Use of coupled dynamic roughing filters and subsurface horizontal flow constructed wetland system as appropriate technology for upgrading waste stabilisation ponds effluents in Tanzania.

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Abstract.

As a part of a comprehensive evaluation of post-treatment techniques for upgrading Waste Stabilization Pond (WSP) effluents, coupled Dynamic Roughing Filters (DyRF) and Subsurface Horizontal Flow Constructed Wetland System (HSSFCW) system was evaluated in Tanzania. Coupled DyRF and HSSFCW were considered as cheaper and yet effective and appropriate alternative technology for upgrading WSP effluents in tropical environments like Tanzania. The main objective of the study was to determine the performance treatment of coupled DyRF and HSSFCW for upgrading WSP effluents with respect to organic compounds (TSS and BOD_5) and pathogen (FC). A pilot of coupled DyRF and HSSFCW was constructed at the outlet of the Maturation WSP at the University of Dar es Salaam, Tanzania.

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The study was carried out in a 2.2 m × 0.7 m × 0.7 m deep DyRF as a first stage, using three different fractions of gravel ranging from 8mm to 32mm, from the top to the bottom respectively. In the second stage, a HSSFCW planted with *Phragmites Mauritianus* with 0.6-m wide, 1.75-m long and 0.6 - m deep was used. The DyRF – HSSFCW system achieved TSS load reduction by 89.35% which is 15.97 $gTSS/m^2/day$, while BOD_5 load reduction by 84.47% which is 9.29 $gBOD_5/m^2/day$ was achieved. The FC mean removal rate of 99.99 % was also achieved. By achieving mean effluent TSS (12.63 ± 4.12 mg/l), BOD_5 (14.12 ± 3.84 mg/l), and mean effluent FC concentrations of 790 FC/100ml it was concluded that application of coupled DyRF and HSSFCW in the tropics can be considered technically one of the most appropriate technology for upgrading WSP effluents.

Keywords: Appropriate Technology, Faecal Coliform, TSS, BOD_5, DyRF, HSSFCW

1. Introduction

The increasing concern about the adverse effects of pollution on many receiving water sources together with emphasis on wastewater recovery and re-use has resulted in current wastewater treatment techniques coming under heavy scrutiny in order to satisfy even more stringent effluent standards and to ensure sustainability of the water resources (Mbwette, 2002). Recently, wastewater re - use has become the centre of attention of the scientists, technologists and socio-economists in the developing countries (Strauss *et al.,* 2000). Tanzania is among of the interested countries (Mbwette and Amusa, 1999). One of the

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treatment techniques which has been intensely scrutinized is the Waste Stabilisation Pond (WSP) systems.

WSP systems classically composed of anaerobic basins followed by Primary Facultative WSP (PFWSP) and Maturation WSP (MWSP) (polishing) in series have, in the 20th century, provided a basic low-cost and appropriate wastewater treatment technique world-wide where land availability is a non–issue. WSPs constitute a major benefit to health and the environment in most developing countries.

The occasional high concentration of Total Suspended Solids (present in the form of algae), which exceed 100 mg/l in their effluents, is the major disadvantage of WSP systems (Saidam *et al.*, 1995). Moreover, as environmental pollution and re - use standards have become more stringent, the "classical" WSPs systems have become increasingly inadequate in many instances particularly with regard to odour, effluent quality (particularly regarding algal suspended matter, nitrogen, pathogen, organic compounds). Their effluent for irrigation is either not permissible or is usually limited to very few inedible crops (Mbwette and Amusa, 1999). In addition, land requirements become prohibitive, particularly when large communities are to be served by WSPs (Shelef and Azov, 1999). These drawbacks have caused many communities to either switch to other treatment systems or to couple WSPs to other tertiary wastewater treatment systems for purpose of upgrading the WSP effluent.

A number of studies have been carried out on the improvement of the quality of the effluent from the WSP systems for purposes of meeting the requirements for the intended re - use or disposal in receiving water bodies (Steinmann *et al.*, 1998). Techniques that have been reviewed for upgrading WSP effluent includes centrifugation, micro-straining, coagulation,

flocculation and in - pond removal of particulate matter (Middlebrooks, 1995). However, most of these techniques have been found to be either costly to construct or expensive to operate and maintain. They furthermore require highly skilled personnel for operation or produce huge amounts of sludge.

This study was intended to introduce an alternative approach of improving further the WSP effluent through the use of coupled DyRF and HSSFCW as appropriate technology for upgrading WSP effluents in Tanzania.

1.1. Background

Historically, DyRF was developed to protect subsequent drinking water treatment units from excessive loads of TSS, particularly those caused by rapid changes in water quality as is frequently the case in the Andean region after rainfall (Galvis *et al*., 1991). DyRF contains a layer of fine gravel on top of a shallow bed of coarse gravel and a system of underdrains. Part of the influent (Q_i) passes downward through the filter medium and then to the subsequent treatment units. The remainder flows over the gravel bed to waste (overflow). DyRF improve the water quality prior to feeding into subsequent treatment units

DyRF performance is described by its adjective "dynamic" which applies to the continuous washing or cleaning of the upper filter layer by the water flow (Wegelin, 1996). A balance is sought between the settling of small particles in the upper layer and re-suspension of these particles by the water flow. The dynamic characteristics also refers to the fact that as particles settle continuously on top of this filter bed, others are washed out and flushed away by the water flow (Pardon, 1989). The removal of a particle from the wastewater flowing through the

DyRF can be treated as comprising three principal mechanisms: transport, attachment (and detachment) and biodegradation.

The experience with DyRF for drinking water has proved the potential of this technology for treating wastewater (Mbwette, 1999). In this study, DyRF was investigated for its potential for use ahead of HSSFCW in treating WSP effluents.

1.2. Constructed Wetlands

Constructed Wetland (CW) technology has grown enormously over the past three decades (Kadlec *et al.*, 2000). CWs are designed to employ ecological processes found in natural wetland ecosystems. These systems utilize wetland plants, soils and associated micro - organisms to remove contaminants from wastewater. These systems treat domestic, industrial, urban and agricultural storm water runoff, animal husbandry – related wastewater, leachates and sludges (IWA, 2003).

As with other natural biological treatment technologies, CW treatment systems are capable of providing additional benefits. They are generally reliable systems with no need for anthropogenic energy sources or chemical requirements and a minimum of operational requirements. The treatment of wastewater using CW technology also provides an opportunity to create or restore wetlands for environmental enhancement, such as wildlife habitat, greenbelts, passive recreation associated with ponds, and other environmental amenities (Kadlec *et al.*, 2000).

Although there are currently thousands of CW in the world, the use of these systems in treating wastewater has been a relatively new technology in most of the tropical countries including Tanzania, i.e. less than a decade old (Mbwette *et al.*, 2002). Special emphasis in using CW technology in tropical countries emanates from the 'ideal' weather throughout the year for effective microbial activities that is vital for the performance of the CW systems (Jørgensen and Henrik, 2002).

1.3. Types of Constructed Wetlands

CW may be classified on the basis of the dominant macrophyte such as: (i) submerged macrophyte (ii) free – floating macrophyte and (iii) emergent macrophyte (Vyamazal *et al*., 1998). These CW systems can be used alone, in combination with other systems or as final effluent polishers when used together with conventional wastewater treatment works (Vymazal *et al*., 1998). The last two types of CW are widely used. The emergent macrophyte systems may be sub - divided into two categories based on the water flow pattern used (Vyamazal *et al*., 1998). The Horizontal Surface Flow CW (HSFCW) or Free Water Surface CW (FWSCW) systems are characterised by wastewater flow above and through the rooting medium in shallow basins. The second category of emergent wetlands, are the Horizontal Subsurface Flow Constructed Wetlands (HSSFCW). In these systems, wastewater is infiltrated into the porous medium with little or no water exposure on the surface. The infiltration can be at the inlet and wastewater flows horizontally under the bed and it is collected in the outlet at the end of the bed (Vyamazal *et al*., 1998). The infiltration can also be introduced vertically and the wastewater percolates down through different layers of the porous medium and the effluent is collected at the bottom. In both cases it is during the

passage of wastewater through the rhizosphere that it gets cleaned by the microbiological degradation and physical/chemical processes.

The attraction of subsurface systems when compared to free water surface and overland flow systems, has been in part the perception of decreased risk of nuisance from flies mosquitoes and odour and greater efficiency in terms of land usage (Vyamazal *et al*., 1998). The type of CW adopted in this study was a HSSFCW.

1.4. Pollutants removal in CW

Biological Oxygen Demand (BOD_5)

BOD_5 removal in CW is due to physical and biological processes which involve sedimentation and microbial degradation, principally by aerobic and anaerobic bacteria attached to plant roots and gravel (Kadlec, 2002).

Total suspended solids (TSS)

TSS removal is primarily a physical process of settling/sedimentation and filtration which are not temperature or season sensitive (Kadlec, 2002). Plants are reported to have a positive effect on TSS removal by reducing water velocity and by encouraging settling and filtration in the root network (Tanner, 2001).

Nitrogen (N)

The main processes in removal of N are nitrification of NH_4^+ to NO_3 and denitrification of NO_3^- to N_2 (Senzia, 2003). Other processes including ammonium sorption, ammonium

volatilisation, dissimilatory nitrate biomass, sedimentation and filtration of particle bound nitrogen comprise from 1 – 34% of the total nitrogen loss (Kadlec and Knight, 1996).

Phosphorus (P)

The processes and factors identified that control phosphorus retention in wetlands together with limitations of phosphorus removal in the treatment wetlands involve interaction with the redox potential, pH, Fe, Al and Ca minerals in the soils or substrata (Molle *et al.*, 2002).

In acid soils, inorganic phosphorus is adsorbed on hydrous oxides of Fe and Al. It can also be precipitated as insoluble Fe – phosphate and Al-phosphate but at pH > 7, it is mainly precipitated as Ca – phosphate. However, sites for adsorption and precipitation are finite and are susceptible to saturation. When that stage of saturation is reached, no further removal of loaded phosphorus can be realised.

Indicator microorganisms

CWs are known to provide efficient mechanisms for the removal of many pathogens from wastewaters (Stott *et al*., 2002). Removal rates for faecal coliforms (commonly > 99%) generally equal or exceed those described for conventional biological wastewater treatment processes. A variety of processes are thought to be involved in the removal of pathogens and parasites from wastewater in CW. These include: filtration through the substrate and attached biofilm, sedimentation, aggregation, oxidation, exposure to biocides, antibiosis, predation, attachment by lytic bacteria and viruses, natural die – off and competition for limiting nutrients or trace elements (Stott *et al*., 2002).

Like all subsurface flow treatment systems, one of the main capacity limitations of HSSFCW systems is their tendency to clog when subjected to high levels of organics and TSS loadings (Herbal *et al.*, 2002). Clogging of the substrate matrix critically hinders the oxygen transport and therefore results in an extremely fast failure of the treatment performance of the system, since most important degradation processes (carbon degradation, nitrification) require aerobic conditions and thus sufficient oxygen supply is of high importance (Harbel *et al.*, 2002). The oxygen supply by the roots of the macrophytes is by far not enough, most of the oxygen has to enter the system via surface by diffusion and convection.

The objective of this study was to assess to what extent the quality of the final effluent from WSPs could be improved by the combination of DyRF and HSSFCW. DyRF was aimed at removal of TSS before a HSSFCW. The removal of TSS before HSSFCW is crucial as clogging of HSSFCW may otherwise occur. The removal of TSS before HSSFCW implies also an overall reduction of TSS, BOD_5, COD and FC which may secure compliance with permitted wastewater discharge limits, in tertiary treatment geared at allowing an increased possibility for re-use/recycling.

2. Methodology

A field pilot scale was constructed downstream of MWSP of the University of Dar es Salaam. The experimental set up consisted of a coupled DyRF and HSSFCW, which were structured in two successive stages (Fig 1 & 2) that is DyRF as first stage and HSFCW as second stage. The system was located at latitude 6° 48' S and longitude 39° 13'E. The area has monthly mean maximum and minimum air temperatures of 30°C and 26° C, respectively.

The study was carried out in a 2.2 m × 0.7 m × 0.7 m deep DyRF as a first stage, using three different fractions of gravel ranging from 8mm to 32mm. In the second stage, a HSSFCW planted with *Phragmites mauritianus* with 0.6-m wide, 1.75-m long and 0.6 - m deep was used. Photo 1 & 2 show the set-ups at different times of experiments.

Physico – chemical parameters were analysed according to Standards Methods (APHA, 1992) and included TSS, Biochemical Oxygen Demand (BOD_5), Faecal Coliforms (FC). Other parameters were measured in situ. Dissolved Oxygen (DO) was measured by DO meter (YSI model 50B). TSS was measured gravimetrically after filtration and drying in oven at 103 – 105 °C. BOD_5 was measured using OxiTop technique. FC was obtained by standard plate count procedures after membrane filtration method.

3. Results and discussion

Figure 3 and 4 respectively shows the outlet DO concentration and DO flux reduction in different systems. The outlet DO concentrations trends obtained in Fig. 3, depicts a typical DO curve (characterized by depletion and recovery), which is a feature in rivers/streams loaded with high amounts of organic matter and nitrogen compounds (Chapman, 1997). The trend shows that DyRF alone has very low DO concentration (0.76 mg/l) compared with all other systems. This effluent concentration in the DyRF is equivalent to DO consumption rate of 4.55 g $O_2/m^2/day$ (Fig. 4). HSSFCW not connected to DyRF had high outlet concentration of 2.22 mg/l which equivalent to DO consumption rate of $0.03gO_2/m^2/day$. With exception of HSSFCW after DyRF, all other systems consume (take) the DO in the systems.

The HSSFCW after DyRF released DO during the study period. The DO concentration was 1.90 mg/l, while the release rate was 0.21 gO_2/m^2/day. In their studies, Tanner and Kadlec, (2002) reported the oxygen release rates of *P. australis* ranging from 0.5 – 5.2 gO_2/m^2/day. Kansiime and Nalubega (1999) reported oxygen release rates of 0.017 gO_2/m^2/day by *C. papyrus plants.* The release of DO in the HSSFCW not connected to DyRF can be attributed to translocation of oxygen from the shoots via their well – developed aerenchyma to the rhizosphere of the aquatic plants. Other natural alternative routes by which oxygen might have been supplied to the HSSFCW also reported in other studies (Brezonik, 1994) and also in this study could have included mass transfer across the water – air interface which is described by Fick´s law of diffusion and Henry's law of equilibrium distribution between a liquid and gaseous phase.

The low residual oxygen concentrations that prevailed in the DyRF during this study indicated that there were anaerobic processes taking place (e.g. methanogenesis and fermentation). This finding is in line with those reported by Kasseva *et al*., (2002) and Sousa *et al.*, (2001) in their studies using UASB as anaerobic pre – treatment step.

3.1. TSS reduction

Fig. 5 shows the TSS load reduction in different systems. DyRF removed an average of 63.64% of the influent TSS. This was equivalent to a load reduction of 41.87 $gTSS/m^2$/day. A HSSFCW connected to the DyRF achieved a TSS load removal of 70.91% equivalent to 9.38 $gTSS/m^2$/day reducing average concentrations from 43.41 ± 12.94 mg/l to 12.63 ± 4.12 mg/l. A single HSSFCW (not connected to DyRF) achieved TSS load removal of 69.53% which is

12.11 gTSS/m^2/day reducing average concentrations from 119.23 ± 42.42 to 36.32 ± 7.59 mg/l.

The DyRF – HSSFCW system achieved TSS load reduction by 89.35% which is 15.97 gTSS/m^2/day the effluent value from this system being 12.63 ± 4.12 mg/l, well below the limit required to discharge into receiving water bodies. In their studies, Adom *et al*., (2002) reported TSS reduction of 80% (70 gTSS/m^2/day), while Jayakumar and Dandingi, (2002), reported a TSS removal of 90%, Kasseva *et al*., (2002) and Senzia *et al.*, (2002) reported the values of 62.1% (21.25 gTSS/m^2/day) and 91.5% (9.728 gTSS/m^2/day) respectively.

Transport (Sedimentation), attachment and accumulation of TSS in the DyRF bed medium were more rapid and they were considered as the main process for the removal of the TSS in DyRF. On the other hand, the primary removal mechanisms for TSS in HSSFCW were considered to be physical process of settling and filtration. In their studies, Bavor *et al*., (1987) reported the same mechanisms for TSS removal in CW.

3.2. BOD_5 results

Fig. 6 shows the BOD_5 load reduction in different systems. DyRF removed an average of 50.79% of the influent BOD_5. This was equivalent to load reduction of 12.34 gBOD_5/m^2/day. A HSSFCW connected to DyRF achieved BOD_5 load removal of 69.43% equivalent to 5.98 gBOD_5/m^2/day reducing the average concentrations from 47.25 ± 4.87 mg/l to 14.53 ± 3.84 mg/l. A single HSSFCW (not connected to DyRF) achieved BOD_5 load removal of 69.46% which corresponded to 7.05 gBOD_5/m^2/day reducing average concentrations from 96.25 ± 23.14 to 28.55 ± 4.40 mg/l.

The DyRF – HSSFCW system achieved BOD_5 load reduction by 84.47% which is 9.29 $gBOD_5/m^2/day$ with the effluent value from this system being 14.52 ± 3.84 mg/l, far less than the limit required to discharge into receiving water bodies. In their studies using sand filters and CW, Bayley *et al*., (2002) reported BOD_5 reduction of 98% (16.69 $gBOD_5/m^2/day$) in sand filters, 33% (0.077$gBOD_5/m^2/day$) in CW systems while the overall system load reduction was 98% (6.88 $gBOD_5/m^2/day$). In their studies, Jayakumar and Dandigi, (2002), reported a BOD_5 reduction of 87.5%, while Kasseva *et al*., (2002) and Senzia *et al.*, (2002) reported the values of 75% (5.83 $gBOD_5/m^2/day$) and 82.2% (4.039 $gBOD_5/m^2/day$), respectively.

Several mechanisms could be responsible for the removal of BOD_5 in DyRF – HSSFCW and were influenced by both, the complex microbial communities present in systems as well as the physical structure of the rooting biomass. The most probable mechanisms could be settling, filtration and predation of Particulate Organic Matter (POC). Dissolved Organic Matter (DOM) component of wastewater could have been degraded in DyRF – HSSFCW by both aerobic heterotrophic bacteria and anaerobic autotrophic bacteria. These bacteria are usually found attached to the plant and other solid matrix structures in the systems. Cooper *et al*., (1996) have also confirmed this.

3.3. Faecal coliform (FC)

Mean effluent FC concentrations of 7.9×10^2 FC/100ml were recorded for the system after MWSP suggesting that WSP effluents guidelines of 10×10^3 FC/100ml would generally be met in receiving waters Fig. 7. In their studies of CW not coupled to DyRF, Senzia *et al.*,

(2002) reported improved FC in the system after MWSP. Furthermore, Stott *et al*., (2002) and Okurut and Brugen, (2000) reported similar removals in their studies.

A variety of processes were thought to be involved in the removal of FC in DyRF - HSSFCW. These included: filtration through the substrate and attached biofilm, sedimentation, aggregation, oxidation, exposure to biocides, antibiosis, predation, attach by lytic bacteria and viruses, natural die – off and competition for limiting nutrients or trace elements. These processes were also reported in the studies of Okurut and Brugen, (2000) and Stott *et al*., (2002).

4. **Conclusions**

By achieving TSS removal of 89.35% (15.97 gTSS/m^2/day), BOD_5 of 84.47% (9.29 gBOD_5/m^2/day) and FC of 99.99% (7.9 x 10^2 no/100ml) of the WSPs effluent content, a coupled DyRF and HSSFCW system seems to be a viable option as an upgrading technique for WSP effluents. Compared to HSSFCW alone, a coupled DyRF – HSSFCW performed best. The mean effluent TSS (12.63 ± 4.12 mg/l) and BOD_5 (14.12 ± 3.84 mg/l) concentrations from a coupled DyRF and HSSFCW were less than the limits set in the Tanzania standards for discharge of effluent into water and land. Based on the overall results of the treatment performance it is concluded that application of DyRF – HSSFCW in Tanzania can be considered technically as appropriate technology for upgrading the WSP effluents.

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Figures and figure captions

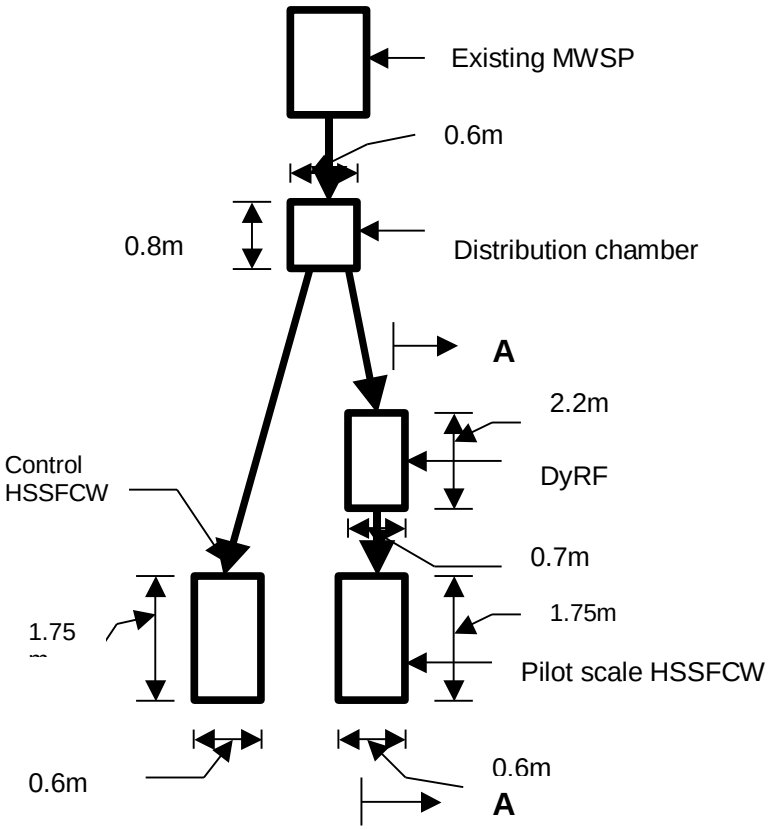


Fig 1. Schematic representation of the layout of WSP, DyRF and HSSFCW

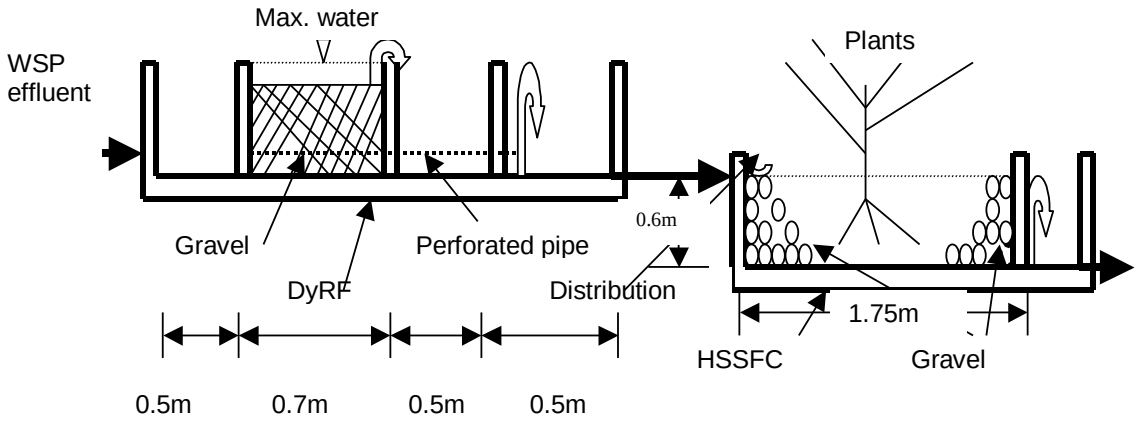


Fig 2. Cross section A - A along the DyRF and HSSFCW

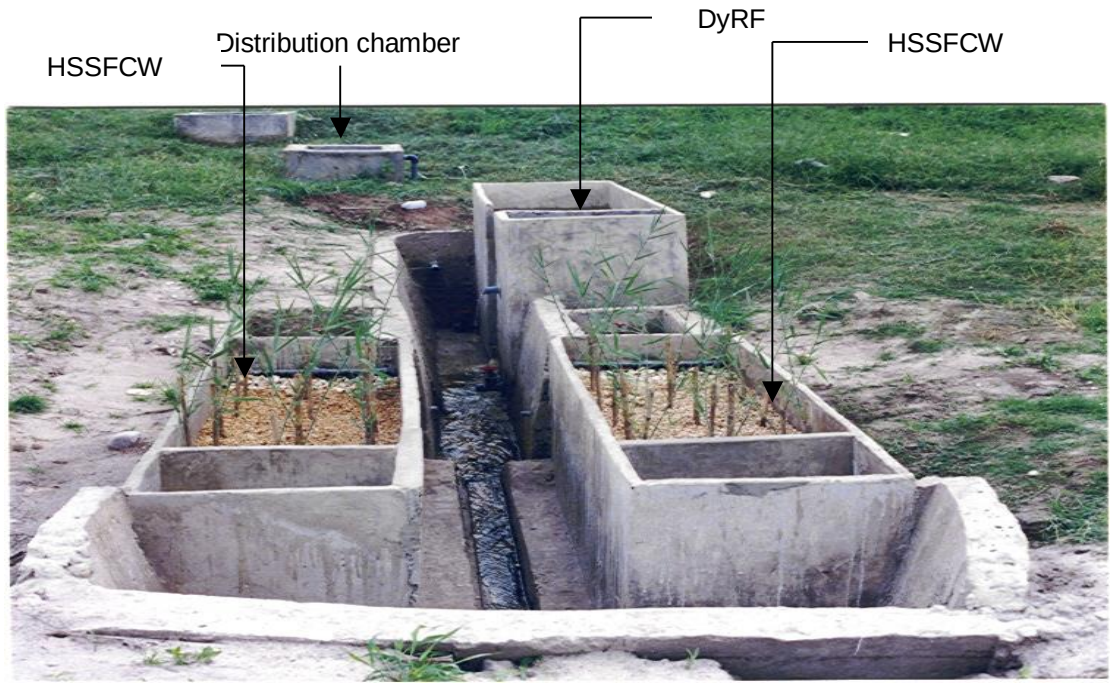


Photo 1: DyRF – HSSFCW at the beginning of operation

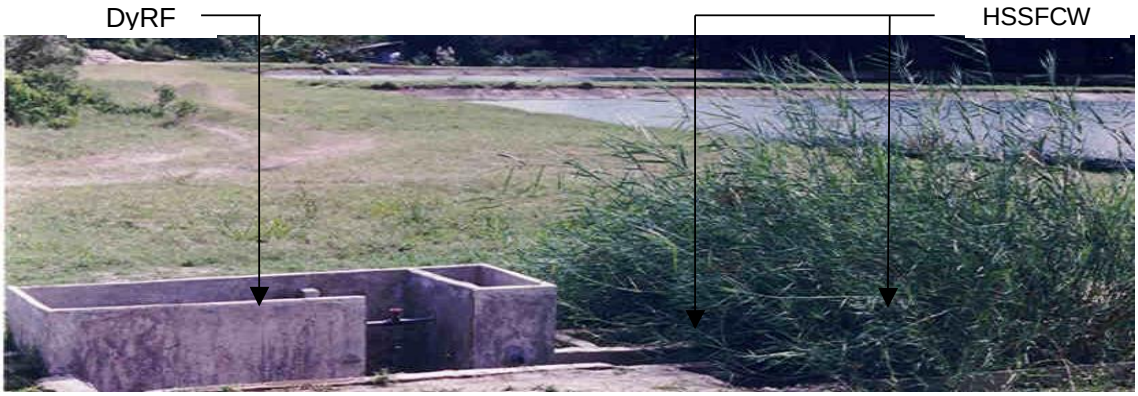


Photo 2: DyRF – HSSFCW during the study period

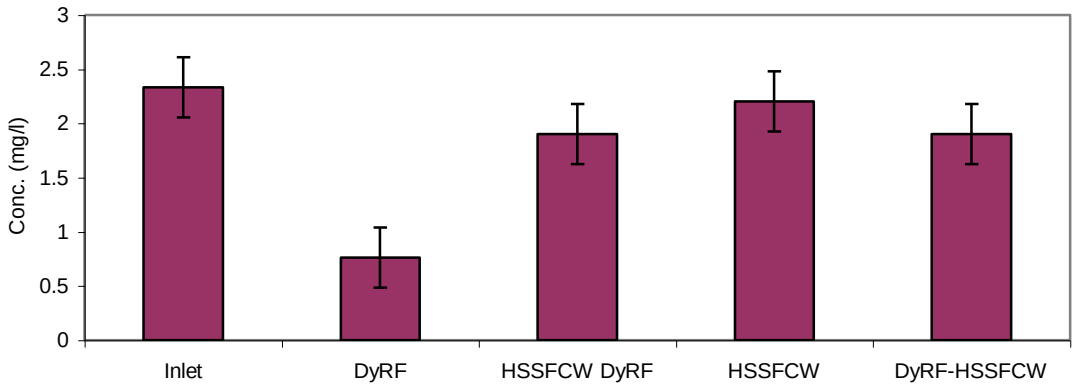


Fig.3. Outlet DO concentrations in different systems

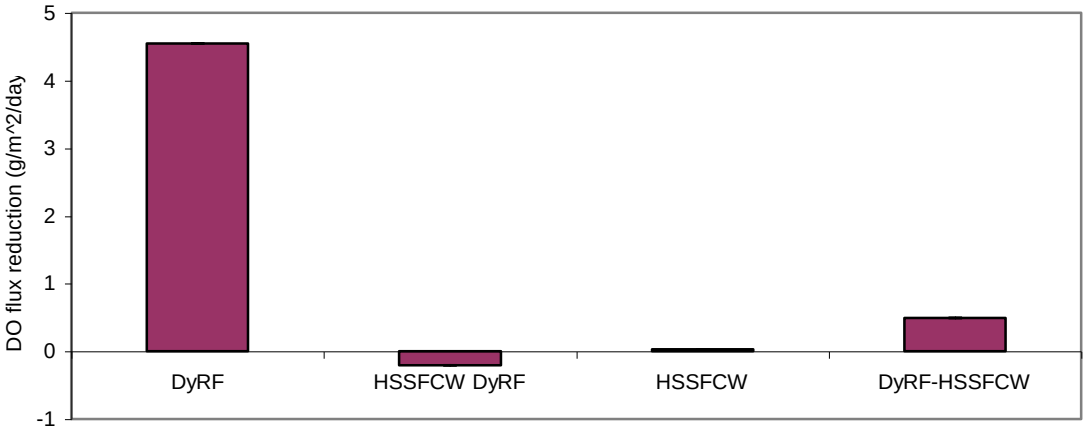


Fig.4. DO flux reduction in all systems

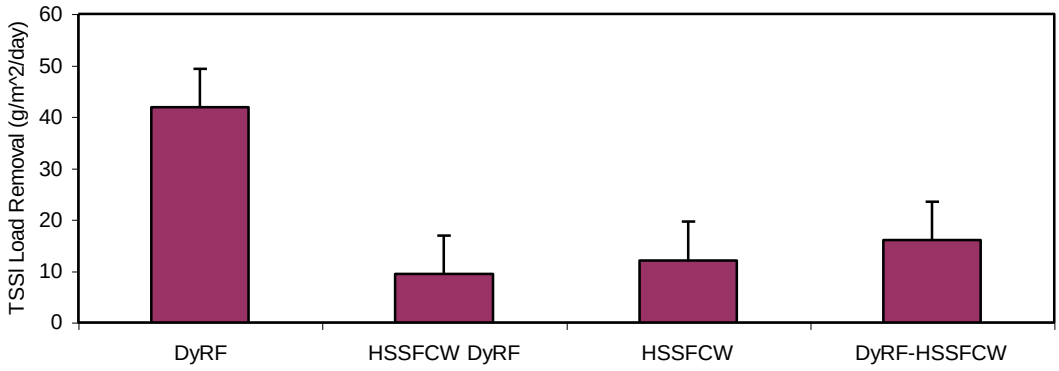


Fig. 5. TSS Load Reduction

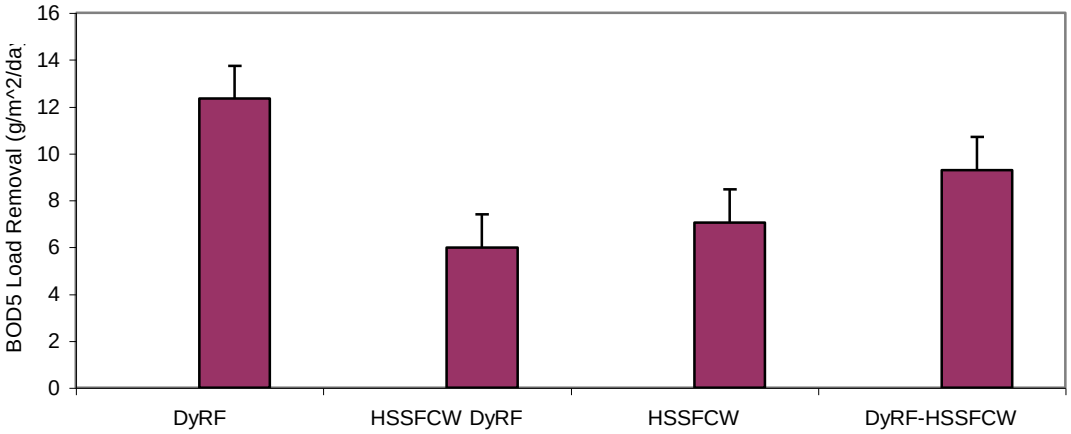


Fig.6. BOD5 Load reduction

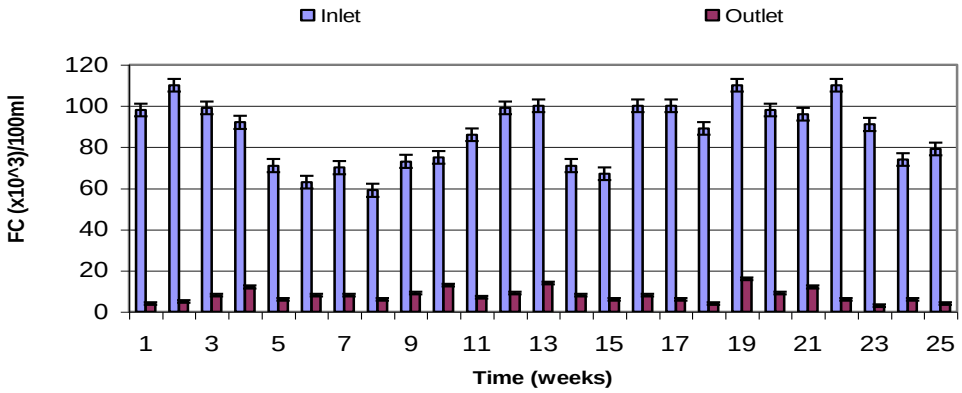


Fig. 7. Weekly FC values in the system after MWSP