OPTIMISING THE MEDIA OF NEXT GENERATION LOW IMPACT DESIGNS FOR PHYTOREMEDIATION AND BIOREMEDIATION

Suman Khareedi, Opus International Consultants

Dr. Lokesh P. Padhye, The University of Auckland

ABSTRACT

Low impact designs (LID) such as raingardens treat stormwater runoff through a combination of physicochemical and biological processes, including filtration, adsorption, phytoremediation, and bioremediation. Some of the most common stormwater pollutants include suspended solids (TSS), heavy metals, nutrients, and dissolved organics such as polycyclic aromatic hydrocarbons. Phytoremediation and Bioremediation are processes that remove or transform such pollutants into nontoxic compounds through the use of plants and microorganisms, respectively.

The role of these processes in treating environmental pollutants has been well documented in the literature. Microorganisms and plants can uptake heavy metals and transform hydrocarbons into nontoxic compounds, thus decontaminating urban stormwater runoffs. These biological processes can also play a significant role in removing nutrients from stormwater. Despite these well-documented benefits, phytoremediation and bioremediation are not well studied and accounted for in designing of the LID media.

The current standards in New Zealand promote a 'deemed to comply' approach and use TSS removal as a sole measure of stormwater treatment. While this approach offers an easy and economical way to compliance, it has potentially led to reliance predominantly on the physicochemical processes for removal of stormwater contaminants.

Careful selection of plants and optimizing the LID media for microbial growth can boost its phytoremediation and bioremediation capabilities and enhance its overall treatment efficiency. Through such amendments leaching of nutrients can also be minimized and specific pollutants can be targeted for treatment.

This paper outlines the findings of the multi-stage research project being carried out at the University of Auckland, jointly by Opus International Consultants and the University of Auckland to enhance phytoremediation and bioremediation in Suspended Raingardens – a next generation LID for treating stormwater runoffs in urban catchments. It also outlines how the findings of this research can be applied to traditional LID for the treatment of pollutants beyond physicochemical processes.

KEYWORDS

Phytoremediation, Bioremediation, LID, Suspended Raingardens, Water Sensitive Designs, WSUD, SUDS, Stormwater Treatment,

PRESENTER PROFILE

Suman is the Work Group Manager – Stormwater and Water Sensitive Designs at Opus International Consultants, Auckland. For more than 25 years Suman has been involved in the design, construction supervision and quality control of stormwater management projects, including public infrastructure, building drainage and reticulation for subdivisions. In the recent times, Suman has been the Project Director and Technical Reviewer for a number of stormwater capital works design projects in Auckland region. Currently, Suman is leading the project to design suspended raingardens, an innovative LID for urban environments.

Dr. Padhye is a senior lecturer at the University of Auckland. His research is focused on water quality management and water/wastewater treatment. Dr. Padhye obtained his master's and the doctorate in environmental engineering from Georgia Institute of Technology in the United States. He then worked as an environmental engineer in Atlanta (GA) for three years before entering an academic career. He has been working in the field of emerging environmental contaminant research for last fifteen years and has published numerous research articles and book chapters.

1 INTRODUCTION

Urban stormwater runoff is the main cause of water quality degradation in our natural waterways (USPEA, 2000). Some of the most common stormwater pollutants include suspended solids (TSS), heavy metals, nutrients, and dissolved organics such as polycyclic aromatic hydrocarbons. Low impact designs (LID) such as raingardens treat stormwater runoff through a combination of physicochemical and biological processes including filtration, adsorption, phytoremediation, and bioremediation.

The physicochemical processes that occur in raingardens include settling, adsorption, filtration, and volatilisation. When stormwater runoff enters a raingarden, the physical depression of the raingarden and the vegetation in it causes the water to slow down. This causes gross pollutants and course suspended solids to settle in the raingarden bed. The vegetation and the media of the raingarden also filter our pollutants. This process by which gross pollutants and soil particle-bound pollutants are trapped is the physical process. On the other hand, removal of pollutants due to their interaction with the soil in raingardens is the chemical process of treatment. This includes chemisorption, which is sticking of pollutants to soil particles by chemical bonds and volatilization, which is the vaporization of pollutants (Jaber, Wood, LaChance and York, 2012).

The current standards in New Zealand promote a 'deemed to comply' approach and use total suspended solids (TSS) removal as a sole measure of stormwater treatment. While this approach offers an easy and economical way of compliance, it has potentially led to reliance predominantly on the physicochemical processes for removal of stormwater contaminants. In particular, settling, filtration, and adsorption are the only physicochemical processes relied upon. While phytoremediation and bioremediation processes do occur in raingardens and are hugely beneficial, they are seldom sufficiently relied upon or studied. Even among physicochemical processes, volatilisation is seldom given consideration. A raingarden that is carefully designed and maintained to enhance the phytoremediation and bioremediation processes can enhance the efficiency of present day raingardens in treating stormwater pollutants. They can also help deal with leaching of nutrients, a serious limitation of present day raindardens.

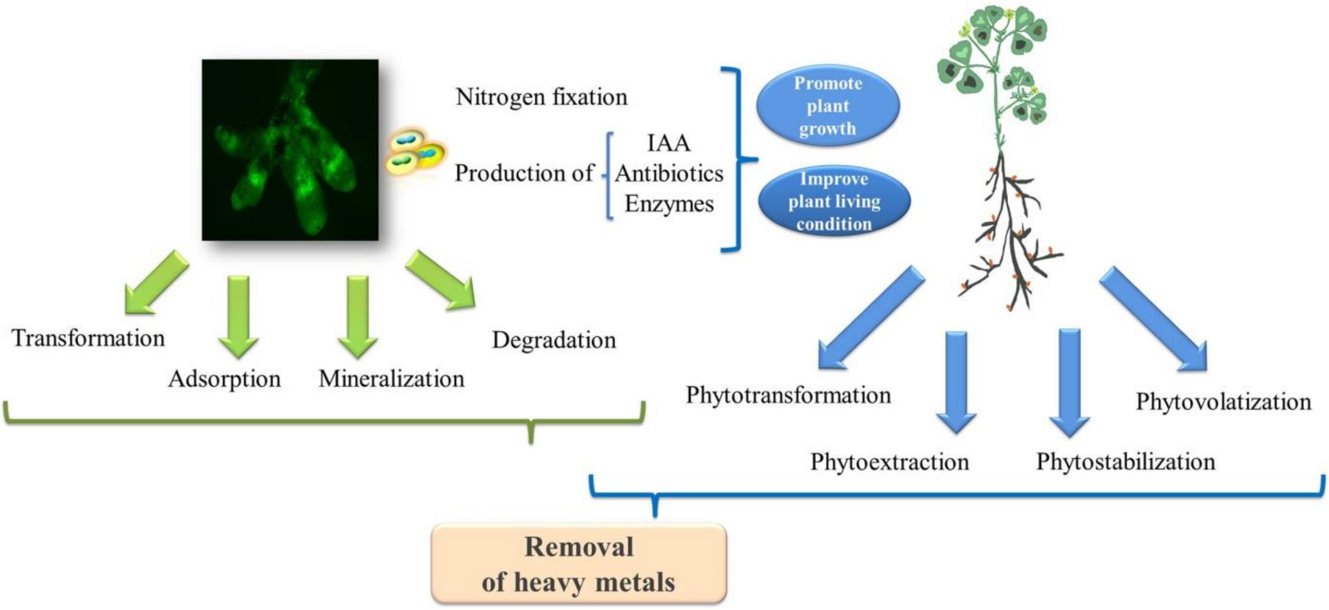

Figure 1: Bioremediation and phytoremediation of heavy metals in soils (Teng et al.) 2015)

The most common pollutants that are recorded in stormwater are suspended solids, dissolved metals including lead (pb), zinc (Zn) and Copper (Cu) (Moores, Pattinson and Hyde, 2010). Studies conducted by a number of researchers (Blecken, Ninger, Deletic, Fletcher and Viklander, 2009; Sun and Davis, 2007; Bratieres, Fletcher, Deletic and Zinger, 2008) have found the typical range of concentrations of these contaminants to be as tabulated below:

Heavy metal	**Concentration (mg/l)**
Copper (Cu)	0.050 – 0.100
Lead (Pb)	0.07-0.180
Zinc (Zn)	0.25-0.6
TSS	6,200

Table 1: Typical concentration of contaminants in stormwater.

The technological changes, increased urbanization, and climate change will all have impact on the stormwater quality and quantity. While it is difficult to say with certainty as to what the composition of stormwater contamination will be in the coming years, it is certain that the nature and quantity of pollutants will be changing. Phytoremediation and bioremediation offer flexible treatment approaches that can be easily integrated into the urban design of a catchment to treat contaminants despite their changing profile. Enhancing phytoremediation and bioremediation can also help us become future ready by being able to treat stormwater pollutants of the future.

1.1 PHYTOREMEDIATION

Phytoremediation, in simple terms, is the use of plants to remediate contaminants in the environment (Bloetscher, 2002). Phytoremediation removes organic compounds and metal pollutants through five different processes: phytoextraction, phytotransformation, phytostabilisation, rhizofiltration and rhizosphere bioremediation.

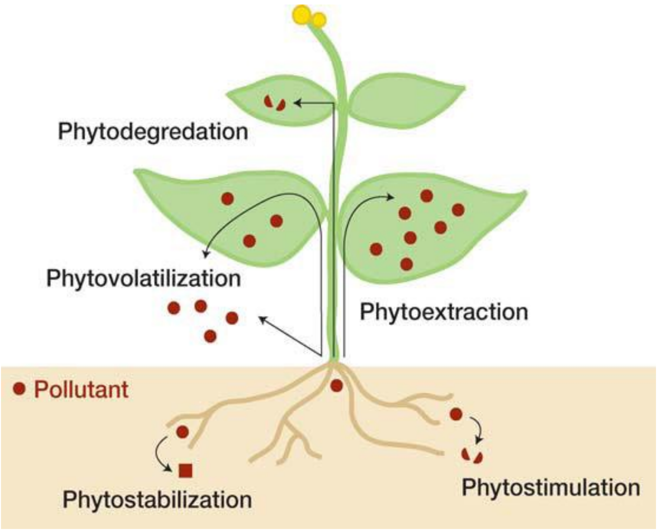

Figure 2: Mechanisms of Phytoremediation
(source: http://www.personal.psu.edu/dgh5037/extEssay.html)

Extraction of metal contaminants and their recoveries into the above-ground biomass is phytoextraction. The uptake of relatively high concentrations of organic compounds by plants without toxic effects or quick conversion of chemicals into less toxic metabolites is phytotransformation. Phytostabilisation is the process by which waste site are stabilized by erosion control and evapotranspiration of large quantities of water. Rhizofiltration is the process by which plants filter out metals from water into the root system. Rhizosphere bioremediation is the process of plants simulating the degradation of organic chemicals by the release of root extrudates and enzymes in the rhizosphere and building organic carbon in the soil.

Phytoremediation can be carried out by many species of both wetland and non-wetland plants. As phytoremediation is a naturally occurring physical, chemical, and biological process, removing contaminants is typically less expensive and easier to maintain than methods that rely on technology (Zhang, Zeng and Sharp, 2010).

1.2 BIOREMEDIATION

Bioremediation is the process through which microorganisms, such as bacteria, fungi, algae, and yeasts, remediate toxic contaminants (Coelho, Rezende, Coelho and de Sousa, 2015; Dixit, et al, 2015). Microbes alter the chemical properties of contaminants converting them into non-toxic forms using a variety of mechanisms such as biosorption, bioaccumulation, biotransformation, and biomineralisation (Dixit et al., 2015). Biosorption retains heavy metals through physicochemical interaction (passive uptake) while bioaccumulation is an extracellular process of uptake i.e., active uptake (Coelho et al, 2015). Biotransformation is the mechanism by which microbes biochemically modify pollutants, particularly heavy metals. When such modifications end up in formation of inorganic end products, the mechanism is referred to as biomineralisation (Coelho et al., 2015; Benzerara, 2011).

1.3 BENEFITS OF BIOREMEDIATION

Human activities add a range of contaminants including nutrients and heavy metals into stormwater both in rural and urban environments. The technological improvements and population growth will require human activities that will continue to add the above pollutants into stormwater that enter our natural waterways. Mitigating the impact of such pollutants on our natural waterways and preserving freshwater, a vital natural resource, for our future generations means managing our freshwater resources better. This will in turn require us to manage our stormwater better, both in rural and urban catchments. The current standards and focus on physicochemical processes only will not be adequate in the future due to the contaminant loading and profile changing. It is vital for us, as an industry, to explore mechanisms of enhancing the performance of our LID media. Phytoremediation and bioremediation offer economical and easy options to enhance the performance of LID, including raingardens.

The media used in the present day raingardens includes compost containing dissolved organic matter to support the growth of plants used in the raingardens. This dissolved organic matter can leach into the receiving environment during storm events adding to the issue of eutrophication of our freshwater bodies (Kaschl, Romheld, and Chen, 2002; Bolea et al., 2006 and Mullane et al., 2015). Bratieres et al. (2008) found that in most studies the present day bioretention systems were good at removing contaminants but recorded nutrient leaching. This is a serious limitation of raingardens given that the eutrophication is likely to be a significant problem due to global warming and climate change. Improving the treatment efficiency, particularly nutrient uptake in raingardens, through enhanced bioremediation has the potential to mitigate the issue of nutrients leaching from raingardens.

Many local authorities are now requiring hydrological mitigation by way volume reduction in highly urban catchments with sensitive receiving environments. For example, under the Auckland Unitary Plan, developments in Stormwater Management Area – Flow 1 and Flow 2 (SMAF) require at least 5mm of the runoff depth from impervious areas to be retained on site. When LID design approach is adopted in such catchments, evapotranspiration could play a significant role in reducing peak flows by increasing abstraction. Therefore enhancing evapotranspiration in raingardens could be significantly beneficial in volume reduction in urban catchments.

In the present day raingardens heavy metal and hydrocarbons get separated by the biofiltration process. After a period of time, the raingarden medium gets clogged with contaminants. This renders the raingardens dysfunctional. Once the raingarden reaches this stage, the media contaminated with heavy metals and hydrocarbons is disposed of at landfills. This approach, while treating stormwater, contributes to land contamination. Hence, it is not a sustainable approach. The ability of plants and microorganisms in converting heavy metals into nontoxic minerals is well studied and documented. However, their contribution to stormwater treatment in raingarden is not well studied or understood. Bioremediation and phytoremediation are effective and low-cost treatment technologies capable of removing nutrients and heavy metals from water and soil. Through these processes, the media can be regenerated by plant and microbial activities prolonging the life of the media and mitigate the transfer of contaminants from water to soil.

2 DESIGN CONSIDERATIONS

The current raingardens design consideration does not account for bioremediation to optimize the benefits of raingardens. Careful consideration needs to be given to factors that improve phytoremediation and bioremediation mechanisms in raingardens while designing raingardens. The design of phytoremediation systems comprises of a number of steps to enhance plant uptake and regular maintenance of such devices to maintain the efficiency of uptake. Such designs include using grasses and plants to encourage uptake of a myriad of nutrients and to accelerate evapotranspiration (Bloetscher, 2002). Plant species differ in their ability to uptake contaminants (Rai, Sinha and Chandra, 1995). Removal of contaminants depends on the type of contaminant and the ability of a plant species accumulating the contaminant (Weiss et al., 2006). Ebbs and Kochain (1998) recommend that, while selecting plant species, a focus must be on striking a balance between a plants species' ability to accumulate high concentrations of a specific contaminant and its tolerance to that contaminant.

The age of a plant and the seasonal variations impacts the uptake of contaminants by plants. As young roots grow faster, they uptake higher loads of nutrients. On the other hand, older plants are faster at transferring contaminants to leaves and stems. In addition, seasonal changes have a significant impact on transpiration rates and contaminant uptake. To enhance phytoremediation in raingardens, such factors need to be optimized. Contaminant removal rate varies with the species of plants used and the target contaminant (Zhang et al., 2010). No one species can remove all contaminants (Wiess, Hondzo, Biesboer and Semmens, 2006). Incorporating a blend of plant species maximizes contaminant removal and removal of multiple contaminants simultaneously (Zhang et al., 2010).

An array of microorganisms, including bacteria, yeasts, fungi, and algae, exists that can remediate environmental media by removing contaminants. While microorganisms cannot destroy heavy metals, they can make them non-toxic by altering their chemical properties. The pH of the soil, the ionic strength, concentration of biomass in the soil, the temperature, particle size and many other factors affect the bioremediation process (Coelho et al., 2015). The selection of microbes should be based on the mechanism required in absorption or modification of heavy metals and other contaminants (Dixit et al., 2015). The interaction of a plant species with sediment microbes is another key element in determining the efficiency of bioremediation (Zhang et al., 2010). Bioremediation is enhanced when microbe-plant symbiosis in the rhizosphere is combined. As such, careful consideration need be given to the selection of plants, modification of the rhizosphere, geochemistry and selection of microbes for effective removal of contaminants. Another factor that has a bearing on bioremediation is the total biomass of microbes.

Other factors that can enhance bioremediation in raingardens are rhizosphere engineering and manipulation of plant-microbe symbiosis. This involves the addition of nutrients to enhance microbial growth and addition of microbes as endophytes. This allows for better degradation of contaminants within the plant tissues (Van Aken, Teharani and Schnoor, 2011). Therefore, we need to consider many other factors than we are considering now while designing raingardens to harness the full potential of raingardens.

Opus International Consultants and the University of Auckland are jointly carrying out a multi-stage research project to enhance phytoremediation and microbial bioremediation in Suspended Raingardens – a next generation LID for treating stormwater runoffs in urban catchments. This paper outlines the findings of this project and how those findings can be applied to traditional LID for the treatment of pollutants using mechanisms beyond the physicochemical processes.

3 RESEARCH METHODS AND MATERIALS

Media testing for contamination removal was performed as two sets of bench experiments in the laboratory. In the first set of experiments, three lightweight media blends were tested using material that are typically used for growing plants in controlled environments. The objective was using lightweight media was to allow the media to be used in suspended raingardens, a stormwater treatment device of the future that could be used in highly urban environments. Media 1 was a mix of perlite and vermiculite. Media 2 was a mix of coconut coir and activated carbon and Media 3 was a mix of sawdust, biochar and Sphagnum moss. The bulk densities of all three media mixes were less than 380 kg/m^3.

Artificial stormwater prepared by mixing sediments collected from catchpits in urban catchments and demineralized water was used in the experiments. The contaminant blend and concentrations were, TSS – 6,200 mg/l, Zn – 0.380 mg/l, Pb – 0.016 mg/l, and Cu – 0.031 mg/l. These concentrations are representative of typical blend and concentrations of contaminants found in runoff from urban catchments (Moores et al., 2010).

Figure 3: Laboratory set up for bench trials

The typical setup consisted of two plastic containers (Figure 3), one bigger (48 liters) and one smaller (20 liters). The larger tub contained the artificial stormwater while the media to be tested for its efficacy was placed in the smaller tub. The depth of media used for testing was 150 mm. The tubs were placed in a manner to allow the artificial stormwater to enter one end of the tub and leave at the other end. The flow rate and detention time were controlled by two valves, one placed at the downstream end of the larger tub and the other placed at the outlet end of the smaller tub.

The bench tests were conducted with a retention time of 20 min. Heavy metals were analysed using inductively coupled plasma mass spectrometry while TSS was measured using Standard Methods.

In the second set of trials Media 3 was replaced with a blend of Grow Stones, Biochar and compost as the blend containing sawdust leached high loads of organic matter during our trials. In this set of trials, three types of plants (drooping, shrub and edible) were grown in each of the media types. The composition of all three blends of media was also altered to contain a minimum of 20% compost to support plant growth. Lab trials were conducted under artificial lighting conditions using fluorescent lights. The intensity was maintained at levels similar to those on overcast days. After initial testing, the media had to be amended to reduce the compost content less than 10% (quantity contained in the sapling pot that the plants came in) as they started leaching large amounts of suspended solids and nutrients. In addition, we had a control set of media without any plants growing in them.

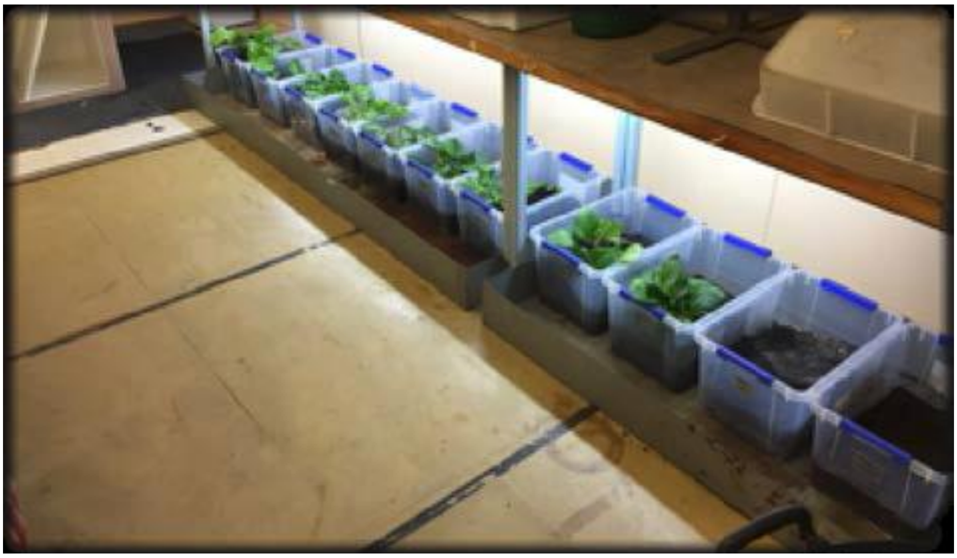

Figure 4: Laboratory set up for the second set of trials

The rest of the methodology used in the second set of trials were kept to be the same as in the first set of trials. In these second set of trials, the effluent from the trial media was tested for nutrients (Nitrate and Nitrite) removal efficiency in addition to testing for efficacy in removal of TSS and heavy metals. The nutrient removal efficiency of the trial media was tested using ion chromatography.

4 RESULTS AND DISCUSSIONS

Below is a qualitative assessment of the trial results of two sets of experiments:

1. Nutrient leaching was a significant issue in the second set despite the proportion of organic matter in the media being less than 10%. TSS, heavy metal and nutrient levels were higher than in the control media without compost in most cases, particularly when the hydraulic conductivity of the media was high. Even with a relatively small proportion of organic matter in the media, it is possible that nutrient leaching from raingardens if proper consideration is not given to enhancing bioremediation in conventional bioremediation systems.

2. Media with the lowest hydraulic conductivity was the most efficient in TSS removal confirming that physicochemical processes play a significant role in TSS removal and the overall treatment efficiency of raingardens.

3. Contaminant (TSS and heavy metals) removal varied significantly depending on the target contaminant and the species of plant confirming that a blend of plant species maximizes contaminant removal, and hence highlighting that phytoremediation plays a significant role in contaminant removal.

4. The media that was the most efficient in the physicochemical process showed improved treatment efficiency with plants. This confirms that biological processes can significantly improve the treatment efficiency of raingardens as they remove multiple contaminants simultaneously.

5. The efficiency of media with higher hydraulic conductivity was less than desirable to make them viable raingarden media because of organics leaching from compost.

6. The treatment efficiency of the best performing lightweight media was better than the efficiency of conventional raingardens.

5 CONCLUSIONS

The results discussed in this paper are findings of the first stage of a multi-stage research project. The overall objective of this multi-stage research is to develop suspended raingardens – a next generation LID for treating stormwater in urban catchments. Nonetheless, the findings this research can be equally applied to conventional raingardens to boot their treatment efficiency. Further research is required to optimize the media for effective nutrient removal and to delineate exact roles of biological processes. The future stages of our research will focus on determining the efficiency of phytoremediation and bioremediation in raingardens separately. Despite the limited research conducted to date, it is clear that suspended raingardens are a viable alternative for the future urban catchments. It is possible to boost the overall treatment efficiency of LID devices like raingardens by giving careful consideration to phytoremediation and bioremediation in LIDs.

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