planning and design firm	Principal
8	Practitioner	Municipality	Green stormwater infrastructure program manager; landscape architect
9	Practitioner	Design-build firm	Founder; landscape architect; formerly horticulture educator
10	Practitioner	Municipality	Green infrastructure project manager
11	Practitioner/educator	Landscape architecture firm; University	Principal; professor
12	Practitioner	County government	Stormwater BMP inspections and maintenance program manager
13	Researcher/manual creator	University	Civil and environmental engineering professor
14	Researcher/educator /former practitioner	University	Landscape architecture professor
15	Practitioner/author	Landscape architecture firm	Principal

All interviews occurred on ZOOM from June to October 2020. Each interview lasted an hour and was either audio or video recorded. We maintained a positivistic stance during the interviews (Guba & Lincoln, 1994) and avoided providing participants with subjective input (e.g., personal views and preferences) that might impact the interviewees' perspectives.

Each expert was asked three primary questions corresponding to the abovementioned research objectives.

(1) *How would you rank the following ten factors in their importance to bioretention planting design decision-making in your experience? The ten factors include plant survival, diversity, aesthetics, soil conditions, maintenance, cost, plant material availability, pollutant removal, and pollinator-supporting functions. Please elaborate on your rationale.*
Due to the interviewees' different backgrounds in research, design, education, the nursery industry, or, in some cases, stormwater manual creation, practitioners were asked to reflect on how they had prioritized various factors in practice, while non-practitioners discussed how factors should ideally be prioritized. The initial list of ten factors was developed based on pilot interviews with the first three experts. The interviewees were also encouraged to add any critical factors absent from the list.

(2) What are the barriers you have experienced regarding implementing planting design for pollutant removal?

(3) What recommendations and ideas would you offer for bioretention planting design and management best practices?

Qualitative data analysis software Nvivo was used for analyzing the transcripts. Based on the coding techniques suggested by Miles et al. (2014), for research objective #1, we first extracted the rank of factors specified by experts directly from transcripts. For experts who did not specify the rank of factors or pointed out new factors, we coded the importance of each mentioned factor into nodes of high, medium, and low based on their synthesis of the factors. When experts ranked a factor differently based on specific circumstances, those circumstances were coded and grouped into themes. The specific linkages between two or more factors emphasized by experts were also coded as supplemental information to showcase the diversity and complexity of experts' thought processes on factor tradeoffs. For research objectives #2 and #3, we first coded all the barriers, potential impacts, and design and management best practices mentioned by the experts. Then, in-depth reading and comparisons of each coded text were performed to generate categories that synthesize the major patterns of initial codes. Linkages between each perceived barrier and its impacts were developed by scrutinizing the logic of the transcripts.

4 RESULTS

4.1 Factors for Decision-Making

First, regarding factors for bioretention planting design, all 15 experts gave examples of their general decision-making process and discussed the significant factors influencing their design, although only seven provided full or partial factor rankings. Eight critical factors were commented on, including aesthetics, plant survival, maintenance (requirements and capacity), soil characteristics, plant availability, plant diversity, pollutant removal, and pollinator-supporting functions (Figure 1). Representative quotes from the experts are included in Table 2. Most experts commented that no single, universal rank of factors could be applied to all the projects they have experienced. Instead, prioritization of these factors in a specific project is influenced by how driven the client's perspective is, the expertise of the design team, and site conditions. Regardless, in general, aesthetics, plant survival, maintenance, and soil characteristics were ranked as high priority, whereas pollutant removal and plant diversity came next, followed by plant availability and support for pollinators (Figure 1). The top four were prioritized because aesthetics are critical to public/stakeholder acceptance, plant survival can be challenging due to highly varied hydrological conditions and other environmental stresses in bioretention systems, and soil characteristics and maintenance both fundamentally affect vegetation survival and aesthetics. Conversely, plant availability and support for pollinators ranked the lowest because obtaining bioretention plants from nurseries is typically no longer a hurdle, and promoting pollinator support has not become a primary objective in most projects. Pollutant removal and plant diversity ranked in the middle, primarily due to a lack of resources on species' pollutant removal capabilities and the aesthetic and maintenance challenges created by diverse plantings. Regardless, experts noted that these two factors should have a higher priority than the current status in the field.

Another reflection was that prioritizing a single factor can significantly influence the outcomes of other factors. For example, prioritizing plant availability can largely determine the types of pollinators that can be attracted and sometimes plant survival rate under the applied contexts (e.g., soil, maintenance). Additionally, experts tended to consider the synergy of multiple related factors more than a single factor's importance. For instance, aesthetics and maintenance requirements/capacity were often brought up together by the experts. For public projects in particular, addressing the public's aesthetical preferences through a regular maintenance regime appropriate for the designed plant community is essential to the public's acceptance and appreciation of bioretention systems.

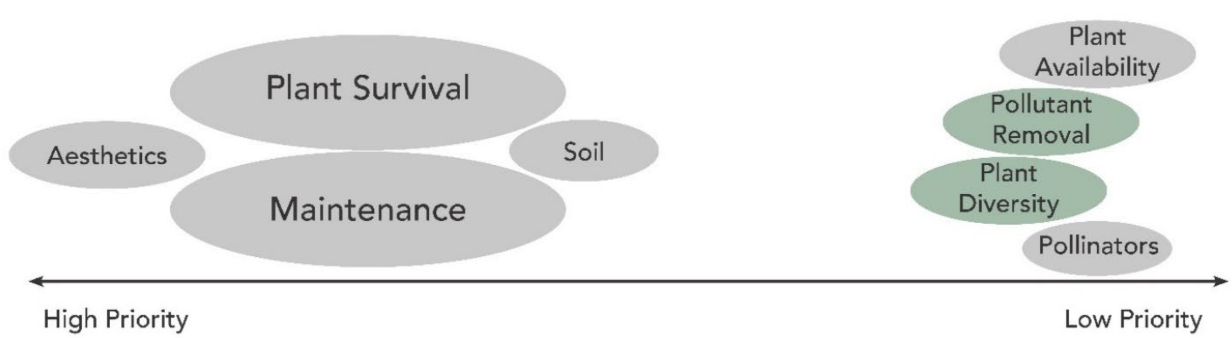

Figure 3: Factors that drive bioretention planting design decision-making. Diagram by the authors.

(Notes: size of ellipses indicates frequency of being mentioned; green ellipses indicate factors recommended to be prioritized more than current practice)

Table 2: Representative quotes of critical design considerations.

Factors	Representative quotes	Interviewee
Aesthetics	*"it's kind of a tie between aesthetics and community stakeholder acceptance. They go together for us because they basically shut down one of our programs for installing green streets because one person didn't like the way they looked."*	Practitioner (#12)
Plant survival	*"so this depends a lot on my client so that I have a hard time with this one because every site is different, right. And, really, you have to see like what the client's priorities are. I just had a large green street project that was super successful, but we did a ton of public engagement and getting community and stakeholder buy-in. Buy-in was extremely important because they're also really litigious. So if it didn't go well, like the city gets sued a lot. […] but when I'm doing facilities for cities, and they are not seen, and they're tucked away, their biggest priorities are survival rates of plants and maintenance."*	Practitioner (#3)
Maintenance (requirements and capacity)	*"We identified our top three are community/stakeholder acceptance, survival rates, and maintenance requirements. So it's kind of a balance between these three things, and they play off of each other. So we want to keep the communities happy and the stakeholders happy; in order to do that, we need our plants to survive. And in order to do that, we need to be able to maintain them."*	Practitioner (#10)
Soil characteristics	*"I think my number one, […] I have to say it's soils. So, whatever the soil mix is or whatever the existing soil is, or whatever materials are used, you have to really understand what that is and match your plants to the soil characteristics."*	Practitioner (#7)
Plant availability	*"So the available plants from nurseries to me is not a limitation. If it's something really, really weird, but as long as the growers know how to propagate it, they're usually happy to grow it as long as you give them time.*	Researcher/ educator/former practitioner (#14)
Plant diversity	*"The problem is so many of these plantings are also monoculture because they want to look clean and maintained."*	Practitioner/educator (#11)
Pollutant removal	*"So why pollution removal is so far down is that I don't have any resources to know what plants are doing, […] it's critical, really important, but as far as me making this influencing my decision making and its own, if I had more information, it would be a huge factor because that's our main goal."*	Practitioner (#12)
Support for pollinators	*"could we be doing more for pollinators? Sure. We have done a lot of research on what pollinators need and have given recommendations to our planners on how to identify projects where we can make a difference. […] we're definitely cognizant of it and do make some*	Practitioner (#10)

recommendations to planners on how to make the most out of that, but it's not like a primary goal of our program."

4.2 Implementation Barriers

The many barriers discussed in the interviews can be summarized into five major themes: knowledge gap, lack of resources, systems thinking, and collaboration, and regulatory and law constraints (Figure 2). These barriers can risk project success and cause maintenance difficulties, design function failure, failure to support ecological systems, and objections from stakeholders, ultimately impacting greater social, environmental, and economic sustainability. Next, we elaborate on each of the five implementation barriers. Representative quotes from the experts are included in Table 2.

Knowledge Gap: Researchers especially agreed that there is a substantial knowledge gap on phytoremediating plants in bioretention systems. Interviewees expressed a lack of research data for how pollutant treatment precisely happens and what a longer-term plan might be for an area once pollutants have been concentrated on site. Conducting relevant research was frequently quoted as costly, requiring expensive sensors and lab tests and a substantial budget for long-term studies for which funding is scarce and very competitive. In addition, most existing research is relatively new and may not have been published and made available to the public, let alone in a digestible, user-friendly medium. Researchers suggested referencing conference proceedings as well as personal communications due to difficulty locating such resources through other means. In summary, research remains inadequate for designers to make educated decisions incorporating phytoremediating plants.

Lack of Resources: Interviewees overwhelmingly expressed a need for more resources for implementing phytoremediation technologies. Existing guidelines often lack scientific references and are not user-friendly. Better networking and data-sharing opportunities are also necessary. For example, many interviewees mentioned needing a plant database that lists critical plant species traits for functionality and tolerance of difficult microclimates within a bioretention system.

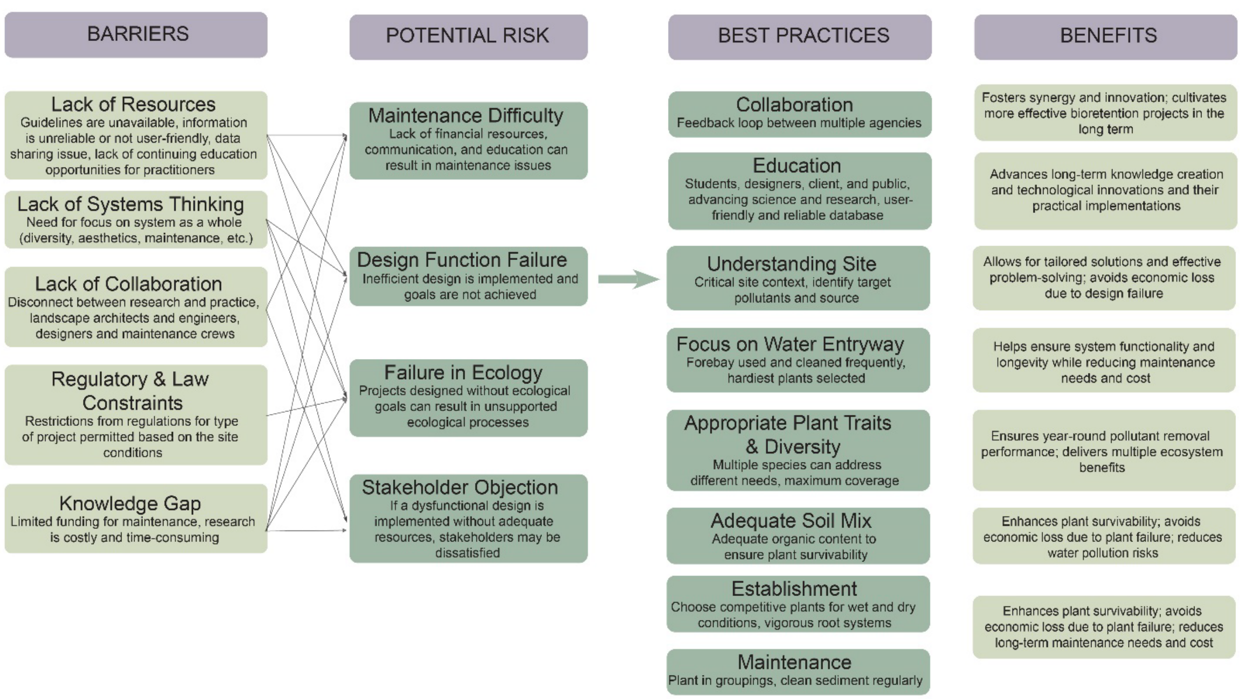

Figure 4: Bioretention pollutant removal implementation barriers, potential risks, best practices, and their benefits. Diagram by the authors.

Lack of Systems Thinking: The need for a more holistic approach to designing bioretention plantings is evident. Traditionally, bioretention design has been compartmentalized, primarily focusing on individual components such as drainage mechanisms, media composition, and plant selection. While these components are undeniably vital, they have not been considered together within the larger context of the entire system. Additionally, current planting designs often narrow their focus on a few primary objectives, such as plant survival, aesthetics (and community acceptance), and maintenance reduction, without considering other potential co-benefits, such as biodiversity enhancement and pollutant removal. Interviewees also stressed the need for planting design that considers growth needs and resilience during all potential conditions, including both times of drought and saturation.
Lack of Collaboration: Researchers and practitioners agreed that communication disconnections hindered the effective implementation of optimal plant functionality in bioretention systems. Such disconnect exists between research and practice, landscape architects and engineers, and designers and maintenance crews. Specifically, there is often a gap between research findings and practical implementation. Researchers may develop valuable insights that may not readily translate into real-world applications. Additionally, landscape architects and engineers, representing two core disciplines involved in bioretention design, may not effectively communicate and integrate their distinct expertise in plant functionality and site engineering. This disconnect can cause a lack of synergy among the various system components, resulting in their failure to function cohesively and efficiently. Finally, the disconnect between those responsible for the initial design and those tasked with ongoing maintenance can result in systems that are challenging to upkeep or fail to meet their intended objectives. Breaking down these communication barriers is essential to ensure all stakeholders' collective knowledge and expertise are leveraged to create and maintain effective bioretention systems.
Regulatory and Law Constraints: Cities have drastically different regulations and requirements for stormwater management. Some may have strict standards targeting both water quantity and quality, while others may pose little limitations on development impacts. In some cases, existing laws and regulations are severely outdated and overly restrictive, limiting the type of projects that can be developed to fulfill compliance.This can stifle innovation and hinder the broad adoption of stormwater management practices. Efforts to modernize regulations, as well as fostering collaboration between policymakers, urban planners, and environmental experts, are crucial steps toward creating a more conducive regulatory environment for the effective implementation of bioretention systems.

Table 3: Representative quotes of the five implementation barriers.

Theme	Representative quotes	Interviewee
Knowledge Gap	*"We don't really know how each individual landscape species contributes to pollutant removal. I think that's an area that there could be more work done in."* *"We can't examine the nutrient removal unless we can remove some of the biomass and actually test the plant tissue, and that costs money. That's not something that we can do without having funding, you know, to conduct the tests."*	Researcher/ researcher/educator (#6)
Lack of resources	*"A lot of the knowledge that the professionals have is not yet published. So the stuff you really need, you can't read in a book to dig deeper. I think the more I realize that that's the case. So, when I say do the research, a lot of it is, going to conferences and you know, connecting with people internationally, not just in the United States."*	Practitioner/ author (#15)
	"It would be great for landscape architects to have a resource they can refer to with different projects that are similar in scope and size to refer to for plant material, depending on soils, climate, some sort of prototypical that they could use, I don't think it's out there. If it is out there, it's not highly used."	Practitioner/ manual creator (# 2)
Lack of Systems Thinking	*"Civil engineers will be very happy to get rid of the plants and just have the soil. And they can, they can make a very strong case for why the soil does all the things that the plants do, and the plants are just a minor annoyance, you know, so we have to, we have to fight back as far as ecological retention."*	Researcher/ educator/former practitioner (#14)
	"Almost, I would say 90 to 95% of both the clients and other people think plants are about aesthetics, and they don't understand the water quality function."	Practitioner (#3)
Lack of Collaboration	*"When you look at the nursery catalog, few species appear there that are specifically selected for this kind of stormwater […] But nurseries still grow, with a focus on horticulture and not on functional systems, but they're the species that we need. And they are the workhorses. There's simply not enough to choose from for landscape architects right now. When they open a nursery catalog, there might be a rain garden list, but the plants in there are purely catch-all garden species, and that's where the shift needs to happen. They breed new flowers and heights and tinker of leaf color. When really, we should be selecting species that take up more phosphorous or, you know, address the issues you identified here in this work. Yeah. There is an enormous gap there."*	Practitioner/ author (#15)
Regulatory & Law Constraints	*"And then there were others [jurisdictions] that are pro developer. They have no tree protection. They're very anti most environmental policy; they want to do as little as possible. And they want to keep their hands off of regulations so that developers have free reign and their codes. There are examples that show you the bare minimum of what they had to do. And then some of them are totally leaders. And they can be jurisdictions that are like next to each other."*	Practitioner (#3)
	"The laws are very restrictive [is so much in volume]. And when you have a big volume, then people are gonna start looking more toward a rock bed infiltration than a rain garden […] we need all the tools, but I look at the vegetative systems of being more resilient and requiring less maintenance."	Researcher/ manual creator (#13)

4.3 Design and Management Best Practices

Experts also discussed five major categories of design and management best practices and their benefits for plant survival and pollutant removal, in addition to recommendations for collaboration, research, and education (also see Figure 2). We summarize the key recommendations in each category as follows. Representative quotes from the experts are included in Table 4.

Understand the Site:

- Gain a thorough understanding of critical site contexts, including the soil, water load, community needs, target pollutants, and their sources.

Focus on Water Entryway:

- Prioritize design efforts where water enters the system;
- Implement a sediment catchment system to avoid build-up;
- Select the hardiest plants for the inlet area.

Appropriate Plant Traits and Diversity:

- Use multiple species to address different needs;
- Maximize vegetation coverage;
- Incorporate evergreen species for year-round pollutant removal;
- Select plants suitable for varying micro-habitat conditions.

Adequate Soil Mix:

- Ensure adequate organic content in the soil mixture to increase plant survivability;
- Strike a balance in nutrient levels to avoid excessive release and sustain plant life;
- Avoid overly high sand concentrations that hinder water absorption by plants.

Design for Swift Establishment and Reduced Maintenance:

- Ensure frequent maintenance in the first 12 months post plant installation to achieve the best establishment;
- Choose competitive plants with strong root systems and propagation capabilities;
- Maintain adequate plant density;
- Use groupings for species clarity;
- Clean out sediment build-up.

Collaboration:

- Increase feedback among multiple agencies during the project's education, design, and maintenance stages;
- Enhance communication between researchers and practitioners, landscape architects and engineers, and practitioners and maintenance crews.

Research and Education:

- Invest in advancing research on effective technologies;
- Create user-friendly and reliable educational resources for students, designers, clients, and the public.
- Encourage collaboration among nurseries, researchers, and practitioners to conduct scientific and practical experiments and bridge the gap between knowledge creation and implementation.

Table 4: Representative quotes of best practices.

Theme	Representative quotes	Interviewee
Understanding the Site	*"What we've seen as to the success of the bioretention design is the soil, the type of soil, the pH of the soil, how much it drains, and then the hydrology of the system. So, understanding 'is water going to be standing in that area?' 'Is water going to be, you know, dissipating really quickly?' 'Is it going to be a really dry condition?' So really understanding that is the mainstay of whether these are successful."*	Practitioner (#7)
Focusing on Water Entryway	*"We want to make sure that the plants aren't going to be so heavily loaded with pollutants that they're not going to survive. So we do some of the practices that you've mentioned, such as, you know, forebays and dissipaters and certain plants. We select for what we call the entrance zones, which are the areas where the stormwater first comes into the garden. So that's going to get the heaviest load of pollutants of sediments, and so in those entrance zones, that's where the plant selection is really critical."*	Practitioner (#10)
Appropriate Plant Traits and Diversity	*"…increase the plant density, because that's another one of my biggest pet peeves of, you know, all about this. These things are under-vegetated. More of everything is the best cure to most of the issues we have when we install these things."*	Practitioner/ author (#15)
	"Bioretention areas are contrived systems. […] you're trying to create a plant community in an environment that's contrived. It's not a naturally occurring type of environment. […] You don't have any consistency in your hydrology, which really starts to limit the types of plants that you can use. That's the reason we really tend to use more."	Practitioner (#7)
Adequate Soil Mix	*"The soil is really the mechanism. […] you just need to have as many binding sites in the soil as you can for the metals and these other pollutants to get adsorbed, so it's more of a chemical reaction. […] you need to have the right soil, but you also need to have a robust planting community that is living all the way through."*	Practitioner/ educator (#11)
	"…there are a lot of mixes out there, for whatever reason, that use a lot of sand. I think for their porosity, etc., and what happens is the bioretention areas tend to be very dry, exceedingly dry, and have a very low pH. And the bioretention plants that people tend to put into these rain gardens or bioretention areas tend to be wet plant material. […] Yeah, there'll be water standing in there for a period of time, but most of the time, these areas are dry, especially because of the amount of sand that's in these mixes."	Practitioner (#7)
Design for Swift Establishment and Reduced Maintenance	*"And I just list like plant mass grouping, using fewer varieties for easier recognition, using dwarf cultivars whenever possible for control, use of groundcover layer, air mulch, don't use plugs or seed, require hand-watering, be aware of sediment, salt, and your pressure like do a site visit. And then the second part of this is grade, plant material. So, understanding what that means and how heavy grade and retail ready, grade is important, plugs may not work, no seeds, and then spacing of plant material. And*	Practitioner (#12)

	these are just suggestions. So, you know, in order to get that quick establishment, component to weed suppression."	
	"So, for example, projects that have a mix of plantings are not as successful as ones that have groupings of plantings, because the groupings are very easy for a maintenance crew to identify. […] So that's been, you know, an example of keeping the designs simple but interesting at the same time, by having hierarchy, having trees, shrubs, ground cover, creating a hierarchy, to create different textures, different colors, different seasonality. […] But at the same time, not having so many plants that it's overwhelming, making that proportionate to the size of the space and making sure that we're having planting and massings are groupings so that they can identify weeds more easily.	Practitioner (#10)
Collaboration	*"I think there has to be more feedback loop with maintenance crews — people who are maintaining these facilities."*	Practitioner (#3)
Education	*"…and we're trying to do an outreach to department of permitting services. So I'm going to try to put together that positive PowerPoint that shows how a planting plan approach might be better and some guidance. […] And then the second part of that is to give the sediment control inspectors who go out and inspect these things and then sign off on them, understanding what they're looking for, because they're not educated in plants. This has been kind of pushed into their, you know, department."*	Practitioner (#12)

Finally, we compiled a short list of examples of the most relevant literature (Table 5) reviewed by the research team and/or recommended by the interviewees. This list includes up-to-date literature review articles on bioretention planting, books and articles with scientific findings on plants' phytoremediating capabilities, municipal bioretention planting manuals or guidelines, university extension websites, and plant databases.

Table 5. A short list of most relevant literature reviewed by the research team and/or recommended by the interviewees.

No.	Type	Theme(s)	Citation
1	Review article	Green infrastructure plant selection framework	Farrell et al. (2022)
2	Review article	Nitrogen removal in bioretention	Biswal et al. (2022)
3	Review article	Plant-microbial interactions in bioretention	Mehmood et al. (2021)
4	Review article	Plant-media interactions on bioretention performance	Skorobogatov et al. (2020)
5	Journal article	Decision-support tool to guide bioretention plant selection	Payne et al. (2018)
6	Journal article	Plant species and traits on metal treatment and phytoextraction in bioretention	Lange, Viklander, & Blecken (2020)
7	Book	Planting design principles and specific plant functionalities	West & Rainer (2015)
8	Book	Comprehensive guide on phytotechnology	Kennen, & Kirkwood (2015)
9	Manual	Landscape design guidebook	Philadelphia Water Department (2020)
10	Guidance document	Planting plan considerations for reducing maintenance	Department of Environmental Protection, Montgomery County, MD (2020)
11	University extension website	Regional bioretention plant recommendations	Penn State Extension (2014)
12	Plant database	Plant trait database	Kattge et al. (2020)

5 DISCUSSION & CONCLUSIONS

Through interviewing 15 experts with diverse backgrounds in bioretention research, practice, and education, we investigated critical factors driving current bioretention planting design decision-making, barriers to implementing phytoremediating plants, and identified design and management best practices for pollutant removal. Given the paucity of related research and the disconnection between science and practice, our study contributes to filling the essential gaps in bioretention planting design for multiple ecosystem benefits, especially pollutant removal.

First, the findings on factors influencing planting design decision-making reveal the complexity in balancing various objectives under differing project contexts. The fact that aesthetics, plant survival, maintenance, and soil characteristics were frequently rated as high priority echoes existing literature (Muerdter et al., 2018). The experts' suggestion to raise the priority of plant diversity and pollutant removal function verifies the critical need to integrate multi-functionality into bioretention planting design (Rainer, 2017).

Second, to address the five barriers identified, namely the knowledge gap, lack of resources, systems thinking, and collaboration, and regulatory and law constraints, more resources need to be allocated to advance cross-disciplinary scientific research and education, facilitate knowledge transfer between researchers and practitioners, and develop publicly available and user-friendly design guidelines. In addition, outdated laws or regulations need to be reviewed and updated to allow innovative design solutions to be adopted or tested for their effectiveness in achieving multiple ecosystem benefits.

Third, the five design and management best practices, including understanding the site, focusing on the water entryway, using appropriate plant traits and diversity, choosing adequate soil mix, and designing for swift establishment and reduced maintenance, align well with existing literature (e.g., Department of Environmental Protection, Montgomery County, MD, 2020; Person et al., 2020; Philadelphia Water

Department, 2020). Future work should continue to synthesize such best practices based on experiences in different regions and develop context-specific guidelines. Finally, collaboration, research, and education, underscored by most of our interviewees, are essential to reducing siloed approaches and facilitating a holistic design approach in future bioretention design.

Despite emerging research and practice guidelines on bioretention planting design, many critical knowledge gaps remain. Examples include the identification of environmental and management factors that contribute to planting successes or failures, metrics for evaluation, transferrable, mechanistic understandings of pollutant removal processes, associated plant traits useful for planting design, vegetation impacts on emerging contaminants, the impact of maintenance on system functions, and many more. Our study leverages perspectives from multiple types of planting experts to better understand the planting design decision-making process, reveal barriers to implementing phytoremediating plants, and compile best design and management practices. However, substantially more research in this area will be necessary to assist practitioners in rebuilding functional planting systems that safeguard the health of both people and the ecosystem in which we reside.

6 REFERENCES

Biswal, B. K., Vijayaraghavan, K., Adam, M. G., Lee Tsen-Tieng, D., Davis, A. P., & Balasubramanian, R. (2022). Biological nitrogen removal from stormwater in bioretention cells: A critical review. *Critical Reviews in Biotechnology, 42*(5), 713–735. https://doi.org/10.1080/07388551.2021.1969888

Center for Watershed Protection. (2020). *District of Columbia Stormwater Management Guidebook*. https://doee.dc.gov/swguidebook

Dagenais, D., Brisson, J., & Fletcher, T. D. (2018). The role of plants in bioretention systems; does the science underpin current guidance? *Ecological Engineering, 120*, 532-545.

Department of Environmental Protection, Montgomery County, MD. (2020). *BMP planting plan considerations for reducing maintenance*. https://mde.maryland.gov/programs/water/StormwaterManagementProgram/Documents/www.mde.state.md.us/assets/document/sedimentstormwater/Appnd_A.pdf

Environmental Protection Agency (EPA). (1999). *Preliminary Data Summary of Urban Storm Water Best Management Practices*. Washington, DC: Office of Water (4303).

Farrell, C., Livesley, S. J., Arndt, S. K., Beaumont, L., Burley, H., Ellsworth, D., Esperon-Rodriguez, M., Fletcher, T. D., Gallagher, R., Ossola, A., Power, S. A., Marchin, R., Rayner, J. P., Rymer, P. D., Staas, L., Szota, C., Williams, N. S. G., & Leishman, M. (2022). Can we integrate ecological approaches to improve plant selection for green infrastructure? *Urban Forestry & Urban Greening, 76*, 127732. https://doi.org/10.1016/j.ufug.2022.127732

Gaffield, S. J., Goo, R. L., Richards, L. A., & Jackson, R. J. (2011). Public Health Effects of Inadequately Managed Stormwater Runoff. *American Journal of Public Health*, 93(9), 1527-1535.

Glaister, B. J., Fletcher, T. D., Cook, P. L., & Hatt, B. E. (2017). Interactions between design, plant growth and the treatment performance of stormwater biofilters. *Ecological Engineering, 105*, 21-31.

Guba, E. G., & Lincoln, Y. S. (1994). *Competing paradigms in qualitative research*. Handbook of qualitative research, 2(163-194), 105.

Hopman, D. (2018, September 4). Call for Research Literature on Plants in Green Infrastructure. *The Field*. https://thefield.asla.org/2018/09/04/call-for-research-literature-on-plants-in-green-infrastructure/

Kattge, J., Bönisch, G., Díaz, S., Lavorel, S., Prentice, I. C., Leadley, P., ... & Cuntz, M. (2020). TRY plant trait database–enhanced coverage and open access. *Global change biology, 26*(1), 119-188.

Kennen, K., & Kirkwood, N. (2015). *Phyto*. Routledge.

Lange, K., Viklander, M., & Blecken, G.-T. (2020). Effects of plant species and traits on metal treatment and phytoextraction in stormwater bioretention. *Journal of Environmental Management, 276*, 111282. https://doi.org/10.1016/j.jenvman.2020.111282

LeFevre, G. H., Paus, K. H., Natarajan, P., Gulliver, J. S., Novak, P. J., & Hozalski, R. M. (2015). Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. *Journal of Environmental Engineering*, 141(1), 04014050. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000876

Liu, J., Sample, D. J., Bell, C., & Guan, Y. (2014). Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater. *Water*, 6(4), 1069–1099. https://doi.org/10.3390/w6041069

Mehmood, T., Gaurav, G. K., Cheng, L., Klemeš, J. J., Usman, M., Bokhari, A., & Lu, J. (2021). A review on plant-microbial interactions, functions, mechanisms and emerging trends in bioretention system to improve multi-contaminated stormwater treatment. *Journal of Environmental Management, 294*, 113108. https://doi.org/10.1016/j.jenvman.2021.113108

Miles, M. B., Huberman, A. M., & Saldana, J. (2014). *Qualitative Data Analysis*. SAGE.

Muerdter, C. P., Smith, D. J., & Davis, A. P. (2020). Impact of vegetation selection on nitrogen and phosphorus processing in bioretention containers. *Water Environment Research, 92*(2), 236-244

Muerdter, C. P., Wong, C. K., & LeFevre, G. H. (2018). Emerging investigator series: The role of vegetation in bioretention for stormwater treatment in the built environment: Pollutant removal, hydrologic function, and ancillary benefits. *Environmental Science Water Research & Technology*, 4, 592-612.

Payne, E. G. I., Pham, T., Deletic, A., Hatt, B. E., Cook, P. L. M., & Fletcher, T. D. (2018). Which species? A decision-support tool to guide plant selection in stormwater biofilters. *Advances in Water Resources, 113*, 86–99. https://doi.org/10.1016/j.advwatres.2017.12.022

Penn State Extension. (2014). Rain Gardens - the Plants. Retrieved from: https://extension.psu.edu/rain-gardens-the-plants

Person, J., Wethington, B., Evans, D., & Ogata, I. (2020, January 9). *The Field*. Retrieved from ASLA Professional Practice Network's Blog: https://thefield.asla.org/2020/01/09/performance-based-plant-selection-for-bioretention/

Philadelphia Water Department. (2020). *Green Stormwater Infrastructure Landscape Design Guidebook (Version 4.0, April 2020).* https://water.phila.gov/pool/files/gsi-landscape-design-guidebook.pdf

Rainer, T. (2017, March 14). *Designed to Fail: How Green Infrastructure Standards Create Conditions for Failed Plantings*. https://www.thomasrainer.com/blog/2017/3/25/green-infrastructure-10-has-failed

Shrestha, P., Hurley, S. E., & Wemple, B. C. (2018). Effects of different soil media, vegetation, and hydrologic treatments on nutrient and sediment removal in roadside bioretention systems. *Ecological Engineering*, 112, 116-131.

Skorobogatov, A., He, J., Chu, A., Valeo, C., & van Duin, B. (2020). The impact of media, plants and their interactions on bioretention performance: A review. *Science of The Total Environment, 715,* 136918. https://doi.org/10.1016/j.scitotenv.2020.136918

West, C., & Rainer, T. (2015). *Planting in a Post Wild World*. Portland: Timber Press.

Yadav, S. K., Singh, S., & Gupta, R. (2019). *Biomedical Statistics: A Beginner's Guide*. Springer Singapore. https://doi.org/10.1007/978-981-32-9294-9