LITERATURE REVIEW

water by design
an initiative of
Healthy land & water

Improving the biology of bioretention systems

Version 1.0

Version history

#	Date	Title	Contributors
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Purpose

This document synthesises over a decade's worth of knowledge and research to address deficiencies in filter media that may be responsible for the unsuccessful establishment and dieback of plants seen in bioretention systems. Based on this review, the document provides specifications for filter media as well as advice and options to improve and maintain healthy plants in bioretention systems.

About Water by Design

Healthy Land & Water's Water by Design initiative works with individuals and organisations to identify and fill knowledge gaps and facilitate the uptake of improved practices in sustainable water management. For more information visit www.waterbydesign.com.au.

About Healthy Land & Water

Healthy Land & Water is the peak environmental group for South East Queensland. For over 20 years it has been dedicated to investing in and leading initiatives to build the prosperity, liveability, and sustainability of our future region. Healthy Land & Water is focused on delivering an environment for future generations to thrive.

We are experts in research, monitoring, evaluation, and project management. Our team has led many thousands of projects to restore receiving waters and landscapes, improve native habitats, manage weeds, protect native species, inform policy, and educate communities on the best ways to improve and protect the environment.

Working in partnership with Traditional Owners, government, private industry, utilities and the community, Healthy Land & Water delivers innovative and science-based solutions to challenges affecting the environment. Through a combination of scientific expertise and on-ground management works, Healthy Land & Water lead and connect through science and actions that will preserve and enhance our natural assets and support resilient regions long into the future.

Traditional Owner acknowledgement

We acknowledge that the place we now live in has been nurtured by Australia's First Nations' Peoples for tens of thousands of years. We believe the spiritual, cultural, and physical consciousness gained through this custodianship is vital to maintaining the future of our region.

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List of abbreviations and acronyms

CEC	Cation exchange capacity
CRCSWC	Cooperative Research Centre for Water Sensitive Cities
FAWB	Facility for Advancing Water Biofiltration
SOM	Soil organic matter
TOC	Total organic carbon (sometimes referred to as soil organic carbon)
WSUD	Water sensitive urban design

1 FOREWORD

From 2005 to 2009, the Facility for Advancing Water Biofiltration (FAWB) undertook extensive research into bioretention filter media. This research, combined with practical experience, lead FAWB to develop bioretention filter media specifications to guide practice (FAWB 2006). The FAWB specifications were later updated (FAWB 2009; FAWB 2012) as further research was published and in 2015, these guidelines became the basis of the filter media specifications provided in the *Adoption Guidelines for Stormwater Biofiltration Systems* (CRCWSC 2015). During the same period, Griffith University in Queensland was also independently undertaking valuable bioretention research.

However, with the cessation of FAWB's operations and scaling back of bioretention research by Griffith University in 2009, research into non-proprietary bioretention filter media in Australia and the publication of related journal articles has become limited and sporadic. That is not to say that industry knowledge on bioretention media performance in Australia has ceased progressing. Since this time, countless bioretention systems have been designed, constructed, established, maintained, and rectified, and along the way, applied industry knowledge has progressed.

While some of this knowledge has been published in conference papers, theses, or debated in forums, much of it remains undocumented. Outside of Australia, research and practice have continued in earnest, from which lessons could be derived locally. This research and the new knowledge it offers is the key driver for this update to the bioretention filter media specifications.

In addition, despite decades of research and practice internationally, there is still a lot to be learnt about how bioretention systems function and how they can be further optimised. One of the key observations of many water sensitive urban design (WSUD) practitioners in Australia is that plants often struggle to establish, particularly compared to the more robust growth of batter planting. Plants in bioretention systems are also failing after several years despite successful initial establishment, with the cause of the dieback typically not linked to construction or establishment issues. These findings are based upon commonly and widely reported anecdotal evidence as well as empirical evidence.

For example, an audit of 119 bioretention systems undertaken by Moreton Bay Regional Council (a region with a subtropical climate and mean annual rainfall of 1250 mm), found that 41% (n = 49) of bioretention systems were experiencing plant dieback (Dalrymple *et al*. 2018). These statistics include assets recently transferred to Council which would be expected to be in good condition. A smaller audit by a Sydney local government also reported four out of five bioretention systems with extensive plant dieback (Dalrymple *et al*. 2018). These observations are not limited to any one region or state in Australia. However, it is noted that in some areas with more consistent and higher mean annual rainfall, plant dieback may be less pronounced.

While the reasons for the observed plant dieback are many and varied, common issues are emerging. These include a lack of maintenance (e.g. shading out by weeds), prolonged dry periods, inadequate flow distribution (especially in larger bioretention systems), the repeated application of herbicides and brush cutting to manage weeds, inappropriate plant species selection, and low water holding capacity of filter media. For many bioretention systems, a combination of these issues may be at fault. However, low water holding capacity of filter media appears to be a universal factor in bioretention systems with plant dieback. This highlights the need to make bioretention systems more resilient to factors which cannot be readily controlled, such as rainfall. Preferably, this would be achieved without compromising stormwater quality improvement outcomes.

Changes in bioretention filter media specifications should be based upon extensive research. While some local governments are undertaking bioretention research (notably Blacktown City Council in New South Wales), there are no other known extensive scientific programs planned in Australia to investigate bioretention filter media performance (at least not at the FAWB scale of investment).

Currently, the leading guidelines used throughout Australia (CRCWSC 2015) include specifications which may potentially exacerbate plant dieback and long-term bioretention performance. Specifically, they suggest that organic matter content should be ≤5%, meaning that media with 0% organic matter would be compliant. However, such media would be unlikely to support typical bioretention plant species long term, especially during drought conditions and/or in climates with prolonged annual dry periods. Thus, the potential exists for media to be used that is compliant with the CRCWSC specifications, but incompatible with successful plant establishment, longevity, and long-term bioretention performance.

In a bid to overcome this issue, some WSUD practitioners have been ameliorating the top 100 mm of filter media with organic material, fertiliser and trace elements. Guidance for this one-off amelioration is available in *Guidelines for Filter Media in Biofiltration Systems* (FAWB 2009) and *Adoption Guidelines for Stormwater Biofiltration Systems* (CRCWSC 2015). This may assist with initial plant establishment, but it is unclear what value it provides to plants in the long term, and what impact it has on water quality in the short term. Initial plant establishment also does not appear to be the problem if adequate watering is undertaken during the establishment phase, so amelioration will not prevent longer-term plant dieback. Saturated zones are another way to improve plant longevity, but they are not feasible in every scenario – this is discussed further below.

This leaves the industry with two key options:

- **Option 1**: Continue to construct bioretention systems in accordance with current specifications knowing that there is likely an issue which contributes to long-term plant dieback in many climates zones (i.e. the 'do nothing' approach).
- **Option 2**: Investigate the issue using current available scientific and industry knowledge and develop revised specifications.

While it is acknowledged that there are limitations with Option 2, there are considerable risks with Option 1. For example, there is already significant funding being invested in bioretention systems – one estimate by Healthy Land & Water in 2011 indicated a $3 billion investment in bioretention systems in Queensland over a 30-year period (or $100 million annually). If bioretention plants fail after several years, that investment is not realised, and developers and local authorities could become reticent to further invest in these systems.

In some regions, plant dieback in bioretention systems has already resulted in potentially misguided backlash against their implementation and raised questions about broader WSUD philosophy. Added rectification costs due to plant dieback only contributes to these negative responses. While it is technically feasible to design bioretention systems without plants and still meet water quality objectives, plants provide immense value in terms of bioretention adoption.

Unvegetated bioretention systems are also characterised by a range of other problems. They lack the same aesthetic appeal as fully vegetated systems, are more prone to weed incursion (leading to increased maintenance costs), have reduced hydraulic efficiency (Hatt *et al*. 2009), contribute less to microclimate management, and have lower biodiversity value.

Perhaps most importantly, plants have been shown in numerous studies to remove nutrients from stormwater (Denman *et al*. 2007; Hatt *et al*. 2007; Henderson 2007; Bratieres *et al*. 2008; Read *et al*. 2008). There are clear implications to downstream water quality associated with plant dieback in bioretention systems.

Option 2 is not without risks either. For example, desirable traits of the filter media could be unintentionally corrupted if changes to specifications are made without adequate knowledge. These risks can be managed, in part, by using the best available scientific literature. There is also an opportunity to use the literature to improve the water quality performance of bioretention systems by establishing desirable soil functional properties. This applies regardless of whether or not plant desiccation is caused by low organic matter in bioretention filter media. Seeking industry feedback on this document and revising it as further information becomes available will also help improve confidence.

In contrast, there are limited options available to manage the risks of Option 1. Healthy Land & Water does not support the 'do nothing' approach given the expected investment in bioretention systems and potential risks to waterway health. After weighing the risks of each option, Option 2 is considered more pragmatic and has been adopted by Healthy Land & Water.

This document has been developed to provide the industry with the option to either continue to use the existing specifications, or use the new specifications (the recommended approach). It should also be noted that there is significant opportunity for further innovation beyond the solutions provided in this document. The risks of each approach need to be considered and balanced individually by local government authorities, who ultimately decide on which option they will adopt.

This document has been released with the specific intent to further capitalise upon emerging science and practice with a view to enhance the specifications over time. We have enabled a 12 month feedback period on this document to ensure it is fit for purpose and captures end user experience. We welcome your feedback and encourage you to submit all comments to info@hlw.org.au by 1 September 2024.

2 SPECIFICATION OPTIONS

There are two options for bioretention filter media presented in this document. Ultimately, it is at the discretion of local governments to specify the preferred option. In determining the preferred option, local governments should give due consideration to a range of factors, including:

- The values offered by both types of bioretention filter media.
- The inherent risks associated with each option.
- Locally-specific conditions, such as current (and expected changing) climate patterns and bioretention resilience through atypical dry conditions.

It is recommended that Option 2 is adopted by local governments. Where local governments indicate compliance with this document, it is also recommended that they make it clear which option they have adopted.

2.1 Compliance with existing guidelines

Some WSUD practitioners have reported good establishment of bioretention systems using bioretention filter media which is compliant with the *Guidelines for Filter Media in Biofiltration Systems* (FAWB 2009) or *Adoption Guidelines for Stormwater Biofiltration Systems* (CRCWSC 2015). It is unclear however, whether those systems will continue to support plants in the longer term (5+ years), especially during drought conditions and in a changing climate.

The minimum organic matter content (0%) in the CRCWSC guidelines (2015) is unlikely to be suitable in drier climates, especially where there is limited water holding capacity to sustain plants through prolonged dry periods. However, where local authorities have expressed confidence that using bioretention filter media which is compliant with the CRCWSC guidelines is supporting plants in the long term (5+ years), for example in areas with high rainfall year-round or where other measures are implemented to address low organic matter (e.g. permanent irrigation), the continued use of those specifications may be justified locally.

Note that low organic matter in bioretention filter media affects a range of soil physical, chemical and biological properties apart from low water holding capacity. This is discussed in further detail in Section 3 to give local governments a better understanding of the broader benefits associated with increasing the appropriate type of organic matter. Also note that many of the other parameters for bioretention filter media in Option 2 have been revised to make compliance easier, especially in regional areas where sourcing materials is typically more challenging.

2.2 Compliance with these specifications

The alternative option presented in this document seeks to incorporate the best available science since the publication of the FAWB guidelines (2009) while also addressing the issue of plant dieback in bioretention systems observed across Australia. A range of other benefits are also expected, as discussed in Section 3.

The specifications provided in Section 4 are based primarily on *Guidelines for Filter Media in Biofiltration Systems* (FAWB 2009) and *Adoption Guidelines for Stormwater Biofiltration Systems* (CRCWSC 2015). The three most notable exceptions are the specifications for organic matter content, hydraulic conductivity and particle size distribution, which have been changed. Each of these are discussed in greater detail in Section 3. Other minor amendments have also been made regarding specification parameters and media testing, which have been derived from recent work by Blacktown City Council (2021).

3 THE SCIENCE UNDERPINNING THE SPECIFICATIONS

As noted in Section 2, the changes to organic matter content, hydraulic conductivity, and particle size distribution are the key deviations from the CRCWSC guidelines (2015). Each of these changes and the associated benefits are discussed below. The section concludes with a figure which maps the complex web of relationships within the soil of a bioretention system. Readers can refer to this figure throughout this section to help keep track of each component, process and benefit within the ecosystem.

3.1 Organic matter

Organic matter is the key to living soil. It provides a range of benefits, including:

- Improving soil aggregation, structure and hydraulic conductivity.
- Providing a source of carbon, which improves water holding capacity.
- Improving soil cation exchange capacity (CEC), which is essential for binding mobile nutrients and soil fertility.
- Supporting fungi and mycorrhizal associations, the relationship between plant roots and fungi which provides mutual benefits.
- Supports and encourages colonisation of soil fauna including:
    - Microfauna (e.g. bacteria and fungi).
    - Mesofauna (invertebrates between 0.1 mm and 2 mm in size).
    - Macrofauna (animals that are >2 mm, including beetles, ants and earthworms).
- Provides a food source for plants and soil fauna.

Collectively, these benefits are essential to healthy soil and microbial communities and therefore critical to the long-term health of bioretention plants.

Initial studies undertaken by FAWB (Fletcher *et al*. 2007; Bratieres *et al*. 2008; Hatt *et al*. 2009) concluded that high organic matter in bioretention filter media results in high nutrient leaching. This led to the recommendation in the FAWB (2009) and CRCWSC (2015) guidelines for low organic matter in filter media (as low as 0% in the CRCWSC guidelines).

However, when organic content is too low, there are both direct and indirect impacts on the benefits which organic matter provides. For example, soil structure and hydraulic conductivity are improved when soil fauna, plant roots and fungal hyphae work together to form soil aggregates. When there is a lack of soil organic matter, soils can no longer support enough of these beneficial biological actors, leading to a breakdown of soil aggregation. This in turn reduces hydraulic conductivity and the ability of plant roots to absorb water and nutrients, further impacting soil fauna, plant roots and fungal hyphae. This can lead to a self-perpetuating cycle of soil decline over time, potentially leading to clogging, plant desiccation, and a subsequent decline in the water quality performance of bioretention systems.

Water quality performance can also decline as result of plant dieback. Lucas and Greenway (2008) compared vegetated and non-vegetated mesocosms and demonstrated that nitrogen oxides (NOx) were retained in vegetated systems by up to 74%, whereas the unvegetated mesocosms leached NOx. They attributed the increased NOx retention to vegetative uptake and microbial activity within a well-established plant rhizosphere. Numerous other studies have also demonstrated the importance of plants for reducing nutrients, including by minimising leaching (Denman *et al*. 2007; Hatt *et al*. 2007; Henderson 2007; Bratieres *et al*. 2008; Read *et al*. 2008). If bioretention filter media is unsuitable for sustaining plants in the long term due to low water holding capacity associated with low organic carbon, increased nutrient leaching from bioretention systems can be expected as plants desiccate over time.

3.2 Soil organic carbon

Larsen (2018) reviewed numerous studies that identified a soil organic carbon (SOC) level of 2% (dry weight (d/w), wet weight (w/w)) as a critical lower limit for establishing and maintaining a range of key soil functional properties, including CEC, aggregate stability, and biodiversity of microbial communities. The health of these microbial communities also has implications for stormwater quality treatment, as the fate of dissolved nitrogen in bioretention systems is often dictated by a series of biochemical reactions mediated by microorganisms.

These include the following steps (LeFevre *et al*. 2015):
1. Initial ammonification of organic nitrogen to ammonia or ammonium.
2. Then, ammonia or ammonium can be oxidised, first to nitrite and then to nitrate, through the process of nitrification.
3. Finally, nitrate can be converted to nitrogen gas under anoxic conditions through denitrification.

Moreover, Larsen's (2018) work highlighted that the 3% soil organic matter (SOM) limit in the FAWB guidelines (2009) equated to a 0.26% TOC deficiency after converting SOM to TOC (or a 0.5% TOC deficiency using an updated conversion factor). Larsen (2018) further identified this as a matter of particular concern given that TOC may further decline over time via microbial respiration, if no additional sources of labile carbon enter the filter media. Total organic matter values of 3% (the lower limit in the 2009 FAWB guidelines) can result in TOC concentrations of less than 2% in filter media, given that approximately 58% of organic matter is organic carbon (Larsen 2018). In such cases, desirable soil functionality and plant/microbial health would decline or fail to establish within bioretention systems as a result of the low organic carbon content.

The SOC content of bioretention filter media should therefore not be any less than 2% (d/w, w/w). Equally, the level cannot be too high, as this increases the risk of nutrient leaching (as identified in the aforementioned FAWB studies). The upper limit of total organic carbon (TOC) in the specification for bioretention filter media in Section 4 has therefore been set to 2 – 3% (d/w, w/w). This is separate to the organic matter content specification for compost, which is also provided in Section 4.

A factor which has not been accounted for well in Australian specifications to date is the type of organic matter used in bioretention filter media. In their analysis of other studies, Dubowski *et al*. (2016) identified that both the quality and quantity of organic carbon in feedstock (which makes up the compost used in bioretention filter media) influences the rate of leaching, with highly labile carbon forms resulting in the most leaching. Thus, not all types of organic carbon will result in the same rates of leaching.

While all types of carbon will result in some leaching of nutrients, the amount of leaching associated with different types of carbon needs to be considered. Leaching potential is lowest with the more stable forms of carbon, which have low nutrient concentration and decay more gradually. A simplified model of leaching from different types of soil carbon is provided in Table 3.1.

Table 3.1 Simplified model of carbon in soils.

Type of carbon	Stability	Period of decay	Nutrient concentration	Leaching potential
Labile/humified	Unstable	Weeks to decades	High	High
Stable/resistant	Moderately stable	Decades to centuries	Medium	Medium
Recalcitrant	Highly stable	Centuries to millennia	Low	Low

The aim should be to balance the labile carbon content in bioretention filter media to reduce nutrient leaching, rather than reducing overall organic matter content at the expense of the associated benefits it provides.

Equally, it is important not to rely strictly on the more stable forms of carbon, as this could risk limiting bioavailable nutrients essential for plant and microbial communities. Labile carbon supports soil microorganisms which in turn, add to the total soil carbon present through their biomass.

Therefore, a balance of all three types of carbon is needed. This can be achieved by using a compost feedstock with a suitable balance of carbon quality and quantity. Table 3.2 provides an example of how using a balanced labile carbon compost at higher percentages than is traditionally used in bioretention filter media can result in a lower percentage of labile carbon overall and lower nutrient leaching potential.

Table 3.2 Indication of labile carbon as percentage of filter media/compost mix.

Percentage of filter media (v/v)	Percentage of compost (v/v)	Equivalent percentage of compost (w/w)	Labile carbon as percentage of total filter media/ compost mix*
95%	5%	1.75%	1%
85%	15%	5.25%	2.5%
80%	20%	7.0%	3.4%
70%	30%	10.5%	5%

* Expected value based on advice of industry panel for 100% aged mature green waste.

Based on Table 3.2, using the correct type of compost means that even at 30% compost by volume, only 5% of labile carbon is expected. By comparison, is noted that some specifications from the United States of America (USA) specify up to 40% volume per volume (v/v) compost. Examples of where this is used include Seattle Public Utilities (2008), Puget Sound Partnership (2009), City of Portland (2020) and Department of Ecology State of Washington (2019a; 2019b).

As labile SOC is the primary nutrient supply for plants and microorganisms, maintaining some supply of labile SOC through onsite bioaccumulation, a mulch layer, or incoming organic matter in stormwater is desirable, as labile carbon pools will decline over time through microbial respiration. To achieve this, particular plant species need to be included in the planting list. Areas known to have numerous established trees upstream from the proposed bioretention system may not need a bioaccumulation bias in the planting list as leaf litter and other organic material may enter the system during rain events. Amending existing soil with labile SOC after the media has been placed is more cost intensive and less desirable, as the rapid input may cause leaching.

Hurley *et al*. (2017) assessed the nutrient leaching potential associated with five different compost types and two compost-amended bioretention soil mixes. Their results indicate that leaching of phosphate (PO_4^{3-}) was significantly higher from pure compost samples relative to the bioretention compost soil mixes. While they did not specifically discuss labile versus stable forms of carbon, leaching of soluble nutrient components (phosphate (PO_4^{3-}), nitrate (NO_3^-), and ammonium (NH_4^+)) was typically lowest in the bioretention soil amended with the most stable form of carbon tested (leaves and/or yard waste) for most saturation durations tested.

As compost breaks down, there is potential for an increase in the percentage of fine material. However, as mature compost typically improves soil structure and hydraulic conductivity, this is not considered to be an issue of concern (discussed further below). Higher organic matter content results in increased plant root mass, which helps to increase hydraulic conductivity and attract soil fauna.

3.3 Soil fauna and bioturbation

Increased organic matter encourages and supports more robust communities of soil fauna. This includes those involved in soil bioturbation, which is the process of mixing plant residues into soils and sediments by biotic activity. While this is a very simplistic explanation of bioturbation and its values, bioturbators (e.g. earthworms, ants, beetles) provide a host of soil development services, which has earned them the title of ecosystem engineers. These services include the development of soil structure, water regulation, nutrient cycling, primary production, and even climate regulation (Blouin 2013).

The terms 'bioturbators' and 'ecosystem engineers' are also used to describe larger vertebrate soil fauna which may be present in bioretention systems, the impact of which has never been studied directly. These include Australia's 29 species of digging mammals (e.g. bandicoots, bettongs, potoroos, bilbies and echidna) which despite their small size, can turn over 1.8 – 3.6 tonnes of soil per kilogram of body mass each year (Flemming *et al*. 2014). Studies examining bandicoots have shown that they can turn over 4.8 tonnes/annum (Garkaklis *et al*. 2004) while greater bilbies (*Macrotis lagotis*) can turn over up to 20 tonnes/annum (Australia Wildlife Conservancy 2022).

This soil turnover provides a range of additional services, including:

- Improving plant seed germination.
- Trapping of organic matter and other materials.
- Increasing nutrient turnover.
- Improving uptake of carbon, turning soils into carbon sinks though carbon sequestration.
- Dispersal of fungal spores, with fungi helping plants to access nutrients unlocked by the soil fungal network (discussed further below).
- Increasing the carbon in soils increases the invertebrate bioturbator populations such as earthworms and beetles, which in turn attracts the larger mammal bioturbators which predate these species.

A healthy balance of different types of soil fauna will assist in improving soil hydraulic conductivity. For example, earthworms have been demonstrated to provide:

- A preventive measure of clogging in vertical flow wetlands (Atalla *et al*. 2019).
- The production of soil macropores (Nogaro & Mermillod-Blondin 2009).
- Increased hydraulic conductivity of stormwater infiltration systems (Nogaro & Mermillod-Blondin 2009).

Li and Davis (2008) found no clogging of bioretention filter media after 1.5 years of field monitoring and attributed vegetation and soil fauna as the reason for maintaining acceptable permeability. In their review, Fassman *et al*. (2013) suggested that bioretention column studies which do not include soil fauna, particularly bioturbators, most likely overestimate the state of clogging in bioretention cells. They went on to suggest that these studies may be more reflective of the maximum potential for clogging rather than the typical potential.

Bioturbators can provide a range of other benefits in bioretention systems. Nogaro and Mermillod-Blondin (2009) demonstrated that a bioturbation-driven modification of hydraulic conductivity in stormwater infiltration systems may positively affect whole-system functioning, including aerobic and anaerobic processes and pollutant fluxes. Mehring and Levin (2015) noted that when earthworm activity causes increased plant nutrient uptake, the effects can be substantial. This was further demonstrated by Xu, Li and Howard (2013) in their study of vertical flow constructed wetlands. They showed that uptake of nitrogen and phosphorus increased as much as 216% and 355% respectively once earthworms were added.

Soil fauna can also have strong positive effects on plant growth and survival, including directly through nutrient recycling and through their interactions with beneficial fungi, namely mycorrhizae (Mehring & Levin 2015). Soil fauna has also been shown to have a positive effect on the growth of plants and the plant rhizosphere which, in turn, improves soil structure. Bioturbators are also commonly used internationally in the remediation of contaminated soils, in a process known as bioremediation.

Most of the laboratory-based column studies, while extremely valuable, provide a limited understanding of how mature bioretention systems (with advanced pedogenesis and a diverse community of soil fauna) actually function. Equally, most of the field-based studies are undertaken on younger bioretention systems, either largely absent of organic matter or relying on compost feedstocks with high labile carbon content.

In their review of existing literature, Mehring and Levin (2015) highlighted a distinct lack of research exploring the relationships between soil fauna and the functioning and performance of bioretention systems. They suggested that the lack of soil fauna in bioretention research studies may contribute to differences in observed function in field and laboratory settings. This is not surprising given that they also state that "*soil fauna have the potential to substantially alter plant growth, water infiltration rates, and the retention and removal of pathogens, nutrients, heavy metals and other contaminants*".

While it is clear that soil fauna have significant potential to influence the functioning of bioretention systems, they are not well accommodated by current bioretention filter media specifications due to low organic matter and water holding capacity. Currently, most Australian bioretention filter media specifications drive a relatively barren soil environment for soil fauna and while some colonisation can be expected, abundance and diversity is limited.

3.4 Pedogenesis

The limiting effect of current bioretention filter media specifications can decrease over time through a process known as pedogenesis. Pedogenesis is the gradual change in soil that occurs naturally in response to weathering, plant growth, decomposition, and the activities of soil fauna (Johnson & Watson-Stegner 1987). As these processes are most prevalent at the surface of soil environments, the development of organically and biologically enriched horizons is also likely to occur most rapidly at the surface of bioretention systems.

Bioretention systems located adjacent to established vegetation with high leaf litter loads (or where there is regular leaf litter load delivered through stormwater) are expected to experience increased rates of pedogenesis (Figure 3.1). In the bioretention system pictured, an abundant bioturbator community was observed in the top layer. The system was located next to an established eucalypt forest with a high leaf litter load.

Pedogenesis is typically a slow process – it takes around ten years just to observe the beginnings of pedogenesis in bioretention systems (Ayers & Kangas 2018). Ameliorating the surface of bioretention systems (including by adding a compost layer) effectively speeds up surface pedogenesis. Below the organic rich surface layer, however, bioretention filter media remains relatively barren.

Figure 3.1 Pedogenesis forming in a mature bioretention system.

In their study of ten bioretention systems in the field, Ayers and Kangas (2018) found that root biomass and the abundance of earthworms and macroinvertebrates increases throughout the soil profile with time. However, they also found that soil organic matter and macrobiological activity decreases exponentially with depth (Ayers & Kangas 2011). Increasing the organic matter content of the bioretention filter media immediately creates a favourable environment throughout the filter media profile, providing conditions which encourage soil fauna abundance and diversity as soon as the bioretention system is constructed.

In terms of the potential for bioretention systems to aid in carbon sequestration, Kavehei (2019) demonstrated that carbon quickly accumulates in the top 5 cm layer (where pedogenesis is occurring), while in the lower depths it accumulated at a more gradual rate. The results show that bioretention systems could be designed for the enhancement of their carbon sequestration potential, and amendments in their design, such as addition of a carbon source layer, are important for better managing carbon availability in the basins. Providing the right type of SOC throughout the bioretention filter media profile is therefore a better option than simply ameliorating the surface.

3.5 Fungi and mycorrhizal associations

Mycorrhizal associations have been defined as "*a mutualistic association between plant roots and fungi, where plants provide photosynthetically derived carbohydrates to fungi, and fungi deliver nutrients and water to plants and offer protection from abiotic and biotic stress*" (Smith & Read 2008). Mycorrhizae spores germinate in the soil and form fine filaments called hyphae which attach to plant roots (the rhizosphere), creating a symbiotic relationship. This network of hyphae is called the mycelium.

Poor *et al*. (2018) evaluated the impact of mycelium on nutrient leaching from three different bioretention filter media. Firstly, they added ectomycorrhizal and endomycorrhizal fungi to a bioretention filter media to promote mycelium growth (Media 1 mix – fungi only). Next, they added a proprietary mix of bacteria and mycorrhizal fungi to bioretention filter media (Media 2 mix – fungi plus bacteria). The control bioretention filter media did not have any fungi or bacteria added (Media 3 mix – control) to enable comparisons in water quality performance with the other two media.

Their results indicated that for Media 1 mix, total phosphorus and phosphate leaching was reduced by 13 – 48% and 14 – 60% respectively compared to the control media (Media 3 mix). They also found that Media 1 mix resulted in greater nitrate retention compared to the control, as well as additional copper uptake. For Media 2 mix, retention rather than leaching of total phosphorus and phosphate was observed. While leaching of nitrate was high from Media 2 mix, Poor *et al*. (2018) noted that the presence of mycorrhizal fungi in the soil likely increased uptake of nitrate compared to the control.

McIntyre *et al*. (2020) studied bioretention filter media (60% sand, 40% compost by volume) with plants, mulch, and inoculation with mushroom mycelium in different combinations in 12 bioretention cells. Similar to the findings of Poor *et al*. (2018), they found that fungi improved water quality for a range of water quality parameters including total phosphorus, orthophosphate, nitrates, dissolved organic carbon, dissolved copper, total lead, and total zinc. They also observed a decrease in fungal activity in the second year of their study as the mulch degraded, highlighting the need to have a longer-term store of carbon in the filter media. Such results may be conservative given that in the same way that studies which lack bioturbators likely overestimate potential for clogging (Fassman *et al*. 2013), it is likely that studies which lack healthy populations of mycorrhizal fungi overestimate potential for leaching.

The benefits of fungi and mycorrhizal associations are not limited to improved water quality treatment. They also include:

- Improved aggregate stability and enhanced soil structure (important where fine particles are included in bioretention filter media, as discussed below).
- Formation of stable soil carbon (discussed above).
- Improved efficiency of water and nutrient uptake by plants (important for both water quality and plant health/longevity).
- Supporting soil fauna.

The benefits of fungi and mycorrhizal associations are also not limited to the relationship between plants and fungi, and there are potentially significantly greater benefits to stormwater quality treatment beyond those suggested by the above studies. For example, mycorrhizal associations are also known to provide benefits between plants. Via the mycelium, plants exchange nutrients, carbon, and water between one another. Given that mycelium networks can stretch over several kilometres, there is potential for plants to access water from outside bioretention systems, helping to sustain them through prolonged dry periods (assuming the bioretention system is not lined). Mycorrhizal fungi can also increase drought resistance by increasing the number and depth of plant roots.

Equally, there is potential for plants outside the filter media to assist in nutrient removal from bioretention systems via the mycelium. In these circumstances, water and pollutant losses would be expected to increase due to connections with plants external to the bioretention filter media (again assuming the bioretention system is not lined). This may include plants growing upon bioretention batters or even further afield. As there are no known studies to confirm whether this is feasible, this represents a significant new area of potential research for bioretention systems.

In any case, the available research highlights the need to maintain a suitable environment for fungi in bioretention filter media (beyond simply adding mulch or ameliorating the surface) to realise and maintain the water quality benefits associated with fungi and mycorrhizal associations. This includes the use of more stable forms of carbon, which prolong favourable growing conditions for fungi and bacteria.

3.6 Hydraulic conductivity

Hydraulic conductivity is a measure of how easily water can pass through soil or rock. The higher the hydraulic conductivity, the less water retention and the more likely that plants will wilt and desiccate. Therefore, increasing the hydraulic conductivity too much is not desirable.

Increasing organic matter content could in theory increase fine particles from organic matter as it breaks down, thereby reducing hydraulic conductivity. However, in one laboratory bioretention column experiment, increased organic matter content was shown to have no effect on hydraulic conductivity (Goh 2015).

Other studies have found mixed results. In a series of column experiments testing saturated hydraulic conductivity (Ksat) of compost amended sand, Paus *et al*. (2014)

found Ksat rates of 1830, 870, 460 and 370 mm/hour for columns with 0, 10, 30, and 50% compost volume fraction (CVF), respectively. The authors attributed the decreasing Ksat to a high percentage of fine particles in the compost used. However, the results were all well above design hydraulic conductivity rates of Australian bioretention systems.

Another study by Olson *et al*. (2013) showed an increase in Ksat with increasing compost content. They found that compost was even more effective than tilling for reducing the soil strength and compaction and increasing infiltration. The geometric mean of Ksat on their compost plots was 2.7 – 5.7 times that of the control plot. As discussed, these laboratory studies may be more reflective of the maximum potential for clogging rather than the typical potential, as they do not account for soil fauna (Fassman *et al*. 2013) and would have limited aggregation due to the low organic matter.

The upper value for hydraulic conductivity provided in Section 4 has been increased compared to other bioretention media specifications, allowing a faster flow rate. This has been done both to compensate for any potential reduced hydraulic conductivity associated with the decay of compost, and to enable further innovation in bioretention filter media design.

A hydraulic conductivity value of up to 750 mm/hour was recommended in the *Construction and Establishment Guidelines: Swales, Bioretention Systems and Wetlands* (Water by Design 2010). While rarely used in practice, this is a reasonable value to enable some flexibility should field studies or observations suggest a decrease in hydraulic conductivity due to increased organic matter.

Further flexibility can be considered if this initial value is still too low. Initially, it is recommended that hydraulic conductivity is not increased above 500 mm/hour even with increased organic matter content, unless there are reasonable grounds for doing so. In practice, it may be difficult to increase hydraulic conductivity beyond 500 mm/hour if increasing the organic matter content as suggested in Section 4.

It is noted that some companies are producing proprietary bioretention systems with filter media hydraulic conductivity values in excess of 3000 mm/hour and still achieving good plant growth. This is expected to be due a range of factors, including the use of additives in their filter media, the use of mulch to retain moisture, regular maintenance (especially top up of mulch) and local climatic conditions. However, these examples help to demonstrate the potential amount of flexibility which can be considered in the future as knowledge and science of non-proprietary bioretention system media evolves.

A key consideration in increasing hydraulic conductivity is its effect on the hydrologic benefits that bioretention systems provide to receiving waterways, as any increase in volumetric losses increases the urban stream syndrome described by Walsh *et al*. (2005). This is clearly not the intent of these specifications. As such, if a bioretention filter media with a hydraulic conductivity above 300 mm/hour is used, this should not change the way the system is modelled or the size of the bioretention system. For clarity, the system should still be modelled with hydraulic conductivity of no more than 200 – 300 mm/hour.

3.7 Particle size distribution

Clay, silt, and very fine sand content play an important role in maximising water holding capacity. However, their content has been limited in Australian specifications due to concerns about clogging and structural collapse of the soil. Bioretention filter media specifications in the USA typically allow for a much higher content of fine particles than Australian specifications, which limit fine particles to <3% clay and silt combined. For example, the clay and silt content recommended in Maryland is up to 25% and 55% respectively (Maryland Department of the Environment 2009). An earlier version of the FAWB guidelines (FAWB 2006) recommended up to 4% clay and 8% silt, however this was later reduced to address concerns about clogging and structural collapse.

Despite the higher percentage of fine particles allowed by USA specifications, clogging and structural collapse of bioretention filter media in the USA does not appear to have been widely reported. Several studies which have examined particle size distribution have actually suggested the opposite (i.e. that higher silt and clay content does not result in clogging) (McIntyre *et al*. 2002; Jenkins *et al*. 2010; Selbig & Baster 2010). Wardynski and Hunt (2012) analysed 43 field-based bioretention systems and concluded that the percentage of fine particles in the soil media was not found to be a significant predictor of permeability. The differences between expected clogging in bioretention systems in Australia and the USA are strongly tied to organic matter content.

The increased organic matter of USA specifications results in increased aggregate formation and bioturbator communities. Studies suggest that this organic matter and the associated soil fauna help to maintain hydraulic conductivity and prevent clogging and structural collapse despite a higher percentage of fine particles (Li & Davis, 2008; Nogaro & Mermillod-Blondin 2009). This is achieved through the presence of fungi, bacteria and other soil fauna, which all play a role in the formation of organic glues and aggregation (the binding of particles into larger units or peds). Along with chemical bonds and physical adhesion, these organic glues bind aggregated peds (often a congregation of sand, silt and clay). As previously discussed, increased plant and root growth, dieoff of plant roots, as well as bioturbation caused by soil fauna, create both micropores and macropores that enhance the permeability and ecological functions of soils (Mitchell *et al*. 1995; Hatt *et al*. 2009).

Several studies identified by Larsen (2018) suggest that soils with low SOM and clay content are vulnerable to nutrient leaching due to having low CEC (Kang *et al*. 2011; Murphy 2014; Azevedo *et al*. 2018). When comparing these studies with the FAWB guidelines (2009), Larsen (2018) identified many similarities, including their sand base, very low clay content, and reliance on SOM (particularly humus) in establishing CEC. This lack of a negative charge in the filter media lead Larsen (2018) to suggest that:

- Bioretention systems could become a source of nutrient pollution for receiving aquatic systems, as demonstrated by Mullane *et al*. (2015).
- Having low CEC may also compromise a bioretention system’s ability to absorb dissolved nutrients and pollutants from stormwater.
- With low nutrient absorption in the soil media, there is reduced opportunity for nutrient uptake by plants and soil fauna.

This has potential implications for the percentage of fine particles permitted in Australian bioretention filter media specifications, especially in filter media with increased organic matter. As fine particles help to retain moisture, increasing the fine particle content locally would be beneficial to plant growth and longevity, provided it can be demonstrated that doing so would not lead to clogging and reduced hydraulic conductivity.

Based on the above studies and the success of bioretention systems in the USA (which have not been found to clog or bind despite a higher percentage of fine particles), it is suggested that a bioretention filter media particle size distribution should have:

- Sufficient clay and silt to provide soil chemical and biological stability.
- Enough sand to maintain adequate drainage.
- Adequate soil organic matter to support healthy populations of fungi, bacteria and other soil fauna.

Maintaining the particle size distribution as an optional property in the specification allows for experimentation and innovation in bioretention filter media, potentially increasing the overall percentage of clay and silt and particles. It is expected that future versions of this document will consider further increasing the permitted fine particle content.

For clarity, it is not suggested at this stage that Australian specification should be amended immediately to permit the high percentage of fine particles adopted in USA specifications. This issue is raised to highlight the need for further research and/or analysis to assess this matter. The particle size comparisons are also provided to demonstrate the potential for greater flexibility in particle size grading if hydraulic conductivity can be maintained. These issues both require further investigation and will be considered further in subsequent versions of this document.

Notwithstanding, some greater flexibility in the particle size gradings recommended for bioretention filter media have been included in the specification provided in Section 4. This includes limiting the larger particle sizes to encourage use of finer organic material mixed into the bioretention filter media.

3.8 Summary

This section covered the following key points:

- Current specifications result in SOC levels below a critical threshold required to establish the minimum soil functional properties to grow and sustain healthy plants.
- To restore SOC above that critical threshold requires a balance of the three different forms of carbon including labile, stable and recalcitrant carbon.
- Restoring SOC levels encourages soil fauna that provide bioturbation.
- Bioturbation improves hydraulic conductivity and reduces nutrient leaching.
- Soil fauna have strong positive effects on plant growth and survival through fungal associations.
- Fungal associations also reduce nutrient leaching and improve the ability of plants to draw in water and nutrients, helping plants to grow and survive.
- The combination of fungi, bacteria, plant roots and bioturbators results in aggregation, which improves hydraulic conductivity and overcomes issues associated with increased fine particles.
- Organic matter provides a preventative measure for clogging and structural collapse.
- Fine particles are not a significant predictor of permeability.
- Pedogenesis takes many years and only benefits the surface layer of bioretention systems, highlighting the need for ameliorating the full depth of the filter media.
- Organic matter is the key to biology – it supports rich biodiversity and improved water holding capacity.
- Improving water holding capacity increases water available to plants and decreases and nutrient leaching.

Figure 3.2 summarises this section in diagram format.

The diagram shows how bioretention systems with well-balanced SOC function as an ecosystem, with a complex web of relationships. It builds upon and complements previous models of bioretention systems, highlighting that healthy bioretention systems provide ecosystem services, such as improved water quality, amenity and biodiversity.

It also shows the cascading effect of correctly balanced SOC on the physical and biological processes which contribute to stormwater quality treatment. Thus, compromising any part of the ecosystem (e.g. by lowering SOC) has flow-on effects to the whole ecosystem and its associated benefits (e.g. ecosystem services).

Further detail is provided in the diagram to help explain the interconnected relationships.

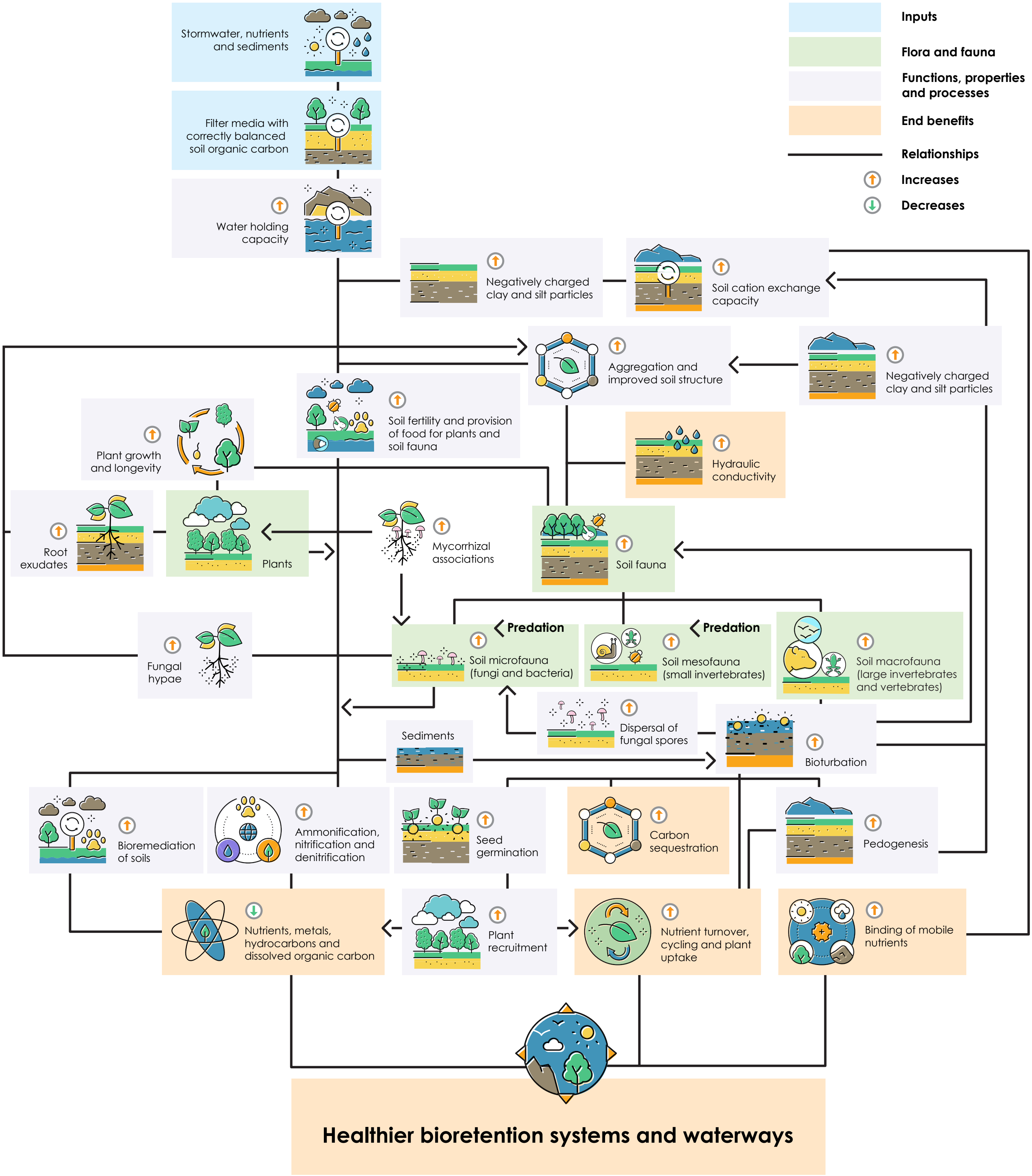

Figure 3.2 Physical, chemical and biological processes in a bioretention system.

4 SPECIFICATIONS

This section covers specifications for bioretention filter media, compost, transition layer and drainage layer materials. The bioretention filter media and compost specifications have been based on the above discussion and review of the best available scientific literature, specifications and standards. Ideally, these specifications will be validated through future monitoring and research.

However, given the pragmatic need to improve plant establishment and survival in bioretention systems, and as these specifications are based on the best available science, they are encouraged to be used prior to further validation. It is expected that these specifications will be revised as new monitoring and research data becomes available.

The transition layer and drainage layer specifications remain generally consistent with previous Water by Design guidance and the FAWB (2009) and CRCWSC (2015) specifications. They are included here for the sake of completeness.

Refer to the *Guidelines for the construction and establishment of bioretention systems and wetlands* (Water by Design 2022) for guidance on testing and chain of custody requirements.

4.1 Filter media

Table 4.1 provides essential filter media specifications. For clarity, filter media under these specifications must include both organic matter mixed into the filter media (to make up the required TOC) and a separate compost layer placed on top of the filter media in accordance with Table 4.3. The ranges/limits provided in Table 4.1 do not include values associated with the compost placed on top of the filter media.

Table 4.1 Essential bioretention filter media specifications.

Parameter	Range/limit	Testing method
Material	Must be free draining, non-toxic, structurally stable and support plant growth. Must comply with bioassay requirements in *AS 4419:2018* for landscape soils (on grade) (i.e. >60 mm or or ≤20% worm avoidance)	*AS 4419:2018 Appendix I*
Hydraulic conductivity	100 – 750 mm/hour	*ASTM F1815-11(2018)*
Total nitrogen (TN)	<1000 mg/kg	*AS 4454-2012 Appendix C* (Induction Furnace or Wet Chemical)
Available phosphate (Colwell)	<80 mg/kg	*AS 4419 Appendix F* (Colwell)
Total organic carbon (TOC)	After mixing with compost, 2 – 3% (w/w)*	*AS 1289.4.1.1* as referenced in *AS 4419:2018*
pH	5.5 – 7.5 (pH 1:5 in water)	*AS 4419:2018 Appendix D*
Electrical conductivity (EC)	<1.2 dS/m	*AS 4419:2018 Appendix D*
Cation exchange capacity (CEC)	3 cmol$^+$/kg ECEC as per *AS 4419:2018*	*Per Soil Chemical Methods – Australasia* (Rayment & Lyons 2011, CSIRO Publishing)
Water holding capacity (WHC)	>20% at 30 cm suction	*AS 3743-2003 Appendix B*
Acid sulphate soils	Filter media must be free from actual and potential acid sulphate soils	*AS 4969* and/or the *Queensland Laboratory Methods Guidelines*
Water repellence	≤60 s (water) or rating of ≤5 (ethanol)	*AS 4419:2018 Appendix C*
Bioassay	>60 mm root growth or ≤20% worm avoidance	*AS 4419 Appendix I*

* Feedstock for TOC should be consistent with acceptable feedstock provided in the compost specifications below. Acknowledging that organic carbon content and density vary between feedstocks and even stockpiles of the same feedstock, 2 – 3% w/w TOC is expected to equate to approximately 10 – 30% organic matter by volume.

Table 4.2 provides optional filter media specifications. Particle size distribution should be considered flexible as long as hydraulic conductivity is within the range/limit in Table 4.1.

Table 4.2 Optional bioretention filter media specifications.

Parameter	Range/limit*	Testing method*
Particle size distribution (PSD)	The filter media should be well-graded and should have all particle size ranges present from the 0.075 mm to the 4.75 mm sieve as defined by *AS 1289.3.6.1* Clay and silt (<0.05 mm): 2 – 5% Clay, silt and very fine sand (<0.15 mm): <10% Compost: <20% of compost may have particle sizes >16 mm, large particles (>20 mm) must be <2%	*ASTM F1632-03(2018)* (USGA Method)

* Values may vary widely.

4.2 Compost

Table 4.3 provides the essential compost specifications. This should be used for the compost mixed into the bioretention filter media to make up the TOC and the compost layer on the surface as indicated in Figure 4.1. The types of feedstock listed below the table must be used to make up the compost.

Table 4.3 Essential compost specifications.

Parameter	Range/limit*	Testing method
Material on top of filter media (compost layer)	100% (w/w) 100% organic 'mature compost' as defined by *AS 4454-2012*. Refer to Table 3.1(A) of AS 4454-2012 and *MRTS16 Form G*	*AS 4454-2012*, *MRTS16 Form G*, and labile carbon test (permanent oxidizable carbon (POXC))
Material mixed into filter media	Prior to mixing with filter media. 100% organic 'mature compost' as defined by *AS 4454-2012**. Refer to Table 3.1(A) of *AS 4454-2012* and *MRTS16 Form G*	*AS 4454-2012*, *MRTS16 Form G*, and labile carbon test (permanent oxidizable carbon (POXC))

* The value adopted here accounts for TOC of the bioretention filter media specified in Table 3.1.

A suitable organic matter with a low nutrient leaching potential must be used.

The following types of feedstock are acceptable:
- Composted green waste.
- Composted pine bark.
- Coconut coir (This may offer additional benefits to water quality performance. Tota-Maharaj and Cheddie (2015) demonstrated up to 90% removal of nitrate, phosphorous, and faecal indicator bacteria by coconut products from natural stormwater runoff).
- Composted wood chip fines.
- Sugar cane bagasse.
- Composted saw dust.

A combination of these feedstocks is also acceptable. It is recommended that the compost layered on top of the filter media is 100 mm deep.

High nutrient composts from feedstocks such as biosolids, manures, food waste, cooking oil/grease, mushroom compost, commercial/industrial waste, and vermicast have a high nutrient leaching potential and are not suitable to be used in bioretention systems. Peat should also not be used as a source of compost because it is non-renewable. Peatlands are an important store of soil carbon and their harvesting and use releases carbon dioxide, the major greenhouse gas driving climate change.

There is no suggested upper limit for labile carbon in the compost at this stage. The labile carbon content is expected to be limited by the use of 100% organic 'mature compost' (consistent with *AS 4454-2012*) and the use of acceptable feedstocks. Nevertheless, understanding how much labile carbon goes into filter media will help build industry knowledge over time.

As WSUD practitioners become familiar with how much labile carbon can be expected in a compliant mature compost, the labile carbon test will become an indicator of whether or not a compost is indeed sourced from an appropriate feedstock. Undertaking the permanganate-oxidizable carbon (POXC) test therefore provides value which far outweighs the cost of the test.

4.2.1 Compost installation

Several studies have found that layering the compost rather than mixing it through the filter media has resulted in less nitrate leaching, at least for the first flush (Hsieh and Davis 2005; Wan *et al*. 2015; Logsdon and Sauer 2016). It is suggested that the compost which does not form part of the filter media is placed between the filter media and the mulch, as shown in Figure 4.1. In the same way that a mulch layer does not change how a bioretention system is modelled, the addition of a compost layer should not change how a bioretention system is modelled.

Further advice on mulching options is provided in the *Guidelines for the construction and establishment of bioretention systems and wetlands* (Water by Design 2022).

Mullane *et al*. (2015) and Xia *et al*. (2007) observed that an initial washout of nutrients can be an issue for composts. Consequently, it is also recommended that prior to delivery to site, all compost is soaked and rinsed to reduce nutrient leaching from the bioretention system. This also applies to the compost being mixed with the bioretention filter media by the supplier. All compost is to be soaked for at least 24 hours and then rinsed for at least two hours prior to mixing with bioretention filter media or layering on top of the filter media. Soaking and rinsing should be undertaken by the supplier, ensuring that the water is not discharged to the local stormwater network or waterways, as it will be high in nutrients and therefore an unlawful contaminant subject to regulatory enforcement.

Beyond the compost requirements outlined in these specifications, further surface amelioration (e.g. as outlined in the FAWB (2009) and CRCWSC (2015) guidelines) is not recommended.

It should be noted that mulching is required in addition to compost. Mulching on top of the compost can be undertaken in accordance with the *Guidelines for the construction and establishment of bioretention systems and wetlands* (Water by Design 2022).

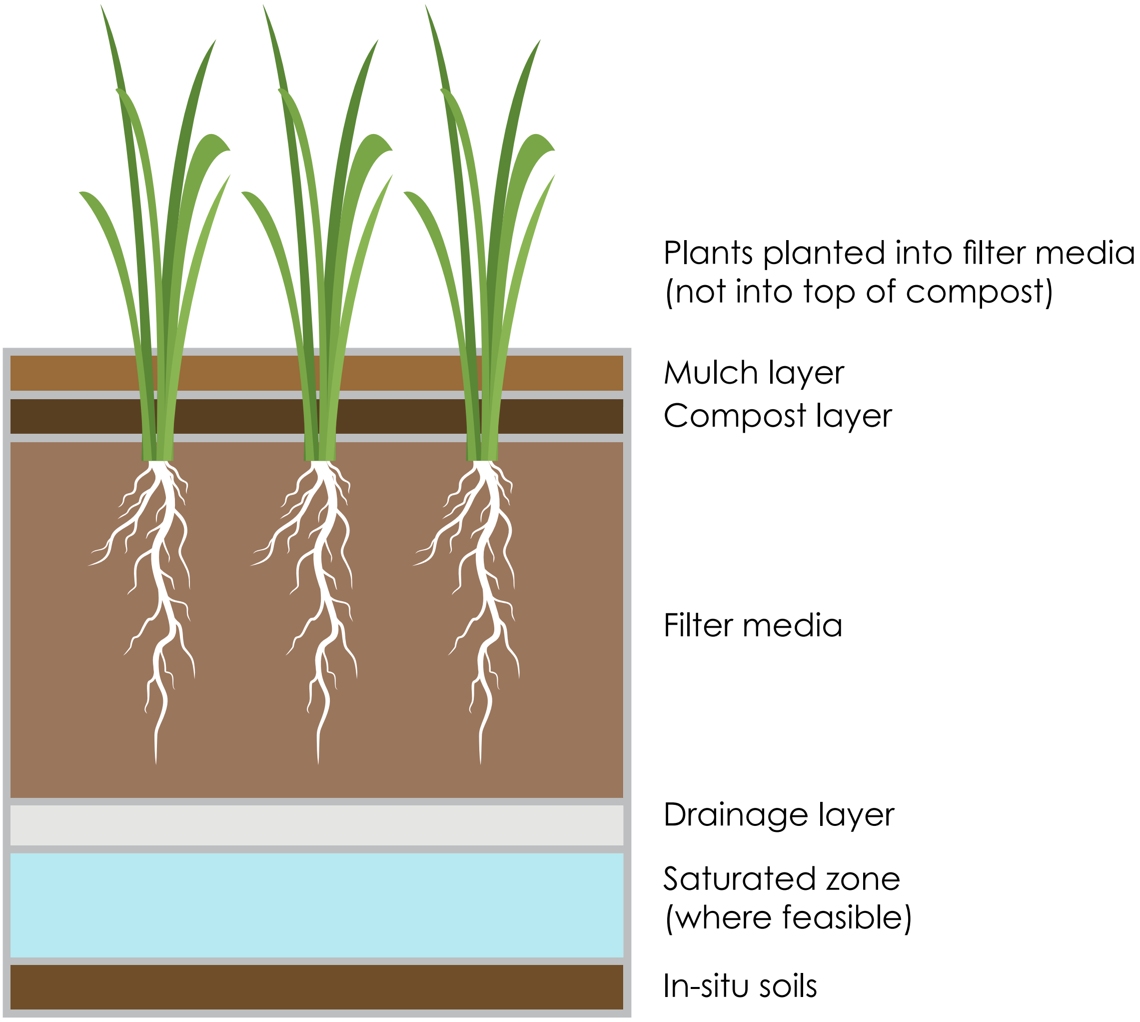

Figure 4.1 Layering of compost on top of filter media.

4.3 Transition layer

Table 4.4 provides essential transition layer specifications.

Table 4.4 Essential transition layer specifications.

Parameter	Range/limit*	Testing method
Material	Must be a clean, well-graded sand/coarse material. Use of a well-washed recycled glass is acceptable	
Hydraulic conductivity	>1.5 x hydraulic conductivity of filter media	*ASTM F1815-11(2018)*
Particle size distribution (PSD)	Clay and silt (0.05 mm): <2%	*ASTM F1632-03(2018)* (USGA Method)
Bridging criteria	D15 (transition layer) ≤5 x D85 (filter media)	*ASTM F1632-03(2018)* (USGA Method)

* Values may vary.

Bridging criteria is based on engineering principles that rely on the largest 15% of the filter media particles bridging with the smallest 15% of the particles. This results in smaller voids, which prevents the migration of filter media particles into the transition layer. The bridging criteria formula provided is taken from the VicRoads *Drainage of subsurface water from roads* (2004).

Where: D15 (transition layer) is the 15th percentile particle size in the transition layer material (i.e. 15% of the sand is smaller than D15 mm), and D85 (filter media) is the 85th percentile particle size in the filter media.

The transition layer can be omitted from the bioretention media provided the filter media and drainage layer meets the following criteria, as defined by VicRoads (2004):

- D15 (drainage layer) ≤ 5 x D85 (filter media).
- D15 (drainage layer) = 5 to 20 x D15 (filter media).
- D50 (drainage layer < 25 x D50 (filter media).
- D60 (drainage layer) < 20 x D10 (drainage layer).

These comparisons are best made by plotting the particle size distributions for the filter media and gravel on the same soil grading graphs and extracting the relevant diameters.

4.4 Drainage layer

Table 4.5 provides essential drainage layer specifications.

Table 4.5 Essential drainage layer specifications.

Parameter	Range/limit*	Testing method
Material	Clean gravel washed screenings (not scoria). Recycled concrete or brick products will not be accepted	
Particle size distribution	Clay and silt (0.05 mm): <2%	*ASTM F1815-11(2018)*
Bridging criteria	D15 (drainage layer) ≤5 x D85 (transition layer)*	*ASTM F1632-03(2018)* (USGA Wet Sieve Method)

* Values may vary.

Bridging criteria is based on engineering principles that rely on the largest 15% of the transition layer particles bridging with the smallest 15% of the particles. This results in smaller voids, which prevents the migration of transition layer particles into the drainage layer. The bridging criteria formula provided is taken from the VicRoads *Drainage of subsurface water from roads* (2004).

Where: D15 (drainage layer) is the 15th percentile particle size in the drainage layer material (i.e. 15% of the aggregate is smaller than D15 mm), and D85 (transition layer) is the 85th percentile particle size in the transition layer material.

4.5 Saturated zone

Saturated zones provide both improved stormwater quality outcomes and a source of water for plants. They could potentially be viewed as an alternative to the provision of compost if all the other benefits of compost described above are ignored. However, it will not always be possible to provide saturated zones in bioretention systems (e.g. where exfiltration is desired or where site constraints prohibit their use).

Equally, while the addition of compost to bioretention systems will improve water holding capacity, the use of compost may not be a replacement for saturated zones in every scenario. LeFevre *et al*. (2015) argue that:

- For true net nitrogen removal from stormwater to occur, a combination of biological denitrification and plant uptake with biomass harvesting is needed.
- Creation of anoxic zones by adding electron donors to the media and/or by maintaining saturation of the media during between flow events facilitates the necessary denitrification.

The use of compost and saturated zones should therefore be considered complimentary design responses to improve both stormwater quality and plant survival.

If saturated zones are used, they should consist of:

- 400 – 500 mm depth (but may be deeper depending on the specific application).
- 10 – 20 mm of clean gravel or coarse washed sand or small rocks of 50 mm diameter maximum.
- 2% by volume of a short-term carbon source (preferably fine straw).
- 4 – 6% by volume of a long-term carbon source (preferably 5 – 40 mm hardwood chips) to support the denitrification process.

The mixing of these media should be undertaken by the local supplier prior to delivery (preferred). If this is not feasible, it can be undertaken by civil contractors on site. For a more detailed description of saturated zone specifications, refer to Chapter 5 of the *Water Sensitive Urban Design Guidelines for the Coastal Dry Tropics (Townsville)* (Townsville City Council 2011).

It is also worth noting that Kim *et al*. (2003) identified newspaper as the best electron donor among the different organic and inorganic materials they investigated (including alfalfa, leaf mulch compost, newspaper, sawdust, wheat straw, wood chips, and elemental sulphur). Therefore, there may be scope to amend the above saturated zone specifications that recommend the use of straw.

5 OPTIONAL BIORETENTION FILTER MEDIA BIOLOGY ENHANCEMENT

Where there is a need to improve the establishment and survival of plants in bioretention systems, or where there are challenging conditions for plant health (such as drier climate zones), designers may want to explore ways to address these issues. Proven methods include:

- Increasing organic matter. As discussed, care needs to be taken not to increase organic matter too high or use the incorrect type of organic matter to avoid excessive nutrient leaching.
- Designing the bioretention system with a saturated zone consistent with the *Bioretention technical design guidelines* (Water by Design 2014).
- Carefully selecting plants which are more resistant to dry conditions. Water by Design has freely available online resources on plant selection.
- Including trees in the planting palette to provide shade. This improves microclimate, lowers the temperature of filter media, reduces evaporation/evapotranspiration and limits weed growth.

New ways to enhance the condition of the bioretention filter media itself are also emerging and may be effective if applied in the right context. Two methods which have been applied in the agricultural sector for many years but which are new to bioretention filter media design are presented below. These are provided to highlight emerging industry knowledge and encourage further experimentation and research within both industry and academia. If applied at a project level, consultation with a soil specialist/agronomist is recommended.

A comprehensive meta-analysis of bioretention filter media specifications and research on bioretention filter media amendments is provided by Tirpak *et al*. (2021). This paper includes a decision support framework which may assist decision makers select amendments which target their local pollutants of concern.

5.1 Increasing the biological diversity and abundance of bioretention filter media microbiota

Soil fungi and bacteria provide many potential benefits to bioretention systems, including (Frąc *et al*. 2018):

- Enhancing soil structure formation (and therefore hydraulic conductivity). They do this by binding soil particles together to create water-stable aggregates which in turn create pore spaces that facilitate water retention and drainage.
- Modifying soil habitats for other organisms including plants and soil fauna.
- Regulating diseases and pests, which are more likely to attack stressed plants.
- Regulating the growth of other organisms (e.g. mycorrhizal fungi improve plant growth by increasing the uptake of nutrients and protecting them against pathogens).
- Supporting nitrogen fixation. Soil fungi are also an effective biosorbent of toxic metals (and therefore stormwater pollutant loads).
- Supporting organic matter decomposition.

Soil fungi and bacteria are critical in the production of living soils. Cultivating soil biodiversity is important to improve the quality of filter media and increase plant productivity. This can be achieved through inoculation of the soil with fungi, bacteria, or a combination of the two. Notably, a study by Rashid *et al*. (2016) found co-inoculation of fungi and bacteria to be more beneficial for reinstating soil fertility and organic matter content than a single inoculum of either fungi or bacteria.

While many companies already sell fungal and bacterial inoculation products that boost plant growth, results can be variable. Any potential manipulation of soil fungal and microbial communities must consider that bioretention filter media characteristics (e.g. pH, texture, SOM, and organic matter content/quality) influence the existing microbiota community and will influence attempts at manipulation. As a result, it is recommended that suitable compost is used to support the inoculation (refer to Section 4). Consultation with a soil specialist/agronomist is recommended if adopting this method.

5.2 Increasing the biological diversity and abundance of bioretention filter media soil fauna

Improving the ecosystem functioning of bioretention filter media may be achieved by colonising bioretention systems with soil fauna (especially bioturbators), either with or without increasing the organic matter or fine particle content. However, the organic matter recommended in Section 4 and finer particles associated with it would increase water holding capacity and provide more suitable conditions for both bioturbators and microbiota. It would also encourage natural colonisation from nearby soil environments.

Colonisation of the filter media with soil fauna would enhance the biology of the filter media with potential flow on effects to plant health. Some soil fauna species (such as earthworms) are commercially available and low cost, making this a cheap, easy and effective option. However, given the impact exotic species have on native biodiversity, care needs to be taken to ensure locally endemic native species are used.

Consideration should also be given to the local environment of the bioretention system. If the system is directly abutting existing natural areas, natural colonisation rates will be higher compared to a bioretention system located in a highly modified urban area (e.g. a car park). In these circumstances, additional colonisation may not provide significant improvements.

6 MAINTENANCE FOR BIORETENTION FILTER MEDIA HEALTH

Like any other asset, all bioretention systems require maintenance. Water by Design has published a suite of resources which support the maintenance of vegetated stormwater assets, including bioretention systems. Key guidelines which support the maintenance of bioretention systems include:

- *Maintaining vegetated stormwater assets* (Water by Design 2012).
- *Rectifying vegetated stormwater assets* (Water by Design 2012).

One of the most important changes asset managers can make to sustain plants in bioretention systems is to avoid brush cutting and prevent the application of herbicides. Brush cutting can damage or destroy bioretention plants directly and can also spread weed seed. While it is often used to control small weed infestations, in the long term it typically worsens the problem, as weeds colonise newly created space more rapidly than native macrophytes. Accidental damage to native plants is particularly prevalent in bioretention systems due the dense planting of macrophytes. Care should be taken if brush cutting is adopted as an occasional maintenance technique in bioretention systems, but even occasional use is discouraged.

Research in other soil environments on the detrimental effect of herbicides on soil biota provides conflicting results. This variability is partially due to the numerous types of herbicide, biota species and soil environments analysed. Nevertheless, there is a growing body of evidence to suggest that impacts may be significant.

For example, in their meta-analysis, Rose *et al*. (2016) concluded that despite some contrasting evidence, "*there are some instances where findings consistently suggest effects that could significantly alter soil function*". While they note a paucity of conclusive evidence for all the types of soil fauna and functions they reviewed, they do identify some effects with confidence. These include:

- Disruptions to earthworm ecology.
- Inhibition of soil nitrogen cycling (including biological N_2 fixation, mineralisation and nitrification).
- Site-specific increases in disease.
- Altered soil fauna population dynamics and microbial activities.

It is likely that these impacts alone would negatively influence the treatment of pollutants from stormwater in bioretention systems. Harmful chemicals identified by Rose *et al*. (2016) include herbicides commonly used in Australia for weed control which are marketed as being safe for natural area management.

Research by Druille *et al*. (2013) also found that herbicides can reduce the spore viability and root colonisation of mycorrhizal fungi and could reduce plant diversity, depending on the degree of mycorrhizal dependency of plant species. Another study by Zaller *et al*. (2014) found a 40% reduction of mycorrhization in soils after the application of a herbicide. Coincidently, they also found that the herbicide tended to reduce soil infiltration and despite the reduced hydraulic conductivity, leaching of the herbicide after simulated rainfall was substantial.

Regardless of the effects of herbicides on hydraulic conductivity, given the high hydraulic conductivity of bioretention filter media, there is a significant potential for leaching into downstream waterways.

There is also growing evidence that suggests that herbicides marketed as being safe for aquatic environments could negatively impact aquatic fauna. For example, Cuhra *et al*. (2013) found that some herbicides can adversely affect the growth, reproduction and survival of aquatic invertebrates. They concluded that authorities responsible for classification have been underestimating the toxicity of these herbicides to aquatic invertebrates. Similarly, Relyea (2005) showed a severe negative impact on frog tadpoles, including high mortality.

Many native plants species used in bioretention systems are more resilient than herbaceous weeds to herbicide application. Because of this, the effects of herbicide on the native plants may be gradual and not readily identified for several years, at which point the condition of the filter media may also be affected. Figure 6.1 and Figure 6.2 provide an example of extensive loss (estimated at >90%) of bioretention plants over several years due to regular herbicide application and brush cutting. Note that the trees in this example are still quite healthy (potentially indicating greater resilience to herbicides) but they were also less likely to have been affected by brush cutting.

Figure 6.1 Loss of plants in a bioretention system due to herbicide application and brush cutting.

Figure 6.2 Off-target damage to plants in bioretention system from herbicide application.

There may be extenuating circumstances which justify a once-off application of herbicides. Where this is the case, herbicide use should still be limited and not form part of regular maintenance practices. The herbicide application technique is also important to consider. For example, spraying herbicides commonly results in overspray which gradually kills native plants. The cut stump method (which is typically used for larger woody weeds and vines) is less likely to affect nearby vegetation. It is therefore more appropriate to use the cut stump method for larger woody weeds where physical removal is impractical.

The most appropriate maintenance methods for bioretention systems are the use of hand tools such as mattocks and shovels (Figure 6.3). Use of mulches and appropriate turf species can help to avoid future weed problems. Further information on mulching and turf options is presented in the *Guidelines for the construction and establishment of bioretention systems and wetlands* (Water by Design 2022).

While maintenance crews should be educated on appropriate maintenance techniques for bioretention systems, they rarely have contact with the asset designer. For this reason, designers should prepare a maintenance plan for the bioretention systems they design. Another response designers can take is to provide a continual reminder to maintenance crews by installing a small, unobtrusive sign/plaque which does not otherwise affect the amenity of the bioretention system (Figure 6.4). The sign can be standalone or integrated with other signage or infrastructure (e.g. fixed to a bollard). This can help prevent costly replanting in the longer term and ensure bioretention filter media remains healthy to support the microbiota the plants rely upon.

Figure 6.3 Preferred approaches to maintenance.

Figure 6.4 Example signage to avoid brush cutting and herbicides.

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