ADVANCED PRIMARY TREATMENT OF DOMESTIC WASTEWATER IN TROPICAL COUNTRIES: DEVELOPMENT OF HIGH-RATE ANAEROBIC PONDS

By

Miguel-Ricardo Peña-Varon

Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

The University of Leeds

School of Civil Engineering

April 2002

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others

ACKNOWLEDGEMENTS

I give special thanks and express my gratitude and admiration to my supervisor Professor David Duncan Mara, for all his patience, guidance and sharp criticism that were very opportune in critical moments.

I am indebted to the Instituto Colombiano para el Desarrollo de la Ciencia y la Tecnología (COLCIENCIAS) for providing me with the financial support to carry out this work.

I also feel that a number of people warrant special recognition. My special thanks go to Dr. Gerardo Galvis for all the help, motivation and enthusiasm he transmitted to me during the development of this work. He also made it possible for me to undertake my doctoral studies by providing the necessary conditions in my home institution (Instituto Cinara at Universidad del Valle). Dear Gerardo, this is a dream that has come true thanks to your vision and endless hard work.

My gratefulness is also to Dr. Huub Gijzen at IHE (NL) for all the interesting and helpful brainstorming sessions when I was just wondering about my research topic. Many thanks also for the financial support to several activities of this work via the cooperation agreement between the Dutch and Colombian governments. My special thanks are also to Ing. Alberto Galvis, Director on the Colombian side of the cooperation agreement with the Dutch government.

I am very grateful to my friends and colleagues at Cinara and Universidad del Valle. I wish to thank Ing. Edgar Quiroga, Director of Cinara for his unstinting support for this work.

My special recognition goes to all my masters and undergraduate students who collaborated patiently and untiringly with long journeys of data collection. They are Ginna Avella, Adriana Sánchez, Margarita Sepulveda, Veronica Manzi, Rick Meynen, Jean Marc Piguet and Gloria Paola Vega.

Many thanks to Dr. Eugenio Giraldo for his invaluable advise on this work and also for the interesting discussions we held on different aspects of anaerobic biotechnology and microbiology.

Many thanks to Mr. Noel Muñoz and Mr. Yimer Velez for their invaluable work and help in the laboratory both at Cinara and the Research Station at Ginebra.

I owe gratitude and thanks to Ms. Dorothy Carr and Miss. Sally Mortimer for all their help while I was at the School of Civil Engineering in the University of Leeds.

I especially wish to thank my family and my wife for all the support and encouragement they gave me particularly during difficult moments.

My appreciation goes to my friend and colleague Carlos Madera who helped me in different ways and, most importantly, we were always able to have a laugh despite the stress of everyday life. My gratefulness is also to my friends in the UK: Christian Dunkerley, Robin Lloyd, Mo Arora and Efstathios Papadimitriou for being always there.

Special acknowledgments are due to Ing. Francisco Ramirez and Ing. Alexander Sánchez at ACUAVALLE S.A ESP and Miss. Alexandra Lucero at EMCALI E.I.C.E. These persons and their institutions collaborated kindly and enthusiastically with this work.

ABSTRACT

Domestic wastewater treatment is far from satisfactory in most Latin American countries. Coverage of sanitation services (i.e. excreta disposal, wastewater collection and conveyance) is low particularly in small municipalities and rural settlements of the Andean Region. WSP and anaerobic reactors have been widely used in various countries of Latin America during the last decades. However, there are some aspects of these technologies that deserve further investigation in order to develop more efficient yet simple and affordable process configurations that can effectively contribute to the reduction of water pollution and public health improvements in small municipalities and rural areas of most Latin American countries.

This work therefore focuses on the study of the hydrodynamics and process performance of two well-established primary anaerobic treatment systems, the anaerobic pond (AP) and the upflow anaerobic sludge blanket (UASB) reactor. The hydrodynamics and biological process performance of APs may be further improved by applying fundamental principles from reactor engineering and anaerobic treatment theory so that current reaction rates in these units are enhanced. This will clearly improve the applicability of this technology and waste stabilisation ponds (WSP) at large provided that simplicity of operation and maintenance (O&M) is kept. An improved or high-rate AP configuration may be obtained by combining the best features of the two technologies mentioned above (AP and UASB) based on their evaluation under the same conditions.

The methodology comprised three main steps: first, studies of the hydrodynamic behaviour of two full-scale AP and a full-scale UASB reactor were carried out to find out their mixing patterns and related process performance. Second, computational fluid dynamics (CFD) simulations of one of the full-scale AP were done so as to study the effects of sludge accumulation, baffling arrangements, inlet-outlet positioning and pond geometry on the overall hydrodynamic efficiency of the AP. Third, results from the full-scale studies were used to run hydrodynamic and process performance evaluations under steady state conditions on various modified pilot-scale AP configurations.

The results showed that full-scale AP had large flow deviations that produced low removal efficiencies related mainly to sludge accumulation, inadequate inlet-outlet positioning and poor geometric design. Meanwhile, the UASB showed a hydrodynamic behaviour very close to the CSTR model with two mixed compartments in series provided that it is properly loaded. Short-circuiting, dead zones and bypassing flows were observed during both underloading and overloading conditions. Experimental hydraulic retention time (HRT) values in the full-scale AP varied from 30 to 50% of the theoretical HRT. Experimental HRT values in the UASB varied from 60 to 100% of the theoretical HRT and this showed the superior hydrodynamic performance of this reactor compared to the AP. The CFD simulations of the full-scale AP showed, however, that two baffles located at L/3 and 2L/3 along with diagonally opposite inlet-outlet devices and a rectangular geometry (L: B = 2:1), increase the experimental HRT up to 84% of the theoretical HRT.

On the other hand, the modified pilot-scale AP configurations [vertically baffled anaerobic pond (VBAP), plastic nets fitted anaerobic pond (PNFAP), horizontally baffled anaerobic pond (HBAP) and mixing pit fitted anaerobic pond (MPAP)] yielded an improved hydrodynamic behaviour in comparison with the conventional AP. The experimental HRT values varied from 70 to 100% of the corresponding theoretical HRT figures. This finding together with the closeness to the complete mixing pattern observed in all the pilot-scale APs confirmed one of the main characteristics of high-rate anaerobic reactors. The best configuration in terms of hydrodynamics was the MPAP, followed by the baffled configurations (VBAP and HBAP) and then the PNFAP. The process performance evaluation showed that the highest COD total removal efficiencies occurred in the MPAP (77-79%), followed by the HBAP (65-51%) and then the AP (67-49%). Improved hydrodynamics, enhanced contact pattern and better biomass retention explain the increasing COD filtered removal efficiencies found in the MPAP (50-78%). The HBAP and the AP removal efficiencies for COD filtered were (41-44%) and (44-53%) respectively. The removal of filtered COD is achieved mainly by direct biological action, which depends on a good external mass transfer process to and from the cells (biomass). The removals of faecal coliforms and *E. coli* were low in all the reactors as expected in anaerobic treatment systems. Removals of helminth eggs were higher in the MPAP configuration (51-67%) compared to the other modified AP configurations.

The whole set of results proved that it is possible to develop a high-rate AP by enhancing its hydrodynamics and related transport phenomena. The high organic matter removal efficiencies achieved at shorter HRT values (18-12 h) together with the enhanced biomass retention and the possibility of biogas recovery, confirmed the advanced primary treatment features of these modified AP configurations.

In memory of my dear granny, Leonor, and my mother Aura Maria. I know they would have been truly pleased with this achievement. This work is also especially dedicated to my beloved wife, Claudia Cecilia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

ABR	Anaerobic baffled reactor
AMB	Acetoclastic methanogenic bacteria
ANOVA	Analysis of variance
AP	Anaerobic pond
ASRB	Acetoclastic sulphate reducing bacteria
BMP	Biochemical methane potential
BOD	Biochemical oxygen demand
CEPIS	Pan-American centre of sanitary and environmental engineering
CFD	Computational fluids dynamics
COD	Chemical oxygen demand
CSTR	Completely stirred tank reactor
DFID	UK-Department for international development
GLS	Gas-Liquid-Solid separation device
HBAP	Horizontally baffled anaerobic pond
HMB	Hydrogenotrophic methanogenic bacteria
HSRB	Hydrogenotrophic sulphate reducing bacteria
HRT	Hydraulic retention time
MB	Methanogenic bacteria
MPAP	Mixing pit fitted anaerobic pond
ORP	Redox potential
PAHO	Pan-American health organization
PNFAP	Plastic nets fitted anaerobic pond
RTD	Retention time distribution curves
SMA	Specific methanogenic activity
SPSS	Statistical package for the social sciences
SRB	Sulphate reducing bacteria
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket reactor
UN	United Nations
UNEP	United Nations environmental programme
VBAP	Vertically baffled anaerobic pond
VFA	Volatile fatty acids
VSS	Volatile suspended solids
WHO	World health organization
WSP	Waste stabilization ponds
WWTP	Wastewater treatment plant