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Article

UASB followed by Sub-Surface Horizontal Flow hytodepuration for the Treatment of the Sewage Generated by a Small Rural Community

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Abstract: The paper presents the results of an experimental process designed for the treatment of the sewage generated by a rural community located in the north-east of Brazil. The process consists of a preliminary mechanical treatment adopting coarse screens and grit traps, followed by a biological treatment in a UASB reactor and a sub-surface horizontal flow phytodepuration step. The use of a UASB reactor equipped with a top cover, as well as of the phytodepuration process employing a porous medium, showed to present important health advantages. In particular, there were no significant odor emissions and there was no evidence of the proliferation of insects and other disease vectors. The plant achieved the following mean abatement efficiencies: 92.9% for BOD_5, 79.2% for COD and 94% for Suspended Solids. With regard to fecal indicators average efficiencies of 98.8% for fecal coliforms and 97.9% for fecal *enterococci* were achieved. The UASB reactor showed an important role in achieving this result. The research was also aimed at evaluating the optimal operating conditions for the UASB reactor in terms of hydraulic load and organic volumetric loading. The achieved results hence indicated that the process may be highly effective for small rural communities in tropical and sub-tropical areas.

Keywords: UASB reactor; constructed wetlands; sub-surface phytodepuration; sewage treatment; rural community

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1. Introduction

The treatment of the domestic wastewater generated by small communities may be achieved applying various types of biological processes. However, the efficiency of conventional processes (*i.e.*, based on extended aeration activated sludge and trickling filters) is significantly affected by fluctuations of either sewage quality or flow rate, which are generally higher the smaller the size of the community. The effects of these fluctuations on the loss in efficiency of the treatment process has been reported in several studies (e.g., [1,2]). This problem can be overcome with the use of natural biological processes characterized by high retention times, such as lagoons and constructed wetlands. These kinds of processes in fact are well suited for the needs of small rural communities as they are of low cost and easy to operate.

However, the wastewater before being fed to these natural depuration systems needs to be pre-treated for the removal of coarse materials, grit and settleable solids. These pre-treatments range from more complex solutions, including screening, grit traps and Imhoff tanks, to simpler solutions (obviously less efficient) including screening and septic tanks. Since the early 90's, solutions based on Up-flow Anaerobic Sludge Blanket (UASB) reactors have begun to be developed. These systems have been traditionally employed, given the interesting results achieved in terms of treatment efficiencies and energy recovery through the production of biogas, for the treatment of high strength industrial wastewaters produced for example by sugar and dairy industries, distilleries, slaughterhouses, breweries, pulp and paper and food industries [3–18].

Early studies and applications of UASB in sewage treatment plants (UASB-STPs) were carried out in Europe [8,13,19,20]. However, the most important full scale installations were first developed and tested in Brazil and Colombia [13,21–26]; then gained popularity in India and other countries with tropical or sub-tropical climates such as the UAE, Iran, Angola, Indonesia, Egypt, Palestine, Jordan, Thailand and others [27–33]. India currently is one of the leading countries in terms of the amount of sewage treated by the UASB process [29]. In this country, over 45 UASB-STPs are in operation, with an average flow rate of over 10,000 m^3 day^{-1}; the largest UASB-STP was designed for a flow rate of 338,000 m^3 day^{-1}. 15 UASB-STPs were identified in Brazil, many of them presenting a very large capacity, serving up to 1,500,000 inhabitants [13].

In developing countries, the UASB reactor is, in many cases, the only treatment applied after preliminary mechanical treatment, although the importance of completing the treatment process with a final oxidative biological treatment is widely recognized. In fact, despite the great advantages presented by UASB reactors, such as biogas production, the quality of the treated effluents generally does not comply with discharge standards. The following removal efficiencies have been reported for UASB-STPs: 43%–47% for COD, 55%–77% for BOD_5 and 18%–85% for suspended solids [13,19,30,34].

Therefore, the effluents from UASB reactors usually require a post-treatment step in order to comply with the limits established by the environmental legislation in force in order not to alter the quality of the receiving water bodies.

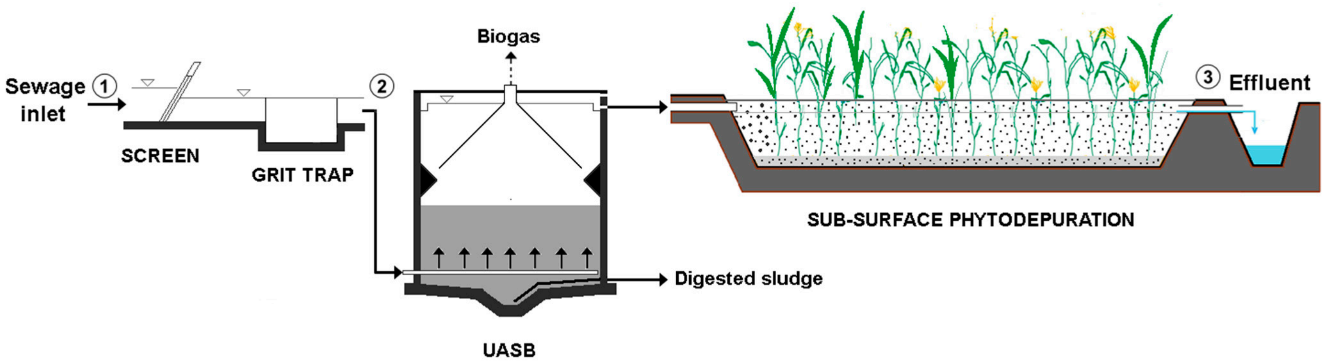
In developing countries, a sewage treatment plant for small rural communities is sustainable if it presents low investment costs, negligible maintenance requirements, low power consumption and ease of operating. In addition it is important that the applied treatment may lead to an effective improvement of the sanitary condition of the population. On the basis of these concepts, an innovative treatment process was tested through the construction and operation of a plant designed to serve a rural community of 1650 inhabitants located in the north-east of Brazil. The process consists of a UASB reactor equipped with a top cover, followed by a sub-surface horizontal flow phytodepuration system (SSHFP). It was conceived in this manner in order to achieve an efficient sewage treatment in terms of BOD_5, COD, suspended solids and fecal microorganisms abatement. Additionally, the top cover of the UASB reactor and the sub-surface flow of the wastewater in the phytodepuration step were selected with the aim of minimizing odor emissions and avoid the proliferation of insects and other disease vectors. The latter is of particular importance for the area where the plant is located, as it is periodically subjected to epidemics of "dengue", a hemorrhagic fever caused by dengue virus, spread by mosquitoes of the *Aedes* species (mainly *Aedes aegypty*) that breed preferentially in stagnant water.

2. Materials and Methods

2.1. The Experimental Plant

Figure 1 schematically shows the treatment process adopted to serve a rural community of 1650 residents, generating a sewage daily flow rate of 220 m^3 day^{-1} (133.3 L $inhab^{-1}$ day^{-1}).

Figure 1. Diagram of the treatment plant. The numbers into the circles identify the location of the sampling points.



The sewage is subjected to mechanical pre-treatment (screening and grit removal), followed by treatment in UASB reactor and a SSHFP system whose construction features are here below reported:

- UASB reactor
    - Diameter: 5.6 m;
    - Total volume: 125 m^3;
    - Volume per capita: 75.75 L $inhab^{-1}$;

- Volume of the anaerobic zone: 57 m^3;
- Volume of the sedimentation zone: 52 m^3;
- Volume of the transition zone (between anaerobic and sedimentation): 16 m^3;
- Total water height: 5.0 m;

• Phytodepuration system:

- type: sub-surface horizontal flow [35];
- parallel lines: 2;
- total surface: 2200 m^2;
- height of porous medium: 0.80 m;
- height of water: 0.65 m;
- porous media: coarse stones (5–10 cm);
- macrophyte plants: Taboa (*Typha domingensis*);
- liner: compacted clay (50 cm) overlaid with a HDPE membrane.

2.2. Research Main Lines and Analytical Methods

The study was aimed at verifying the efficiency of the whole treatment process and also of the individual treatment stages with respect to BOD_5, COD, Suspended Solids (SS), settleable solids and two of the main microbiological indicators (fecal coliforms and fecal enterococci). The efficiency was evaluated during the regular operation of the plant, at an average sewage flow rate of 220 m^3 day^{-1}, over a period of 8 months. In this period, daily average water samples were taken in the following three points of the plant (Figure 1):

- at the inflow of the plant (raw sewage; sampling point 1);
- at the outlet of the UASB reactor (intermediate effluent; sampling point 2);
- at the outlet of the SSHFP system (final effluent; sampling point 3).

For each point 65 samples were collected and analyzed.

In addition, for a period of two months, the efficiency of the UASB treatment was evaluated as a function of two key design and operational parameters:

- the hydraulic load (m^3 m^{-2} h^{-1}) for suspended solids;
- the volumetric loading (kg COD m^{-3} day^{-1}) for COD.

Sampling and analysis were performed in compliance with standard methods [36]; in particular, potassium dichromate closed reflux tritrimetic method for determining COD and multiple tube method for microbiological indicators were used.

3. Results and Discussion

3.1. Sewage Quality

Table 1 shows the average quality of the raw sewage with the associated standard deviation and the minimum and maximum values.

Table 1. Quality of the raw sewage referred to 65 samples (along a period of 8 months), expressed as average, standard deviation and minimun-maximum values (min-max range).

Parameter	**Unit**	**Average (*m*)**	**Standard Deviation (*s*)**	**min-max range**
Temperature	°C	24.3	3.5	20.5–28.6
pH	-	7.45	0.15	7.28–7.65
COD	mg L^{-1}	875.0	295.4	548.0–1224.6
BOD_5	mg L^{-1}	418.5	122.2	281.1–568.0
Suspended solids	mg L^{-1}	402.8	101.6	295.6–522.8
Settleable solids *	mg L^{-1}	245.0	57.9	178.7–311.3
Fecal coliforms	CFU/100 mL	9.2×10^6	1.9×10^6	7.1×10^6–11.5×10^6
Fecal enterococci	CFU/100 mL	2.5×10^6	0.4×10^6	1.9×10^6–3.0×10^6

* evaluated as the difference between the suspended solids in the raw sewage and the suspended solids measured after 2 h of settling in an Imhoff cone.

The quality recorded indicates a "high strength" sewage, with the following mean values: BOD_5 = 418.5 mg L^{-1}, COD = 875.0 mg L^{-1} and SS = 402.8 mg L^{-1}. The fluctuations around these average values are very pronounced (as evidenced by the standard deviation and the min-max range values), due to the small size of the rural community and the short length of the sewer to the treatment plant (about 200 m).

3.2. Operating Conditions of the Plant

The operating conditions of the plant that were maintained during the experimental period, were as follows:

- UASB reactor:
  - Hydraulic load at average flow rate: 0.37 m^3 m^{-2} h^{-1};
  - Average retention time: 13.6 h;
  - Average volumetric loading, referred to BOD_5: 0.73 kg BOD_5 m^{-3} day^{-1};
  - Average volumetric loading, referred to COD: 1.54 kg COD m^{-3} day^{-1};
  - Average sludge loading, referred to BOD_5: 0.021 kg BOD_5 kg^{-1} SS day^{-1};
  - Average sludge loading, referred to COD: 0.043 kg COD kg^{-1} SS day^{-1};
  - Sludge bed concentration: 78 kg SS m^{-3} (as average);
  - VSS content in sludge SS: 60.2% (as average);
- SSHFP system:
  - Average volumetric loading, referred to BOD_5: 0.017 kg BOD_5 m^{-3} day^{-1};
  - Average volumetric loading, referred to COD: 0.039 kg COD m^{-3} day^{-1};
  - Average superficial organic load, referred to BOD_5: 109 kg BOD_5 ha^{-1} day^{-1};
  - Average superficial organic load, referred to COD: 253 kg COD ha^{-1} day^{-1};
  - Average Hydraulic load: 100 L m^{-2} day^{-1};
  - Average retention time: 78 h.

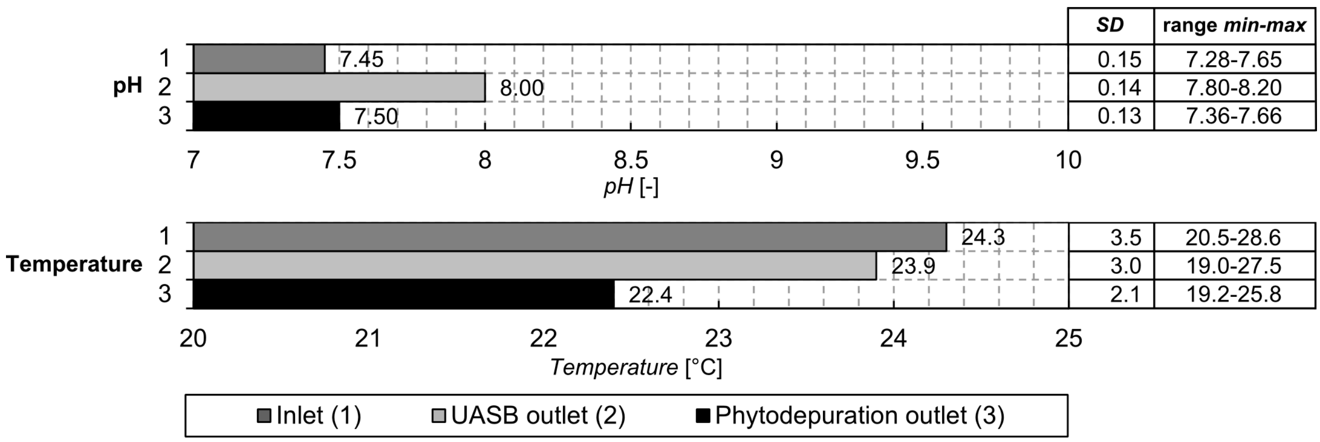
It should be noted that the operating conditions of the UASB reactor are aligned with the typical values reported for other full scale plants achieving removal efficiencies of 75%–80% for COD, 65%–70% for BOD_5 and 75%–80% for suspended solids [30]. In contrast, the wetland system is operated at a relatively high load, since in previous studies, although a wide range of average superficial organic loads were tested (20–120 kg BOD_5 ha^{-1} day^{-1}), the recommended value was reported to be lower than 67 kg BOD_5 ha^{-1} day^{-1} [35,37–39]. The choice made in the present study was aimed at achieving an overall treatment efficiency exceeding 90% for BOD_5, suspended solids and fecal indicators, while minimizing the required surface. Of course, it was considered a viable option because of the favorable climatic conditions and of the expectation of attaining good abatement efficiencies in the previous treatment step carried out in the UASB reactor.

3.3. Plant Performance

3.3.1. Temperature and pH

Figure 2 shows the pH and temperature values measured at the previously mentioned three sampling points along the plant.

Figure 2. Temperature and pH values measured at the 3 sampling points (data as mean, standard deviation and min-max range).



The temperature of the raw sewage is typical of the local tropical climate, with a mean value of 24.3 °C and a range of 20.5–28.5 °C. This value is maintained quite well during the whole treatment process. This represents a particularly favorable condition for achieving high treatment efficiencies for both the UASB process and the phytodepuration step.

The pH, typical of any sewage, is characterized by a slight rise in the weakly basic field downstream of the UASB reactor as a result of the methanogenesis process. The slight decrease in the next step (constructed wetlands) is due to the production of CO_2 by aerobic biological activities.

3.3.2. Removal Performances of BOD_5, COD, Suspended Solids and Settleable Solids

Figure 3 shows the BOD_5, COD, suspended solids and settleable solids concentration, while Figure 4 reports the same results in terms of removal efficiencies.

Figure 3. Values of BOD5, COD, suspended solids and settleable solids measured at the 3 sampling points (data as mean, standard deviation and min-max range).

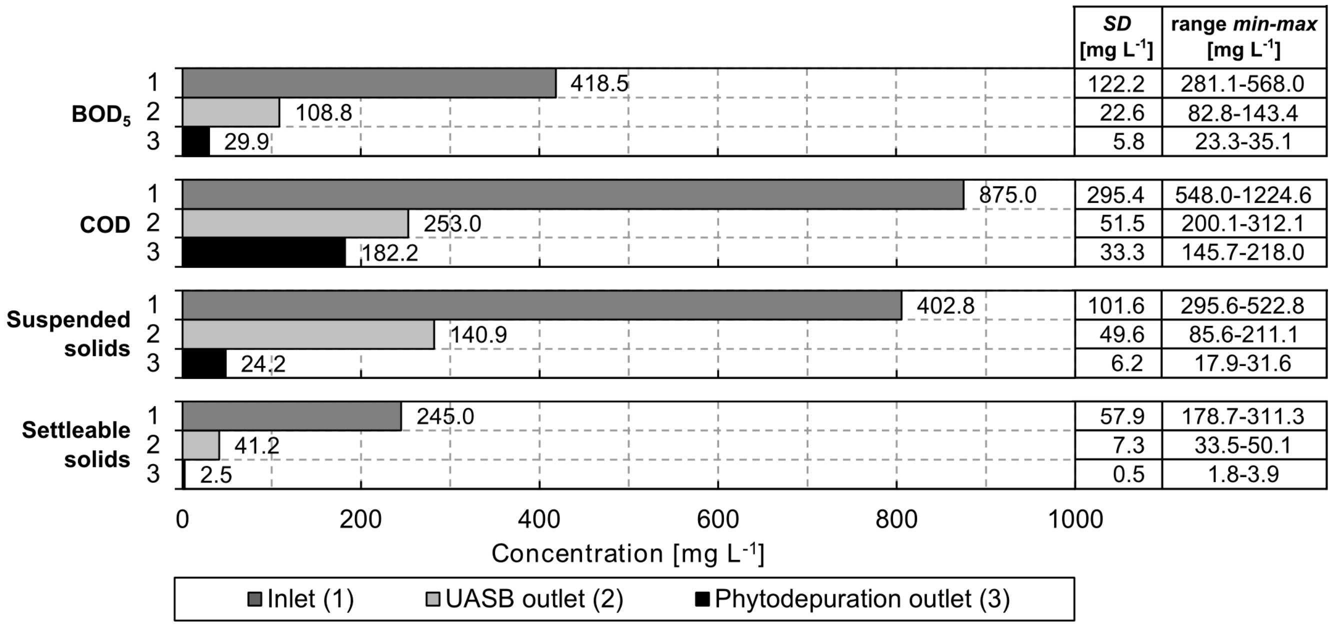
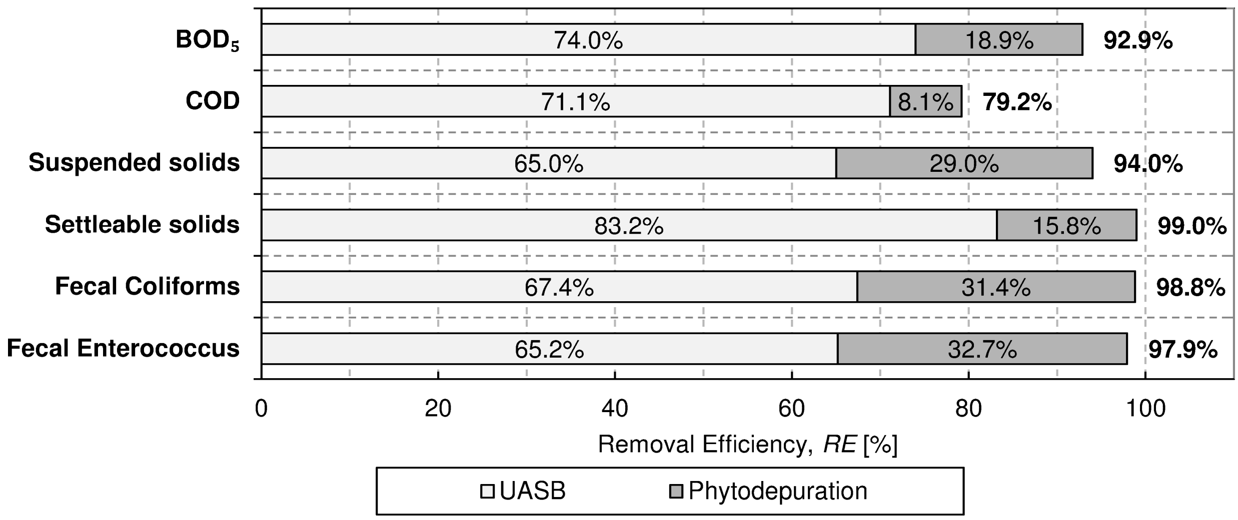


Figure 4. Average removal efficiencies for each parameter attained by the overall process and the individual two tested treatments.



The examination of the results allows to make the following observations:

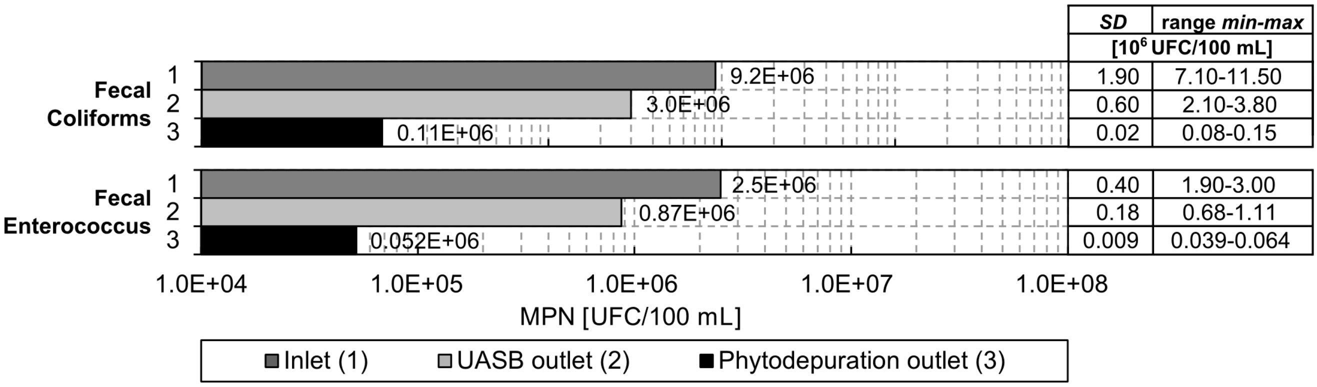
- The raw sewage proves "high strength" characteristics because of the high concentrations of BOD_5, COD and suspended solids. This condition, coupled with the high temperature, results in the achievement of average removal efficiencies in the UASB reactor as high as 74.0% for BOD_5, 71.1% for COD and 65.0% for suspended solids. These efficiency values are significantly higher than those that are typically obtained by a simple primary sedimentation step and may be related to both the anaerobic biological process occurring in the granular sludge blanket and the mechanical filtration process taking place in the same biological bed. The resulting average efficiency values prove in accordance with those reported for well operated UASB-STPs [5,19,25,28,34].

- The SSHFP step achieves a further reduction of BOD_5 and COD concentrations, bringing the total yield to the values of 92.9% for BOD_5 and 79.2% for COD. But the greatest impact of this step regards the removal of suspended solids that reaches an overall efficiency of 94%, despite the very coarse filling medium adopted. Therefore, this treatment stage consists not only in a biological process but also in a mechanical treatment step with regard to suspended solids (by filtration, sedimentation and other interception mechanisms of suspended particles). It is worth noting that during the course of the experimentation no appreciable increases in pressure drop along the wetland system were observed. For this reason it is reasonable to assume that further efficiency benefits could be achieved employing a finer porous medium with a diameter of about 10–20 mm in the final zone of the constructed wetland.

3.3.3. Removal Performances of Fecal and Enterococcus Coliforms

Figure 5 shows the fecal coliforms and fecal enterococci concentration measured at the three sampling points along the plant.

Figure 5. Values of fecal coliforms and enterococcus coliforms measured at the 3 sampling points (data as mean, standard deviation and min-max range).



The average removal efficiency resulting from the UASB reactor amounts to 67.4% for fecal coliforms and 65.2%. for fecal enterococci (Figure 4). These values are appreciably higher than those achieved with a simple primary sedimentation step for which efficiencies of 30%–50% [37], 38% (as average value in 15 plants) [40], and 25%–75% [41] are reported. The lower values of these ranges are typical of very diluted sewage [42]. The result achieved in the present study may be attributed to both the higher removal yield of suspended solids achieved and the high retention time in anaerobic conditions adopted. The scientific literature indicates that for a simple primary sedimentation treatment the percentage of fecal coliforms removal is lower than that of suspended solids [40]. In this case instead, the two reduction values are comparable, further confirming the important role exerted by the anaerobic sludge blanket treatment for the reduction of fecal indicators. In fact mesophilic anaerobic digestion is considered very effective in removing pathogens [43,44]. With reference to sewage sludge, Berg and Berman [45] reported that anaerobic digestion inactivated 1.44 to 2.3 Log of fecal coliform, 1.05 to 1.36 Log of *Entrovirus* and 0.92 to 2.08 Log of Salmonella. Also Ponugoti *et al.* [46] evidenced that anaerobic digestion may reduce many pathogenic organisms and indicator bacteria by 1 to 3 Log [45,46]. With regard to the UASB process the data available is rather scarce. A recent study indicates that UASB-STPs remove fecal coliforms by about one order of magnitude [47]. In another work an average removal by UASB treatment of 79% for fecal coliforms, 88% for Salmonella and Shigella and 87% for Vibrio was observed [48]. In another plant the removal of fecal coliforms was indicated to be above 80% [49]. Hence, actually the results reported in the above mentioned studies regarding the effects of UASB treatment on pathogens abatement appears to be slightly better than what achieved in this specific research.

The SSHFP step completes the removal of these indicators bringing the overall efficiency to the average values of 98.8% for fecal coliforms and 97.9% for fecal enterococci. Also for this step the relevant contribution of suspended solids removal which acts as the main driving force for the treatment of microbiological pollution stands out. It is worth mentioning that a traditional mechanical-biological plant produces an average reduction of fecal coliforms of about 90% with peaks of 98% [37,40,41,50]. Therefore, the tested process proves to be particularly effective in terms of removing microbiological pollution compared to traditional systems.

Despite this positive aspect it seems correct to point out that several other similar studies showed significantly better results with efficiencies exceeding 99% just for the constructed wetland (citing [51–53]). This greater efficiency is justified by the lower volumetric loading and the finer filling material (usually 5–20 mm against the value of 50–100 mm applied in this specific research with the aim to achieving very long operating times without any risk of clogging). Apart from the cited removal efficiency of fecal indicators it is worth to note that SSHFP is considered a highly efficient system for the removal of protozoan pathogens (*Cryptosporidium* and *Giardia*) and coliphages with efficiencies in the range of 94%–98% [54].

3.3.4. Further Results

Besides the discussed results, it should be noted that the operation of the whole plant was quite regular during the whole experimentation period, without the occurrence of noteworthy maintenance problems. In addition, the plant did not produce odors, thereby demonstrating the effectiveness of the top cover of the UASB reactor and the sub-surface flow adopted in the phytodepuration step. An important role in odor control should be also ascribed to the water solubility of the different volatile odorous compounds. However, the biogas production was quite small due in part to the mentioned solubility in water (17–20 mg L^{-1} and 1450 mg L^{-1} at 20 °C and atmospheric pressure for methane and carbon dioxide, respectively [55]) and to the feeble mesophilic conditions employed in the UASB reactor. Previous studies have also shown that the quantity of biogas produced by these types of treatments is limited and inadequate to guarantee exploitable bioenergy generation [56].

3.4. Evaluation of the Efficiency of the UASB Treatment at Variable Loads

For a period of three months the UASB reactor was fed with a gradually increasing flow rate in order to verify the effects on the treatment efficiency of both the hydraulic load and the COD volumetric loading. The results are presented in Figures 6 and 7.

Figure 6. Removal efficiency of suspended solids in the UASB reactor as a function of the hydraulic load (mean and 95% interval of confidence).

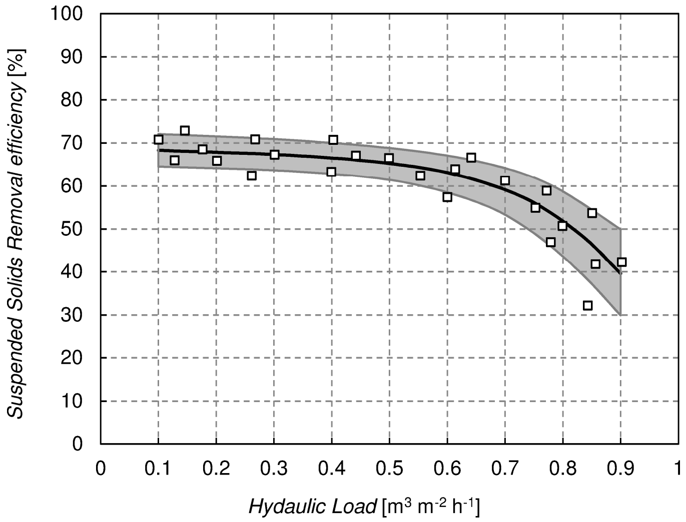


Figure 6 shows that the removal efficiency of suspended solids remains quite constant and above 65% for hydraulic loads lower than 0.5 m^3 m^{-2} h^{-1}. Beyond this value there is a progressive loss of efficiency down to 40% for a hydraulic load of 0.9 m^3 m^{-2} h^{-1}. The progressive loss of efficiency is initially due only to the transport of the suspended solids present in the wastewater, while at higher hydraulic loads also the sludge blanket granules are extracted with the effluent. For comparison, the results of previous studies suggested to adopt hydraulic load values of 0.52 to 0.58 m^3 m^{-2} h^{-1} [30] and below 0.35 m^3 m^{-2} h^{-1} [57].

Figure 7. Removal efficiency of COD in the UASB reactor as a function of COD loading (mean and 95% interval of confidence).

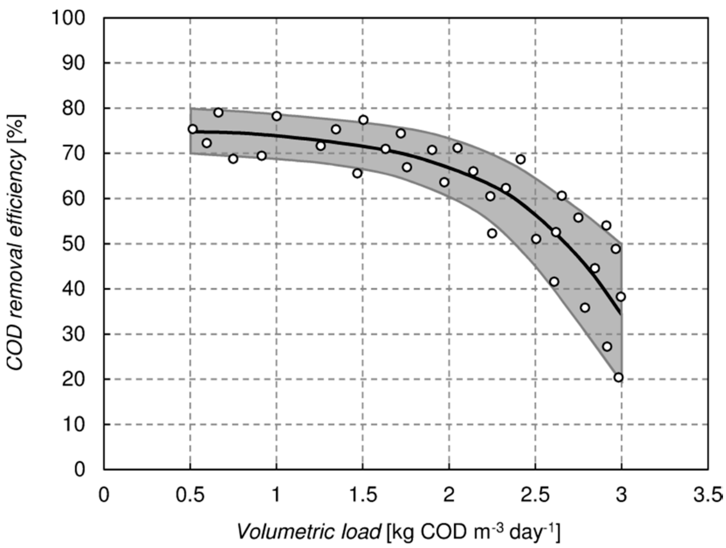


Figure 7 shows that a COD removal efficiency above 70% may be achieved for a volumetric loading lower than 1.75 kg COD m^{-3} day^{-1}, while for higher values there is a progressive loss of efficiency, which decreases to 30% for a volumetric loading of 3 kg COD m^{-3} day^{-1}. Obviously, the removal efficiency of COD (Figure 7) is strongly correlated to the removal efficiency of suspended solids (Figure 6), and this justifies the analogy of the trends of the two curves. It should be noted, however, that the decreasing gradient of the curve of the COD removal efficiency is greater than that of the suspended solids. This evidence can be justified by considering that at the highest volumetric loadings tested COD removal is affected by both the transport of solids in the effluent and the shorter contact time in the anaerobic biological reactor.

4. Conclusions

The results of this study indicate that the tested process making use of a UASB reactor followed by a sub-surface horizontal flow phytodepuration system is particularly effective for the treatment of the sewage generated by small rural communities in tropical and sub-tropical areas. The use of a UASB reactor equipped with a top cover, as well as of the phytodepuration process employing a porous medium, showed to present important health advantages. In particular, there were no significant emissions of odors and there was no evidence of the proliferation of insects and other disease vectors. The latter is of particular note in the location of the plant because it is periodically subjected to outbreaks of "dengue", a hemorrhagic fever caused by dengue virus spread by mosquitoes of the species *Aedes* (mainly *Aedes aegypty*) that prefer to breed in stagnant water.

Globally, the following abatement efficiencies were achieved: 92.9% for BOD_5, 79.2% for COD and 94% for suspended solids. With concern to fecal indicators, an average efficiency of 98.8% for fecal coliforms and 97.9% for fecal enterococci were achieved. The UASB reactor showed a relevant role in achieving this result as alone it allowed to attain efficiencies of 74% for BOD_5, 71.1% for COD, 65% for suspended solids and approximately 65% for the microbiological fecal indicators.

In the wetland system a coarse filling material was adopted (50–100 mm) in order to ensure long operating times without the risk of clogging and consequent need of maintenance. Nonetheless, the removal efficiency of suspended solids (and of all others parameters) resulted very significant. However, due to the verified negligible lack of head loss in the porous media, it seems reasonable to take into consideration also the application of a finer porous medium (10–20 mm) in a part of the final zone of the wetland in order to achieve further improvements of the treatment efficiency.

The analysis of the performance of the UASB reactor has led to identify as optimum operating conditions a hydraulic load below 0.5 $m^3\ m^{-2}\ h^{-1}$ and a volumetric loading lower than 1.75 kg COD m^{-3} day^{-1} (for an average temperature of 23.9 °C) which allows to achieve removal efficiencies of suspended solids and COD above 65% and 70%, respectively. Beyond this limit, the performance shows a decreasing gradient due to suspended solids leakage in the effluent and a low retention time within the anaerobic sludge blanket.

Author Contributions

The authors contributed equally to this work. Renato Gavasci, Massimo Raboni and Giordano Urbini developed the idea and designed the plant. Massimo Raboni was the responsible of the plant operation and data analysis. Renato Gavasci and Giordano Urbini acted as supervisors. The article has been written with full collaboration of all the authors. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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