Development and Demonstration of Vertical Flow Constructed Wetlands as Decentralized Wastewater Treatment System in Tropical Climate

THESIS

Submitted in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

Mr. Anant Yadav

Under the Supervision of

Prof. Srikanth Mutnuri

and Co-Supervision of

Prof. Florent Chazarenc

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE, PILANI

2019

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE, PILANI

Certificate

This is to certify that the thesis entitled "Development and Demonstration of Vertical Flow Constructed Wetlands as Decentralized Wastewater Treatment System in Tropical Climate" submitted by **Mr. Anant Yadav**, ID no. **2014PHXF0407G** for the award of Ph. D. of the Institute embodies original work done by him under my supervision.

M. Srikanth

Signature of the Supervisor

Prof. Srikanth Mutnuri
HOD (Dept. of Biological Sciences)
Date: 23/10/2019

Signature of the Co-supervisor

Prof. Florent Chazarenc
Directeur de recherche chez Irstea
Date:14-10-2019

Acknowledgement

It is my pleasure to convey my gratitude to all those who supported and helped me in many ways during the completion of this thesis.

I am very grateful to my supervisor, Prof. Srikanth Mutnuri, Professor, Department of Biological Sciences, BITS Pilani, K. K. Birla Goa Campus, for his guidance, valuable suggestions, constructive criticism and help. I want to thank him for his patience and guidance throughout my research and career. It would never have been possible for me to grow as a researcher without his encouragement.

I would also like to thank my co-guide Prof. Florent Chazarenc Director of research Irstea for his guidance and valuable suggestion. His scientific experience in the field of constructed wetland has influenced and guided me throughout my research work here in India and also in his laboratory at IMT Atlantique, Nantes. Without his valuable input in my research work, it would never have been possible for me to complete my thesis.

I would like to thank Vice-Chancellor Prof. Souvik Bhattacharyya; Director, Prof. Raghurama G; Deputy Registrar BITS Goa Mr. Sailesh Narayan Mohanty: Associate Dean ARD, Prof. Bharat Deshpande; Ex. Associate Dean ARD, Prof. P. K. Das; Dean SRCD, Prof. S. Bhand for all their support.

I am thankful to my Doctoral Advisory Committee (DAC) members, Prof. Judith Bragança and Prof. Saroj S. Baral, who is also Head, Department of Chemical Engineering BITS Pilani K K Birla Goa Campus for their valuable insights, help and guidance throughout my thesis.

My sincere thanks to the faculty members of the Department of Biological Sciences, Dr. Anasuya Ganguly, Prof. Meenal kowshik Prof. Vijayashree Nayak, Dr. Indrani Talukdar, Dr. Malbika Biswas, Prof. Utpal Roy, Prof. Dibakar Chakrabarty, Dr. Sumit Biswas, Prof. Angshuman Sarkar, Dr. Veeky Baths, Dr. Sukanta Mondol, Dr. Kundan Kumar, Dr. Raviprasad Aduri, Dr, Sandhya Mehrotra, Dr. Rajesh Mehrotra and Dr. Arnab Banerjee for their cooperation throughout this study.

I would like to acknowledge the funding agencies CORE WWE, DBT and CEFIPRA (Raman Charpak fellowship) for providing the timely financial support.

I would like to thank Dr. Aviraj Datta, ICRISAT, for helping me by providing samples for BMP assay and saplings of Canna indica for the wetlands.

I am grateful to Prof. N. N. Ghosh, Associate Professor, Department of Chemistry, BITS Pilani, K K Birla Goa Campus, and his student Madhurya Chandel for XRD analysis.

I would also like to thank Prof. Hoysala Chanakya, Chief research scientist at ASTRA/ Centre for Sustainable technologies, Indian institutes of sciences, Bangalore for his valuable suggestions throughout the research work of my thesis.

I would also like to thanks my master's guide Dr. Rahul Shrivastava and His Ph.D. Student Dr. Shivani Sood and Ms. Poonam katoch for their valuable input to my career.

I would like to thank Ms. V. Radhamani, our lab manager for all the support, encouragment and helps provided throughout the research.

I owe my deepest gratitude to my colleague Dr. Lalita Baragi, Dr. Meghanath Prabhu, Dr. Rajesh Pasumarthi, Dr. Gowdaman, Ms Prajakta Patil, Dr. Vidya, Ms. Navodita Bhatnager, Ms. Eshita Verma, Mr. Abhilash Tripathi, Ms. Anumeha Vats, Mr. Ram Chavan, Mr. Guruprasad Talekar, Ms. Priya Sharma, Mr. Pratik kachoria, Mr. Swapnil Punyapawar, Mr Ravikiran Seth, Ms. Rajshree Yaragal and Mr. Naveen for their timely help, support, encouragement and motivation throughout this research.

Thanks to my overseas friends from France, Dr. Hernan Ruiz, Mr. Sebastian Rodriguez, Mr. Guy Dejiang, Mr. Vincent Serdobbel and all the laboratory engineers of GEPEA, UMR CNRS 6144, IMT Atlantique for all the support and fun we had together during the part of this study.

I like to thank Mr. Sandeep, our contractor, for his patience in understating scientific aspect of the wetlands and to help us in designing and construction of wetlands

My thanks to Mr. Mahaling Lamani, who has helped me in maintaining the plants during the entire period of the study. I thank Mrs. Kamna Uphadhay, Ms. Pallavi Borkar, Ms. Kavita Jena and Mr. Mahadeo Shetkar for their timely help during the study.

I am deeply indebted to my dear friends and research scholars for their timely help Mr. Om Prakash, Mr. Makhan Kumar, Mr. Mayur Jartarkar, Mr. Yogesh, Mr. Ajay, Ms. Bhakti, Ms. Shruti, Dr. Kabilan, Dr. Ramya, Dr. Geethanjali, Mr. Gautam Krishnan, Ms. Deepthi, Mrs. Pallavee, Mrs. Jigni, Ms. Akriti, Ms. Nupur, Ms. Mansi, Dr. Ansie, Dr. Kshipra Naik, Dr. Pallavee, Dr. Monsoor, Dr. Ketaki, Dr. Ankush, Dr. Priyanka, Dr. Archana, Mr Laxminarayan, Mr. Gautam Kumar, Mr. Rehan, Mr. Rakesh Manuka, Ms Pranjita, Ms Reshma, and all the research scholars of the Biological Sciences Department for all the good times and fun, apart from the unconditional support and motivation.

Finally, I would not have been able to complete this thesis without the understanding and support of my parents Mummy (Durgawati Devi), Papa (Moti Lal Yadav) and My Brother (Dhruvakant Yadav). Thank you all, and I will be forever grateful to you all.

Anant Yadav

Dedicated to My Parents

I would like to dedicate this thesis to my

Mother Mrs. Durgawati Devi and Father

Mr. Moti Lal Yadav who valued education above all and inspired me throughout my life

Abstract

Wastewater treatment is one of the most severe issues in the country. Wastewater is generated from various sources that enter the sewage system, such as households, schools, hospitals, companies, restaurants, etc. It ends up in rivers without appropriate treatment from the sewage treatment system, causing issues such as waterborne diseases, eutrophication of water bodies, i.e. reducing the quantity of oxygen in water and disturbing the ecology of the water system. The number of treatment facilities in the country is very low compared to the amount of wastewater produced every day. Different sewage sources produce different quality of wastewater and treatment systems should be designed based on the quality of the sewage generated. Most wastewater treatment plants (STPs) in India are based on conventional designs with the same treatment method for all kinds of wastewater generated from distinct sources.

All states in India currently generate 61948 MLD of wastewater and the wastewater treatment facility installed is only 23277 MLD, showing a huge gap of 38671 MLD. There are only 522 operating plants in the country out of a total of 816 treatment plants, suggesting a treatment plant for only 18883.2 MLD. Most of the plants operating in the county are under construction or not maintained due to the low supply of resources, the lack of skilled staff at the site, which further degrades the quality of wastewater dumped in the open setting. Decentralized wastewater treatment scheme such as Constructed wetlands (CW) could be a useful wastewater treatment alternative. CW system requires very low maintenance and operating costs and can also be operated without any skilled worker. The primary goal of the thesis was to develop a system that could operate with all the different types of wastewater.

The second chapter of the thesis aims at identifying suitable plants for the wetland. Plants play a very significant role in the wetlands, they need to be selected very carefully. Four plants were selected for this study: *Ageratum conyzoides*, *Typha latifolia*, *Canna indica* and *Hybrid Napier spp*. They were selected and compared on the basis of their bio-methane potential. The volume of biogas produced and the percentage of methane in the biogas generated were estimated by water displacement method and gas chromatography respectively. The cumulative volume of biogas generated in 100 ml batch rectors by *Hybrid Napier spp.*, *Ageratum conyzoides*, *Canna indica* and *Typha latifolia* was 187 ml (54.59 percent methane) at 4gVS / l, 166.5 ml (62.24 percent methane) at 4gVS / l, 166.5 ml (63.53 percent methane) at 3gVS / l and 157 ml (62.22 percent methane) at 4gVS / l, respectively. Despite *Canna indica's* low biochemical methane potential (BMP), it has been shown to be appropriate for both wastewater treatment and

anaerobic digestion, considering factors such as effectiveness in wastewater treatment, simple establishment, high growth rate, ease of harvesting. In 200 liters of drums, a vertical flow CW was set up at the campus to comprehend the working and select an appropriate plant for single-household reactor. *Typha angustata* and *Canna indica's* nutrient removal efficiency and Biochemical Methane Potential (BMP) were studied by 200L drum experiments for the CW. *Typha angustata* was chosen for planting in the single household two-stage vertical flow wetland system (VFCW) as it is common in Goa's natural wetlands, as well as having high BMP efficiency than *Canna indica*. The system was operated for a period of two years at two different hydraulic loading rates. The nutrient removal efficiency of the VFCW pilot scale was monitored at two Hydraulic Loading Rate (HLR) i.e. 0.150 m / day and 0.225 m / day. Since the treatment capacity of the systems was satisfactory at a higher load rate, the overall footprint of the system was reduced from 1.5 m2 per person to 0.79 m2 per person.

The 4th chapter of the thesis deals with the removal of phosphorus; the aim of the study was to select a suitable reactive material that can be used for scrubbing phosphorus from treated waste water. The removal of phosphorus primarily occurs in vertical wetlands through substratum adsorption, to a lesser extent plant uptake and incorporation into organic matter can remove a fraction of Phosphorus, but this is not sustainable. Seven different materials have been analyzed for their ability to remove phosphorus from synthetic waste water. Steel slag (SSGS), kiln ash (KAS), bauxite ore (BOX), bentonite clay (BNC) and fire (Red) brick (RB) were obtained from India. Bovec Nervac (BON) and Binvec Pivel (BOP) are obtained from drinking water treatment facilities in France. It was discovered that BON and BOP are very efficient substrate for phosphorus removal, having a phosphorus removal capacity of 7.6 mgP/g and 10 mgP/g respectively.

A two-stage vertical flow built wetland was set up at Dr K B Hedgewar School, Cujira, Bamboli, Panjim, Goa, India to comprehend the further functioning of wetland in different types of wastewater. School wastewater quality is very different from the campus raw sewage. The idea was to alter the hydraulic loading method and design of 2nd stage to increase system efficiency. The wetland's 1st phase was properly aerated and the aeration tubes were removed in the 2nd phase to create anaerobic conditions for denitrification. The system tested two different condition. The removal efficiency of COD, TKN, nitrate, nitrites, NH_4-N, and Phosphorus was around 89 %, 57 %, 38 %, 64 %, 62 % and 62 % respectively in the 1st set of experiments and in the 2nd set of experiment the removal efficiency of COD, TKN, Nitrate, Nitrites, NH_4-N, and Phosphorus was around 84 %, 64 %, 4 %, 46 %, 69 % and 63 %

respectively. Both statistics indicate that the nitrification and denitrification rate of the system also decreased as the COD/N ratio decreased. This could be due to the increase in the effectiveness of ammonia nitrogen treatment. The effectiveness of phosphorus removal in both the test set was the same. It was found that the system's overall pollutant removal effectiveness was better in the first approach. Based on the outcomes acquired from the BITS pilot scale system and school wetland, a 500 m^2 wetland was constructed for the treatment of the water from Sal river at Margaon whole sale fish market. This system was developed as per the HLR of BITS campus VFCW and 2^{nd} stage of the system was made anaerobic as per the school wetland. As the C/N ratio of the inlet wastewater (3.5) was very low for denitrification to happen. This could be increased by adding the wastewater from fish market which have COD (980 mg/L) and Nitrogen (TKN =117 m/L). This could be the future scope of the work.

List of Table

List of Figures

Table of Contents

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Origin of research

Among the multiple environmental problems that India is facing in this decade, freshwater scarcity for domestic and economic uses are ranked very high. Treatment and reuse of wastewater could be the best answer to the issue. Most of the wastewater generated in the cities and rural parts of India end up untreated in the nearby river, pond and lakes, leading to pollution of the water bodies (Kaur et. Al., 2012; Sugam et. al., 2018). The wastewater from household and industries leads to an increase in the organic compounds, heavy metals, human bacterial pathogen and many other harmful chemicals in water bodies (Agrawal et al., 2010). The disposal of wastewater into the lakes leads to eutrophication in most cases. In some cases, it leads to the foaming and fire in the lake, as observed in the recent instance of catching fire in Bellandur lake of Bangalore city (Saluga et. at., 2017; Keller et al.; 2018; lele et al., 2018). A complete focus from the government and awareness in the society regarding treatment of waste and wastewater is required to prevent the pollution in the lakes and rivers in the city. The increasing concentration of population in the cities leads to generation of huge amount of solid waste and wastewater. The informal settlement (unplanned settlements and areas where housing is not in compliance with current planning and building regulations) in these concentrated cities leads to lack of sanitation structure. It leads to improper sanitation facilities and disposal of wastewater and solid waste to open environment.

The adverse environmental effect of disposal of untreated wastewater on water bodies and groundwater are as follows.

1. Production of large quantity of greenhouse gases due to the decomposition of organic matters present in wastewater (Eijo-Rio et al., 2015; Isgren et al., 2013).
2. Consumption of dissolved oxygen in the water, thereby causing death of fishes in the rivers and other undesirable effects (Moustaka-Gouni et al., 2017).
3. Stimulation of the growth of underwater plants and algal bloom due to an increased nutrient in the water bodies phenomenon known as eutrophication (Sanseverino et al., 2016).
4. Contamination of surface water by pathogenic bacteria, which increases child mortality and hamper human health (Jamieson et al., 2002).

The disposal of sewage from domestic sources in cities and towns is one of the primary cause of pollution of water bodies in India. The problem arises due to a considerable gap in the production of sewage and treatment facilities available. 38354 million litters of wastewater per day (MLD) are produced in major cities in India, but wastewater treatment capability is only 11786 MLD, generating a huge treatment gap of 78.7%. (Kaur et. al., 2012; CPCB, 2013, Gautam et. al., 2009). One of the main reason for the difference in the production of wastewater and sewage treatment is either the non-availability of the treatment facilities in the cities or the available systems are not working properly due to lack of funds or lack of political will (Mekala et al., 2007).

The operation and maintenance of existing plants and sewage pumping station are left out in many cities and nearly 39% plants are no longer conforming to the general requirements prescribed below the Environmental (Protection) rules for discharge into streams (CPCB 2013, Gautam S. P. et al., 2009). Most of the facilities are under-utilized due to lack of power back-up facilities, which is required for all the intermediate and main pumping stations of STPs. The sewage treatment plants are generally handled by persons having low technical knowledge on the working of the system and the laboratories to analyse the wastewater qualities are also not appropriately maintained. Hence, the day to day variations in overall performance is no longer evaluated in most of the sewage treatment plant. There is a need for skilled persons having the knowledge and trained enough to understand the operation and maintenance of the plants. An expert should be engaged to visit the STPs at least once a month to monitor the working of the plants and advice for the improvement of its performance (CPCB 2013, Mauskar J.M. et al., 2007). In this context, the main aim of this chapter was to identify and develop a suitable decentralised technology for wastewater treatment under tropical climates. The technology should be extensive and should be more adaptable to small villages and medium size villages of India. It should be able to treat wastewater from all type of sources and effectively consider all types of pollutants

1.2 Literature review

1.2.1 Nature and scope of the problem

The wastewater coming from a single household or big colonies mainly contains biodegradable organics, which can be degraded by the microorganism present naturally in the environment in some time (Chen et al., 2018). The problem occurs due to the rapid increase in the population mostly in the form of concentrated cities, thus resulting in the production of massive amount of organic waste in a concentrated area. Moreover, the microorganism is incapable of degrading the organic waste at the same pace as it is produced in the cities and towns. As a result, most of the waste is discarded into the environment, which stays there for long enough to pollute the surrounding and releasing hazardous gases and chemical (Macklin et al., 2011). The wastewater from households (1-5 people equivalent) and small colonies or villages (100-200 people equivalent) generally contains water from kitchen, toilets, and bathrooms. The wastewater is termed as domestic wastewater or municipal wastewater or sewage water which mainly comprises of faeces, urines, detergent, personal care products and organics from the kitchen (Ajay et al, CPCB 2013, Jönsson et al., 2005). In a centralized system for wastewater treatment, the wastewater either pumped or through gravity is transferred to municipal treatment plants returned to water bodies after treatment. Most of the water form small colonies and single household in the cities goes untreated. This is mainly because there is no proper drainage system to connect it to centralised system or decentralized system to treat the wastewater. There is a need to make an effort to develop an appropriate drainage system connecting every colony and single household or to develop a proper decentralized system, which can work at the level of colonies and single household. This can only be possible if government and society operates in a closed loop to develop a system and monitoring them regularly to make the system more sustainable and friendly (Kuttuva et al., 2018).

According to the Census in India, only 13% of Goa's urban population is served by the sewerage system, much lower than all India average of 28%, the state lacks well-knit sewerage network, and majority of population is still dependent on traditional septic tanks with soak pit system for disposal of wastewater (Singh et al., 2016. The primary purpose of this proposal is to develop financially affordable and simple to operate decentralized technologies that will produce high-quality effluent for safe disposal or agricultural re-use. The methodology is to validate a small-scale wastewater treatment solution in the Indian context. It is clear that according to the contexts the treatment requirements might be different vary from colonies in cities to small village or slum. After the validation of methodology for the treatment plant the technology can be to Indian companies for their commercialization.

1.2.2 Wastewater generation, the current situation of treatment in India

Dumping of 2900 MLD of sewage from cities and town is the primary source of pollution of the rivers and water bodies in India. The major big cities in India are along the river, and the sewage from these cities goes to the river directly without any treatment. Treatment and reusing this of domestic wastewater for irrigation will prevent pollution of water bodies and also save a huge amount of fresh water to be used in irrigation and can also provide nutrient to the fields.

According to the report publish by Ministry of Environment in 2017, the sewage generation in urban areas of India is 61948 MLD, and the installed treatment capacity is just for 23277 MLD creating a massive gap of 38671 MLD, which released out in open environment and pollutes water bodies and groundwater sources (Siddeshwara et al., 2017; Vasanthi et. at., 2017). From the Table 1.1, it can be seen that there are states and union territory in India, which do not have any treatment facility. State of Tripura is only treating 0.05 MLD, which is negligible compared to what it is generating per day. Gujrat is generating 4119 MLD, and the state is treating 3062 MLD, which is one of the most efficient state in the list in case of treatment of sewage. The state Kerala generates 2552 MLD wastewater but the treatment facility is only available for 152.97 MLD. Two states, Himachal Pradesh, Sikkim and one union territory have installed treatment capacity more than the sewage generation in the state.

Table 1.1: State-wise sewage generation in urban areas and treatment capacity available

Sl. No.	State/Union Territory	Sewage Generation ,in urban areas (MLD)	Installed Treatment Capacity (MLD)
1.	Andaman & Nicobar Islands	22	-
2.	Andhra Pradesh	2871	247 .27
3.	Arunachal Pradesh	50	-
4.	Assam	703	0.21
5.	Bihar	1879	124.55
6.	Chandigarh	164	314 .5
7.	Chhattisgarh	951	-
8.	Dadra & Nagar Haveli	26	-
9.	Daman & Diu	29	-
10.	Goa	145	74.58
11.	Gujarat	4119	3062.92
12.	Haryana	1413	852.7

13.	Himachal Pradesh	110	114.72
14.	Jammu & Kashmir	547	264.74
15.	Jharkhand	1270	117.24
16.	Karnataka	3777	1304.16
17.	Kerala	2552	152.97
18.	Lakshadweep	8	-
19.	Madhya Pradesh	3214	482.23
20.	Maharashtra	8143	5160.36
21.	Manipur	132	-
22.	Meghalaya	95	1
23.	Mizoram	90	10
24.	Nagaland	92	-
25.	Delhi	4155	2693.7
26.	Odisha	1121	385.54
27.	Puducherry	136	68.5
28.	Punjab	1664	1245.45
29.	Rajasthan	2736	865.92
30.	Sikkim	24	31.88
31.	Tamil Nadu	5599	1799.72
32.	Telangana	1671	685.8
33.	Tripura	154	0.05
34.	Uttar Pradesh	7124	2646.84
35.	Uttarakhand	495	152.9
36.	West Bengal	4667	416.9
	Total	61948	23277

Source : G.M. Siddeshwara et al ; 2017

As per Central Pollution Control Board, there are total 816 STPs in India out of which only 522 are under operation, and 79 are non-operational, whereas remaining are either under construction or proposed. From the Table 1.2 it can be analysed that in current situation only 18883.2 MLD of wastewater is getting treated effectively out of 61948 MLD. That is only 30% of the whole volume of wastewater produced. This concludes that 70% of sewage generated in India end up in rivers or other disposing areas (Shekhar et al., 2015).

Tale 1.2: Sewage treatment plants (STPs) located in India in the year 2014-15

Sl.No.	Status	Nos. Of STPs	Capacity (MLD)
1.	Operational	522	18883.2
2.	Non-operational	79	1237.16
3.	Under Construction	145	2528.36
4	Proposed	70	628.64
	Total	**816**	**23277.36**

Source : Vishal et al. 2015

1.2.3. Wastewater treatment technologies in India and their problems

The major system used in India for the treatment of sewage water is Activated sludge process (ASP). ASP is a biological system for wastewater treatment, in this system the sludge rich in bacterial biomass is responsible for the treatment of wastewater. It works on the principle of continuous aeration, where the energy is injected to the system in the form of oxygen for the growth of microorganism which grows and feed on the organic materials available in the wastewater and form particle which clump together which can be separated by physical means. This clumps formed will settles down in settling tank from which clean water can be separated (Eckenfelder et al., 1998; Hreiz et al., 2015). This technology is very effective in the treating organic carbon, nitrogen, phosphorus etc. form the wastewater. There are disadvantages of this technology that it requires huge operation and maintenance cost also require skilled labours (operational costs is around .028 dollars per cubic meter) (Pincince et al.,1997; Hansen et al., 2007). There are other technologies which can also be used depending on the water quality to be treated and space available for the construction of the system. All the different treatment technologies are given in Table 1.3 with their advantages and disadvantages. These technologies also require constant electricity supply for aeration and pumping of water (energy requirement is 0.46 kWh/m3) (Bodik et al., 2013). Irregular power supplies hamper the treatment capacity of the system (Soares et al., 2017).

Membrane bioreactors are very impressive technology for the treatment of wastewater in a small area. This technology has certain limitation such as membrane surface fouling, membrane channel clogging, process complexity, high capital cost and operating costs, limited flow capacity – equalization required, cleaning chemicals necessary, increased foam potential, fine screening required, all of them effects the result of membrane bioreactors (Santos et .at al., 2011; Judd et. al., 2008, Lo et al., 2015). Fixed aerated bed (FAB) reactor requires extra media. This media is designed in such way to provide large surface area for the growth of microbes. In this technology, each vendor provides different criteria for the relative ratio between the media and volume of the reactor which makes it difficult to make a common standard and also the quality of media varies that affect the treatment efficiency of the system. This system also requires higher energy, if it has to be used without methanation (Suresh Kumar et al., 2013). The main disadvantage of FAB is that it requires efficient design of inlet and outlet for proper distribution of flow and also requires continuous source of energy for pupping (Burghate et al., 2013). This type of reactors also requires controlled condition such as pH, temperature and oxygen content (Ye et al., 2016).

All this technology does not handle sudden changes in the volume and quality of sewage; they are generally designed for particular volume and type of sewage. They are very sensitive to certain type of industrial wastewater which have high antibiotic or having a COD to BOD ratio less than 0.6. The sludge obtained after the treatment of waster also require suitable treatment for the disposal (Sezgin et al., 1982; Nilsson et al., 2005). One of the significant problems with these technologies is that it requires high energy, high operational and maintenance cost and skilled labour to maintain and run the system. They are not suitable for small or very little systems, so a technology needs to be developed that can be adjusted for small or very small systems. In India most of the plants are run by unskilled person (particular civil or some other engineers) not having proper technical knowledge. To manage these technology, it requires certain knowledge about the biology of the system. Thus, to understand the biology of the system it requires person which should have some short training (Chatterjee et al., 2016).

Table 1.3: Different wastewater treatment technologies used in India.

	ASP (Activated Sludge Process)	MBR (Membrane bioreactor)	SBR (Sequential Batch reactor)	MBBR/FAB (Fluidized aerated bed)	ASFF(Aeration Submerged fixed film)
Working Principal	Activated Sludge Process (Continuous Process)	Activated sludge coupled with Ultrafiltration (Continuous)	Modified activated sludge process (Batch process)	Activated sludge with suspended media support (Continuous)	Activated sludge with fixed submerged media
Advantage	Good COD BOD reduction	Good quality effluent	Can handle flow rate variations. Works fine in high COD-BOD. Better nitrogen removal	Good COD BOD reduction. Smaller footprint.	Smaller footprint compared to ASP
Disadvantage	Huge footprint	Highly expensive. High recurring and operational expenses due to the usage of UF membrane	Requires bigger tank.	Cannot handle flow rate variations. Plant fails easily with slight variations in influent. Hard to troubleshoot.	Fixed media clog easily. No proper growth of microbes on media as it is not moving.
Energy consumption	0.46 kWh/m^3 (Bodik et al., 2013)	of0.5-0.7 kWh/m^3 (Krzeminski et al., 2012)	0.330 kWh/m^3 (Gu et al. 2017)	0.38 $kWh\ m^3$ (Li et al., 2016)	0.17 kWh/m3 (Stillwell et al., 2010)

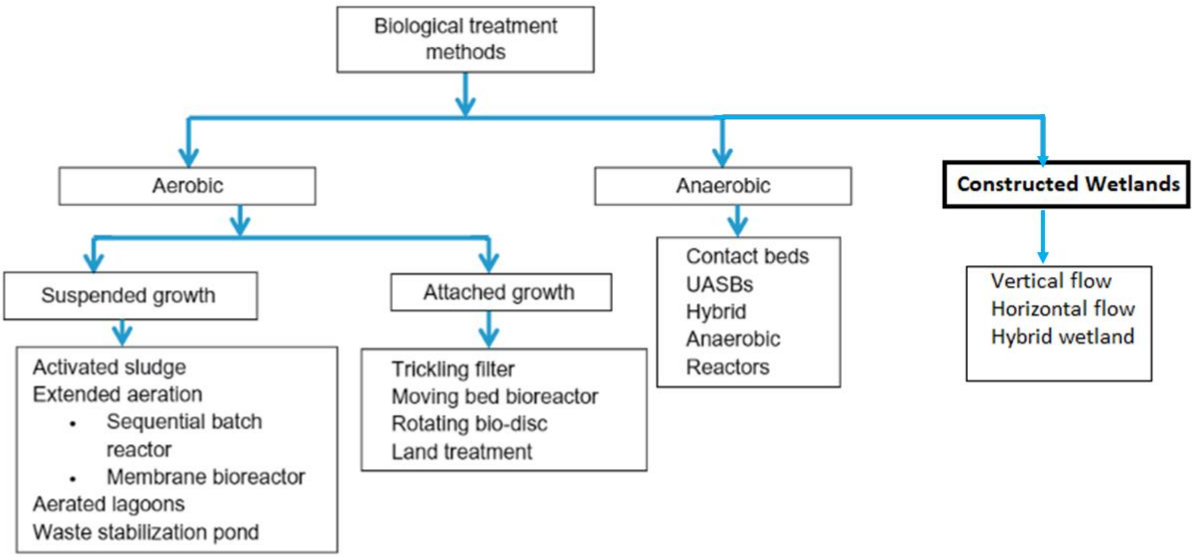


Fig 1.1: Types of wastewater treatment technology source (modified from Ranade et al., 2014)

The other alternative technology to treat wastewater is anaerobic digestion (AD) (Figure 1.1). In AD, the anaerobic microbes decompose larger complex organic molecules to a smaller molecule like CO_2, H_2S, NH_3 and produce energy in the form of methane (CH_4) (Rasi et al., 2007). This technology is widely used to treat wastewater and solid waste all over the world. In India, this technology was first established to treat human waste for the first time in 1897 (Patha et al., 2014). AD technology is seen as one of the most versatile technology as it can be used to almost all the organic waste. It is easy to use, locally manageable and can be used in the septic tank itself without adding anything to the cost (Deng et al., 2017). This technology on one side solve the problem associated with waste disposal and on the other side it produces energy. In Haryana and Maharashtra, most of the houses have a toilet fitted with AD tanks which solve the purpose of waste disposal and also provides electricity for home and manure for agricultural fields (Issar et al., 2003; Diwakar et al., 2012).

In anaerobic digestion only 5-10% of energy is available for the bacteria from organic matter compared to its counterpart aerobic digestion. In AD most of the energy ends up in methane formation, due to this the energy available for bacterial growth is less. Thus, the growth rate of bacteria’s is prolonged and they became sensitive to other environmental conditions like pH, temperature and alkalinity of the system (Feilden et al., 1983). The loading rate of the system should be managed strictly as these systems are susceptible to changes. Change in loading rate causes stress to the system. Which results in sifting of methane production pathway bacteria to fatty acid production pathway, which changes the alkalinity of the system (Dasa et al., 2016). The anaerobic system could be a great alternative, but the rate of treatment is low as compared to the amount of wastewater generating in the cities (Fulhage et al., 1979). Anaerobic digestors are incapable of handling sludge released after treatment of wastewater. Hence, it requires a post-treatment method for the sludge generated from the digester (Virkutyte et al., 2015).

Decentralized Wastewater Treatment Systems (DEWATS) can provide a great alternative to treat wastewater in the rural parts of India. The technology was developed by international experts to make the system low cost and reliable. DEWATS system can be used to treat waster from domestic, industrial source and housing complex/settlements. The system can treat wastewater from $1m^3$ to $1000m^3$ per day (Ulrich et al., 2009). The system contained four steps, primary treatment, i.e. settling; secondary treatment has anaerobic baffled reactors; the secondary aerobic or facultative treatment it includes horizontal gravel filters; and the last step is post-treatment which has aerobic polishing ponds (Sindall et al., 2018). DEWAT systems have high reliability and longevity, due to their modular design it can be changed according to the need. They need very low resource and cost efficient and all the type of treatments is provided in one package. This has high reusability of treated water and is easy to maintain with very little technical knowledge. This decentralized system is a very effective alternative to a centralised system, in small villages and single household (Hazarika et al., 2019).

India as one of the developing countries, 70% of the area comes under rural area, which in turn limits the development of wastewater facilities regarding cost and management. In this critical scenario, two stages French vertical flow constructed wetland (VFCW) will be a sustainable alternative as it does not require high maintenance cost and expertise to maintain it (Khan et a., 2017). The cost of development of a subsurface constructed wetland (CW) is around $ 12,328 which far less than that of Sequential Batch Reactors (SBR), i.e. around $ 29,177 / m^3 of wastewater per day. A SBR system requires around $ 0.80 for the treatment of 1000 litters of wastewater whereas only $0.19 is required for French two stage VFCW (EPA, Wastewater Technology Fact Sheet., 2000).

For many decades constructed wetland (CW) has been used as a wastewater treatment technology. It is one of the simplest and robust systems that can work very efficiently in the rural parts of India. CW being a green technology is used for the treatment of various types of wastewater like domestic sewage, industrial wastewater, wastewater from agriculture, stormwater runoffs, latchet from landfills and river water (Al-Zreiqat et al., 2018). It is important to select a technology which is low cost and efficient to treat wastewater particular in the rural parts of developing countries like India. CW is one of the techniques which can be used, as it has low operational and maintenance cost, and also an unskilled worker can handle the system with little training in the field (Riggio et al., 2018). One of the most important things is that it does not require any pre-treatment of waste (in case of French two-stage VFCW) water or post-treatment of the sludge (Dubois et al., 2018). Many studies have been performed in the field to develop and design CW with higher performance in different condition and on various sources of water. CW could be a great alternative against all the other traditional system to treat wastewater in the rural parts of India.

1.2.4. Constructed wetland

CW because of their benefits of high effectiveness, a suitable ecological environment, low price and esthetic value, have been commonly used in many nations and regions in the past few decades. In CWs, the interaction of substrate, plants (the most common one are *Phragmites australis, Canna indica,* and *Typha lotifelia*) and microorganisms leads to natural processes (i.e., physical, chemical and biological) that are used to remove contaminants from wastewater (Haberl et al., 1999, Wang et al., 2015). CWs are designed to mimic the natural wetlands with a filling of different sizes of gravel or other materials which can be used. CW is a complete ecosystem which provides an environment for the growth of diverse flora and fauna. In CWs many physical, chemical and biological processes are simultaneously active and mutually influence each other to make the system entirely natural to treat wastewater (Langergraber et al., 2008).

The studies on CW first started in 1950s at Max Planck Institute Germany by Dr. Kaethe Seidel. At the beginning, i.e. around the 1970's and 1980's the CW were mainly used for the treatment of domestic water and sewage water (Vymazal, et al., 2010). In the 1990's there was a major development in the installation of CW technology for the treatment of wastewater and also in the field of research to make the technology more reliable and efficient. At present situation, it significantly expanded to treat wastewater from different industrial sources and agriculture runoffs.

CWs are divided into two major categories, surface flow, and subsurface flow CW. In the surface flow wetland, the water can be seen flowing over media. In case of subsurface flow wetland, there are two types: (a) horizontal flow constructed wetlands (HFCW) in which the water flow horizontal to the surface and also flows below the surface of media; and (b) vertical flow constructed wetland (VFCW) in which the flows from the top and seeps inside the media to flow downward through gravity and come out from the bottom (Kadlec et al., 2017). There are hybrid systems to enhance the treatment efficiency of a CW. Hybrid system is generally a combination of a system, like VFCW combined with HFCW or combined with any other treatment technology in different combinations show in Figure 4.2 (Wu et al., 2015b). The CW system can also be used with other conventional technologies like SBR technology or with recently developed technologies like electrochemical cells or Microbial fuel cell (Talekar et al., 2018). Some of the CW are forcefully aerated from outside by using air pumps to enhance the working of the system, this type of system is called enhanced CW (Wallace et al., 2006).

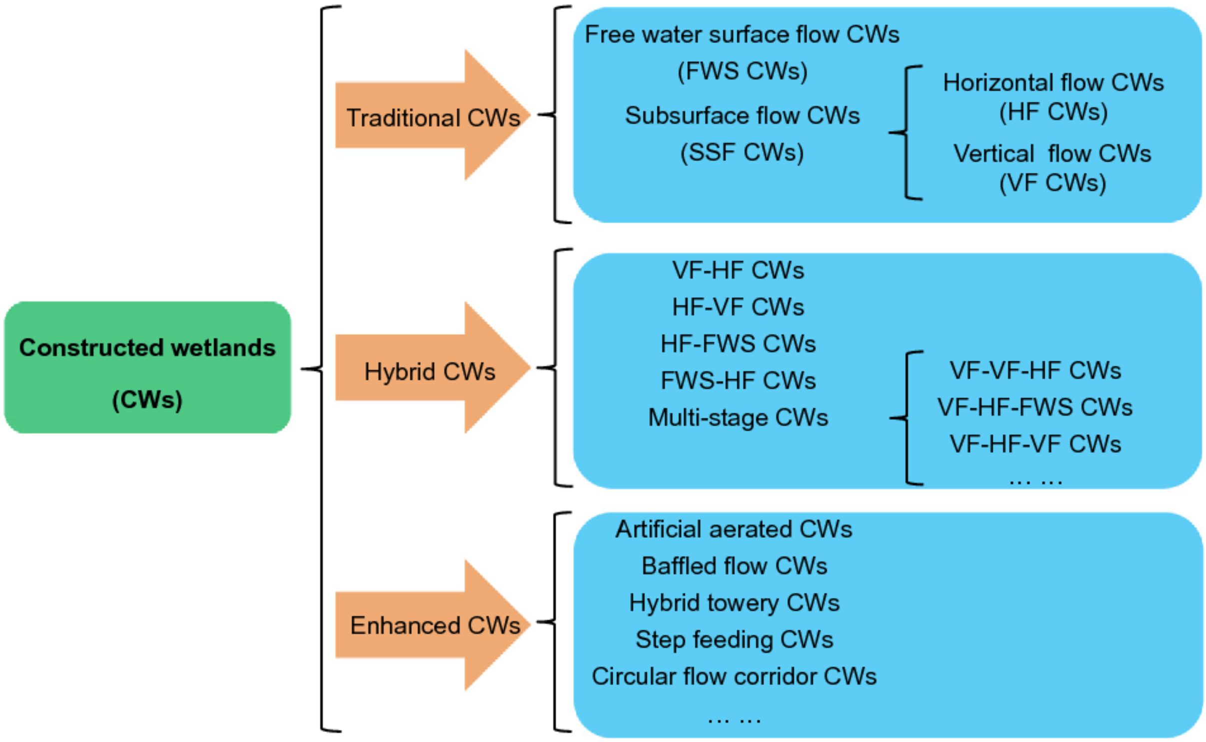


Fig 1.2: Types of constructed wetland technology. Source: Wu et al., 2015b

1.2.2.1 French two-stage vertical flow wetland

The French style two-stage VFCW contain two stages. French systems are very effective in treating raw sewage without any pre-treatment. The 1st stage includes gravel of sizes 4-8 mm on the top and the 2nd stage includes sand on the top (Fig 1.3). As the first stage have bigger size gravels which remove most of the organic materials from the wastewater and the second stage is used for the further polishing of water. The system also does not require post-treatment of the sludge, as a sludge layer accumulated at the surface of the wetland and plays a role on treatment performances (Molle et al., 2005). These specific types of CWs can work continually for 10-15 years without any sludge removal. After 10-15 years when the wetland media stops operating, the filter material can be removed, washed and returned to the system. (Masi et al., 2018).

For vertical flow, wetland plant plays a very important role (Shelef et al., 2013). As the raw sewage is fed to the French style vertical flow wetland, the plants prevent the wetland from clogging due to the mechanical action of stems through the sludge layer. The mechanical movement of the plant depends on many parameters like the height of the plant, density of the plant in the system and stem type of the plant (Vymazal et al., 2011; Mole et al., 2006). The rhizomes on plant roots provide the support for the bacterial growth and also provides aeration to the upper layer of the system (Brix et al.,2003). The roots allow water to percolate down through the media (Ziqiang et al., 2017). Selection of plant is a very important factor for the CW. The selection of plants depends on many factors like, plants should be native to the place and should not have invasive properties, they should be resistance to high organic and water stress, they should be non-woody should survive for at least three seasons and should not have thorns on upper part of the stems. Plants should have high growth rate so that they can adequately cover the surface of the wetland. Plants with low fertility are generally used, to minimize the seed propagation (Lombard Latune et al., 2017). Latune et al., 2017, focussed on the selection of plants species for the tropical climate, they observed that of 25 plants studied five were suited for the tropical climate. *Heliconiaceae* and *Cannaceae* showed good adaptation to the main stresses generated by VFCWs. *Canna indica* and *Canna glauca* can also be preferred as *Heliconiaceae* and *Cannaceae* can increase the phytosanitary risk to a banana plantation. In literature it is reported that mixed plants species in the wetland give better pollution removal as compared to single species. Source?

CW being a very suitable and robust technology for the treatment of wastewater in the rural parts of India, it has few limitations which affect the treatment quality and thus we need to focus on to make the system more efficient. The French VFCW are very well designed to treat COD, total suspended solids (TSS) and for nitrification. There is a need to be the focus on the removal of phosphorus from treated wastewater (Haritash et al., 2017). Phosphorus removal in French VFCW depends on many biotic and abiotic factors which are present in the media of the wetland. The uptake of phosphorus by plants depends on two factors like plant life cycle (growth phase) and the type of species. The phosphorus is mainly adsorbed to the root surface of plants. The shoot (structure above the ground) uptake of phosphorus is very less. The absorption of the phosphorus from the roots of the plants depend on the growth rate of the plants. However, this is only short-term storage of phosphorus in the plants until the plants get harvested (Laakso et al., 2017; Quan et al., 2016). The primary Phosphorus removal mechanism in VFCW is phosphorus adsorption in the media of the wetland. The phosphorus sorption capacity of the media mainly depends on the iron, aluminium and calcium content of the media. The CW are generally made of sands and gravel form River which have very less affinity for adsorption of phosphorus and have a very low content of ions for precipitation of phosphorus, thus shows a low phosphorus removal capacity (Barca et al., 2012). The system gets saturated with phosphorus in few years of working, resulting back reflux of phosphorus into the treated water. Thus providing a separate filter with media having a high affinity for phosphorus adsorption or precipitation would be a sustainable solution (Vohla et al., 2011).

The other limitation with French VFCW is the incomplete removal of total Nitrogen due to the absence of denitrification. The process of removal of nitrogen in CW is uptake by plant and microbes, mineralization of organic nitrogen (ammonification), direct reduction of nitrate to ammonia (nitrate-ammonification), anaerobic ammonia oxidation (ANAMMOX) (Vymazal et al., 2007). VFCW are fully aerated with the aeration pipes at the bottom and plants root on the top, it provides aerobic conditions inside which is suitable for nitrification of the organic nitrogen present in the wastewater but provides insufficient denitrification (Kadlec et al., 2009). Although many developments in the field of VFCW over the last few decades, the nitrogen removal efficiency of CW is still questionable. In many CW the removal efficiency of nitrogen is just 40-50 %, which is far from the satisfactory result and failed to meet the increasing nitrogen discharge (Zhang et al., 2014). In previous studies it was, demonstrated that nitrification and denitrification is the dominant nitrogen removal pathway in CW, but the process is very oxygen intensive for the nitrification of the nitrogen and denitrification process requires abundant organic carbon (Li & Sung, 2015). Thus, it’s very hard to achieve satisfactory nitrogen removal performance in a CW with a carbon-limited wastewater. In a study by Fan et al., 2013 it was reported that the optimal COD/N ration for 90% TN treatment is 10. In a similar study by Zhu et al. 2014 and Zhao et al.,2013 reported that COD/N ratio was 2.5 -5 respectively for maximum treatment of TN. The optimal COD/N ratio for a particular system depends on many factor like macrophyte species, size and working of the wetland, media of the system, input water quality, loading rate and many other parameters (Vymazal, 2007, Wu et al., 2011, Wu et al., 2015b, Zhu et al., 2014). It is also affected by other parameters like temperature, pH and dissolved oxygen on the system (Saeed and Sun, 2012, Fan et al., 2013, Wu et al., 2015a).

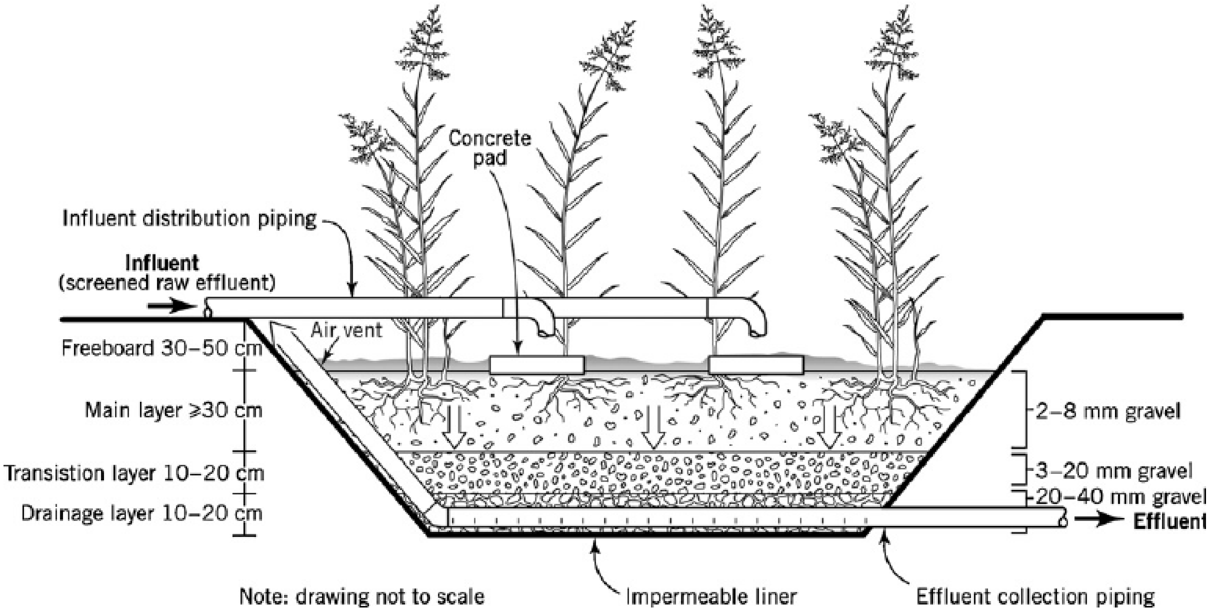


Fig 1.3: Working design of VFCW. Source Knowles et al., 2011

1.3 Gaps in Existing research

CWs are popular systems which effectively treat different kinds of polluted water and are therefore sustainable environmentally friendly solutions. However, there is a need to understand the mechanisms (Organics, Nitrogen and Phosphorus Removal mechanism) occurring in wastewater treatment wetlands. Several CWs are in operational in India. Up to now, the design of wastewater treatment wetlands is very empirical. The objective of this work is to design vertical VFCW systems to answer a need by adapting this well-known technology to Indian requirements (effluent quality, climate, etc.). Although CWs are recognized as an excellent alternative for conventional wastewater treatment systems, their application in India has remained limited. Most of the CW systems designed in India were built at experimental scale, treating different kinds of wastewater (Juwarkar et al., 1995, Billore et al., 1999, Billore et al., 2001, Billore et al., 2002).

One of the major constraints to field-scale CW systems is the requirement of a relatively large footprint not always available but lower than what is expected for WSP (waste stabilization pond) ($10m^2$/Pe for a WSP, about 2-3 m^2 per PE for a VFCW). However, unlike traditional biological treatment systems, no specific guidelines exist for designing a CW system. Several key aspects including the selection of plant species, the hydraulic retention time, organic and hydraulic loading rates are not documented at all for India

1.4 Aims and objectives of the research work

The aim of this study was to develop a small-scale wastewater treatment solution in the Indian context and to transfer this developed technology to Indian companies for their commercialization. It was clear that according to the context, the treatment requirements might vary. Indeed, the needs and the financial means for wastewater treatment of a hotel in Goa, for example, might be very from those of a small village or a slum.

VFCW technology is considered as "Extensive" since it requires low energy input and no chemical addition for treatment. It also has the advantage of being one of the most cost-effective wastewater technologies in the market, which is easy to operate and reliable. VFCWs require a larger area than conventional extensive wastewater system but it can be more adaptable to small and medium-size villages.

One of the innovative aspects of this work is to optimize VFCWs to Indian specific sewage and climatic conditions and to develop a system which can treat wastewater from all the type of sources and effectively consider all the type of pollutants.

The four objective proposed for the study:

- Experiments at laboratory scale and construction of the demonstration plant.
  - Initially lab experiments had been conducted to characterize the wastewater at different locations. The aim of this experimental work was to go deeper into specific problems, which still need further investigations before the implementation of pilot scale processes. One of the main parameter to study was the organic loading rate (OLR) to apply. The choice of the OLR was a very important parameter as it is used to calculate the surface area of the tank. In this context, it was important to run experiments with different organic loading rates in order to study the influence of the OLR on different parameters, such as pollution removal efficiency.

- Demonstration plants construction (condominium/ small village / slum) follow up protocol implementation.
  - In parallel to the experimental work being done, pilot-scale platforms have been implemented. The platform was demonstrated inside the campus of BITS Pilani K.K. Birla Goa campus so that they are field ready. The results of the laboratory experiments carried out were integrated before the final implementation of the pilots.

- Scientific investigations, treatment performances, and follow-up to validate systems under process conditions at the demonstration plants.
  - The pilot plants were operated for 6 months at field-scale to validate their design and operation. The reactors were fed with domestic wastewater pumped from the receiving tank of the existing treatment plant. The reactors were operated according to the optimal OLR found during the first experiments carried out.

- System up-scaling to add the systems as a new competitive commercial offer.
  - At the end of the experimental phase, we will work on the up-scaling of the processes in order to propose a new competitive commercial offer on the Indian market for decentralized treatment of small sources of pollution of domestic origin in different ranges: wastewater generated at house level (4-8 people) or by small settlements, condominium or hotels (100-400 people) or by small villages (400-1,000 people).

CHAPTER 2

SELECTION OF SUITABLE MACROPHYTES FOR THE VERTICAL FLOW CONSTRUCTED WETLAND

Abstract

CW offers a technically feasible option towards improved wastewater management and its safe reuse for rural communities through decentralized wastewater treatment (DWAT). The DWAT technology not being chemical or skill intensive but it can be operated and maintained by rural self-help groups (SHGs). The revenue generated through safe reuse of the treated wastewater and biomass generated in the CW can provide the sustenance for such self-help groups, which enhances the long-term financial viability of such units. The present study compares different macrophyte harvested from CWs species for their biochemical methane (biogas generation) potential. Four different plant species viz. *Ageratum conyzoides*, *Typha latifolia*, *Canna indica*, and Hybrid *Napier* spp. were compared for their biochemical methane potential. The amount of biogas produced and the percentage of methane in the generated biogas were estimated by water displacement and gas chromatography, respectively. The cumulative amount of biogas produced by Hybrid *Napier* spp., *Ageratum conyzoides*, *Canna indica*, and *Typha latifolia* in 100 ml batch rectors was 187 ± 22.5 ml (54.59% methane) at 4 gVS/L, 166.5 ± 4.5 ml (62.24% methane) at 4 gVS/L, 166.5 ± 5.5 ml (63.53% methane) at 3 gVS/L and 157 ± 2 ml (62.22% methane) at 4 gVS/L, respectively. The highest biogas was produced by Hybrid *Napier* spp. but the methane percentage was found to be highest in *Canna indica*.

2.1. Introduction

Rural wastewater management remains neglected in most developing countries due to the absence of feasible technological solutions. This situation has led to wide-scale groundwater and surface water pollution, semi-arid tropics (SAT) raw wastewater irrigation for crops is a contemporary reality. Such irrigation practices also cause pathogen related diseases deteriorate the soil quality through salt and solid accumulation (Scott et al., 2009). CW is an environmentally friendly technology, which utilizes the phytoremediation capacity of specific macrophyte to facilitate wastewater treatment. Wastewater treatment using CWs is considered to be technically feasible and financially viable method compared to other conventional wastewater treatment methods such as activated sludge processes, membrane bioreactors or sequential batch reactors for small or resource-poor communities with limited access to skilled supervision (Mahmood et al., 2013). Increasing water and nutrient use efficiency in combination with the efficient management of water resources is critical for the survival of resource-poor rural communities living in the semi-arid tropics (Wani et al., 2018). CWs have the potential to enhance the water and nutrient use efficiency of these rural communities while inculcating improved wastewater management practices. Safe reuse of the treated wastewater through DWAT can generate revenue through reuse in cultivation, seed production, flower cultivation and fodder production depending upon the treated wastewater characteristics (Datta et al., 2015). The biomass generated from the CW and the agro-waste biomass can be used for biogas production through a co-digestion method in an anaerobic bio-digester. The treated wastewater and generated biomass if utilized locally for the suitable application can make DWATs (CWs) function as a business model for rural self-help groups. Biogas production from anaerobic digestion of different organic wastes is a sustainable way of producing alternative energy to fossil fuels (Balat et al., 2009), also results in a reduction of greenhouse gases (Khalid et al., 2011). Biogas is a mixture of methane (55–65%), carbon dioxide (35–45%) and minute amount hydrogen sulfide (0–1%) produced by the anaerobic action of microorganisms (Pastorek et al., 2004). The production of biogas from natural wetlands (Dipu et al., 2011), as well as co-digestion of the biomass harvested from natural wetland and buffalo dung (Kurniawan et al., 2014) has been reported as an environmentally friendly way to handle biomass from wetlands. It is essential to find out the biochemical methane potential of the different macrophytes species, which exhibits high phytoremediation capacity in a CW to identify species best suited for both wastewater treatment and biogas production (Yadav et al. 2018).

There are different factors like fibre content, organic loading rate (OLR), hydraulic retention time (HRT) that affect the biogas yield from wetland macrophytes. Plant biomass, the abundant feedstock available as agro waste is mostly comprised of lignocellulosic material (Awasthi et al., 2015). The structural complexity and low nutrient level of lignocellulosic material is the limiting factor in anaerobic digestion (Sawatdeenarunat et al., 2015). Cellulose, hemicellulose, and lignin are the three polymers present in lignocellulosic material. The biodegradation of cellulose and hemicellulose is comparatively easier than lignin (Elena et al., 2012). OLR is a significant operational parameter because at low OLR, the complete efficiency of the anaerobic digester will not be utilized, and high OLR hampers biogas generation by the formation of volatile fatty acid in the plant, which leads to low biogas production (Eslami et al., 2018).

As per the extensive research published on biogas production from agro waste, natural wetland waste and aquatic plant waste can be utilized for the revenue generation potential of the biomass harvested from CW (Lauer et al., 2018). The main aim of this chapter is to focus on the selection of suitable macrophyte for the CWs in tropical climate. The selection of appropriate plant species for CW was made on the basis of biogas generation as a value-added commodity to make CWs more financially feasible and sustainable. It also focuses on discovering the ideal OLR for distinct macrophyte biomass.

2.2. Methodology:

2.2.1. Biochemical characterization of different Macrophyte biomass:

The sample was obtained from ICRISAT (International Crops Research Institute for Semi-Arid Tropics) Hydarabad. For all the experiments, the biomass samples were sun-dried, ground into fine powder and filtered with 0.2 mm sieve. It was packed in a plastic bag to prevent moisture and was transferred for evaluation to the BITS campus. The samples were analysed for the VS (volatile solids), Carbon, Nitrogen, Hydrogen and Sulphur. The fibre from each macrophyte was extracted by acid extraction method in pelican fibre extraction unit and estimated as per the manufacturer's protocol (Holinger et al., 2018).

2.2.2. Biochemical methane potential of Macrophytes and gas chromatography:

The Biochemical methane potential (BMP) of wetland macrophytes was estimated by seeding different loading rates of biomass i.e., 0.5, 1, 2, 3, 4 gVS/L in 130 ml glass serum vials at room temperature as per the protocol reported by Angelidaki et al., (2009). One ml (containing macro and micronutrients) of synthetic media was added to each vial. The chemical constituents of the synthetic media are presented in Table 2.2. Eighty ml sludge from an anaerobic pilot reactor was used as inoculum with 4 gVS/L, and the final volume was raised to 100 ml using distilled water. Control was maintained without the addition of any substrate to estimate the gas generated by inoculum. The headspaces of the reactors were purged with nitrogen gas at the beginning of the experiment to make the system anaerobic. The biogas produced has been estimated by the water displacement method (Prabhudesai et al., 2013). The biogas generated has been analyzed on the 8th and 20th day of an experiment by gas chromatograph (CHEMITO 7610) equipped with packed stainless steel column (spherocarb support) and thermal conductivity detector (TCD). The injector and detector temperatures were 150^{o}C and 250^{o}C, respectively. The gas chromatograph was programmed to increase the oven temperature from 60^{o}C to 120^{o}C at the rate of 5^{o}C per minute. The peak areas obtained for sample constituents were converted to percentage of gas by Chemito software (Prabhu et al., 2016).

2.2.3. Continuous 5-liter reactor study:

To analyse the effect of increasing organic loading rate (OLR) on the reactor, lab scale experiments with 5 L reactors were set up with biomass of *Ageratum conyzoides, Typha latifolia, Canna indica,* Hybrid *Napier* spp. as substrate (fig 2.1). The organic loading rates studied for each biomass types were 1, 2, 3, 4, 5 gVS/L and the reactors were supplied with of macro and micronutrients in the same ratio as supplied for 100 ml vials in the previous experiment (section number 2.3). The reactor was fed with the sample on a daily basis, with gradually increasing loading rates from 1 gVS/L/day to 5 gVS/L/day for 50 days. The system was maintained on each loading for number of days as given in fig 2.3. The pH of each reactor was checked on a daily basis with a digital pH meter (OAKLON pH 700). The biogas produced was estimated on a daily basis by water displacement method.

2.3. Results:

2.3.1. Biochemical characterization:

Total volatile solids content (g) of *Ageratum conyzoides*, *Typha latifolia*, *Canna indicia*, and Hybrid *Napier* spp. are 0.927 g, 0.949 g, 0.869 g, and 0.947 g, respectively. The fibre content of *Ageratum Conyzoides* is 17.58% of hemicellulose, 30.87% of cellulose, and 17.22% of lignin. Hybrid *Napier* spp. has high hemicellulose content of 35.77% whereas the cellulose and lignin contents was 30.79% and 11.17%, respectively. *Canna indica* has 24.91% of hemicellulose, 7.71% of cellulose, and 6.69% of lignin. The fibre content of *Typha latifolia* is 32.26% of hemicellulose, 27.42% of cellulose, and 7.82% of lignin (Table 2.1). The X-ray powder diffraction (XRD) results indicated carbon (C), nitrogen (N), hydrogen (H), sulphur (S) content (%) of each biomass (Table 2.1). The C/N ratios of *Ageratum conyzoides*, *Typha latifolia*, *Canna indica*, and Hybrid *Napier* spp. were 17.9, 26.73, 24.95 and 28.56, respectively (Table 2.1).

2.3.2. Biochemical methane potential of Macrophytes and gas chromatography

The biochemical methane potential (BMP) for organic loading rates of 0.5, 1, 2, 3 and 4 gVS/L was estimated by water displacement method. A control, which was devoid of any substrate was maintained for the BMP experiment. Gas production of 79 ml was observed for the control throughout 26 days. Increase in the BMP was observed for higher loading rate for *Ageratum conyzoides*, Hybrid *Napier* spp., and *Typha latifolia.* The volume of biogas produced by *Ageratum conyzoides*, Hybrid *Napier* spp., and *Typha latifolia* with 0.5gVS/L were 85.5 ml, 98.5 ml, and 79 ml, respectively. For an OLR of 4 gVS/L, the BMP for *Ageratum conyzoides,* Hybrid *Napier* spp., and *Typha latifolia* were found to be 166.5 ml, 187 ml, and 157 ml, respectively. For *Canna indica*, OLR 3g VS/L and 4g VS/L produced biogas volume of 166.5 and 130 ml, respectively (fig 2.2- A, B, C, and D). Hybrid *Napier* spp. produced a high volume of biogas i.e., 187 ml (4gVS/L loading rate) compared to other macrophyte biomass. Gas chromatographic analysis of the biogas generated revealed that the percentage of methane present in the biogas generated decreased at higher OLRs. The percentage of methane present in the biogas produced from *Ageratum Conyzoides* biomass were 62.24% and 65.73 % for OLR of amount 0.5 gVS/L and 4 gVS/L, respectively. The percentage of methane present in biogas produced by Hybrid *Napier* spp., *Canna indica,* and *Typha latifolia* for OLR of 0.5gVS/L were 65%, 73.19%, and 69.49%, respectively and the amount of methane produced was 64.03, 61.11 and 54.90 ml, respectively. The volume of methane gas produced for the different OLRs applied in the present study, on 8th and 20th day of the experiment is given Table 2.3. The percentage of methane present in biogas produced by Hybrid *Napier* spp.*, Canna indica,* and *Typha latifolia* with 4gVS/L loading rate were 54.59%, 63.53%, and 62.22%, respectively (fig 2.2- A, B, C and D) and the amount produced was 102.10 ml, 82.59 ml, and 97.70 ml, respectively (Table 2.3). The low biochemical methane potential of *Canna indica* compared to other macrophytes could be due to less VS/TS ratio (0.869) whereas the VS/TS ratio of *Ageratum conyzoides*, Hybrid *Napier* spp., and *Typha latifolia* were 0.927, 0.947 and 0.949, respectively.

2.3.3. Continuous 5-liter reactor study:

The findings showed that the hybrid *Napier* spp. generated the largest quantity of biogas among macrophytes (fig 2.3). The suitable organic loading rates were 4g, 3g, 4g, and 4g VS/L for Hybrid *Napier* spp., *Canna indica*, *Typha latifolia*, and *Ageratum conyzoides*, respectively. The average biogas produced for each organic loading rate was calculated (fig 2.3). It was found that the gas production increased along with the organic loading rate till 4gVS/L for *Ageratum conyzoides,* Hybrid *Napier* spp., and *Typha latifolia.* For *Canna indica* it was found that biogas production increased with the organic loading rate till 3g VS/L and decreased with 4gVS/L and 5gVS/L. The pH of the system decreases every time the loading rate was increased. This was because, the bacteria in the system need time to adapt to the increased loading rate. The decrease in pH with 5g VS/L (fig 2.3) might be attributed to the accumulation of volatile fatty acids and other inhibitorsIt has been reported that if the methanogenic bacterial action cannot maintain up with the previous hydrolysis phase, it results in the accumulation of volatile fatty acids and a decline in the manufacturing of biogas (Yang et al., 2015). The drop and raise in pH after increasing the loading rate (fig 2.3) is also related to the synergistic balance between hydrolytic and methanogenic bacteria (Yang et al. 2015).

2.4. Discussion

Revenue generation through safe reuse of the treated wastewater and the biomass generated in the CWs can lead to its financial self-sustainability. Often post-installation and initial implementation phase, village level scientific interventions such as Gobar gas plants, percolation tanks, and check dams fail because of the lack of a sustainable source of maintenance funds. Ideally, such installations should involve local self-help group to inculcate a sense of ownership among the local stakeholders. Biogas generation can significantly augment the revenue generation potential of a CW-based wastewater treatment scheme ensuring its long-term viability. The present study demonstrated the suitability of using different macrophyte species, which showed high phytoremediation capacity in CWs for their biogas generation potential (biochemical methane potential). Anaerobic digestion of organic material depends on pH, temperature, organic loading rate, particle size distribution, etc. (Ofoefule et al., 2009). The presence of lignocellulosic material also affects the biochemical methane potential of the biomass; however, the fermentable nature of cellulose and hemicellulose (after hydrolysis) makes lignocellulose an acceptable feedstock for anaerobic digestion (Patil et al., 2016). The high amount of lignin results in low biochemical methane potential as the degradability of lignin is slow and has been reported to be a recalcitrant polymer present in the plant (Li et al., 2013). *Ageratum conyzoides* had low cellulose to lignin and hemicellulose plus cellulose to lignin ratio (1.79 and 2.78, respectively) compared to other macrophytes used in the experiment and produced less amount of biogas in the 5L continuous study. Although Hybrid *Napier* spp. has 5.96% cellulose plus hemicellulose to lignin ratio, it has produced high amount of biogas compared to *Canna indica* and *Typha latifolia*, which has 7.63 and 4.86 of lignin, respectively (Table 2.1). Therefore, in the present experiment, it was proved that along with lignocellulose content there are other factors influencing the biochemical methane potential of wetland biomass. For instance, the organic loading rate influences the pH, because overloading of the reactor leads to a decrease in pH as observed in continuous 5L experiment (fig 2.3). Based on the continuous stirred tank reactor studies conducted by Adebayo A.O et al., (2015), it was found that the increase in organic loading rate (beyond the optimal ORL) leads to decrease in both biogas and methane yield. There were studies conducted to estimate biochemical methane potential of water hyacinth (WH), *Cattail*, and *C. papyrus* in batch experiments and found that WH has produced the highest amount of methane compared to *C. papyrus* (Adeniran et al., 2017). Though Hybrid *Napier* spp. has produced high amount of biogas (cumulative of 187 ml in 100 ml batch reactors), it produced less percentage of methane (54.59%). The percentage of methane produced by *Ageratum conyzoides*, *Canna indica*, and *Typha latifolia* was 62.24%, 63.53%, and 62.22%, respectively. It has been found that Hybrid *Napier* spp. has produced comparatively more amount of biogas (cumulative) with both 100 ml and 5 L setup, i.e., 187 mL (4gVS/L) and 1129 mL (4gVS/L), respectively. Hybrid *Napier* spp. was known for low wastewater treatment efficiency in a CW and has less tolerance to drought or ponding condition. It has been reported that C/N ratio is one the important parameters influencing anaerobic digestion. Bardiya et al., (1997) reported that an optimal C/N ratio ranges from 20 to 30 for anaerobic digestion. In this study, *Ageratum* *conyzoides* was found to have C/N ratio of 17.89 and produced comparatively less biogas in 5 L reactors whereas C/N ratio of other macrophytes are in optimal range (Table 2.1). According to Resch et al., (2011) the deficiency of nitrogen leads to decreased consumption of carbon by microorganisms and eventually results in low biogas production. As per the previous studies conducted by Tilak et al., (2017), *Canna indica* has been proved to be best suitable for wastewater treatment in a CW and also been appreciated for their advantage in ease of handling. The macrophytes harvested from CW can generate a decent amount of biogas as a potential source of energy for treatment wetland systems. Thought it cannot provide constant source of energy as plants can only be harvested at the specific moment of year, it could be held as an option.

2.5. Conclusion

Although *Canna indica* has produced less amount of biogas compared to Hybrid *Napier* spp., it was found to produce a high amount of biomass, i.e., 0.2 kg/m^2/d. In spite of high BMP by Hybrid *Napier* spp. it is recommendable only if its wastewater treatment efficiency and growth rate improvises. In spite of the low BMP of *Canna indica* it has been proved to be suitable for both wastewater treatment and anaerobic digestion, considering the factors like wastewater treatment efficiency, easy establishment, high growth rate, and ease of harvesting. However, we need to look at pre-treatment techniques for the improving biogas production for different macrophytes.

Table 2.1: Biochemical characterization of different macrophyte biomass

Parameter	***Ageratum Conyzoides***	***Typha latifolia***	***Canna indica***	**Hybrid *Napier***
Hemi cellulose (%)	17.06	32.26	24.91	35.77
Cellulose (%)	30.87	27.42	7.71	30.79
Lignin (%)	17.22	7.82	6.69	11.17
Cellulose/ Lignin (%)	1.79	3.51	1.15	2.76
Hemicellulose + Cellulose/ lignin (%)	2.78	7.63	4.86	5.96
VS/TS	0.927	0.95	0.87	0.95
Carbon (%)	41.89	41.03	38.29	41.88
Nitrogen (%)	2.34	1.53	1.53	1.47
Hydrogen (%)	6.02	6.10	5.74	0.11
Sulphur (%)	0.55	0.31	0.29	0.19
C/N (%)	17.89	26.73	24.95	28.56
C/H (%)	6.96	6.73	6.68	6.86

Table 2.2: Chemical constituents of the synthetic media

Nutrients	Compound	Concentration g/l	Sources
Macronutrients (1ml/ 100 ml)	Ammonium Chloride (NH_4Cl)	26.6	N
	Potassium dihydrogen phosphate KH_2PO_4	10	K, P
	Magnesium Chloride $MgCL_2$. $6H_2O$	6	Mg
	Calcium chloride $CaCl_2$. $2H_2O$	3	Ca
	Sodium sulfide nonahydrate $Na_2S.9H_2O$	40	Na, S
Micronutrients (1ml/100ml)	Ferrous chloride $FeCl_2.4H_2O$	2	Fe
	Cobaltous chloride $CoCl_2.6H_20$	0.5	Co
	Manganese(II) chloride $MnCl_2.4H_2O$	0.1	Mn
	Zinc chloride $ZnCl_2$	0.05	Zn
	Boracic acid H_3BO_3	0.05	B
	Sodium selenite Na_2SeO_3	0.05	Se
	Cupric chloride $CuCl_2.2H_2O$	0.04	Cu
	Sodium molybdate $Na_2MoO_4.2H_2O$	0.01	Mo
Tampon Bicarbonates (5ml/100ml)	Sodium bicarbonate $NaHCO_3$	50	

Table 2.3: Amount of Methane (ml) produced at each loading rate after 8th and 20th days

Loading Rate	*Ageratum Conyzoides*			Hybrid *Napier*			*Canna indica*			*Typha latifolia*		
	Biogas (ml)	Methane(ml)		Biogas (ml)	Methane(ml)		Biogas (ml)	Methane(ml)		Biogas (ml)	Methane(ml)	
		After 8 days	After 20 days		After 8 days	After 20 days		After 8 days	After 20 days		After 8 days	After 20 days
0.5	85.5	57.31	56.20	98.5	62.90	64.03	83.5	54.00	61.11	79	57.42	54.90
1	96.5	65.12	62.33	142.5	90.06	88.19	106	71.47	70.19	103.5	71.93	72.04
2	107	68.36	66.56	140	85.19	82.68	98	66.77	65.10	130.5	84.68	85.31
3	154.5	100.05	96.76	180.5	103.28	94.37	166.5	111.54	107.96	141.5	92.57	90.86
4	166.5	109.14	103.65	187	111.12	102.10	130	87.72	82.59	157	100.29	97.70

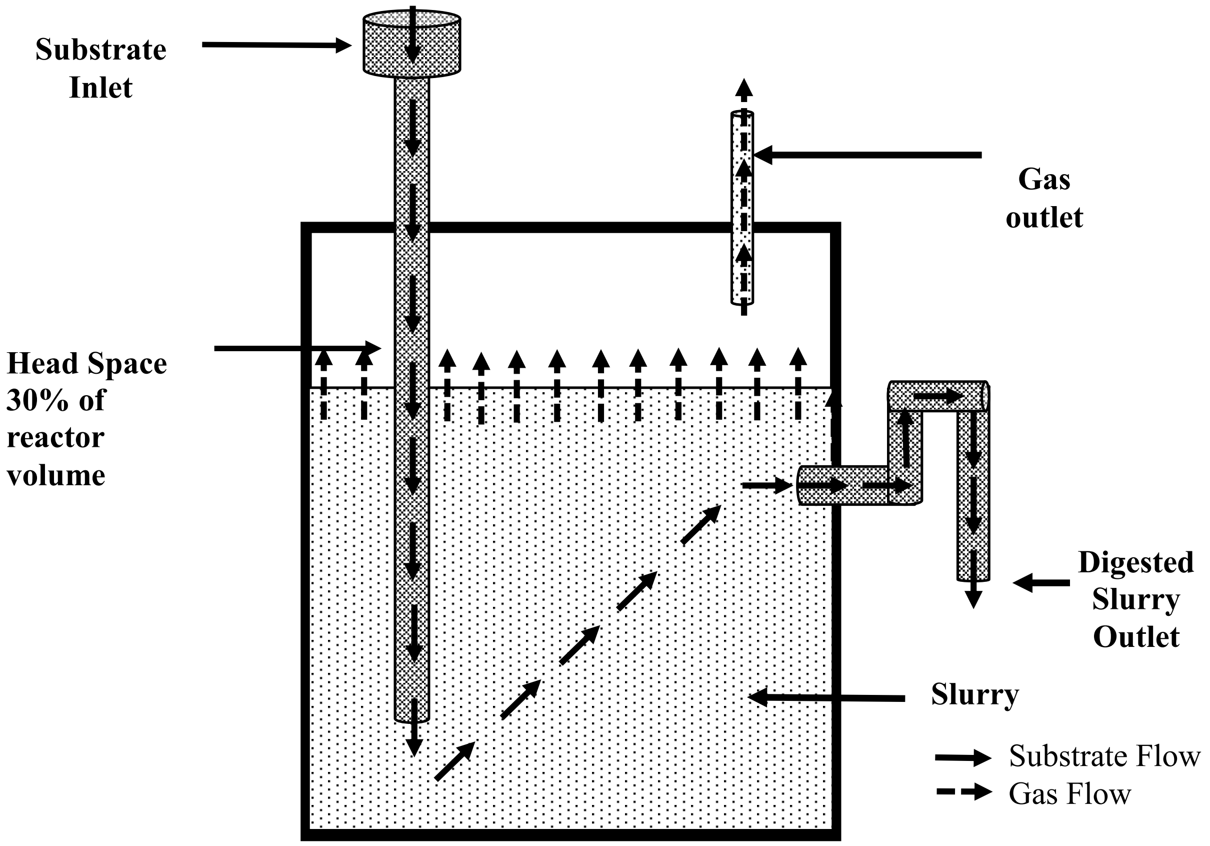
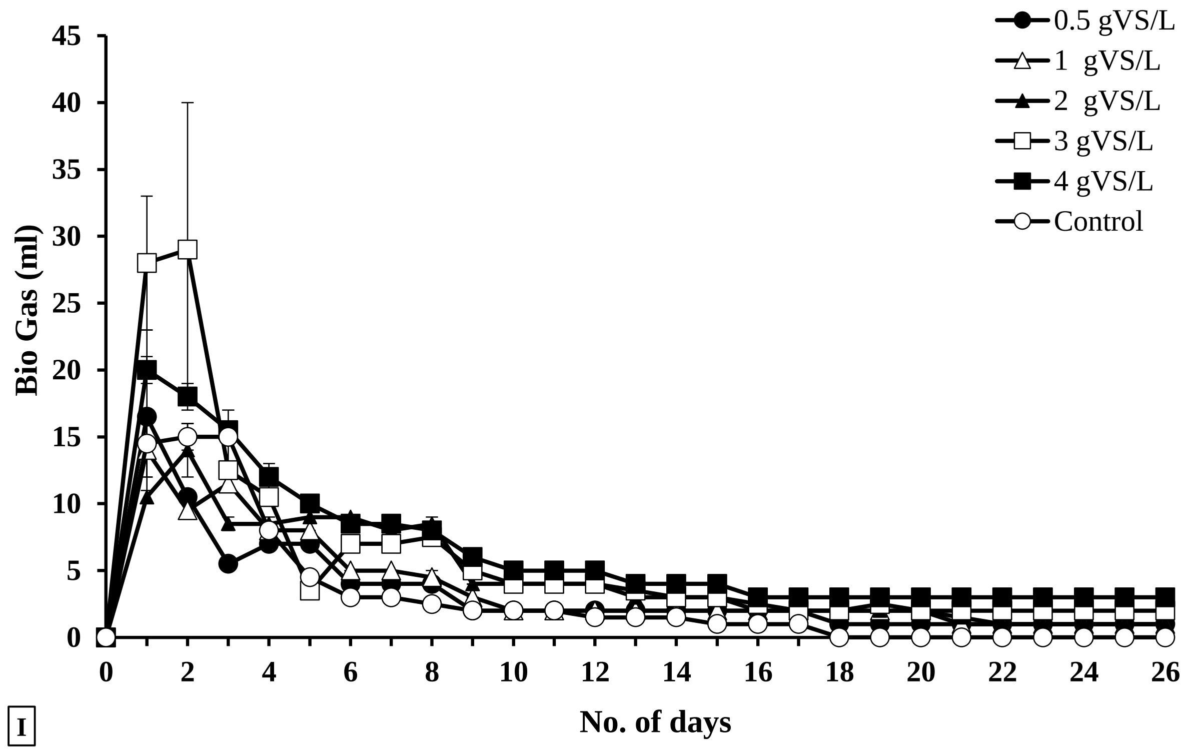
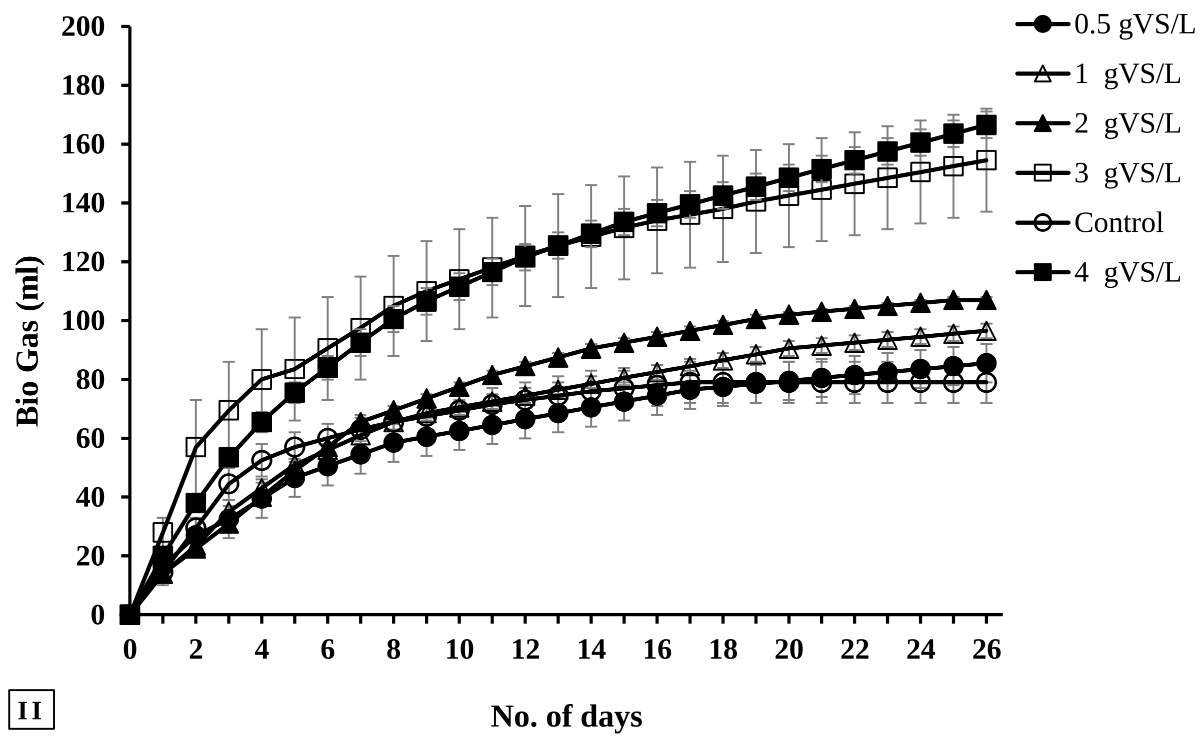
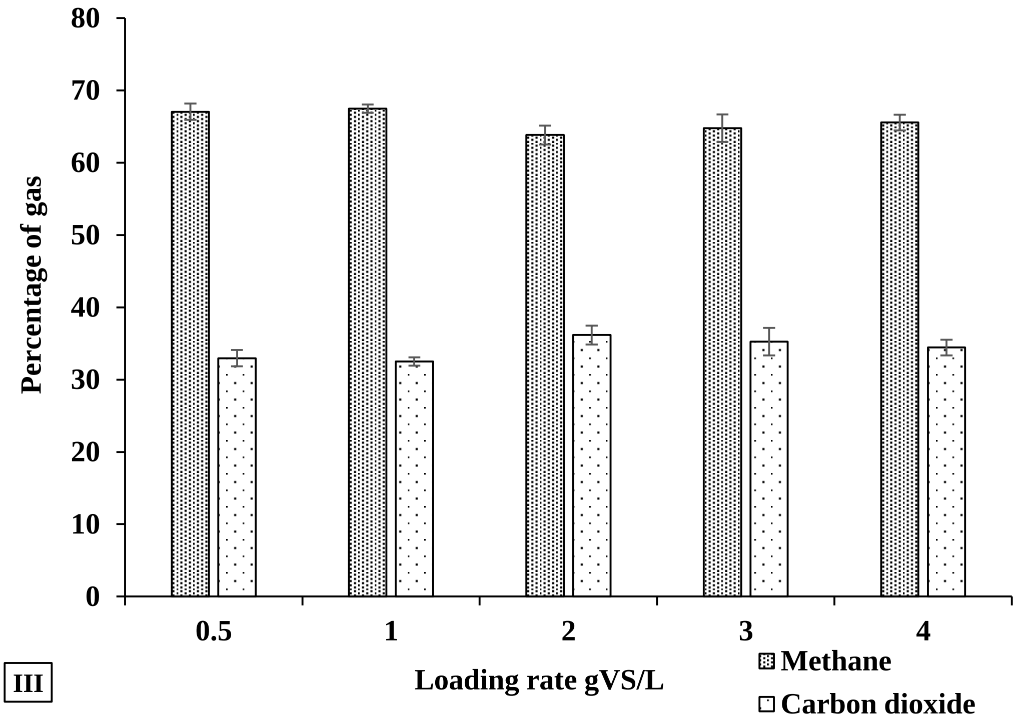


Fig 2.1: 5 Litter biogas reactor design with the 30 % head space.


0.5 gVS/L
1 gVS/L
2 gVS/L
3 gVS/L
4 gVS/L
Control
Bio Gas (ml)
45
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
No. of days
I


0.5 gVS/L
1 gVS/L
2 gVS/L
3 gVS/L
Control
4 gVS/L
Bio Gas (ml)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
No. of days
II



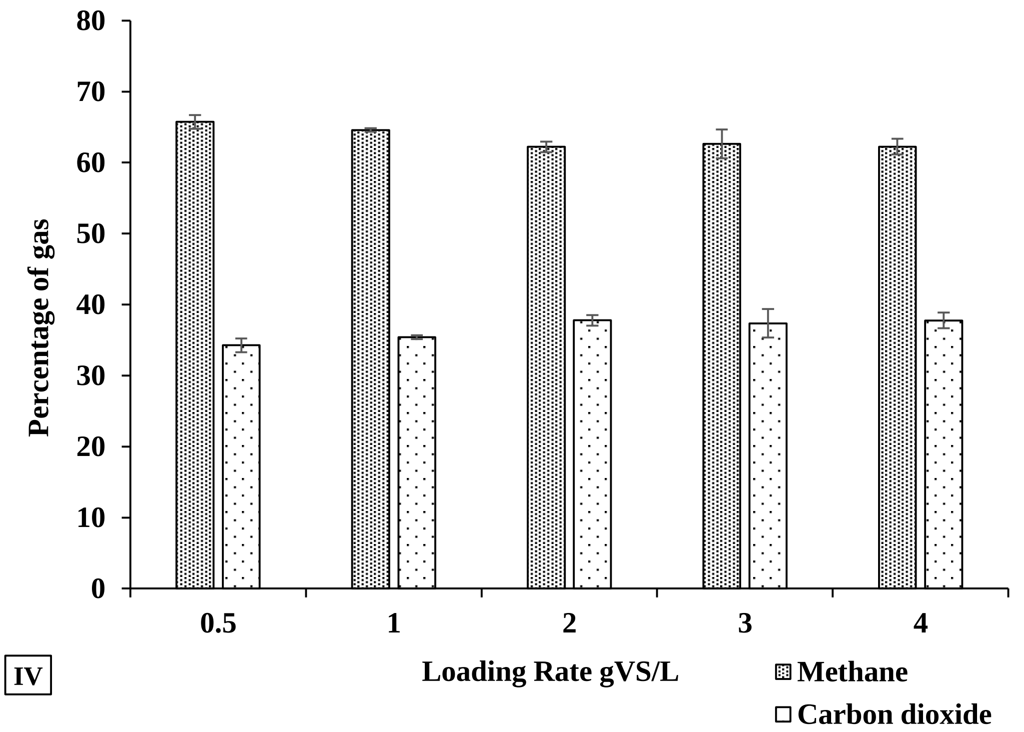
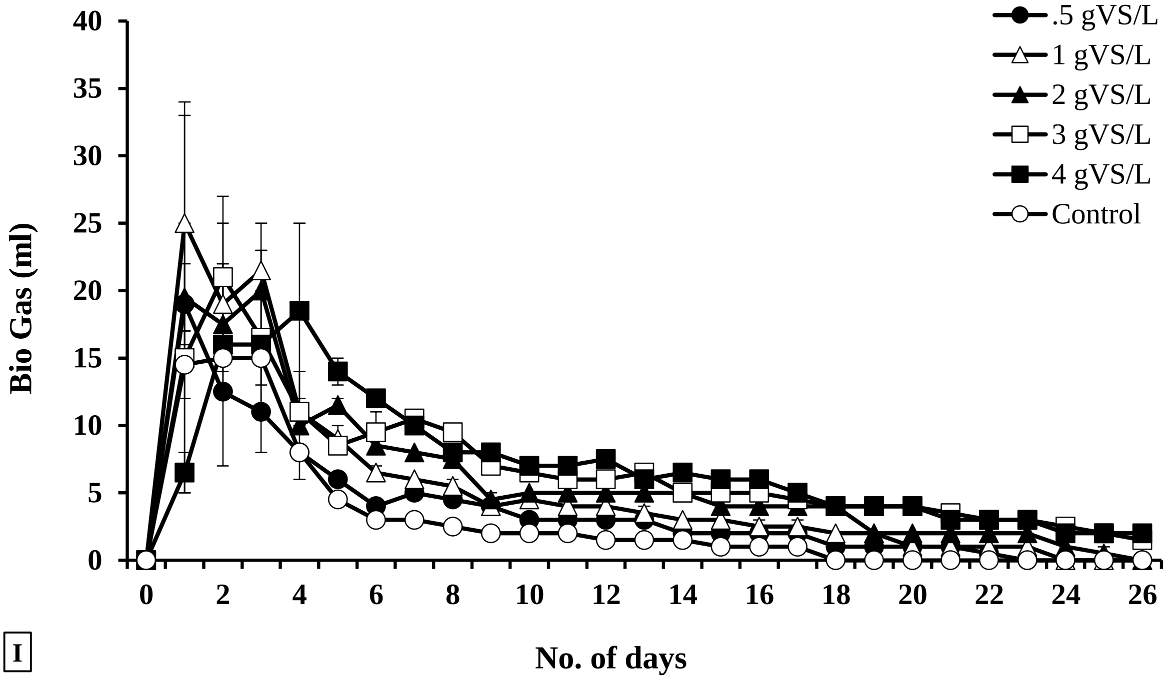
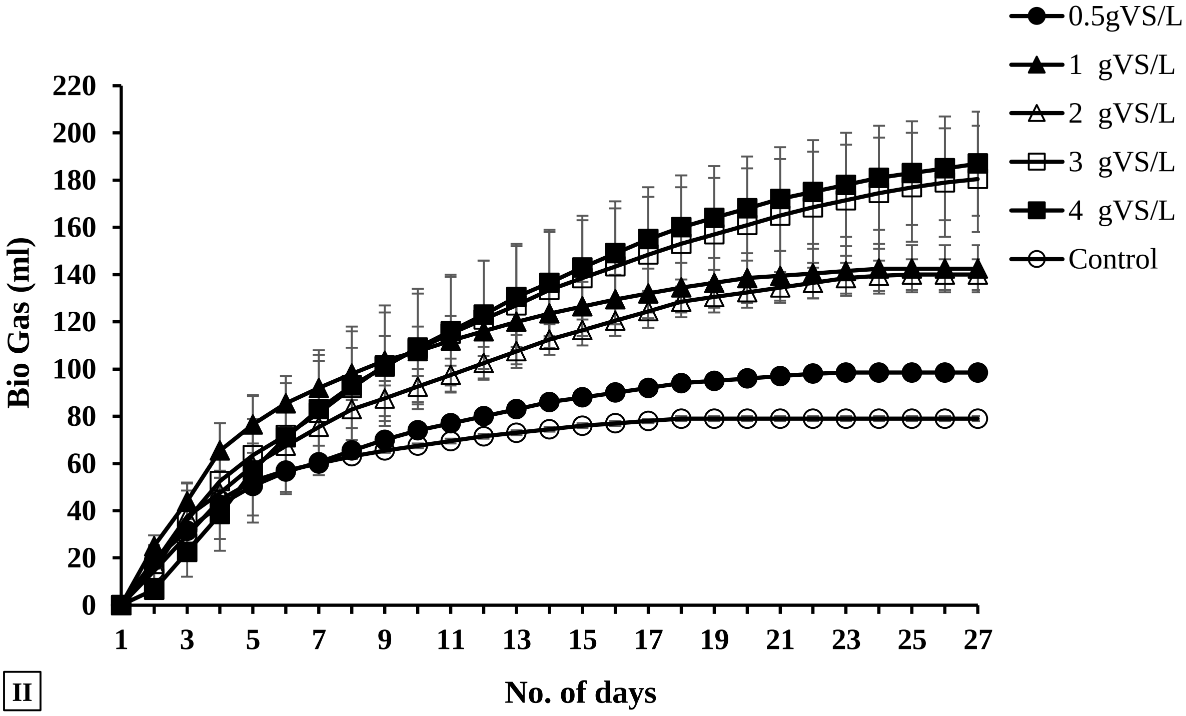


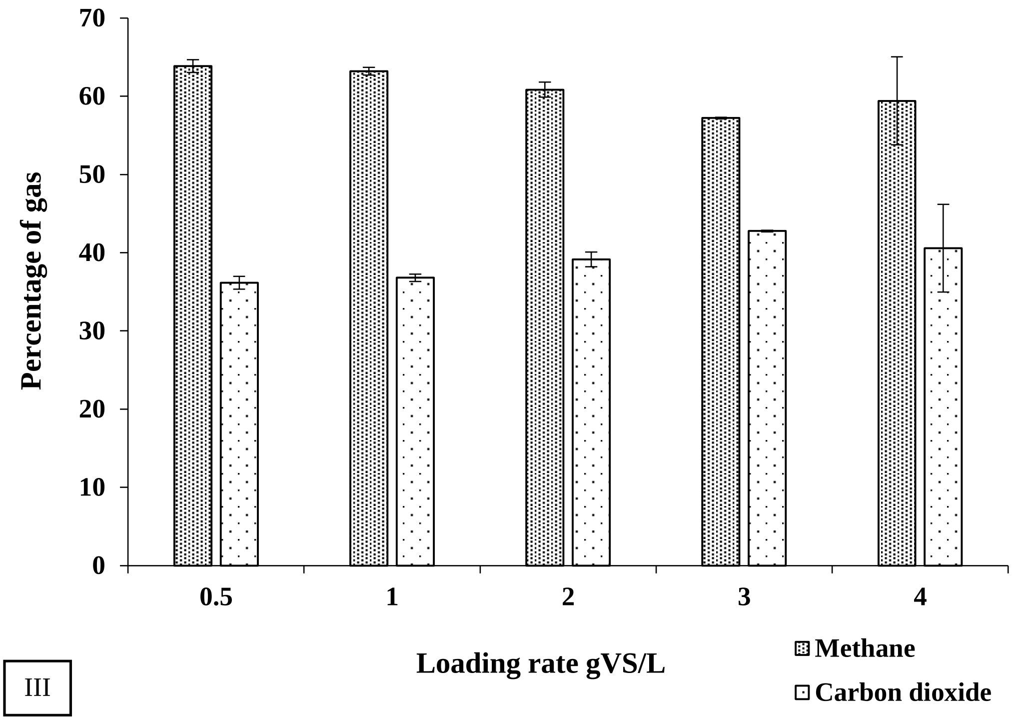
Fig 2.2 A: BMP assay of *Conyzoits*. (i)Daily estimation of Gas (ii) Cumulative estimation of gas (iii) Methane Percentage estimation of Different gases at 8th day (iv) Methane Percentage estimation of Different gases at 20th day


.5 gVS/L
1 gVS/L
2 gVS/L
3 gVS/L
4 gVS/L
Control
Bio Gas (ml)
No. of days
0
5
10
15
20
25
30
35
40
0
2
4
6
8
10
12
14
16
18
20
22
24
26

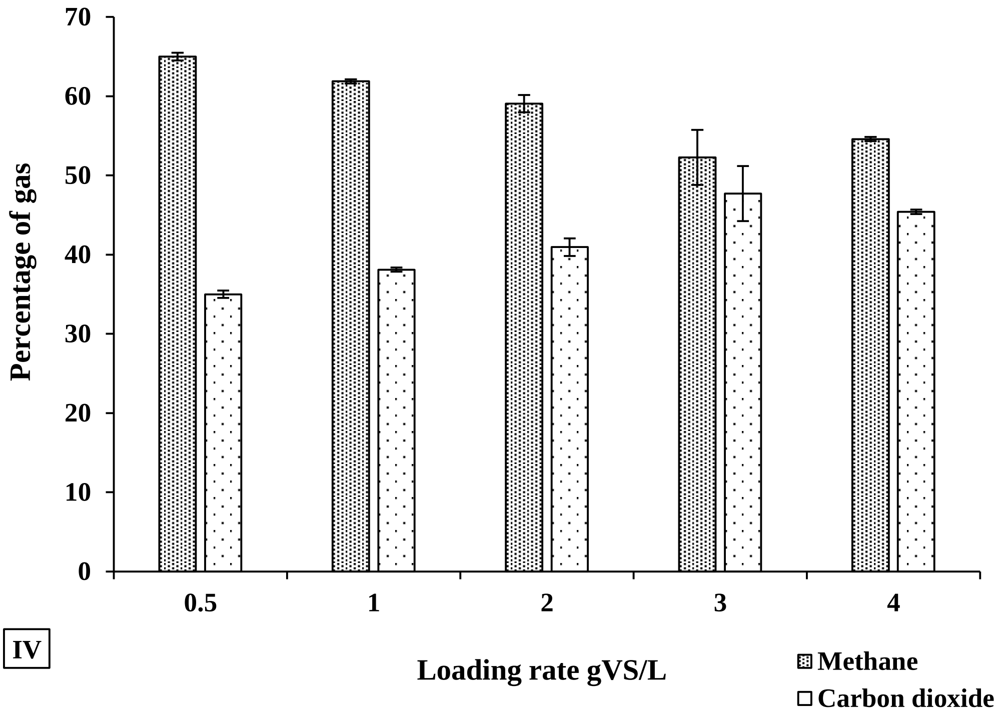
I


0.5gVS/L
1 gVS/L
2 gVS/L
3 gVS/L
4 gVS/L
Control
Bio Gas (ml)
No. of days
0
20
40
60
80
100
120
140
160
180
200
220
1
3
5
7
9
11
13
15
17
19
21
23
25
27

II

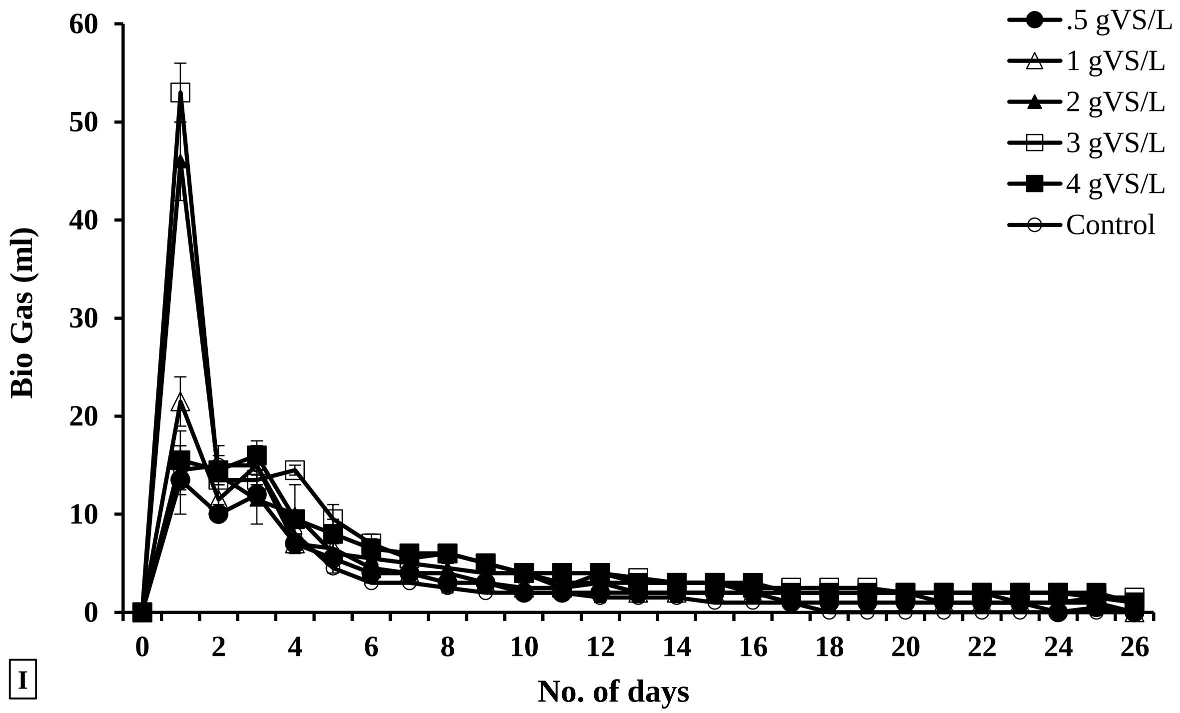


III



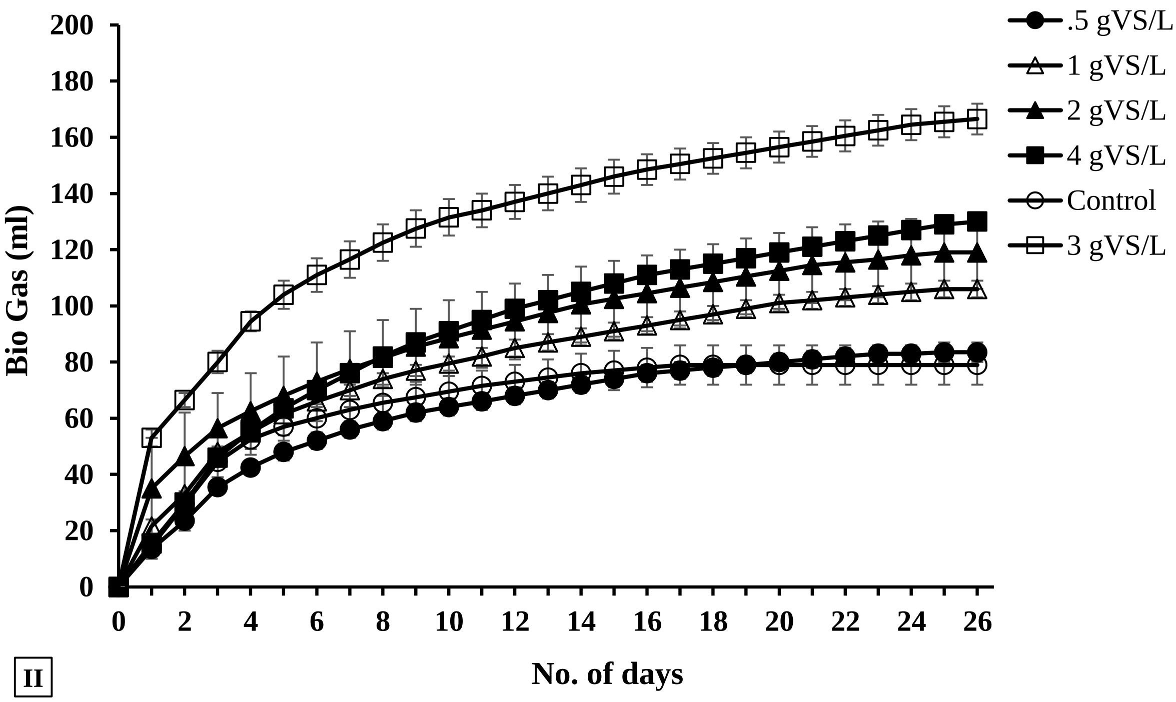
IV

Fig 2.2 B: BMP assay of Hybrid *Napier* spp. (i)Daily estimation of Gas (ii) Cumulative estimation of gas (iii) Methane Percentage estimation of Different gases at 8th day (iv) Methane Percentage estimation of Different gases at 20th day



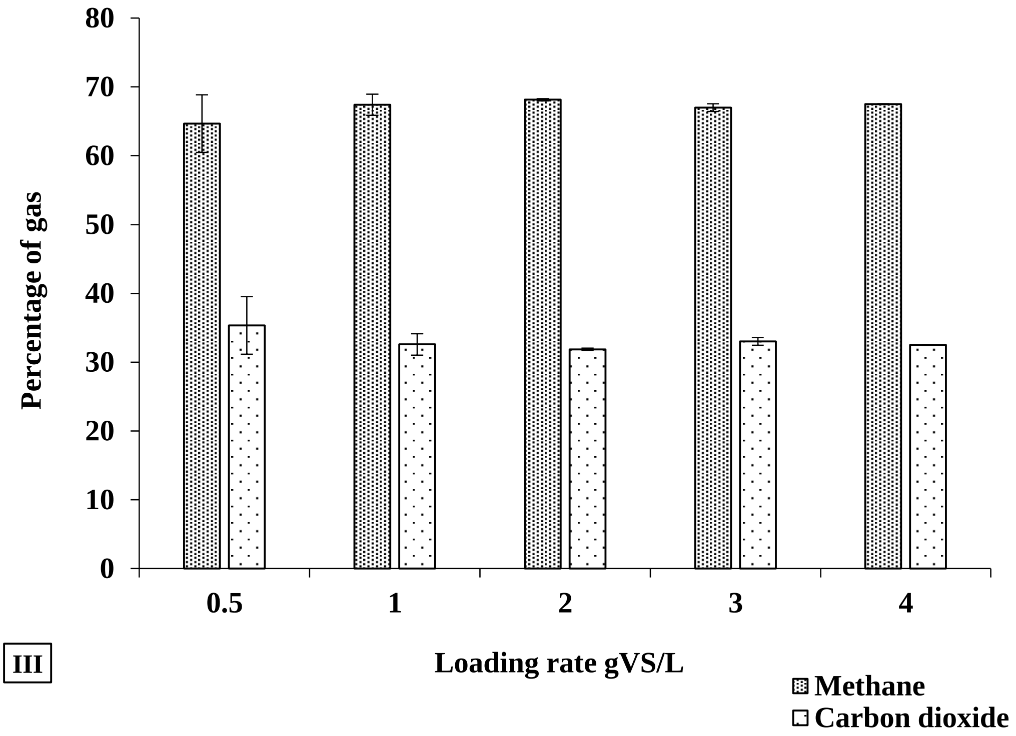
.5 gVS/L
1 gVS/L
2 gVS/L
3 gVS/L
4 gVS/L
Control
Bio Gas (ml)
No. of days

I

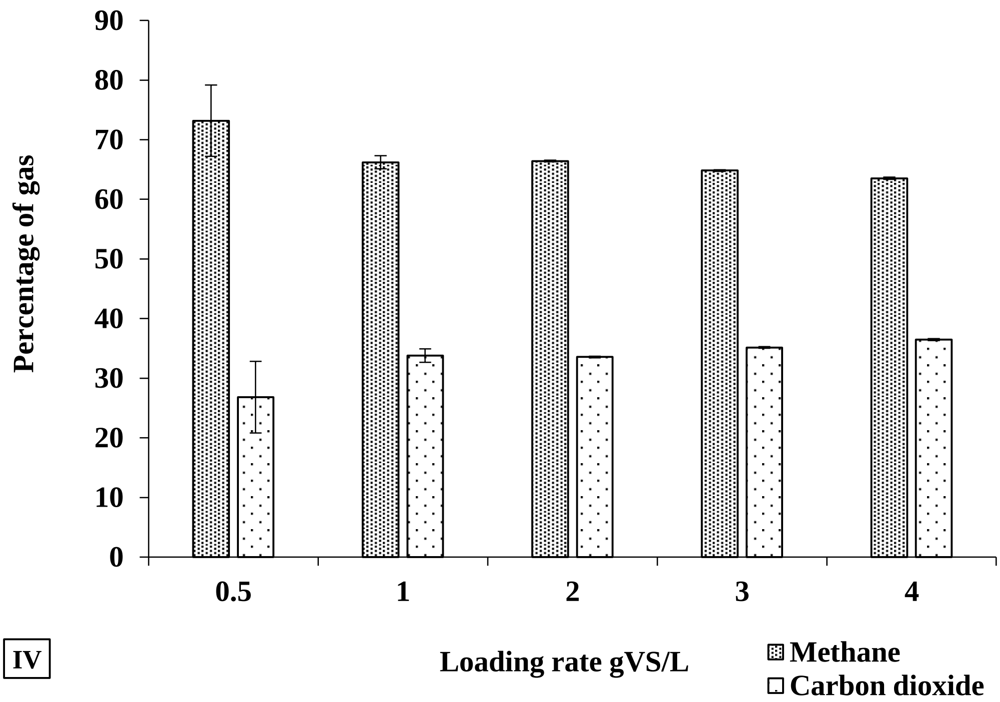


.5 gVS/L
1 gVS/L
2 gVS/L
4 gVS/L
Control
3 gVS/L
Bio Gas (ml)
No. of days

II

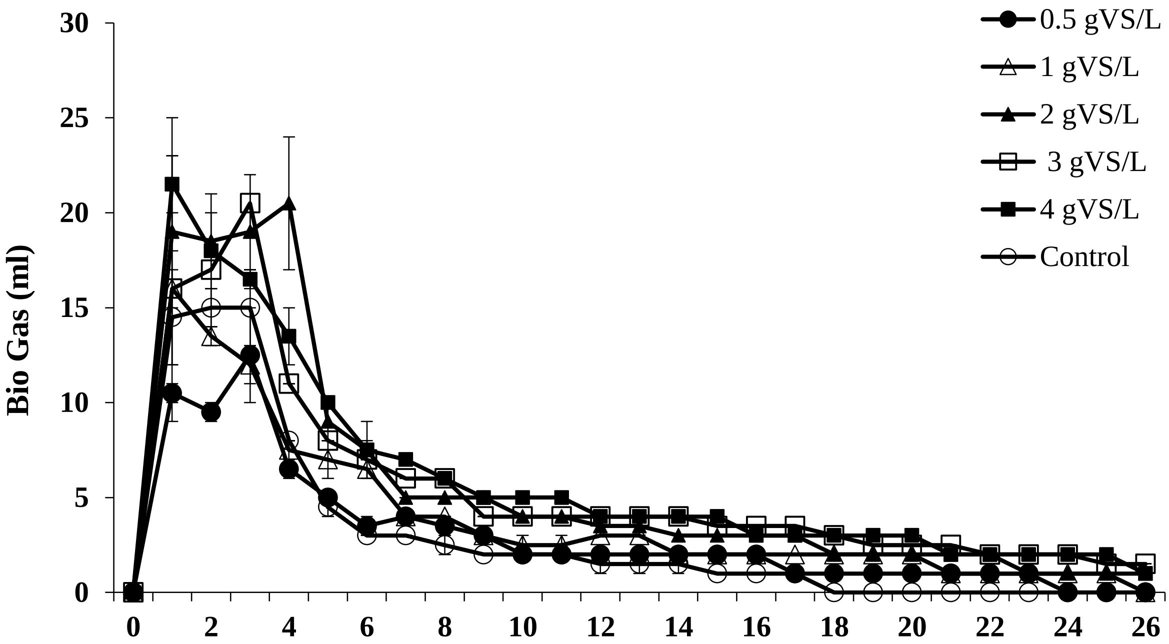


III



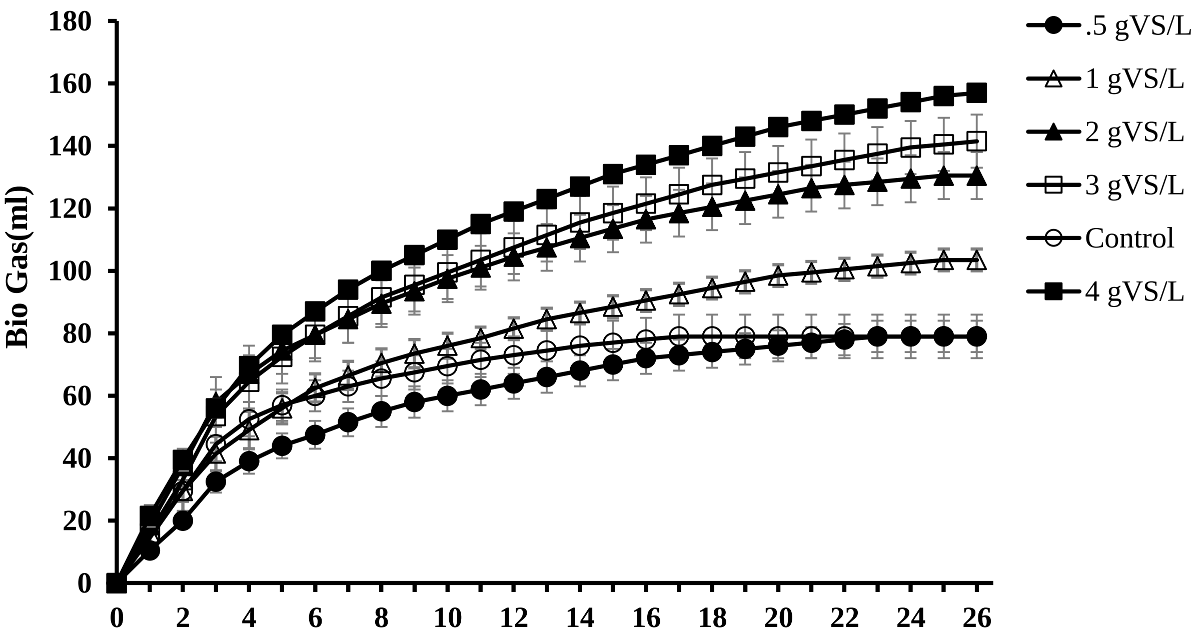
IV

Fig 2.2 C: BMP assay of *Canna indica*. (i)Daily estimation of Gas (ii) Cumulative estimation of gas (iii) Methane Percentage estimation of Different gases at 8th day (iv) Methane Percentage estimation of Different gases at 20th day



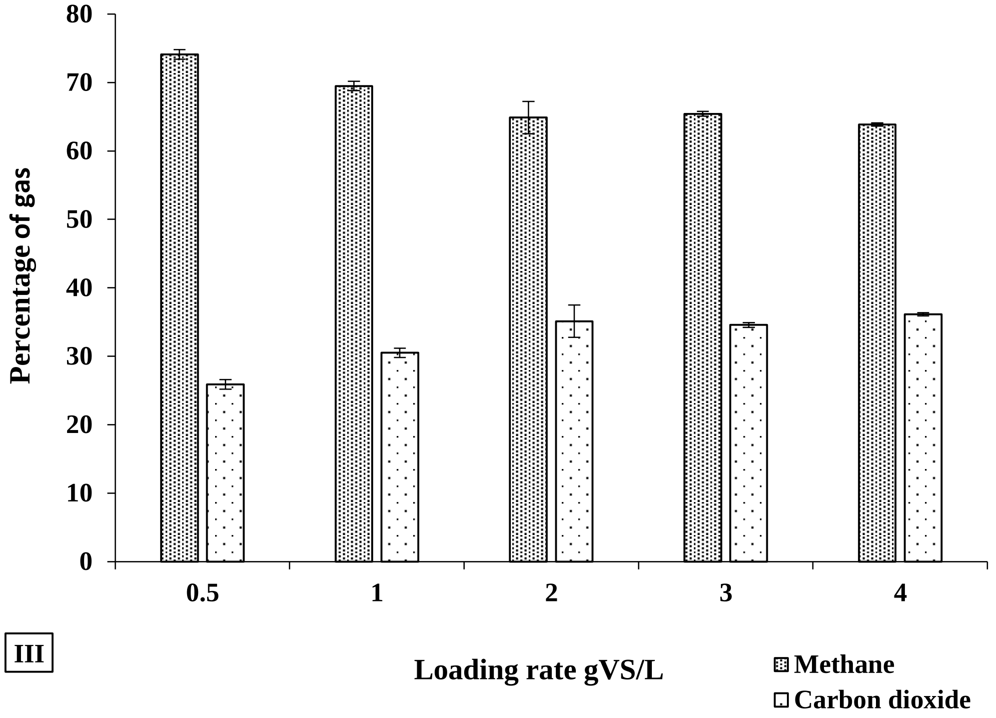
I

No. of days

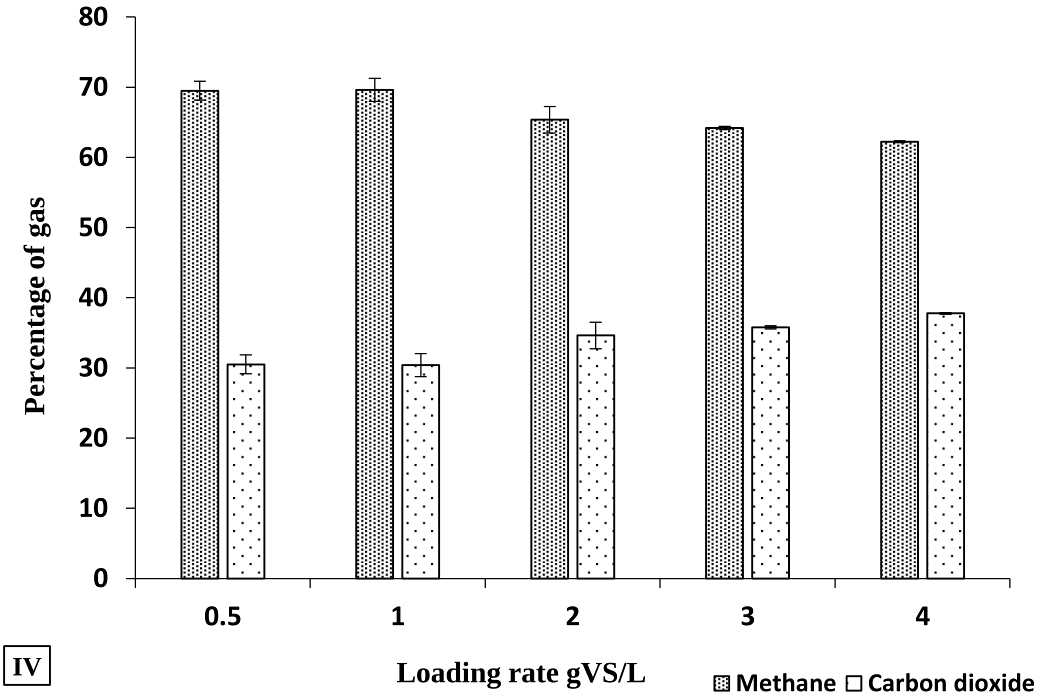


II

No. of days



III



IV

Fig 2.2 D: BMP assay of *Typha latifolia*. (i)Daily estimation of Gas (ii) Cumulative estimation of gas (iii) Methane Percentage estimation of Different gases at 8th day (iv) Methane Percentage estimation of Different gases at 20th day

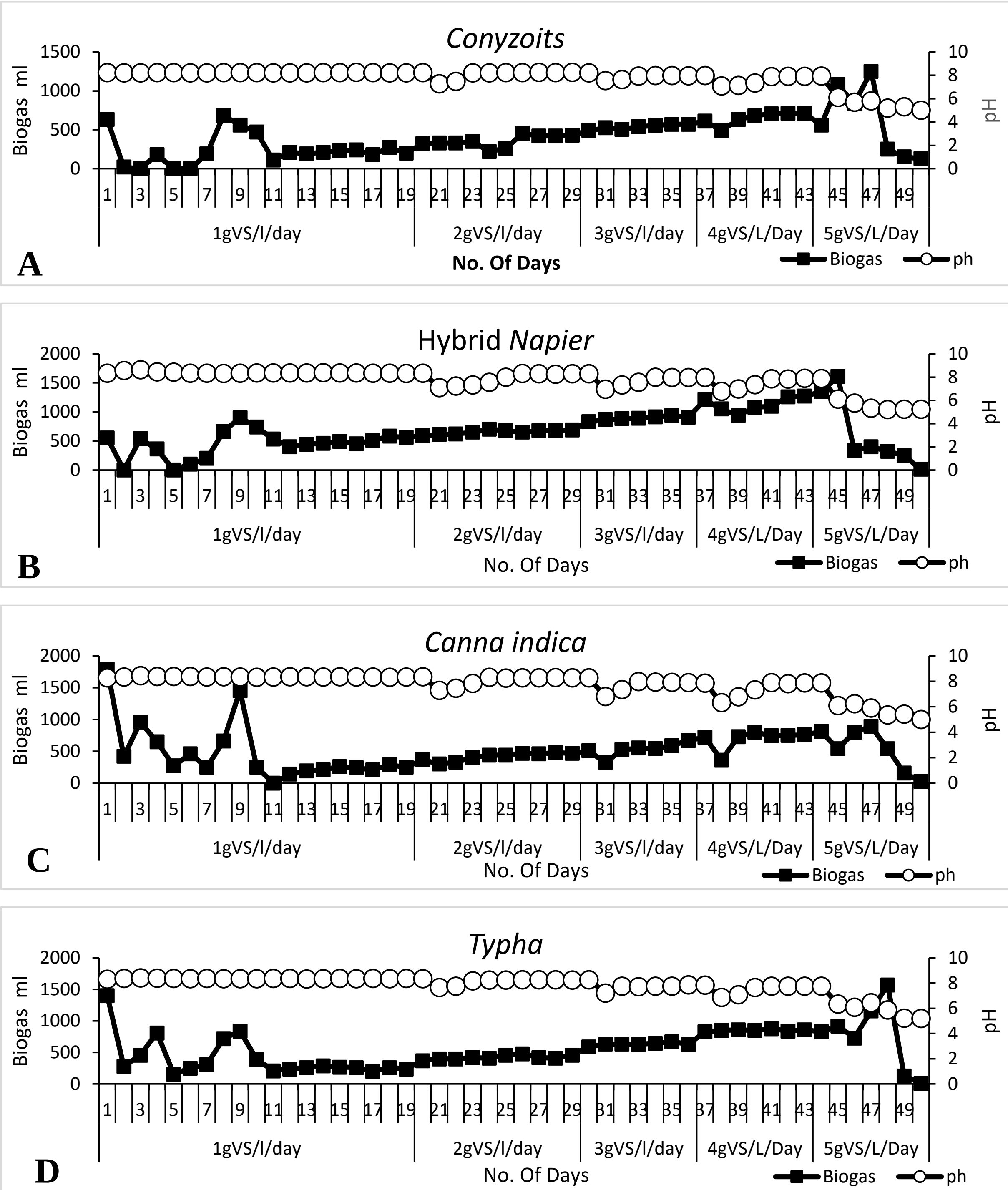


Fig 2.3: Continuous biogas production in 5 L reactor A) *Ageratumconyzoides* B) Hybrid *Napier* C) *Canna indica* D) *Typhalatifolia*

CHAPTER 3

DEVELOPMENT AND OPTIMISATION OF PILOT SCALE VERTICAL FLOW CONSTRUCTED WETLAND

3.1. Abstract

The main aim of our study was to construct a two-stage VFCW system to treat single household raw sewage water in India under a tropical climate. The nutrient removal efficiency and BMP of two beds planted with *Typha angustata* and *Canna indica* were analyzed by 200 L drum experiments for the CWs. The overall nutrient removal efficiency was the same for both the plant species that were tested. BMP Batch assays were conducted in 130 mL serum bottle which was monitored regularly for 30 days to determine BMP efficiency of selected plant species (viz. *Typha angustata* and *Canna indica*) biomass. *Typha angustata* had been selected for planting in the single household wetland system as it is found in the natural wetlands of Goa. Also they have high BMP efficiency than *Canna indica*. The nutrient removal efficiency of pilot scale two stage VFCW was monitored at two Hydraulic Loading Rate (HLR) i.e.; 0.150 m/day and 0.225 m/day. At 0.150 m/day HLR, the removal of Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Kjeldahl Nitrogen (TKN), Ammoniacal Nitrogen (NH_4-N), Total Phosphorous (TP), Total Dissolved Solids (TDS) and Total volatile solids (TVS) at 1st stage was 64%, 65%, 15%, 21 %, 34% and 54% and for the 2nd stage reactor it was 90%, 88%, 50% ,52%, 58% and 71% respectively (on an average). At 0.225 m/day HLR the removal of- COD, BOD, TDS, TVS, TKN and NH3-N at 1st stage was 61%, 62%, 33%, 40 %, 35 %, 58% and; for the 2nd stage reactor it is 90%, 84%, 61%, 64%, 47% and 82% respectively (on an average). It was observed that as the loading rate increases there was no change in the removal of TKN but the removal of NH_4-N increases, and there was a slight decrease in COD and BOD removal. The overall footprint of the system was reduced from 1.47 m^2 per person to 0.79 m^2 per person.

3.2. Introduction

In rural areas of India, the aspect of wastewater treatment plants is mostly neglected because of the lack of infrastructure to improper design, poor maintenance, cost of running is high and lack of technical manpower. The facilities constructed to treat wastewater do not function properly and remain closed most of the time (Konnerup et al., 2009). In this context CW represents a good alternative as it has public acceptance being a natural process, low maintenance cost, avoids chemical treatment, etc., over conventional wastewater treatment technologies and it provides a great alternative for decentralized system in rural India as most of the towns do not have lined sewage system (Álvarez et al.,2017; Ramprasad et al., 2017; Tilak et al., 2017). There is an urgent need for the development of enviroment protection law and social pressure required for the rapid development of good sanitation.

French systems, made of two stage vertical flow, are well established system in the climate of France with more than 4000 systems in operation in 2019. This system can be adapted for the tropical climates of India, mainly in terms of plants selection and system operation under warm temperatures. The tropical climate is expected to enhanced the microbial growth which will help in the better treatment of wastewater (Kantawanichkul et al., 2009).

The main objective of this work was to establish a Decentralised French Two Stage VFCW treatment system for the tropical climate of India.

This study was focused on 1) the reduction of the footprint of the system to adapt it to warm tropical conditions and 2) to test and select several plants species (viz. *Typha angustata* and *Canna indica*.) on the basis of their BMP potential as already highlighted in a recent study (e.g. chapter 2). Based on its BMP research, Canna indica was chosen as one of the plant species for the tropical climate in the past section. Understanding the efficacy of plant species from the Goa region is crucial. An experimental set-up was to estimate again the BMP effectiveness of the two green plants grown in a drum scale experiment. After selection of the plant species, the working of the pilot scale plant has been compared for two different hydraulic loading rate (0.150 m/day and 0.225 m/day). The first loading rate selected was 600 L / day of wastewater generated in a single household and the second one was increased to 900 L/day understand the highest loading capacity of the system to reduce the initial footprint of 1.47 m2 per person (Roshan et al., 2008).

3.3. Materials and Methods

3.3.1. Drum experiment

A Drum experiment was first conducted to select the most suitable plant species adapted to the tropical climate of Goa, India. *Typha angustata* and *Canna indica* were selected because of their natural availability in Goa, India. Three drums each of 200 L total volume and 90 cm height were tested at the sewage treatment plant of BITS-Pilani K K Goa Campus, India (fig 3.1). Each unit was filled with gravel layers similar to a 1st stage VF system (Table 3.1). A ventilation system was provided by perforated pipes at the bottom of the drum connected to the surface (fig 3.2 A). The first drum was left unplanted as a control, and other two were planted with a monoculture of *Typha angustata* and *Canna indica* respectively. Drums were first fed during 1 month with treated water to enable plants establishment. Then drums were fed with raw sewage during 2 months with a HLR of 0.109 m/day corresponding to an organic loading of 148 $gCOD.m^{-2}d^{-1}$.

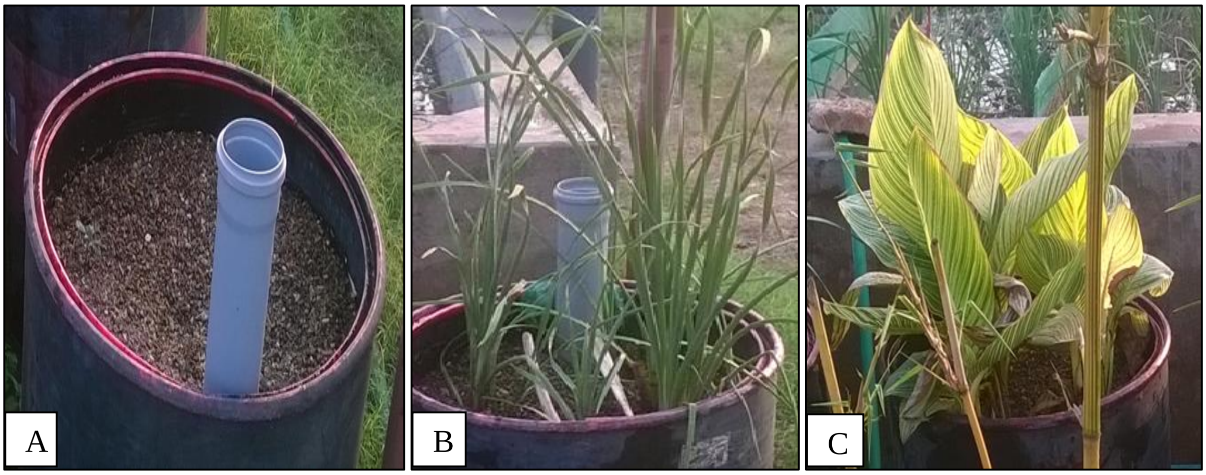


Fig 3.1: Batch scale CW in 200 l barrels. (A) Control Barrel (B) *Typha angustata* (C) *Canna indica*

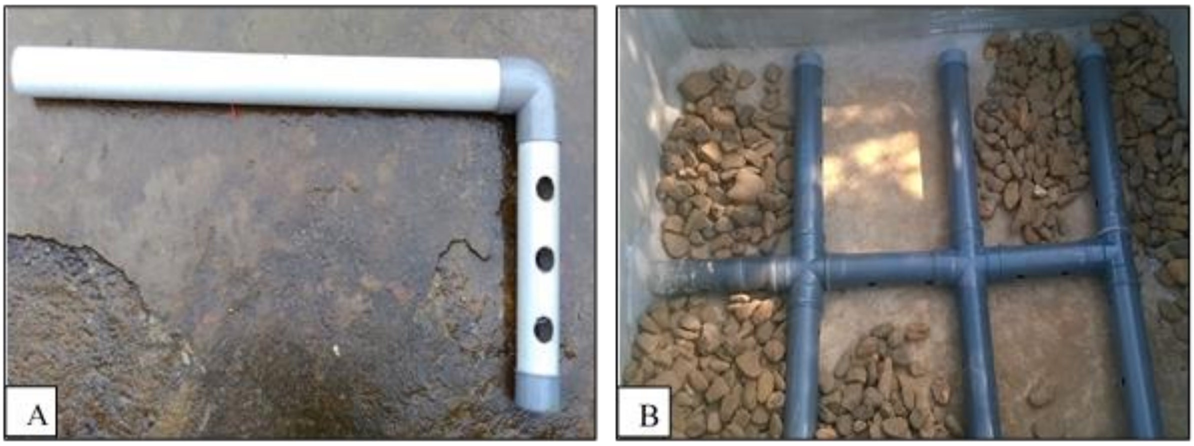


Fig 3.2: Ventilation system for drum (A) and Pilot plant (B)

3.3.2. Biogas experimental setup for the plant biomass generated in the wetland

At the end of the drum experiment to BMP assay was conducted for the harvested plants, cultivated in the drums. Firstly, cellulose, hemicelluloses and lignin content of the samples were analyzed for each plant by VAN SOEST method (Figure 3.4). The BMP assay for the plants was studied in 100 ml glass bottles at room temperature at five different loading rate – 0.5, 1, 2, 3, 4 g VS/L, to determine the highest loading rate. The slurry from already existing biogas plant in the campus was used as inoculum, which was enriched in ethanol to obtain optimum number of methanogenic bacteria before carrying out the anaerobic digestion studies. BMP assay were carried out according to the methods presented by Angelidaki and Sanders (2004); Angelidaki et al. (2009); Yadav et al., (2016). The volume of biogas produced every day was measured by water displacement method up to 29 days. The purity and percentage composition of gases were measured by gas chromatography (Chemito Technologies gas chromatograph) on 5th, 12th, and 18th day of the experiment.

3.3.3. Pilot-scale VFCW

Two-stage VFCW was constructed inside the campus of BITS-Pilani K K Birla Goa Campus. The VFCW was made up of cement and cement bricks and a liner was put to make it leak proof. The surface area of Stage 1 VFCW was 4.0m^{2,} and the surface area of Stage 2 was 1.88m^2. The construction design of the wetland is shown in Figure 3.3. The ventilation system was similar to one of the drum experiments (Figure 3.1 B). Both the stages of wetlands were filled with different sizes of gravels sand from the river as given in Table3.1. The gravels and sand from the river have high hydraulic conductivity which helps to provide a better surface for the developments of biofilms and nutrition adsorptions (Sundaravadivel et at., 2003). The system was planted in the first week of April 2015 and fed with treated wastewater from the campus treatment plant to favor plant development for the first month of the experiment. The system was then fed with raw wastewater at low loading rate during 4 weeks from the buffer storage tank of the campus: Stage 1 was divided in 3 beds, fed in alternance with 0.05 m/batch of raw sewage thrice a day (i.e. total 0.15 m/day) to provide one-day loading and two days of resting. Stage 2 was fed with treated water from Stage 1. Stage 2 was divided in 2 bed; each bed was fed each day therefore alternating 1 day feeding and 1 day resting with the same HLR (0.150 m/day:bed).

Then the system was fed with high loading rate with HLR of 0.225 m/day/bed (3 batches of 0.075 m) during 12 weeks to check the nutrient removal efficiency, and to decreases the footprint 1.47 m^2 required per person of VFCW.

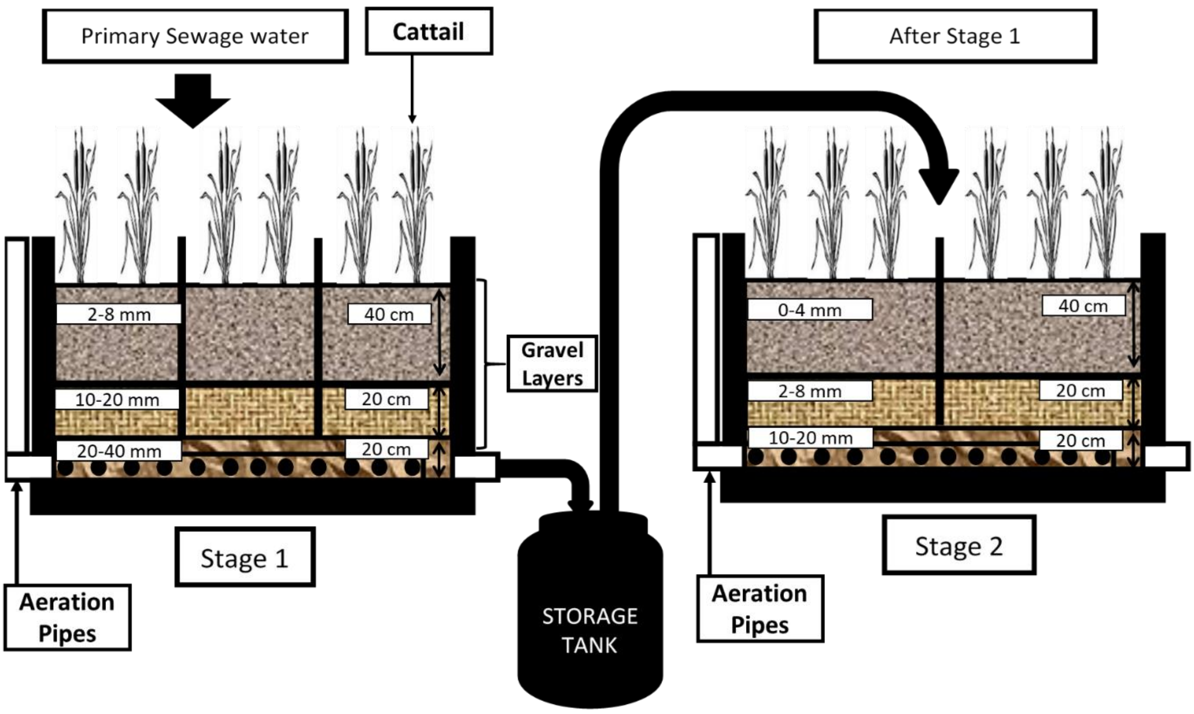


Fig 3.3: Side View of Vertical Flow Construed Wetland System

3.3.4. Analytical methodology

The samples were collected from each of the sites and analysed for different wastewater parameters; - COD, TKN, Total dissolve solids (TDS), Total volatile solids (TVS) and

Phosphorus according to standard APHA methods (APHA et al., 2005). BOD (Biological oxygen demand) was determined by WTW OxiTop ®.

3.4. Results and discussion

3.4.1. Drum experiment

The COD measured at the outlet of Control, *Typha angustata* and *Canna indica* VFCW bed is presented in Table 3.2. The planted drum performances regarding COD removal were found to be very similar to an unplanted drum; this may be because the system was very new, and ran for a concise period of 8 weeks and it has already been reported that for COD unplanted beds were having similar performances under warm climate.

The TKN outlet concentration of Control, *Typha angustata*, and *Canna indica* VFCW beds were observed of 67 ± 3.5 mg/L, 60 ± 5 mg/L, and 77 ± 8 mg/L respectively (Table 3.2). *Canna indica* did grow very fast and covered the wetland surface entirely providing high plant biomass to wetland volume ratio which increases the contact between plant roots and wastewater and provides high plant sink for nutrient removal (Zhang et al., 2007). On an average 35% and 34%, removal efficiency of NH_4-N and TKN respectively were observed in both the planted wetlands, there was no difference in the removal efficiency. A better nitrification was expected, maybe plants and the wetland systems were not old enough and the plants roots were not fully grown (Calheiros et al., 2009).

The phosphorous removal efficiency of *Typha angustata*, *Canna indica*, and control, as shown in Table 3.2 there was no significant difference in phosphorus removal from the wastewater. This indicates that the removal was occurring may be because of the adsorption on the media (Gerritse et al, 1993, Arias et al, 2001) or maybe because of biological mineralization (release of mineral phosphorous during degradation of organic matter) and biochemical mineralization (release of mineral phosphorous through enzymatic hydrolysis by extracellular enzymes) (Oehl et al, 2004). The only mechanism through which phosphorous can be removed is by plant uptake and harvesting (Lantzke et al., 1998), but the actual amount of phosphorous removed by harvesting plants constitute the minor amount loaded by the sewage water (Brix et al., 1994; Brix et al., 1997).

3.4.2. Gas production from Typha angustata and Canna indica

Anaerobic digestion of the biomass from the wetland will help in the reduction of heavy metals and other nutrients present in the wastewater which are absorbed by the plants and will also produce energy for the system (Verma et al., 200; Debuts et al., 1995). Form the literature there were not many studies done on the biogas production from the biomass of VFCW, but there are many other studies which show biogas production from *Typha* species and *Canna indica* and different types of wetland plants (Song et al., 2012; Paepatung et al., 2009; Yue et al., 2007). In our study, Biogas production was highest in case of 4gVS/L for both the plants. The fibre estimation for the same is given in Figure 3.4, showing the considerable percentage of cellulose and hemicellulose which is the significant component for biogas production (Zhong et al.,2011). The maximum gas production was observed in *Typha angustata* on the 4th day of the experiment (50 ml) and showed a continuous decreasing until the end of the experiment. The cumulative gas production after 29 days was 477 ml at 4gVS/L. In the case of *Canna indica*, the maximum gas production was also observed on the 4th day, then showed a decreasing trend until the 13th day of the experiment. The cumulative gas production after 29 days was of 126 ml at 4gVS/L. The output of biogas in case of *Typha* species was more than that of *Canna indica* species, which was similar to the result obtained by Jiang et al. 2014.

The percentage composition of methane and CO_2 was measured on 5th, 12th, and 18th day of the experiment, for *Canna indica* there was no difference in the composition of methane and CO_2 concentration at different loading rate and time intervals, but in the case of *Typha angustata* the methane percentage decreases from 73.8% to 48.4% as the loading rate increased from 0.5 gVS/L to 4gVS/L. The overall methane production at the highest loading rate (i.e.; 4gVS/L) in *Typha angustata* and *Canna indica* was 230.0mL and 94.5mL respectively (Table 3.3). The biomass yield for *Typha* species is around 2.8 Kg/m^2 (Ciria et al., 2005) and for *Canna indica* the biomass yields are around 1.9 Kg/m^2 (Zang et al., 2007). So, *Typha angustata* was selected for the pilot scale plant studies as the energy produced from the biogas can be utilized as an alternative source of energy for running the pumps.

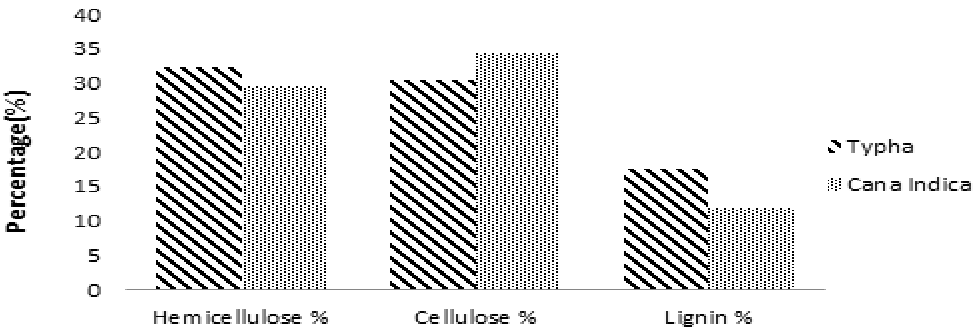


Fig 3.4: Fibre estimation of *Typha angustata* and *Canna indica.*

3.4.3. Pilot-scale VFCW for a single household

Based on the drum experiment, a demonstration-scale Two Stage Pilot VFCW experiment was implemented and regularly monitored at two different HLR i.e. 0.150 m/day and 0.225 m/day. *Typha angustata* was selected for plantation in the wetlands; it was selected according to the result obtained from the drum experiment and the BMP assay experiment which showed that there was not significant difference in the treatment efficiency by *Canna indica* and *Typha angustata*; also, *Typha angustata* showed highest BMP capacity. It was also acquired in the previous studies that Typha spp generated more biomass which could provide more biogas (Solano et al., 2004).

Initially, the pilot system was fed with 0.15 m/day of raw sewage water; all the parameters were monitored regularly. The usual organic load for the Stage 1 of French VFCW is around 40-50 g $BOD_5.m^{-2}d^{-1}$, so considering this as the system was started with a loading rate of 51 g $BOD_5.m^{-2}d^{-1}$ (Paing et al., 2015). The specific characteristics of the inlet wastewater and the treated water, are given in Table 3.4. The removal of COD, BOD, TDS, TVS, TKN and NH4-N at 1st stage was 64%, 65%, 15%, 21 %, 34% and 54%; and for 2nd stage reactor 90%, 88%, 50% ,52%, 58% and 71% respectively (on an average). As Goa has a tropical climate with very high evapotranspiration condition (Caselles-Osorio et al., 2017; Gumbricht et al., 2017) and for warm climate, the recommended loading rate is around 60–70 g COD $m^{-2}d^{-1}$ (Hoffmann et al. 2011). After monitoring the plant at 0.15 m/day HLR, the HLR was increased to 0.225 m/day, i.e. 98 g $BOD_5.m^{-2}d^{-1}$). At higher loading rate the removal of COD, BOD, TDS, TVS, TKN and NH_4-N at 1st stage was 61%, 62%, 33%, 40 %, 35 % and 58%; and for the 2nd stage 90%, 84%, 61%, 64%, 47% and 82% respectively (on an average) (Figure 3.5).

A slight decrease in the COD and BOD removal efficiency was observed which complied with the result obtained by Chang et al., 2007. A 90% COD removal was obtained from the system installed at the Aligarh Muslim University (AMU) system (Álvarez et al., 2017). This was accomplished after all the other heavy maintenance system was integrated. Compared to the system at AMU, a two-stage French system can readily achieve 94 percent COD removal, although the removal efficiency of all other parameters are less than that of the AMU system, which can be accomplished by incorporating a straightforward polishing system at the end of the CWs. TKN's overall removal efficiency has been reduced as the loading rate has been increased, this finding is consistent with the outcomes reported by Kantawanichkul et al., 1999.In case of NH_4-N as the loading rate increases, the removal efficiency also increased from 54 to 58% in Stage 1 and 71% to 82% in Stage 2, which is similar with the finding by Xu et al. 2014. The TKN and NH_4-N can be increased if anaerobic system could be added for further processing. VFCW can provide good condition for Nitrification with helps in the conversion of nitrogen to nitrates and nitrites and further denitrification can be achieved by adding anoxic conditions for further polishing of treated wastewater. The removal efficiency of TDS and TVS was decreased as the HLR was increased which is very similar to the outcome saw by Xu et al. 2014.

Two-stage vertical flow classical wetlands system can be very effective for the developing countries like India as these systems are elementary to maintain and the cost of running the system is also less than any other conventional system. If the footprint calculated according to hydraulic loading rate of 150 l per person, the footprint got reduced from 1.47 m^2 per person to 0.98 m^2 per person, but considering the BOD organic load, the system footprint got reduced to 0.79 m^2 per person. Molle et, al, 2005 also reported similar finding, the system developed was operated using twin-filter stage and was able achieve over 90% COD, SS and TKN removal for a total surface of 0.8 m^2/p.e. The main problem faced in maintaining the system was a long rainy season of Goa, as the campus has open drainage system, the rainwater mix with the sewage and dilutes the raw sewage water, also during the vacation time the system had to shut down due to low organic load in the sewage water. The system was not tested for at further higher loading rate, so there is chances that it may work at higher loading rate. This could be the further studies that can be done.

3.5. Conclusion

Even though the wetland was run for short period of 40 weeks, the result obtained to provide a strong indication that the decentralized two-stage vertical flow CW with a small area of 0.79 m^2 per person can reduce the COD by 90% and BOD by 84%. The TKN and NH_4-N removal was observed to be quite less i.e. only 82% after the 2^{nd} stage. As vertical flow wetland does not provide condition for denitrification, so they do not provide complete removal of Nitrogen from the waste water. Regarding TKN and NH_3-N treatment recirculation or third stage with horizontal flow wetland, which provide denitrification condition, could be a good solution. The footprint per person of the wetland can be reduced more as reported by other authors, i.e. around 0.5 m^2 per person for the tropical climate if the controlled condition like closed drainage system has been provided (Molle et. al. 2005). The primary collection tank in the campus has the aeration system which alters with the inlet parameter of the water. The treatment efficiency can be increased if the direct source of wastewater is provided to the wetland. The *Typha* spp. plant was very tough to handle in vertical flow CW as it requires stagnant water in the wetland to grow. In vertical flow wetland the water flows vertically and flow out of the wetland due to gravity. So, for further studies in chapter 5 and chapter 6 *Cana Indica* was planted in the system as *Cana* spp. do not require stagnant water and are suitable for vertical flow CWs. The water released form the system was not reaching the permissible limit. This could be achieved by making modification to the system like adding one more step for polishing. The system may be attached with electrochemical cell or Microbial fuels cell to achieve the permissible limits. This can also be achieved by adding an algal treatment step after the wetland system.

Table 3.1: Design characteristics of VFCW (Paing et. al. 2015)

Filter Media	Stage 1	Stage 2
River gravels	40-50 cm gravel 2/8 mm	40 cm sand 0/4 mm
	15-20 cm gravel 10/20 mm	15-20 cm gravel 4/10 mm
	20 cm gravel 20/40 mm	20cm gravel 10/20 or 20/40 mm

Table 3.2: Performance of selected plant Species

	COD mg/l	TKN mg N/L	NH_4-Nmg N/L	Total Phosphorus mg P/L
Inlet	1334	224	37.5	7.85
Outlet				
Unplanted drum	724	156	26.6	7.25
Typha angustata	670	163	25.7	7.05
Canna indica	619	147	21.3	6.58

Table 3.3: Methane production at the highest loading rate (4 gVS/L)

Plants	Cumulative biogas produced	Methane percentage at a highest loading rate	Overall methane Production
Typha angustata	477 ml	47%	230 ml
Cana indica	126 ml	74%	94 ml

Table 3.4: Mean and standard deviation of different parameters of the inlet and outlet water at different HLR

Parameter	**HLR 0.150 m/day**				**HLR 0.225 m/day**			
	Inlet		**Outlet**		**Inlet**		**Outlet**	
	Mean	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
COD	716.56	320.20	70.44	70.71	1802.97	582.81	173.78	128.78
BOD	509.25	110.75	57.2	32.76	642.85	198.80	101.57	69.31
TKN	235.81	130.16	97.70	47.40	270.13	136.29	141.5	33.54
NH_3-N	28.79	12.88	8.33	2.98	28.05	15.34	4.98	1.32
TS	0.65	0.21	0.32	0.18	0.63	0.10	0.24	0.05
VS	0.41	0.12	0.19	0.16	0.39	0.05	0.139	0.05

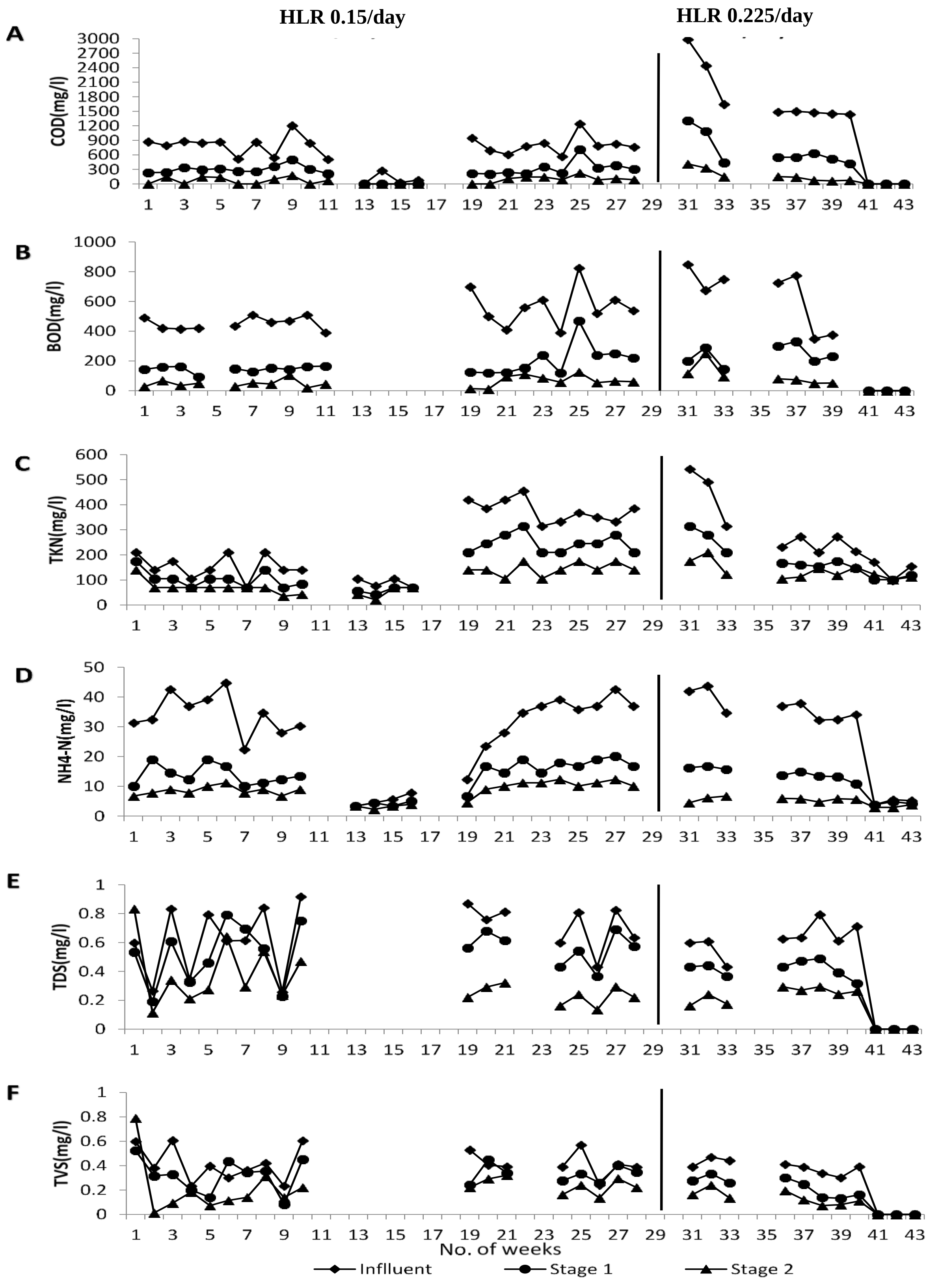


Fig 3.5: Nutrient removal efficiency of the wetland after stage 1 and stage 2

CHAPTER 4

USE OF REACTIVE MATERIAL FOR PHOSPHORUS REMOVAL IN SMALL TREATMENT PLANTS

4.1. Abstract

The main aim of this study was to select a suitable reactive material which can be used for the removal of phosphorus from treated wastewater. In this study, different reactive materials were sampled from several parts of India and France. Seven different materials were analyzed for their phosphorus removal capacity from synthetic wastewater. Steels slag (SSGS), kiln ash (KAS), Bauxite ore (BOX), Bentonite clay (BNC) and Red brick (RB) were collected from India. Bovec Nervac (BON) and Binvec Pivel (BOP) were collected from drinking water treatment facility in France. All the samples were analyzed for their Phosphorus removal capacity in a controlled experimental set up by static test isotherms. The kinetic study for the release of Ca^{2+} and OH^- were performed for all the samples. It was found that the samples that were collected from India showed worse results for kinetic studies and Phosphorus removal. Both the samples BOP and BON released considerable amounts of Ca^+ and OH^- into distilled water. BOP and BON were able to remove 10 mg P/g of BOP at an initial concentration of 700 mg/L and 7.6 mg P/g of BON at an initial concentration of 700 mg/L respectively.

4.2. Introduction

Global demand for phosphate rock for food production is around 148 million tonnes which constitutes about 90% of the phosphate rock that is mined every year (Cordell et al.; 2009). These phosphates are used as fertilizers for the agriculture industry, of which, only 20% of the phosphorus actually reaches the food that is consumed. Rest of it ends up in rivers and other water bodies through rain and surface run off. Discharge of phosphorus rich wastewater into neighbouring water bodies is one of the main reasons for excessive growth of photosynthetic algae and cyanobacteria which leads to eutrophication of surface water bodies (Conley et al.;2009, U.S.EPA; 1987). Most of the centralised and decentralized systems in India treat all other parameters except phosphorous (Soranno et al., 1996). With increasing eutrophication of the freshwater bodies and increasing pressure from government regulations, phosphorous has become a critical parameter to be reduced in the effluent from the wastewater treatment system.

Phosphorus in wastewater exists mainly under three different forms: phosphate, polyphosphate and, organic phosphate (Roques H., 1990). Phosphorus forms a hard to dissolve complex compounds with chemical salts in aquatic environment (Siwek at al. 2019). Different phosphorus treatment processes are applied including chemical precipitation, absorption, and biological removal. In chemical precipitation, different such as aluminium sulfate, ferric chloride and lime are generally added to wastewater to precipitate phosphate as aluminium phosphate, ferric phosphate, and calcium phosphate respectively. Among the many reactive material, materials rich in CaO are the most promising for the chemical precipitation of phosphorus because they release large amount of Ca^{2+} and OH^{-} in large quantity. Ca^{2+} reacts with phosphorus to form different forms of calcium phosphate depending upon the pH value, Ca^{2+} and PO_4-P concentration in the sample (Roques H. et al. 1990; Stumm and Morgan et al. 1996). One interesting approach for the lowest cost is to discover reactive materials, by-products from several sectors with elevated concentrations of these precipitating materials (Gunning et al. 2010).

The study aims to provide selection criteria for substrates that would enhance phosphate removal downstream of existing wastewater treatment plants such as CW system. A horizontal flow system can be added to the end of main treatment system by calculating the required flow rate for the removal remaining phosphorus after wastewater treatment. CWs systems provides efficient treatment for BOD, suspended solids (SS) and Kjeldahl nitrogen but are limited in their phosphorus removal abilities (Moshiri et al., 1993). Phosphorus removal in CW depends on biotic and abiotic factors (Kadlec and Wallace et al.; 2009). The maximum phosphorus removal by plant uptake can range from 1 to 8 mg P/g (Tanner et al. 1996) and the adsorption by bed media is mainly because of iron, aluminium and calcium content (Rustige et al. 2003).

In this context, the aim of this work was to establish and compare the phosphate removal capacities of five different materials such as steel slag, bauxite ore, bentonite clay, fire brick, and kiln ash from blast furnace. These materials were selected according to the previous studies and on the basis of their chemical composition. Steel slags and Kiln ash are the by-product coming from high temperature process having high CaO content (Das et al. 2007; Barbour et al. 2003). Bentonite clay and Bauxite ores had been used in previous studies for the removal of phosphorus from water (Zamparas et al. 2012; Altundoğan et al. 2002). There are studies in which shows that drinking water sludge could be a great alternative for the removal of phosphorus form wastewater. Alum sludge was used in a study performed by Yang et al. 2006 for the removal of phosphorus from wastewater. Searing an efficient and long lasting material for phosphorus adsorption is still a key issue (Vohla et al. 2011). In light of the above discussion, there is an urgent requirement for new and better technologies for phosphorous removal from wastewater.

4.3. Material and Methods

4.3.1. Reactive material collection and preparation

Reactive materials were collected from different places in India and France. The samples were collected from different places to define the region wise availability of by-product from different industries which can be used for scrubbing the phosphorus from wastewater. The region wise availability of product will reduce the cost of procurement. Steel slag (SSGS) and kiln ash (KAS) were procured from Goa Sponge Ltd, Bauxite ore (BOX) was obtained from the mining industry in Goa. Bentonite clay (BNC) was available commercially, and fire red brick (RB) was taken from the waste from firebrick manufacturing industry in Uttar Pradesh. BOP (Binvec Pivel) and BON (Bovec Nervac) were drinking water sludge procured form drinking water treatment facility form France. Steel, Bauxite ore and Fire Brick were grinded manually to the granular size of 5-10 mm to perform the batch experiments. This enabled the results to be compared with the size of field scale filters. Other samples; Kiln Ash(KAS), Bentonite clay(BNC), Bovec Nervac (BON) and Binvec Pivel (BOP) were already in powdered form and did not require grinding or sieving. Before the experiments, the samples were washed first with tap water to remove fine particles and then dried at 105°C for 24 h. Energy dispersive X-ray fluorescence analyses (EDX) were performed to determine the semi-quantitative chemical composition of the samples (Rayny series EDX-800HS spectrometer, Shimadzu Corporation, Kyoto, Japan).

4.3.2. Kinetic study on Ca^{2+} and OH^-

In this setup of the experiment, release of Ca^{2+} and OH^- ions from the reactive materials was studied. The aim of these was to demonstrate that the increase in Ca^{2+} and pH of the solutions depended primarily on CaO dissolution. The lime or hydrated lime present in the sample were dissociate into the solution producing Ca^{2+} and OH^-. Then, Ca^{2+} ions react with the phosphates to form Ca phosphates. Several Ca phosphates are formed depending on the pH values, Ca^{2+} and PO4-P concentrations of the solutions. 40 g of each reactive material were placed in deionized water in a 1 L glass bottle (Figure 4.1). The bottle was agitated at 125 rpm under a controlled temperature of 20°C for 7 days. Samples were taken on days - 0, 1, 2, 3, 4, and 7. Samples were acidified after measuring the pH and stored at 4℃. The Ca^{2+} concentration of the solutions was estimated after 7 days of agitation when an equilibrium was reached. The Ca^{2+} and OH^- release capacity of each reactive material was measured by equation (1) and (2). Where Q^t was the capacities of Ca^{2+} and OH^- release at time t (mg/g), V was the volume of the solution (L), M was the mass of samples (g) and Ca^t and OH^t are the total Ca^{2+} and OH^- concentrations of the solutions at time t (mg/L).

$$\mathrm{Q_t} = \frac{\mathrm{Ca^t V}}{\mathrm{M}} \qquad (1)$$

$$Q_t = \frac{OH^t V}{M} \qquad (2)$$

4.3.3. Phosphate removal from Synthetic solution (Development of Phosphorus Removal Isotherms)

For each reactive material, a series of 6 glass bottles each containing 1 L of a synthetic solution with different initial PO_4^{3-}-P concentrations (0, 5, 10, 20, 25, 100 mg P/L) was prepared. Initial concentrations of phosphorus were taken from Barca et al. (2012). The bottles were placed on a shaker incubator at 125 rpm under controlled temperature conditions (20°C). The residual PO_4^{3-}-P and Ca^{2+} concentration of the solutions was measured after 7 days of agitation when a pseudo-equilibrium in PO_4^{3-}-P removal was reached. The solution was filtered before residual PO_4^{3-}-P, TP (Total phosphorus) and Ca^{2+} concentration were measured. The P removal capacity of the samples was calculated and it was found that capacity P removal of the material was increasing as the initial concentration was increased, this suggests that the equilibrium was not obtained. Thereafter, second set of experiments were performed for BOP and BON at a higher initial concentration of phosphorous (BOPH and BONH). Isotherms were prepared for the higher initial concentrations of 0, 100, 200, 400, 700 and 1000 mg P/L. Samples for the second set of experiment were taken at time intervals - 0, 15, 30, 60, 180, 1020 and 1440 min.

The phosphorus removal capacity (PRC) (mg P/g reactive material) was measured according to equation (3) where P_{in} is the initial concentration of phosphorus, P is the final concentration of phosphorus after 7 days of the experiment. V is the volume of the solution (L) and M is mass of the reactive material taken for each set of experiment.

$$PRC = \frac{(P_{in} - P)V}{M} \tag{3}$$

EDX analysis of each reactive material was carried before and after the experiment.

4.3.4. Analytical methods

Phosphorus and Calcium concentrations were analysed by using Ammonium Molybdate spectrophotometric method (EN ISO 6878, 2004) and Atomic Absorption spectrophotometric method (EN ISO 7980, 1986), respectively. U DR/4000 spectrophotometer (Hach Company, Loveland USA) was used for measuring phosphate concentration and model A Analyst 200 spectrophotometer (Perkin Elmer Instruments) was used for measuring Ca^{2+} concentration. Before measuring these concentrations, slandered graphs were the plot for each experiment. All chemicals used were of analytical grade.

4.4. Results and Discussion

4.4.1. The chemical composition of reactive materials

The primary chemical composition of reactive material is Fe_2O_3, Al_2O_3, CaO, SiO_2, and P shown in Table 4.1 (Razali et al. 2006). BON and BOP have the highest concentration of CaO (9 % and 48 % respectively) as the material used in coagulation and flocculation in the drinking water treatment facility contains a high amount of lime. BON and BOP also have 16 and 14 % of Fe_2O_3 respectively. The main material used in coagulation and flocculation is either an Iron coagulant which contains ferric sulfate, ferrous sulfate, ferric chloride, and ferric chloride sulfate or an aluminum-based coagulant which contains aluminum sulfate, aluminum chloride and sodium aluminate. The other chemical used is hydrated lime and magnesium chloride (Bratby et al. 2016). The samples SSGS and KAS have the highest composition of Fe_2O_3 as the sample SSGS was obtained from an electric arc furnace waste from a steel manufacturing plant and the KAS was obtained from dust condensation unit of rotary kiln furnace (Santamaría et al.; 2017, Mantovani et al.; 2013, Lam et al.; 2017). As SSGS was obtained from an unknown waste collection site, the samples may be being coal cinders, as the CaO concentration of the sample was very similar to coal cinders (Yang et al.; 2009). RB and BNC have a high amount of SiO_2 as the soil used for making bricks and bentonite clay are taken from river banks. They have very less amount of CaO which is not suitable for creating an alkaline condition for scrubbing of phosphorus from wastewater (Barca et al.; 2013).

4.4.2. Kinetics of $Ca^{2+}$and OH^- release

It can be seen in Figure 4.1 that the concentration of Ca^{2+} and pH increases as the pseudo first order equilibrium was achieved on the 7th day of the experiment. In case of BOP and BON, there is a release of Ca^{2+} in the regular tap water and pH increase in the samples can be observed. These can be related to the EDX results from Table 4.1. Several authors have concluded that for softening of drinking water lime is a widely used material which contains a high concentration of CaO. This lime after coagulation and flocculation enters into the sludge (Rescorla et al.; 2017, Hobson et al.; 2017, Katsoyiannis et all; 2017).

In case of other samples, there was no release of $Ca^{2+,}$ and no increase in the pH was observed. This was expected from the EDX analysis because these samples did not have an appropriate percentage concentration of CaO. Even though KAS samples had a comparable percentage of CaO (Table 4.1) but it was not available in the free form to get released in the water producing free Ca^{2+} and OH^-. The sample bottles with BNC shows no Ca^{2+}. The initial concentration of calcium in the tap water was also not present. The initial Ca^{2+} is either get absorbed to BNC or got precipitated with OH^- which got filtered during sample collection. SSGC did not show any increase in pH as the coal cinders have less percentage of CaO available freely to get released in the water.

Table 4.1 - EDX analyses: chemical composition of all the samples (weight %).

	EDX Before Isotherm experiment(%)						**EDX After Isotherm experiment(%)(After 7 days)**					
	Fe_2O_3	CaO	SiO_2	Al_2O_3	MnO	P	Fe_2O_3	CaO	SiO_2	Al_2O_3	MnO	P
BON	16.83	9.58	29.79	32.32	0.54	1.43	16.57	9.87	30.11	30.18	0.57	3.63
BOP	14.60	48.57	27.60	- *	- *	1.05	9.59	44.32	21.75	12.90	0.31	4.76
SSGS	44.93	4.52	27.80	9.69	8.22	0.67	45.33	4.71	22.69	9.57	10.85	2.29
BOX	11.87	0.19	5.89	45.14	0.101	0.64	22.18	0.45	8.62	- *	0.38	- *
RB	12.97	2.52	58.31	14.15	0.13	1.54	12.91	2.82	54.25	13.32	0.14	2.86
KAS	52.38	8.23	17.87	14.22	0.13	1.26	55.58	8.16	17.30	13.45	0.19	1.54
BNC	29.32	1.05	40.80	18.11	0.37	0.69	32.69	2.92	36.10	15.69	0.39	1.08

*Not Detected

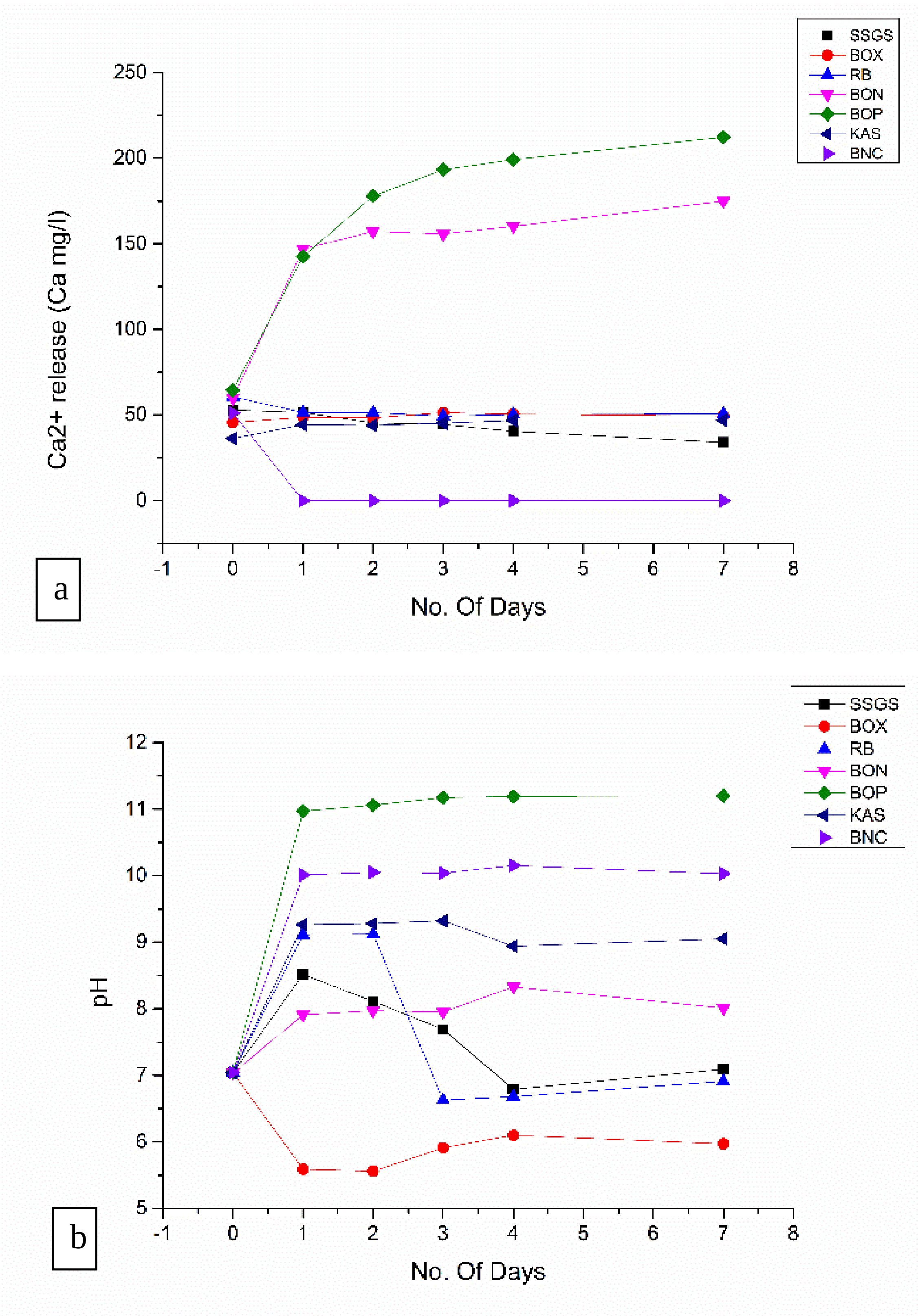


Fig 4.1: Kinetics of Ca^{2+} and OH^- release: total Ca^{2+} concentrations (a) and pH values (b) of the solutions

4.4.3. Phosphate removal from synthetic solutions

The phosphorus removal capacity of the reactive material was calculated according to equation 2 and plotted in Figure 4.2. From Figure 4.2 it can be analysed that the other materials BON and BON higher phosphorus removal efficiency than other samples which was anticipated from the EDX and Kinetic study of Ca^{2+} and OH^- release. The PRC of BOP and BON was found to be the highest i.e. 2.4 mg P/g and 2.5 mg P/g of each sample respectively. From Figure 4.2, it can be seen that the rate of PRC increases as the initial concentration of phosphorus was increased. So, to attain the equilibrium another set of experiment was performed at a higher initial concentration of phosphorus. In the second set of analysis the phosphorus removal capacity of BOP and BON was found to be around 10 mg P/g of BOP at an initial concentration of 700 mg/L and 7.6 mg P/g of BON at an initial concentration of 700 mg/L (Figure 4.3). The PRC of material with CaO depends on two things 1) Ca^{2+} concentration in the solution and 2) OH^- concentration, i.e. pH of the samples. As pH of the sample changes, several Ca-PO_4 –P complex are formed: amorphous calcium phosphates (ACP), dicalcium phosphate (DCP), dicalcium phosphate dihydrate (DCPD), octocalcium phosphate (OCP), tricalcium phosphate (TCP) and the most stable hydroxyapatite (HAP) and Fluorapatite (FAP) (Valsami-Jones et al; 2001). From the fig 4.2 it was observed that at 1000 mg/L initial concentration the P removal capacity of the samples got decreased. This could be happening, because the equilibrium was achieved at 700 mg/L initial concentration. This could be because molar ratio of Ca to P at 1000 mg/L of BON and BOP was 3.6 and 4.6 respectively. The molar ratio of Ca to P of these Ca-P complex ranges from 1 to 1.67 (HAP to FAP) (Roques et al.; 1990, Stumm et al.; 1996). Thus, the phosphorus could get dissolved back to the solution. From Table 4.2 it can be seen that the molar ratios PO_4-P/Ca of residual PO_4-P to Ca^{2+} concentrations of the solutions after 7 days of PO_4-P removal for BOP and BON was 1.9 and 1.7. At this molar ratio the most stable form of Ca-PO_4 –P complex can be formed, i.e. HAP and FAP (Roques et al.; 1990, Stumm et al.; 1996). Form the result it can be concluded that the main mechanism of removal of phosphorus is dissolution of CaO in the water to form Ca^{2+} and OH^-, formation of HAP and HAP adsorption or crystallisation on the material (Barca et al. 2012). Yang et al. 2006 also demonstrated that the maximum PRC range from 0.7 to 3.5 Mg-P/g when the pH of the synthetic P solution was varied from 9.0 to 4.3. In Razali et al. 2006 is was found that sludge from drinking water treatment facility at ph 4.0, has an adsorption capacity for orthophosphate was 10.2 mg-PO43−/g DWTS, polyphosphate was 7.4 mg-PO43−/g DWTS and organic phosphate was 4.8 mg-PO43−/g. Ippolito et al. 2003 found that the drinking water sludge has a phosphorus-binding ability of roughly 12.5 g P / kg, while Dayton and Basta et. al. 2005 stated a PRC of 10.4 to 37.0 g P / kg for the sludge.

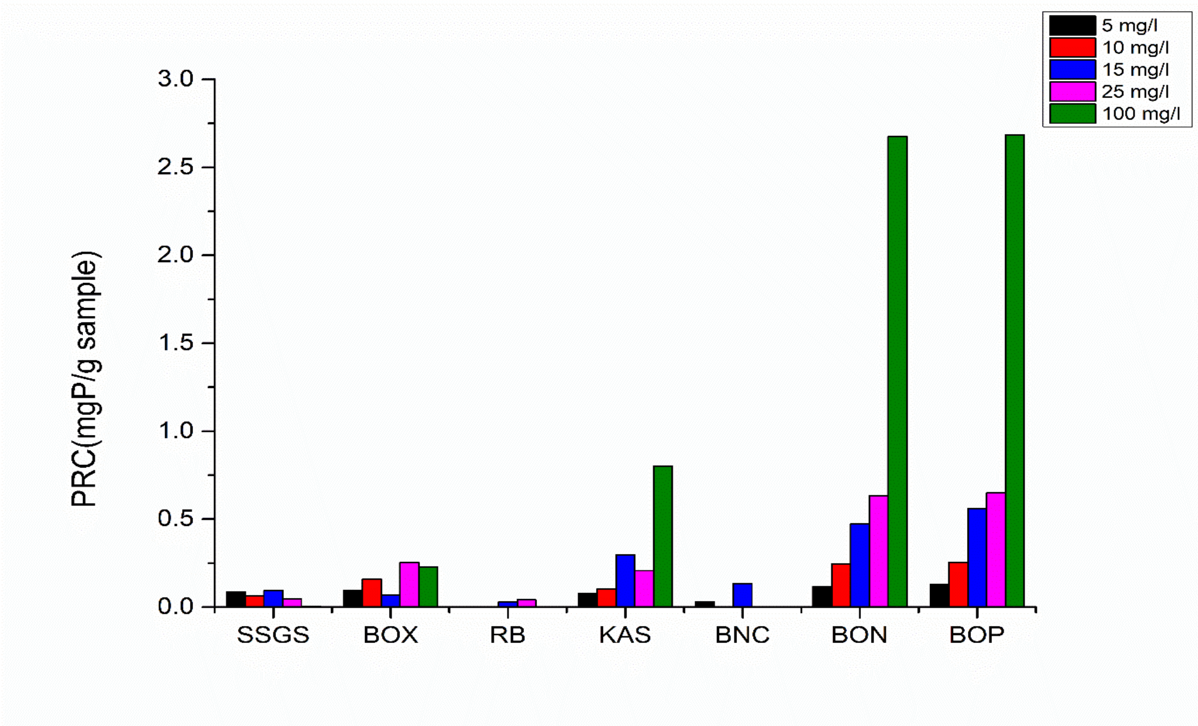


Fig 4.2. - Mean PRCs after 7 days of PO_4eP removal from synthetic solutions at lower initial concentration of phosphorus.

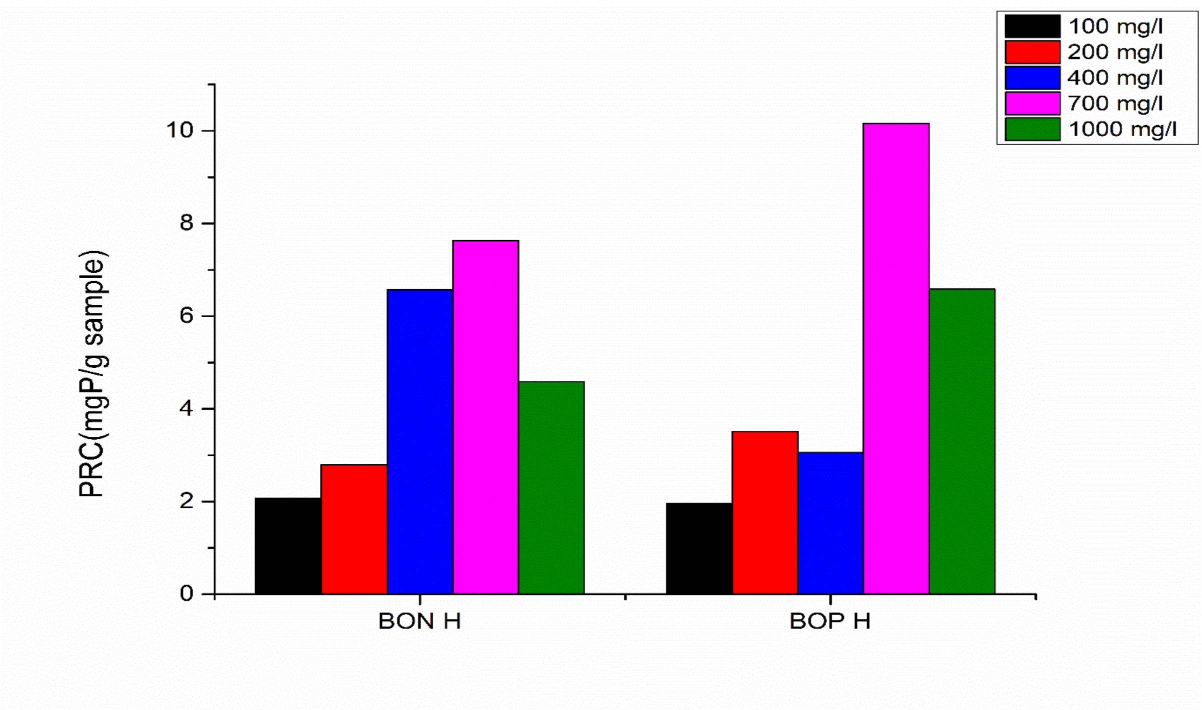


Fig 4.3 - Mean PRCs after 7 days of PO_4eP removal from synthetic solutions at a higher initial concentration of phosphorus for BOP and BON.

Table 4.2 - Range of molar ratios PO_4-P/Ca of residual PO_4-P to Ca_2 concentrations after 7 days of PO_4eP removal from synthetic solutions

	Residual PO_4eP/Ca (mol P/mol Ca)					**Residual PO_4eP/Ca (mol P/mol Ca) for higher initial concentration**		
Initial PO_4-P (mg/l)	SSGS	BOX	RB	KAS	BNC	Initial PO4-P (mg/l)	BON	BOP
5 mg/l	0.003	0.012	0.071	0.023	0	100 mg/l	0.054	0.007
10 mg/l	0.065	0.057	0.152	0.063	0	200 mg/l	0.213	0.117
20 mg/l	0.172	0.149	0.323	0.151	0	400 mg/l	0.841	1.227
25 mg/l	0.288	0.222	0.445	0.198	0	700 mg/l	1.968	1.754
100 mg/l	1.498	1.648	1.911	1.657	0	1000 mg/l	3.649	4.632

4.5. Conclusion

The research demonstrates that BOP and BON from the drinking water plant could be an effective solution for removing P from wastewater treated in CW. The P removal capacity of the samples were 10 mg P/g and 7.6 mg P/g of BOP and Bon respectively. Form EDX analysis it was observed that KAS can also be a good alternative as its 8.23 % of CaO. But it did not show low Kinetics of Ca^{2+} and OH^- release. It was observed that the samples provide Ca^{2+} and OH^- for the formation of HAP complex. The molar ratios PO_4-P/Ca of BOP and BON was 1.7 and 1.9, which supports the formation of more stable HAP complex. Also the BOP and BON have higher pH which supports the formation of stable calcium phosphate complex. The study suggest that the P removal capacity of the samples depend on the release of Ca^{2+} and OH^-into the water samples. The reactive materials which were procured from India did not perform well as the reactive materials did not have a good concentration of CaO.

CHAPTER 5

PILOT SCALE VERTICAL FLOW CONSTRUCTED WETLAND FOR TREATMENT OF SCHOOL SEPTIC TANK WASTEWATER

5.1. Abstract

VFCW are very efficient in the treatment of COD and BOD, but the biological removal of total nitrogen is often restricted by lack of anoxic conditions and carbon source. VFCW provide a good condition for nitrification as the system has good air to water contact. There has been a lot of efforts to perofrm full nitrogen treatment by combining aerobic and anoxic systems. The objective of our work was to change the hydraulics of vertical flow under tropical climate to maximise total nitrogen removal. A two stage VFCW was installed at a school. The system was commission in February 2018. The 1st stage of the wetland was passively aerated by natural percolation with unsaturated flow whereas in the 2nd stage, the aeration pipes were sealed to make anoxic conditions and by implementing saturated flow for denitrification. In the previous study (VFCW at BITS campus) only one feeding mechanism was followed i.e. pumping the wastewater to the 1st stage and after 1st stage it was pumped to the 2nd stage. In this case two feeding strategies were applied. In the first feeding strategy the wastewater (10 m^3/day) was pumped for 15 weeks from the first chamber of a septic tank (before settling) to the 1st stage, from there it flows to 2nd stage which is kept anoxic. In the second feeding strategy 50% of the wastewater was pumped for 8 weeks to the 1st stage and the rest was pumped to 2nd stage directly for 8 weeks. This was done to increase the COD content in the 2nd stage for denitrification. The system was monitored for COD, TKN, nitrites, nitrates, NH_4-N and phosphorus removal. The removal efficiency of COD, TKN, nitrates, nitrites, NH_4-N, and phosphorus were in average of 89 %, 57 %, 38 %, 64 %, 62 % and 62 % respectively in the first feeding strategy. During the second feeding strategy assay, the removal efficiency of COD, TKN, nitrate, nitrites, NH_4-N, and phosphorus were in average of 84 %, 64%, 4%, 46%, 69% and 63% respectively. It was observed that as the COD/N ratio decreased, the nitrification and denitrification rate of the system also decreases. The overall treatment efficieny of the system was better in the first strategy than in the second strategy.

5.2. Introduction

The complete treatment of nitrogen is one of the major concerns of wastewater treatment by VFCW. It can provide efficient treatment for organics and other parameters (Luederitz et. al. 2001). The treament of nitrogen in VFCW is affected by various factors like oxygen availability and C/N ratio. The biological removal of nitrogen in conventional wetlands is often limited by the absence of an organic carbon source (Xia et al. 2008). Daigger et. al., 2004, reported that 2.44 mg of oxygen were required for 1 mg of nitrogen removal. Zhao et al. 2010 reported that when COD/N ratios changed from 2.5 to 10 in conventional VFCWs, 25–62% total nitrogen (TN) removal efficiency can be achieved and the highest TN removal rates were observed at COD/N ratio of 2.5 – 5. The complete removal of nitrogen depends both on the nitrification process with enough oxygen and denitrification with adapted anoxic conditions and enough organic carbon source (Fan et al. 2013).

VFCW installed with passive aeration ventilation tubes provides a favorable condition for nitrification hence, nitrogen and ammonia are converted to Nitrates. The denitrification process in the vertical unsaturated wetland is difficult to achieve due to the lack of anoxic conditions (Kim et al., 2015). The conventional technologies available like sequential batch reactor (SBR), Membrane Bioreactors etc. are effective but rather expensive and hard to maintain for small decentralized sources of wastewater (Zhang et al., 2014; Hauck et al., 2016; Hu et al., 2019). The CW system have a strong potential for implementation in developing nations, especially in small schools.

The objective of this work was to develop a decentralised wastewater treatment system for schools. Goa government constructed a sschool complex in cujira housing six schools. Each school generates approximately 10m3 of wastewater per day. These schools have septic tanks for primary treatment. These septic tanks are not equipped with proper soakpits, so the septic tanks overflows and partially treated wastewater is realeased to neighboring creeks and rivers. One of the major concern with the school wastewater is that it has high concentration of Nitrogen as compared to municipal wastewater as urinals are mainly used and the schools are non-residential. This composition indicates an imbalance between carbon and nitrogen, resulting into low C/N ratio (Garzón-Zúñiga et al. 2011).

5.3. Materials and methods

5.3.1. Design of the wetland

A two-stage vertical flow wetland was designed and implemented in Dr. K B Hedgewar School, Cujira, Bamboli, Panjim, Goa, India. The existing septic tank at the school is a 16 m^3 RCC (Reinforced Cement Concrete) tank with baffles in the middle. The school generate 10 m^3 of wastewater per day, it was calculated on the basis of number of times the overhead tanks has to be filled per day [3 (Refill) x 3 m^3 (Tank size) = 9 m^3]. The CW was made up of MS sheet, coated with fibre reinforced plastic (FRP) to make it rust proof and to increase the lifespan of wetland. The surface area of 1st stage VFCW is 1.2 m^2 and 2nd stage is of 4.8 m^2. The surface area of the 1st stage was kept smaller as compared to the 2nd stage (1:4), this was done to increase the loading rate per square meter and minimizes the reduction of COD in the 1st stage. The advantage of reducing the surface area of the 1st stage was that there will be less COD reduction in the 1st stage and this help to target a C / N ratio of 5-10 in the 2nd stage to improve denitrification (Zhao et al. 2012).

The ventilation system was provided in the 1st stage to maintain aerobic condition to facilitate nitrification process. The second stage was kept anoxic at the bottom to facilitate denitrification by removing the ventilation pipes. The ventilation system in the 1st stage was modified as compared to our previous studies (Chapter 3). The new design of ventilation pipes is shown in Figure 5.1; in which the pipes were cut at the bottom instead of making holes (Figure 3.1) to avoid the chances of water retention in the pipes which can leads to the development of anaerobic patches at the bottom of the 1st stage. The sand filling in the system was adopted from Paing et al.,2015 (Table 5.1) The gravel and sand from the river have high hydraulic conductance which helps to provide better surface for the development of biofilm and nutrition adsorption (Sundaravadivel et at., 2003).

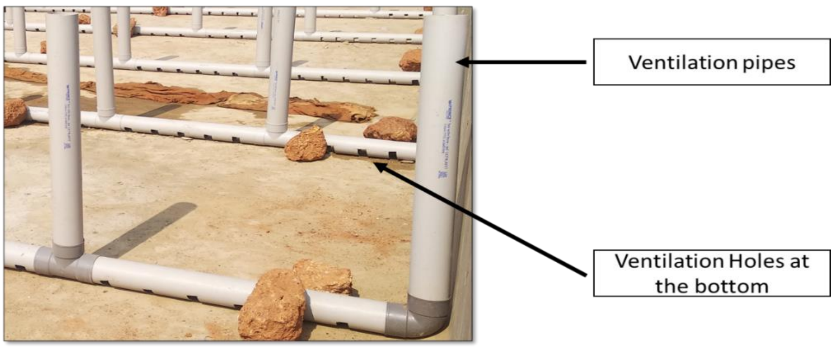


Fig 5.1: Modified ventilation system for the wetland

5.3.2. System operation

The wastewater from the school toilets was first collected in the septic tank then pumped to the 1st stage of the wetland which was placed on an elevated platform (fig 5.2). From the 1st stage, the water percolated to the 2nd stage by gravity. From the 2nd stage, the treated water goes to the storage tank and can be used for different purposes like gardening, car wash etc. The system was designed to minimize energy use by implementing only one pumping system. 10 m^3 wastewater was treated per day by as system. The system was fed with 8 batches of wastewater per day. This was done to keep the wetland wet during the day times as the environmental temperature in Goa is very high (>35°C) and water evaporates from the surface of wetland. Based on previous research, *Canna indica* was chosen as the plant species for the system (Lombard et al. 2017).

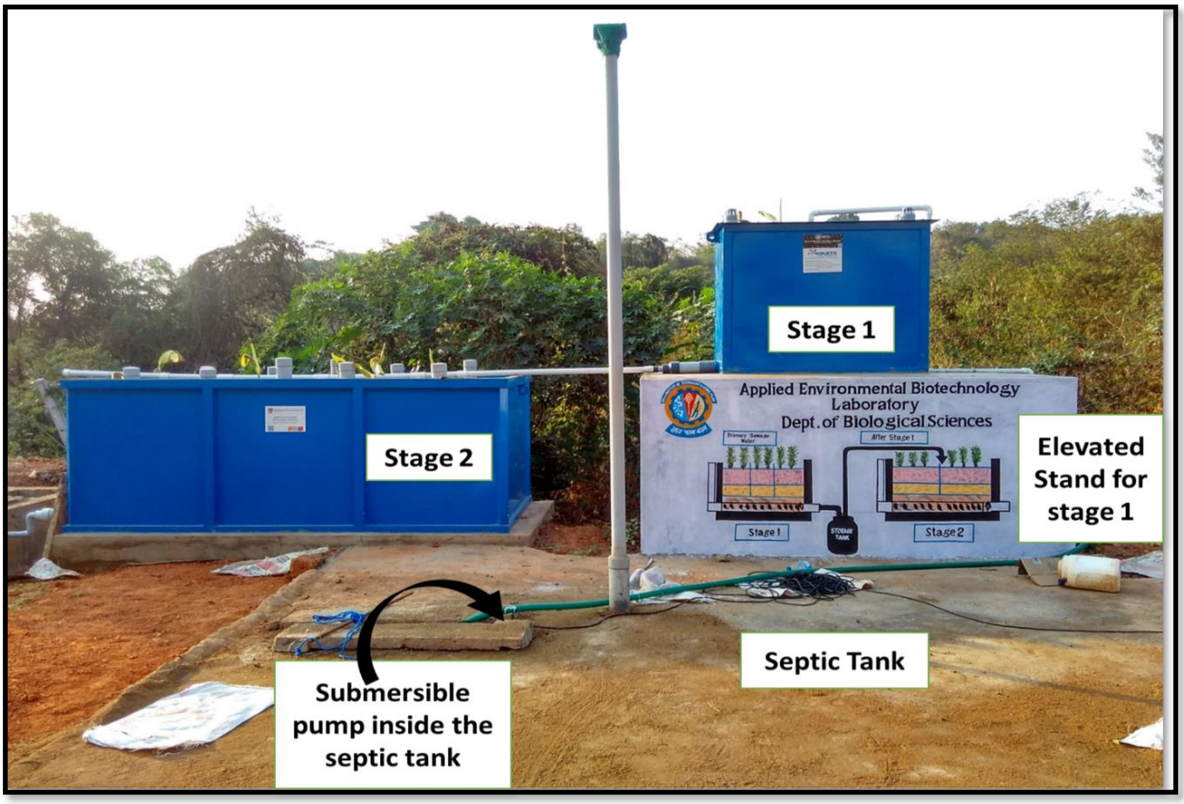


Fig 5.2: Design and construction of the wetland

5.3.3. Conditions of operation

In the first feeding strategy, 10 m^3 water was flushed in 8 batches per day from the septic tank into the 1st stage, which flows into the 2nd stage by gravity. From the 2nd stage, it goes to the storage tank. The first feeding strategy was designed as per the previous studies. These experiments were performed for four months after the CW commissioning to understand the working of the wetland as the 2nd stage was partially anaerobic. Sampling was done weekly and all the parameters were analyzed.

In the second feeding strategy assay the treatment of wastewater was divided into two steps. In 1st step 5 m^3 of water was pumped to the 1st stage from the septic tank. In the 2nd step the remaining 5 m^3 water was directly fed into the 2nd stage with another pumping system. Both the steps were carried out simultaneously. This was done to increase the carbon to nitrogen ratio in the second stage.

5.3.4. Analytical Methodology

The samples were collected from each of the beds and analysed for different wastewater parameters; COD, TKN, total solids, volatile solids and phosphorus according to standard APHA methods. TOC was analysed by Shimadzu TOC analyser. Nitrates, Nitrites, and NH_4-N were analysed by Merck kits.

5.4. Results and discussion

Table 5.2 shows that, as expected, school wastewater was high in nitrogen (ammonia) content (300 ± 100 mg N/ L TKN, 100 ± 27 mg N / L (NH4-N)) and proportionally low in COD content (300 ± 31 mg / L). The ratio of COD / N was of 2.95. As the HRL (8.33 m/day) and the OLR (2.52 kg COD.$m^{-2}d^{-1}$) for the 1st stage was very high, only 42 percent decrease in COD was observed (down to 174 ± 47 mg / L in average). After the 2nd stage, a complete decrease in the COD was observed which indicated a comprehensive treatment of the wastewater from the septic tank (Van Cleemput et al., 2007). The 1st stage of the of the VFCW was offering aerated conditions (percolation and passive ventilation) such as an increase in the concentration of Nitrate was clear (From 69 ± 11to 117 ± 45 mg N-NO_3/L) and even Nitrites were observed (From 22 ± 13 to 38 ± 18 mgN-NO_2/L) which means that the nitrification process was incomplete. After 2nd stage a decrease in the concentration of Nitrates (From 117 ± 45 to 71 ± 32 mgN_NO3/L) and Nitrites (from 38 ± 18 to 13 ± 9 mgN-NO2/L) was observed. The increase in the concentration in the 1st stage was due to aerobic condition in the wetland and the decrease after 2nd stage was due to anaerobic condition in the wetland (Table 5.2) (Tao et al., 2012). From the 1st stage result, it could be concluded that the nitrification was occurring in the system and that enough COD was also available for the 2nd stage anoxic process (Molle et al., 2008).

From Table 5.2 it could be concluded that the COD in the septic tank was around 302 mg/l and the total nitrogen was 102 mg/l. Therefore the COD/N ratio was 2.95 in the 1st stage and 1.85 in the 2nd stage. Theoretically, the COD/N requirement for nitrification and denitrification is 2.86 considering the electron transmission balance between organics and nitrates, but in practice the values will always be larger than 2.86 (Copp et al., 1998). The complete removal of nitrogen depends on how efficient is the system for nitrification (Maltais-Landry et al. 2009). For most wetlands, the DO requirement for nitrification is around 1.5 mg / L of wastewater. Mostly passively aerated VFCW failed to achieve the high level demand of oxygen, causing an anaerobic environment in the system thus leading to low transformation of NH4-N by the nitrifiers (Fan et al.2013). This could be achieved by intermittent forced aeration to the 1st stage of the system (Fan et al. 2013). Small quantity of nitrate concentration was rapidly removed by effective denitrification in anoxic conditions in the 2nd stage of the reactor where the C/N ratio was 1.89 (Table 5.2). TN and NH4-N was still present in the effluent because 1st stage was too small and only partial nitrification occurred.

From Table 5.3 and fig 5.5 it could be noted that after four months of operation of the wetland, the COD in the septic tank water reduced from 302.47 ± 30.83 mg/L to 166.23 ± 91.74 mg/L (OLR for 1st stage = 0.69 kg/m^2/day). As the school was non-residential and the pollution load was mostly due to urinals, COD value decreases in the septic tank over a period of time. This is primarily due to the operation of wetland which was not allowing the solids to accumulate in the septic tank. Due to this, COD/N ratio was also reduced to 2.0 in the 1st stage (OLR for the 1st stage = 0.69 kg/m^2/day). As per the 2nd set of experiments, the COD/N ratio for the 2nd stage was just 1.68 (OLR for the 2nd stage = 0.26 kg/m^2/day). COD removal efficiency of the system in the 1st set of experiment was 89 % (N=15). It got reduced to 84 % in the 2nd set of experiment (N=8), but there was an increase in the treatment efficiency of ammonia (64 % to 69 %) and TKN (57 % to 64 %). A decrease in the treatment efficiency of Nitrate (38 % to 4 %) and Nitrites (64 % to 46 %) was observed after 2nd stage, which indicate that, as the COD/N ratio got decreased in both the stages, the nitrification and denitrification rate also got reduced. Qian Feng et al. (2011) found that, the nitrification rate increases and denitrification rate decreases with the decrease in COD/N ratio. As per the study conducted by Zhimin Fu et al. 2009 the TN removal efficiency decreases with the reduction of COD/N ratio. The phosphorus removal efficiency in the first strategy was 62.02 % and in the second strategy it was 63.32 %. There was no significant difference in the phosphorus removal efficiency. The phosphorus is mainly removed by adsorption to surface media (Kovacic et al. 2000). As, it can be observed from the results, that the overall pollutant removal efficiency of the system was better in first strategy. From the results it could be concluded that the first strategy of purging waste water to the system was a better strategy to be followed than the second strategy of purging.

5.5. Conclusion

The wetland deigned at the school was monitored for all the parameters. The removal efficiency of COD, TKN, nitrate, nitrites, NH_4-N, and Phosphorus was around 89 %, 57 %, 38 %, 64 %, 62 % and 62 % respectively in the 1st set of experiments and in the 2nd set of experiment the removal efficiency of COD, TKN, Nitrate, Nitrites, NH_4-N, and Phosphorus was around 84 %, 64 %, 4 %, 46 %, 69 % and 63 % respectively. The wetland was designed in such a way so as to ensure nitrification process in the 1st stage and denitrification process in the 2nd stage. Form the data it could be concluded that both processes were occurring in the wetland. The inlet COD of the water decreased with passage of time, due to the removal of solid deposits in the septic tank. In the 2nd set of the experiments total nitrogen removal was just 1 % higher than in the 1st set of experiments. In our study the total nitrogen removal was comparatively low due to reduction of COD in the septic tank water which reduced the COD/N ratio from 2.95 in the 1st set of experiments to 2.0 in the 2nd set of experiments. This suggests that the first strategy to handle sewage from the school's septic tank could be better. The efficiency of the system can be increased by providing some source of carbon in the inlet water.

Table 5.1: Design characteristic of VFCW (Modified from Paing et al.,2015)

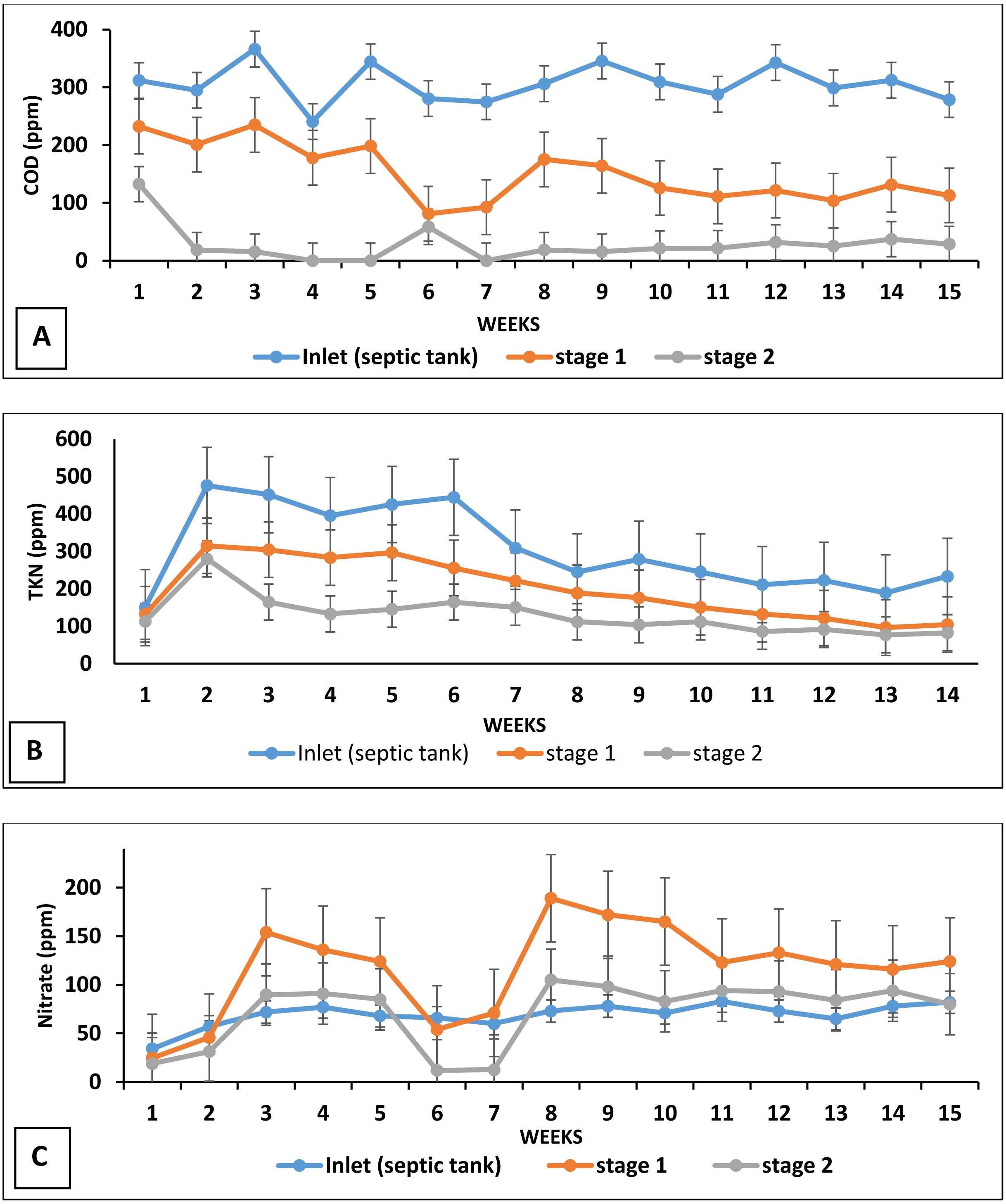
Filter Media	Stage 1	Stage 2
River gravel	40-50 cm gravel 2/8 mm	40 cm sand 0/4 mm
	15-20 cm gravel 10/20 mm	15-20 cm gravel 4/10 mm
	20 cm gravel 20/40 mm	5 cm 20/40 mm and 15 cm gravel 10/20 mm

Table 5.2: Mean and standard deviation of different parameters of the inlet and outlet water for 1st set of experiments

Parameter (mg/l)	Inlet (septic tank)	Stage 1	Stage 2	% Reduction
COD	302 ± 30	174 ± 47	30 ± 30	89.92
TKN	299 ± 101	193 ± 74	127 ±48	57.60
Nitrate	69 ± 11	116 ± 44	71 ± 31	38.85
Nitrite	21 ± 13	37 ± 17	13 ± 8	64.88
NH4	103 ± 27	72 ± 22	38 ± 15	62.98
Phosphorus	18 ± 7	12 ± 5	6. ± 3	62.02
TN	102.61	94.11	49.96	51.31

Table 5.3: Mean and standard deviation of different parameters of the inlet and outlet water for 2nd set of experiments

Parameters (mg/l)	Inlet (septic tank)	Stage 1	Stage 2	% Reduction
COD	166 ± 91	84 ± 60	26 ± 14	84.16
TKN	204 ± 101	118 ± 40	72 ± 17	64.75
Nitrate	67 ± 14	80 ± 28	77 ± 9	4.16
Nitrite	17 ± 9	16 ± 15	8 ± 4	46.03
NH4	80 ± 10	52 ± 8	24 ± 5	69.61
Phosphorus	15 ± 2	10 ± 3	5 ± 2	63.32
TN	83.07	64.09	39.20	52.82


400
300
200
100
0
COD (ppm)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
WEEKS
A
Inlet (septic tank)
stage 1
stage 2
600
500
400
300
200
100
0
TKN (ppm)
1 2 3 4 5 6 7 8 9 10 11 12 13 14
WEEKS
B
Inlet (septic tank)
stage 1
stage 2
200
150
100
50
0
Nitrate (ppm)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
WEEKS
C
Inlet (septic tank)
stage 1
stage 2

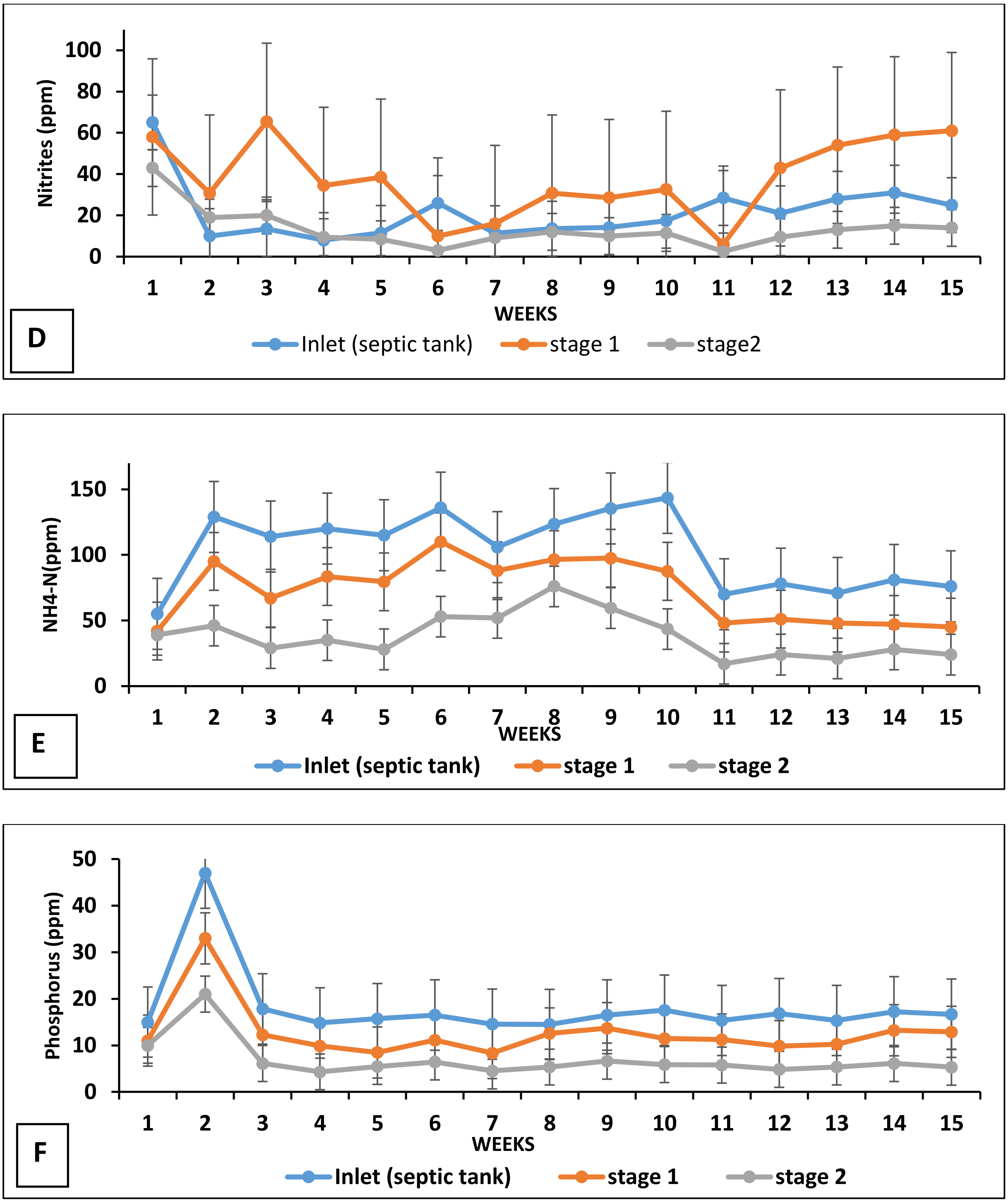
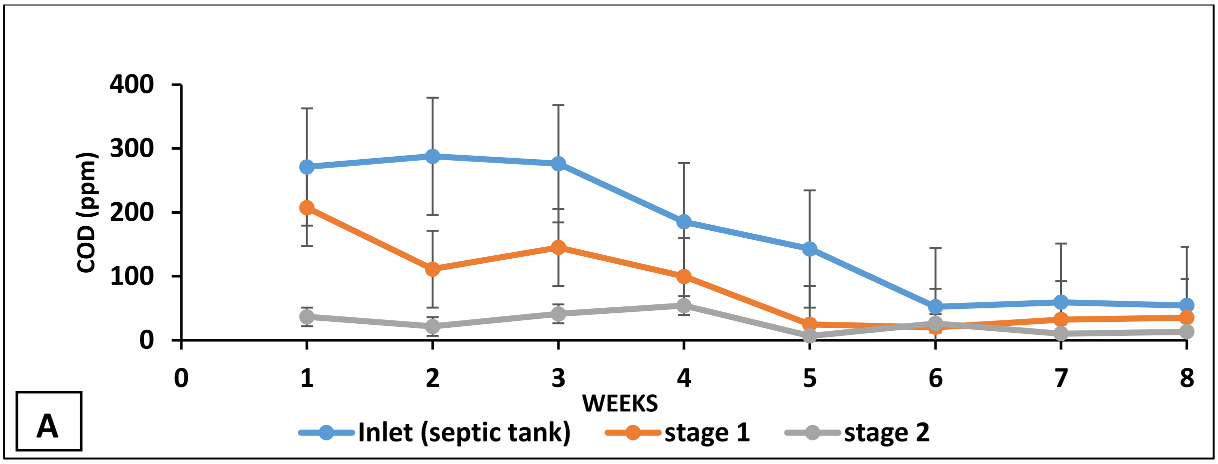
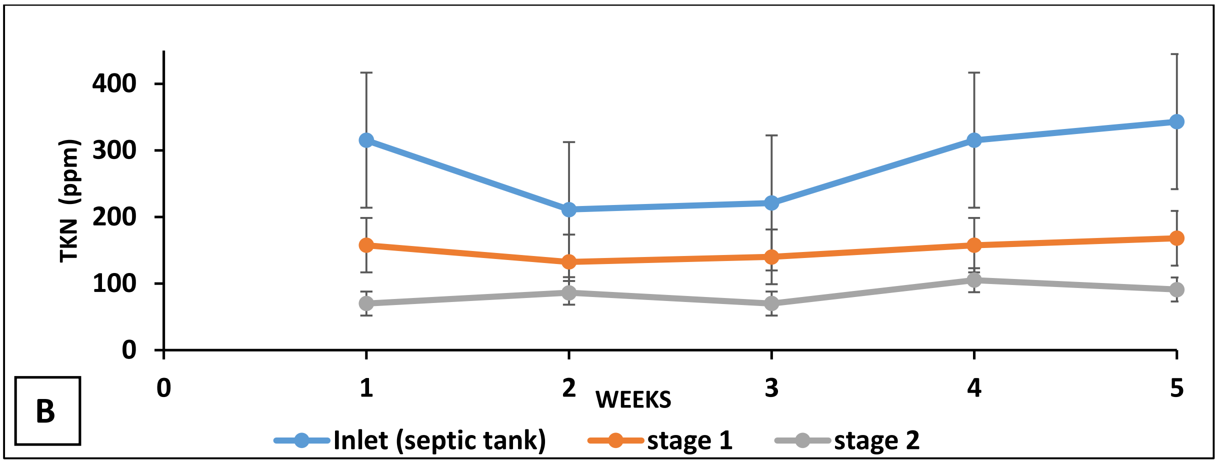
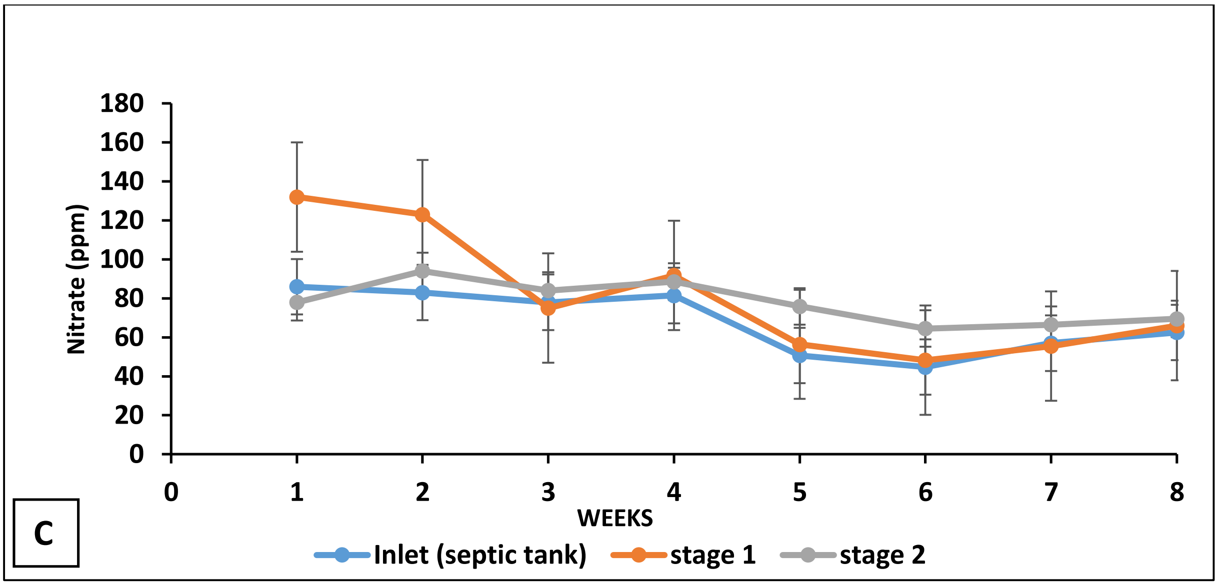


Fig 5.3: Nutrient removal efficiency of the wetland after 1st stage and 2nd stage for 1st set of experiments. (A) COD, (B) TKN (C) Nitrate (D) Nitrite (E) NH_4- N (F) Phosphorus


COD (ppm)
400
300
200
100
0
0 1 2 3 4 5 6 7 8
WEEKS
A
Inlet (septic tank)
stage 1
stage 2


TKN (ppm)
400
300
200
100
0
0 1 2 3 4 5
WEEKS
B
Inlet (septic tank)
stage 1
stage 2


Nitrate (ppm)
180
160
140
120
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8
WEEKS
C
Inlet (septic tank)
stage 1
stage 2

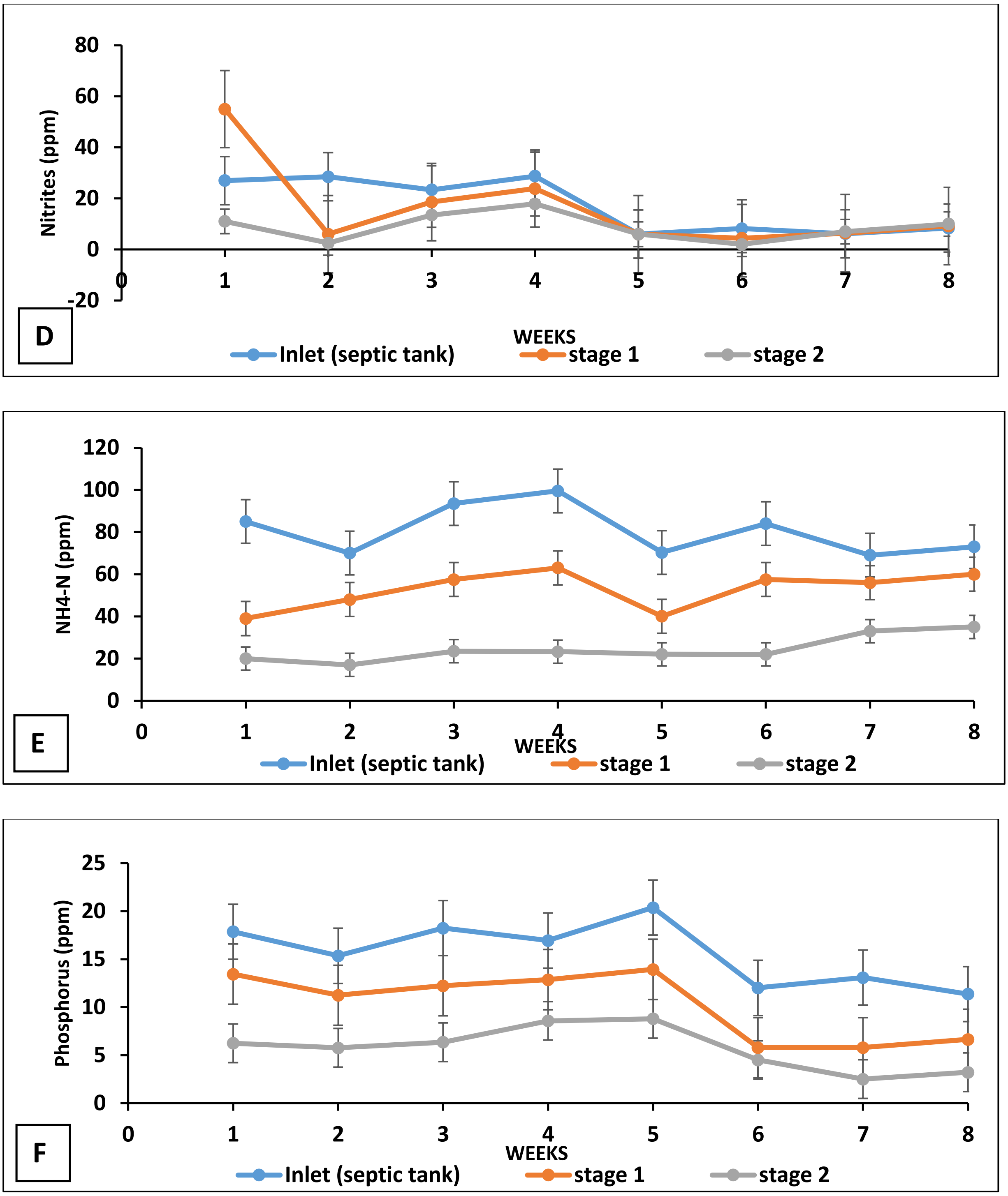


Fig 5.4: Nutrient removal efficiency of the wetland after 1st stage and 2nd satge for 2nd set of experiments. (A) COD, (B) TKN (C) Nitrate (D) Nitrite (E) NH_4- N (F) Phosphorus

CHAPTER 6

DEMONSTRATION OF IMPROVING RIVER SAL QUALITY BY VERTICAL FLOW CONSTRUCTED WETLANDS

6.1. Abstract

The main objective of this study was to demonstrate the treatment of 40 m^3/day of highly contaminated river water by constructing a 500 m^2 VFCW. River Sal is one of the most important rivers in Margaon city, Goa, India. This river is about 35 kms long and is contaminated by domestic wastewater and industrial waste having an average content of 73mgCOD/L, 55 mgN-NO3/L and 31 mg NH_4-N/L which make it closer to a primary settled domestic wastewater rather than a surface water. Two-stage VFCW was chosen as a treatment technology, as it has many advantages over conventional techniques, being one of the most cost-effective, simple to use and reliable wastewater treatment techniques. A two stage VFCW was constructed to provide nitrification in 1st stage and denitrification in the 2nd stage by making the 2nd stage anoxic to favour total nitrogen removal. The surface area for the 1st stage is 150 m^2 and for the 2nd stage is 350 m^2. The HLR of the system was 0.266 m/day. The Nitrate in the inlet wastewater was 49 mg/L and in the outlet it was 38.89 mg/L, indicating very low removal efficiency. It might be treated by increasing the C / N ratio in input water (3.5 current ratio) for proper denitrification in the 2nd stage.

6.2. Introduction

According to the United Nations Environmental Protection report, an estimated 90 % of all untreated wastewater in developing countries is discharged directly to rivers, lakes or the oceans (Corcoran et. al. 2010). Such discharges are part of the reason why de-oxygenated dead zones are growing rapidly in the water bodies. The Sal River is a small river with an average flow of 694.4 MCM (Million cubic meter)/day in Salcette Taluka, Goa, India. The river opens near Verna, Margaon (15°20'22.8"N 73°54'45.4"E) and passes through the villages of Benaulim, Navelim, Varca, Orlim, Carmona, Dramapur, Chinchinim, Assolna, Cavelossim, Mobor and drains itself into the Arabian Sea at Betul. The river passes through 11 villages, one industrial estate and many agricultural fields getting polluted by many point source and non-point source of pollution. The focus remains on thousands of litres of untreated sewage from Margaon and Fatorda (area 15.1 km^2) being discharged into the river Sal. This discharged is often untreated and remain a major source of pollution leading an average BOD of 4.2 - 16.8 mg/L of the river (RCC report Govt. of Goa).

The recent report by the Goa state pollution control board (GSPCB) had categorised River Sal as the most polluted river in the state. The GSPCB who examined the river on various parameters from April 2011 to January 2013 found that two major components – BOD (4.2 – 16.8 mg/L) and faecal coliform (780 – 4900 MPN/100 ml) have largely exceeded the permissible limits (BOD < 3mg/L, FC < 500 MPN/ 100 ml) at all seven monitoring stations in river Sal (Swati et. al. 2015, RCC report Govt. of Goa 2019).

As the pollution level in the river is very high and there is a need to implement treatment system. A pilot scale demonstration of treatment systems which is practical and affordable will be of utmost importance. The conventional activated sludge or related treatment processes are capital and energy intensive and it will take several years for complete infrastructure (sewer network and STPs) to cover 100 % population (Gkika et al. 2014). There is different nature based solution that can be implement for the treatment of river Sal such as treatment ponds, horizontal flow wetlands, Vertical flow wetlands, Algal ponds etc. Among all the NBS technologies (Garfí et al. 2017) VFCW system is interesting as it requires low energy input. It also has the advantage of being one of the most cost-effective wastewater treatment technologies, easy to operate and reliable. Nonetheless, VFCWs require larger area than conventional technologies but less than horizontal CW or waste stabilization ponds (Luederitz et al. 2001). To our Knowledge little is known about treating highly polluted river water by CW (Green et al. 1996). Therefore, decentralized VFCW as natural treatment systems could be a better alternative for the treatment of polluted river water. The aim of this study was to demonstrate the improving the quality of river water by treating 40 m^3 /day of polluted river water and draining into river Sal by of vertical flow CW.

6.3. Materials and Methods

6.3.1. Site selection

The first condition of site selection was to select a site which is a highly polluted drain and tributary covering a major part of the Margaon city. The second condition for selection was to find a land which is available for setting up the VFCW. After collecting the data from four different sites (Appendix III), Margaon wholesale fish market site (On the bank of Sal river) was selected for the construction of demonstration plant.

Margaon whole Sale fish market

The site is located on the side of river Sal (15°17’17.9” N 73°56’59.6” E) and has available area for the construction of the wetland. The site has two advantages 1) Wetland can treat the water from the river providing treatments for all the point and nonpoint sources of pollution. 2) It can also provide a solution for the treatment of wastewater from the fish market. The wastewater from the fish market is highly polluted and is released into the River Sal (Point source of pollution). This site was finalized for the construction of wastewater treatment plant (fig 6.1, A and B). The condition of the site before the establishment of VFCW is shown in fig 6.2.

Fig 6.1: Google images of the site (A) Boundary of the fish market (B) Location of the site

Fig 6.2: Fish market before the construction of VFCW system.

6.3.2. Design and Construction of VFCW

VFCW was constructed next to Margaon wholesale fish market, having total surface area of 500 m^2. The 1st stage has total surface area of 150 m^2 and the 2nd stage has of 350 m^2. The VFCW at fish market was designed based upon VFCW already operational in BITS campus (Chapter 3). The BITS campus system was operated with an OLR varying from 71.6 g/L/day (HLR = 0.15 m/day) to 275.96 g/L/day (HLR = 0.225 m/day). Following the same HLR and OLR, the VFCW at fish market was specifically designed for 0.266 m / day HLR and 80.74 g/L/day OLR. The 2nd stage of the system was made anaerobic, based on the school wetland design (Chapter 5). First stage was constructed on an elevated platform of one meter from the ground level in order to maintain the gravitational flow of water from 1st stage to 2nd stage (Fig 6.3). The walls of the tanks were made from locally accessible laterite stone and as this is less expensive than other stone kinds (Bricks). Water proofing of the tank was done by cement and sand mixture to avoid any leakage to the ground. The 1st stage was provided with ventilation pipes similar to school wetland (Chapter 5). The distance between aeration outlets was kept 1m in the row and 2m in the columns. The sand filling of the wetland was made according to the table 3.1 (Chapter 3). Two septic tanks of capacity 7 m^3 each were placed underground before the 1st stage of the CW to store wastewater from the River and also from the fish market (future scope). *Canna indica* was planted in both the wetlands (1st stage and

2nd stage). 500 plantlets of *Canna indica* were procured from ICRISAT Hyderabad. Each plantlet was planted per meter square to ensure the proper distribution of vegetation all over the system (Fig 6.4).

Fig 6.3: Two stage vertical flow wetland after construction

Fig 6.4: 1st stage and 2nd stage of vertical flow CW with *Canna indica* plantation

6.3.3. Working of the wetland system

The plant was designed to treat 40 m^3 of effluent per day. 40 m^3 of water from River Sal was pumped to the underground septic tanks of total capacity 14 m^3 with the help of submersible pumps at regular intervals (4 times in a day i.e. 10 m^3 each time). 5 m^3 of wastewater was pumped to the 1st stage from the septic tank in each flush spread over 8 times a day with the help of pumps (fig 6.5).

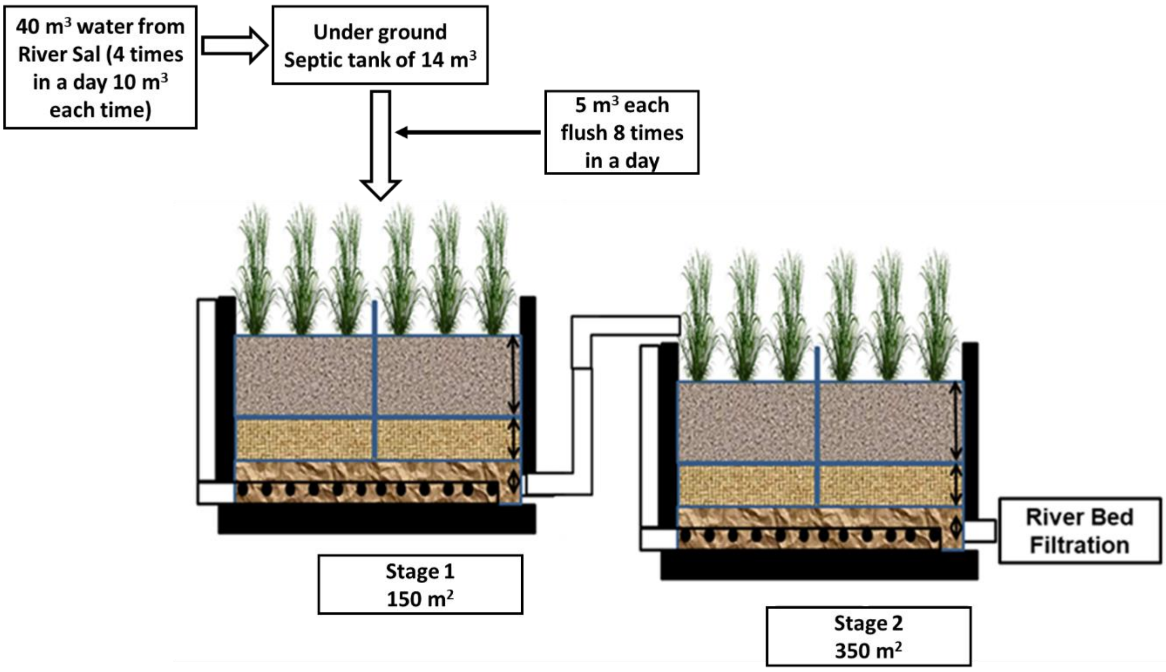


Fig 6.5: Design and working of Vertical flow CW at Margaon whole sale fish market

6.3.4. Sample collection and Analytical methods

A grab sampling was done at each site and from the wetland. The samples were analysed for wastewater parameters including COD, TKN, Total solids, Volatile solids and Phosphorus according to standard APHA methods. The TOC and Total nitrogen (TN) was analysed by Shimadzu TOC analyser. Nitrates, Nitrites, and NH_4-N were analysed by Merck kits.

6.4. Results and Discussion

6.4.1. Site selection

Margaon wholesale fish market

The idea of constructing a wetland near fish market originated from the protest of people, as the fish market wastewater was polluting the adjacent river Sal. VFCW would treat the wastewater from the river water (Nonpoint source) and also the fish market (Point source). The treated water could be reused inside the market for washing purpose. The flowering plants in the system could increase the aesthetic value of the market and also motivate the peoples to maintain cleanliness in and around the market area.

From Table 6.3 it can be observed that the site was highly polluted and the acquisition of land was under South Goa Planning and Development Authority (SGPDA). The SGPDA was planning to renovate the fish market and was forth coming to set up our proposed VFCW. The wastewater from fish market had a very high COD of 980.96 mg/L (N = 9) on an average (Site 1, 2, 3 in table 6.1 were the wastewater from fish market from three different drains) and the water (Site 4 in table 6.1 was the water from river Sal) from river had a COD 72.97mg/L (N = 9). Jing et al. 2001 also found similar COD for river water i.e around 96 mg/ L. However, the Nitrate (55.285 mg/L), Nitrite (12.088 mg/L) and NH_4-N (31.142 mg/L) was very high in River Sal. From Jing et al. 2001 the Nitrites and Nitrates in the river was in the range of 0.007 mg/L to 0.234 mg/L and 0.212 mg/L to 1.109 mg/L respectively, suggesting a very pollution rate in river Sal. The quality of river water was affected by various point and nonpoint sources of pollution (Suthar et al. 2010). Considering the high organic load form the fish market wastewater of 65 g/m^2/day, the plant was designed for maximum HLR (0.266 m/day) according to the data acquired from the BITS campus VFCW (Chapter 3) which has the highest HLR of 0.225 m/day. This design can easily handle the wastewater from river Sal and if needed it can also treat the wastewater from fish market. From table 6.4 it can also be noted that the TKN in River water is high i.e. 117.14 mg/L. To treat the nitrogen present in the River water the 2nd stage of the system was made anaerobic to support denitrification (Sirivedhin et al. 2006, Vymazal et al. 2007).

Table 6.1: Analysis of wastewater from site

Sampling points	**COD (mg/l)**	**Nitrite (mg/l)**	**Nitrate (mg/l)**	**NH_4-N (mg/l)**	**Phosphorus (mg/l)**	**TKN (mg/l)**
Back side drain (site 1)	1206 ±297	281 ± 25	61 ± 3	252 ± 21	57 ± 13	702 ± 54
Front drain(Site 2)	1190 ± 234	285 ± 22	53 ± 3	217 ± 18	49 ± 9	548 ± 72
Side drain (Site 3)	545 ± 123	399 ± 44	61 ± 3	149 ± 14	75 ± 13	672 ± 60
River site 4	72 ± 38	55 ± 10	12 ± 1	31 ± 7	15 ± 5	117 ± 43

6.4.2. Two stage vertical flow CW

The system started working fully in the first week of February, 2019. The system was fed with 40 m^3 of wastewater per day from the river. The different pollution parameters are depicted in the fig 6.6, 6.7 and 6.8. From the figure it can observed that the COD of the river water was 18.02 mg/L but during the site selection it was around 72.97 mg/L. This can be because of the settling of most of the organic content at the bottom of the river or may due to high eutrophication of the river itself (When samples were collected for the selection of site i.e. during march 2018 just before the rainy season, there was no growth of grasses or any other type of vegetation in the river but after the rainy season huge growth of vegetation was found in the river) (Morrall et. al. 2004). The river is covered with thick grass which acts as a natural wetland, which could have contributed to the reduction of COD in the river (Wang et. al. 2011). Further reduction of COD after treatment can be observed from the data.

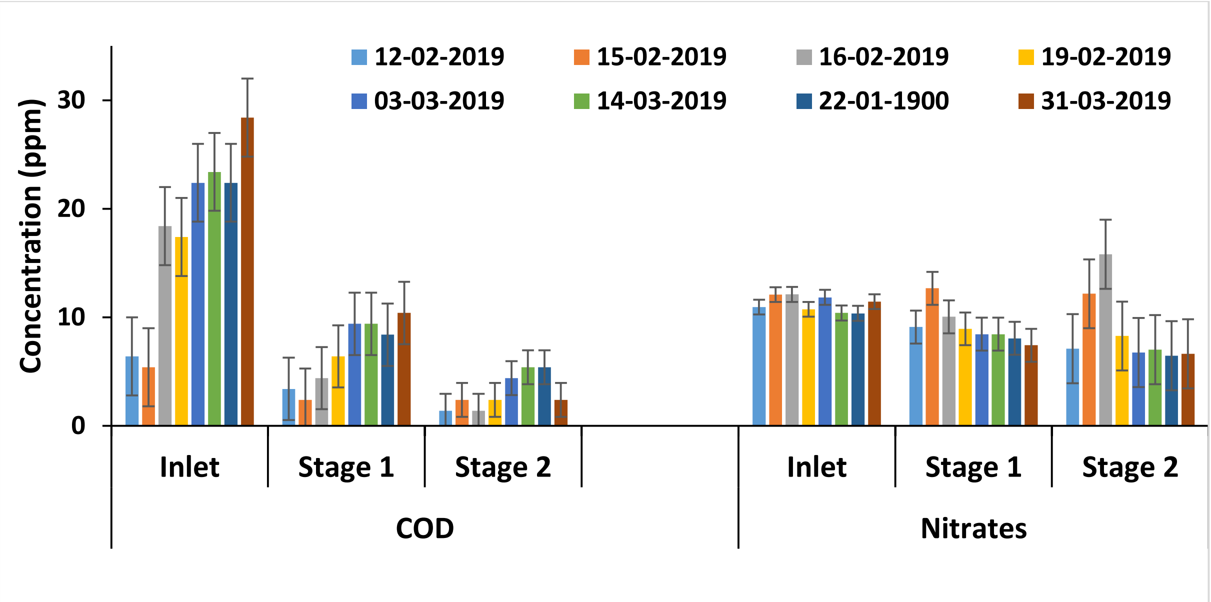


Fig 6.6: COD and Nitrates content of inlet, after first stage and the outlet of the system

The TOC of the water from the river was low but the inorganic carbon (IC) was higher than the TOC (Fig 6.7). This could be due to the industrial pollution of the river as it originates near an industrial area and flows through different parts of Verna industrial areas (Sikder et al. 2013). The river also passes through different villages along the flow route, were the outlets of toilet and domestic wastewater is directly discharged into the river.

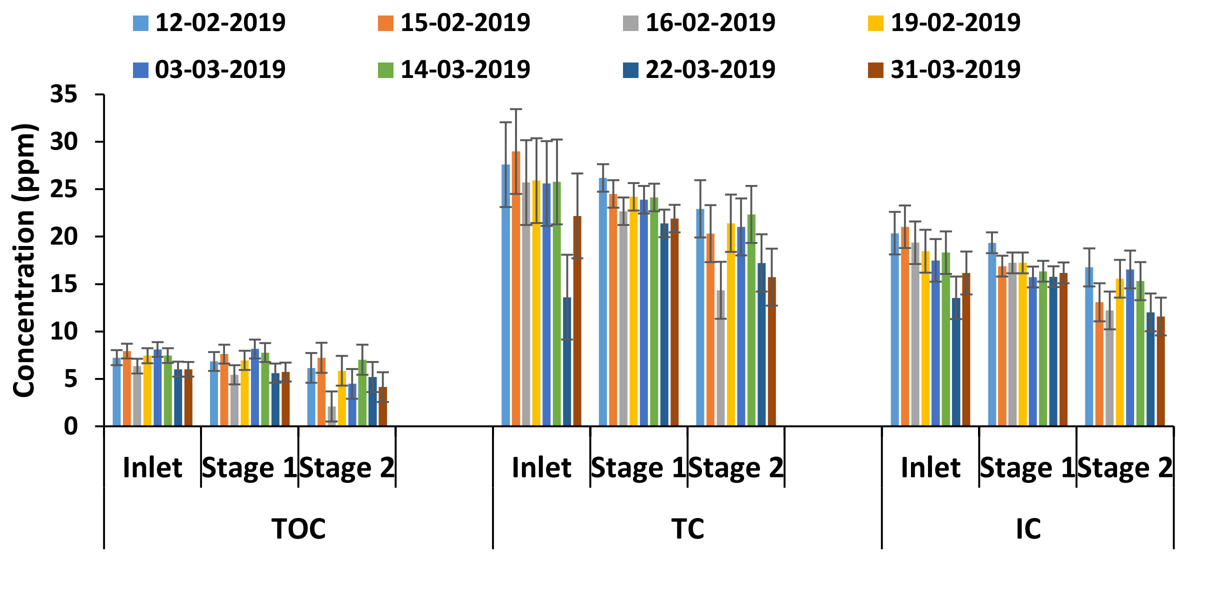


Fig 6.7: TOC, TC and IC content of Inlet, after first stage and the outlet of the system

The nitrate (NO_3) in the inlet water was found to be high i.e. 11.24 mg/l (fig 6.6) and the COD was very low (18.02 mg/l). The total nitrogen of inlet water was 5.086 mg/L. This suggests that the denitrification could not be achieved as the carbon to nitrogen ratio was very low i.e. 3.54. For effective denitrification the C/N ratio should be in the range of 5-10 (Ingersoll et al. 1998; Chen et al. 2018). As the nitrogen was already in the form of nitrates, the process of denitrification can be achieved if some amount of carbon could be brought in to the system to increase carbon to nitrogen ratio. Carbon can be brought in by adding the wastewater from the fish market which has high COD and Nitrogen content. Form fig 6.8 it can be concluded that the ammoniacal nitrogen in the water is relatively very and does not complies with the US EPA limits, according to which natural unpolluted should have ammonia less than 0.02 mg/l as nitrogen. The increased level of ammonia adversely affects the flora and fauna of water bodies. This would adversely affect the growth and development of fishes and finally leads to the death (Eddy et al. 2005). The natural level of phosphorus in water should be less than 0.03 m/l, but as we can see from fig 6.8 the level of phosphorus is very high in the river that is around 2 mg/l. The high level of phosphorus and ammonia in the river water will leads to eutrophication of the river. Due to eutrophication the level of DO in the river water will be decreased, this will lead to the death of flora and fauna present in the river and thus, disturbing the ecosystem.

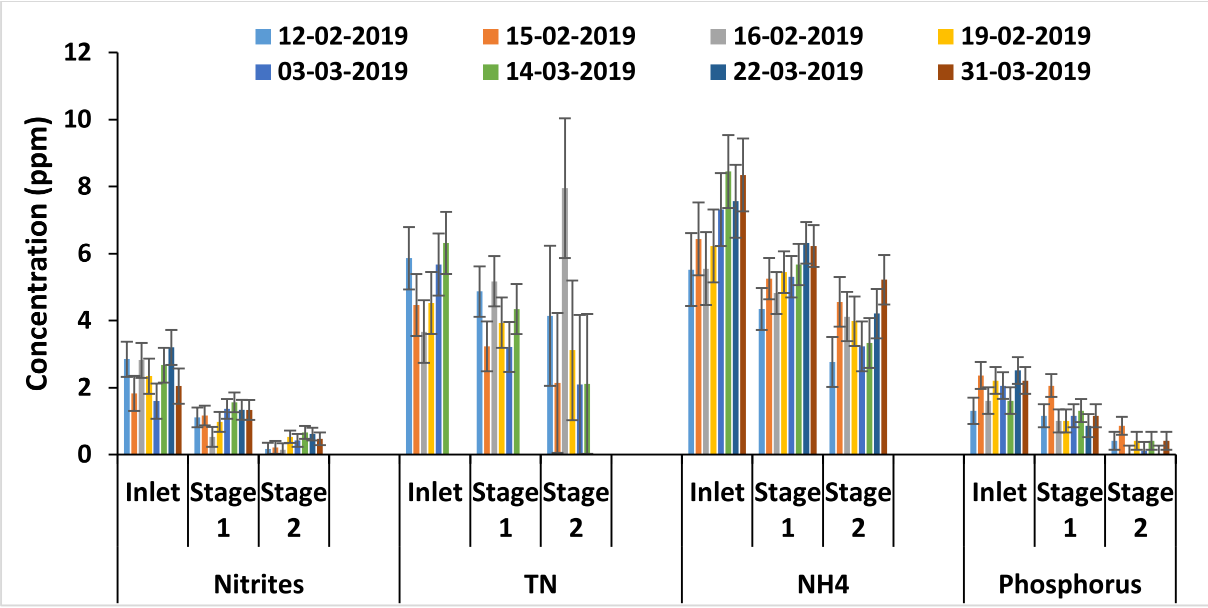


Fig 6.8: Nitrites, total nitrogen, NH_4- N and phosphorus content of Inlet, after first stage and the outlet of the system

6.5. Conclusion

It was observed that the river Sal is extremely polluted with the elevated concentration of nitrates and TKN in the river. The inlet nitrate concentration of wastewater is very high i.e. 11.24 mg/L. The Nitrate removal efficiency of the system was low; 8.77 mg/L nitrate was found in the outlet water. The system's nutrient removal efficacy was minimal; work efficiency was anticipated to improve with the generation of Bacterial Biofilm in the wetland and plant growth. The nitrates in the River water inlet were high and the COD was very low. The C/N ratio of the inlet River water was 3.5. High C/N ratio was needed for denitrification to happen in the 2nd stage. To increase the COD, the wastewater from the fish market, which is about 10 m^3 with COD of 980 mg / L needed to be transfer to the septic tank and mixed with the river water to provide more carbon for denitrification. This will increase the COD to nitrogen ratio, which in turn will provide greater scope for system nitrification and denitrification.

SUMMARY OF RESULTS AND CONCLUSION AND FUTURE SCOPE OF WORK

Summary of Results and conclusion

India being a developing country facing many environmental issues, including the treatment and management of wastewater in extremely alarming conditions. Most of the large towns in India were developed on the banks of the river. Water is procured upstream of the river for domestic uses and other industrial purposes. After the uses wastewater is discharged downstream of the river or to other water bodies like pond, lakes etc. with minimal treatment or without no treatment in most of the cases, polluting these water bodies. The problem arises due to a considerable gap in the production of sewage and treatment facilities available. Although after increasing the number of treatment systems in India, the country's wastewater treatment capacity has not been fully developed to fulfil the growing rate of sewage generation. Most of the treatment facilities currently available in India are centralized systems that are underutilized or not functioning due to absence of proper sewage pipeline, adequate funding and skilled labours. The rural areas of India mostly do not have sewage treatment plants, the wastewater from these small villages and towns is discharged into rivers directly. There is a need to make an effort to develop an extensive decentralized technology that needs very low energy input, can be effortlessly managed and treat waste water at the point of generation, offering an excellent alternative to treating wastewater in rural areas of India.

Constructed wetlands (CW), because of their benefits of high effectiveness, a suitable ecological environment, low price and aesthetic value, have been commonly used in many nations and regions in the past few decades. CW is a complete ecosystem which provides an environment for the growth of diverse flora and fauna. In CWs many physical, chemical and biological processes are simultaneously active and mutually influence each other to make the system entirely natural to treat wastewater.

In CW, plant plays a very important role, selection of plant is a very important factor for the working of constructed wetlands. In this study the selection of plant was done on the basis of their Biochemical methane potential (BMP). Four different plants were selected for their BMP analysis (*Ageratum conyzoides*, Hybrid *Napier* spp., *Typha latifolia* and *Canna indica*) at five different loading rate. The volume of biogas produced by *Ageratum conyzoides*, Hybrid *Napier* spp., and *Typha latifolia* with 0.5gVS/L were 85.5 ml, 98.5 ml, and 79 ml, respectively. For an OLR of 4 gVS/L, the BMP for *Ageratum conyzoides,* Hybrid *Napier* spp., and *Typha latifolia* were found to be 166.5 ml, 187 ml, and 157 ml, respectively. For *Canna indica*, OLR 3g VS/L and 4g VS/L produced biogas volume of 166.5 and 130 ml, respectively. Hybrid *Napier* spp.

produced a high volume of biogas i.e., 187 ml (4gVS/L loading rate) compared to other macrophyte biomass. The percentage of methane present in the biogas produced from *Ageratum Conyzoides* biomass were 62.24% and 65.73 % for OLR of amount 0.5 gVS/L and 4 gVS/L, respectively. The percentage of methane present in biogas produced by Hybrid *Napier* spp., *Canna indica*, and *Typha latifolia* for OLR of 0.5gVS/L were 65%, 73.19%, and 69.49%, respectively and the amount of methane produced was 64.03, 61.11 and 54.90 ml, respectively. From the result it can be concluded that *Canna indica* could be the most desirable plant species for the CW.

A Drum experiment was first conducted to select the most suitable plant species adapted to the tropical climate of Goa, India. *Typha angustata* and *Canna indica* were selected because of their natural availability in Goa, India. The removal efficiency of both the plant species was found to be very similar but the overall methane production of green *Typha angustata* (230.0mL) at the highest loading rate (i.e.; 4gVS/L) was much higher than green *Canna indica* 94.5mL. So, *Typha angustata* was selected as a plant species for the pilot scale plant at BITS goa campus. Based on the drum experiment, a demonstration-scale Two Stage Pilot VFCW experiment was implemented and regularly monitored at two different HLR i.e. 0.150 m/day and 0.225 m/day for 40 weeks. At higher loading rate the removal of COD, BOD, TDS, TVS, TKN and NH_4-N at 1st stage was 61%, 62%, 33%, 40 %, 35 % and 58%; and for the 2nd stage 90%, 84%, 61%, 64%, 47% and 82% respectively. At higher organic loading rate, the system footprint got reduced from 1.47 m^2 to 0.79 m^2 per person.

CWs systems provides efficient treatment for BOD, suspended solids (SS) and Kjeldahl nitrogen but are limited in their phosphorus removal abilities. Phosphorus removal in French VFCW depends on many biotic and abiotic factors which are present in the media of the wetland. The primary Phosphorus removal mechanism in VFCW is phosphorus adsorption in the media of the wetland. The phosphorus sorption capacity of the media mainly depends on the iron, aluminium and calcium content of the media which is not sustainable. Eight different reactive materials such as Steel slag (SSGS), kiln ash (KAS), Bauxite ore (BOX), Bentonite clay (BNC), red brick (RB) BOP (Binvec Pivel) and BON (Bovec Nervac) were collected from different places in India and France and were analysed for their phosphorus removal capacity (PRC). The research demonstrates that BOP and BON from the drinking water plant could be an effective solution for removing P from wastewater treated in constructed wetlands. The P removal capacity of the samples BOP and BON (10 mg P/g and 7.6 mg P/g respectively) was found to be highest. It was observed that the samples provide Ca^{2+} and OH^- for the formation of HAP complex. The molar ratios PO_4-P/Ca of BOP and BON was 1.7 and 1.9, which supports the formation of more stable HAP complex. Also the BOP and BON solutions have higher pH which supports the formation of stable calcium phosphate complex. The study suggest that the P removal capacity of the samples depend on the release of Ca^{2+} and OH^-into the water samples.

To understand the further working of CW with low C/N wastewater a two-stage vertical flow wetland was designed and implemented in Dr. K B Hedgewar School, Cujira, Bamboli, Panjim, Goa, India. The wetland deigned at the school was monitored for all the parameters. The removal efficiency of COD, TKN, nitrate, nitrites, NH4-N, and Phosphorus was around 89 %, 57 %, 38 %, 64 %, 62 % and 62 % respectively in the 1st set of experiments and in the 2nd set of experiment the removal efficiency of COD, TKN, Nitrate, Nitrites, NH4-N, and Phosphorus was around 84 %, 64 %, 4 %, 46 %, 69 % and 63 % respectively. The wetland was designed in such a way so as to ensure nitrification process in the 1st stage and denitrification process in the 2nd stage. Form the data it could be concluded that both processes were occurring in the wetland. The inlet COD of the water decreased with passage of time, due to the removal of solid deposits in the septic tank. In the 2nd set of the experiments total nitrogen removal was just 1 % higher than in the 1st set of experiments. In our study the total nitrogen removal was comparatively low due to reduction of COD in the septic tank water which reduced the COD/N ratio from 2.95 in the 1st set of experiments to 2.0 in the 2nd set of experiments. This suggests that the first strategy to handle sewage from the school's septic tank could be better.

On the basis of result obtained from BITS Goa campus pilot scale system and the VFCW at school. A 500m^2 two stage vertical constructed wetland was designed and implemented at Margaon wholesale fish for treatment of 40 m^3/day of water from river Sal and fish market wastewater (if needed). This river is about 35 kms long and is contaminated by domestic wastewater and industrial waste having an average content of 73mgCOD/L, 11 mg NO3/L and 31 mg NH_4-N/L which make it closer to a primary settled domestic wastewater rather than a surface water. The 1st stage has total surface area of 150 m^2 and the 2nd stage has of 350 m^2. The VFCW at fish market was designed based upon VFCW already operational in BITS campus (Chapter 3). The Nitrate removal efficiency of the system was low. The nitrogen in the River water was high and the COD was very low. The C/N ratio of the inlet River water was just 3.5. High C/N ratio was needed for denitrification to happen in the 2nd stage. To increase the COD, the wastewater from the fish market, which is about 10 m^3 with COD of 980 mg / L needed to be transfer to the septic tank and mixed with the river water to provide more carbon for denitrification.

Future Scope of Work

- There is need to understand the bacterial diversity of the wetland to understand how fauna of the system is getting effected by different quality of wastewater.
- Need to understand the ecology (interaction of abiotic and biotic factors) to find out how the abiotic factors effects biotic factors of CW.
- The wetlands should be run continuously for much more years and the samples should be analysed at regular intervals, to understand how it behaves in tropical climate after several years to understand life of wetland.
- More work is needed to understand, how the C/N ratio in the wastewater effect the nitrifications and denitrification in the system.
- Different types of media need to be investigated which can have better treatment efficacy for the removal of different types of nutrient from the CW. There also a need to find more suitable substrate for phosphorus removal.

REFERENCES

References

Adebayo, A.O., Jekayinfa, S.O. and Linke, B., 2015. Effects of organic loading rate on biogas yield in a continuously stirred tank reactor experiment at mesophilic temperature. British Journal of Applied Science and Technology, 11(4), pp.1-9.

Adeniran, A.E. and Onothoja, U.B., 2017. The potentials of production of biogas from constructed wetland macrophytes. African Journal of Biotechnology, 16(33), pp.1724-1732.

Agrawal, A., Pandey, R.S. and Sharma, B., 2010. Water pollution with special reference to pesticide contamination in India. Journal of Water Resource and Protection, 2(05), p.432.

Altundoğan, H.S. and Tümen, F., 2002. Removal of phosphates from aqueous solutions by using bauxite. I: Effect of pH on the adsorption of various phosphates. Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology, 77(1), pp.77-85.

Álvarez, J.A., Ávila, C., Otter, P., Kilian, R., Istenič, D., Rolletschek, M., Molle, P., Khalil, N., Ameršek, I., Mishra, V.K. and Jorgensen, C., 2017. Constructed wetlands and solar-driven disinfection technologies for sustainable wastewater treatment and reclamation in rural India: SWINGS project. Water Science and Technology, 76(6), pp.1474-1489.

Al-Zreiqat, I., Abbassi, B., Headley, T., Nivala, J., van Afferden, M. and Müller, R.A., 2018. Influence of septic tank attached growth media on total nitrogen removal in a recirculating vertical flow constructed wetland for treatment of domestic wastewater. Ecological Engineering, 118, pp.171-178.

Angelidaki, I. and Sanders, W., 2004. Assessment of the anaerobic biodegradability of macropollutants. Re/Views in Environmental Science & Bio/Technology, 3(2), pp.117-129.

Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J.L., Guwy, A.J., Kalyuzhnyi, S., Jenicek, P. and Van Lier, J.B., 2009. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water science and technology, 59(5), pp.927-934.

APHA 2540 B.; 2540 E., 2005. Standard methods for the examination of water and wastewater. 21st ed. American Public Health Association, Washington, DC, USA.

Arias, C.A., Del Bubba, M. and Brix, H., 2001. Phosphorus removal by sands for use as media in subsurface flow constructed reed beds. Water research, 35(5), pp.1159-1168.

Balat, M. and Balat, H., 2009. Biogas as a renewable energy source—a review. Energy Sources, Part A, 31(14), pp.1280-1293.

Barbour, R.L., 2003. Settable composition containing cement kiln dust. U.S. Patent 6,645,290.

Barca, C., Gérente, C., Meyer, D., Chazarenc, F. and Andrès, Y., 2012. Phosphate removal from synthetic and real wastewater using steel slags produced in Europe. Water research, 46(7), pp.2376-2384.

Bardiya, N. and Gaur, A.C., 1997. Effects of carbon and nitrogen ratio on rice straw biomethanation. J. Rural Energy, 4(1-4), pp.1-16.

Bello, M.M., Raman, A.A.A. and Purushothaman, M., 2017. Applications of fluidized bed reactors in wastewater treatment–a review of the major design and operational parameters. Journal of cleaner production, 141, pp.1492-1514.

Billore, S.K., Ram, H., Singh, N., Thomas, R., Nelson, R.M. and Pare, B., 2002, September. Treatment performance evaluation of surfactant removal from domestic wastewater in a tropical horizontal subsurface constructed wetland. In proceedings of the 8th international conference on Wetland Systems for Water Pollution Control (pp. 393-399).

Billore, S.K., Singh, N., Ram, H.K., Sharma, J.K., Singh, V.P., Nelson, R.M. and Dass, P., 2001. Treatment of a molasses based distillery effluent in a constructed wetland in central India. Water Science and Technology, 44(11-12), pp.441-448.

References

Billore, S.K., Singh, N., Sharma, J.K., Dass, P. and Nelson, R.M., 1999. Horizontal subsurface flow gravel bed constructed wetland with Phragmites karka in central India. Water Science and Technology, 40(3), pp.163-171.

Bodik, I. and Kubaska, M., 2013. Energy and sustainability of operation of a wastewater treatment plant. Environment Protection Engineering, 39(2), pp.15-24.

Bratby, J., 2016. Coagulation and flocculation in water and wastewater treatment. IWA publishing.

Brix, H., 1994. Functions of macrophytes in constructed wetlands. Water Science and Technology, 29(4), pp.71-78.

Brix, H., 1997. Do macrophytes play a role in constructed treatment wetlands?. Water science and technology, 35(5), pp.11-17.

Brix, H., 2003, May. Plants used in constructed wetlands and their functions. In 1st International Seminar on the use of Aquatic Macrophytes for Wastewater Treatment in Constructed Wetlands, edit. Dias V., Vymazal J. Lisboa, Portugal (pp. 81-109).

Calheiros, C.S., Duque, A.F., Moura, A., Henriques, I.S., Correia, A., Rangel, A.O. and Castro, P.M., 2009. Changes in the bacterial community structure in two-stage constructed wetlands with different plants for industrial wastewater treatment. Bioresource Technology, 100(13), pp.3228-3235.

Caselles-Osorio, A., Vega, H., Lancheros, J.C., Casierra-Martínez, H.A. and Mosquera, J.E., 2017. Horizontal subsurface-flow constructed wetland removal efficiency using Cyperus articulatus L. Ecological Engineering, 99, pp.479-485.

Chang, J., Zhang, X., Perfler, R., Xu, Q.S., Niu, X.Y. and Ge, Y., 2007. Effect of hydraulic loading rate on the removal efficiency in a constructed wetland in subtropical China. Fresenius Environmental Bulletin, 16(9), pp.1082-1086.

Chatterjee, P., Ghangrekar, M.M. and Rao, S., 2016. Low efficiency of sewage treatment plants due to unskilled operations in India. Environmental chemistry letters, 14(3), pp.407-416.

References

Chen, X., Zhu, H., Xu, Y., Shutes, B., Yan, B. and Zhou, Q., 2018. Effect of Aeration Modes and COD/N Ratios on Organic Matter and Nitrogen Removal in Horizontal Subsurface Flow Constructed Wetland Mesocosms. Water, 10(11), p.1530.

Chen, X., Zhuang, J. and Bester, K., 2018. Degradation of triclosan by environmental microbial consortia and by axenic cultures of microorganisms with concerns to wastewater treatment. Applied microbiology and biotechnology, 102(13), pp.5403-5417.

Ciria, M.P., Solano, M.L. and Soriano, P., 2005. Role of macrophyte Typha latifolia in a constructed wetland for wastewater treatment and assessment of its potential as a biomass fuel. Biosystems Engineering, 92(4), pp.535-544.

Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., Lancelot, C. and Likens, G.E., 2009. Controlling eutrophication: nitrogen and phosphorus.

Copp, J.B., 1998. COD balances in biological nutrient (nitrogen and phosphorus) removal activated sludge systems (Doctoral dissertation).

Corcoran, E. ed., 2010. Sick water?: the central role of wastewater management in sustainable development: a rapid response assessment. UNEP/Earthprint.

Cordell, D., Drangert, J.O. and White, S., 2009. The story of phosphorus: global food security and food for thought. Global environmental change, 19(2), pp.292-305.

Daigger, G.T., 2014. Oxygen and carbon requirements for biological nitrogen removal processes accomplishing nitrification, nitritation, and anammox. Water Environment Research, 86(3), pp.204-209.

Das, B., Prakash, S., Reddy, P.S.R. and Misra, V.N., 2007. An overview of utilization of slag and sludge from steel industries. Resources, conservation and recycling, 50(1), pp.40-57.

References

Dasa, K.T., Westman, S.Y., Millati, R., Cahyanto, M.N., Taherzadeh, M.J. and Niklasson, C., 2016. Inhibitory effect of long-chain fatty acids on biogas production and the protective effect of membrane bioreactor. BioMed research international, 2016.

Datta, A., Wani, S.P., Patil, M.D. and Tilak, A.S., 2016. Field scale evaluation of seasonal wastewater treatment efficiencies of free surface-constructed wetlands in ICRISAT, India. Current Science, 110(09), pp.1756-1763.

Datta, A., Wani, SP., Tilak, A., Patil, M., Kaushal, M., Kuravi, D., 2015. Assessing the performance of free water surface constructed wetlands in treating domestic wastewater: Apotential alternative for irrigation

Dayton, E.A. and Basta, N.T., 2005. A method for determining the phosphorus sorption capacity and amorphous aluminum of aluminum-based drinking water treatment residuals. Journal of Environmental Quality, 34(3), pp.1112-1118.

DeBusk, T.A., Peterson, J.E. and Reddy, K.R., 1995. Use of aquatic and terrestrial plants for removing phosphorus from dairy wastewaters. Ecological Engineering, 5(2-3), pp.371-390.

Del Bubba, M., Arias, C.A. and Brix, H., 2003. Phosphorus adsorption maximum of sands for use as media in subsurface flow constructed reed beds as measured by the Langmuir isotherm. Water research, 37(14), pp.3390-3400.

Deng, L., Liu, Y., Zheng, D., Wang, L., Pu, X., Song, L., Wang, Z., Lei, Y., Chen, Z. and Long, Y., 2017. Application and development of biogas technology for the treatment of waste in China. Renewable and Sustainable Energy Reviews, 70, pp.845-851.

Dipu, S., Kumar, A.A. and Thanga, V.S.G., 2011. Potential application of macrophytes used in phytoremediation. World Appl Sci J, 13(3), pp.482-486.

Diwakar, Y.R., 2012. Practising Dissemination of Biogas: Promoting.

Dong, Z. and Sun, T., 2007. A potential new process for improving nitrogen removal in constructed wetlands—promoting coexistence of partial-nitrification and ANAMMOX. Ecological engineering, 31(2), pp.69-78.

References

Dubois, V. and Molle, P., 2018. On-site single-stage constructed wetland fed by raw wastewater: performances and resilience of the system. Water Science and Technology, 78(2), pp.459-465.

Eckenfelder, W., 1998. Activated sludge: process design and control. CRC Press.

Eddy, F.B., 2005. Ammonia in estuaries and effects on fish. Journal of Fish Biology, 67(6), pp.1495-1513.

Eijo-Rio, E., Petit-Boix, A., Villalba, G., Suárez-Ojeda, M.E., Marin, D., Amores, M.J., Aldea, X., Rieradevall, J. and Gabarrell, X., 2015. Municipal sewer networks as sources of nitrous oxide, methane and hydrogen sulphide emissions: a review and case studies. Journal of Environmental Chemical Engineering, 3(3), pp.2084-2094.

EN ISO 6878, 2004. Water Quality - Determination of Phosphorus -Ammonium Molybdate Spectrometric Method.

EN ISO 7980, 1986. Water Quality - Determination of Calcium and Magnesium - Atomic Absorption Spectrometric Method.

EPA, Wastewater Technology Fact Sheet, Wetlands: Subsurface Flow, Office of Water, Washington DC, September 2000.

Eslami, H., Hashemi, H., Fallahzadeh, R.A., Khosravi, R., Fard, R.F. and Ebrahimi, A.A., 2018. Effect of organic loading rates on biogas production and anaerobic biodegradation of composting leachate in the anaerobic series bioreactors. Ecological engineering, 110, pp.165-171.

Fan, J., Wang, W., Zhang, B., Guo, Y., Ngo, H.H., Guo, W., Zhang, J. and Wu, H., 2013. Nitrogen removal in intermittently aerated vertical flow constructed wetlands: impact of influent COD/N ratios. Bioresource technology, 143, pp.461-466.

Fan, J., Wang, W., Zhang, B., Guo, Y., Ngo, H.H., Guo, W., Zhang, J. and Wu, H., 2013. Nitrogen removal in intermittently aerated vertical flow constructed wetlands: impact of influent COD/N ratios. Bioresource technology, 143, pp.461-466.

Feilden, N.E.H., 1983. The theory and practice of anaerobic digestion reactor design. Process biochemistry, 18(5), pp.34-37.

Feng, Q., Cao, J.S., Chen, L.N., Guo, C.Y., Tan, J.Y. and Xu, H.L., 2011. Simultaneous nitrification and denitrification at variable C/N ratio in aerobic granular sequencing batch reactors. Journal of Food, Agriculture & Environment, 9(3&4), pp.1131-1136.

Fu, G., Yu, T., Ning, K., Guo, Z. and Wong, M.H., 2016. Effects of nitrogen removal microbes and partial nitrification-denitrification in the integrated vertical-flow constructed wetland. Ecological engineering, 95, pp.83-89.

Fu, Z., Yang, F., Zhou, F. and Xue, Y., 2009. Control of COD/N ratio for nutrient removal in a modified membrane bioreactor (MBR) treating high strength wastewater. Bioresource technology, 100(1), pp.136-141.

Fulhage, C., Sievers, D. and Fischer, J.R., 1979. Generating methane gas from manure.

G.M. Siddeshwara; 2017, Discharge of Untreated Sewage into Rivers, Government of India ministry of environment, forest and climate change lok sabha unstarred question no.2541

Garfí, M., Flores, L. and Ferrer, I., 2017. Life cycle assessment of wastewater treatment systems for small communities: activated sludge, constructed wetlands and high rate algal ponds. Journal of cleaner production, 161, pp.211-219.

Gautam S. P. (2009). Status of water supply, wastewater generation and treatment in Class-I cities & class-II towns of India. Control of urban pollution series: CUPS/ 70 / 2009 – 10. Ministry of Environment and Forests (MEF), Central Pollution Control Board (CPCB), Govt. of India.

Gerritse, R.G., 1993. Prediction of travel times of phosphate in soils at a disposal site for wastewater. Water Research, 27(2), pp.263-267.

Gilbert, E.M., Agrawal, S., Brunner, F., Schwartz, T., Horn, H. and Lackner, S., 2014. Response of different Nitrospira species to anoxic periods depends on operational DO. Environmental science & technology, 48(5), pp.2934-2941.

References

Gkika, D., Gikas, G.D. and Tsihrintzis, V.A., 2014. Construction and operation costs of constructed wetlands treating wastewater. Water Science and Technology, 70(5), pp.803-810.

Green, M., Safray, I. and Agami, M., 1996. Constructed wetlands for river reclamation: experimental design, start-up and preliminary results. Bioresource Technology, 55(2), pp.157-162.

Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Robinson, Z.P., Wang, X., Wu, J. and Li, F., 2017. The feasibility and challenges of energy self-sufficient wastewater treatment plants. Applied energy, 204, pp.1463-1475.

Gumbricht, T., Roman-Cuesta, R.M., Verchot, L., Herold, M., Wittmann, F., Householder, E., Herold, N. and Murdiyarso, D., 2017. An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor. Global change biology, 23(9), pp.3581-3599.

Güven, D., Dapena, A., Kartal, B., Schmid, M.C., Maas, B., van de Pas-Schoonen, K., Sozen, S., Mendez, R., den Camp, H.J.O., Jetten, M.S. and Strous, M., 2005. Propionate oxidation by and methanol inhibition of anaerobic ammonium-oxidizing bacteria. Appl. Environ. Microbiol., 71(2), pp.1066-1071.

Haberl, R., 1999. Constructed wetlands: a chance to solve wastewater problems in developing countries. Water Science and Technology, 40(3), pp.11-17.

Hansen, R., Thøgersen, T. and Rogalla, F., 2007. Comparing cost and process performance of activated sludge (AS) and biological aerated filters (BAF) over ten years of full sale operation. Water science and technology, 55(8-9), pp.99-106.

Haritash, A.K., Dutta, S. and Sharma, A., 2017. Phosphate uptake and translocation in a tropical Canna-based constructed wetland. Ecological Processes, 6(1), p.12.

Hauck, M., Maalcke-Luesken, F.A., Jetten, M.S. and Huijbregts, M.A., 2016. Removing nitrogen from wastewater with side stream anammox: What are the trade-offs between environmental impacts?. Resources, Conservation and Recycling, 107, pp.212-219.

Hazarika, S. and Pandit, D., 2019. Feasibility Analysis of Decentralized Wastewater Treatment Systems. In Innovations in Infrastructure (pp. 207-219). Springer, Singapore.

Hobson, K., 2017. Evaluation of High pH Infiltration Water and Recycled Bedding Material. Proceedings of the Water Environment Federation, 2017(2), pp.578-585.

Hoffmann, H., Platzer, C., Winker, M. & Von Muench, E. 2011 Technology review of constructed wetlands: subsurface flow constructed flow constructed wetlands for greywater and domestic wastewater treatment. Deutsch Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH (Eschborn, Feb, 35pp.).

Holinger, M., Früh, B., Stoll, P., Pedan, V., Kreuzer, M., Bérard, J. and Hillmann, E., 2018. Long-term effects of castration, chronic intermittent social stress, provision of grass silage and their interactions on performance and meat and adipose tissue properties in growing-finishing pigs. Meat science, 145, pp.40-50.

Hreiz, R., Latifi, M.A. and Roche, N., 2015. Optimal design and operation of activated sludge processes: State-of-the-art. Chemical Engineering Journal, 281, pp.900-920.

Hu, H. and Ren, H., 2019. Removal of bioavailable dissolved organic nitrogen in wastewater by membrane bioreactors as posttreatment: Implications for eutrophication control. Bioresource technology, 271, pp.496-499.

Ingersoll, T.L. and Baker, L.A., 1998. Nitratfe removal in wetland microcosms. Water research, 32(3), pp.677-684.

Ippolito, J.A., Barbarick, K.A., Heil, D.M., Chandler, J.P. and Redente, E.F., 2003. Phosphorus retention mechanisms of a water treatment residual. Journal of Environmental Quality, 32(5), pp.1857-1864.

Isgren, M. and Mårtensson, P., 2013. Methane formation in sewer systems. Lund University.[online].

References

Issar, D., 2003. Farmers knowledge and adoption of biogas technology in Haryana (Doctoral dissertation, Chaudhary Charan Singh Haryana Agricultural University; Hisar).

Jamieson, R.C., Gordon, R.J., Sharples, K.E., Stratton, G.W. and Madani, A., 2002. Movement and persistence of fecal bacteria in agricultural soils and subsurface drainage water: A review. Canadian Biosystems Engineering, 44(1), pp.1-9.

Jiang, X., Song, X., Chen, Y. and Zhang, W., 2014. Research on biogas production potential of aquatic plants. Renewable energy, 69, pp.97-102.

Jing, S.R., Lin, Y.F., Lee, D.Y. and Wang, T.W., 2001. Nutrient removal from polluted river water by using constructed wetlands. Bioresource Technology, 76(2), pp.131-135.

Jönsson, H., Baky, A., Jeppsson, U., Hellström, D. and Kärrman, E., 2005. Composition of urine, feaces, greywater and biowaste for utilisation in the URWARE model. Urban water report, 2005(6).

Judd, S., 2008. The status of membrane bioreactor technology. Trends in biotechnology, 26(2), pp.109-116.

Juwarkar, A.S., Oke, B., Juwarkar, A. and Patnaik, S.M., 1995. Domestic wastewater treatment through constructed wetland in India. Water Science and Technology, 32(3), pp.291-294.

Kadlec, R. & Wallace, S. 2009. Treatment Wetlands, 2nd edition.CRC press, Boca Raton, FL, USA.

Kadlec, R.H., Knight, R., Vymazal, J., Brix, H., Cooper, P. and Haberl, R., 2017. Constructed wetlands for pollution control. IWA publishing.

Kadlec, R.H., Wallace, S.D., 2008. Treatment Wetlands, 2nd ed. CRC Press, Boca Raton, 952 pp.

Kantawanichkul, S., Kladprasert, S. and Brix, H., 2009. Treatment of high-strength wastewater in tropical vertical flow constructed wetlands planted with Typha angustifolia and Cyperus involucratus. Ecological engineering, 35(2), pp.238-247.

References

Kantawanichkul, S., Pilaila, S., Tanapiyawanich, W., Tikampornpittaya, W. and Kamkrua, S., 1999. Wastewater treatment by tropical plants in vertical-flow constructed wetlands. Water science and technology, 40(3), pp.173-178.

Katsoyiannis, I.A., Gkotsis, P., Castellana, M., Cartechini, F. and Zouboulis, A.I., 2017. Production of demineralized water for use in thermal power stations by advanced treatment of secondary wastewater effluent. Journal of environmental management, 190, pp.132-139.

Kaur, R., Wani, S.P., Singh, A.K. and Lal, K., 2012, May. Wastewater production, treatment and use in India. In National Report presented at the 2 nd regional workshop on Safe Use of Wastewater in Agriculture.

Keller, R.P., Masoodi, A. and Shackleton, R.T., 2018. The impact of invasive aquatic plants on ecosystem services and human well-being in Wular Lake, India. Regional environmental change, 18(3), pp.847-857.

Khalid, A., Arshad, M., Anjum, M., Mahmood, T. and Dawson, L., 2011. The anaerobic digestion of solid organic waste. Waste management, 31(8), pp.1737-1744.

Khan, U.M. and Khalil, N., 2017. Constructed Wetlands for Domestic Wastewater Treatment–A Promising Technology for Rural Areas in India.

Kim, B., Gautier, M., Olvera Palma, G., Molle, P., Michel, P. and Gourdon, R., 2015. Pilot-scale study of vertical flow constructed wetland combined with trickling filter and ferric chloride coagulation: influence of irregular operational conditions. Water Science and Technology, 71(7), pp.1088-1096.

Kivaisi, A.K., 2001. The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review. Ecological engineering, 16(4), pp.545-560.

Knowles, P., Dotro, G., Nivala, J. and García, J., 2011. Clogging in subsurface-flow treatment wetlands: occurrence and contributing factors. Ecological Engineering, 37(2), pp.99-112.

References

Konnerup, D., Koottatep, T. and Brix, H., 2009. Treatment of domestic wastewater in tropical, subsurface flow constructed wetlands planted with Canna and Heliconia. Ecological engineering, 35(2), pp.248-257.

Kovacic, D.A., David, M.B., Gentry, L.E., Starks, K.M. and Cooke, R.A., 2000. Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. Journal of environmental quality, 29(4), pp.1262-1274.

Krzeminski, P., van der Graaf, J.H. and van Lier, J.B., 2012. Specific energy consumption of membrane bioreactor (MBR) for sewage treatment. Water Science and Technology, 65(2), pp.380-392.

Kuttuva, P., Lele, S. and Mendez, G.V., 2018. Decentralized wastewater systems in Bengaluru, India: success or failure?. Water Economics and Policy, 4(02), p.1650043.

Laakso, J., Uusitalo, R., Heikkinen, J. and Yli-Halla, M., 2017. Phosphorus in agricultural constructed wetland sediment is sparingly plant-available. Journal of Plant Nutrition and Soil Science, 180(5), pp.554-562.

Lam, M.N.T., Jaritngam, S. and Le, D.H., 2017. Roller-compacted concrete pavement made of Electric Arc Furnace slag aggregate: Mix design and mechanical properties. Construction and Building Materials, 154, pp.482-495.

Langergraber, G., 2008. Modeling of processes in subsurface flow constructed wetlands: A review. Vadose Zone Journal, 7(2), pp.830-842.

Lantzke, I.R., Heritage, A.D., Pistillo, G. and Mitchell, D.S., 1998. Phosphorus removal rates in bucket size planted wetlands with a vertical hydraulic flow. Water research, 32(4), pp.1280-1286.

Lauer, M., Hansen, J.K., Lamers, P. and Thrän, D., 2018. Making money from waste: The economic viability of producing biogas and biomethane in the Idaho dairy industry. Applied energy, 222, pp.621-636.

References

Lele, S. and Sengupta, M.B., 2018. From lakes as urban commons to integrated lake-water governance: The case of Bengaluru's urban water bodies. SAWAS: South Asian Water Studies, 8(1), pp.5-26.

Li, J., Luo, S. and He, Z., 2016. Cathodic fluidized granular activated carbon assisted-membrane bioelectrochemical reactor for wastewater treatment. Separation and Purification Technology, 169, pp.241-246.

Li, X. and Sung, S., 2015. Development of the combined nitritation–anammox process in an upflow anaerobic sludge blanket (UASB) reactor with anammox granules. Chemical Engineering Journal, 281, pp.837-843.

Lo, C.H., McAdam, E. and Judd, S., 2015. The cost of a small membrane bioreactor. Water Science and Technology, 72(10), pp.1739-1746.

Lombard Latune, R., Laporte-Daube, O., Fina, N., Peyrat, S., Pelus, L. and Molle, P., 2017. Which plants are needed for a French vertical-flow constructed wetland under a tropical climate? Water Science and Technology, 75(8), pp.1873-1881..

Luederitz, V., Eckert, E., Lange-Weber, M., Lange, A. and Gersberg, R.M., 2001. Nutrient removal efficiency and resource economics of vertical flow and horizontal flow constructed wetlands. Ecological Engineering, 18(2), pp.157-171.

Macklin, Y., Kibble, A. and Pollitt, F., 2011. Impact on health of emissions from landfill sites. Advice from the Health Protection Agency.

Mahmood, Q., Pervez, A., Zeb, B.S., Zaffar, H., Yaqoob, H., Waseem, M. and Afsheen, S., 2013. Natural treatment systems as sustainable ecotechnologies for the developing countries. BioMed research international, 2013.

Maltais-Landry, G., Maranger, R., Brisson, J. and Chazarenc, F., 2009. Nitrogen transformations and retention in planted and artificially aerated constructed wetlands. Water research, 43(2), pp.535-545.

References

Mantovani, M.C., Takano, C. and Büchler, P.M., 2002. Electric arc furnace dust-coal composite pellet: effects of pellet size, dust composition, and additives on swelling and zinc removal. Ironmaking & steelmaking, 29(4), pp.257-265.

Masi F. and Bresciani R., 2018. Vertical Flow Constructed Wetland (VFCW). Retrieved from:https://sswm.info/sswm-university-course/module-6-disaster-situations-planning-and-preparedness/further-resources/vertical-flow-constructed-wetland-%28vfcw%29

Mauskar J.M. CPCB. 2007. Evaluation of Operation and Maintenance of Sewage Treatment Plants in India-2007, Control of Urban Pollution Series: CUPS/68/2007.Central Pollution Control Board, India.

Mekala, G.D., Davidson, B., Samad, M. and Boland, A.M., 2007. Wastewater reuse and recycling systems: a perspective into India and Australia (Vol. 128). IWMI.

Moe, C.L. and Rheingans, R.D., 2006. Global challenges in water, sanitation and health. Journal of water and health, 4(S1), pp.41-57.

Moetaz, E.L. and Shanableh, A., Phosphorus Removal using Al-modified Bentonite Clay–Effect of Particle Size.

Molle, P., Liénard, A., Boutin, C., Merlin, G. and Iwema, A., 2005. How to treat raw sewage with constructed wetlands: an overview of the French systems. Water Science and Technology, 51(9), pp.11-21.

Molle, P., Liénard, A., Grasmick, A. and Iwema, A., 2006. Effect of reeds and feeding operations on hydraulic behaviour of vertical flow constructed wetlands under hydraulic overloads. Water Research, 40(3), pp.606-612.

Molle, P., Lombard Latune, R., Riegel, C., Lacombe, G., Esser, D. and Mangeot, L., 2015. French vertical-flow constructed wetland design: adaptations for tropical climates. Water Science and Technology, 71(10), pp.1516-1523.

Molle, P., Prost-Boucle, S. and Lienard, A., 2008. Potential for total nitrogen removal by combining vertical flow and horizontal flow constructed wetlands: a full-scale experiment study. Ecological engineering, 34(1), pp.23-29.

Morrall, D., McAvoy, D., Schatowitz, B., Inauen, J., Jacob, M., Hauk, A. and Eckhoff, W., 2004. A field study of triclosan loss rates in river water (Cibolo Creek, TX). Chemosphere, 54(5), pp.653-660.

Morvannou, A., Troesch, S., Esser, D., Forquet, N., Petitjean, A. and Molle, P., 2017. Using one filter stage of unsaturated/saturated vertical flow filters for nitrogen removal and footprint reduction of constructed wetlands. Water Science and Technology, 76(1), pp.124-133.

Moshiri, G.A., 1993. Constructed wetlands for water quality improvement. CRC Press.

Moustaka-Gouni, M., Hiskia, A., Genitsaris, S., Katsiapi, M., Manolidi, K., Zervou, S.K., Christophoridis, C., Triantis, T.M., Kaloudis, T. and Orfanidis, S., 2017. First report of Aphanizomenon favaloroi occurrence in Europe associated with saxitoxins and a massive fish kill in Lake Vistonis, Greece. Marine and Freshwater Research, 68(4), pp.793-800.

Nilsson, C. and Dahlström, H., 2005. Treatment and Disposal Methods for Wastewater Sludge in the Area of Beijing, China/Behandlings-och hanteringsmetoder för avloppsslam i Pekingområdet, Kina.

Oehl, F., Frossard, E., Fliessbach, A., Dubois, D. and Oberson, A., 2004. Basal organic phosphorus mineralization in soils under different farming systems. Soil Biology and Biochemistry, 36(4), pp.667-675.

Ofoefule, A.U., Uzodinma, E.O. and Onukwuli, O.D., 2009. Comparative Study of The Effect of Different Pretreatment Methods on Biogas Yield From Water Hyacinth (Eichhornia Crassipes.

References

Paepatung, N., Nopharatana, A. and Songkasiri, W., 2009. Bio-methane potential of biological solid materials and agricultural wastes. Asian Journal on Energy and Environment, 10(1), pp.19-27.

Paing, J., Guilbert, A., Gagnon, V. and Chazarenc, F., 2015. Effect of climate, wastewater composition, loading rates, system age and design on performances of French vertical flow constructed wetlands: a survey based on 169 full scale systems. Ecological Engineering, 80, pp.46-52.

Patil, P.N., Gogate, P.R., Csoka, L., Dregelyi-Kiss, A., Horvath, M., 2016. Intensification of biogas production using pretreatment based on hydrodynamic cavitation. UltrasonicsSonochemistry. 30, 79-86.

Pincince, A.B., Braley, B.G., Sangrey, K.H. and Reardon, R.D., 1997. Minimizing costs of activated-sludge systems. Water Environment Research, 69(3), pp.326-330.

Postorek, Z., Kara, J., Jevic, P., 2004. Biomasa- Obnovitelny Zdroj Energie (Biomass-renewable energy resource). Prague, FCC Public: 286.

Prabhu, M.S., Mutnuri, S., 2016. Anaerobic co-digestion of sewage sludge and food waste. Waste Manag. Res. 34 (4), 307-315.

Pragati, A., Smriti, S., Kharkwal, A.C. and Ajit, V., 2015. Biofuel from agricultural waste: a review. International Journal of Current Microbiology and Applied Sciences, 4(1), pp.470-477.

Putra, Y., Murni, D. and Kurniawan, T., 2014. Study of biogas production rate from water hyacinth by hydrothermal pretreatment with buffalo dung as a starter. Waste Technol, 2, pp.26-30.

Quan, Q., Shen, B., Zhang, Q. and Ashraf, M.A., 2016. Research on Phosphorus Removal in Artificial Wetlands by Plants and Their Photosynthesis. Brazilian Archives of Biology and Technology, 59(SPE).

References

Ramprasad, C., Smith, C.S., Memon, F.A. and Philip, L., 2017. Removal of chemical and microbial contaminants from greywater using a novel constructed wetland: GROW. Ecological Engineering, 106, pp.55-65.

Ranade, V.V. and Bhandari, V.M., 2014. Industrial wastewater treatment, recycling and reuse. Butterworth-Heinemann.

Rasi, S., Veijanen, A. and Rintala, J., 2007. Trace compounds of biogas from different biogas production plants. Energy, 32(8), pp.1375-1380.

Resch, C., Worl, A., Waltenberger, R., Broun, R., Kirchmayr, R., 2011. Enhancement options for the utilization of nitrogen rich animal by-products in anaerobic digestion. Bioresource Technology. 102, 2503-2510.

Rescorla, A., Semmens, M.J. and Hozalski, R.M., 2017. Effect of NOM and Lime Softening on Geosmin Removal by PAC. Journal-American Water Works Association, 109(4), pp.15-26.

Riggio, V.A., Ruffino, B., Campo, G., Comino, E., Comoglio, C. and Zanetti, M., 2018. Constructed wetlands for the reuse of industrial wastewater: A case-study. Journal of Cleaner Production, 171, pp.723-732.

Roques H., 1990. Fondements théoriques du traitement chimique des eaux. Volume II, Technique et Documentation – Lavoisier, Paris (France), pp. 382.

Saluja, R. and Garg, J.K., 2017. Trophic state assessment of Bhindawas Lake, Haryana, India. Environmental monitoring and assessment, 189(1), p.32.

Sanseverino, I., Conduto, D., Pozzoli, L., Dobricic, S. and Lettieri, T., 2016. Algal bloom and its economic impact. Report no. EUR, 27905.

Santamaría, A., Orbe, A., Losañez, M.M., Skaf, M., Ortega-Lopez, V. and González, J.J., 2017. Self-compacting concrete incorporating electric arc-furnace steelmaking slag as aggregate. Materials & Design, 115, pp.179-193.

Santos, A., Ma, W. and Judd, S.J., 2011. Membrane bioreactors: two decades of research and implementation. Desalination, 273(1), pp.148-154.

Sawatdeenarunat, C., Surendra, K.C., Takara, D., Oechsner, H., Khanal, S.K., 2015. Anaerobic digestion of Lignocellulosic biomass: challenge and opertunities. Bioresource technology. 178 (0), 178-186.

Scott, C.A., Drechsel, P., Raschid-Sally, L., Bahri, A., Mara, D., Redwood, M., Jimenez, B., 2009. Wastewater irrigation and health: Challenges and outlook for mitigating risks in low-income countries. Wastewater irrigation and Health: Assessing and mitigating risk in low-income countries. Earth scan. 381-394.

Sezgin, M., 1982. Variation of sludge volume index with activated sludge characteristics. Water Research, 16(1), pp.83-88.

Shekhar S., 2015. Inventorization of sewage treatment plants, central pollution control board (Ministry of Environment and Forests, Govt. of India), control of urban pollutionseries: CUPS/ / 2015.

Shelef, O., Gross, A. and Rachmilevitch, S., 2013. Role of plants in a constructed wetland: current and new perspectives. Water, 5(2), pp.405-419.

Sheng, S., Liu, B., Hou, X., Liang, Z., Sun, X., Du, L. and Wang, D., 2018. Effects of different carbon sources and C/N ratios on the simultaneous anammox and denitrification process. International Biodeterioration & Biodegradation, 127, pp.26-34.

Siddeshwara G.M., 2017. Discharge of Untreated Sewage into Rivers, government of india ministry of environment, forest and climate change, Lok sabha unstarred question no.2541.

Sikder, M.T., Kihara, Y., Yasuda, M., Mihara, Y., Tanaka, S., Odgerel, D., Mijiddorj, B., Syawal, S.M., Hosokawa, T., Saito, T. and Kurasaki, M., 2013. River water pollution in developed and developing countries: judge and assessment of physicochemical characteristics and selected dissolved metal concentration. CLEAN–Soil, Air, Water, 41(1), pp.60-68.

Sindall, R., Mercer, S.J., Sutherland, C., Buckley, C., Gounden, G., Pillay, C. and Macleod, N., 2018. Municipal-academic partnerships for innovation in sanitation delivery: a case study in Durban, South Africa.

Singh, A., Kazmi, A., Starkl, M., Bawa, I., Khale, P., Patil, V., Nimkar, I. and Naik, M., 2016. Sewage Treatment and Management in Goa, India: A Case Study. Exposure and Health, 8(1), pp.67-77.

Sirivedhin, T. and Gray, K.A., 2006. Factors affecting denitrification rates in experimental wetlands: field and laboratory studies. Ecological Engineering, 26(2), pp.167-181.

Siwek, H., Bartkowiak, A. and Włodarczyk, M., 2019. Adsorption of Phosphates from Aqueous Solutions on Alginate/Goethite Hydrogel Composite. Water, 11(4), p.633.

Soares, R.B., Memelli, M.S., Roque, R.P. and Gonçalves, R.F., 2017. Comparative Analysis of the Energy Consumption of Different Wastewater Treatment Plants. International Journal of Architecture, Arts and Applications, 3(6), p.79.

Solano, M.L., Soriano, P. and Ciria, M.P., 2004. Constructed wetlands as a sustainable solution for wastewater treatment in small villages. Biosystems Engineering, 87(1), pp.109-118.

SONG, X.H., JIANG, X.Y. and ZHAO, M.J., 2012. Trail on anaerobic fermentation of 7 kinds of wetland aquatic plants for biogas production. Guangdong Agricultural Sciences, 3, p.037.

Soranno, P.A., Hubler, L., Carpenter, S.R., Lathrop, R.C., 1996. Phsophorus loads to surface waters: a simple model to account for spatial pattern of land use. Ecol. Appl. 6, 865–878

Stillwell, A., Hoppock, D. and Webber, M., 2010. Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus. Sustainability, 2(4), pp.945-962.

Stretches of Rivers in Goa.

Stumm W., Morgan J.J., 1996. Aquatic chemistry – Chemical equilibria and rates in natural waters. 3rd edition, Wiley-Interscience Publication, USA (Iowa), pp. 1022.

Sugam, R., Gupta, B. and Deka, D., 2018. Dying Traditional Water Bodies in India Struggling to Survive against Unplanned Development. Journal of Water Resource and Protection, 10(06), p.539.

Suresh Kumar D. and Dr. Sekaran V., 2013. FBBR and MBBR Bioreactors for Sewage Treatment. International Journal of Environmental Engineering and Management, ISSN 2231-1319 Volume 4, Number 1, pp. 73-88

Suthar, S., Sharma, J., Chabukdhara, M. and Nema, A.K., 2010. Water quality assessment of river Hindon at Ghaziabad, India: impact of industrial and urban wastewater. Environmental Monitoring and Assessment, 165(1-4), pp.103-112.

Swati bansal, Goa river waters contains high content of feacal coliform: Study, India water portal, 2015. https://www.indiawaterportal.org/articles/goa-river-waters-contains-high-content-feacal-coliform-study

Talekar, G.V., Sharma, P., Yadav, A., Clauwaert, P., Rabaey, K. and Mutnuri, S., 2018. Sanitation of blackwater via sequential wetland and electrochemical treatment. npj Clean Water, 1(1), p.14.

Tanner, C.C. and Kadlec, R.H., 2003. Oxygen flux implications of observed nitrogen removal rates in subsurface-flow treatment wetlands. Water Science and Technology, 48(5), pp.191-198.

Tao, W., Wen, J., Han, Y. and Huchzermeier, M.P., 2012. Nitrogen removal in constructed wetlands using nitritation/anammox and nitrification/denitrification: effects of influent nitrogen concentration. Water Environment Research, 84(12), pp.2099-2105.

Tilak, A., Wani, S.P., Datta, A., Patil, M.D., Kaushal, M., Reddy, K.R., 2017. Evaluation of Ageratum conyzoides in field scale constructed wetlands (CWs) for domestic wastewater treatment. Water Science and Technology. 75, 10.

References

Tsavkelova, E.A. and Netrusov, A.I., 2012. Biogas production from cellulose-containing substrates: a review. Applied Biochemistry and Microbiology, 48(5), pp.421-433.

Ulrich, A., Reuter, S. and Gutterer, B., 2009. Decentralised wastewater treatment system (DEWATS) and sanitation in developing countries: a practical guide. Water, Engineering and Development Centre (WEDC) Loughborough University of Technology.

UNICEF, W., UNICEF, W. and World Health Organization, 2012. Progress on drinking water and sanitation. New York, USA.

UNITY I. E. World Pvt. Ltd, 2019. Preparation of Action Plan for Rejuvenation of Polluted

Van Cleemput, O., Boeckx, P., Lindgren, P.E. and Tonderski, K., 2007. Denitrification in wetlands. In Biology of the nitrogen cycle (pp. 359-367).

Vasanthi M., 2017, capacity of sewage treatment plants, government of india ministry of environment, forest and climate change, Lok sabha unstarred question no.2541.

Verma, V.K., Singh, Y.P. and Rai, J.P.N., 2007. Biogas production from plant biomass used for phytoremediation of industrial wastes. Bioresource technology, 98(8), pp.1664-1669.

Vigneswaran, S. and Sundaravadivel, M., 2003. Wastewater recycle, reuse, and reclamation. Conventional Water-treatment technologies, 2.

Virkutyte, J., 2015. The use of power ultrasound in biofuel production, bioremediation, and other applications. In Power Ultrasonics (pp. 1095-1122).

Vishal Gandhi, Jagdeep Kumar, J. K. Vimal, A.K Shinha, R.M. Bhardawaj, A.B. Akolkar; 2015; Inventorization of sewage treatment plants; Central Pollution Control Board (Ministry of Environment and Forests, Govt. of India).

Vohla, C., Kõiv, M., Bavor, H.J., Chazarenc, F. and Mander, Ü., 2011. Filter materials for phosphorus removal from wastewater in treatment wetlands—A review. Ecological Engineering, 37(1), pp.70-89.

Vymazal, J., 2007. Removal of nutrients in various types of constructed wetlands. Science of the total environment, 380(1-3), pp.48-65.

Vymazal, J., 2010. Constructed wetlands for wastewater treatment. Water, 2(3), pp.530-549.

Vymazal, J., 2011. Plants used in constructed wetlands with horizontal subsurface flow: a review. Hydrobiologia, 674(1), pp.133-156.

Wallace, S., Higgins, J., Crolla, A., Bachand, A. and Verkuijl, S., 2006, September. High-rate ammonia removal in aerated engineered wetlands. In Proceedings of 10th International Conference on Wetland Systems for Water Pollution Control (pp. 255-264).

Wang, H., Zhang, H. and Cai, G., 2011. An application of phytoremediation to river pollution remediation. Procedia Environmental Sciences, 10, pp.1904-1907

Wang, X., Tian, Y., Zhao, X., Peng, S., Wu, Q. and Yan, L., 2015. Effects of aeration position on organics, nitrogen and phosphorus removal in combined oxidation pond–constructed wetland systems. Bioresource technology, 198, pp.7-15.

Wang, X., Yang, R., Guo, Y., Zhang, Z., Kao, C.M. and Chen, S., 2018. Investigation of COD and COD/N ratio for the dominance of anammox pathway for nitrogen removal via isotope labelling technique and the relevant bacteria. Journal of Hazardous Materials.

Wani, SP., Patil, M., Datta, A., 2018. Clean water and sanitation in rural communities through people-centric water shed management. 88-92.

WHO/UNICEF Joint Water Supply, Sanitation Monitoring Programme, World Health Organization and UNICEF., 2008. Progress on drinking water and sanitation: Special focus on sanitation. World Health Organization.

Wu, H., Fan, J., Zhang, J., Ngo, H.H., Guo, W., Hu, Z. and Liang, S., 2015. Decentralized domestic wastewater treatment using intermittently aerated vertical flow constructed wetlands: impact of influent strengths. Bioresource technology, 176, pp.163-168.

References

Wu, H., Zhang, J., Li, P., Zhang, J., Xie, H. and Zhang, B., 2011. Nutrient removal in constructed microcosm wetlands for treating polluted river water in northern China. Ecological Engineering, 37(4), pp.560-568.

Wu, H., Zhang, J., Ngo, H.H., Guo, W., Hu, Z., Liang, S., Fan, J. and Liu, H., 2015. A review on the sustainability of constructed wetlands for wastewater treatment: design and operation. Bioresource technology, 175, pp.594-601.

Xia, S., Li, J. and Wang, R., 2008. Nitrogen removal performance and microbial community structure dynamics response to carbon nitrogen ratio in a compact suspended carrier biofilm reactor. Ecological Engineering, 32(3), pp.256-262.

Xu, J., Shi, Y., Zhang, G., Liu, J. and Zhu, Y., 2014. Effect of hydraulic loading rate on the efficiency of effluent treatment in a recirculating puffer aquaculture system coupled with constructed wetlands. Journal of Ocean University of China, 13(1), pp.146-152.

Yadav, A., Chazarenc, F. and Mutnuri, S., 2018. Development of the "French system" vertical flow constructed wetland to treat raw domestic wastewater in India. Ecological Engineering, 113, pp.88-93.

Yadav, A., Choudhary, P., Atri, N., Teir, S. and Mutnuri, S., 2016. Pilot project at Hazira, India, for capture of carbon dioxide and its biofixation using microalgae. Environmental Science and Pollution Research, 23(22), pp.22284-22291.

Yang, L., Fuqing, Xu.,Xumeng, Ge., Yebo Li., 2015. Challenges and strategies for solid state anaerobic digestion of lignocellulosic challenges and strategies for solid waste anaerobic digestion of lignocellulosic biomass. Renewable and Sustainable Energy Reviews. 44, 824-834.

Yang, Y., Tomlinson, D., Kennedy, S. and Zhao, Y.Q., 2006. Dewatered alum sludge: a potential adsorbent for phosphorus removal. Water Science and Technology, 54(5), pp.207-213.

Ye, Y., LaBarge, N., Kashima, H., Kim, K.Y., Hong, P.Y., Saikaly, P.E. and Logan, B.E., 2016. An aerated and fluidized bed membrane bioreactor for effective wastewater treatment with low membrane fouling. Environmental Science: Water Research & Technology, 2(6), pp.994-1003.

Yue, Z.B., Yu, H.Q., Harada, H. and Li, Y.Y., 2007. Optimization of anaerobic acidogenesis of an aquatic plant, Canna indica L., by rumen cultures. Water research, 41(11), pp.2361-2370.

Yue, Z.B., Yu, H.Q., Hu, Z.H., Harada, H. and Li, Y.Y., 2008. Surfactant-enhanced anaerobic acidogenesis of Canna indica L. by rumen cultures. Bioresource technology, 99(9), pp.3418-3423.

Zamparas, M., Gianni, A., Stathi, P., Deligiannakis, Y. and Zacharias, I., 2012. Removal of phosphate from natural waters using innovative modified bentonites. Applied Clay Science, 62, pp.101-106.

Zhang, D.Q., Jinadasa, K.B.S.N., Gersberg, R.M., Liu, Y., Ng, W.J. and Tan, S.K., 2014. Application of constructed wetlands for wastewater treatment in developing countries–a review of recent developments (2000–2013). Journal of environmental management, 141, pp.116-131.

Zhang, L.Y., Zhang, L., Liu, Y.D., Shen, Y.W., Liu, H. and Xiong, Y., 2010. Effect of limited artificial aeration on constructed wetland treatment of domestic wastewater. Desalination, 250(3), pp.915-920.

Zhang, Z., Rengel, Z. and Meney, K., 2007. Nutrient removal from simulated wastewater using Canna indica and Schoenoplectus validus in mono-and mixed-culture in wetland microcosms. Water, air, and soil pollution, 183(1-4), pp.95-105.

Zhao, Y.J., Yan, C., Li, Y.L., Li, J.H., Yang, M., Nie, E., Zheng, Z. and Luo, X.Z., 2012. Effect of C/N ratios on the performance of earthworm eco-filter for treatment of synthetics domestic sewage. Environmental Science and Pollution Research, 19(9), pp.4049-4059.

Zhong, W., Zhang, Z., Luo, Y., Sun, S., Qiao, W. and Xiao, M., 2011. Effect of biological pretreatments in enhancing corn straw biogas production. Bioresource technology, 102(24), pp.11177-11182.

Zhu, H., Yan, B., Xu, Y., Guan, J. and Liu, S., 2014. Removal of nitrogen and COD in horizontal subsurface flow constructed wetlands under different influent C/N ratios. Ecological Engineering, 63, pp.58-63.

Ziqiang, A., Jie, Z., Guiqun, P., Jiaqi, F., Cheng, J. and Jihai, X., 2017. Plant Selection of Constructed Wetlands for Treatment of Piggery Wastewater. Meteorological and Environmental Research, 8(2), p.85.

APPENDIX

8.1. Appendix I

8.1.1. Vertical flow constructed wetland system (VFCW)

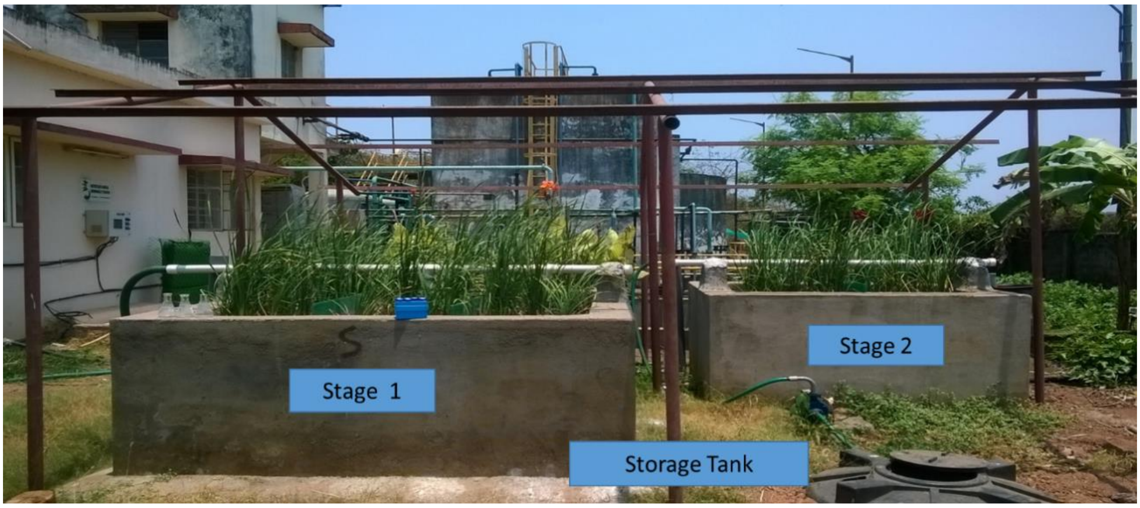


Fig 8.1.1: French Two stage vertical flow constructed wetland system at BITS Pilani Goa Campus.

8.2. Appendix II

8.2.1. Site selection

Site 1: Margaon STP site

The first site selected was a drain which comes from the city and passes through the Margaon STP (sewage treatment plant) area. The Margoa STP engineers had already constructed a diversion on the drain to transfer the wastewater directly into STP fig 8.2.1, A). This diversion could be easily used for the wetland inside the STP premises (fig 8.2.1, B). On the basis of these findings the site inside the Margaon STP was suggested to the Margaon Municipal Corporation (MMC).

Fig 8.2.1: Google image of the drain (A) and (B) the diversion made by MMC

In the meantime, samples were collected from four different points for analysis (Table 1).

- BS: before STP (Upstream of the drain considering STP as the site)
- AS: after STP (Downstream of the drain considering STP as the site)
- US: upstream of River Sal
- DS: downstream of River Sal

The Margaon STP site was ideal for setting up of wastewater treatment plant. The wastewater from the core city comes to the drain. A diversion was also made by Margaon STP engineers to transfer and store waste water at the STP. However, the volume of waste water could not be handled at the STP. Hence, this water was let off into River Sal, thus, polluting the river. The COD and TKN in the drain water (BS) was very high. As the wastewater from the drain was not currently getting treated, the COD and TKN in the downstream (AS) of the drain was also very high as shown in Table 8.1. Setting up of a vertical flow constructed wetland in this area could have made a great impact in the quality of wastewater being disposed into the river.

Table 8.2.1: Analysis of wastewater from site 1

Parameters (mg/l)	BS	AS	US	DS
COD	277.84 ± .039	82.95 ± .005	202.27 ± .017	110.23 ± .011
TOC	26.89 ± 4.07	22.99 ± 3.91	27.34 ± 7.16	14.78 ± 2.53
TKN	200.66 ± 0.03	181.22 ± 0.03	112.78 ± 0.02	140.78 ±0.04
Ammonia	6.86 ± 2.67	4.97 ± 2.14	7.46 ± 3.15	3.33 ± 1.53
Nitrate	38.93 ± 19.28	38.81 ± 14.72	44.44 ± 23.38	19.34 ± 7.98
Nitrite	16.67 ± 5.56	8.79 ± 4.67	14.83 ± 8.20	5.96 ± 5.44
Phosphorus	1.250 ± 0.02	1.38 ± 0.002	1.68 ± 0.009	1.20 ± 0.004
Total Solids	0.29 ± 0.045	0.24 ± 0.027	0.30 ± 0.056	0.25 ± 0.04
Volatile Solids	2.15 ± 0.57	1.95 ±0.034	0.17 ± 0.03	0.14 ± 0.012

Site 2: Old Sessions Court

This site is near the Old Session court of Margaon on the Colva beach road. It is a drain which is coming from the city and is a combination of two small drains (fig 8.2.2). Sampling was carried out at three points (Table 8.2.2).

- CS1: Colva sample 1 (sample from small drain 1)
- CS2: Colva sample 2 (sample from small drain 2)
- CS3: Colva sample 3 (sample where both drains merge)

Fig 8.2.2: Google image of site 2 near to Sessions Court

The site 2 was selected as it was very near to the main road of the city and was having two drains directly coming from the heart of the city carrying most of the city wastewater to the River Sal. From the Table 8.2.2 it can be seen that the pollution parameters of the water were also very high. The wastewater from both drains get mixed and the waste water entering form other sources increases the final COD of the CS3 drain.

Table 8.2.2: Analysis of wastewater from site 2

Parameters (mg/l)	**CS1**	**CS2**	**CS3**
COD	130.97 ± 4.26	67.05 ± 2.84	420.74 ± 21.31
TOC	15.98 ± 0.18	12.40 ± 0.80	20.02 ± 1.46
TN	1.3745 ± 0.13	1.09 ± 0.07	2.02 ± 0.03
Ammonia	2.10 ± 0.10	1.85 ± 0.15	4.90 ± 0.20
Nitrate	7.05 ± 0.15	8.45 ± 0.25	13 ± 0.20
Nitrite	1.00 ± 0.00	0.65 ± 0.05	19.20 ± 0.90
Phosphorus	1.10 ± 0.02	1.19 ± 0.03	1.48 ± 0.08
Total Solids	0.32 ± 0.06	0.27 ± 0.05	0.27 ± 0.09
Volatile solids	0.25 ± 0.04	0.12 ± 0.02	10.21 ± 0.02

This site was also not available as it was very close to the main road and a commercial area.

Site 3: Navelim Village Site

One of the natives from Navelim village was ready to provide land for the construction of treatment plant. A small tributary in this village flows into the Sal river (fig 8.2.3). Samples were collected from this tributary and analysed (Table 8.2.3).

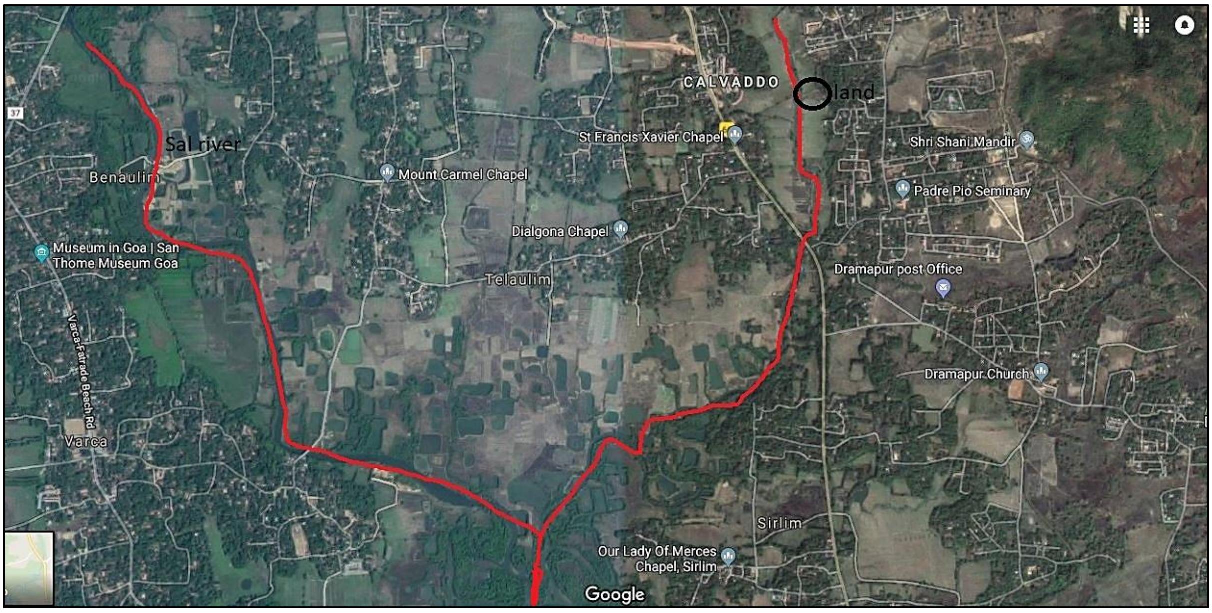


Fig 8.2.3: Google image of the site 3

Site 3: Navelim Village Site

The site was ruled out as the pollution parameters were below the CPCB Effluent Discharge standards, which can be observed in Table 8.2.3.

Table 8.2.3: Analysis of wastewater from site 3

Parameters (mg/l)	Upstream	Sight	Down stream
COD	Below detectable limit		
NITRATE	4.60	4.70	4.40
AMMONIA	4.70	4.45	4.40
PHOSPHORUS	0.14	0.25	0.25
TKN	Below detectable limit, not able detect by distillation		

8.3. Appendix III

8.3.1. List of Publications

- Anant Yadav, Piyush Choudhary, Neelam Atri, Sebastian Teir, and Srikanth Mutnuri. "Pilot project at Hazira, India, for capture of carbon dioxide and its biofixation using microalgae." *Environmental Science and Pollution Research* (2016): 1-8.

- Yadav, A., Chazarenc, F. and Mutnuri, S., 2018. Development of the "French system" vertical flow constructed wetland to treat raw domestic wastewater in India. *Ecological Engineering*, *113*, pp.88-93.

- Talekar, G.V., Sharma, P., Yadav, A., Clauwaert, P., Rabaey, K. and Mutnuri, S., 2018. Sanitation of blackwater via sequential wetland and electrochemical treatment. *npj Clean Water, 1*(1), p.14.

8.4. Appendix IV

8.4.1. List of conferences, workshops and Courses

- Participated in “Conference on Terra Preta sanitation and decentralized wastewater system” on 19-21 November 2015, at BITS Pilani Goa Campus, Goa.
- Attended a workshop on “BIRAC Workshop on Bio-entrepreneurship Grant writing and Intellectual Property Management” on 18-19 February 2016 at BITS Pilani Goa campus, Goa.
- Presented in a workshop on “Novel Sanitation Approaches and Emerging Trend in Wastewater Treatment technologies” on 19-21 December 2017 at BITS Pilani Goa campus, Goa.
- Participated in the “4th Asia Pacific- International Society of Microbial Electrochemistry and Technology (AP- ISMET) Meeting with a special focus on Bio-electrochemical and Electrochemical Approaches for Decentralised Sanitation” on 13-17 November 2018 at BITS Pilani Goa campus, Goa.
- Participated in “Fulbright Specialist Program on Engineering-Economics-Entrepreneurship” on 18 may – 6 July 2018 at BITS Pilani Goa campus, Goa.
- Completed a 3-credit unit course in “Water Sanitation and Solid waste management – BIOF216” a Joint programme of Ewag-Sandec and BITS Pilani Goa campus, Goa.

8.5. Appendix V

8.5.1. Brief Biography of the Candidate

Personal details

Name	Mr. Anant Yadav
Education	B.Tech – M. Tech Biotechnology(Dual degree) Jaypee University of Information Technology, India
E-mail	anantyadav27@gmail.com

8.5.2. Research Experience

- Research Project (1st August 2017- till date)

Currently working on the project funded by DBT titles “Demonstration of River Sal Cleaning by Vertical Wetlands and Riverbed filtration” as a Junior, research fellow.

- Research Project (2nd February 2017-31st July 2017)

Visiting Research Scholar IMT Atlantique, 4 Rue Alfred Kastler, 44300 Nantes, France.

Project title: Use of reactive material for P removal in small treatment plants, the potential of industrial by-products in India. Funded by CEFIPRA (Raman Charpak Fellowship)

- Research Project (Ph.D. Work) (25th October 2014- 31st January 2017)

Junior research fellow in BITS Pilani K.K. Birla Goa campus on a research project entitled “Development and Demonstration of two decentralized wastewater treatment plants,” funded by CORE WWE Birla Group.

- Research project (5th June 2014-24 October 2014)

Completed Oil and Natural Gas Corporation(ONGC) sponsored research project entitled “Setting up of a pilot project at Hazira for fixation of carbon dioxide and greenhouse gas abatement with microalgae” as a junior research fellow at ONGC Hazira, Surat, Gujarat.

No. of publications- 03
No. of conferences/workshop attended 05

8.6. Appendix VI

8.6.1. Brief Biography of the Supervisor

Dr. Srikanth Mutnuri is a recipient of DAAD-UGC Scholarship to complete his Doctoral Research at UFZ – Centre for Environmental Research, Germany and obtained his degree from Anna University Chennai in the year 2004. He joined BITS Pilani K.K Birla Goa Campus as a full-time faculty by 2005. He worked as convener for three International Conferences in Environmental Biotechnology held in the year 2009, 2011 and 2014 at BITS Pilani K.K Birla Goa Campus. Dr. Srikanth Mutnuri conducted International Workshop on Bioremediation in association with Dr. Max Haggblom, Rutgers University USA for two weeks from January 4 – 16, 2010. He was the principal investigator for four research projects funded by DST, DBT, UGC, and GEDA and currently, he has research projects funded by CSIR, GIZ and DBT BIRAC & Bill and Mellinda Gates foundation. He has published 21 research papers in International Journals and written two Book Chapters. He received Helmholtz association's Junior Scientist Award and FEMS Young Scientist Award to participate in International Conference on Environmental Biotechnology, Leipzig, Germany, 2006 and 14th International Biodeterioration and Biodegradation symposium Sicily, Italy, 2008 respectively. He had attended National and International Conferences to present his research work as Oral and Poster presentations. He has Research Collaborations with Scientists from IISc Bangalore, INRA France, UFZ Germany, GTZ-BMU Germany, Ecole de mines Nantes – France, Caltech – USA, International Water Management Institute Colombo – Srilanka, Cranfield University – UK and Rutgers University USA. He is a Recipient of American Society for Microbiology & Indo US Science and Technology Forum (ASM IUSSTF) Indo US Research Professorship for October 2010. There are two start-ups from his lab one is Sustainable Biosolutions LLP started by two of our former M.E Biotech students and other started by him is Bactreat Environmental solutions LLP, his company has bagged 25 lacs from DBT BIRAC for its project on Resource Recovery from Septage project.

8.6.2. Brief Biography of the Co–Supervisor

Dr. Florent Chazarenc is a Ph.D and Engineer in environmental engineering. He is working as a senior Researcher (Director of Research) and group leader at Irstea in the research unit REVERSAAL (Lyon-France). He had done his PhD in Environmental Engineering at the University of Savoie, France. He carried out his post-graduate research jointly at Polytechnique Montréal and at Institut de recherche en biologie végétale in Montréal, before returning to France in 2007 where he took his accreditation to Lead Research in 2013. Having organized the 5th WETPOL conference (International Symposium on Wetland Pollutant Dynamics and Control) in 2013 in Nantes, he is also strongly involved in specialist groups of the IWA (International Water Association) on the subject of reed bed filters and water pollution control. He also successfully organised the 14th Specialized Conference on Small Water and Wastewater Systems in 2017 (S2SMALL2017). He was principal investigator for many research projects funded by national and international agencies. He had attended National and International Conferences to present his research work as Oral and Poster presentations. He has published 46 research papers in International Journals and written two Book.