Living Walls for Treatment of Greywater

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Dedicated

to

our families and friends
for their endless support, praise and encouragement

By virtue of whose prayers, we have been able to attain this position and whose hands are always raised for prayers, for our well-being

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List of Abbreviations

APHA	American Public Health Association
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
EPA	Environmental Protection Agency
HRT	Hydraulic Retention Time
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solids
UNDP	United Nations Development Programme

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Abstract

The living wall system allows an alternative route for wasted greywater taking into account the water intensive nature of Pakistan's economy and considering the sheer amount of lightly polluted greywater being drained on a daily basis. This study addresses this issue with the aim to achieve effluent water quality defined by US EPA under Greywater Reuse Characteristics. Three different locally available plant species were tested, namely *Lonicera japonica*, *Alternanthera ficoidea* and *Chlorophytum comosum*. A standard composition of synthetic greywater was prepared and used as influent. The media used was lightweight perlite and coco coir in ratios of 2:1 and 3:1, respectively. Final results presented *C. comosum* with significantly higher overall pollutant removal levels, with all parameters well within USEPA's Greywater Reuse Quality Standards, 2004. Total Nitrogen and Total Phosphorus levels were particularly exceptional at 87% and 67% lower than the allowable limits, respectively. Water retrieved from the living wall as effluent is suitable for irrigation, toilet flushing and car washing. However, the effluent achieved met tap water quality standards with the exception of the presence of E. coli and bacterial contamination. Addition of an advanced disinfection process it may allow the living wall to completely recycle tap water for buildings.

Two parameters were optimized:

- Influent flow rate was varied from 0.01 to 0.06L/min
- Perlite to coco-coir media ratio

1. Introduction

1.1 Pakistan's Water Crisis

According to the International Monetary Fund (IMF), "Pakistan is among the world's 36 most water-stressed countries, with its agricultural, domestic, and industry sectors scoring high on the World Resource Institute's Water Stress Index. The UN-Water describes water scarcity as 'the physical shortage of water supply, scarcity of water due to inadequate infrastructure or the scarcity of water due to the failure of government organization in providing adequate water supply in a particular region'. Pakistan Council of Research in Water Resources (PCRWR) stated in its report titled "Water Requirements of Major Crops in the Central Punjab" that Pakistan utilizes up to 93 % of its available water resources for irrigation. However, 60% of water is lost in conveyance and application due to lack of an efficient irrigation management system.

Moreover, Pakistan being an agriculture-intensive country has a vast network of unregulated irrigation system where most of the water is lost due to seepage and inadequate use by farmers. The IMF ranks Pakistan at four among the most water-consuming countries. This may be attributed to the huge amount of water that is wasted on a daily basis because it is a free commodity.

1.2 Wastewater Re-Use and Recycling

At present, political instability in Pakistan hinders development of large-scale projects such as dams and reservoirs, and lining of canals. Hence, measures to conserve water must be based on small-scale or individual level. Spreading awareness about water pollution and water scarcity, rainwater harvesting, and water-metering are few options to deal with this crisis. Another possible solution is the treatment and reuse of wastewater. Wastewater may be biologically treated through anaerobic or aerobic processes, physically treated through sedimentation and filtration, or chemically treated using ozone or chlorine as disinfectants. Traditionally, wastewater is divided into greywater and black water (Friedler, 2004). Domestic greywater may be categorized into effluent from sources such as sinks, showers and laundry. It includes wastewater generated in households or office buildings from streams without fecal contamination. As greywater contains fewer pollutants than domestic wastewater, it is generally safer to handle and easier to treat. Therefore it can be reused onsite for toilet flushing, landscape or crop irrigation, and other non-potable uses. However, due to combined plumbing system, greywater and black water, which is wastewater containing fecal contamination, is mixed together before reaching the treatment facility. This increases volume of the wastewater to be treated, creating a greater land footprint. It also increases the amount of chemicals used and thus increasing the cost of treatment. Moreover, disposal of sludge is another issue. An economically viable solution is to separate greywater stream and reuse it separately to reduce load on wastewater treatment facilities. This way greywater could easily be reused with slight treatment according to its intended usage.

1.3 Living Walls for Greywater Treatment

Living Walls also known as Green Walls are constructed from modular panels which contain soil, sand or other growing media, for example foam, perlite, coco-coir and mineral wool. These systems usually consist of perennial plant species such as small shrubs which do not naturally grow vertically (Perini et al., 2012).

Living walls are becoming increasingly popular due to a number of reasons. Plants can improve both outdoor as well as indoor air quality by filtering out airborne particles through their leaves and branches as well as by absorbing gaseous pollutants through photosynthesis (Dwyer et al., 1994). The green cover from the wall results in a shading effect, which reduces the indoor building temperatures and the amount of UV light falling on building exterior. Since UV light deteriorates the material and affects mechanical properties of coatings, paints, plastics, etc., plants also have an effect on durability aspects (Wong et al., 2010). Additionally, urban green area and plants around the buildings is viewed as a suitable alternative habitat for native wildlife such as insects and birds. The presence of wildlife may enhance the ecological quality and health of the environment as well as provide additional emotional, intellectual, social and physical benefits to humans (Johnston & Newton, 1996). The aesthetic value of urban landscape, where horizontal space is limited, is improved by the addition of greenery. Vegetation can provide visual contrast and relief from the highly built-up city environment.

The modules of a living wall are watered with storm water or through a network of pipes. For our project, we combined light greywater treatment with watering system of the wall. According to various studies, the media and plants are known to absorb pollutants from water such as nitrogen and phosphorus, hence living walls can be used to treat on-site greywater for reuse.

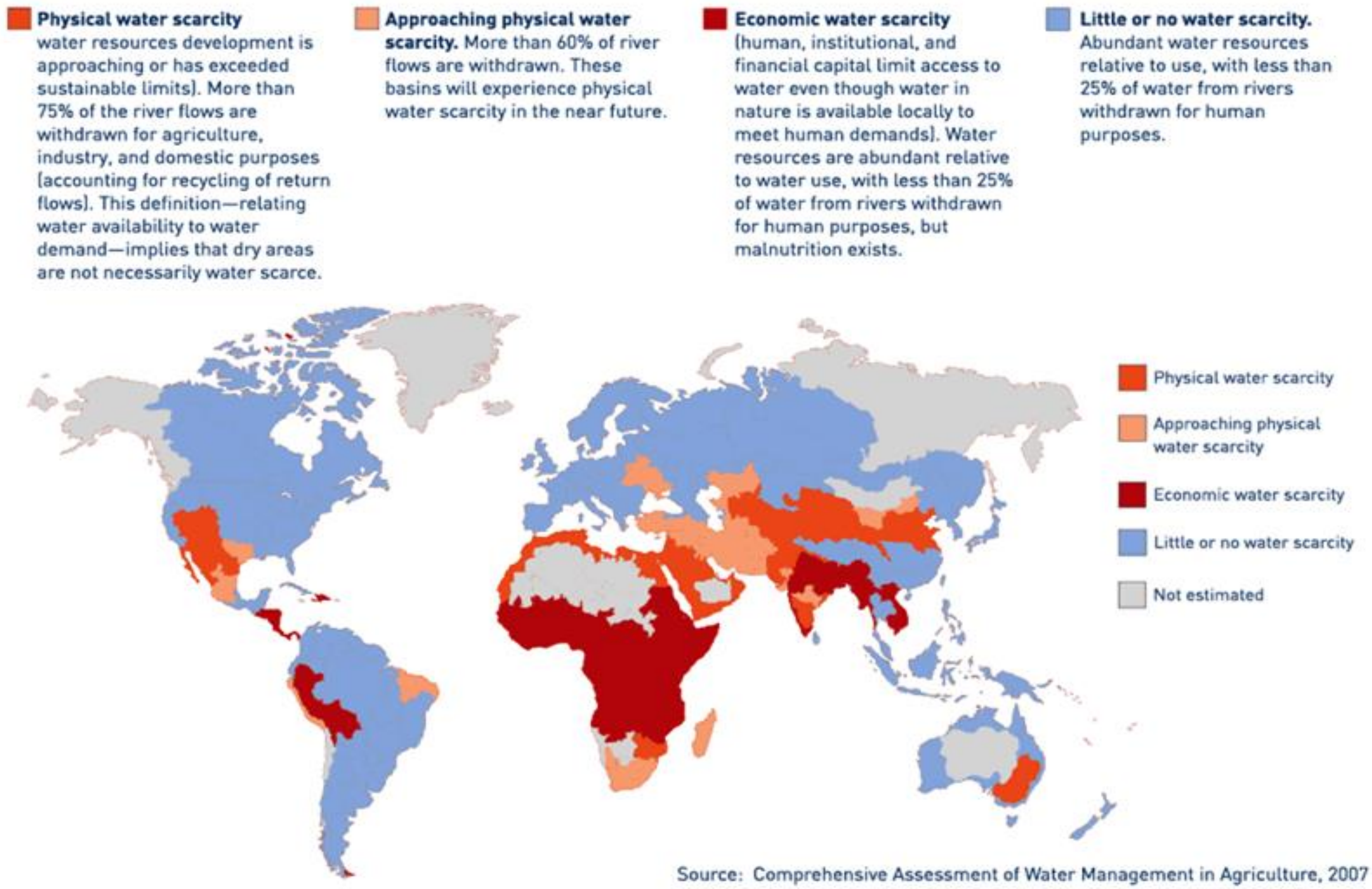


Figure 1 Areas of Physical and Economic Water Scarcity

1.4 Sustainable Development Goal 6:

Our project fulfils Clean Water and Sanitation Goal defined by the UNDP under Sustainable Development Goals. According to UNDP, 80% of the wastewater is discharged into waterways without any adequate treatment. Treatment of Greywater through living walls is a novel approach that aims at achieving two targets of Goal 6:

- By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally

- By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity

1.5 Objectives

During the course of this project, following two objectives were expected to be fulfilled:

1. Design pilot scale model of a living wall with an integrated greywater supply system.
2. Determine suitable plant species and optimum flow-rate for treatment of greywater.

A pilot scale model was built to study the living wall in natural, outdoor conditions. For the prototype design, following factors were considered:

- Low cost
- Good quality materials
- Angle of the pots to allow lateral and vertical infiltration throughout the media
- Position of the pots must be such that the bottom plants receive ample sunlight and all plants have vertical and horizontal space to grow without covering other plants.
- Position of tank to allow greywater flow under gravity
- The model must be easily up-scalable

2. Literature Review

2.1 Background

Pakistan moving closer to water scarcity is a terrifying fact. Due to excessive urbanization and unsustainably rapid industrialization, Pakistan cuts down 7000 to 9000 hectares of jungle yearly. (Khoso & Ansari, 2015). This has depleted evaporation rates exponentially and resulted in far more arid conditions than previously existed and increasing rapidly. Low rainfall has translated to drier periods for water bodies get longer, forcing greater dependence on groundwater supplies which in themselves are depleting due to the decreased rainfall and low infiltration rates. Prevention and mitigation of water scarcity is a countrywide priority. Water conservation and recycling studies have revealed that filtration of nutrients polluting the water through a vertical wetland is the most effective method for recycling greywater.

We consulted various literature sources over the course of the project. We determined the viability of utilizing green walls to treat light greywater. We learnt of the standards for greywater reuse in domestic areas as well as the requirements for water utilized for irrigation and horticulture. Dedicated studies on pollutant removal mechanisms in green walls led us to better understand and develop the final system design. There were no relevant studies done in Pakistan on the subject, which was troublesome. We consulted studies that has been conducted in areas with similar climatic conditions such as Pune (India) and Melbourne (Australia). Some of the more significant findings are mentioned below.

2.2 Characteristics of Greywater

Between 41-91% of domestic water is converted into greywater. Thus, greywater is an important resource to utilize in water savings approaches. Studies were consulted that took a transparent look into the many different techniques with which greywater can be treated and reused. The research was in depth, analyzing all the processes with a fine-tooth comb. One important distinction developed early on was that high load greywater mostly containing surfactants and detergents would be toxic to plants due to the heavy metal load. For high load or heavy greywater, the COD to BOD ratio was 4:1, which meant that the heavy metal content was high and very difficult to remove. In comparison, light or low load greywater has near to none heavy metals with the most potent pollutants being Nitrogen and Phosphorus. These are much easier to remove and are vital nutrients for plants that they readily uptake. This proved that only light greywater should be used for the project, separated at source.

2.3 Living Wall Design

Green walls may be designed in several different ways like vegetated mat walls or vertical gardens with horizontal pots but if used for greywater treatment, the only sensible approach is a modular set up using a container-based design (Jim 2015). This is so because the modular design is much more lightweight than other styles and also provides for a significant growing media volume for pollutant removal. A review was conducted of different approaches in living wall design. The study outlined the challenges that could hinder the success rate of the system. One of these challenges was an arid climate. Arid conditions make plant survival difficult as the plants require sufficient water, nutrients, and very specific light conditions to grow. Winds and air movement were also highlighted as important contributing factors as the air flow prevents fungal growth on the plants. This air flow is variable over the depth and width of the entire living wall. The study recommended extra ventilation space at the time of setup of the wall itself. We then decided to use a stand slightly ahead of the wall itself on which we mounted the plants. The distance between the plants and the wall would create enough of a density difference to allow air flow to maintain ventilation. As arid regions tend to lie in the horse latitudes (30° N/S), low air flow for arid living walls and green roofs may be a particular concern (Pradhan et. al., 2019).

2.4 Vegetation in Living Walls

Type of vegetation is a primary factor in the effectiveness of living walls as greywater treatment systems. Plants in modules in green walls affectively act as parallel vertical surface wetland units. The main pollutant removal mechanism is biofiltration. Non-vegetated media is efficient in removing Total Suspended Solids and organics from the water but is limited in removing nutrients like Phosphorus and Nitrogen. Plant species filter out these strong nutrients from the water. Plants in the living walls must be climbers for the major portion descending from the top of the buildings and ornamentals for the lower storey as they do not have enough space to expand without losing storm water capture ability. An experimental research goes on to select different perennial and abundant species to test for nutrient removal efficiency. Of the species they chose, *Lonicera japonica* (Picture 5), a Japanese honeysuckle climber was the only one that was also available in Pakistan. Fortunately, *L. japonica* exhibited some of the best results for pollutant removal. Particularly for Total Nitrogen, *L. japonica* removals were up to 89% (Fowdar et al., 2017). This was an encouraging discovery and allowed for *L. japonica* to be chosen as one of the three plant species selected for this project.

2.5 Growth Media in Living Walls

One singular research team has conducted and documented live long-term research entirely on the effectiveness of growth media in living walls. Initially, they determined that only lightweight media could be used for these systems to reduce loads and stresses on the supporting wall. For this reason, tested and known efficient media in wetland-based treatment systems like sandy clay loam were not utilized due to their weight. Additionally, the different media were divided into two categories, fast and slow based on infiltration rates. The researchers then picked seven different media types to determine the most efficient water retention and pollutant removal mechanisms. Of these, perlite (Picture 2) and coco coir (Picture 1) had shown the best results in fast and slow categories respectively.

Further research leading from the results obtained from the previous year was conducted by the same team in the following year. This study was based around the determination of the optimum media mix by combining the best of both fast and slow media. They tested greywater through six non-vegetated green wall modules, each with a mixture of perlite and coco coir over a range of ratios. The conclusion reached was that the optimum mix lies at a point between 2:1, perlite to coco-coir to 3:1, perlite to coco coir because clogging did not occur up until this point. We consulted this study to reach the decision that we would test our setup with both of these media mixes to determine which mixture is better at pollutant removal (Prodanovic et al., 2017).

3. Materials and Methodology

Two pilot-scale prototypes were set up with different ratios of media mix.

3.1 Materials

3.1.1 Media

The media had some very specific requirements such that it had to be soil-less so as to prevent nutrient provision to plants in order to maximize nutrient uptake through the greywater alone. Studies were conducted to find the optimum media for pollutant removal and plant growth suggested perlite (Fast Media) and coco coir (Slow Media) were the most efficient materials (Prodanovic et al., 2017). For this purpose, a combination of perlite and coco coir as growth media with ratios of 3:1 and 2:1 respectively were chosen for two prototypes (Prodanovic et al., 2018). The total mass of media mix for each prototype was kept constant i.e. 180 gms per pot.

Picture 1 Coco-coir

Picture 2 Perlite

3.1.2 Plants

Selection of plants was determined by their climatic durability and local abundance. Plant species for a living wall must be perennial, resistant to variation in temperature, and may tolerate water saturated conditions for continuous greywater treatment. Under these considerations, three species were chosen to be tested for level of pollutant removal.

i. *Lonicera japonica*
ii. *Alternanthera ficoidea*
iii. *Chlorophytum comosum*

These plants are cheap and abundantly available across Pakistan.

Picture 3 Chlorophytum comosum

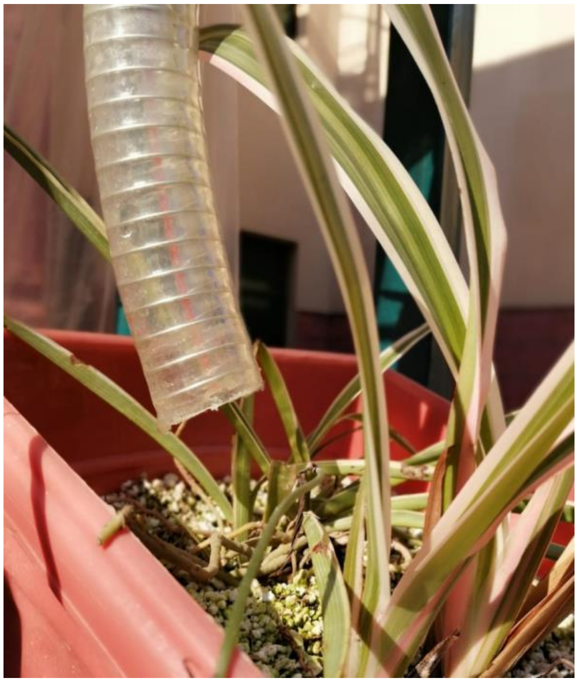
Picture 4 Alternanthera ficoidea

Picture 5 Lonicera japonica

3.1.3 Prototype design

- Recycled HDPE pots with dimensions of 14cm x 14cm x 15cm were used. The prototype consisted of 20 pots arranged in vertical columns of 5 pots each, and were hung over specifically designed spaces on the metal frame. All three plant species were planted in separate columns, and one column was left non-vegetated. The pots in a column were connected to each other through PEX pipes. The pots were attached to the frame such that the pots slanted slightly, making an angle of 35 degrees with the frame. This was done to allow lateral infiltration along with vertical, as the inlet pipe was at the higher edge of the pot and the outlet pipe was at the steeper bottom edge.
- The watering system consisted of a PVC pipe (Picture 7) at the top of the prototype which was connected to flow-control valves (Picture 8) above each plant column. The other end of the pipe was connected to a synthetic greywater supply tank (Picture 6) placed above the prototype to allow gravity-driven flow. The greywater trickled down through a column of pots through the PEX pipes connecting each pot.
- Standard sampling bottles were used to collect effluent for testing. PET bottles were used to find out total volume of effluent generated per day.

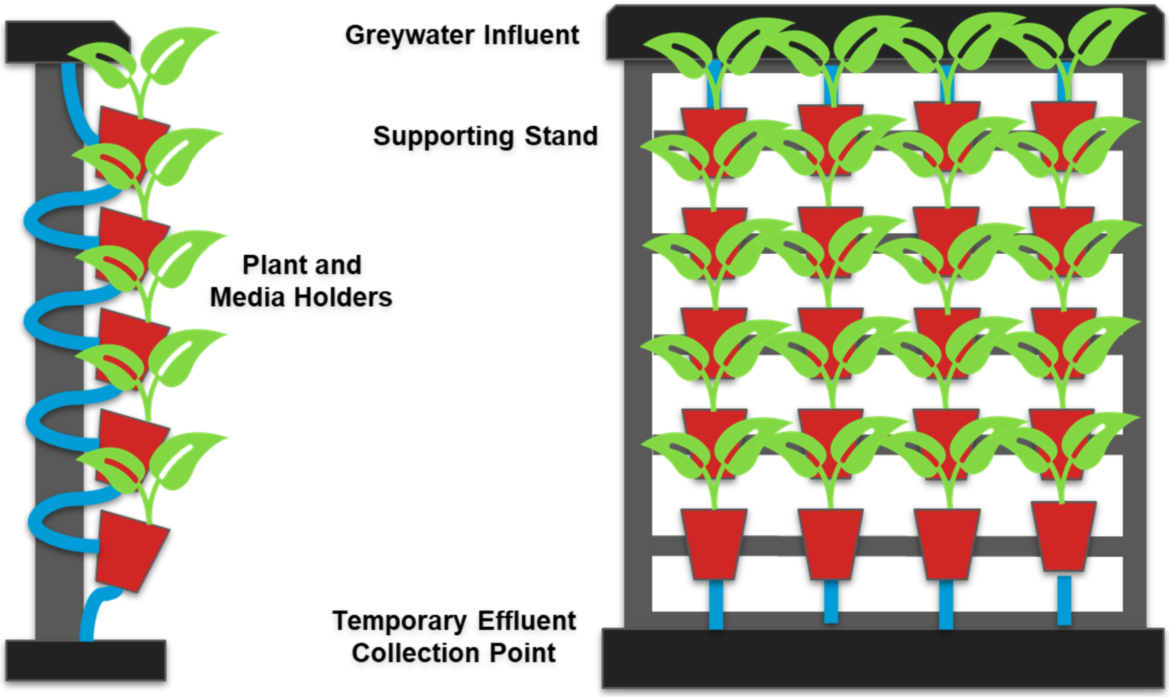
Picture 6 Influent Supply



Picture 7 PVC pipe to First Row

Picture 8 Flow Control Valves

Picture 9 Media Mixture in Pots



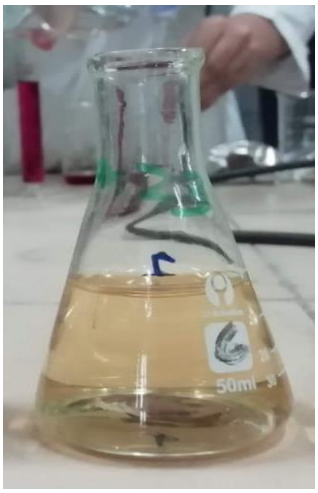
Picture 10 Schematic of Living Wall Prototype

Picture 11 Living Wall Prototype

3.2 Methodology

3.2.1 Flushing

The media mix in all the pots was initially flushed with tap water before plantation, for two weeks starting from October 2018. Flushing was performed at a flow rate of 0.1 L/min for 4 hours a day, to remove residual particles from infiltration pathways. It was observed the coir initially imparted color to the effluent, however after adequate flushing the color faded away.



Picture 12 Effluent Color Before Flushing

Picture 13 Effluent Color After Flushing

3.2.2 Influent Greywater Characteristics

Synthetic greywater with the following characteristics was fed to the plants

Table 1 Synthetic Greywater Characteristics (Eriksson et al., 2002)

Parameters	Units	Results
BOD	mg/L	100
COD	mg/L	200-250
TDS	mg/L	650-750
TSS	mg/L	100
TP	mg/L	5
TN	mg/L	10
pH	_	7.5-8.5
Turbidity	NTU	10

3.2.3 Dosing Regime and Sampling

After flushing both the non-vegetated and vegetated pots were dosed with synthetic greywater (Table 1) five days a week. The wall was not watered during the weekend providing plants with a two-day drying period. The greywater was fed with constant flow rate at typical office peak loading hours i.e. 12 to 2p.m and 3 to 5pm (Figure 2). This time was selected on the basis of maximum greywater generation as well as availability of sunlight for plants. The flow rate was manually varied using a stopwatch and measuring cylinder.

After every three weeks, flow rate was increased by 0.01L/min. Effluent samples were collected once a week, on every Thursday to acclimatize the plant and biofilm to the new flow rate. Hence, three test results were averaged out for each flow rate.

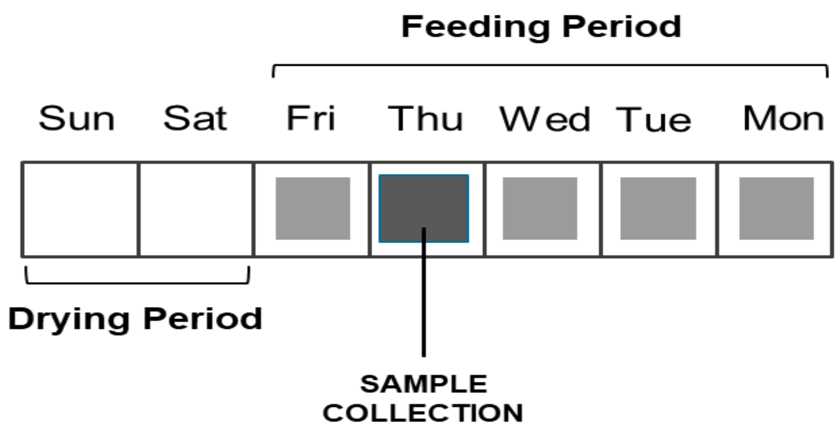


Figure 2 Feeding Pattern

3.3 Effluent Tests

- **Total Kjeldahl Nitrogen**: ASTM D3590-17, Standard Test Methods for Total Kjeldahl Nitrogen in Water, colorimetric analysis method was used to measure organic nitrogen in the samples. The method includes below mentioned steps:
    1. Digestion of sample with Sulfuric acid
    2. Distillation involves raising the pH of sample with Sodium hydroxide followed by separation of nitrogen using Boric acid in a TKN assembly
    3. Titration with HCl is the final step to quantify organic nitrogen in the sample.

- **Nitrate**: The method used was selected on the basis of literature review (Navone 1964)

  Water sample was digested with 1N HCl and its absorbance at 220 and 275nm was measured using UV-Vis Spectrophotometer.

  Absorbance of sample = Abs at 220nm – 2(Abs at 275nm)

  Nitrate concentration was determined through a standard calibration curve.

- **Nitrite**: was determined using the most common method which includes addition of sulphanilic acid and N-(1-naphthy1) ethylenediamine (Saltzmann, 1954; Montgomery & Dymock, 1961; Sen Nrishinka & Donadson, 1978). Absorbance at 543nm was measured through a UV-Vis Spectrophotometer and was used to determine nitrite concentration from a calibration curve.

Picture 14 Addition of Color Reagent to Sample

- **Total Phosphorous**: Method in accordance with 4500-P PHOSPHORUS (2017)

  Digestion of sample was performed with ammonium persulfate and sulfuric acid. Molybdovenedate was added to the digested solution. Samples were incubated for 30 minutes to develop yellow color. Absorbance of each sample and blank was measured through a UV-Vis Spectrophotometer at 470nm.

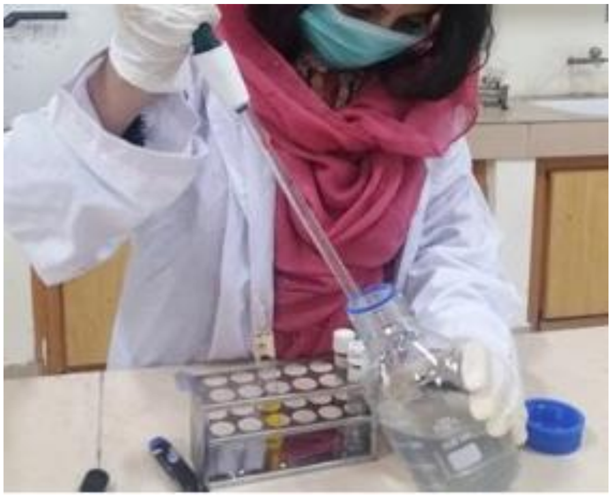
Picture 15 Sample Digestion for TP. Make: Valencia Scientifica. Model: ARE

- **Chemical Oxygen demand**: In accordance with IS: 3025 (Part 58)-Reaffirmed 2006.
  1.5 mL Potassium dichromate and 3.5 mL sulfuric acid was added to 2.5 ml sample in a test tube. These solutions were digested for 3 hours in a COD digester and then titrated with Ferrous Ammonium Sulfate.

$$\textbf{COD mg/L} = \frac{(\mathbf{A-B})*\mathbf{Normality}*\mathbf{8}*\mathbf{1000}}{\mathbf{Volume\ of\ Sample\ used}}$$

Where; A= Volume of FAS for blank

B= Volume of FAS for sample



Picture 16 Preparing Samples for COD Test

- **Biological Oxygen Demand**: A factor of 0.55 was used to calculate BOD from COD (Al-Momani, et al., 2002).

BOD mg/L = 0.55 * COD

- **Total Hardness**: was determined using Erichrome Black T indicator and titration with EDTA solution in accordance to IS: 3025 (Part 21)-Reaffirmed 2002.

- **Total Dissolved Solids**: Conductivity meter was used to measure conductivity in µS/cm. Correlation factor used was 0.55

TDS (mg/L) = conductivity * 0.55

- **Total Suspended Solids**: In accordance with IS: 3025 (Part 17) A 50ml of sample was passed through 0.45micron cellulose filter which was pre-dried at 105 ºC.

- **pH**: was measured using a pH meter with probe.

- **Turbidity**: A portable turbidity meter was used to measure turbidity in NTU.

- ***Escherichia coli**:* MPN Technique approved by EPA Method 1603 (m-TEC media) was used to determine *E.coli* in effluent dilutions.

4. Results and Discussion

Each prototype was run on 6 flowrates over the course of six months; starting from 0.01 to 0.06L/min. Three effluent samples at each flowrate were collected and analyzed for Total Nitrogen, Total Phosphorous, Chemical Oxygen Demand, Biological Oxygen Demand, Total Suspended Solids, Total Dissolved Solids and Turbidity. The results were averaged and pollutant removal rates were calculated for non-vegetated and vegetated columns at each flow rate.

4.1 Hydraulic Performance

The hydraulic retention time was observed to decline with increase in flow rate. The 3:1 media had lower HRT than 2:1 media due to higher ratio of coco-coir which has smaller pore spaces than perlite thus causing more rapid clogging (Prodanovic et al., 2018). Perlite was introduced in the media to lower HRT because coco-coir is a slow medium and water ponding starts to occur in it at higher flow rates. Among the plant species, *Alternanthera ficoidea* had the highest retention time while *Chlorophytum comosum* had the lowest retention time.

4.2 Pollutant Removal Performance

- **pH, Total Suspended Solids and Turbidity**

  pH of effluent remained between 7.5 to 8.0 for all columns.

  Initially, during flushing, TSS count was high as the effluent retrieved was murky. After flushing TSS remained negligible for all three plant species in both prototypes (100% removal). The non-vegetated columns occasionally had TSS in its effluent with 3:1 column having higher TSS than 2:1 column. 2:1 column efficiently strained particulate matter since it has greater quantity of coco-coir which has smaller pore spaces (Mohamed et al., 2014). These results further show that most particles are filtered out by the media, but additional filtration also occurs by plant roots.

  Turbidity occurs due to clay, silt, very tiny inorganic and organic matter, algae, dissolved colored organic compounds, and plankton and other microscopic organisms. Coco coir present in the media mixture imparted color to the effluent. Flushing and subsequent feeding reduced the color which had direct effect on turbidity. Samples collected after the first week of feeding had turbidity less than 2 NTU which lies within US EPA 2004 Greywater reuse standards (Table 3)

- **Total Hardness**

The overall removal efficiency for hardness was higher for 2:1 media as compared to 3:1 media. At initial flow rates most of hardness was removed due to adsorption of Mg and Ca ions on the media, particularly coco-coir, rather than the plants because in winter plant growth is slowed down (Hatfield et al., 2015). As the temperature began to rise, plants began to utilize these ions and removal rate increased significantly for both media types. The maximum removal rate of up to 65% was observed at 0.04L/min by *Chlorophytum comosum* species in 2:1 media. Slight decrease was observed at higher flow rates however the removal rate was still above 50%. *Alternanthera ficoidea* and *Lonicera japonica* also showed removal rates above 50% as shown in Figure 3a. As depicted by Figure 3b, *C. comosum* had the highest removal efficiency of 52.77% at 0.05L/min. Again, the removal rates at 0.04, 0.05, and 0.06L/min remained fairly constant.

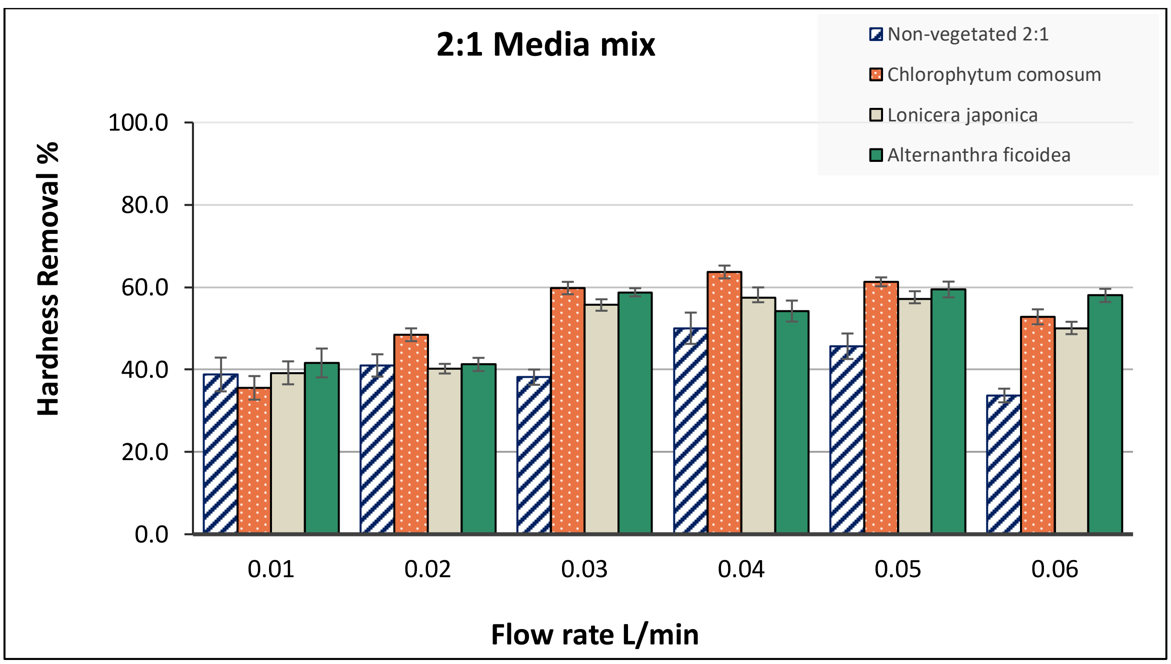


Figure 3a Percentage Removal of Total Hardness in 2:1 Media

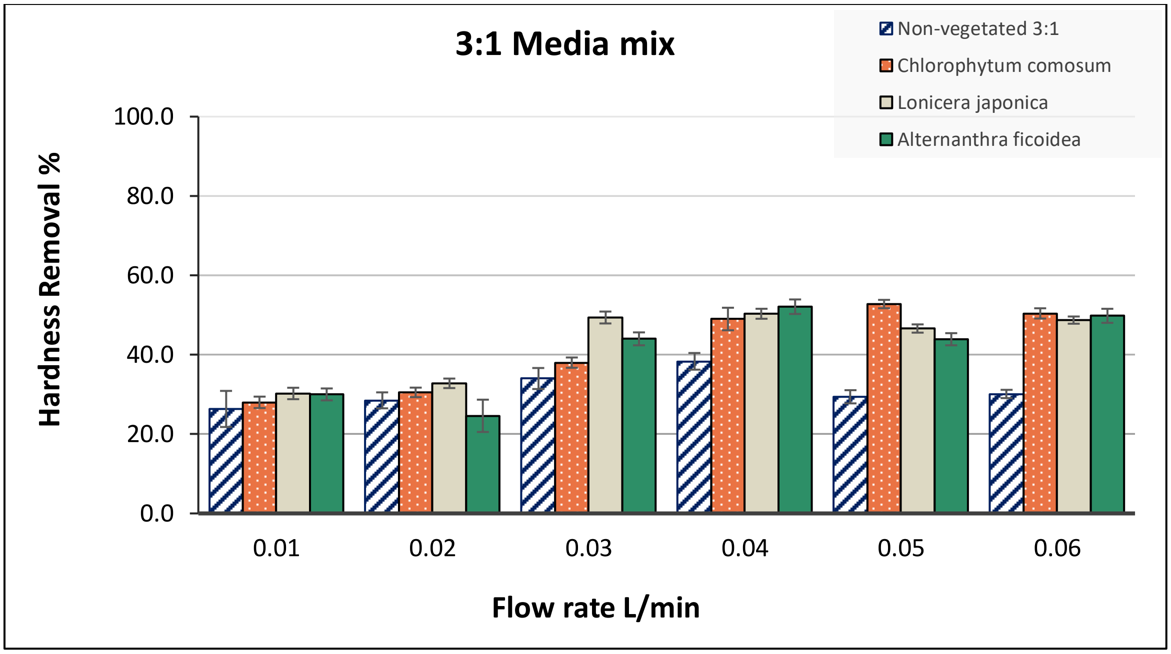


Figure 3b Percentage Removal Total Hardness in 3:1 Media

- **Total Nitrogen**

At 0.01L/min, both media and plants had low removal efficiencies of around 30% to 40%. This could be due to absence of a biofilm and low temperatures retarding plant growth. All three plant species showed significant removal rates, greater than 80%, below 0.05 L/min flow rate in both media (Figure 4a, Figure 4b). However, for 3:1 media (Figure 4b), hydraulic retention time decreased rapidly after 0.04 L/min, which did not allow much time to the biofilm for complete nitrification-denitrification of nitrogen. The retention time decreased more rapidly than 2:1 media because of greater perlite ratio which has larger pore spaces and low adsorption capacity compared to coco-coir (Prodanovic et al., 2018). Additionally, TN removal occurred through Nitrogen assimilation through microbial activity (Fowdar et al., 2017). This nitrogen starts leaching from perlite after drying periods of 3 days (Prodanovic et al., 2017). Removal efficiency for *Lonicera japonica* was slightly higher than other species.

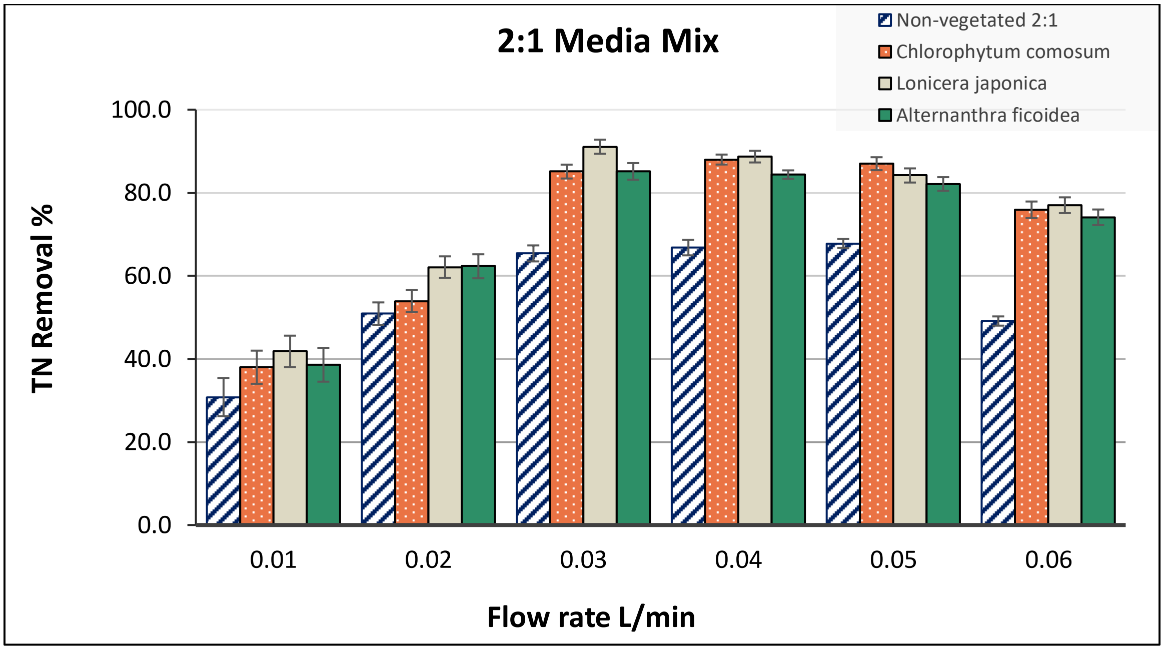


Figure 4a Percentage Removal of Total Nitrogen in 2:1 Media

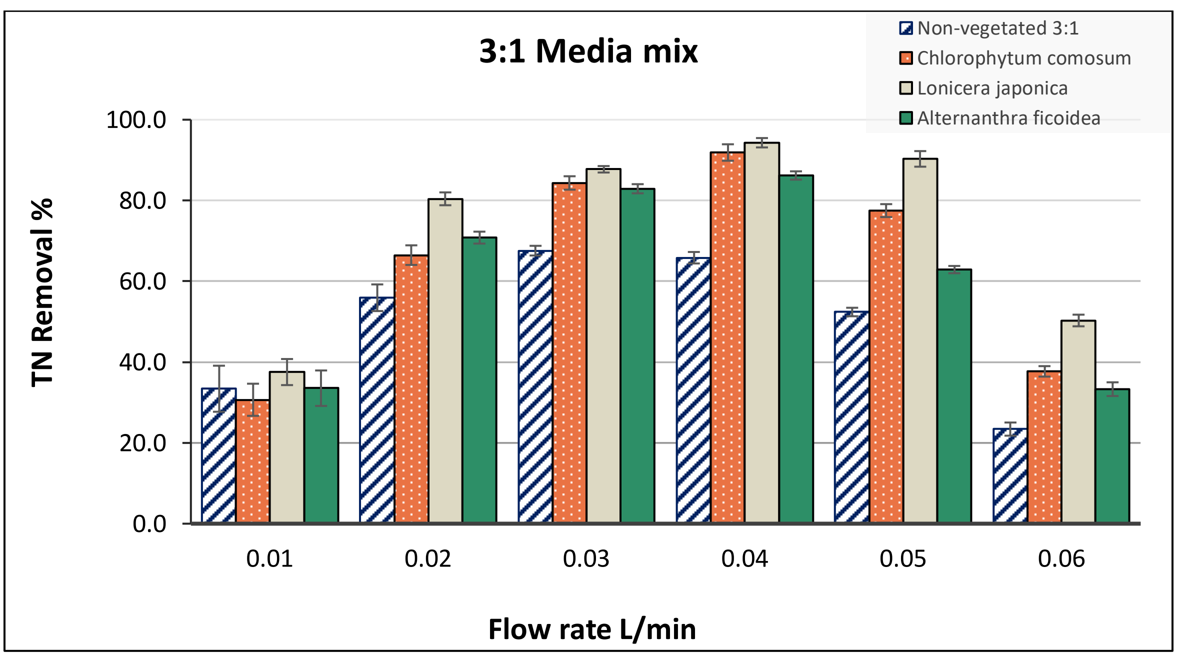


Figure 4b Percentage Removal of Total Nitrogen in 3:1 Media

➢ Total Phosphorus

A comparison of Figure 5a and Figure 5b shows that adsorption of phosphorous in non-vegetated pots was slightly higher for 2:1 media (60%) as compared to 3:1 media (55%). It is likely that coco-coir has greater affinity to adsorb phosphorous than adsorption capacity of perlite (Prodanovic et al.,2017). Moreover, plants also improved phosphorus removal efficiency by 20 to 40%, particularly *Chlorophytum comosum* in 2:1 media (greater than 80% removal rate). At initial flow rates, the HRT was high but removal of phosphorous adsorption was low. It could be hypothesized that low temperatures have an adverse effect on phosphorous adsorption along with plant uptake. At 0.06 L/min, HRT decreased significantly, and the influent passed through the media without adequate phosphorous removal.

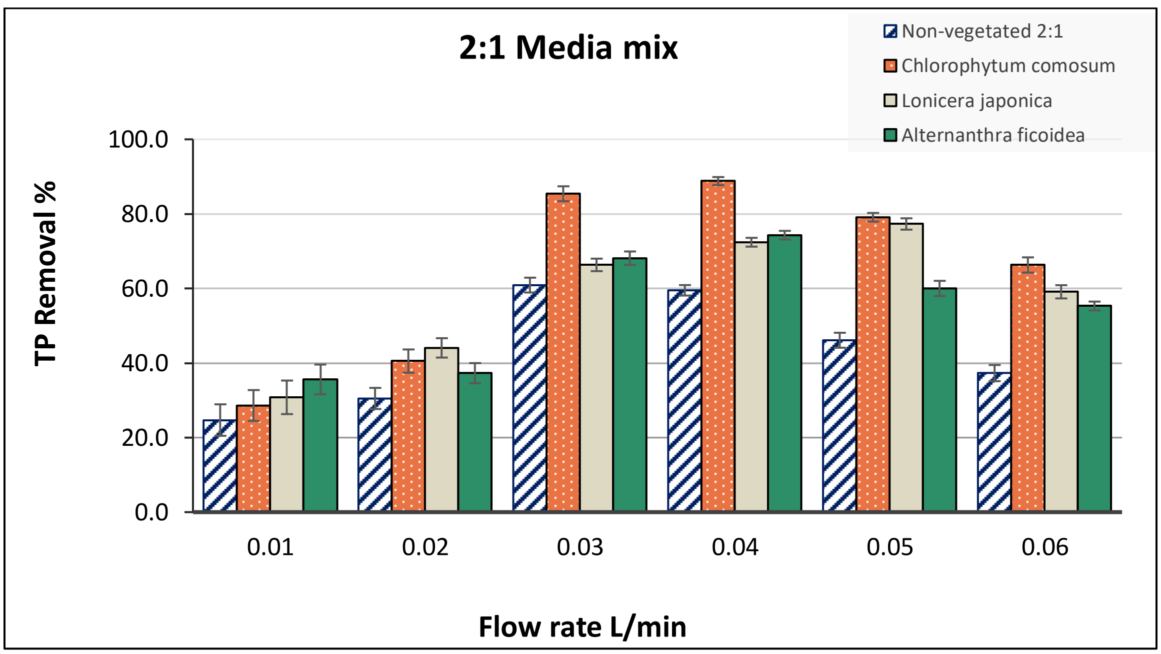


Figure 5a Percentage Removal of Total Phosphorous in 2:1 Media

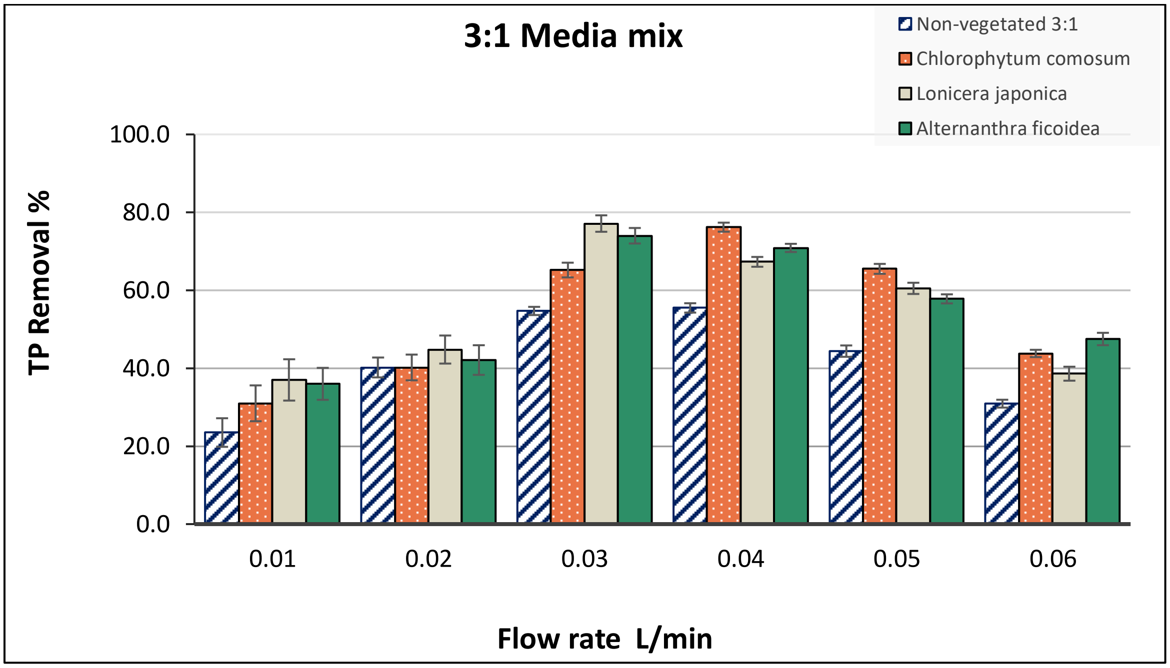


Figure 5b Percentage Removal of Total Phosphorous in 3:1 Media

- **Chemical Oxygen Demand**

It is suggested that COD removal is linked to biological and physico-chemical processes, and removal rate increases over time due to straining (Prodanovic et al., 2017). The results (Figure 6a and Figure 6b) depict that most COD is treated by biofilm established on the media rather by plants or their roots. For both media ratios, all three species achieved maximum COD removal of greater than 85% at 0.04L/min. This may be due to higher retention by 2:1 media allowing for increased biological uptake. 2:1 prototype initially had lower removal rate than 3:1 however at high flow rate, efficiency of 3:1 mix dropped more rapidly. It was observed that *Alternanthera ficoidea* and *Lonicera japonica* had relatively higher removal rates than *Chlorophytum comosum.*

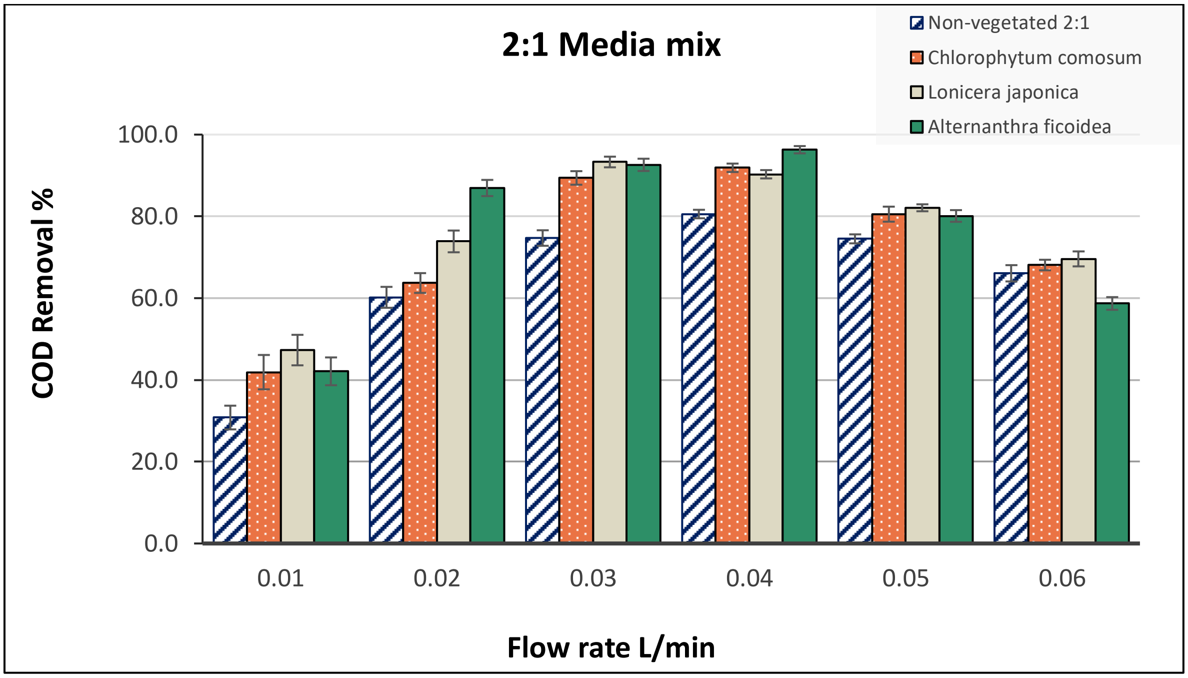


Figure 6a Percentage Removal of Chemical Oxygen Demand in 2:1 Media

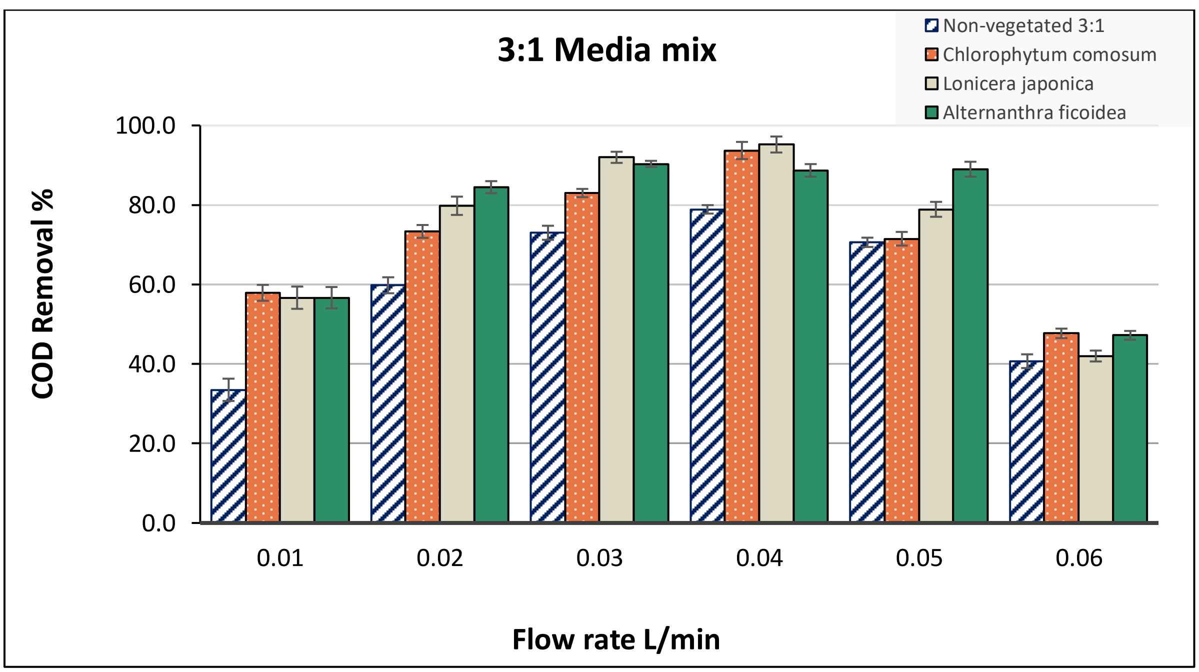


Figure 6b Percentage Removal of Chemical Oxygen Demand in 3:1 Media

➢ Biological Oxygen Demand

Both media mixes depicted excellent pollutant removal rates of greater than 90% at 0.04 L/min. For 3:1 media, BOD of the effluent started to increase due to decrease in the hydraulic retention time at greater flow rates since BOD is reduced by microorganisms. *Alternanthera ficoidea* and *Lonicera japonica* had relatively higher removal rates than *Chlorophytum comosum.*

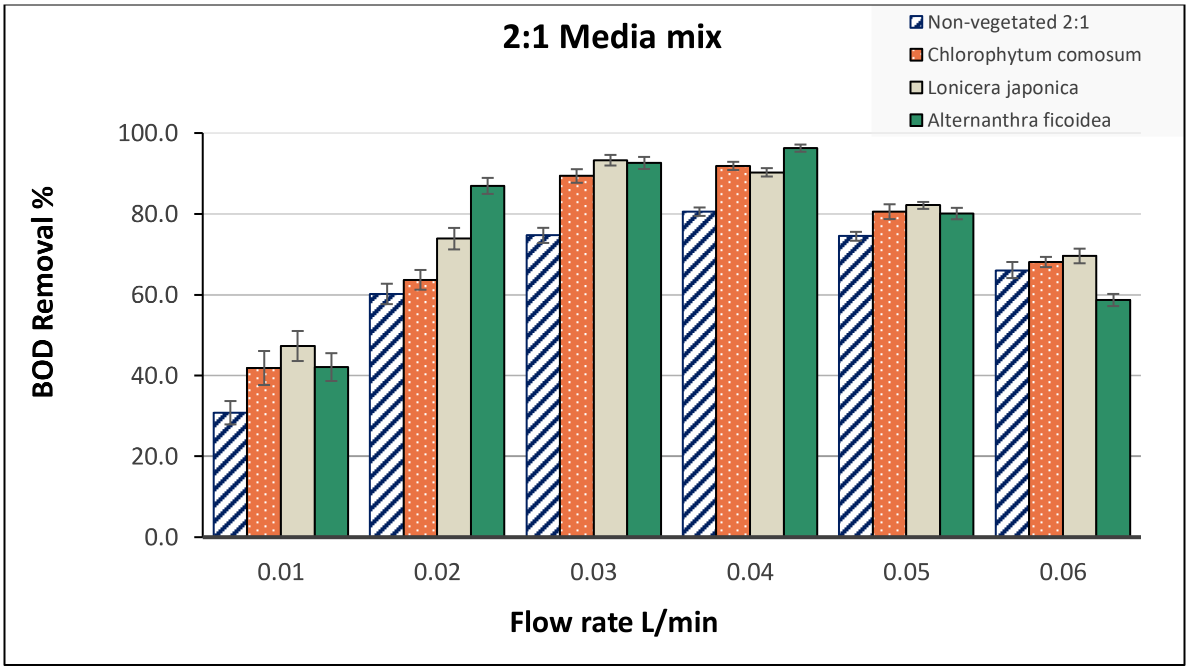


Figure 7a Percentage Removal of Biological Oxygen Demand in 2:1 Media

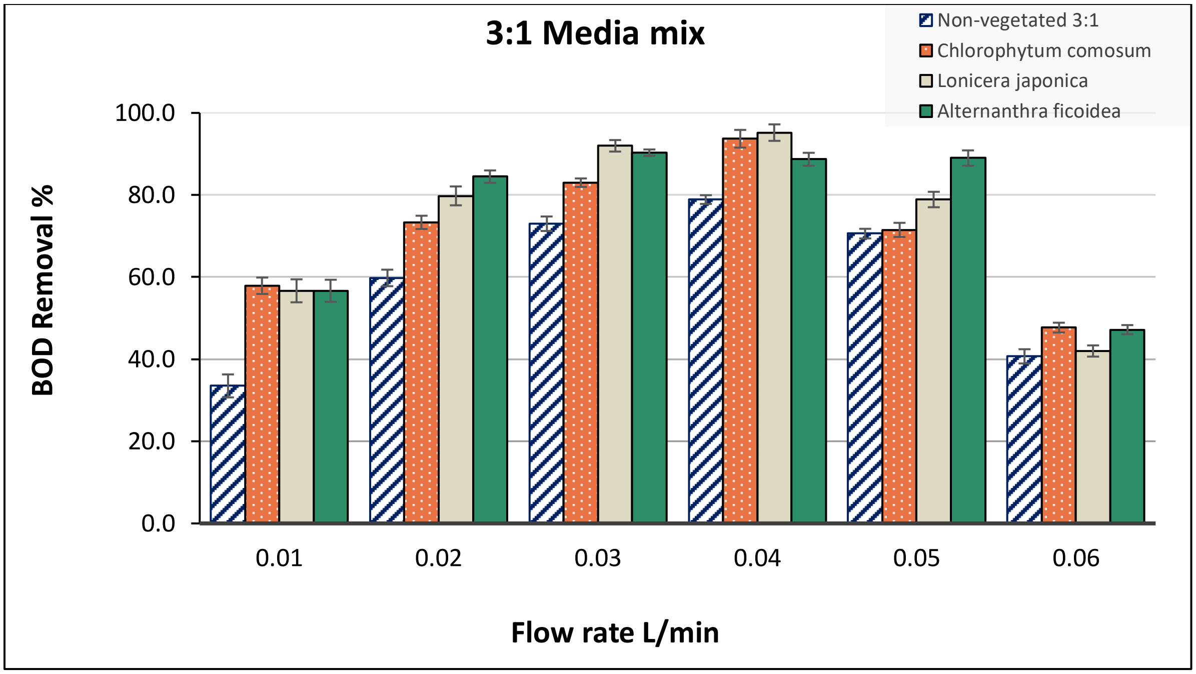


Figure 7b Percentage Removal of Biological Oxygen Demand in 3:1 Media

- **Total Dissolved Solids**

Removal of total dissolved solids remained constant around 40 to 50% for 2:1 mix. The 3:1 media mix depicted removal efficiencies higher than 50%, with *Chlorophytum comosum* having peak removal of 68% at 0.05 L/min. At 0.06 L/min a slight decrease in removal efficiency was observed. The inorganic content of TDS was filtered out by the media and then biodegraded. The biodegraded material along with ions are likely to be taken up by plants and this uptake increased in warmer temperatures as shown by Figure 8a and Figure 8b.

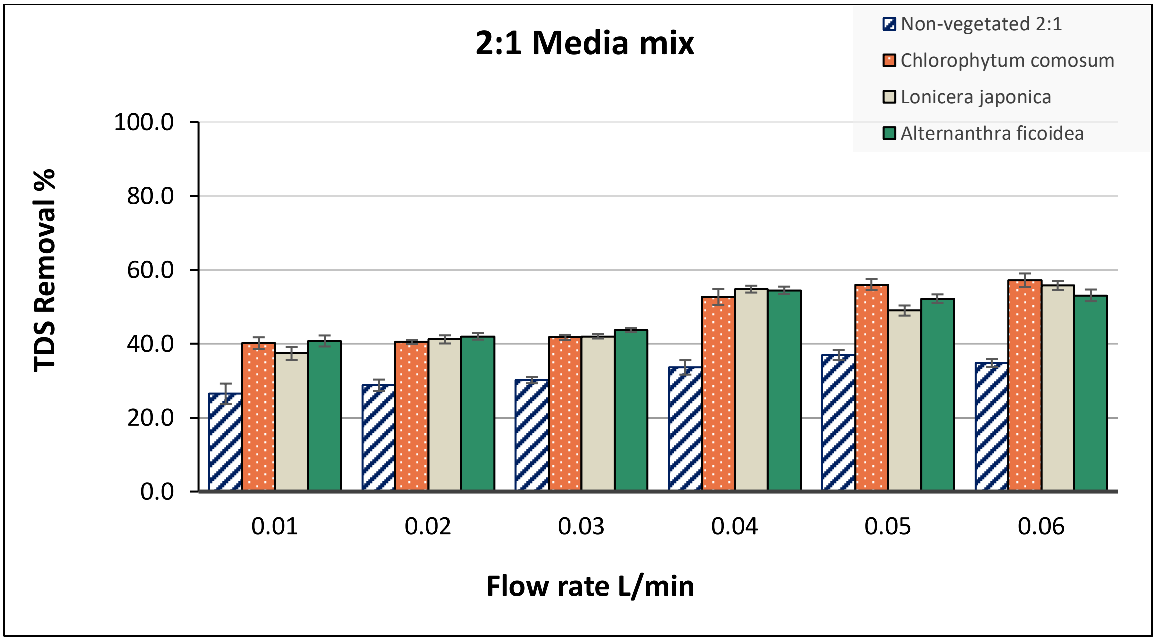


Figure 8a Percentage Removal of Total Dissolved Solids in 2:1 Media

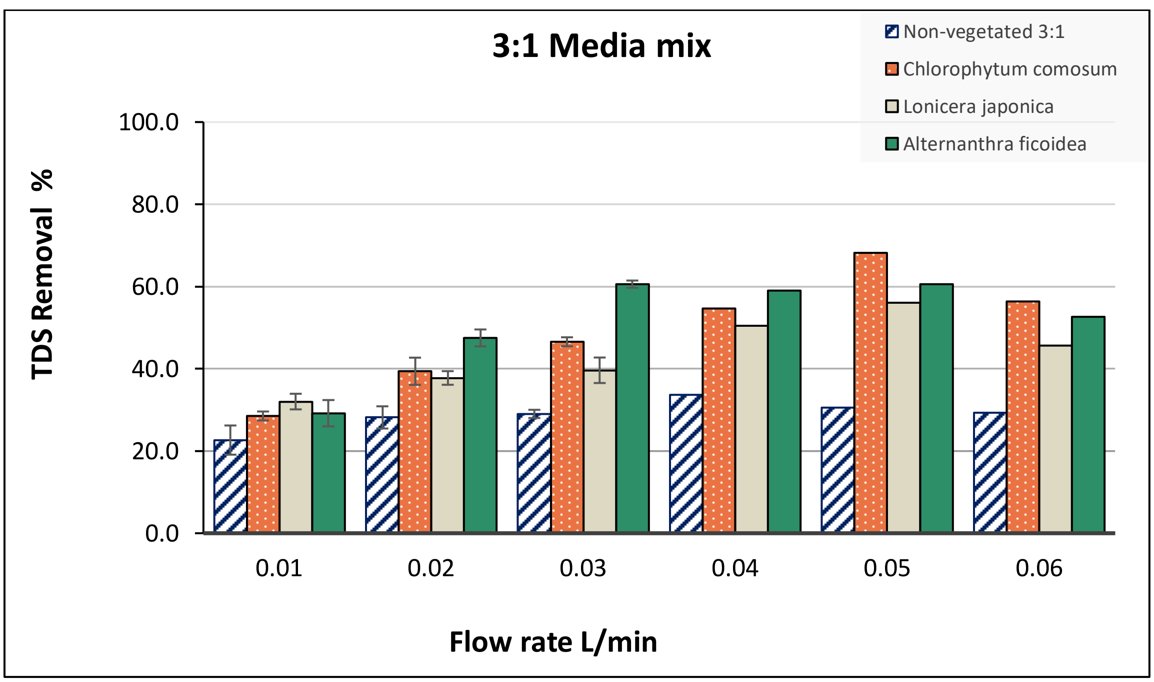


Figure 8b Percentage Removal of Total Dissolved Solids in 3:1 Media

- ***Escherichia coli***

The effluent samples from 0.04 L/min and 0.05 L/min were tested for *E. coli* using MPN technique because these flow rates had optimum pollutant removal rates. It was observed that both samples presented significant bacterial counts albeit less than microbial count of influent. Hence, disinfection would be recommended in any case.

5. Analysis

It was determined that appropriate flow rate for both 3:1 media mix setup and 2:1 media mix was found out to be 0.04 L/min. Results are shown in Table 2.

Approximately 70% of influent was retrieved as effluent from Prototype 1 having 3:1 while 63% was retrieved from Prototype 2 having 2:1 perlite to coco-coir. Total Phosphorus and Total Hardness concentrations in effluent were significantly lower for Prototype 2 as compared to Prototype 1.

Table 2 Comparison of 2:1 and 3:1 Media Performance at Optimum Flow Rate

Parameter	Units	2:1 Media	3:1 Media
pH	_	7.5 - 8	7.5 – 8
TSS	mg/L	BDL	BDL
Turbidity	NTU	0.5 - 2	0.5 – 2
TDS	mg/L	230 - 260	250 – 300
Total Hardness	mg/L	100 - 180	100 – 200
Total Nitrogen	mg/L	1 - 2	1 – 2
Total Phosphorous	mg/L	0.4 – 0.7	0.5 – 0.9
COD	mg/L	10 - 30	15 – 30
BOD	mg/L	5 - 10	5 – 10
Retrieved Volume	L/day	10	11

6. Conclusions

Determining the suitable performance level of the system from analysis of the results, conclusions were drawn about the most effective overall system design.

6.1 Flow Rate

Interpreting the results, a flow rate of 0.04 L/min proved most efficient for both prototypes. At this infiltration rate, pollutant removals were highest for both systems and within greywater reuse quality limits as apparent from **Error! Reference source not found..** Evidently, mix with higher quantity of coco coir, achieved relatively higher removals in comparison with the lower quantity of coco coir, particularly in the case of Total Phosphorus and Total Hardness concentrations.
For Prototype 1, the 3:1 perlite to coir mix, volume of retrieved effluent was approximately 11 L in a day. This is nearly 70% of the influent volume. For media mix of 2:1 perlite to coir, at 0.04 L/min, retrieved a volume of nearly 10 L in a day which is around 63% of influent volume.

6.2 Media Mix

Analysis of all test results revealed that Prototype 2 had a higher overall pollutant removal efficiency. At optimum flow rate, Prototype 2 exhibited higher removal of Total Dissolved Solids, Total Hardness, Total Phosphorous and Chemical Oxygen Demand. It may be concluded that a media mix of 2:1 perlite to coco coir, is the preferred choice for the living wall setup.

6.3 Plant Species

Between the three plant species chosen for the course of this research, *Chlorophytum comosum*, the spider plant, was most effective in removing pollutants from the greywater. These determinations are based off of media mix of 2:1 perlite to coco coir and a flow rate of 0.04L/min. *C. comosum* removed all pollutants to extents below the limits of greywater reuse standards and at percentages relatively higher than both *Lonicera japonica* and *Alternanthera ficoidea. C. comosum* was particularly efficient in removing Total Nitrogen, Chemical Oxygen Demand and Total Phosphorous as shown in Figure. It was also least affected by weather changes and remained healthy throughout the experimental period.

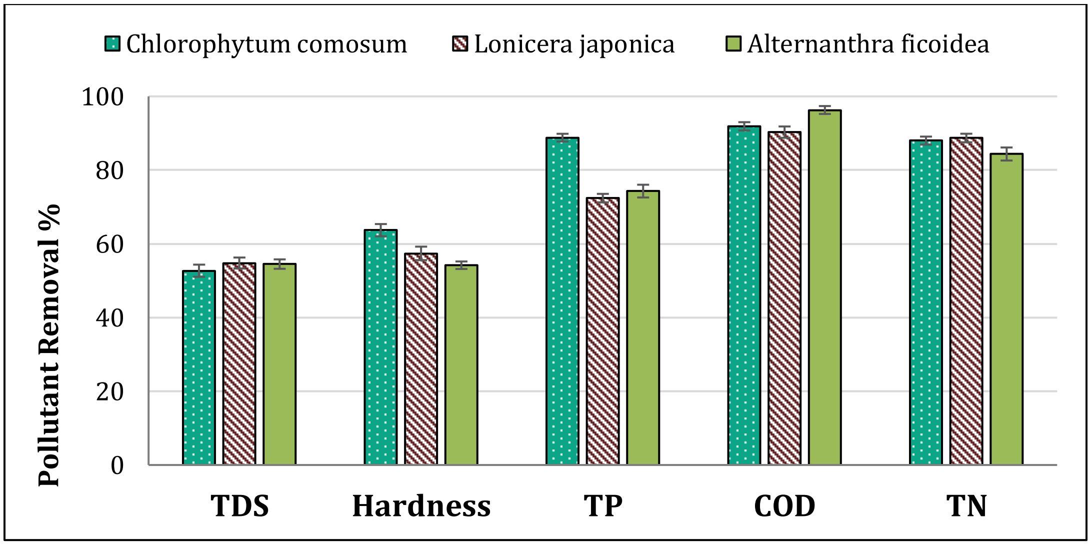


Figure 9 Comparison of Removal Percentage between Three Plant Species at Optimum Flow Rate

Table 3 Effluent Quality of C. comosum in 2:1 Media at 0.04L/min

Parameter	Units	Greywater Re-use Standards (USEPA 2004)	*C. comosum* in 2:1 media
pH	_	6 -9	7.5 - 8
TSS	mg/L	< 10	Negligible
Turbidity	NTU	< 2	1 - 2
TDS	mg/L	< 500	240 – 265
Total Nitrogen	mg/L	< 10	1 – 1.3
Total Phosphorous	mg/L	< 2	0.5 – 0.65
COD	mg/L	< 100	20 - 30
BOD	mg/L	< 10	5 - 10

7. Recommendations

Living walls provide an effective and efficient method for water conservation and treatment in urban localities where free land area is minimal. As green walls are vertical structures, gravity should be effectively utilized wherever possible to minimize intensive energy usage. These structures are most productive and efficient if set up with new buildings.

The living wall consideration should be added before the building design is finalized and a piping layout conscious of the greywater treatment system should be implemented. The piping should be such that light greywater sources are separated from toilet, laundry and kitchen streams and flow to a storage tank on the same level. To fix the pollutant loading rates, this storage tank should be an equalization tank. Flow control valves from the tank may then supply greywater to the living wall under gravity with the clean effluent collected and stored in a tank at the bottom of the building for further use.

The results proved that the effluent presented a significantly high microbial count that could prove harmful to the people and environment the water gets exposed to. To remedy this, the effluent collection tank may be connected to a disinfection apparatus by either chlorination or UV disinfection.

UV disinfection is the proposed route to be considered as it is environmentally safer and more effective than chlorination as chlorine is not able to remove more resistant microbes like *Giardia* and *Cryptosporidium.*

In the commercial sector, green wall treated water may be used for horticultural purposes near the building or for cleaning floors and vehicles. In households, this water may be utilized for car washing, cleaning or irrigating vegetable gardens. Where possible and acceptable to people, disinfected living wall effluent can even effectively be recirculated in the building as tap water as the final treated product has the same physical and chemical characteristics.

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