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PERFORMANCE OF GREEN WALL TREATMENT OF BREWERY WASTEWATER

Green walls or living walls are architectural installations comprised of plants growing in soil filled, modular panels that are attached to interior or exterior walls. The objective of this study is to evaluate the effectiveness of using green walls to pretreat wastewater generated by small to medium sized food and beverage manufacturers. A 1.2 m high green wall was constructed using two, 610 mm×610 mm panels filled with recycled glass media and planted with *Epipremnum aureum*. Brewery wastewater was recirculated through the system under four experimental scenarios: media, only; media with biofilm; media with plants; and media with plants and biofilm. Reduction of BOD was at least 65% after 24 hours in all four scenarios. Removal of turbidity, BOD, and total nitrogen was similar in scenarios involving biofilm with or without plants. Green walls appear to offer a space and cost efficient method for pre-treating wastewater generated by beverage and food industries.

1. INTRODUCTION

Green walls or living walls, as an architectural installation, have become increasingly popular this century as sustainable design and living practices have become more common [1]. It is estimated that installation of green roofs and walls will increase by 70% over the next five years because of incentives and mandates by municipalities [2]. The benefits of green walls are reported [3] to include reduction of urban heat island effect, improved exterior air quality, aesthetic improvement, improved energy efficiency, building structure protection, improved indoor air quality, local job creation,

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improved energy efficiency, noise reduction, green marketing potential, increased biodiversity, improved health and well-being, and urban agriculture. Green walls have also been used to treat household wastewater (WW) [4–7] on a limited basis. However, documentation of green walls being used to treat something other than grey or black water is absent in the literature.

The objective of this study was to explore the possibility of using green walls to pre-treat non-sanitary WW from small to medium sized food and beverage manufacturers. Conceptually, the pre-treatment system would operate under continuous flow conditions. The system would include an equalization basin to dampen spikes in WW concentration and flowrates, reduce solids loading to the green wall, and act as a sump for recycling flow through the green wall (Fig. 1).

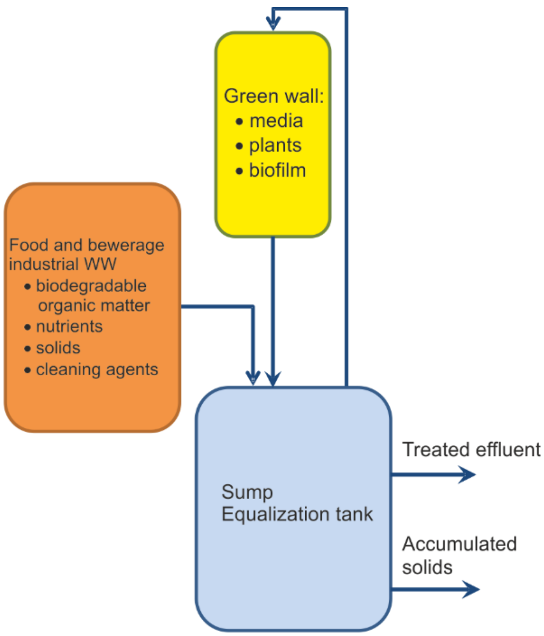

Fig. 1. Conceptual green wall schematic

In general, removal mechanisms of contaminants by green walls are similar to vertical flow constructed wetlands. Physical treatment occurs through filtration of suspended solids. Chemical sorption onto media surfaces also removes a fraction of the dissolved contaminants. However, biological transformations of molecular contaminants play a major role in reducing contaminant concentrations [8]. The addition of vegetation enhances the removal of organic compounds and nutrients through plant uptake and the creation of a rhizosphere that supports increased microorganism populations [9].

Green walls have been demonstrated to be effective in removing contaminants from grey water[4] in a limited number of studies. Svete [8] reported removal of total suspended solids (TSS), biochemical oxygen demand (BOD), total phosphorous (P), and total nitrogen (N), from settled grey water using a vegetated filter wall. While not statistically significant, the vegetated green wall removal efficiencies were 1–8% greater than the control wall without vegetation [9]. Cameron [4] incorporated a green wall and living column in an integrated biofilter that also included a green roof and constructed wetland. The results of the study indicated that the existence of an established biofilm was responsible for an increase in the removal of various contaminants rather than plants. A thesis study from Uppsala University, Sweden also used a green wall as part of an integrated household greywater treatment system that included treatment ponds [7]. Grey water was pumped from a collection well at the house to the green wall which was followed by two ponds in series. The green wall was responsible for significant removal of nitrate-N, orthophosphate, and total organic carbon. Other reported uses of green walls to treat greywater include the Sanitas wall in South Africa [10], Bertschi School in Seattle, Washington [6], proposed Editt Tower in Singapore [11], and Clovelly House in Australia [12].

In this study, high strength organic WW will be applied to green walls. This WW is often generated by food and beverage industries and characterized by five day BOD (BOD_5) concentrations greater than 1000 mg O_2/dm^3 variable pH between 4.5 and 12, total N between 25 and 80 mg N/dm^3, and a range of total P concentrations, 10–50 mg P/dm^3 [13]. By comparison, a typical sanitary WW has a BOD_5 concentration of 190 mg O_2/dm^3, a pH range of 6.5 to 8.5, total N of 40 mg N/dm^3, and total P concentrations of 7 mg P/dm^3 [14].

Agencies require onsite treatment of WW prior to direct discharge to the environment. Typically, the WW is amendable to aerobic and/or anaerobic biodegradation processes [15]. Many aerobic processes have some limitations such as high capital costs, complex operation and maintenance requirements, produce large amounts of sludge requiring disposal [16], and have significant energy costs [17]. A principle disadvantage of anaerobic systems is longer hydraulic retention times, in some cases five days [18]. Small to medium sized breweries and wineries are often too small to afford an onsite treatment system, but can be required by municipalities to pre-treat the WW prior to discharge to local sanitary sewer systems. If the WW is left untreated, high BOD_5 concentrations and low pH WW may disrupt treatment efficiencies at municipal WW treatment plants [19].

Septic systems are another traditional treatment system that is utilized by small to medium sized food and beverage manufacturers located in rural areas. Many existing residential septic systems have been found to be ineffectual in providing sufficient treatment of N

[4]Grey water is generally considered to be wastewater generated at sinks, showers, baths and wash water. Wash wastewater is sometime separated from this stream because of high concentrations of surfactants.

and P because of preferential pathways, poor sitting and/or design, maintenance, age and overloading [20, 21].

The objective of this study was to explore the possibility of using green walls to pre-treat non-sanitary wastewater from small to medium sized food and beverage manufacturers. We also investigated the effect of adding plants and biofilm to the green wall with regard to contaminant reduction. To do this, the four experimental scenarios consisting of media only, media with plants, media with biofilm, and media with plants and biofilm were conducted.

2. MATERIALS AND METHODS

Apparatus. The green wall used in this research was constructed of two 610×610 ×100 mm aluminum panels (Fig. 2) in a vertical alignment.

Fig. 2. Green wall experimental setup

A panel consisted of 24 cells each having dimensions of 100×150×100 mm. Packets, made of fiberglass screen and having dimensions similar to an individual cell, were filled with media. Each packet was placed in a cell and the front of the panel was covered with 0.6 cm opening hardware cloth to secure the packets in place. The media were expanded recycled glass beads manufactured by Poraver. The light weight, white spheres had a loose bulk density of 0.18 g/cm^3 and a diameter range of 4–8 mm. Standard Golden Pothos, *Epipremnum aureum*, propagated from cuttings, were used in this study. Two plants were placed in each cell. Full spectrum light was provided by four 122 cm fluorescent tubes hung vertically.

Wastewater was continuously pumped from a 38 dm^3 sump to the top of the green wall using a magnetically-driven, electrical submersible pump. The section of 13 mm inside diameter polyethylene tubing at the top of the green wall was perforated to evenly distribute WW across the top width of the panel. Wastewater freely drained by gravity from the upper panel to a lower panel and back to the sump through a return gutter.

Experimental procedure. Wastewater used in the experiments was collected from the aeration basin of a pretreatment system located at a small local brewery. Sanitary WW was plumbed separately from the brewery WW and directly discharged to the sanitary sewer. The collected WW contained aerobic microorganisms that are part of the microbial community found in the brewery's onsite activated sludge process. The characteristics of the WW used in this work are presented in Table 1.

Table 1

Characteristics of unfiltered brewery wastewater

Parameter	Value
BOD, mg O_2/dm^3	504–1999
Turbidity, NTU	67–573
Total nitrogen, mg N/dm^3	7.8–66
Total phosphorous, mg P/dm^3	3.0–4.6

The flow rate was 15 dm^3/min for all scenarios with complete recycling in this batch flow experimental system. The surficial area hydraulic loading rate (HLR) was 354 000 dm^3/(m^2·day). By comparison, the average HLR of municipal roughing trickling filters is 114 000 dm^3/(m^2·day) [14] and the HLR used in previous grey water green wall research by Svete [9] was 670 dm^3/(m^2·day). We selected a larger HLR to increase throughput in the system, thereby increasing treatment length, which could favorably affect detention time and the full scale equalization tank size.

The four experimental scenarios conducted in this study were media only, media with plants, media with biofilm, and media with plants and biofilm. Wastewater collected in October was used in the media, only and media with plants scenarios (phase I).

A later collection event in February supplied WW for the latter two scenarios that include biofilm (phase II). Figure 2 shows the experimental setup for the phase I experimental scenarios: media, only on the left and media with plants on the right. The media and plants scenario was conducted first and ended after 25 hours. The tubing, return gutter, and sump were moved and the media, only scenario was started and then terminated after 27 hours.

Immediately following the end of the phase I experiments, new tubing and an expanded return gutter system was installed so that all water was returned to a single sump. Growth of biofilm on media was facilitated by continuously pumping a mixture (1:1) of WW and tap water through the green wall for a period of 130 days. After 130 days, the WW delivery and collection system was reconfigured for a single column of two panels. The media, plants and biofilm experimental scenario was carried out first and terminated after 45 hours. The tubing, return gutter, and sump were moved and the media and biofilm scenario was started and then terminated after 46 hours.

Prior to conducting each experimental scenario, the sump was emptied and refilled with approximately 35 dm^3 of fresh WW. 100 cm^3 samples were collected at the return gutter. The samples were analyzed for turbidity, BOD_5, total N, and total P. Turbidity was tested using a 2100P IS portable turbidimeter. BOD_5 was tested in accordance with standard methods 5210 [22]. Nitrogen was tested in the form of total N using Hach® total nitrogen method 10071. Phosphorus was tested using Hach® total phosphorus method 8190. HACH analyses were performed using a HACH® DR3900 bench top spectrophotometer.

Data analysis. Statistical analyses, using Excel, were performed to estimate the strength of association of the experimental results with a non-linear decay rate with time. The coefficient of determination, R^2, was calculated for each set of analytical data. A low R^2 value resulted if there was significant scatter of the analytical results and indicated that the scenario had not provided reliable treatment of whichever parameter was tested. In 2006, Asuero et al. [23] presented a rule of thumb scale to evaluate the strength of correlation. This rule of thumb scale has been expanded to include R^2 in Table 2.

Table 2

Rule of thumb scale for interpretation of R^2

Size of R	Size of R^2	Interpretation
0.90–1.00	0.81–1.00	very high correlation
0.70–0.89	0.49–0.80	high correlation
0.50–0.69	0.25–0.48	moderate correlation
0.30–0.49	0.09–0.24	low correlation
0.00–0.29	0.00–0.08	little or no correlation

[a]After [23].

There was variation in the characteristics of each batch of WW collected from the brewery. The removal rates have been normalized to address the variation in the contaminant concentrations of the untreated WW. Results presented in Figs. 3–6 are reported as C/C_0, or the concentration of the contaminant at time $t(C)$, divided by C_0, the contaminant concentration in the raw WW. The removal efficiency can be determined using the equation:

$$\text{Removal efficiency} = \left(1 - \frac{C}{C_0}\right) \times 100\% \tag{1}$$

3. RESULTS AND DISCUSSION

3.1. TURBIDITY

Turbidity was used as a surrogate for total suspended solids (TSS) in these experiments. Turbidity is a measure of the relative loss of water clarity caused by suspended particles and dissolved compounds. Turbidity measurements (nephelometric turbidity units – NTU) were performed for filtered and unfiltered samples. The results indicated that there was a significant difference between the two data sets ($p < 0.05$) and a strong correlation ($r > 0.90$) between turbidity measurements of filtered and unfiltered samples with time. Therefore, reductions in turbidity levels can be considered to correspond to reduction of TSS.

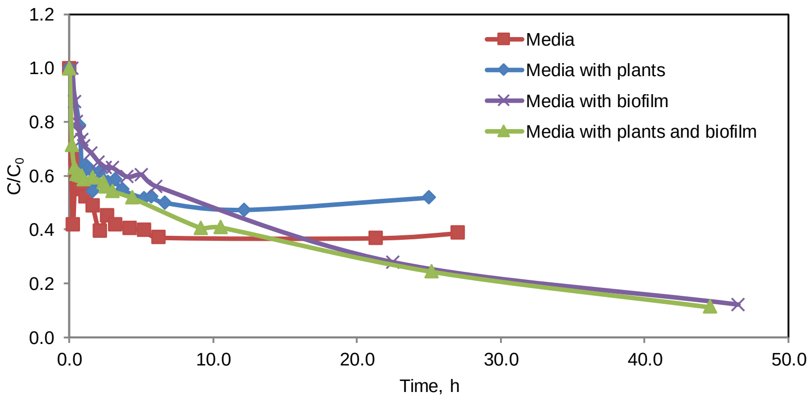

Fig. 3. Analytical results for unfiltered turbidity samples (C/C_0 vs. time)

Analytical results presented in Fig. 3 show that turbidity is reduced in the four scenarios shortly after initiation of cycling WW through the system. Reduction of turbidity continues with time and each scenario had a removal efficiency of 40% or greater after

24 hours. The removal efficiency for turbidity was greatest in the media with biofilm and plants scenario after 24 hours at 76%. Turbidity removal efficiency is equal or greater than 80% at 45 hours for scenarios involving biofilm. Svete [9] reported a TSS removal efficiency of 90% with an initial concentration of 39 mg TSS/dm^3 and a HLR of approximately 670 dm^3/m^{2}day. The HLR of the current research was 354 000 dm^3/m^{2}day.

Based on the coefficients of determination, R^2, there is a strong correlation of the data to a power function for media, only (R^2 = 0.51) and media with plants (0.69). C/C_0 values had a very high correlation to exponential functions for media with biofilm (0.96) and media with plants and biofilm (0.99).

The relationship C/C_0 versus time approaches asymptotic conditions after approximately five hours for media, only and media with plants scenarios. Asymptotic conditions are not reached at 45 hours for scenarios involving biofilm. The trend of decreasing concentrations appears to continue for the biofilm scenarios.

3.2. 5-DAY BIOCHEMICAL OXYGEN DEMAND (BOD_5)

BOD_5 is a measure of the organic content in water that can be easily biodegraded. BOD_5 concentrations are reduced in the four scenarios. However, there was considerable scatter in the BOD_5 results for media only and media with plants scenarios. This indicates that removal of soluble organic matter was not achieved through green wall treatment and therefore, the results are not presented in Fig. 4. Reduction of BOD_5 continues with time and a removal efficiency of 70% or greater was achieved after 24 hours for scenarios including biofilm. BOD_5 removal efficiency is equal or greater than 80% at 45 hours. For media with plants and biofilm, C/C_0 approaches asymptotic conditions at approximately 10 hours. In the media with biofilm scenario, C/C_0 also appears asymptotic, but after 24 hours. Based on the coefficients of determination, R^2, there is a very high correlation of the data to a natural log fit for samples for media with biofilm (0.92) and media with biofilm and plants (0.90).

Svete [9] reported a BOD_5 removal efficiency of 95% with the initial BOD_5 concentration was 129 mg O_2/dm^3 and a HLR of 670 dm^3/(m$^2\cdot$day). The current research achieved approximately 80% removal of BOD_5 after 24 hours of cycling with an initial unfiltered BOD_5 concentration of 1,190 mg O_2/dm^3 and an HLR 354,000 dm^3/m^{2}day for the scenarios including biofilm.

Cameron [4] indicated that the addition of plants in the green wall and living column did not significantly increase the removal of various contaminants over the cases when the integrated biofilter (IBF) included the green wall/living column with media and established biofilm. However, BOD removal efficiency increased from 61% to 95% when the IBF included the green wall/living column with media and biofilm [4]. A green wall used as part of an integrated household grey water treatment system was responsible for removing 40% of the total organic carbon [7].

The increased rate of BOD removal in green walls with plants and biofilm might be explained by the beneficial effects of rhizosphere habitat for microorganisms. The number of microbes in the rhizosphere has been demonstrated to be two to four orders of magnitude greater than in surrounding bulk soils [24].

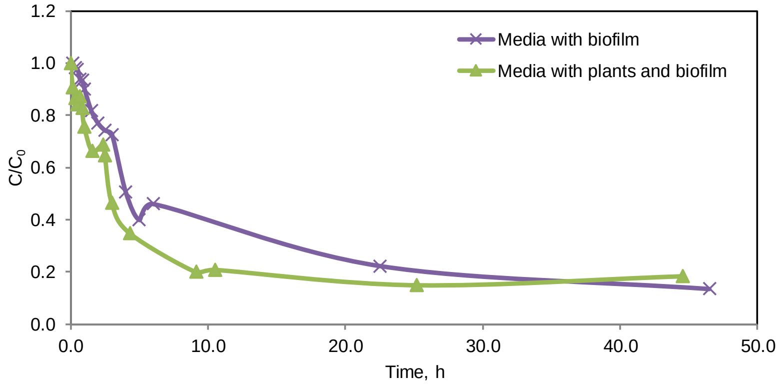

Fig. 4. Analytical results for unfiltered BOD_5 samples (C/C_0 vs time)

It is hypothesized that aerobic organisms are the predominate species in the biofilm. This is primarily because the biofilm was developed using WW from a small activated sludge system at a local craft brewing facility. Also, the experimental set up is well aerated as the face of the panels is open to the atmosphere and WW flows under unsaturated conditions; free falling into the sump.

3.3. TOTAL NITROGEN

There was considerable scatter of the total N concentrations in WW samples. This was particularly true for the media only and media with plants scenarios where the data was estimated to have little or no correlation. Based on the results, it would be difficult to determine if reduction in total N occurred for these two scenarios. The total N results for media only and media with plants scenarios have not been presented in Fig. 5.

Data correlation for the media with plants and biofilm scenario was estimated to be low to moderate (0.21), but achieved a 25% reduction of total N at 24 hours. In contrast, data correlation (0.93) for media with biofilm was very high. At 24 hours, the removal efficiency of total N was 56%. Overall there was a decreasing trend in concentrations of total N for scenarios including biofilm. The difference in total N reduction between the scenarios is hypothesized to be associated with the relative amounts of inorganic nitrogen available for uptake in the raw WW.

These results are comparable to Svete [9] who reported a removal efficiency of 30% for total N with an initial concentration of 12.7 mg N/dm^3. The average initial total N concentration of the scenarios with biofilm in the current research was 45 mg N/dm^3.

Bussy [7] reported nitrate-N removal efficiency of 24% with an initial concentration of 1.02 mg nitrate-N/dm^3. Curiously, Bussy [7] also reports an increase in ammonia-N of 64% with an initial concentration of 2.99 µg ammonia-N/dm^3.

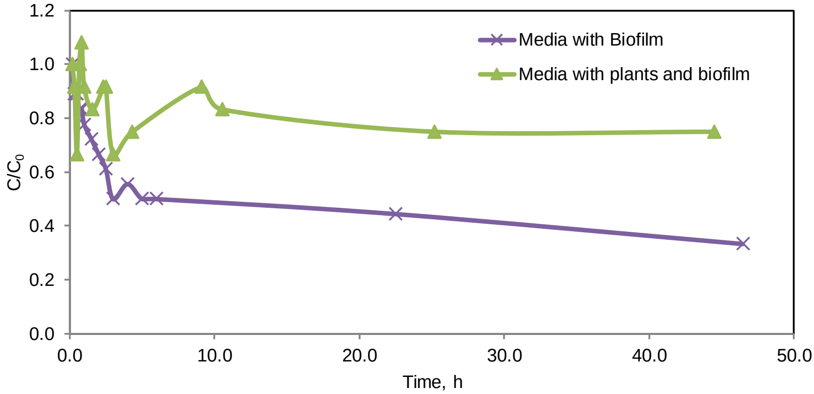

Fig. 5. Analytical results for unfiltered total nitrogen samples (C/C_0 vs. time)

Aerobic bacteria transform organic forms of nitrogen to inorganic forms through ammonization and ammonium conversion to nitrate and nitrite by nitrification. Denitrification by anaerobic bacteria is not probable in the well aerated green wall setup. Adsorption of nitrogen to biofilm and the media is possible. Nitrogen can be removed from WW in constructed wetlands through ammonia volatilization and plant uptake [25]. Suitable conditions exist for ammonia volatilization when pH > 10. No ammonia odors were noted in the laboratory during the experiments. Plant uptake does not appear to play a direct role in the reduction of total nitrogen in these experiments.

3.4. TOTAL PHOSPHOROUS

Total P concentrations detected in raw WW samples were within a range of 3.0–4.6 mg P/dm^3. The reduction in total P after 24 hours for the four scenarios is presented in Table 3.

Table 3

Total P reduction at 24 h

Scenario	Total P removed [%]
Media only	28
Media with plants	24
Media with biofilm	14
Media with plants and biofilm	12

There was considerable amount of scatter in the total P results. There was little correlation in scenarios including biofilm, low correlation in the media with plants scenario and high correlation in the media only scenario. Phosphorous removal under the media and media with plants scenarios can be partially explained by adsorption of phosphates to the fresh media. The decreasing trend in total P concentrations does correspond with earlier green wall research. Svete [9] reported total P removal efficiency of 30% when the initial concentration was 1.15 mg P/dm^3. Bussy [7] reported 44% removal *ortho*-phosphate from greywater was removed using a green wall. The initial concentration of *ortho*-phosphate was 480 μg *ortho*-phosphate-P/dm^3 in the Bussy research.

4. CONCLUSION

The objective of this study was to evaluate the possibility of using green walls to pretreat WW generated by small to medium sized food and beverage industries. These facilities often need to pretreat WW prior to discharging to municipal sewers or onsite treatment systems. Total suspended solids and BOD_5 are common measures of the strength of these organic WWs. The results of this study indicate that turbidity and BOD_5 can be effectively reduced using green walls consisting of media, biofilm, and plants. Turbidity was reduced by 50 and 75% after 6 and 24 hours of treatment, respectively. The concentration of BOD_5 was reduced by 70 and 85% after cycling through the wall for 6 and 24 hours, respectively. An equalization tank of 5400 dm^3 could be used if the effluent concentrations after 6 hours of treatment are sufficient for discharge to a sanitary sewer or on-site leach field. A 5400 dm^3 is within the typical range of septic tanks.

The concentration of total nitrogen and total phosphorous were also lowered through green wall treatment. Total N was reduced by 25–56% after 24 hours of treatment in scenarios including biofilm. Phosphorous removal was the lowest of the four parameters analyzed and the data were poorly correlated. However, total P reductions of 10–15% seem possible.

Experimental scenarios with biofilm resulted in greater reductions of turbidity, BOD_5 and N than scenarios without biofilm. Also, experiments that simulated green walls (i.e. with media, biofilm and plants), exhibited the largest percent reduction in turbidity and BOD_5.

The experiments in this study were designed to provide a preliminary investigation of the ability of green walls to remove contaminants from high strength organic WW. Further research is necessary to confirm the current results, further define the relative contribution of media, biofilm, and plants in the treatment process, select plants and media for green wall treatment, and optimize physical and hydraulic parameters.

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