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Removal of chemical and microbial contaminants from greywater using a novel constructed wetland: GROW

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Abstract:

The availability of freshwater resources is becoming universally depleted, leading to the requirement for a focused management strategy for treating and reusing wastewater. In particular for urban and developing areas, small scale decentralized treatment systems are becoming popular. The GROW (Green Roof-top Water Recycling System) constructed wetland is one such option that provides a solution without a permanent land requirement and offering medium to high treatment efficiency. The performance of the GROW system was monitored from November 2013 to April 2015 in treating greywater from the Krishna Student Hostel in IIT Madras. The performance of the GROW wetland cells were examined over four monitoring periods in Phase 1 namely: 1) start-up stage, 2) seasonal variation 3) change of flow rate and 4) change in organic fraction (26.8, 25.9 and 25.5 g COD/ cubic. meter/ day respectively). In Phase 2, the plants and the filling materials were changed and the performance of GROW wetland cells were evaluated. The system was fed with greywater at a flow rate of 62, 70, 82, 100 and 120 L/ day respectively with hydraulic retention time of 0.7 – 1.3 days. The samples taken from the inlet and the outlets of the GROW system were taken weekly and analyzed for the following parameters; pH, COD, BOD, TSS, TN, NO_3 – N, TP, FC, SDS, PG and TMA. In the study, the overall removal efficiency was greater than 82% for all the parameters. The GROW wetlands reduced all the above mentioned parameters to within or closely to the USEPA standard limits for reuse. The reusable effluent water is named ‘Green Water’.

Keywords:

Constructed wetland, Greywater, Recycle, Surfactants and Personal care products, Nutrients, Organics

1. Introduction:

Increasing stress on the availability of freshwater sources worldwide has forced water providers to develop wastewater management strategies giving emphasis for recycling and reuse of treated wastewater. Wastewaters from households are classified into two types, i.e., i) greywater and ii) black water. Greywater includes wastes generated from bathroom sinks, baths or showers, washing clothes and possibly dishwasher except the wastewater from toilet whereas black water is the wastewater generated from toilets. Wastewater from dishwashers is usually excluded from greywater, due to high loading of fats/oils/ greases (FOGs), organic content and bacterial contamination, which makes the wastewater difficult to degrade and handle (Jefferson et al., 2000; Avery et al., 2007). Greywater treatment and reuse is one of the efficient solutions which offer the largest potential of water savings, accounting for 50-80% of freshwater water consumption (Eriksson et al., 2002; Gross et al., 2007) in domestic purposes. Moreover, greywater is lightly polluted and requires less expensive treatment prior to non-potable reuse

(Jefferson et al., 2000; Avery et al., 2007). There are various technologies available for treatment of greywater such as activated sludge process (ASP), membrane bioreactors (MBR), sequential batch reactor (SBR), rotating biological contractor (RBC), photocatalysis and electro coagulation (Merz et al., 2007; Masi et al., 2010). However, capital/infrastructure cost, social acceptance and power requirement may limit their application in rural and peri-urban areas in developing countries.

Treatment and reuse of greywater (as 'Green Water') for non-potable/secondary applications using various low cost less land intensive, sustainable and efficient technologies have been carried out in the past. The greywater was treated using a novel organic cation octadecyl trimethyl ammonium (ODTMA) with montmorillonite as a filtration unit along with a moving bed biological reactor for decomposition of part of the organic matter in the GW. The ODTMA complex was efficient in purifying GW due to its large surface area, positive charge and existence of hydrophobic domains (Rakovitsky et al., 2016). Another study uses an anaerobic filter followed by ultraviolet disinfection system for the treatment and reuse of greywater from an airport in Brazil (Do Couto et al., 2015). In-order to improve the green area of the city and to treat domestic greywater through a shallow horizontal subsurface constructed wetland that can be located in a household roof. A Wetland roof (WR) system was developed by Thanh et al. (2014), the system achieved an average COD removal efficiency of 77–78% or 20–28 kg COD/ha d for both sunny and rainy days. The system was able to remove nutrients also effectively with a TN removal efficiency of 88–91% or 17–20 kg TN/ha d, and a TP removal efficiency of 72–78% or 1.6 kg TP/ha d for different HLRs. A pilot installation of a green wall treating greywater from an office building in Pune, Maharashtra State, India. Green walls were filled with LECA®

(lightweight expanded clay aggregate) and coconut fibers. COD removal efficiency of this system was in the order of 14–86% (Masi et al., 2016).

Constructed wetlands (CW) are also one of such systems considered as sustainable, cost effective and a viable treatment option for treating greywater for small communities. Over the past few years, CW has gained popularity due to its effectiveness, low capital investment and low cost of operation with less maintenance over the conventional systems for treating various types of wastewaters such as municipal wastewater, textile effluent and landfill leachate (Masi et al., 2010). The earlier researches are mainly focused only on the treatment of real-time greywater using CWs for the overall removal of organics, nutrients and pathogens (Avery et al., 2007; Gross et al., 2007; Frazer Williams et al., 2008; Winward et al., 2008). But the present study focuses on the performance of novel constructed wetland (GROW) under various operating conditions (start-up, seasonal, hydraulic loading rate and organic loading rate) in treatment of real-time greywater. Additionally, the current study also focuses on the removal of surfactants and personal care products (SDS, PG and TMA) from real time greywater using GROW system.

There are various types of constructed wetland classified based on their flow pattern;

i) Horizontal subsurface flow constructed wetland,

ii) Vertical subsurface flow constructed wetland and

iii) Hybrid subsurface flow constructed wetland. The most commonly used hybrid flow CW is that in which the wastewater flows first into a horizontal flow CW (HFCW) and then to a vertical flow CW (VFCW) or vice versa, whereas in a few other studies hybrid systems are differentiated from other systems by introducing the baffles in the bed to make horizontal and vertical flow pattern in a single basin (Tee et al., 2012; Cui et al., 2015; Ramprasad and Philip, 2015). The advantage of the hybrid system is that the nitrogen can be nitrified completely in vertical flow CW and denitrified in horizontal flow CW (Sayadi et al., 2012). However, the disadvantage is that it requires large areas of land and complex construction and operation. To overcome the problem, a novel GROW constructed wetland (Green Roof-top Water Recycling System) was developed which is suitable for use in urban areas where ground space is limited

The performance and working of the GROW system was originally monitored and subsequently studied at Cranfield University, UK by Avery et al., (2007), Memon et al., (2007) and Winward et al., (2008). A novel GROW system for treating 480 L/day of the hostel greywater with a hydraulic retention time of 18.6 hours. The system consisted of a sequence of trough and weirs that were placed above the wooden frame on a pitched roof. The troughs were filled with expanded clay (size 0.1m) and gravel chippings (size 0.2m) and were planted with 8 varieties of native aquatic species. They found that the GROW system was most effective in the removal of suspended solids and turbidity (mean removal rates 91.2% and 98.2%, respectively). They also reported a 4.2 log reduction of total coliforms in the system. With a COD and BOD removal efficiencies of 59-80% and 84-92%, respectively, the treated water from the system was able to meet the stringent United States Environmental Protection Agency (USEPA) standard for water reuse (BOD <10 mg/L). They also claimed that the GROW system performed better than horizontal and vertical flow constructed wetlands (Avery et al., 2007). A comparative studies on the life cycle impact assessment of GROW system with other three biological treatment systems like membrane bioreactors (MBR), membrane chemical reactors (MCR) and reed beds were done by Memon et al. (2007). They concluded that the GROW system performed best in most of the impact assessment categories and MCR appeared to be less environmentally friendly (Memon et al. (2007). Similar way, another study evaluated the presence of common pathogens (total coliforms, *E. coli*, *Enterococci*, *Clostridia* and Heterotrophs) in greywater and compared the performance of GROW, VFCW, HFCW, MBR and MCR in the removal of pathogens. These systems were operated continuously with a flow rate of 480 L/day with an HRT of 2.1 days. It was found that MBR system provided better quality treated effluent by meeting the stringent USEPA standard limits for reuse followed by VFCW, GROW, HFCW and MCR (Winward et al., 2008).

In general constructed wetlands performances were affected by various factors such as climatic conditions, greywater characteristics, native plant species and substrate materials. The literature on GROW system were found to be mostly concentrated in the temperate maritime climate. The substrate (filling) material and plant species used in the earlier studies were mostly indigenous to the UK. Hence, it is necessary to evaluate the performance of the GROW system in different climatic conditions, vegetation patterns and greywater characteristics to determine the suitability of the system in other regions. Moreover, previous studies on GROW systems were conducted mostly at one particular flow rate, at constant HRT and at single organic loading rate (OLR). Information regarding the fate of surfactants and personal care products in GROW systems, is also lacking. Therefore, the present study focused on the evaluation of the performance of the GROW system in Indian tropical conditions and with native filling materials (sand, brick bat and gravel (1:1:1)) and 8 different plant species commonly available in India (*Canna indica, Canna flaccida, Canna lily – hybrid, Cardamina pratensis, Plectranthus amboinicus, Crossandrain fundibuliformis, Phragmiies australis, Solanum trilobatum*), at different flow rates (62, 70, 82, 100 and 120 L/day), and organic loading rates (26.8, 25.9 and 25.5 g COD/ cubic. meter/ day). The study also evaluated the effect of seasonal variations, change of plant species and substrate materials on the performance of GROW system. The fate of surfactants in GROW system was also evaluated.

2. Materials and Methods:

2.1 GROW constructed wetlands:

A novel constructed wetland system, Green Roof-Top Water Recycling System (GROW), was developed by Water Works UK Ltd., London, UK and was fabricated and installed in Krishna Hostel, IIT Madras, Chennai, India (GPS coordinates12° 59' 1.266" N; 80° 13' 57.3852" E). Chennai lies on the thermal equator and features a tropical wet and dry climate with the temperature ranging from 18°C - 42 °C and average annual rainfall of 1400 mm. The pilot scale experimental system for the treatment of greywater from the hostel was in operation from November, 2013 to December, 2016. The GROW system consisted of four rows of troughs connected laterally and placed on a mild steel scaffolding frame. Each row consisted of two troughs mounted in series and butted up to each other. The scaffolding frame was placed on the leveled ground surface, and the top row of the troughs ’A‘ was placed 0.8 m above the ground surface and the lowest one (trough ‘D’) was positioned at 0.4 m above the ground surface (Fig. 1). The troughs of the GROW system were made of high density polyethylene sheet of 6 mm thickness 4 m length and 2 m wide. The trough had a depth of 25 cm with a water holding capacity 125 L per trough. The troughs were fitted with intermediate ‘baffles’ and ‘weirs’ arranged in such a way that the wastewater was forced to have contact with the whole depth of media/ substrate and thereby reducing any short-circuiting. In first phase of the study, troughs were filled with a support medium which consisted of a mixture of sand, brick bats and gravel in equal proportion (1:1:1) to approximately 15 cm depth. The total volume of the GROW system was 1.84 cubic. meter and each substrate material occupied a volume of 0.4 cubic meters.

The troughs were planted with 8 varieties of native plant species of *Canna indica*, *Canna flaccida*, *Canna lily – hybrid*, *Cardamine pratensis*, *Plectranthus amboinicus*, *Crossandrain fundibuliformis*, *Phragmites australis*, *Solanum trilobatum*. The planting plan employed for the study is shown in Fig 2. Trough 1 was used only with substrate without any plants to act as an additional settling unit; trough 2 was planted with 4 plants of *Canna indica*, trough 3 was planted with 4 *Canna flaccid*, trough 4 was planted with *Canna lily – hybrid* (3 numbers), trough 5 was planted with 3 plants of *Cardamine pratensis and*, trough 6 was planted with 3 plants of *Plectranthus amboinicus*, trough 7 was planted with 1 plant of *Canna indica and 2* plants of *Solanum trilobatum*, trough 8 was planted with *1 plant of Phragmites australis* and 1 plant of *Crossandrain fundibuliformis*, trough 9 was planted with 4 numbers of *Crossandrain fundibuliformis*, trough 10 was planted with 2 numbers of *Canna lily – hybrid*, and 3 varieties of *Canna flaccid*, trough 11 and 12 were planted with 5 numbers of *Canna indica*. In Phase 1, above mentioned plant species were planted on the trough having a surface area of 8 square. meter with a plant density of 4 plants per square. meter. In phase 2, the substrate material filled was removed and replaced with gravel of size < 5 cm and the plants were replaced with *Canna Sp* with a planting density of 4 plants per square. meter.

2.2 Substrate Characteristics

In phase 1, the filter media used was a mixture of sand, brick bats and gravel of equal proportion (1:1:1). Three different filter media were purchased commercially, sand with a particle size of 0.5 mm, gravel (10 mm) and brick bat of size < 5 cm were filled in the troughs for a depth of 15 cm. In phase 2, the old filter media were replaced completely with gravel of particle size <10 mm.

2.3 Greywater Sources:

The influent raw greywater was collected from the Krishna student hostels on IIT Madras campus, Chennai, India. Wastewater from baths, showers, wash basins and washing machine were collected separately and drained into a common settling tank from which 100 L was pumped to an over head tank. The greywater from the overhead tank was allowed to flow by gravity into the GROW system through a flow control valve. The water entered from one trough to another (1 to 12) through the weirs and baffles continuously from the top trough to bottom trough where it reached the outlet pipe. The greywater was supplied to the GROW system continuously with a hydraulic loading rate of 53.1 – 58.9 L/ cubic. meter/ day with a hydraulic retention time varied from 0.7 to 1.3 days. The operating history of GROW system is tabulated in Table 1.

2.4 Sampling and Analysis:

The raw greywater and treated water samples were collected every week starting from November, 2013 between 09:00 and 12.00 hours. In addition, samples were collected from the end of each row of troughs 1, 2, 3 and 4 every month. The samples were carried to the laboratory in air tight plastic bottles and were stored in refrigerator at 4°C. The water samples were further examined for the physico-chemical and biological parameters as per standard methods for the examination of water and wastewater (APHA, 2012). pH of the sample was analyzed using Eutech cyberscan PCD 650 multi parameter kit (Thermo scientific, Singapore). Chemical oxygen demand (COD) was measured using a closed reflux chromate titrimetric method, Biochemical oxygen demand (BOD) was measured using the 5 day incubation method, Total organic carbon (TOC) and total nitrogen (TN) were measured using total organic carbon analyzer V600 series (Shimandzu, Japan).Nitrate nitrogen ($NO_3 – N$) and total phosphate (TP) was analyzed using UV spectrometer (UV-VIS 8000, Shimandzu, Japan) (APHA, 2012). Fecal coliform (FC) was measured by chromocult nutrient media plates supplied by Sartorius, Germany. The sodium do-decyl sulphate (SDS) was measured calorimetrically at 467 nm using a UV 1800 spectrophotometer (Shimadzu, Japan). Propylene glycol and Trimethyl amine were measured using gas chromatography fitted with flame ionization detector (PerkinElmer Clarus 500).

2.5 Statistical Analysis

The performance of the GROW constructed wetland system was statistically evaluated by comparing the means of effluent concentrations of various parameters under different operating conditions, using paired sample ‘t’ test. The paired ‘t’ test are commonly applied for comparing the means of data’s from two related samples or variables. The statistical analysis was performed using IBM SPSS statistics 20 software at 95% confidence level ($p < 0.05$).

3. Results and Discussion

3.1 Influent raw greywater quality

The raw wastewater characteristics analyzed over a period of time is shown in Table 2. In general the pollutant concentrations such as organics, solids and indicator organisms in greywater are comparatively less than that in domestic wastewater. The greywater also has lesser macronutrients (N and P) than the domestic wastewater. The organics concentration and fecal coliforms of greywater used in this study were lower than the reported values. The mean value of COD was 216–320 mg/L and BOD was 68-120 mg/L. The obtained values of COD and BOD were lesser than earlier reported values by Gilboa and Friedler, 2008. The reason for lesser concentration of these parameters is apparently due to the very high per capita water consumption. The COD: BOD ratio was in the range of 2.7-3.0, which indicates that greywater contains higher amount of recalcitrant organics than sewage (Metcalf et al, 2010). The reason for higher COD: BOD ratio may be due to higher usage of surfactants and personal care products during laundry services. As no urination bowls were connected with the separated greywater, the concentrations of nitrogenous and phosphorus compounds in greywater were also lesser than the reported values. The phosphorus present in the greywater mostly originated from the detergents used in washing powders. The values of emerging contaminants i.e., surfactants namely sodium do-decyl sulphate (SDS), propylene glycol (PG) and trimethyl amine (TMA) were present in the concentration ranges of 14.9-35.9 mg/L, 11.6-46.6 mg/L and 8.7-15.5 mg/L, respectively. The obtained values were similar to earlier reported values for SDS by Gross et al., 2007. There were no supporting data available regarding the concentrations of PG and TMA in the raw greywater.

3.2 Performance of GROW System under different operational conditions

The performance of GROW system was evaluated in two different phases, phase 1 was further subdivided into four different sub-phases viz. a viz., start-up phase (Phase1.1), seasonal variation

(Phase 1.2), flow rate variations (Phase1.3) and organic load variations (Phase1.4). The first 4 weeks of Phase 1.1.covered the start-up stages of the GROW system. During this phase, the system was fed with greywater at the flow rate of 70 L/day. During this period, the plants and microbes were allowed to acclimatize to the newer environment. In Phase1.2, the performance of the GROW system at various seasons and temperature, i.e., summer, monsoon, pre-monsoon and post monsoon, were evaluated for the designed flow rate of 70 L/ day. In phase1.3, different hydraulic loading rates were employed, i.e., 62 L/day, 82 L/day, 100 L/day and 120 L/day. Finally in Phase1.4, the performance of the system was evaluated for various organic loading rates (25.5 g COD/ cubic. meter/ day, 25.9 g COD/ cubic. meter/ day and 26.8 g COD/ cubic. meter/ day) by adding sucrose as an external carbon source at a flow rate of 100 L/day. In Phase 2, the GROW system was operated at constant flow rate of 100 L/day to evaluate the effect of different substrate materials and plant species on the performance of GROW system. The short term equilibrium was attained within 2 months from the date of plantation in the GROW system and performing well after 3 years of continuous operation. If the GROW system is properly maintained, the system can work for another 2-3 years.

3.2.1 Organics

During the study period, the influent BOD and COD varied from 68-120 mg/L and 216-320 mg/L, respectively as shown in Table 2. However, the variation of influent quality did not affect the outlet biochemical oxygen demand (BOD) and chemical oxygen demand (COD) concentrations during the monitoring period. It was consistently below 10 mg/L for BOD and 20 mg/L for COD, which is below the USEPA standard limits for secondary reuse. It was also found that the GROW system showed a better removal efficiency during the summer season compared to other seasons as shown in Fig 3(a)-(b). As stated by Vymazal, 2002; Akratos and Tsihrintzis, 2007 that the organic pollutants are removed mostly by microbial degradation and also by adsorption to a certain extent. Hence, at an elevated temperature, the activities of aerobic and anaerobic microbes are enhanced, resulting in higher organic pollutant degradation during summer season. During phase 1.3, it was found that the BOD and COD concentration in the effluent were comparable at the flow rates of 62, 82 and 100 L/day and were increased as the flow rate increased to 120 L/day. This indicates that 100 L/day can be considered as the optimal flow rate for the maximum pollutant removal. As the flow rate increased, the retention time (HRT) decreased, resulting in lesser removal of organic pollutant. Similar results were reported by Akratos and Tsihrintzix, 2007. In phase 1.4, the effluent BOD and COD concentrations were changed slightly. As the OLR increased from 25.5 to 26.8 g COD/ cubic. meter/ day, the effluent COD and BOD concentrations were increased. It was observed that at 26.8 g COD/ cubic. meter/ day, the COD values were 16-24 mg/L, while it was <16 mg/L during the other two OLRs. These results were in accordance with the results reported by Lin et al., 2002 and Saeed and Sun, 2012. This indicates that 26.8 g COD/cubic. meter/day OLR exceeded the degradation capacity of the wetland system (Dalahmeh et al., 2014). The variance of means of the effluent quality at various monitoring periods were found to be statistically significant ($p<0.05$) [Supplementary Table S1]. In phase 2, the COD and BOD removal efficiency was found to be 88% and 84%, respectively [Supplementary Fig. S1]. The reason is that the organic pollutants are mostly removed by microbial degradation and by adsorption (Vymazal, 2002).

3.2.2 Suspended solids

The inlet and outlet suspended solids concentrations and percentage removal during the monitoring period are shown in Fig. 4. The suspended solids in the constructed wetlands are removed from the wastewater by physical processes such as filtration and sedimentation (Haghshenas-Adarmanabadi et al., 2016). According to Masi and Martinuzzi (2007), the solids removals by the constructed wetlands are in the range of 72-84% in the Mediterranean countries, and 65-91% in the tropical regions of developing countries (Singh et al., 2014). In the present study about 85-90% (< 20 mg/L) removal of solids particles from inlet to outlet tank was achieved. The reason for higher removal efficiency may be due to the baffled CW configuration that prolonged the water flow path and enhanced the filtration process which favored the removal of suspended solids.

It was also observed from Fig. 4 that during phase 1.1, the removal of suspended solids was less (<80%). The microbes and plants started growing at this stage and they were not completely matured. This may be the reason for the low performance. As the time progressed, in phase 1.2, the removal of solids improved and remained almost at a constant level (88-95%). During phase 1.3, (i.e., change of flow rate), it was observed that as the flow rate increased, the removal of solids concentration decreased due to lesser hydraulic retention time. Similar results were reported by other researchers also (Akaratos and Tsihrintzis, 2007). As the organic load were increases from 25.5 to 26.8 g COD/cubic. meter/ day, the solids concentration in treated water also increased. The above obtained results were in good agreement with Dominguez et al., 2012 that the increased organic loading rate resulted in increased biomass growth which in turn increased the suspended solids concentration in the effluent. However, the overall removal of solids was comparatively lesser compared to other constructed wetlands like horizontal, vertical and hybrid flow systems (Ramprasad and Philip, 2016). The statistical analysis (paired‘t’ test) were conducted to evaluate the performance of GROW system for the removal of solids during various monitoring periods (start-up, seasonal, hydraulic loading rate and organic loading rate) and paired ‘t’ test showed that the treated effluent quality during all the monitoring periods are statistically significant at 95% confidence interval ($p < 0.05$; $p = 0.039$) [Supplementary Table S1]. The removal of suspended solids was highly affected by lowering the HRT and increasing the OLR.

3.2.3 Nutrients

Nutrients (nitrogen and phosphorous) presence in wastewater is one of the major factors that causes eutrophication, deplete the dissolved oxygen level and can be toxic to the ecosystem. Generally, the removal of nutrients is by ammonification, nitrification, denitrification, plant uptake, volatilization and biomass assimilation (Vymazal, 2002; Akratos and Tsihrintzis, 2007). In the present study, the concentrations of nitrates, ammonia and phosphates present in the influent were low as compared to earlier reports (Gilboa and Friedler, 2008; Antonopoulou et al., 2013). The nitrogen compounds removal was around 88 to 99% during summer season and was found to be lesser during other seasons (Fig. 5-). Microbial reactions such as organic nitrogen decomposition, nitrification and de-nitrification are favored at higher temperature resulting in greater removal efficiency. Similar to nitrogen compounds, phosphate removal was also favored at high temperatures. During the summer season, the removal of total phosphate was maximum at 92%, which was less during other seasons (Fig. 6). It was reported in earlier studies that the main mechanism involved in phosphate removal were sorption and plant uptake (Vymazal, 2002). Sorption of phosphate is an endothermic reaction (Jin et al., 2005), which means that low temperatures decrease the sorption capacity of the bed (Rustige et al., 2003). The results obtained by GROW systems were compared with the other three wetlands (horizontal vertical and hybrid) studied by Ramprasad and Philip, 2016. The hybrid wetland performed better than GROW and other two systems. Many reports suggested that the nutrients removal in constructed wetlands was predominantly due to de-nitrification activity (Vymazal, 2002). During phase 1.3, enhanced activity of de-nitrifiers was observed due to high HRT which resulted in higher removal rate. In phase 1.4, as the OLR increased from 25.5 to 26.8 g COD/ cubic. meter/ day, the removal rates of nutrients increased (Fig. 5-6). The probable reason might be that, increased organic load triggered an increased growth of anoxic microbes near the root nodules, providing a favorable condition for de-nitrification (Dalahmeh et al., 2014). The statistical analysis confirms that the effect of different operating conditions on the nutrients content was recognized as highly significant (T = 4.367; $p = 0.005$).

In phase 2, the removal of nutrients and phosphate were in the range of 82-88% and 65-74%, respectively [Supplementary Fig S1]. The GROW system was capable of removing the nutrients from the greywater below the reusable standard level. It was observed that the nitrate - nitrogen in the treated wastewater were in the range of 1.2-3.5 mg/L and 0.8-1.4 mg/L for total phosphates. (Fig. 5 - 6)

3.2.4 Fecal Coliforms

The fecal coliform concentration in the inlet was relatively low (50-120 CFU/100 mL) compared to the earlier reported values (Antonopoulou et al., 2013). The major reason for the lesser coliform contamination may be due to the age group of inhabitants and avoidance of kitchen wastewater. Most of the inmates were in the age group of 19-25 years. The fecal coliform removal in constructed wetland is attributed to physical process such as sedimentation, filtration and natural die-off. The removal rates of the fecal coliform were in the range of 70-85% during the start-up stage, and gradually increased and reached around 98% during phase 1.2. It is clear from Fig 7 that during the summer seasons the FC removal was more than the other seasons. It is also evident that with increase in hydraulic retention time, during phase 1.3, the removal rates also increased from 94% to 98% (Fig 7). Akaratos and Tsihrintzis, 2007 have previously reported that as the HRT increased the coliform have higher contact time in the system to get removed or degraded resulting in higher removal efficiency. As the OLR increased, the effluent coliform concentration also increased from 4 CFU/ 100 mL to 12 CFU/ 100 mL, due to increased biomass growth by utilizing the readily available carbon source. . Similar results were reported by other researchers also (Dalahmeh et al., 2014). Statistically significant difference ($p<0.05$; T=5.860) in the average fecal coliform content occurred in different operational phases. During Phase 2, the fecal coliform removal was in the range of 88-90%. The coliform removal efficiency of phase 2 was comparatively lower than one obtained during phase 1. The reason for lesser removal is due to the high pore size available in gravel medium compared to sand gravel mix. In-spite of higher removal efficiency, the coliform counts did not comply with the USEPA standard limits for reuse. Therefore the treated water should be provided with little dose of disinfectant before reused.

3.2.5 Emerging contaminants

3.2.5.1 Sodium do-decyl sulphate

Sodium do-decyl sulphate (SDS) is the most commonly used surfactant, and the removal efficiency of this pollutant in GROW system varied between 85-96% (Fig. 8) SDS is considered to be highly hydrophobic in nature having a log K_{ow} of 3.6 (Hansch et al., 1996). Generally, the compounds that are hydrophobic (with high K_{ow}) values are removed from the system by adsorption, hydrolysis and microbial degradation/ biosorption (Lv et al., 2016; Ramprasad and Philip, 2016). The SDS in the treated water was in the range of 2.8-4.2 mg/L (60-80%) during the start-up phase, and was improved in the following phases to 82-96%. It was also found that the removal of SDS was affected by seasons. The seasonal variability was mainly attributed to two main physical conditions, namely solar radiation and water temperature. Low temperatures decreased the bio-degradation rates and low solar irradiation decreased the phyto degradation rates (Simonich et al., 2002). In phase 1.3, the removal efficiency of SDS increased from 88% to 96% with decrease in flow rate and increased hydraulic retention enhanced the biodegradation of adsorption of SDS. This is in good agreement with the results reported by Langford et al., 2005. In phase 1.4, as the OLR increased from 25.5 g COD/ cubic. meter/ day to 26.8 g COD/ cubic. meter/ day, the rate of SDS removal decreased from 92% to 85%. The presence of readily available carbon source (sucrose) reduced the biodegradability of SDS as reported by Nyberg et al., 1992. The statistical analysis confirms that, although the difference in the effluent SDS concentrations is statistically significant ($p<0.05$), it is relatively small. The SDS removal efficiency after the change of plant species and filling media was reduced to 85-88%, due to the availability of less adsorption space as the media sizes were larger.

3.2.5.2 Propylene Glycol and Tri Methyl amine

The propylene glycol (PG) and tri-methyl amine (TMA) are commonly used in personal care products likes soap and shampoos. PG and TMA are highly water soluble, have low log K_{ow} value and are also easily biodegradable. It was reported by Avila et al., 2014, that the compounds that are highly water soluble is predominantly taken up by plants / phyto-degraded and biodegraded. In phase 1.1, the PG and TMA removal efficiency was in the range of 40-60% (Fig. 9 and 10) due to the low density of plants and microbes in the system. During phase 1.2, the, the removal efficiency was more during summer than in winter or monsoon. In phase 1.3, as the flow rate increased, the removal efficiency decreased (96% to 80%), due to less retention time. Also, when the OLR increased (25.5 to 26.8 g COD/ cubic. meter/ day) the removal efficiency decreased from 94% to 86%, as the system exceeded the biodegradation capacity. Due to addition of external carbon source, the degradation rates of organic pollutants were hindered. Sucrose is a readily biodegradable compound than PG and TMA. Therefore, microbial consortia would have utilized more sucrose as a carbon source than the target pollutant. As a result, lesser biodegradation was observed for target pollutants with increase in OLR. Similar trend was reported by other researchers also (Nyberg et al., 1992). During phase 2, the removal efficiency did not change much from phase 1, as the mechanism for PG and TMA removal was mostly plant uptake and biodegradation.

4. Conclusion

This study confirmed that shallow horizontal subsurface flow GROW system with 8 varieties of native plant species can effectively improve quality of greywater in tropical countries. The performance of the GROW system was monitored over a significant period of time at various operating conditions. The removal efficiency obtained for various parameters were; biochemical oxygen demand (BOD) 90.8%, chemical oxygen demand (COD) 92.5%, total suspended solids (TSS) 91.6%, nitrate-nitrogen (NO_3 – N) 83.6%, total phosphate (TP) 87.9%, total nitrogen (TN) 91.7%, fecal coliform (FC) 91.4%, sodium do-decyl sulphate (SDS) 85.7%, propylene glycol

(PG) 93.4% and trimethyl amine (TMA) 88.9%. It was found that the removal rate was high during summer season compared to other seasons. Also the removal efficiency was more at higher HRT. The promising results from this study may increase the applicability of GROW systems as a robust, cost-effective and reliable green roof systems in India and other tropical countries.

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Removal of chemical and microbial contaminants from greywater using a novel constructed wetland GROW

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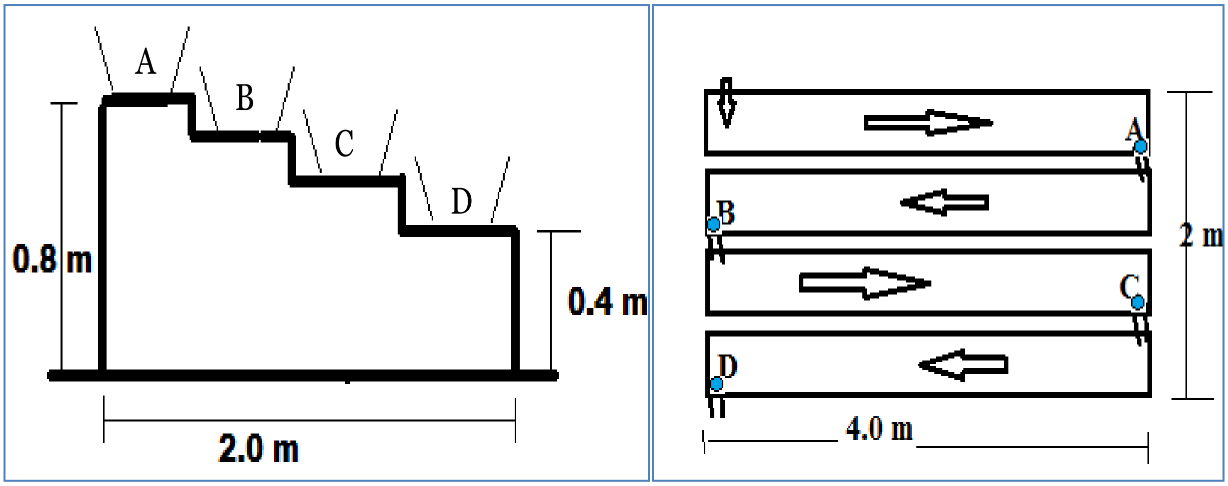


Fig. 1 Schematics of GROW system

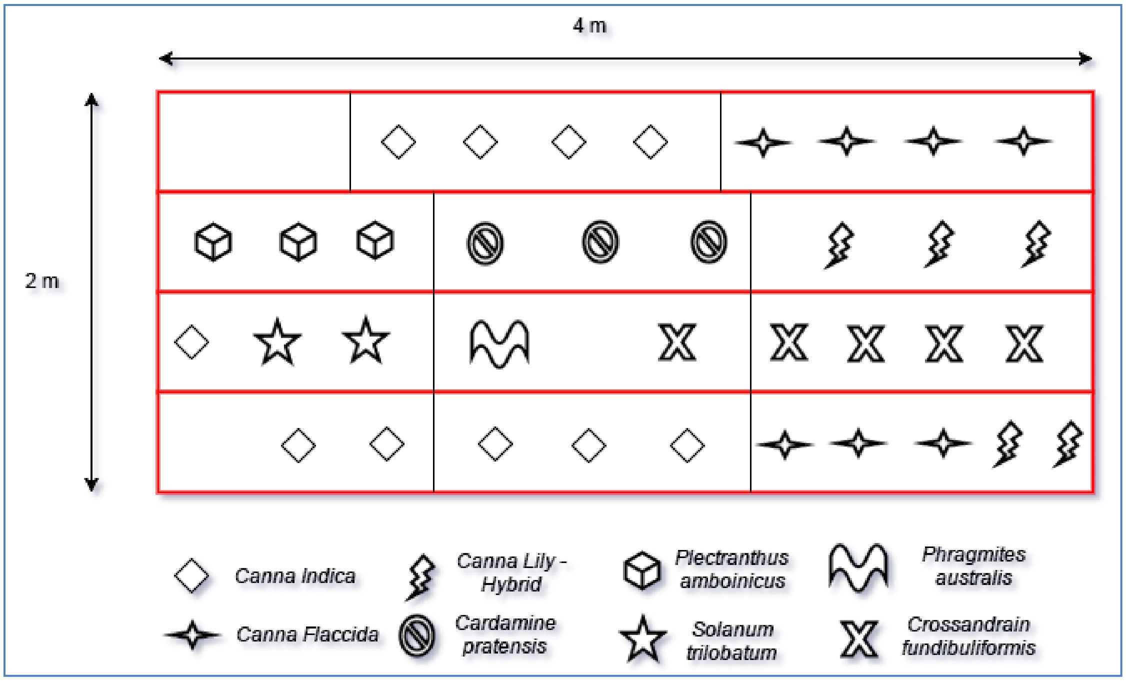


Fig. 2 Planting Plan of Each trough in GROW system

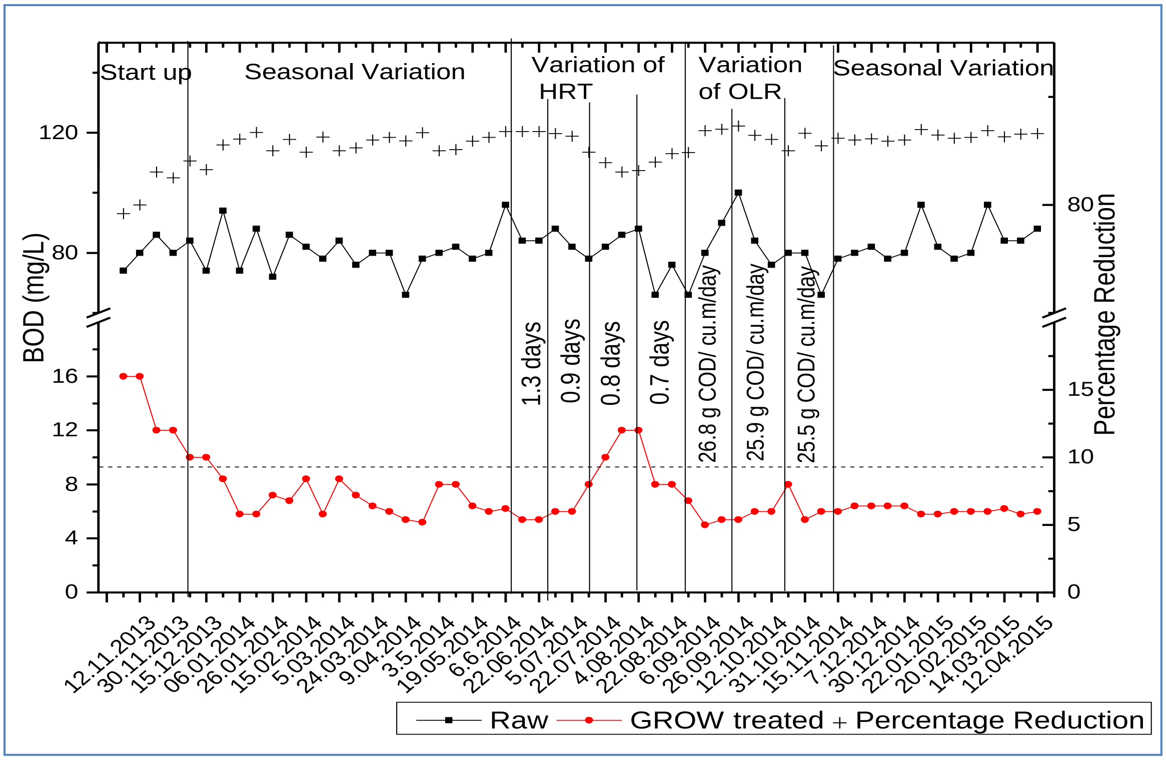


Fig. 3(a) Performance of GROW systems with respect to BOD removal during various operational conditions

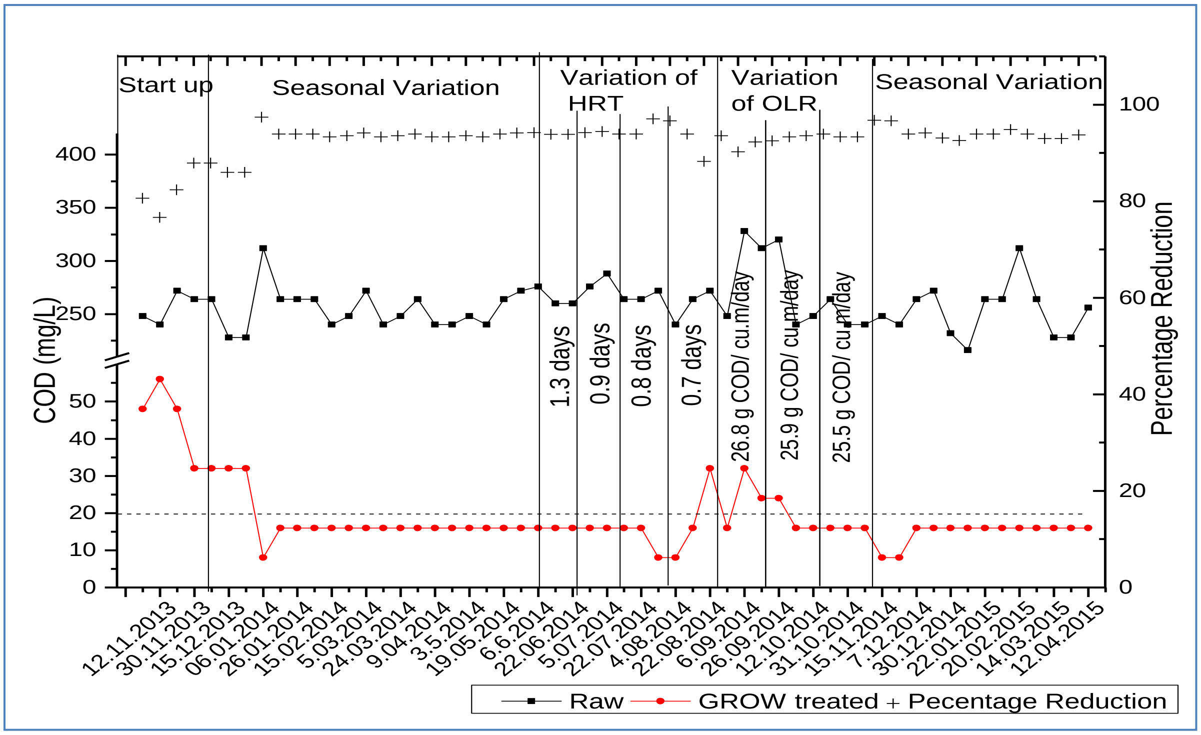


Fig. 3(b) Performance of GROW systems with respect to COD removal during various operational conditions

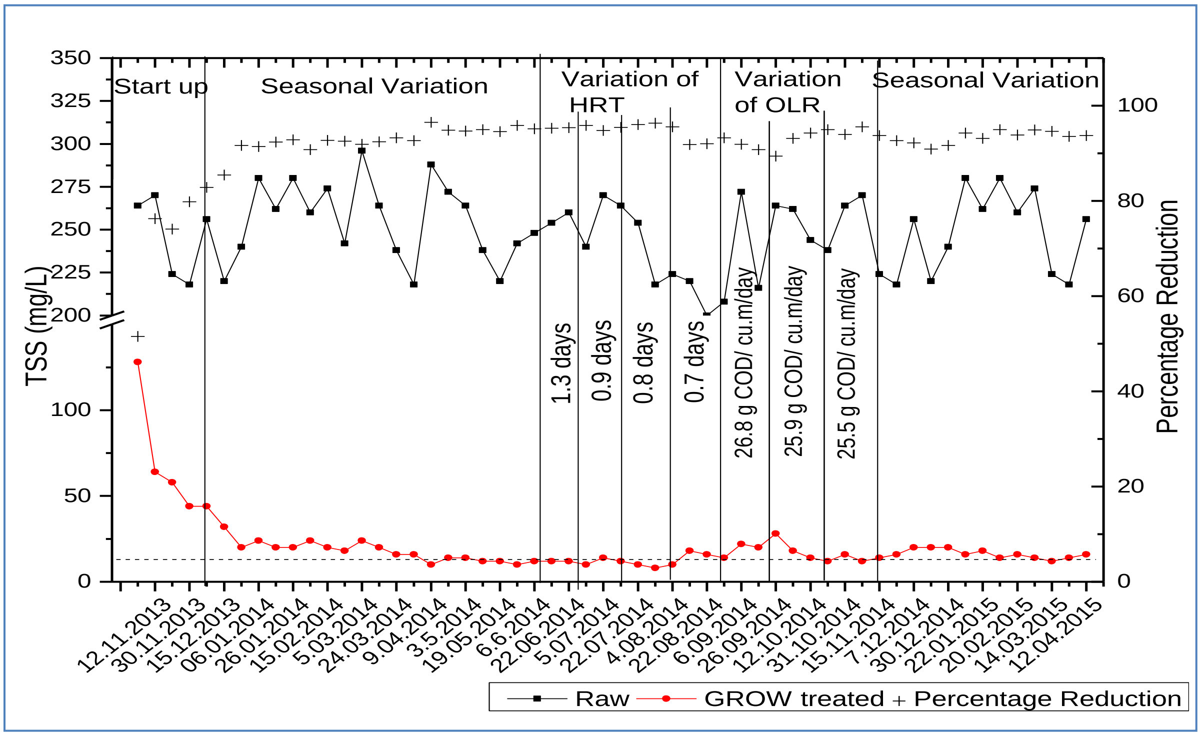
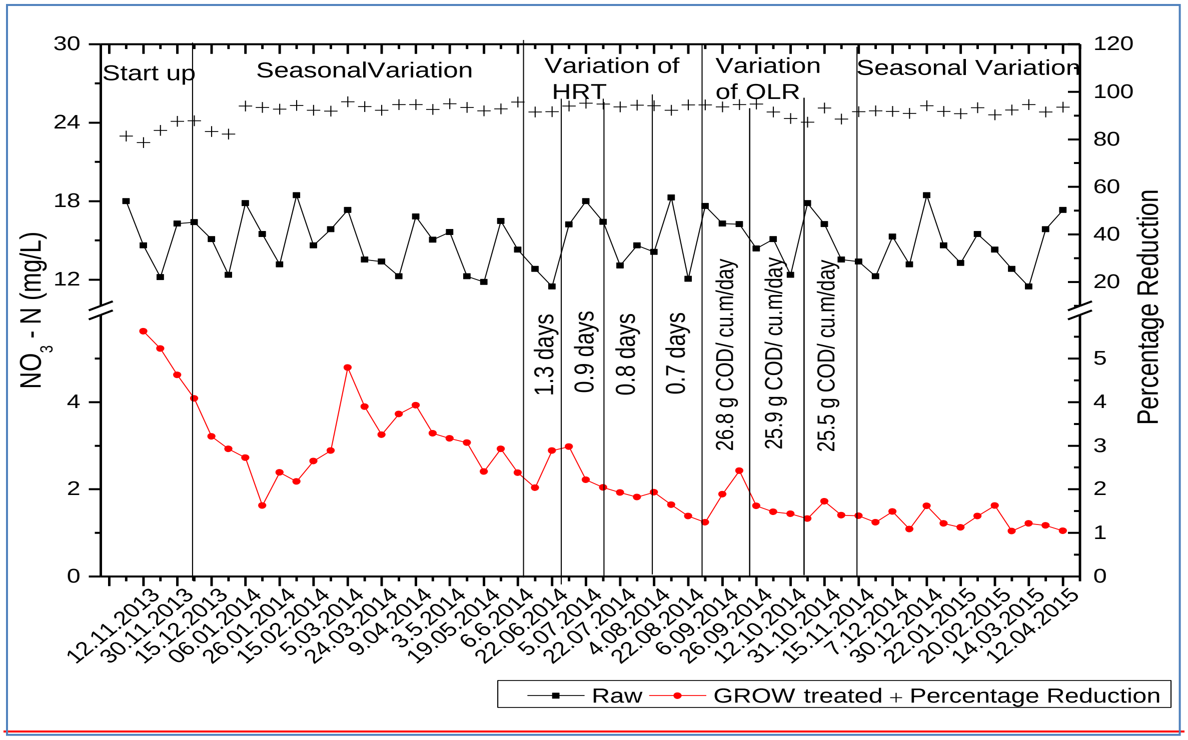


Fig. 4 Performance of GROW systems with respect to the total suspended solids removal during various operational conditions



~~**Fig. 5 Performance of GROW systems with respect to nitrate nitrogen removal during various operational conditions**~~

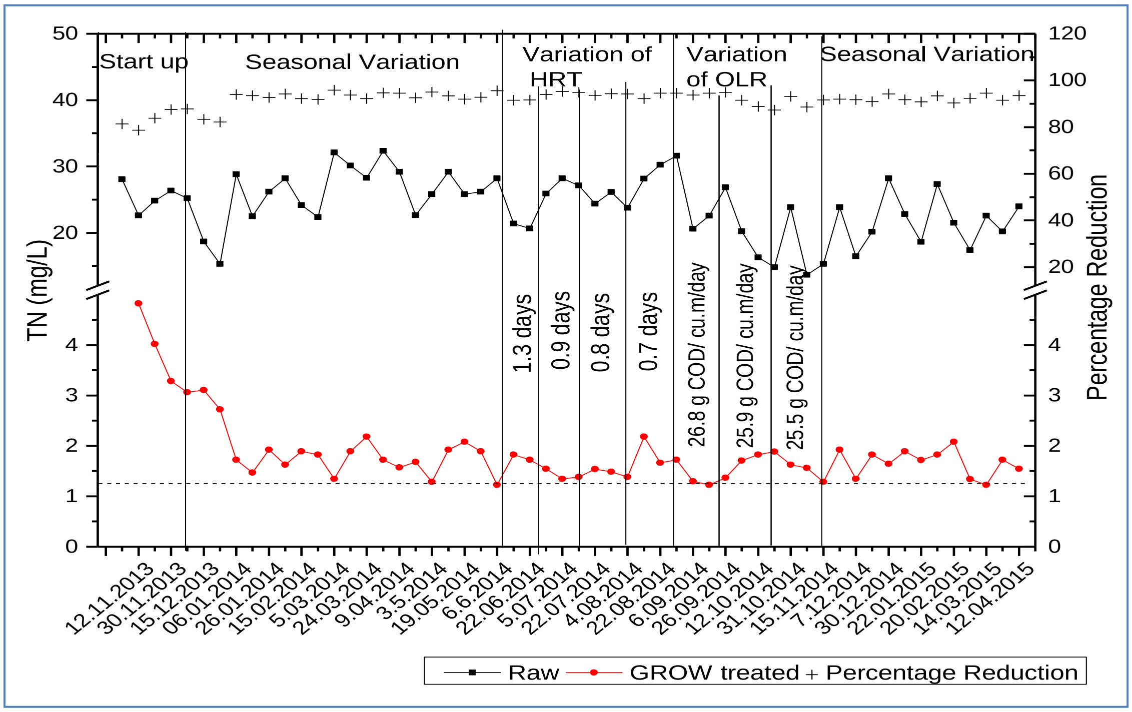


Fig. ~~6~~5 Performance of GROW systems with respect to total nitrogen removal during various operational conditions

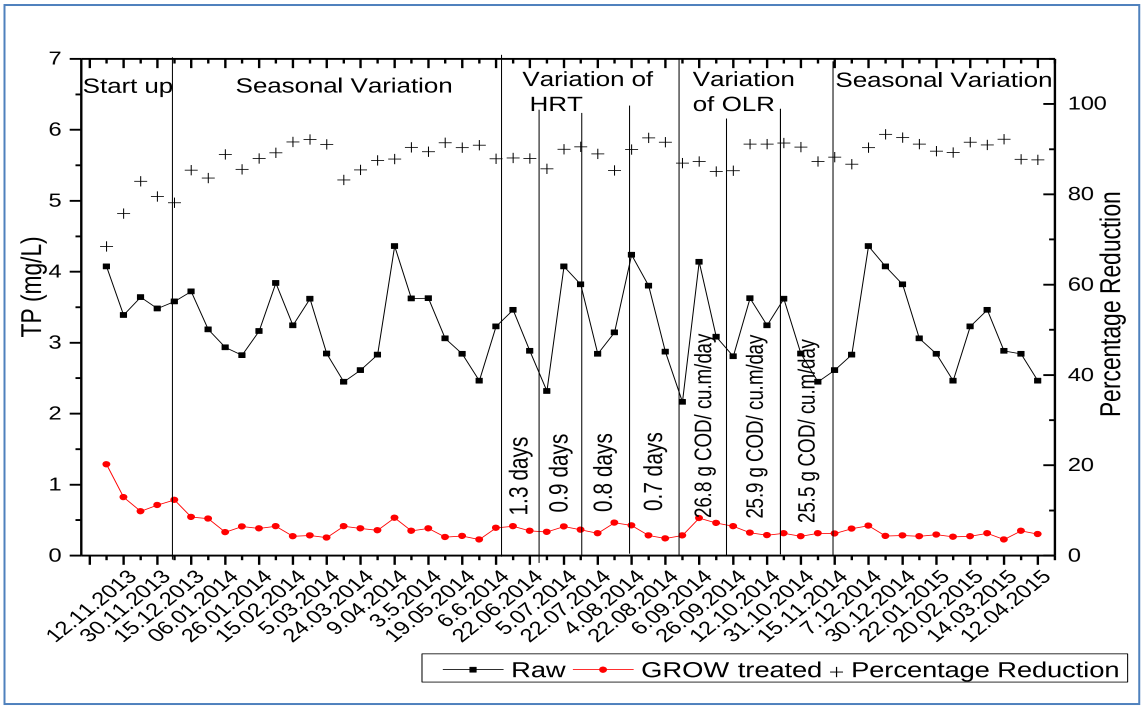


Fig. ~~7~~ 6 Performance of GROW systems during with respect to total phosphate removal during various operational conditions

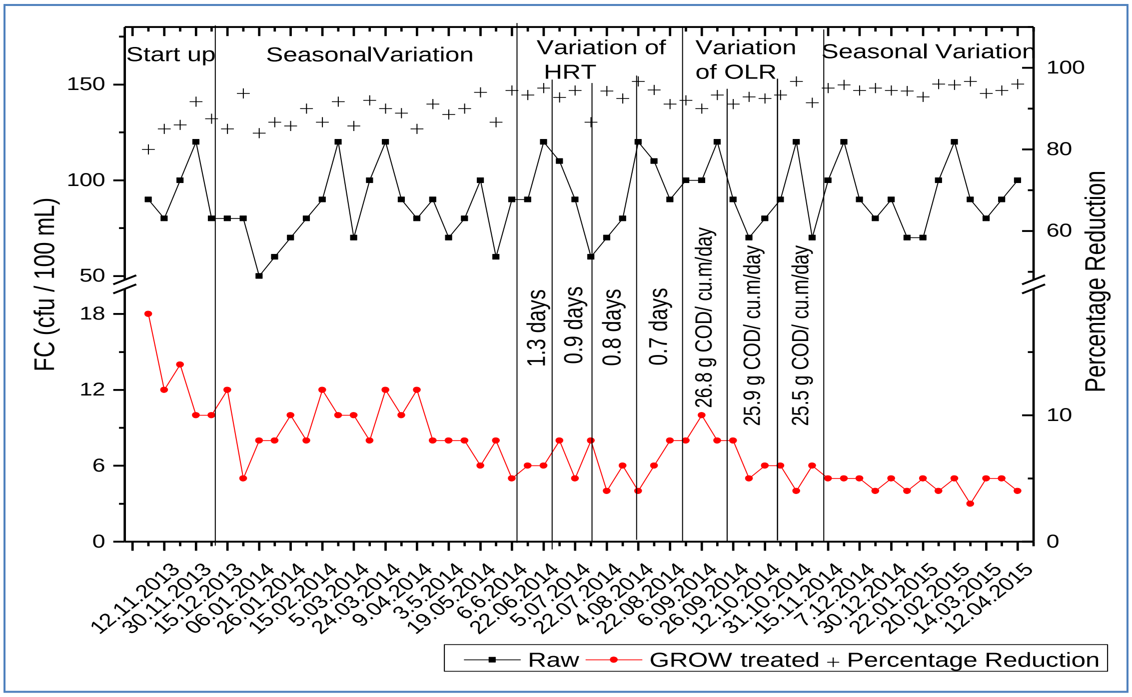
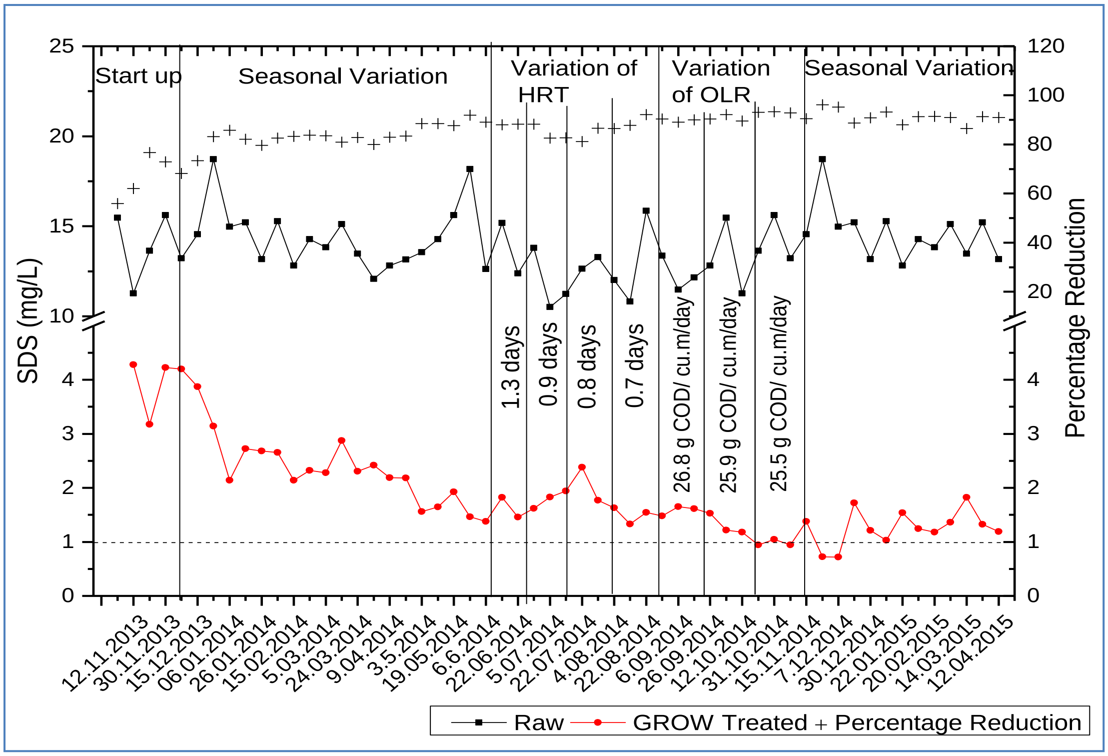


Fig. 7~~8~~ Performance of GROW with respect to the fecal contamination removal during various operational conditions



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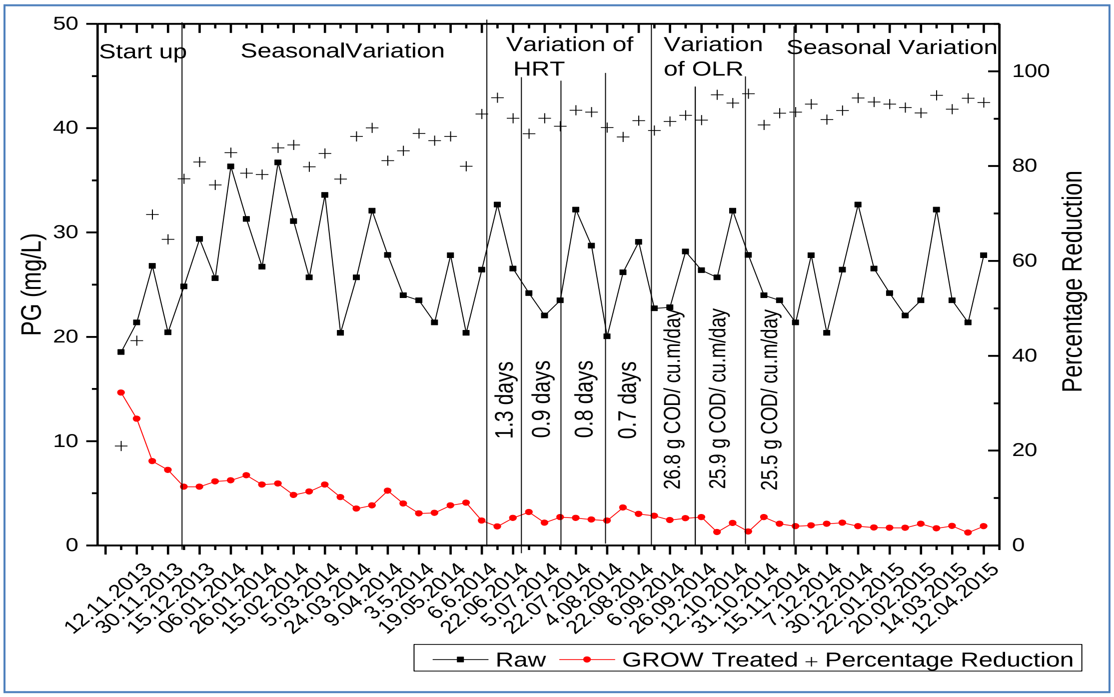

Fig. 9~~10~~ Performance of GROW systems with respect to propylene glycol removal during various operational conditions

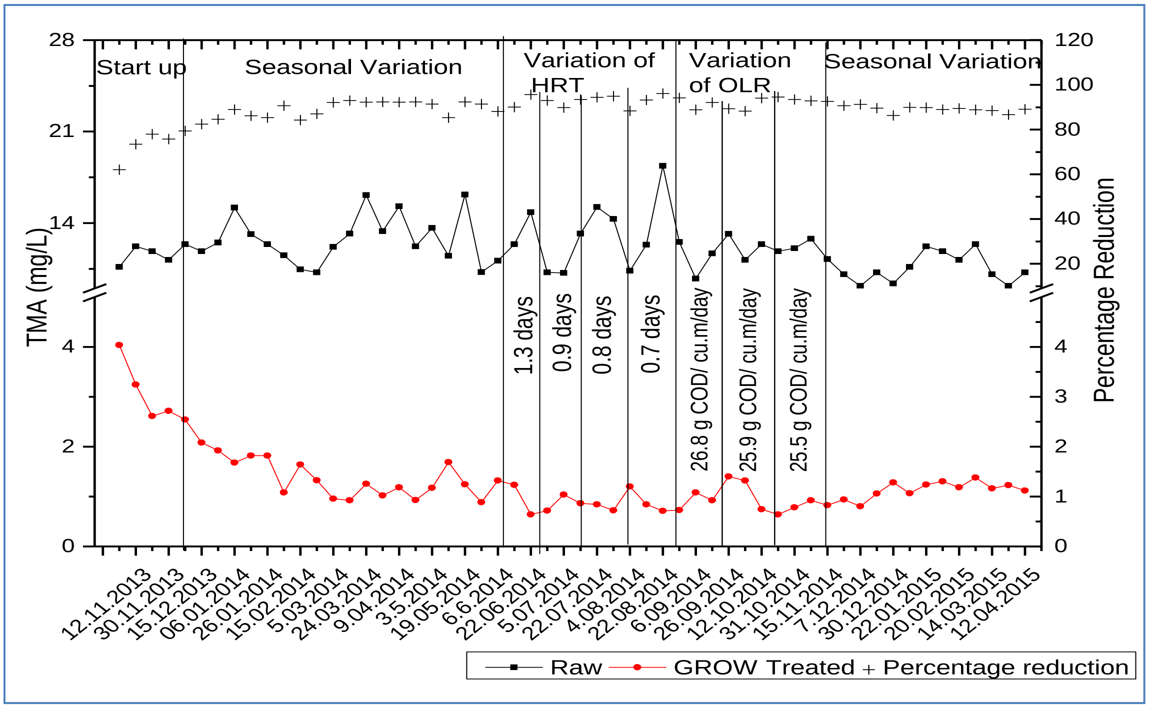

Fig. ~~11~~ 10 Performance of GROW system with respect to tri-methyl amine removal during various operational conditions

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Table 1 Operating history for GROW constructed wetland

Months of operation	HRT (days)	HLR (L/ cu. m/ day)	OLR (g COD/ cu. m / day)
Start – up phase			
November to December, 2013	1.09	58.3	14.0
Performance Evaluation of GROW system			
Jan to June, 2014 and Nov – August 2015	1.09 – 1.22	58.3	14.0
Effect of Flow			
3rd and 4th week of July 2014	1.3-0.9	58.9	12.9
August 2014	0.7-0.8	53.1	14.9
Effect of additional organic loading			
September – October 2014	1.09	53.3	25.5 - 26.8

Table 2 Raw greywater characteristics

Parameters	Raw Greywater
pH	7.24 - 8.34
COD (mg/L)	216 - 320
BOD (mg/L)	68 - 120
TSS (mg/L)	240 - 280
TOC (mg/L)	23 -36.48
TN (mg/L)	17 - 28.82
NO_3 – N (mg/L)	12.32 -17.84
TP (mg/L)	2.934 – 3.84
NH_4 – N (mg/L)	10.28 -14.56
FC (CFU / 100 mL)	50 - 120
SDS (mg/L)	14.99 – 35.89
PG (mg/L)	11.58 - 46.59
TMA (mg/L)	8.67 - 15.54