PROGRAMA DE DOCTORADO EN INGENIERÍA AMBIENTAL

(Distinguido con Mención hacia la Excelencia por el Ministerio de Educación)

DPTO. DE CIENCIAS Y TÉCNICAS DEL AGUA Y DEL MEDIO AMBIENTE

E.T.S. DE INGENIEROS DE CAMINOS, CANALES Y PUERTOS

UNIVERSIDAD DE CANTABRIA

TESIS DOCTORAL

Para optar al grado de Doctor por la Universidad de Cantabria con Mención Internacional

ANOXAN: UN REACTOR ANAEROBIO-ANÓXICO INNOVADOR PARA ELIMINACIÓN BIOLÓGICA DE NUTRIENTES DE AGUAS RESIDUALES

ANOXAN: A NOVEL ANAEROBIC-ANOXIC REACTOR FOR BIOLOGICAL NUTRIENT REMOVAL FROM WASTEWATER

RUBÉN DÍEZ MONTERO

Director

IÑAKI TEJERO MONZÓN

Santander, octubre de 2015

Ella está en el horizonte. Me acerco dos pasos, ella se aleja dos pasos.
Camino diez pasos y el horizonte se corre diez pasos más allá.
Por mucho que yo camine, nunca la alcanzaré.
¿Para qué sirve la utopía? Para eso sirve: para caminar.

Las palabras andantes, Eduardo Galeano (1940-2015)

Agradecimientos

Durante el desarrollo de esta tesis he tenido la oportunidad de participar en la creación de un algo desde la nada, desde la intuición a la idea y finalmente a la realización. Algo que toma vida desde el momento en que se le pone nombre, y se convierte en el envoltorio de una importante etapa de la vida, envoltorio que se antoja difícil de despegar o incluso imposible. Y durante ese trayecto, la suerte de estar acompañado, compartiendo, recibiendo y aportando. Será imposible olvidar a todas aquellas personas que han contribuido a esta tesis, pero que sirvan estas líneas como recuerdo y sincero agradecimiento.

En primer lugar quiero agradecer a Juan Ignacio Tejero, a Iñaki, su dirección y supervisión. Esta tesis no hubiera sido posible sin su genialidad y sin su apoyo incondicional. Y su cercanía desde que nos conocimos y me sentó en aquel despacho para atenderme durante horas y así engancharme al Graduado Superior en Ingeniería Ambiental… y hasta hoy… He de agradecer el hecho de valorarme desde el primer día e incluso sobrevalorarme y sobreestimarme en ocasiones durante este largo bagaje. Y por encima de todo, por ser la persona que más me ha enseñado y de la que más he aprendido en esta profesión.

Me gustaría mencionar y agradecer su participación a todas aquellas personas que de una u otra manera han ayudado a mejorar el contenido de esta tesis: Dana, Marta, Lorena, Eveline, Claudio. Y a todas aquellas personas que en algún momento han sido "perturbadas" por AnoxAn: Paula, Patricia, María, Laure, Raquel, Leyre, Juliette.

Por supuesto, quiero agradecer el apoyo prestado y la compañía al resto del grupo GIA (y no GIA…), desde quienes estaban ahí el día que llegué hasta con quienes he compartido esta última etapa. Profesor@s, compañer@s, amig@s. Amaya Lobo, Lorena Esteban, Javier Temprano, Ramón Collado, Juanjo Amieva, Carlos Rico, Xabier Moreno y el Grupo de Ecología, Marta González, Loredana De Florio, Lucía Cacho, María Castrillo, Leticia Rodríguez, Juan Munizaga, Ana López, Ancella Molleda, Nuria Lozano, María Fernanda Román, Ana García. También a quienes en algún momento se han cruzado en este camino dejando su huella (David Presmanes, Isabel Gutiérrez, David Martínez, Sara Cantera, Begoña Perea, Esther Zugasti, Patricia Fernández, José Herminsul Martínez,…) y máximas disculpas a todos aquellos que se me olvide mencionar… También me gustaría agradecer la acogida y trato de Eveline Volcke y su gran equipo Biosystems Engineering, así como todo el entorno que hizo tan fácil y agradable el tiempo en Gent.

No puedo olvidar a los colegas NOVEDAR, que compartimos retos e inquietudes desde el primer día de esta tesis. Puedo estar orgulloso de que ahora mismo engorden mi agenda de contactos y muy especialmente de amigos. No puedo evitar emocionarme al mandaros un gran abrazo, especialmente a Jose Abelleira.

También quiero dar las gracias a mi familia "elegida", por preocuparse, preguntarme, ayudarme, escucharme, desahogarme,…, por los pequeños detalles, la música y el mar. Durante esta etapa crucial de la vida, la vida sigue pasando, y ocurriendo, y uno se arrepiente de no haberle prestado en ocasiones la atención que merecía. Pero agradezco enormemente, de manera invalorable e incomparable a quien durante este tiempo me ha hecho sentir y acercarme a la felicidad. Sabéis muy bien que os quiero.

Finalmente, mi gran Familia. Gracias Sergio, por recordarme que hay que estar despierto y reivindicativo. Y por estar ahí, siempre disponible y fácil, como hermanos. Y gracias por todo, nada hubiera sido posible ni tendría sentido sin María y Abilio, por darme todo, por ayudarme en todo, por entenderlo todo, y por la vida… os quiero. Por último, quiero dedicar esta tesis a Emilia, por su esfuerzo por comprenderme ¡creo que lo consiguió hace tiempo!, y a la memoria de Lidia, Ciano y Pepe, para que sonriáis allá donde estéis.

Rubén Díez Montero
Santander, 5 de octubre de 2015

Summary

The need for nutrient removal from wastewater before discharge is pursued by stringent regulation for the protection of the receiving water bodies. Specifically, nitrogen and phosphorus effluent requirements are to be imposed for discharges into sensitive areas, subject to eutrophication. In addition, there is an upward trend in the requirement for nutrients removal, as it is the case in Spain, where the areas declared as sensitive have been significantly increased in the last years. This fact compels to upgrade, modify or build-up a great number of wastewater treatment plants (WWTP) for nutrient removal. Conventional processes for biological nutrient removal (BNR) require complex and large treatment systems, which could result in a noteworthy constraint when space availability is limited, not only for new WWTP build-up, but also for existing WWTP upgrade to nutrient removal.

Increasing research and development efforts are been done in order to provide more compact and efficient technologies, compared to conventional systems, in order to face such facilities designs and upgrades. Much research has been carried out aimed at achieving more compact and efficient aerobic reactors. In order to further increase the compactness of a BNR process, the incorporation of the anaerobic and/or anoxic zones (required for the BNR treatment train) into the aerobic reactor has been also proposed and investigated. In a different approach, but with the same purpose, the anaerobic and anoxic zones could be unified in a single non-aerated reactor. However, few studies have been found compacting the anaerobic and anoxic zones in a single suspended sludge reactor for BNR. This alternative would avoid the construction of separate anaerobic and anoxic tanks, and would take advantage of the complete separation from the aerobic reactor, thus preventing the undesired intrusion of oxygen into the anoxic and anaerobic zones and avoiding the difficulty of hydraulic separation in a bubbled reactor.

In this framework, a novel anaerobic-anoxic reactor for BNR has been conceived, named AnoxAn, which is presented in this doctoral thesis. The novel technology has been characterized and tested through experimental bench-scale pilot plant operation and model simulations, in order to describe the key features of the reactor, to assess the feasibility of the reactor concept, and to assess its performance in the removal of organic matter and nutrients from wastewater.

Chapter 1 introduces the topic of this doctoral thesis and places it within the context of the current scientific research. The scope and objectives of the thesis are also stated in this chapter.

Chapter 2 presents the literature review about anaerobic-anoxic biological reactors, focusing on BNR. Concepts and applications of upflow sludge blanket reactors and denitrifying phosphate uptake are also reported.

Chapter 3 describes the materials and methods used in the experimental and modelling work. Although specific materials and methods for the feasibility evaluation of the hydraulic anoxic-anaerobic separation are reported in **Chapter 5**, for the performance evaluation of the reactor for biological nutrient removal treating municipal wastewater in **Chapter 6**, and for the model-based evaluation of an anaerobic-anoxic primary clarifier for the upgrading of an existing WWTP in **Chapter 7**, all of them are gathered in this chapter, aimed at providing an overall view of the materials and methods used in this thesis in a self-contained section of the document.

In **Chapter 4**, the AnoxAn reactor is presented and described. A complete description of the invention can be found in the Spanish patent ES2338979 "Reactor biológico anóxico-anaerobio para la eliminación de nutrientes de aguas residuales", which is reported as an **Annex** in this thesis. In this chapter, the technical features of the reactor are explained in detail, highlighting the advantages of the invention, and a summary of the technical and economic assessment of the reactor, as well as full-scale perspectives are also included.

The AnoxAn reactor is presented as an innovative technology for BNR, consisting in a continuous upflow sludge blanket reactor, with an anaerobic zone at the bottom prior to an anoxic zone above. A clarification zone at the top of the reactor avoids the escape of large amounts of suspended solids, thus promoting high biomass concentration in a sludge blanket reactor type. The biological anaerobic-anoxic functioning of AnoxAn is meant to be coupled with an aerobic reactor and a secondary sedimentation unit (or a final filtration step), in order to complete the BNR treatment train. The main features of the reactor are: (i) upflow operation; (ii) hydraulic separation between the anoxic and anaerobic zones; and (iii) suspended solids retention. Such characteristics aim at achieving high compactness and efficiency, thus reducing the surface requirement and energy consumption. Overall, the novel configuration claims anaerobic phosphate release, anoxic denitrification and phosphate uptake in a single reactor with high biomass concentration and low energy demand.

The potential economic savings of the implementation of the AnoxAn reactor have been assessed considering a hypothetical full-scale realization of the reactor. The results showed remarkable differences between AnoxAn and the equivalent anaerobic and anoxic stages of a conventional BNR treatment system (specifically, UCT), which was used for comparison purposes. The investment cost of the AnoxAn reactor, not including the land cost, was estimated 23% higher than that of the equivalent UCT system, mainly due to the additional cost of lamellas or baffles. However, the energy savings for mixing of the AnoxAn reactor led to an operational cost lower than half of that of the UCT system. Eventually, the total annualized equivalent cost (including investment and operation) of the AnoxAn reactor resulted from 20 to 26% lower than the one of the equivalent UCT system, considering an electricity cost from 0.10 to 0.14 € per kWh. This indicates the significance of the AnoxAn potential energy savings and the corresponding economic benefit.

In **Chapter 5**, the feasibility evaluation of the anoxic-anaerobic hydraulic separation in the AnoxAn reactor is tackled. At this aim, a bench-scale prototype was built up and hydraulically characterized. In AnoxAn, the environmental conditions are vertically divided up inside the reactor with the anaerobic zone at the bottom and the anoxic zone above. One of the main goals of the reactor setup is to establish the anoxic-anaerobic hydraulic separation while achieving adequate mixing conditions in the two zones and keeping the continuous influent flow up-way through it. The concept of hydraulic separation in this study is interpreted as the ability of maintaining two zones under different environmental conditions inside the single reactor, including negligible nitrate concentration in the anaerobic zone. The feasibility assessment of the desired hydraulic behaviour, prior to the evaluation of its biological performance treating wastewater, was considered essential and was addressed in the study presented in this chapter.

The capability of the AnoxAn configuration to establish two hydraulically separated zones inside the single reactor was assessed by means of hydraulic characterization and model simulations. Residence time distribution analysis by means of tracer tests in clean water were performed in the bench-scale AnoxAn prototype (48.4 L reactor volume). Specific mixing devices and baffles were selected in order to provide adequate mixing in the individual anaerobic and anoxic zones, as well as the required hydraulic separation between both zones. The observed behaviour was described by a hydraulic model consisting of continuous stirred tank reactors and plug-flow reactors. The model was used to assess the feasibility of the anoxic-anaerobic hydraulic separation inside the reactor in several scenarios. The simulation results showed that the desired hydraulic behaviour was achieved, involving adequate mixing in each zone and little mixing between the anoxic and the anaerobic zones. A back-mixing flowrate between both zones was estimated to be only 40.2% of influent flowrate, which is lower than typical anoxic recycle ratio (from the anoxic to the anaerobic reactor) in several conventional BNR configurations, such as UCT. Subsequently, the impact of the denitrification process on the hydraulic separation was evaluated through further model simulations. When denitrification in the anoxic zone (in the virtual presence of biomass) was incorporated to the model, nitrate concentration was drastically reduced, even with a continuous nitrate injection of 20 mgN L^{-1} in the recycle stream. The ratio between nitrate concentrations in the two zones remained the same, indicating that denitrification did not affect the extent of hydraulic separation. Nevertheless, the occurrence of denitrification resulted in negligible nitrate concentration (less than 0.1 mgN L^{-1}) in the anaerobic zone, as desired, for biomass concentration of 1.2 g L^{-1} or higher.

Finally, a tracer test was performed with biomass within the reactor in order to assess the influence of biomass on the reactor hydrodynamics. The experimental results were compared to those obtained through hydraulic model simulation. The experimental and simulated tracer concentration profiles in the anoxic zone matched very well, while in the anaerobic zone the simulation results slightly overpredicted the measured concentrations. This suggests that the presence of biomass further increase the hydraulic separation between the anoxic and anaerobic zones, which was attributed to the different total suspended solids (TSS) concentration in both zones. The lower TSS concentration in the anoxic zone (approximately 5 g L^{-1}) compared to the TSS concentration in the anaerobic one (approximately 10 g L^{-1}) can be imputed mainly to the nitrate recycle stream, which enters the AnoxAn reactor with high flowrate and lower concentration of TSS, thus provoking TSS dilution in the anoxic zone. Due to these different concentrations, different densities in each zone have slightly enhanced the hydraulic separation.

Once proved the feasibility of the anoxic-anaerobic hydraulic separation in the AnoxAn reactor, the performance evaluation of the novel reactor was carried out, which is reported in **Chapter 6**. The AnoxAn prototype was coupled with an aerobic hybrid membrane bioreactor (HMBR) and operated treating municipal wastewater, aimed at the performance evaluation of the novel reactor in the removal of organic matter and nutrients. The AnoxAn sludge blanket was developed achieving TSS concentration up to 10 g L^{-1} in the anaerobic zone and approximately 5 g L^{-1} in the anoxic one. The upper clarification zone did not avoid the escape of biomass from the reactor; however TSS concentration in the AnoxAn effluent was lower than those in the anaerobic and anoxic zones of the reactor, indicating that the biomass was retained to some extent.

Denitrification successfully occurred, with a low nitrate concentration (lower than 1 mgN L^{-1}) in the AnoxAn effluent. The overall nitrogen removal efficiency averaged 75%. The overall phosphorus removal was also satisfactory, with an average removal efficiency of 89%. However, under the conditions of the present study, simultaneous denitrification and phosphate uptake by means of denitrifying phosphate accumulating organisms (DPAO) did not achieve the desired phosphorus removal efficiency. Nitrate was depleted in the anoxic zone, due to the denitrification activity, while phosphate was not fully taken up. This entails that the subsequent aerobic stage was necessary to complete the phosphate uptake, achieving an effluent phosphorus concentration below 1 mg L^{-1}. The operation of AnoxAn, allowing the escape of certain amount of biomass resulted essential for the achievement of such low overall effluent phosphorus concentration. It was observed partial hydrolysis of the particulate organic matter in the AnoxAn reactor, estimated at 42% of the average influent particulate organic matter, according to mass balances. This feature would be beneficial to the performance of BNR, since hydrolysis produces readily biodegradable organic matter which is needed for phosphate release and denitrification.

The multi-environmental functioning of the novel setup was observed during the experimental campaign. Phosphate release in the anaerobic zone was possible thanks to the achievement of anaerobic conditions, and confirmed the occurrence of enhanced biological phosphorus removal (EBPR). On the other hand, according to nitrate mass balances, 95% of the nitrate entering the AnoxAn reactor was removed in the anoxic zone while only the remaining 5% was removed in the anaerobic zone. Summarizing, AnoxAn performed several functions with a hydraulic retention time (HRT) of 4.2 hours: biomass retention; hydrolysis of influent particulate organic matter; phosphate release with an anaerobic HRT of 1.1 hours; and nearly complete denitrification with an anoxic HRT of 2.7 hours.

Chapter 7 presents a real case study regarding an existing WWTP upgrade to BNR. The study evaluated, by means of model simulations, the prospective conversion of a secondary treatment plant to BNR. The existing facility was based on trickling filters, and the objective of the upgrading was to achieve nitrogen and phosphorus effluent standards. The main constraint for the process selection was the limited available space. Therefore, the proposed treatment train would make use of the existing facilities in the current plant, avoiding the need for new tanks or reactors. Specifically, a large primary clarifier (average HRT of 8.4 hours) was proposed to be modified in order to host the anaerobic and anoxic zones required for BNR, based on the anaerobic-anoxic sludge blanket reactor, AnoxAn. Several scenarios were simulated to preliminarily design and to optimize the anaerobic-anoxic reactor.

The anoxic zone, incorporated in the modified primary clarifier (MPC), denitrified satisfactorily and the required effluent nitrogen concentration was achieved in all of the simulated scenarios. The anoxic zone performed satisfactorily with TSS concentration of approximately 2.7 g L^{-1} and an HRT of 4.7 hours. Good denitrification was maintained when the anoxic volume was reduced up to 2.4 hours.

However, EBPR was not achieved by solely alternating anaerobic and anoxic conditions, which was attributed to the competition for nitrate of conventional denitrifying heterotrophs and DPAO, due to the influent wastewater characteristics with no limiting organic matter availability. In order to provide aerobic conditions for the suspended growth biomass and promote EBPR, an additional aerobic zone and a bypass of activated sludge from the anoxic zone to the trickling filter were incorporated. A reduction of the anoxic volume to host an aerobic zone in the same MPC was found to achieve EBPR with several combinations of aerobic volume – sludge bypass, while maintaining excellent nitrogen removal. In conclusion, by means of this facility upgrade, BNR would result feasible by using the existing facilities in the existing WWTP, with no need for new reactors.

Finally, **Chapter 8** presents the general conclusions of this doctoral thesis and suggestions for further research on this topic.

Resumen

La necesidad de eliminar los nutrientes de las aguas residuales antes de su vertido está contemplada en legislaciones rigurosas que tienen como finalidad la protección de los medios acuáticos receptores. Concretamente, se imponen limitaciones al vertido de nitrógeno y fósforo en áreas sensibles a la eutrofización. Además, existe una tendencia creciente en cuanto a los requisitos impuestos sobre eliminación de nutrientes, como es el caso de España, donde las áreas declaradas como sensibles a la eutrofización han sido incrementadas de manera importante en los últimos años. Este hecho obliga a ampliar, modificar o construir un gran número de estaciones depuradoras de aguas residuales (EDAR) para eliminar nutrientes. Los procesos convencionales de eliminación biológica de nutrientes (EBN) requieren sistemas de tratamiento relativamente grandes y complejos, lo cual puede suponer una dificultad en casos de limitada disponibilidad de espacio, tanto para construcción de nuevas EDAR como para ampliación de EDAR existentes para eliminación de nutrientes.

Para hacer frente a tales limitaciones y dificultades, se está llevando a cabo una gran labor en investigación y desarrollo de tecnologías de tratamiento de aguas que sean más compactas y eficientes que los sistemas convencionales. Se han llevado a cabo numerosas investigaciones con el objetivo de desarrollar reactores aerobios compactos y eficientes. También se ha propuesto e investigado la posibilidad de incorporar las zonas anaerobias y/o anóxicas (necesarias para el proceso de EBN) en los propios reactores aerobios, intentando conseguir una mayor compacidad del proceso. Con un enfoque diferente, pero con el mismo objetivo, se pueden unificar las zonas anaerobia y anóxica en un único reactor no aireado. Sin embargo, se han encontrado muy pocos estudios en la literatura científica sobre reactores anaerobio-anóxicos de fango activo en suspensión para EBN. Esta alternativa evitaría la construcción de tanques independientes para los compartimentos anaerobio y anóxico, y aprovecharía la completa separación del reactor aerobio de manera que se protege a las zonas anaerobia y anóxica de la indeseada intrusión de oxígeno y además se evita la dificultad de conseguir separación hidráulica en un reactor con burbujas.

En este contexto, se ha concebido un reactor anaerobio-anóxico innovador para EBN, denominado AnoxAn, el cual se presenta en esta tesis doctoral. El reactor se ha caracterizado y analizado mediante la operación de una planta piloto a escala de bancada y simulación de modelos matemáticos, con el objetivo de describir sus características específicas, evaluar la viabilidad del concepto del reactor, y evaluar su funcionamiento eliminando materia orgánica y nutrientes de agua residual.

El **Capítulo 1** introduce la temática de esta tesis y la enmarca dentro del contexto de la investigación científica actual. Este capítulo también describe el alcance y los objetivos de la tesis.

El **Capítulo 2** presenta la revisión de la literatura científica sobre reactores anaerobio-anóxicos, orientados hacia la EBN. También se revisan otros conceptos y aplicaciones de reactores de lecho de fango de flujo ascendente y acumulación de fosfato y desnitrificación simultáneas.

En el **Capítulo 3** se describen los materiales y métodos utilizados en el trabajo experimental y de modelización. Los materiales y métodos específicos utilizados para la evaluación de la viabilidad de la separación hidráulica entre zonas anóxica y anaerobia se muestran en el **Capítulo 5**; los utilizados para la evaluación del funcionamiento del reactor tratando agua residual urbana se muestran en el **Capítulo 6**; y los utilizados para la evaluación basada en modelización de la ampliación de una EDAR existente mediante un decantador primario anaerobio-anóxico se incluyen en el **Capítulo 7**. Sin embargo, en el presente capítulo se han recopilado todas las metodologías, con la intención de proporcional una visión global de los materiales y métodos utilizados en esta tesis, en un capítulo con autonomía e independencia del resto.

En el **Capítulo 4** se presenta y describe el reactor AnoxAn. La descripción completa de la invención se puede encontrar en la patente ES2338979 "Reactor biológico anóxico-anaerobio para la eliminación de nutrientes de aguas residuales", que se incluye como **Anexo** en esta tesis. En este **Capítulo 4** se detallan las características técnicas de reactor, destacando las ventajas de la invención, y además se incluye un resumen de las evaluaciones técnicas y económicas que se han realizado del reactor, así como las perspectivas para su implantación a escala real.

Se presenta al reactor AnoxAn como una tecnología innovadora para EBN, que consiste en un reactor continuo de lecho de fango y flujo ascendente, con una zona anaerobia en la parte inferior seguida de una zona anóxica por encima. Una zona de clarificación en la zona superior del reactor evita el escape de sólidos en suspensión, de tal manera que se favorece el aumento de la concentración de biomasa en el reactor dando lugar a un lecho de fango. El funcionamiento biológico anaerobio-anóxico de AnoxAn se ha de combinar con un reactor aerobio y sedimentación secundaria (o filtración final) para completar el tren de tratamiento de EBN. Las principales características del reactor son: (i) flujo ascendente; (ii) separación hidráulica entre zonas anóxica y anaerobia; y (iii) retención de sólidos en suspensión. Estas características están orientadas a conseguir una elevada compacidad y eficiencia, reduciendo el requerimiento de superficie y el consumo energético. Y con tales características, el reactor es capaz de conseguir liberación de fosfato en ambiente anaerobio, y desnitrificación y acumulación de fosfato en condiciones anóxicas, en un único reactor con elevada concentración de biomasa y baja demanda energética.

Se ha evaluado el potencial ahorro económico de la implantación de AnoxAn, considerando una hipotética realización a escala real. Los resultados mostraron diferencias entre AnoxAn y las etapas anaerobia y anóxica equivalentes de un sistema de EBN convencional (en concreto UCT) con el que fue comparado. Se estimó un coste de inversión de AnoxAn, sin considerar el coste del terreno ocupado, un 23% superior al correspondiente al sistema equivalente UCT, principalmente debido al coste adicional de lamelas o deflectores. Sin embargo, el ahorro energético en mezcla del reactor dio lugar a un coste operacional menor de la mitad del correspondiente al sistema UCT. Finalmente, el coste anual equivalente total (incluyendo inversión y operación) del reactor AnoxAn resultó entre un 20 y 26% menor que el correspondiente al sistema equivalente UCT, considerando un precio de la energía eléctrica entre 0.10 y 0.14 € por kWh. Este resultado demuestra la importancia del potencial ahorro energético del reactor AnoxAn y su correspondiente beneficio económico.

El **Capítulo 5** aborda el análisis de viabilidad de la separación hidráulica entre zonas anóxica y anaerobia en el reactor AnoxAn. Para ello se construyó un prototipo a escala de bancada y se llevó a cabo su caracterización hidráulica. En AnoxAn, las condiciones ambientales están divididas verticalmente dentro del reactor con la zona anaerobia en el parte inferior y la zona anóxica por encima. Uno de los principales objetivos de la configuración del reactor es establecer dos zonas hidráulicamente separadas, mientras se mantiene una mezcla adecuada en cada una de ellas, con un flujo continuo de agua ascendente circulando a través de ambas zonas. En el presente estudio, el concepto de separación hidráulica se entiende como la capacidad de mantener dentro del mismo reactor dos zonas con diferentes condiciones ambientales, incluyendo una presencia despreciable de nitrato en la zona anaerobia. El análisis de la viabilidad del comportamiento hidráulico deseado se consideró un paso fundamental, previo a la evaluación del funcionamiento biológico tratando agua residual, y es el objeto del estudio mostrado en este capítulo.

La capacidad de establecer dos zonas hidráulicamente separadas dentro del mismo reactor con la configuración de AnoxAn se evaluó mediante ensayos de caracterización hidráulica y simulación de modelos matemáticos. Se llevaron a cabo ensayos de trazadores con agua limpia para el análisis de la distribución del tiempo de residencia en el prototipo de AnoxAn a escala de bancada (reactor de 48.4 L de volumen). Se dispusieron equipos de mezcla y deflectores específicos para conseguir la mezcla en cada una de las zonas (anaerobia y anóxica) y la separación hidráulica entre ambas. Posteriormente se construyó un modelo hidráulico compuesto por compartimentos de mezcla completa y compartimentos de flujo pistón, representando el comportamiento observado en los ensayos experimentales. Este modelo se utilizó para comprobar la viabilidad de la separación hidráulica entre zonas anóxica y anaerobia en diversos escenarios. Los resultados de las simulaciones mostraron que se obtuvo el comportamiento hidráulico deseado, con mezcla adecuada en cada zona y mezcla reducida entre ambas. Se estimó una corriente de retro-mezcla entre ambas zonas con un caudal de tan sólo un 40.2% del caudal afluente, el cual es significativamente menor que el típico ratio de recirculación anóxico (desde el reactor anóxico al anaerobio) en configuraciones convencionales para EBN, como el proceso UCT. A continuación se analizó la influencia que tiene la desnitrificación sobre la separación hidráulica, incluyendo el proceso de desnitrificación en la zona anóxica en el modelo, en presencia teórica de biomasa. La concentración de nitrato se redujo drásticamente incluso manteniendo una inyección continua de 20 mgN L^{-1} en la corriente de recirculación. El ratio entre la concentración de nitrato en ambas zonas se mantuvo sin cambios, indicando que la desnitrificación no afecta al alcance de la separación hidráulica, pero la incorporación del proceso de desnitrificación en el modelo dio lugar a una concentración despreciable de nitrato (menor de 0.1 mgN L^{-1}) en la zona anaerobia, tal y como se deseaba, con concentraciones de biomasa a partir de 1.2 g L^{-1}.

Finalmente se realizó un ensayo de trazador con biomasa en el reactor, con el objetivo de analizar la influencia de la biomasa en la hidrodinámica. Los resultados experimentales se compararon con los obtenidos mediante simulaciones del modelo hidráulico. Los perfiles de concentración de trazador en la zona anóxica en los resultados experimentales y simulados coincidieron adecuadamente, mientras que en la zona anaerobia los resultados pronosticados en las simulaciones excedieron ligeramente las concentraciones medidas experimentalmente. Esto indica que la presencia de biomasa mejoró la separación hidráulica entre las zonas anóxica y anaerobia, lo cual fue atribuido a las diferentes concentraciones de sólidos en suspensión (SST) en ambas zonas. En la zona anóxica se observó una menor concentración de SST que en la anaerobia (aproximadamente 5 g L^{-1} frente a 10 g L^{-1} en la zona anaerobia), posiblemente debido a la corriente de recirculación de nitratos, la cual entra a la zona anóxica del reactor con elevado caudal y menor concentración de SST, por lo tanto provocando cierta dilución en la zona anóxica. La ligera diferencia de densidades del fango activo entre ambas zonas, debida a las diferentes concentraciones de SST, podría causar el aumento de la separación hidráulica.

Una vez comprobada la viabilidad del concepto principal de AnoxAn, es decir la separación hidráulica entre zonas anóxica y anaerobia, se llevó a cabo la evaluación del funcionamiento del reactor, la cual se muestra en el **Capítulo 6**. Para ello se operó el prototipo del reactor AnoxAn, combinado con un reactor biológico con membranas aerobio híbrido, tratando agua residual urbana, y se analizó su funcionamiento en la eliminación de materia orgánica y nutrientes. El lecho de fango se desarrolló en AnoxAn alcanzando una concentración de SST de hasta 10 g L^{-1} en la zona anaerobia y aproximadamente 5 g L^{-1} en la anóxica. La zona superior de clarificación no evitó el escape de biomasa del reactor, pero permitió mantener una concentración de SST en el efluente menor que la concentración en el reactor, actuando como retenedor o concentrador de biomasa en el interior del mismo.

La desnitrificación tuvo lugar correctamente, obteniendo una baja concentración de nitrato en el efluente de AnoxAn (menor de 1 mg L^{-1}). La eliminación global promedio de nitrógeno fue del 75%. La eliminación global de fósforo también resultó satisfactoria, con un rendimiento medio de eliminación del 89%. Sin embargo, en las condiciones de este estudio no se consiguió la eliminación de fósforo a través de desnitrificación y acumulación de fosfato simultáneas en AnoxAn, mediante organismos acumuladores de fósforo desnitrificantes (OAFD). El nitrato prácticamente se agotó en la zona anóxica, debido a la actividad desnitrificante, mientras que el fosfato no se consumió. Esto implica que la etapa posterior aerobia fue necesaria para completar la acumulación de fósforo, alcanzando un efluente con una concentración inferior a 1 mgP L^{-1}. El modo de operación de AnoxAn, permitiendo el escape de cierta cantidad de biomasa, resultó determinante para lograr tal concentración de fósforo en el efluente. Por otra parte, mediante balances de masa de materia orgánica, se estimó que en el reactor AnoxAn se produjo la hidrólisis de un 42% de la materia orgánica particulada afluente. Este hecho pudo ser favorable para la EBN, ya que la hidrólisis produce materia orgánica fácilmente degradable la cual es necesaria para los procesos de liberación de fosfato y desnitrificación que tuvieron lugar en AnoxAn.

El funcionamiento multi-ambiente de la innovadora configuración quedó demostrado durante la experimentación. La liberación de fosfato en la zona anaerobia fue posible gracias al mantenimiento de las condiciones anaerobias y confirmó la actividad de eliminación biológica de fósforo (EBF). Por otra parte, de acuerdo a balances de masa de nitrato, el 95% del nitrato entrante en AnoxAn fue eliminado en la zona anóxica y sólo el restante 5% fue eliminado en la zona anaerobia. En resumen, el reactor AnoxAn llevó a cabo varias funciones con un tiempo de retención hidráulico (TRH) de 4.2 horas: retención de biomasa; hidrólisis de materia orgánica particulada; liberación de fosfato con un TRH anaerobio de 1.1 horas; y desnitrificación con un TRH anóxico de 2.7 horas.

En el **Capítulo 7** se presenta un caso real de estudio sobre la ampliación de una EDAR existente para EBN. El estudio evaluó la posible conversión de una planta de tratamiento secundario a EBN, mediante modelización y simulaciones. La planta consistía en un proceso de lechos bacterianos, y el objetivo de la ampliación era lograr nuevos requisitos de concentración de nitrógeno y fósforo en el efluente. La principal restricción para la selección de alternativas era la limitada disponibilidad de superficie. Por lo tanto, el tren de tratamiento propuesto utilizaba las instalaciones existentes en la planta, evitando la necesidad de nuevos tanques o reactores. Concretamente, se propuso la adaptación de un gran decantador primario existente (con un TRH medio de 8.4 horas) para alojar las zonas anaerobia y anóxica necesarias para el proceso de EBN, basada en el reactor anaerobio-anóxico de lecho de fangos, AnoxAn. Se simularon diversos escenarios para el diseño preliminar y optimización de la modificación propuesta.

La zona anóxica incorporada en el decantador primario modificado (DPM) permitió una desnitrificación satisfactoria, alcanzando en todos los escenarios simulados la concentración efluente de nitrógeno exigida. La zona anóxica funcionó correctamente con una concentración de SST de aproximadamente 2.7 g L^{-1} y un TRH de 4.7 horas, y una buena desnitrificación se mantuvo incluso al reducir el volumen anóxico hasta 2.4 horas de TRH. Sin embargo, la EBF no se consiguió mediante la alternancia de condiciones anaerobia y anóxica, lo cual fue atribuido a la competición por nitrato entre los organismos heterótrofos desnitrificantes convencionales y los OAFD, debido a las características del agua residual afluente con elevada disponibilidad de materia orgánica. Con el objetivo de proporcionar condiciones aerobias a la biomasa en suspensión y fomentar la EBF, se incluyó un volumen aerobio adicional y un bypass de fango activo desde la zona anóxica al lecho bacteriano. La zona aerobia se incluyó en el mismo DPM con la correspondiente reducción de volumen de la zona anóxica. De esta manera, y mediante combinación de la zona adicional aerobia con el bypass de fango al lecho bacteriano, se encontraron diversas combinaciones volumen aerobio – caudal de bypass con las que se logró la EBF, manteniendo una excelente eliminación de nitrógeno. En conclusión, mediante esta modificación de la planta, la EBN resultaría posible utilizando las instalaciones existentes en la EDAR, sin necesidad de nuevos reactores.

Por último, el **Capítulo 8** presenta las conclusiones generales de esta tesis doctoral así como recomendaciones para futuros trabajos de investigación y desarrollo en esta línea.

List of publications

A patent, several communications in national and international congresses, articles in national and international journals, Bachelor's degree final projects and Master's thesis have emerged from this work.

Patent:

Tejero, I.; **Díez, R.**; Esteban, A.L.; Lobo, A.; Temprano, J.; Rodríguez, L. (2010) Reactor biológico anóxico-anaerobio para la eliminación de nutrientes de aguas residuales. Spanish Patent ES2338979

International journal publications:

Díez-Montero, R.; De Florio, L.; González-Viar, M.; Volcke, E.I.P.; Tejero, I. (2015) Feasibility of hydraulic separation in a novel anaerobic-anoxic upflow reactor for biological nutrient removal. Bioprocess and Biosystems Engineering 38(1), pp. 93-103

Díez-Montero, R.; De Florio, L.; González-Viar, M.; Herrero, M.; Tejero, I. (2015) Performance evaluation of a novel anaerobic-anoxic sludge blanket reactor for biological nutrient removal treating municipal wastewater. Under review (submitted to Bioresource Technology)

Díez-Montero, R.; Casao, M.; Tejero, I. (2015) Model-based evaluation of a trickling filter facility upgrade to biological nutrient removal. Under review (submitted to Water Environment Research)

National journal publication:

Tejero Monzón, J.I.; Esteban-García, A.L.; De Florio, L.; **Diez Montero, R.**; Lobo García de Cortázar, A.; Rodríguez-Hernández, L. (2012) Tecnologías de biopelícula innovadoras para la depuración de aguas residuales: veinticinco años de investigación del Grupo de Ingeniería Ambiental de la Universidad de Cantabria. Ingeniería Civil 168, pp. 61-73

Book chapter:

Baeza, J.; Cema, G.; Tejero, I.; Huelsen, T.; Lyberatos, G.; Mosquera, A.; Oehmen, A.; Plaza, E.; Soares, A.; Fatone, F. (2015) Novel Efficient Wastewater Treatment Processes. Section 1.- Reducing Requirements and Impacts. Reducing energy requirements. Nutrients removal (Book developed within the network of the COST action ES1202 Water_2020). Under review

Contributions to congress:

Díez, R.; De Florio, L.; Tejero, I. Characterization of a novel anoxic-anaerobic biological reactor: AnoxAn. Spain IWA Young Water Professionals (oral presentation). Madrid (Spain), June 2011

Díez-Montero, R.; De Florio, L.; Herrero, M.; Pérez, P.; Tejero, I. Biological nutrient removal in a novel anoxic-anaerobic reactor followed by a membrane biofilm reactor. EcoSTP: EcoTechnologies for Wastewater Treatment (oral presentation). Santiago de Compostela (Spain), June 2012

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Bachelor's degree final projects and Master's thesis:

Rubén Díez (2009) Reactor biológico compacto anóxico-anaerobio para la depuración y eliminación de nutrientes de aguas residuales. Tutor: Iñaki Tejero Monzón. Master's thesis. Máster de Investigación en Ingeniería Ambiental, Universidad de Cantabria/Universidad del País Vasco

Patricia Pérez (2010) Eliminación biológica de nutrientes en aguas residuales urbanas mediante un reactor biológico anóxico-anaerobio (AnoxAn) y un reactor biopelícula con membrana de filtración (RBpM). Tutors: Iñaki Tejero Monzón y

Rubén Díez Montero. Master's thesis. Máster de Investigación en Ingeniería Ambiental, Universidad de Cantabria/Universidad del País Vasco

María Herrero (2011) Eliminación biológica de nutrientes en un reactor anóxico-anaerobio (AnoxAn) seguido de un reactor biopelícula aerobio con membranas (RBpM). Tutors: Iñaki Tejero Monzón y **Rubén Díez Montero**. Master's thesis. Máster de Investigación en Ingeniería Ambiental, Universidad de Cantabria/Universidad del País Vasco

María Henar Carbajosa (2013) Caracterización del fango en suspensión de dos procesos biológicos integrados innovadores. Tutors: Iñaki Tejero Monzón, Marta González Viar y **Rubén Díez Montero**. Master's thesis. Máster de Investigación en Ingeniería Ambiental, Universidad de Cantabria/Universidad del País Vasco

Ana María Hernández (2013) Optimización de la eliminación biológica de fósforo en dos procesos integrados innovadores mediante caracterización de la actividad y distribución de la biomasa. Tutors: Iñaki Tejero Monzón, **Rubén Díez Montero** y Marta González Viar. Master's thesis. Máster de Investigación en Ingeniería Ambiental, Universidad de Cantabria/Universidad del País Vasco

Raquel Ruiz (2013) Eliminación de nutrientes mediante procesos combinados en un reactor anóxico-anaerobio seguido de un reactor biopelícula y un decantador lamelar. Tutors: Iñaki Tejero Monzón, **Rubén Díez Montero** y Marta González Viar. Bachelor's degree final Project. Ingeniero de Caminos, Canales y Puertos, Universidad de Cantabria

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Chapter 1

Introduction: background and objectives

1.1. Effects of nutrients on receiving waters

An excessive discharge of nutrients to surface waters can lead to serious ecological problems that affect the health of aquatic life and consequently that of humans and animals. Several major effects are associated with such discharge of nutrients to receiving waters. These include: (i) eutrophication; (ii) ammonia toxicity; and (iii) nitrate contamination of groundwater (Water Environment Federation and American Society of Civil Engineers/Environmental and Water Resources Institute, 2005).

Eutrophication is the accelerated growth of algae and higher forms of plant life in receiving waters, due to excessive presence of macronutrients. The two most prominent macronutrients in aquatic systems are nitrogen and phosphorus, which can act as limiting nutrients or result in phytoplankton production. Human activity contributes to eutrophication due to the addition of macronutrients through detergents, fertilizers, or sewage, to an aquatic system. Specifically, over the past century humans have significantly increased nitrogen and phosphorus inputs to such aquatic systems. The major concern with regard to eutrophication is its effect on water quality and aquatic life. Excessive phytoplankton production can result in plants and algae death. As plants and algae die and decay, the resulting excessive respiration reduces the dissolved oxygen concentration, which may cause a severe reduction in aquatic life diversity. The limiting nutrient of freshwater and marine aquatic ecosystems, typically nitrogen or phosphorus, is the one that should be targeted for removal by wastewater treatment systems to control eutrophication (Water Environment Federation, 2011).

Regarding toxicity, the molecular or un-ionized form of ammonia nitrogen is toxic to fish and other aquatic life. The effect for living beings as fishes can be acute, implying mortality, or chronic, being harmful to reproduction or health. Molecular free ammonia (NH_3) and ionized ammonium ion (NH_4^+) are in equilibrium in aqueous solution, where their relative percentages are a function of pH and temperature (Water Environment Federation and American Society of Civil Engineers/Environmental and Water Resources Institute, 2005).

Finally, wastewater treatment systems that discharge to groundwaters have the potential to contaminate the groundwater with nitrates. This can occur directly by the discharge of nitrates in the effluent or by the discharge of ammonia, which then is nitrified in the soil column as rainwater brings in dissolved oxygen. Nitrate can persist in ground water for decades and accumulate to high levels as more nitrogen is applied to the land surface every year. Although nitrate generally is not an adult public health threat, ingestion in drinking water by infants can cause a blood disorder called methemoglobinemia, which implies low oxygen levels in the blood, a potentially fatal condition. The result is suffocation, which is also why the condition is referred to a "blue baby" syndrome (Water Environment Federation and American Society of Civil Engineers/Environmental and Water Resources Institute, 2005).

1.2. Regulation of nutrients in the effluents of Wastewater Treatment Plants

The need for nutrient removal is pursued by stringent regulation for the protection of water bodies, such as Directive 91/271/EEC in Europe (European Commission, 1991). This Directive concerns the collection, treatment and discharge of urban wastewater and the treatment and discharge of wastewater from certain industrial sectors. The objective of the Directive is to protect the environment from the adverse effects of the abovementioned wastewater discharges.

According to this Directive, urban wastewater entering the collecting system shall before discharge into sensitive areas be subject to more stringent treatment than secondary treatment. Specifically, nitrogen and phosphorus effluent requirements are to be imposed for discharges into such sensitive areas which are subject to eutrophication. Member States shall identify such sensitive areas. Typical water bodies identified as sensitive areas include natural freshwater bodies, estuaries and coastal waters which are found to be eutrophic or which in the near future may become eutrophic if protective action is not taken. Examples of these systems are lakes and streams reaching lakes, reservoirs and closed bays which are found to have a poor water exchange, whereby accumulation may take place, as well as estuaries, bays and other coastal waters which are found to have a poor water exchange, or which receive large quantities of nutrients. Nutrient removal should also be considered before discharge into areas where further treatment than secondary treatment is necessary to fulfill Council Directives such as the Water Framework Directive 2000/60/EC (European Commission, 2000). In addition, surface freshwaters intended for the abstraction of drinking water which could contain more than the concentration of nitrate laid down under the relevant provisions of Directive 75/440/EEC (European Commission, 1975) concerning the quality required of surface water intended for the abstraction of drinking water in the Member States, should be considered as sensitive areas so nutrients removal from wastewater should be carried out before discharge.

In the case of Spain, Directive 91/271/EEC was transposed into the national legislation through Royal Decree-Law 11/1995 (Gobierno de España, 1995) and Royal Decree 509/1996 (Ministerio de Obras Públicas, Transportes y Medio Ambiente, 1996), maintaining the same considerations and criteria regarding sensitive areas and nutrient removal. The first declaration of sensitive zones (Ministerio de

Medio Ambiente, 1998) was afterwards significantly increased (Ministerio de Medio Ambiente, 2006), affecting to discharges representing 25 million p.e. while the previous evaluation accounted for 6 million p.e. (Ministerio de Medio Ambiente, 2007), and further extended in the last review (Ministerio de Medio Ambiente, y Rural y Marino, 2011). This is an example of the clear worldwide trend of increasing requirements for nutrient removal from wastewater, which compels to upgrade, modify or build-up a great number of wastewater treatment plants (WWTP) for nutrient removal.

1.3. Wastewater nutrient removal processes

Biological wastewater treatment processes have been widely used due to the lower investment and operating costs compared to alternative treatment systems. Specifically, the activated sludge process has been in practice over a century and it has been applied for carbon, nitrogen and phosphorus removal. Design and operation of activated sludge systems, comprising biological reactors and secondary clarifiers, is nowadays established and well-known.

However, activated sludge systems for nutrient removal present several limitations which have led to the development and implementation of a variety of advanced biological treatment processes in recent years. On the one hand conventional activated sludge configurations for biological nutrient removal (BNR) require complex and large treatment systems providing anaerobic, anoxic and aerobic compartments. An aerobic reactor sufficiently large to establish nitrification should be combined with an anoxic one, in which nitrate serves as an electron acceptor allowing organic matter consumption for denitrification. In the anaerobic compartment, phosphate is released through the phosphate accumulating organisms (PAO) metabolism, which can only take place under strict nitrate absence. Several biological reactors must be implemented to provide such different environmental conditions, followed by a secondary clarifier, with several recirculation systems between them. On the other hand the total suspended biomass concentration must not exceed around 3.5 g L^{-1} in order to avoid suspended solids overflowing from the secondary clarifier. This leads to relatively large systems with high hydraulic retention times, which consequently requires a large footprint. This inconvenience could result in a noteworthy constraint when space availability is limited, not only for new WWTP build-up, but also for existing WWTP upgrade to nutrient removal. Existing plants are often not able to fulfill nutrients removal requirements when space is limited, due to the significant volume increase compared to the one needed for organic matter removal only. In this framework, increasing research, development and innovation efforts is been done in order to provide compact and efficient technologies to face such facilities designs and/or upgrades.

Much research has been carried out aimed at achieving more compact and efficient aerobic reactors, such as biofilm reactors, membrane bioreactors (MBR), and the combination of biofilms and membranes in the hybrid membrane bioreactor (Ivanovic and Leikness, 2012) and membrane aerated biofilm reactor (Casey et al., 1999; Martin and Nerenberg, 2012). The incorporation of the anaerobic and/or anoxic zones into the aerobic reactor in order to further increase the compactness of a BNR process has been also proposed and investigated. For instance Yerushalmi et al. proposed the multi-environment air-lift reactor which includes an anoxic zone in the aerobic reactor by means of baffles and hydraulic separation (Yerushalmi et al., 2011; Alimahmoodi et al., 2013). Nevertheless this system still requires an additional anaerobic reactor to achieve the enhanced biological phosphorus removal (EBPR). Finally, different environmental conditions can be realized inside biofilms and granules (Oehmen et al., 2007; Adav et al., 2008), which additionally increase the biomass content per unit reactor volume. However, in biofilm systems the phosphorus extraction depends on backwashes (Rogalla et al., 2006), and sequential operation tends to be used in both biofilm and granular reactors in order to provide alternate conditions for EBPR (Castillo et al., 1999; Rogalla et al., 2006; Adav et al., 2008).

In a different approach, the anaerobic and anoxic zones could be unified in a single non-aerated reactor. This alternative avoids the construction of separate anaerobic and anoxic tanks, and takes advantage of the complete separation from the aerobic reactor preventing the undesired intrusion of oxygen into the anoxic and anaerobic zones and avoiding the difficulty of hydraulic separation in a bubbled reactor. Few studies have been found compacting the anaerobic and anoxic zones in a single suspended sludge reactor (state of the art is provided in Chapter 2), thus suggesting that research efforts could be done in such topic, and that is the aim of this study.

1.4. Objectives of the study

According to the aforementioned background, a novel technology for BNR has been conceived, named AnoxAn, consisting in a continuous non-aerated reactor, unifying the anaerobic and anoxic zones for BNR in a single reactor with reduced surface requirements. The scope of this thesis is to develop and assess the novel AnoxAn reactor. The objectives of this study can be stated as follows:

(1) Conception and design of a novel anaerobic-anoxic reactor for BNR from wastewater, aimed at achieving high compactness and efficiency.
(2) Feasibility evaluation and optimization of the anoxic-anaerobic hydraulic separation, based on hydrodynamic characterization and modelling.
(3) Performance evaluation of the novel reactor in the removal of organic matter and nutrients from municipal wastewater.
(4) Feasibility evaluation and preliminary design of an existing WWTP upgrade to BNR based on the novel anaerobic-anoxic reactor, by means of mathematical model simulations.

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Chapter 2

State of the art

Biological reactors (or bioreactors) for wastewater treatment can be classified according to different criteria. One of these criteria is the presence of dissolved oxygen. Considering the diffusion of air as the main way to introduce oxygen into the bioreactor, they can be categorized as aerated or non-aerated reactors. The combination of aerated and non-aerated zones in a single reactor can be found in the literature, as it is the case of the hybrid vertical anaerobic sludge-aerated biofilm reactor proposed by Phattaranawik and Leiknes (2010). Regarding non-aerated reactors for wastewater treatment, they can be classified as anoxic or anaerobic reactors. Anoxic reactors are characterized by the presence of nitrate, which is used as an alternative electron acceptor to oxygen, while anaerobic reactors are characterized by a strict absence of oxygen or nitrate. On the one hand, anoxic bioreactors are applied for denitrification, as a step of the biological nutrient removal (BNR) process. They can precede or follow the aerobic nitrifying reactor, thus leading to pre-anoxic or post-anoxic denitrifying reactors, respectively. On the other hand, anaerobic bioreactors can be applied with three different objectives: (i) anaerobic treatment of wastewater and/or sludge, with the corresponding production of biogas; (ii) pretreatment influent wastewater, by means of hydrolysis and fermentation of the organic compounds; and (iii) phosphate release and organic matter storage through phosphate accumulating organisms (PAO). Objectives (i) and (iii) are in general no compatible, while in BNR processes objectives (ii) and (iii) are usually combined.

The AnoxAn reactor consists of the combination of the non-aerated zones of a BNR process in a single reactor, that is the combination of the anaerobic and anoxic zones for phosphate release and denitrification, respectively. Besides, in order to achieve high compactness and efficiency, several features are added to the AnoxAn concept, as: (i) upflow operation; (ii) sludge blanket; and (iii) encouragment of denitrifying phosphate uptake. A brief review of upflow sludge blanket reactors and processes encouraging denitrifying phosphate uptake is presented below, and finally a review of anaerobic-anoxic bioreactors is provided.

2.1. Upflow sludge blanket reactors

Upflow bioreactors present several advantages, such as energy saving for mixing, plug-flow and sustainable high sludge concentration (Lettinga et al., 1980). An upflow setup results in biomass retention to some extent, due to suspended solids settling, which in AnoxAn is assisted by means of an upper clarification zone at the top of the reactor, avoiding the escape of large amount of suspended solids. Biomass retention inside the reactor will promote the formation of a sludge blanket, characterized by the circulation of wastewater through a blanket with high biomass concentration which is partially retained in the reactor. In other upflow sludge blanket reactors, such as the anaerobic sludge blanket reactor (UASB), the produced biogas bubbles affect the fluid flow and disturb the sludge blanket, leading to mixing (Heertjes and van der Meer, 1978). However, in the AnoxAn reactor the envisaged biomass concentration is lower than the sludge concentration in UASB reactors, and the hydraulic retention time (HRT) for BNR is shorter than the one for anaerobic biogas production, so it should be pointed out the need for mechanical mixing in order to keep the biomass in suspension reducing the extent of sludge settling and to provide good contact between the wastewater and biomass. This mechanical mixing can be performed through intermittent operation of the mixing devices providing periodic disruption of the sludge blanket.

Upflow operation and sludge blanket bioreactors have been extensively used in wastewater treatment, being the UASB a great example. However, the treatment objective of anaerobic digestion processes is to remove organic matter from mainly soluble non-complex wastewaters in an economical mean, while taking advantage of the biogas production. To achieve such goal, specific operational conditions are usually applied in UASB reactors (high HRT, mesophilic or thermophilic temperature, etc.), which differ from the BNR objective of the AnoxAn reactor and the corresponding operational conditions.

2.2. Denitrifying phosphate uptake

The accumulation of phosphate by PAO takes place in excess of metabolic requirements, under aerobic conditions, after being exposed to strict anaerobic conditions. Phosphate uptake is also feasible using nitrate as electron acceptor, instead of oxygen (Vlekke et al., 1988), by means of denitrifying phosphate accumulating organisms (DPAO). This leads to energy savings for aeration, less sludge production and maximal influent organic substrate exploitation (Kuba et al., 1993), and makes it possible to biologically remove nutrients from wastewaters with low C/N ratio. Due to the suspended solids retention in the AnoxAn reactor, alternate anaerobic and anoxic environmental conditions are provided to the biomass, encouraging efficient phosphate uptake by means of DPAO.

Much research has been done regarding denitrifying phosphate uptake since the late 1980s, and several BNR configurations have been proposed based on the DPAO capabilities. Among them, the noteworthy DEPHANOX process (Wanner et al., 1992; Sorm et al., 1996; Bortone et al., 1994; Bortone et al., 1996; Sorm et al., 1997; Bortone et al., 1999; Wang et al., 2004b; Hamada et al., 2006; Torrico et al., 2006; Wang et al., 2007; Torrico et al., 2008) or A_2N (Kuba et al., 1996; Hao et al., 2001; Wang et al., 2004a; Wang et al., 2009; Wang et al., 2013). The process is a two-sludge system based on anaerobic-anoxic phosphate removal and denitrification coupled with nitrification in a side-stream fixed-film nitrifying reactor (Figure 2-1).

Wastewater is fed into the anaerobic reactor where phosphate is released and organic substrate is accumulated in PAO (or DPAO) as polyhydroxyalkanoates (PHA). A downstream settler separates the activated sludge with organic substrate from an ammonia-rich supernatant. The liquid stream then goes to the side-stream biofilm reactor where nitrification occurs, while the settled sludge bypasses nitrification and is resuspended in the anoxic reactor together with the nitrified effluent from the biofilm reactor. Here nitrates are denitrified and phosphate is taken up. A post-aeration step allows nitrogen gas stripping from the sludge and favours a complete regeneration of PAO (or DPAO) before final settling. Afterwards, several modifications of the DEPHANOX or A_2N process have been proposed. Patel et al. (2005) combined the anaerobic-anoxic phosphate removal and denitrification with an aerobic membrane bioreactor (MBR). Ryu et al. (2008) and Kim et al. (2009) added an extra intermittent aeration reactor in the process between the anoxic and the post-aeration reactors while reducing the size of the post-aeration reactor. In order to avoid the need for the first settling tank, Xu et al. (2011) proposed a modified anaerobic/aerobic/anoxic (AOA) process which transferred part of the anaerobic mixed liquor to the post-anoxic zone for utilizing PHAs as internal carbon source, thus promoting denitrifying phosphorus removal (Figure 2-2).

Similarly to the DEPHANOX, the ENBNRAS system was proposed, in which the aerobic nitrifying reactor is a trickling filter. That is, the system consists of a biological nutrient removal (BNR) activated sludge (AS) process with external nitrification (EN) in a trickling filter. It was investigated at lab-scale (Hu et al., 2000; Sotemann et al., 2002; Hu et al., 2003) and later on assessed in a full-scale experience (Muller et al., 2004; Muller et al., 2006).

All these processes demand complex treatment systems, with multiple reactors and settling tanks. In a different approach, the AnoxAn configuration aims at high compactness, taking advantage of the upflow operation, sludge blanket, and anaerobic-anoxic unification in a single reactor.

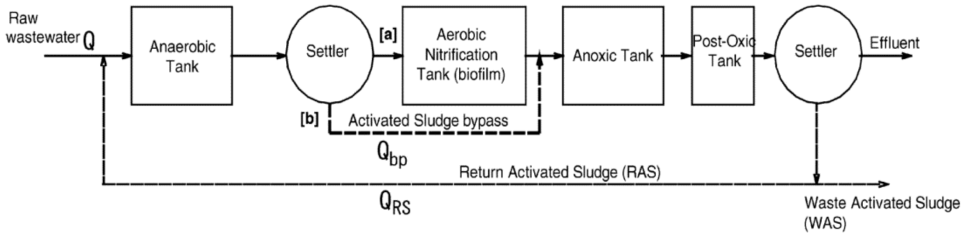

Figure 2-1 DEPHANOX (or A2N) system (Torrico et al., 2008)

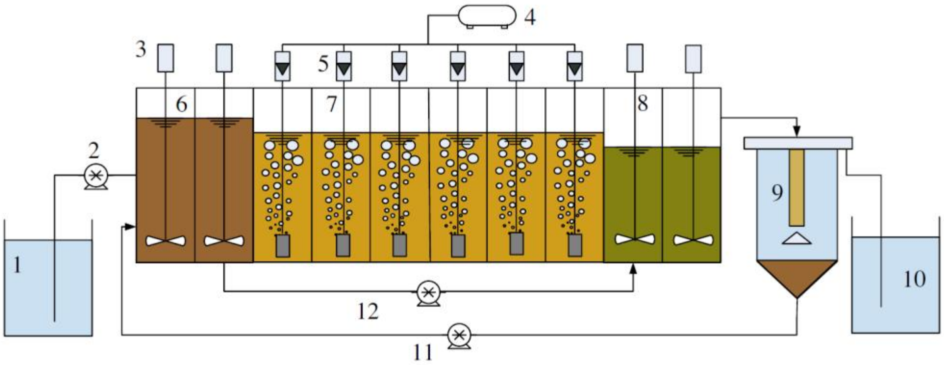

Figure 2-2 Diagram of the AOA process. 1-Feed tank; 2-pump; 3-mixer; 4-air pump; 5-gas flow meter; 6-anaerobic zones; 7-aerobic zones; 8-anoxic zones; 9-settler; 10-effluent tank; 11-sludge return; 12-diversion of anaerobic sludge (Xu et al., 2011)

2.3. Anaerobic-anoxic biological reactors

Several configurations have been found combining anaerobic and anoxic zones in an upflow biological reactor for anaerobic pretreatment and denitrification, aimed at enhancing the removal efficiency of organic matter and nitrogen, but not for both nitrogen and phosphorus biological removal. In this type of reactor, hydrolysis in the anaerobic zone enhances denitrification in the subsequent anoxic zone, by means of organic acids production.

For instance, the upflow staged sludge bed (USSB) reactor is vertically compartmentalized in several stages by means of skew baffles (Jenicek et al., 1999; Jenicek et al., 2002). Anaerobic treatment of surplus sludge is performed in the first compartment at the bottom of the reactor. The following compartments are used for anaerobic pretreatment of the influent wastewater and the final compartments perform denitrification, where a nitrate-rich stream is recycled from a subsequent aerobic reactor. The reactor is operated in the mesophilic range temperature (35°C) for the above mentioned purposes. Biomass is retained in the USSB reactor, stably maintaining specific biomass in each compartment. The suitable design of baffles and controlled upflow velocity of liquid and biogas enable the effective control of the sludge concentration and distribution. Similarly, Tilche et al. (1994) proposed a hybrid upflow anaerobic filter, a mesophilic reactor for both anaerobic digestion and denitrification. Anaerobic digestion takes place in the sludge bed at the bottom of the reactor, while denitrification is carried out in the upper anoxic filter zone where a stream of nitrified effluent is recycled. A random packed polypropylene biofilm support was used in the anoxic filter. Quite similar to this reactor was the anaerobic upflow bed filter (AUBF) proposed by Shin et al. (2005). The AUBF reactor combines a UASB type lower zone for acidogenesis and an upper anoxic filter for denitrification, packed with plastic media. In a similar approach, Park et al. (2003) studied a treatment system for nitrogen and organic matter removal with low sludge production, using an upflow anaerobic digester with anoxic filter. The anaerobic digester received the aerobic surplus sludge together with the influent wastewater, while the media used in the anoxic filter were plastic rings.

Aimed at BNR, anaerobic and anoxic zones should be provided for phosphate release and denitrification, respectively. To avoid the construction of separate tanks, combining both zones in a single reactor, the anaerobic and anoxic conditions can be established through sequential operation. For instance, the alternation of anoxic and anaerobic conditions through intermittent recirculation of the nitrate-rich effluent from the aerobic reactor to the anoxic/anaerobic reactor was obtained by Ahn et al. and Song et al. at lab-scale (Ahn et al., 2003; Song et al., 2009) and at pilot-scale (Song et al., 2010), in the sequencing anoxic/anaerobic reactor (SAAR), coupled with an aerobic MBR (Figure 2-3). The system showed excellent phosphorus removal at lab-scale (93%) while nitrogen removal (about 60%) resulted lower than the one obtained in similar conventional BNR systems, as expected according to the duration of the anoxic phase and the internal recycle flowrate (Ahn et al., 2003). The effects of internal recycling time mode and hydraulic retention time were studied later on and it was concluded that denitrification and phosphorus release were reciprocally dependent on the anoxic/anaerobic time ratio (Song et al., 2009; Song et al., 2010). The separation in time of the anaerobic and anoxic conditions while keeping continuous wastewater inflow may hinder the achievement of both high nitrogen and phosphorus removal efficiencies.

Better efficiencies may be realized through the separation of the anaerobic and anoxic conditions in space. Few studies have been found compacting the anaerobic and anoxic zones for BNR (both nitrogen and phosphorus) in a single suspended sludge reactor, all of them regarding the upflow multi-layer bioreactor (UMBR) proposed by Kwon et al (2005). The UMBR is a plug-flow reactor, in which raw wastewater is fed into the reactor by means of rotating distributors at the bottom, together with a nitrate-rich stream recycled from the subsequent aerobic reactor. This flow generates an anoxic zone, followed by an upper anaerobic one (where nitrate has been depleted). The UMBR was tested at pilot scale coupled with an aerobic biofilm reactor treating municipal wastewater (Figure 2-4). Satisfactory nitrogen removal was achieved (total nitrogen removal efficiency of 75%), while phosphorus was removed only through settling and adsorption in the UMBR (Kwon et al., 2005). Phosphate removal resulted negligible suggesting that EBPR did not occur. In the UMBR configuration, the availability of biodegradable substrate needed for phosphate release in the anaerobic zone is limited due to consumption during denitrification in the previous anoxic zone, resulting in a system clearly biased toward nitrogen removal. In addition, following studies did not achieve significant phosphorus removal through EBPR (Suh et al., 2006; An et al., 2007; An et al., 2008).

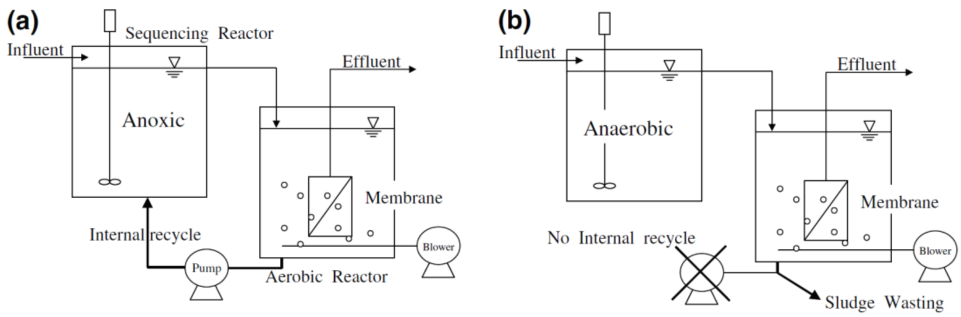

Figure 2-3 Operation of the sequencing anoxic/anaerobic membrane bioreactor process at (a) anoxic phase and (b) anaerobic phase (Song et al., 2009)

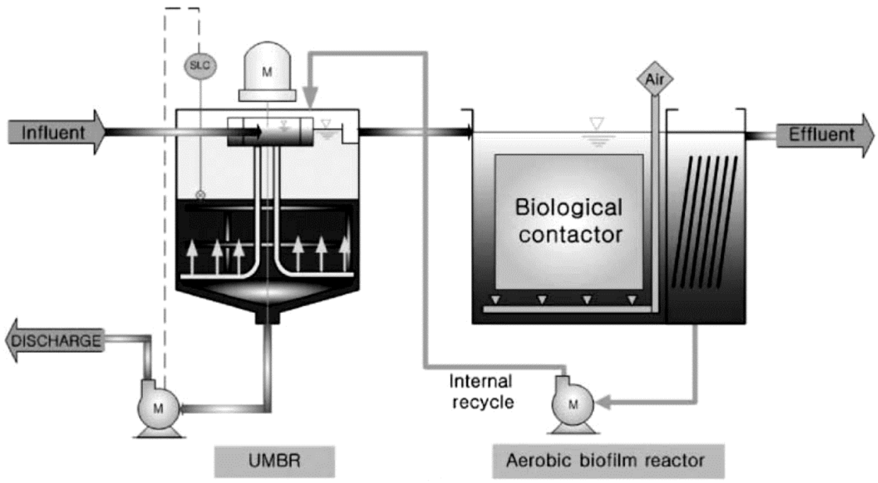

Figure 2-4 Schematic diagram of the UMBR followed by an aerobic biofilm reactor at pilot scale (Kwon et al., 2005)

The AnoxAn setup claims to combine the four aspects aforementioned (anaerobic–anoxic single reactor, upflow operation, sludge blanket, and encouragement of denitrifying phosphate uptake), representing a common element between all of them, and taking advantage of their main characteristics. To our knowledge no studies have been carried out combining all these features in a biological reactor. The originality of such multi-topic combination, with promising advantages, stimulates the interest in going in depth in the AnoxAn reactor proposal.

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Chapter 3

Materials and methods

The specific materials and methods for the feasibility evaluation of the anoxic-anaerobic hydraulic separation, the performance evaluation of the novel reactor for biological nutrient removal treating municipal wastewater, and the model-based evaluation of an anaerobic-anoxic primary clarifier for the upgrading of an existing wastewater treatment plant (WWTP) to biological nutrient removal are reported in Chapters 5, 6 and 7, respectively. All those methodologies are gathered in this chapter, aimed at providing an overall view of the materials and methods used in this thesis in a self-contained section of the document. Part of the information and figures presented in this chapter are reported again in each specific chapter.

3.1. Description of the AnoxAn prototype

A prototype of the AnoxAn reactor was designed and built up at bench-scale, as shown in Figure 3-1. This reactor was used for (i) the selection and optimization of the mixing devices based on preliminary tracer tests in clean water; (ii) the feasibility evaluation of the anoxic-anaerobic hydraulic separation by means of residence time distribution (RTD) experiments; and (iii) the performance evaluation of the reactor in the removal of organic matter and nutrients from municipal wastewater.

The 48.4 L AnoxAn reactor was made of polymethyl methacrylate (PMMA) with an internal square section of 0.20 x 0.20 m^2 and a height of 1.30 m. The upflow reactor contains an anaerobic zone at the bottom (12.4 L; 26 %), an anoxic zone above (32.0 L; 66 %) and a clarification zone at the top (4.0 L; 8 %). An AnoxAn reactor is typically followed by an aerobic reactor (not displayed in Figure 3-1), from which a nitrate-rich stream is recycled to the anoxic zone of AnoxAn for denitrification. The suspended biomass in the reactor is exposed to the anaerobic and anoxic conditions needed for enhanced biological phosphorus removal (EBPR) and denitrification.

The mixing devices consisted of:

- Mechanical mixing by means of a Heidolph RZR-2000 impeller (100 rpm) in the anoxic zone (Figure 3-2).
- Continuous internal recycle of the anaerobic zone by means of a peristaltic pump Watson Marlow 313U.
- An expanded polyvinyl chloride (PVC) baffle of 0.040 m width along the wall, between the anoxic and anaerobic zones, in order to limit the flow exchange (Figure 3-3).
- A baffle of a rigid horizontal polyethylene (PE) net of 0.039 m height, inserted 0.10 m below the water surface, in order to establish the upper clarification zone (Figure 3-4).

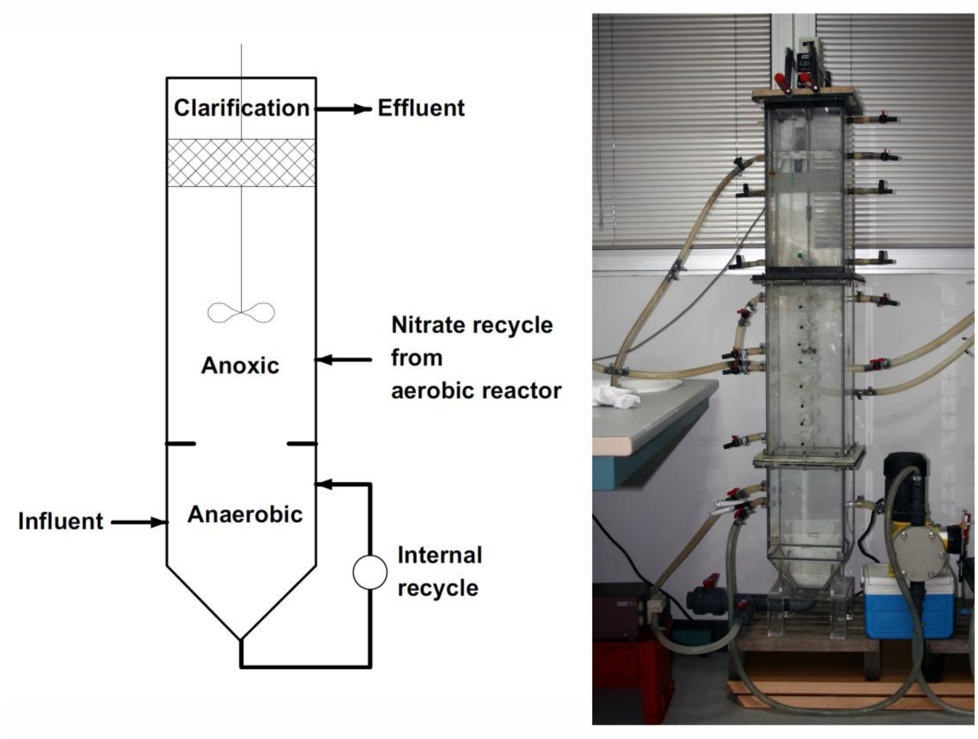

Figure 3-1 Schematic diagram (left) and picture (right) of the AnoxAn prototype

Figure 3-2 Heidolph RZR-2000 impeller for mechanical mixing in the anoxic zone

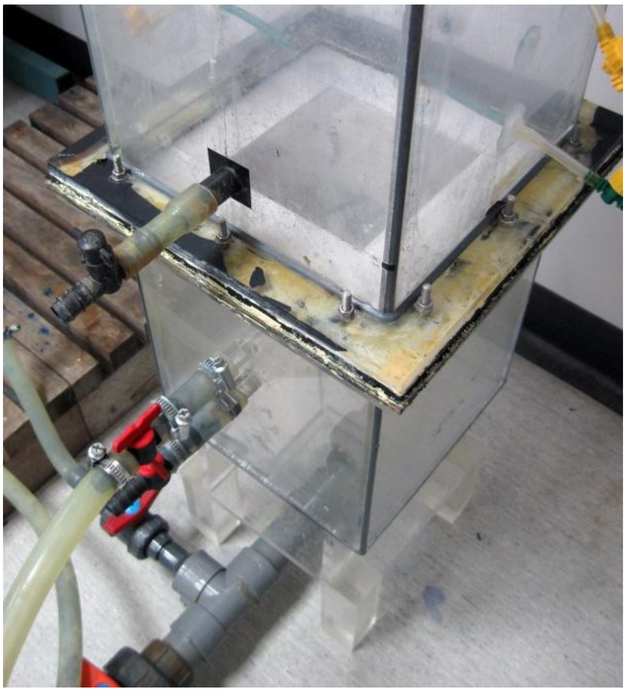

Figure 3-3 Expanded PVC baffle between the anoxic and anaerobic zones

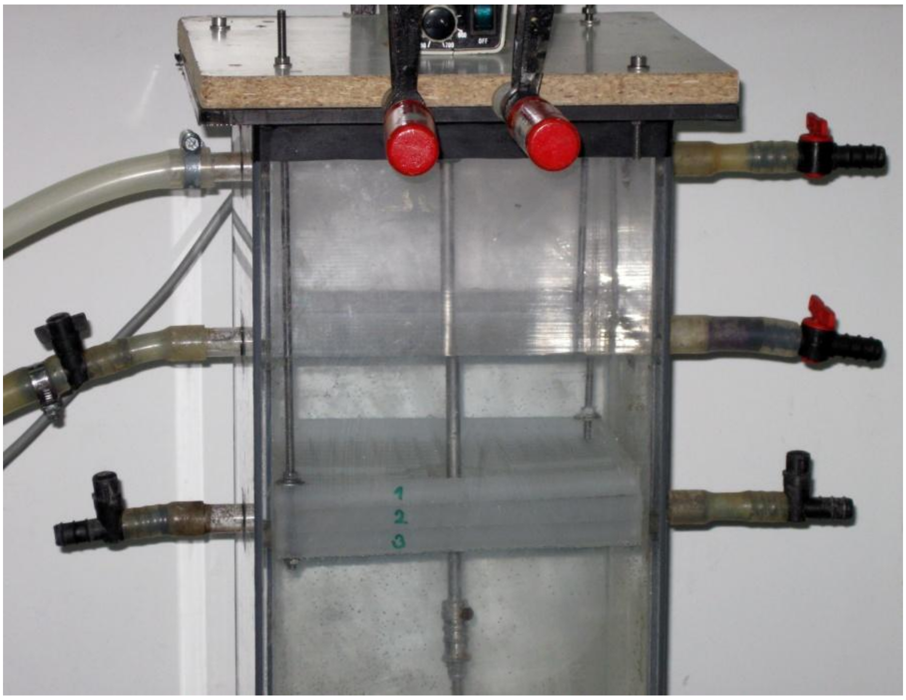

Figure 3-4 Rigid horizontal net baffle for clarification

The AnoxAn reactor was designed for a hydraulic residence time (HRT) up to 5 hours (depending on the organic load applied), corresponding with an influent flowrate (Q_{in}) of approximately 10 L h^{-1}. The nitrate recycle rate was set to about 3 times the influent flowrate ($R_{NR} \approx 3$).

3.2. Description of the bench-scale pilot plant

The biological anaerobic-anoxic functioning of AnoxAn is meant to be coupled with an aerobic reactor (for the removal of residual organic matter, phosphate uptake, and nitrification) and a secondary sedimentation unit (or a final filtration step), as to complete the biological nutrient removal (BNR) treatment train. In this study AnoxAn was coupled with an aerobic hybrid membrane bioreactor (HMBR) in order to evaluate the performance of the novel reactor in the removal of organic matter and nutrients from wastewater. The setup of the bench-scale pilot plant is illustrated in Figure 3-5. The experimental campaign was performed in the municipal wastewater treatment plant of Santander (North coast of Spain). A picture of the pilot plant is shown in Figure 3-6.

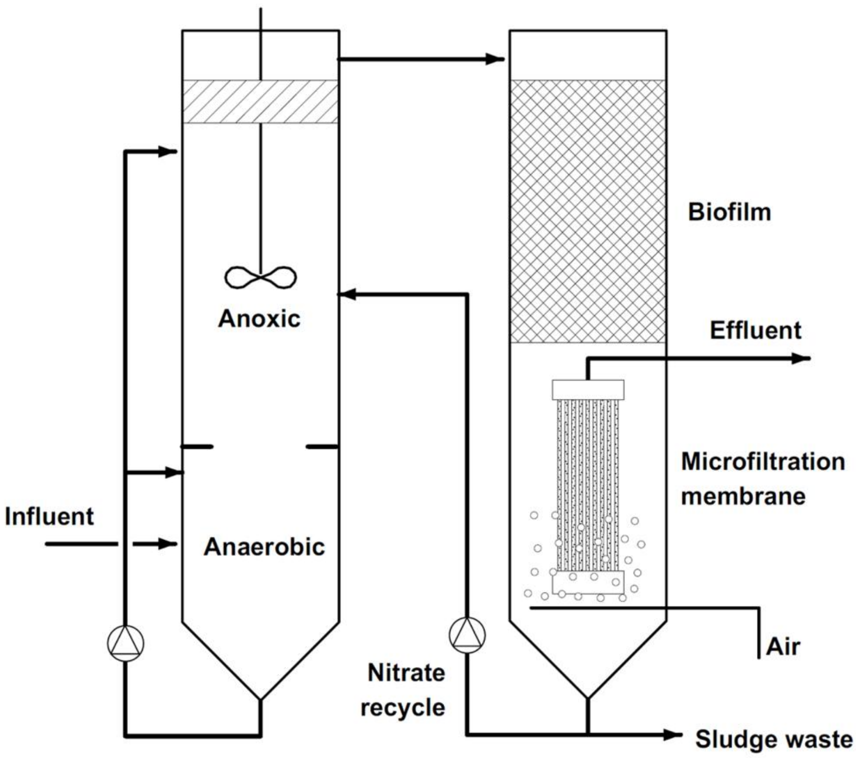

Figure 3-5 Schematic diagram of the bench-scale pilot plant AnoxAn + HMBR

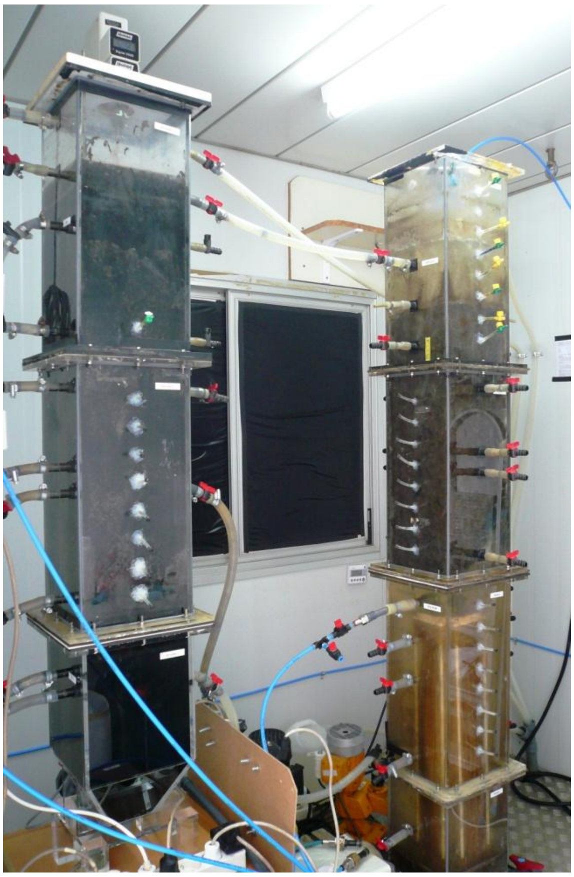

Figure 3-6 Picture of the bench-scale pilot plant AnoxAn + HMBR

The AnoxAn prototype described in the previous section of this chapter was the AnoxAn reactor used in this pilot plant. The turnover rate of the anaerobic volume was set to 4.2 h^{-1} (by means of the continuous internal recycle). Additionally, the same peristaltic pump provided intermittent recycling from the anaerobic to the anoxic zone performing repeating sequences of anoxic/anaerobic recirculation (t_{anox}/t_{anae}) in order to enhance the suspended biomass circulation inside the reactor being exposed to the alternating anaerobic and anoxic conditions. A nitrate-rich stream, set to about 3 times the influent flowrate, was recycled from the subsequent aerobic reactor to the anoxic zone of AnoxAn with a dosing pump DOSAPRO MILTON ROY Pompe D.

The 69.0 L HMBR, also made of PMMA, with internal square section of 0.20 x 0.20 m^2 and a height of 1.80 m, was partially filled with a sponge type biofilm support (polyurethane pieces of 2 x 1 x 1 cm^3, Figure 3-7) occupying 46% of the total reactor volume. A polyvinylidene difluoride (PVDF) hollow fibre microfiltration membrane module (2 m^2 filtering surface, produced by Porous Fibers, Spain) was placed underneath the biofilm bed, as described in Rodríguez-Hernández et al. (2012). An automatic backwashing was conducted using permeate water for 4 minutes every 45 minutes, according to manufacturer instructions. At the bottom of the reactor a coarse bubble air diffuser was placed. The air supply (14 L min^{-1}) was set in order to provide sufficient and continuous stirring in the membrane zone, eventually controlling membrane fouling rate. This air flowrate resulted in a bulk liquid oxygen concentration of about 5 mg L^{-1}.

Figure 3-7 Piece of the sponge type biofilm support

3.3. Hydraulic characterization

The preliminary hydraulic characterization of the AnoxAn prototype was performed through tracer tests in clean water with methylene blue, which were visually analyzed. An example of these visual tracer experiments is illustrated in Figure 3-7.

Right after, the hydraulic characterization was performed by means of RTD analysis. A concentrated solution of sodium chloride (NaCl, 350 g L^{-1}) was used as tracer for the RTD tests in clean water. The conductivity of the effluent was measured with a Hach CDC40103 probe, connected to a HQ30d meter. From the conductivity measurement, the corresponding tracer concentration was evaluated through a previously established linear relationship, as in Tang et al. (2004) and Martín-Dominguez et al. (2005). Each experiment was preceded by an electrical conductivity measurement of the tap water used during the RTD test. This value was deducted from the electrical conductivity measured at the outlet before calculating the tracer (NaCl) concentration.

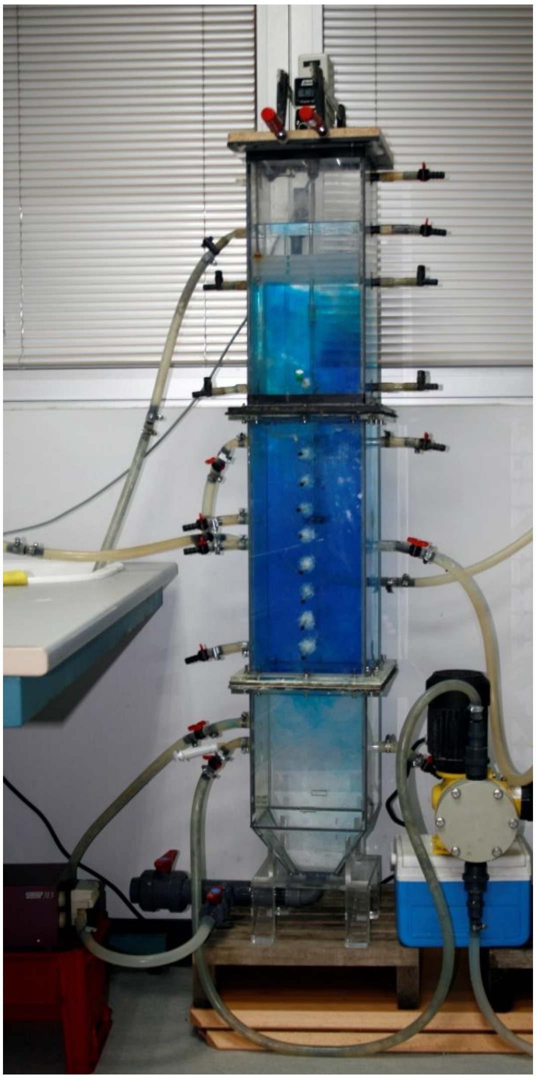

Figure 3-8 AnoxAn tracer tests in clean water with methylene blue

The RTD experiments were performed through pulse injection of the tracer into the feed stream entering the reactor and measuring its concentration in the outlet stream as a function of time (Levenspiel, 1999). For the tracer pulse injection a syringe was employed. Due to the complexity of the reactor configuration, including several mixing devices and baffles, separate RTD tests were carried out for the individual anaerobic and anoxic zones and for the overall reactor. The detailed description of the experiments is presented in Chapter 5. A picture of the experimental setup for the individual anaerobic zone is showed in Figure 3-8.

Figure 3-9 RTD experimental setup for the individual anaerobic zone

An additional tracer test for the overall reactor was performed with biomass inside the reactor. This test was carried out after several months of operation treating municipal wastewater, once stable biomass concentrations were achieved, in order to evaluate to which extent the presence of biomass influenced the hydraulic separation between the two zones (anoxic-anaerobic). A solution of lithium chloride (LiCl) was used as tracer, which was continuously injected in the nitrate recycle with a constant concentration of lithium (11.15 mgLi L^{-1}). In this way, the effect of a nitrate-rich stream coming from the subsequent aerobic reactor was observed, by comparing the resulting tracer concentrations in the anoxic and anaerobic zones of the reactor. Samples of both the anaerobic and anoxic zones were periodically collected and the concentration of Li was measured by atomic absorption spectroscopy in a PERKIN ELMER AAnalyst 300 Atomic Absorption Spectrometer.

3.4. Pilot plant operational conditions and analytical procedures

The experimental campaign for the performance evaluation of the AnoxAn reactor in the removal of organic matter and nutrients from wastewater was performed in a municipal WWTP, as aforementioned. The WWTP was located in Santander (North coast of Spain), with a population equivalent of about 428,000 p.e., combined sewer system and average flow of 7,668 $m^3\ h^{-1}$. The detailed description of the experimental conditions and the analytical procedures is presented in Chapter 6, but it is introduced in the following.

3.4.1. Wastewater and operational conditions

The experimental campaign lasted 88 days. Pre-treated wastewater was fed into the bench-scale pilot plant, with an overall HRT of 10.1 hours. The composition of the influent wastewater showed high fluctuations due to wet weather and it was characterized by high salinity as typical for coastal area with combined sewer system. The mixed liquor solids retention time (SRT) was set at 39 days through sludge wastage from the HMBR. The recirculation sequence t_{anox}/t_{anae} was set to 3 min/9 min in order to tackle progressive sedimentation and to improve the alternation of anaerobic-anoxic conditions.

3.4.2. Analytical methods

24-hours composite samples of the influent wastewater, HMBR effluent, nitrate-recycle stream, anaerobic zone, anoxic zone and effluent from the AnoxAn reactor, were collected two or three times a week and kept cool until laboratory analysis. Total and filtered chemical oxygen demand (COD and fCOD), biochemical oxygen demand (BOD_5), total and volatile suspended solids (TSS and VSS), ammonium (NH_4), total nitrogen (TN) and total phosphorus (TP) were measured according to the Standard Methods (APHA, 2005). Ion-chromatography (761 COMPACT-IC METROHM) was used for nitrite (NO_2), nitrate (NO_3) and phosphate (PO_4). Dissolved oxygen concentration, temperature and electrical conductivity were measured using portable meters (HACH HQ40d meter with LDO101 and CDC40103 probes).

In order to characterize the functional microorganisms, activated sludge grab samples were taken from the anoxic zone of the AnoxAn reactor, while biofilm samples were extracted from the biofilm support at three different locations: top, middle and bottom of the biofilm zone. The sponge pieces were immersed in phosphate buffer solution (PBS), centrifuged and strongly vortexed to extract the biofilms as in Chae et al. (2012). Microbial activity batch tests were carried out to determine the following specific rates: (i) ammonium uptake rate (AUR) of biofilm extracts; and (ii) nitrate uptake rate (NUR) and phosphate release and uptake rates (PRR and PUR) of the AnoxAn activated sludge samples. The AUR and NUR tests were performed according to Kristensen et al. (1992), while the PRR and PUR were determined as described in Wachtmeister et al. (1997). The fraction of denitrifying phosphate accumulating organisms (DPAO) out of phosphate accumulating organisms (PAO) was also estimated using the approach proposed by Wachtmeister et al. (1997), as the ratio between the PUR under anoxic and aerobic conditions (PUR_{anox}/PUR_{aero}). A set of batch tests for each specific rate were performed during the experimental campaign. The identification and abundance of specific microorganisms present in the activated sludge samples and biofilm extracts of the reactors were analyzed by fluorescent in-situ hybridization (FISH) analysis as specified by (Amann, 1995). After fixation, samples were immobilized and hybridized using selected probes. To visualize all the cells the microscope slides were counterstained with DNA stain 4', 6'-diadimino-2-phenylindol (DAPI). The target organisms were detected by the examination of their characteristic fluorescence using an epifluorescence Leiz Laborlux D microscope in combination with a digital camera Leica DCF42 and software LAS (v3.7.0) from Leica Microsystems. The probes used in this study were: Nso_1225 for ammonia oxidizing bacteria (AOB); Ntspa_662 and Nit_3 for nitrite oxidizing bacteria (NOB); Pao_462 for Accumulibacter phosphatis (PAO); and Amx_368 for anammox bacteria (anaerobic AOB). The target cells were counted to determine the fraction of FISH positive out of the total DAPI count.

3.5. Modelling

In this thesis mathematical modelling has been performed (i) to better understand the hydraulic behaviour of the novel AnoxAn reactor and assess the feasibility of the anoxic-anaerobic hydraulic separation; and (ii) to assess the feasibility of the novel reactor concept for upgrading an existing WWTP to BNR.

3.5.1. Hydraulic reactor model

The model was used to evaluate the extent of hydraulic separation between the anaerobic and anoxic zones, with and without considering biological nitrate consumption (denitrification), based on the results of the RTD experiments. This study was considered a necessary step for the development of the novel technology, proving the feasibility of the proposed configuration, prior to the performance evaluation in the removal of nutrients treating wastewater.

A hydraulic model for the reactor was set up and implemented in AQUASIM (Reichert, 1994). Several alternatives to represent the physical compartments and thus mimic hydraulic behaviour of the reactor were tested through trial-and-error. The anaerobic zone was represented as a single continuous stirred tank reactor (CSTR) or a series of two or three CSTR, with different volumes, connections and recycle streams. For the anoxic and clarification zones, several combinations of CSTR and plug-flow reactor (PFR) with axial dispersion were tested. The selected setups for the anaerobic zone on the one hand and the anoxic and clarification zone on the other hand were combined to form the hydraulic model for the overall AnoxAn reactor, while adding an additional interconnection between the anoxic and anaerobic zones. The total volume of these compartments was set equal to the total reactor volume (48.4 L).

The best model was identified based on the calculation of χ^2, i.e. the sum of the squares of the weighed deviations between measurements and simulation results, as follows:

$$\chi^2(\mathrm{p}) = \sum_{\mathrm{i}=1}^{\mathrm{n}} \left(\frac{\mathrm{y_i(p)} - \mathrm{y_{meas,i}}}{\sigma_{\mathrm{meas}}}\right)^2 \quad (3\text{-}1)$$

Where:

$y_{meas,i}$ = measured tracer concentration at time i

σ_{meas} = global standard deviation of the measured tracer concentration

$y_i\ (p)$ = the ith simulated value at time i

$p = (p_1, \ldots, p_m)$ = the model parameters

n = the number of data points

Furthermore, the coefficient of determination R^2 was calculated for each model, as follows:

$$R^2 = 1 - \frac{SS_{err}}{SS_{tot}} \quad (3\text{-}2)$$

$$SS_{err} = \sum_{i=1}^{n} \left(y_i - y_{meas,i}\right)^2 \quad (3\text{-}3)$$

$$SS_{tot} = \sum_{i=1}^{n} \left(\overline{y_{meas}} - y_{meas,i}\right)^2 \quad (3\text{-}4)$$

Where:

SS_{err} = residual sum of squares

SS_{tot} = total sum of squares (proportional to the sample variance)

$\overline{y_{meas}}$ = average value of measured tracer concentration

The optimum values for the parameters *p*, being the input tracer concentration, the diffusion coefficient in the axial dispersion model and the interconnection flowrate between the anoxic and anaerobic zones, were obtained by fitting the model results to the experimental RTD data. The best models were selected as constituting a compromise between model complexity (number of compartments) and data fit (low χ^2).

Finally, the obtained model was used to evaluate the hydraulic separation between the two zones of the reactor (anoxic-anaerobic). Similarly to the experimental tracer test performed with biomass inside the reactor, the continuous injection of a tracer component in the nitrate recycle was simulated to study the effect of a nitrate-rich stream coming from the subsequent aerobic reactor, by comparing the resulting steady tracer concentrations throughout the reactor. The extent of the separation was evaluated not taking into consideration the biological activity, i.e. only due to hydraulic separation. Subsequently, a saturation type (Monod equation) (Tchobanoglous et al., 2003) denitrification model was included in the anoxic zone in order to assess the influence of the nitrate consumption:

$$\frac{dC_{NO3}}{dt} = -k \cdot \frac{C_{NO3}}{K_{NO3}+C_{NO3}} \cdot X_H = -\frac{1-Y_H}{2.86 \cdot Y_H} \cdot \mu_H \cdot \eta_{NO3} \cdot \frac{C_{NO3}}{K_{NO3}+C_{NO3}} \cdot X_H \qquad (3\text{-}5)$$

Where:

C_{NO3} = nitrate concentration (mgN L^{-1})

k = denitrification rate (mgN $gVSS^{-1}$ day^{-1})

K_{NO3} = half saturation constant for nitrate (mgN L^{-1})

X_H = heterotrophic biomass concentration (mgVSS L^{-1})

Y_H = heterotrophic yield coefficient (dimensionless)

μ_H = maximum growth rate on substrate (day^{-1})

η_H = reduction factor for denitrification (dimensionless)

The denitrification kinetics (Eq. 3-5) were adapted from the Activated Sludge Model ASM2d (Henze et al., 1999), assuming substrate, nutrients, and alkalinity to be present in non-limiting amounts, in the absence of dissolved oxygen. Typical values for the kinetic (K_{NO3}, μ_H, η_H) and stoichiometric (Y_H) parameters were used as proposed in the ASM2d (Henze et al., 1999).

3.5.2. BioWin mathematical model

A mathematical model was built in order to assess the feasibility of a novel process proposed for the retrofit of an existing trickling filter WWTP for nutrient removal. The proposed process configuration consists of a modification of the existing primary clarifier to host an anaerobic-anoxic sludge blanket reactor. The proposed treatment train claims that both nitrogen and phosphorus biological removal using the existing facilities avoids the construction of new tanks or reactors, and does not require an external carbon source or the addition of chemicals. The modification of the primary clarifier was based on the anaerobic-anoxic sludge blanket reactor, AnoxAn. To preliminarily design and optimize the upgrading of the facility, mathematical model simulations were carried out.

A model of the current WWTP was implemented in BioWin Process Simulator v4.0 (EnviroSim Associates Ltd., Ontario, Canada). All of the biological processes have been described according to the default BioWin General Model (ASDM) and the default model parameters and values. The settling tanks have been implemented as ideal clarifiers. Steady-state simulation results have been compared with the operational results of the WWTP during 2013. Some model parameters have been adjusted in order to improve the fit between predicted (simulations) and observed (operating) results. Subsequently, the model has been modified to represent the proposed upgrade to BNR, while the model parameters have been unchanged. The primary clarifier was divided into two chambers to host the anaerobic and anoxic zones, or three chambers to host anaerobic, anoxic and additional aerobic zones. A final settling tank has been included at the end of the modified primary clarifier (MPC), to consider the clarification zone. The waste activated sludge in the simulations were adjusted in order to achieve suitable biomass concentration in the MPC, compared to conventional activated sludge systems, not exceeding TSS concentration of approximately 3 g L^{-1}. The biomass concentration in the MPC was kept fairly similar in all the simulations, making a comparison between the different analyzed scenarios possible. A set of steady-state simulations was performed covering a range of different configurations and operational conditions.

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Chapter 4

AnoxAn: a novel anaerobic-anoxic reactor for biological nutrient removal

Part of this chapter is under review for publication in:

Baeza, J.; Cema, G.; Tejero, I.; Huelsen, T.; Lyberatos, G.; Mosquera, A.; Oehmen, A.; Plaza, E.; Soares, A.; Fatone, F. Novel Efficient Wastewater Treatment Processes. Section 1.- Reducing Requirements and Impacts. Reducing energy requirements. Nutrients removal (Book developed within the network of the COST action ES1202 Water_2020)

4.1. Introduction

Biological nutrient removal (BNR) processes avoid the use of chemicals and chemical sludge disposal. However, conventional configurations for BNR require complex and large treatment systems providing anaerobic, anoxic and aerobic compartments in order to carry out nitrification, denitrification and phosphate release and uptake. The aerobic reactor should be coupled with additional non-aerated (anoxic and anaerobic) reactors, which results in a significant volume increase compared to the one needed for organic matter removal only.

To avoid the construction of separate tanks, the anaerobic and anoxic zones could be unified in a single non-aerated reactor, which takes advantage of the complete separation from the aerobic reactor preventing the undesired intrusion of oxygen into the anoxic and anaerobic zones. For instance, anaerobic and anoxic conditions can be established through sequential operation in a single reactor. The alternation of anoxic and anaerobic conditions through intermittent recirculation of the nitrate-rich flow effluent from the aerobic reactor to the anoxic/anaerobic reactor was obtained by Ahn et al. (2003) and Song et al. (2009; 2010) at lab-scale and at pilot-scale, respectively. However, the separation in time of the anaerobic and anoxic conditions while keeping continuous wastewater inflow may hinder the achievement of both high nitrogen and phosphorus removal efficiencies. Better efficiencies may be attained through the separation of the anaerobic and anoxic conditions in space. Few studies have been found compacting the anaerobic and anoxic zones in a single suspended sludge reactor. Kwon et al. (2005) proposed an upflow multi-layer suspended sludge bioreactor. The reactor was fed with raw wastewater and a nitrate-rich stream recycled from the subsequent aerobic reactor by means of rotating distributors at the bottom. This flow generates an anoxic zone, followed by an upper anaerobic one once nitrate is depleted. However, in such configuration, the availability of biodegradable substrate needed for phosphate release in the anaerobic zone is limited due to consumption during denitrification in the previous anoxic zone. For this reason, configurations with an anaerobic zone preceding an anoxic one are preferred for biological phosphorus removal.

In this framework, the AnoxAn reactor was conceived and patented by Tejero et al. (2010) with the objective of unifying the anoxic and anaerobic zones in a continuous upflow sludge blanket reactor, aimed at achieving high compactness and efficiency. The environmental conditions are vertically divided up inside the reactor with the anaerobic zone at the bottom and the anoxic zone above. Its application is envisaged in those cases where retrofitting of existing wastewater treatment plants

(WWTP) for BNR, or the construction of new ones, is limited by the available surface area.

4.2. Technical description

The AnoxAn reactor is a continuous upflow sludge blanket reactor, with an anaerobic zone at the bottom prior to an anoxic zone above (Figure 4-1). This setup avoids the use of chemicals and the need of additional source of organic matter for BNR by means of Enhanced Biological Phosphorus Removal (EBPR) and anoxic pre-denitrification, as it is in the configurations A^2/O, Modified Bardenpho, UCT and VIP. A clarification zone at the top of the reactor avoids the escape of large amounts of biomass, thus promoting high sludge concentration in a sludge blanket reactor type.

The biological anaerobic-anoxic functioning of AnoxAn is meant to be coupled with an aerobic reactor (for the removal of residual organic matter, phosphate uptake, and nitrification) and a secondary sedimentation unit (or a final filtration step), in order to complete the treatment train. A nitrate rich stream is recycled to the anoxic zone of AnoxAn, providing the conditions for denitrification.

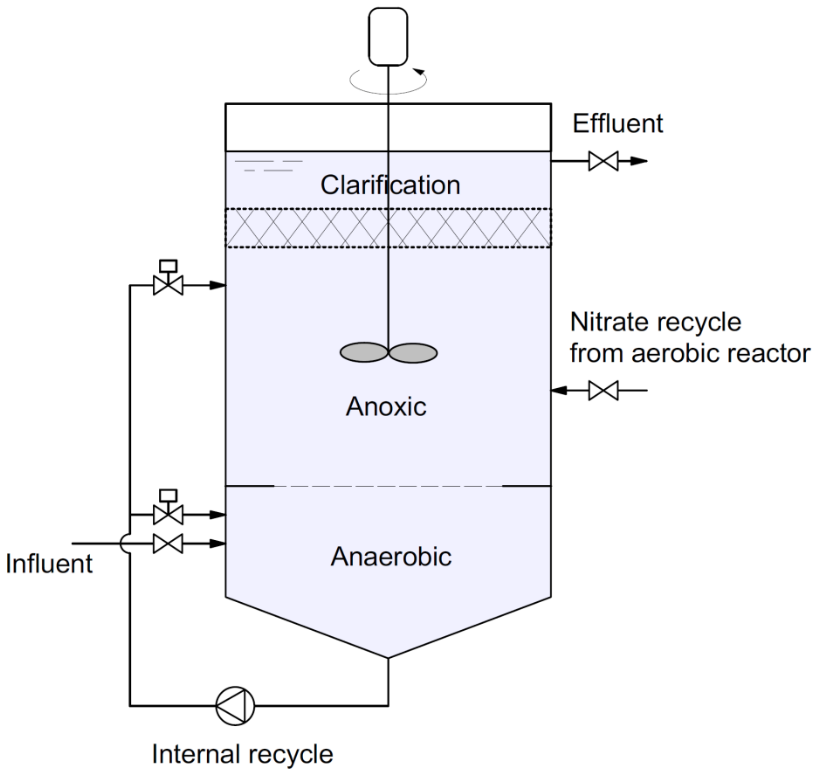

Figure 4-1 AnoxAn reactor scheme

The main specific features of the AnoxAn reactor are: (i) upflow operation; (ii) hydraulic separation between the anoxic and anaerobic zones; and (iii) suspended solids retention. Such characteristics allow for a reduced footprint requirement, providing high compactness and efficiency. First of all, the upflow operation contributes to energy saving for mixing, plug-flow and sustainable high sludge concentration (Lettinga et al., 1980). Regarding the hydraulic separation, it is required in order to establish separate anoxic and anaerobic conditions, that is to keep negligible nitrate concentration in the anaerobic zone. The desired hydraulic separation between the anoxic and anaerobic zones is achieved through specific mechanical mixing devices and baffles, while keeping the influent flow up-way through the reactor. Independent mixing devices should be implemented for the anaerobic and anoxic zones, by means of top entry or side entry dry-installed agitators, submersible mixers, and/or recirculation pumps. The targets of those devices are to keep the biomass in suspension reducing the extent of sludge settling and to provide good contact between the wastewater and biomass in each zone. Excessive mixing energy should be avoided in order to allow for the hydraulic separation between both zones, which can be performed through intermittent operation of the mixing devices. In addition, in order to limit the flow exchange and to improve the hydraulic separation, a baffle is introduced between the anoxic and anaerobic zones. This baffle could be implemented as a perimeter frame along the wall or by means of a rigid horizontal net whose voids allow for wastewater and biomass flow. Regarding the suspended solids retention, it is aimed at achieving a high biomass concentration inside the reactor. The upflow setup results in biomass retention to some extent, due to suspended solids settling, and it is assisted by means of an additional baffle at the top of the reactor. This baffle consists of a set of rigid horizontal nets, or a set of lamellas, providing favourable conditions for suspended solids settling. In this way, an upper clarification zone is established so that large biomass escape from the reactor is prevented. Nevertheless, some escape of suspended solids is expected in order to provide alternating anaerobic-aerobic conditions to perform biological phosphorus removal by means of phosphate accumulating organisms (PAO). Additionally, a periodic recirculation of suspended solids is carried out from the anaerobic to the anoxic zone, in order to avoid excessive biomass accumulation in the anaerobic zone and to enhance biomass circulation inside the reactor being exposed to alternating anaerobic-anoxic conditions. This setup encourages phosphate uptake using nitrate as electron acceptor, instead of oxygen, by means of denitrifying phosphate accumulating organisms (DPAO), which leads to energy savings for aeration, less sludge production and maximal influent organic substrate exploitation (Vlekke et al., 1988; Kuba et al., 1993), and makes it possible to biologically remove nutrients from wastewaters with low C/N ratio. Overall, the novel configuration claims anaerobic phosphate release, anoxic denitrification and phosphate uptake in a single reactor.

4.3. Main advantages

The main advantages of the AnoxAn reactor are summarized as follows:

- ✓ **Simplicity, high efficiency and compactness.** The unification of the anaerobic and anoxic compartments in a single reactor leads to a simple layout, compared to conventional configurations for BNR. Additionally, a better exploitation of the reactor volume is achieved due to high biomass concentration.
- ✓ **No need for chemicals addition.** An external carbon supply for denitrification is not needed due to pre-anoxic denitrification, and phosphorus is removed biologically without the need for chemicals.
- ✓ **Reduced energy requirement.** Energy savings for mixing due to upflow operation.
- ✓ **Simultaneous denitrification and phosphate uptake.** Phosphate uptake by DPAO leads to energy savings for aeration, less sludge production and provides a suitable alternative for influent wastewaters with low C/N ratio.

4.4. Pilot scale studies

The capability of the AnoxAn configuration to establish two hydraulically separated zones inside the single reactor, while achieving adequate mixing conditions in the two zones and keeping the continuous influent flow up-way through it, was assessed by means of hydraulic characterization experiments and model simulations (Díez-Montero et al., 2013; Díez-Montero et al., 2015a). The feasibility assessment of the desired hydraulic behaviour, prior to the evaluation of its biological performance treating wastewater, was considered essential and was addressed in that study. Residence time distribution (RTD) experiments in clean water were performed in a bench-scale (48.4 L) AnoxAn prototype. The observed behaviour was described by a hydraulic model consisting of continuous stirred tank reactors and plug-flow reactors. The impact of the denitrification process in the anoxic zone on the hydraulic separation was subsequently evaluated through model simulations. The desired hydraulic behaviour proved feasible, involving little mixing between the anaerobic and anoxic zones (mixing flowrate 40.2% of influent flowrate) and negligible nitrate concentration in the anaerobic zone (less than 0.1 mgN L^{-1}) when denitrification was considered (Figure 4-2).

The same AnoxAn prototype was coupled with an aerobic hybrid membrane bioreactor for the performance evaluation of AnoxAn in the removal of organic matter and nutrients from municipal wastewater without primary settling (Díez-Montero et al., 2012a; Díez-Montero et al., 2012b; Díez-Montero et al., 2015b). The overall average removal efficiencies of TN and TP reached 75% and 89%, respectively, with a hydraulic retention time (HRT) of 10 hours. The development of a sludge blanket allowed several purposes in the single multi-environment AnoxAn reactor: suspended solids retention; hydrolysis of influent particulate organic matter; phosphate release in the anaerobic zone with an HRT of 1.3 hours; and nearly complete denitrification with an anoxic HRT of 2.7 hours. Phosphate uptake in the anoxic zone resulted virtually negligible under the conditions of the study, in spite of the potential denitrifying phosphate accumulating activity evaluated through batch tests. This was attributed to the influent wastewater characteristics, with no limiting organic matter availability (C/N > 10 gCOD gTN^{-1}) for both PAO and conventional denitrifying heterotrophs. Regarding nitrate removal, it was observed that only 5% of the nitrate recycled from the aerobic reactor was removed in the anaerobic zone, thus confirming the success of the anoxic zone performing denitrification and the feasibility of the hydraulic separation between the anoxic and the anaerobic zones of the AnoxAn reactor.

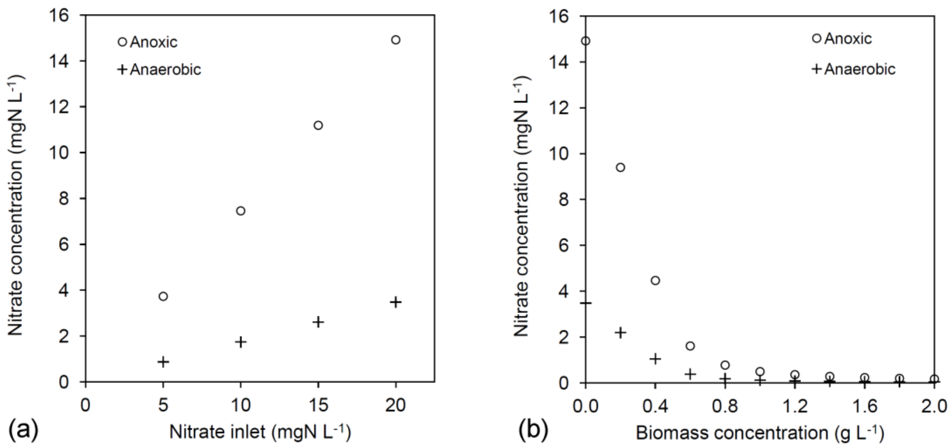

Figure 4-2 Tracer (nitrate) concentration in the anoxic and anaerobic zones: (a) for different tracer (nitrate) injections in the nitrate recycle inlet not taking into account denitrification and (b) for different biomass concentrations including denitrification model in the anoxic zone with a tracer (nitrate) injection in the nitrate recycle inlet of 20 mgN L^{-1}

4.5. Economic assessment

Cost estimates are dependent on local requirements and specific application and economy of scale applies. Nevertheless, in order to assess the potential economic savings of the implementation of the AnoxAn reactor, an economic analysis of a hypothetical realization has been carried out. An AnoxAn reactor has been designed based on a 16,500 m^3 d^{-1} average daily flow, and compared with the equivalent anaerobic and anoxic stages of a conventional BNR treatment system. The economic study has considered the investment and operational costs of the resulting AnoxAn reactor, and the investment and operational costs of the anaerobic and anoxic stages of a UCT treatment system. The investment cost included construction works, electrical and mechanical equipment, electrical facilities, instrumentation and control. The operational cost included the energy consumption corresponding to the operation of the electrical devices. The economic assessment did not include: (i) pretreatment, primary treatment, aerobic stage, and sludge handling and treatment; (ii) land cost, buildings and urbanization; and (iii) staff, maintenance and chemicals consumption. The result has been expressed as the total annualized equivalent cost (TAEC) of both alternatives (AnoxAn vs. UCT anaerobic-anoxic), as shown in Table 4-1, assuming an expected life of the proposed treatment systems of 20 years and an interest rate of 3%.

Table 4-1 Investment, operational and total annualized equivalent costs of the hypothetical AnoxAn realization compared to the equivalent anaerobic and anoxic stages of a UCT type BNR process

	Unit	**AnoxAn**		**UCT**	
Investment cost	€	652885		528918	
Electricity cost	€ kWh^{-1}	0.10	0.14	0.10	0.14
Operational cost	€ $year^{-1}$	17713	24798	41045	57464
TAEC	**€ $year^{-1}$**	**61597**	**68682**	**76597**	**93015**

The results of the economic assessment show remarkable differences between both alternatives. The investment cost of the AnoxAn reactor was estimated 23% higher than that of the equivalent UCT system, mainly due to the additional cost of lamellas or baffles. However, the energy savings of the AnoxAn reactor lead to an operational cost lower than half of that of the UCT system. Eventually, the TAEC of the AnoxAn reactor resulted from 20 to 26% lower than the one of the equivalent UCT system, considering an electricity cost from 0.10 to 0.14 € per kWh. This indicates the significance of the potential energy savings and the corresponding economic benefit of the AnoxAn reactor.

4.6. Full-scale perspectives

Despite the fact that there are no full-scale installations of the AnoxAn reactor, some of its fundamentals have been applied in several proposals for existing WWTP upgrade for BNR. In one specific case study, two similar trickling filter WWTP were asked to be upgraded to achieve nitrogen and phosphorus effluent standards. The proposed upgrade aimed to use the existing primary clarifier to host an anaerobic-anoxic reactor for BNR, with suspended solids retention, based on the AnoxAn setup. However, due to the shape and dimensions of the primary clarifier in such case study, a concentric configuration was proposed instead of a vertically compartmentalized upflow reactor. Several scenarios were simulated to preliminarily design and to optimize the anaerobic-anoxic reactor, and eventually several of them were found to successfully achieve both nitrogen and phosphorus removal, using the existing facilities without the need for new reactors (Díez-Montero et al., 2015c).

The present AnoxAn setup, with upflow operation, could be applied at full-scale for small WWTP, while new configurations of AnoxAn are being conceived and developed addressing the scalability of the reactor for medium and large scale plants. The study of the hydrodynamics of these specific new configurations by means of experimental tests and model simulations is considered a crucial step in order to assess its feasibility and scalability. Such AnoxAn configurations could be applied for retrofitting existing WWTP, since there are an increased number of areas being declared as sensitive to eutrophication which therefore require nitrogen and phosphorus removal from wastewater before it is discharged into such areas. The upgrades based on AnoxAn attempt to use the existing facilities, thus reducing the capital expenditure for new reactors, and will provide an energy efficient process for BNR. AnoxAn could also be applied for the construction of new WWTP for BNR, in cases of limited available surface area.

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Chapter 5

Feasibility of hydraulic separation in a novel anaerobic-anoxic upflow reactor for biological nutrient removal

Part of this chapter has been published as:

Díez-Montero, R.; De Florio, L.; González-Viar, M.; Volcke, E.I.P.; Tejero, I. Feasibility of hydraulic separation in a novel anaerobic–anoxic upflow reactor for biological nutrient removal. Bioprocess Biosyst Eng (2015) 38:93–103

5.1. Introduction

The presence of the nutrient elements nitrogen and phosphorus in wastewater discharged into water bodies is a contributor to eutrophication. Conventional configurations for biological nutrient removal (BNR) require anaerobic and anoxic compartments, besides aerobic ones which are sufficiently large to establish nitrification, which results in a significant volume increase compared to the one needed for organic matter removal only. The larger footprint needed for the retrofitting of existing wastewater treatment plants (WWTP) to achieve BNR is often not available. In the same way, the construction of new WWTP discharging into sensitive areas may also be limited by the available surface area or may be more conveniently solved by installing compact configurations.

For BNR, separate anoxic and anaerobic conditions are required. In the anaerobic zone, phosphate is released through the phosphate accumulating organisms (PAO) metabolism, which can only take place under strict nitrate absence. In the anoxic zone, nitrate serves as an electron acceptor allowing organic matter consumption for denitrification. The accumulation of phosphate by PAO takes place in excess of metabolic requirements, under aerobic conditions. Phosphate uptake is also feasible using nitrate as sole electron acceptor, instead of oxygen (Vlekke et al., 1988), which leads to energy savings for aeration, less sludge production and maximal influent organic substrate exploitation (Kuba et al., 1993).

To avoid the construction of separate tanks, anaerobic and anoxic conditions can be established through sequential operation in a single reactor. For instance, the alternation of anoxic and anaerobic conditions through intermittent recirculation of the nitrate-rich flow effluent from the aerobic zone to the anoxic/anaerobic zone was obtained by Ahn et al. and Song et al. at lab-scale (Ahn et al., 2003; Song et al., 2010) and at pilot-scale (Song et al., 2009). However, the separation in time of the anaerobic and anoxic conditions while keeping continuous wastewater inflow may hinder the achievement of both high nitrogen and phosphorus removal efficiencies.

Better efficiencies may be realized through the separation of the anaerobic and anoxic conditions in space. Few studies have been found compacting the anaerobic and anoxic zones in a single suspended sludge reactor. Kwon et al. (2005) proposed an upflow multi-layer suspended sludge bioreactor with a plug-flow circulation; the reactor was fed with raw wastewater and a nitrate-rich stream recycled from the subsequent aerobic reactor by means of rotating distributors at the bottom. This flow generates an anoxic zone, followed by an upper anaerobic one. However, in such configuration, the availability of biodegradable substrate needed for phosphate release in the anaerobic zone is limited due to consumption during denitrification in the previous anoxic zone. For this reason, configurations with an anaerobic zone preceding an anoxic one are preferred for biological phosphorus removal.

The reactor presented in this study was patented and identified by the name AnoxAn (Tejero et al., 2010). It is a continuous upflow sludge blanket reactor, aimed at achieving high compactness and efficiency. Advantages of upflow bioreactors are energy saving for mixing, plug-flow and sustainable high sludge concentration (Lettinga et al., 1980). The setup, with an anaerobic zone at the bottom prior to an anoxic zone above, avoids the use of chemicals and the need of additional source of organic matter for BNR by means of Enhanced Biological Phosphorus Removal (EBPR) and anoxic pre-denitrification, as it is in the configurations A^2/O, Modified Bardenpho, UCT and VIP (Tchobanoglous et al., 2003). A clarification zone at the top of the reactor avoids the escape of large amounts of biomass, thus promoting simultaneous denitrification and phosphate uptake. Overall, the novel configuration claims anaerobic phosphate release, anoxic denitrification and phosphate uptake in a single reactor.

One of the main goals of the AnoxAn reactor setup is to establish the anoxic-anaerobic hydraulic separation while achieving adequate mixing conditions in the two zones and keeping the continuous influent flow up-way through it. The concept of hydraulic separation in this study is interpreted as the ability of maintaining two zones under different environmental conditions inside the single reactor, including negligible nitrate concentration in the anaerobic zone. The feasibility assessment of the desired hydraulic behaviour, prior to the evaluation of its biological performance treating wastewater, was considered essential and is addressed in this study. For this purpose, residence time distribution (RTD) analysis coupled with hydraulic modelling of a prototype of the AnoxAn reactor was carried out. The RTD of a reactor represents the lapse of time a fluid element spends inside the reactor. This can be obtained by a pulse-input tracer test consisting in the addition of a tracer into the feed stream entering a reactor and measuring the outlet concentration of the tracer as a function of time. RTD analysis has been widely used to determine important hydraulic characteristics in wastewater treatment bioreactors such as mixing conditions (Olivet et al., 2005; Hu et al., 2012; Yerushalmi et al., 2013), type and characteristics of flow (Fall and Loaiza-Navía, 2007; Sarathai et al., 2010; Gómez, 2010; Ji et al., 2012; Behzadian et al., 2013), dead volume (Hu et al., 2012; Fall and Loaiza-Navía, 2007; Sarathai et al., 2010; Ji et al., 2012), channelling (Gómez, 2010; Zeng et al., 2005; Nemade et al., 2010) and dispersion (Yerushalmi et al., 2013; Ji et al., 2012; Zeng et al., 2005; Nemade et al., 2010), contributing in the description of non-ideal flow. The non-ideal hydraulic behaviour of a reactor can be described by several models, among them the tank-in-series model and the dispersion model (Behzadian et al., 2013). The former consists in the division of the reactor volume into several continuous stirred tank reactors (CSTR) connected in series, while the latter consists of a plug-flow reactor (PFR) with a diffusive component in the axial direction. These models can be applied to simple flow-through reactors, while more complex flow patterns, such as the AnoxAn reactor containing two hydraulically separated zones, require special consideration and comprehensive characterization (Hartley, 2013). A model based on the combination of ideal CSTR and PFR with axial dispersion, consistently representing the actual reactor, was proposed.

This study aims at a better understanding of the AnoxAn reactor hydraulics to assess its feasibility and scalability in treating urban wastewater. First, the reactor was hydraulically characterized by means of experimental tracer tests with clean water. The results of the hydraulic characterization were used to select the mixing devices, to set the internal recycle flowrate, to evaluate the mixing of each zone and to propose a model describing the hydraulic behaviour observed. The model was used to evaluate the extent of hydraulic separation between the anaerobic and anoxic zones, with and without considering biological nitrate consumption (denitrification). Finally, it was also investigated how the presence of biomass inside the reactor contribute to the hydraulic separation between both zones. This study is considered a necessary step for the development of the novel technology, proving the feasibility of the proposed configuration.

5.2. Materials and methods

5.2.1. Reactor setup

A prototype of the AnoxAn reactor was designed and built up at bench-scale (Figure 5-1). The 48.4 L AnoxAn reactor was made of polymethyl methacrylate (PMMA) with an internal square section of 0.20 x 0.20 m^2 and a height of 1.30 m. The upflow reactor contains an anaerobic zone at the bottom (12.4 L; 26 %), an anoxic zone above (32.0 L; 66 %) and a clarification zone at the top (4.0 L; 8 %). An AnoxAn reactor is typically followed by an aerobic reactor (not displayed in Figure 5-1), from which a nitrate-rich stream is recycled to the anoxic zone of AnoxAn for denitrification. The suspended biomass in the reactor is exposed to the anaerobic and anoxic conditions needed for EBPR and denitrification.

The selection of the mixing devices for the AnoxAn prototype was performed based on tracer tests in clean water with methylene blue, which were visually analyzed. The desired hydraulic conditions in the reactor were achieved through mechanical mixing. A Heidolph RZR-2000 impeller (100 rpm) was used for the anoxic zone while continuous internal recycle of the anaerobic zone was carried out by means of a peristaltic pump Watson Marlow 313U. The hydrodynamic reactor behaviour was further optimized introducing an expanded polyvinyl chloride (PVC) baffle of 0.040 m width along the wall, between the anoxic and anaerobic zones, to limit the flow exchange. A baffle of a rigid horizontal polyethylene (PE) net of 0.039 m height was inserted 0.10 m below the water surface to establish the upper clarification zone.

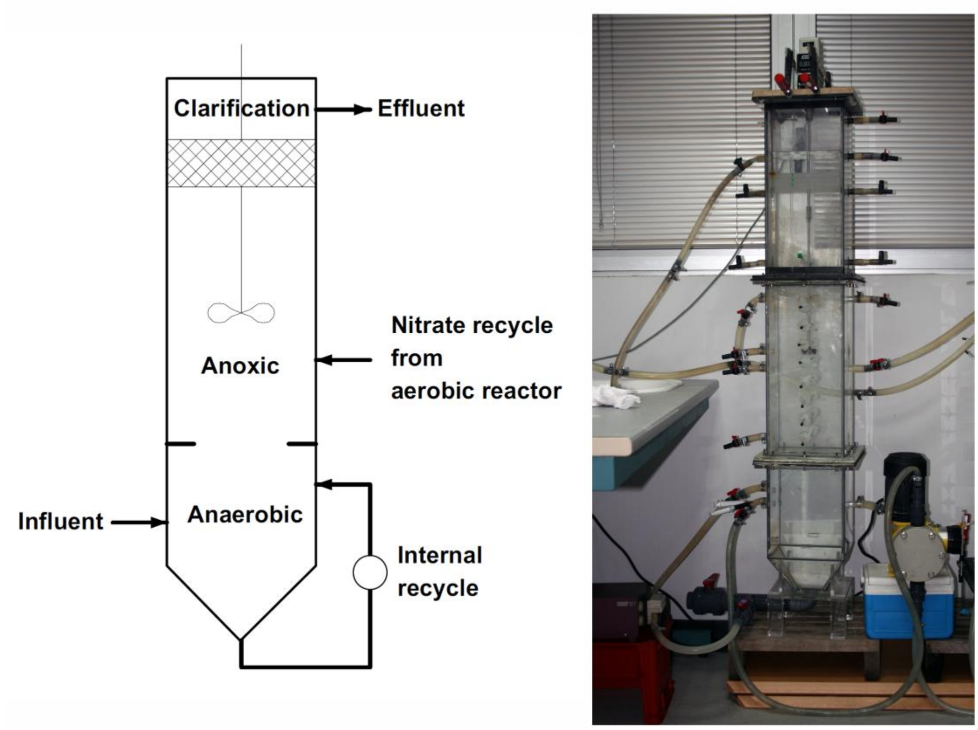

Figure 5-1 Schematic diagram (left) and picture (right) of the AnoxAn bench-scale reactor

The AnoxAn reactor was designed for a Hydraulic Residence Time (HRT) up to 5 hours (depending on the organic load applied), corresponding with an influent flowrate (Q_{in}) of approximately 10 L h^{-1}. The nitrate recycle rate was set to about 3 times the influent flowrate ($R_{NR} \approx 3$).

5.2.2. Residence time distribution (RTD) experiments

A concentrated solution of sodium chloride (NaCl, 350 g L^{-1}) was used as tracer for the RTD tests in clean water. The conductivity of the effluent was measured with a Hach CDC40103 probe, connected to a HQ30d meter. From the conductivity measurement, the corresponding tracer concentration was evaluated through a previously established linear relationship, as in Tang et al. (2004) and

Martín-Dominguez et al. (2005). Each experiment was preceded by an electrical conductivity measurement of the tap water used during the RTD test. This value was deducted from the electrical conductivity measured at the outlet before calculating the tracer (NaCl) concentration.

The RTD experiments were performed through pulse injection of the tracer into the feed stream entering the reactor and measuring its concentration in the outlet stream as a function of time (Levenspiel. 1999). Due to the complexity of the reactor configuration, including several mixing devices and baffles, separate RTD tests were carried out for the individual anaerobic and anoxic zones and for the overall reactor, as displayed in Figure 5-2. Table 5-1 summarizes the experimental conditions. The tests RTD1, RTD2 and RTD3 correspond with the bottom (anaerobic) zone at different internal recycle ratio (R_{IR}) providing different mixing conditions and thus a different turnover rate of the anaerobic volume. The RTD4 test relates to the top zones (anoxic + clarification), injecting the tracer in the nitrate recycle stream. The overall reactor behaviour was studied by the RTD5 test.

An additional tracer test for the overall reactor (Figure 5-2, setup c) was performed with biomass inside the reactor. This test was carried out after several months of operation treating municipal wastewater, once stable biomass concentrations were achieved, in order to evaluate to which extent the presence of biomass influenced the hydraulic separation between the two zones (anoxic-anaerobic). A solution of lithium chloride (LiCl) was used as tracer, which was continuously injected in the nitrate recycle with a constant concentration of lithium (11.15 mgLi L^{-1}). In this way, the effect of a nitrate-rich stream coming from the subsequent aerobic reactor was observed, by comparing the resulting tracer concentrations in the anoxic and anaerobic zones of the reactor. Samples of both the anaerobic and anoxic zones were periodically collected and the concentration of Li was measured by atomic absorption spectroscopy in a PERKIN ELMER AAnalyst 300 Atomic Absorption Spectrometer.

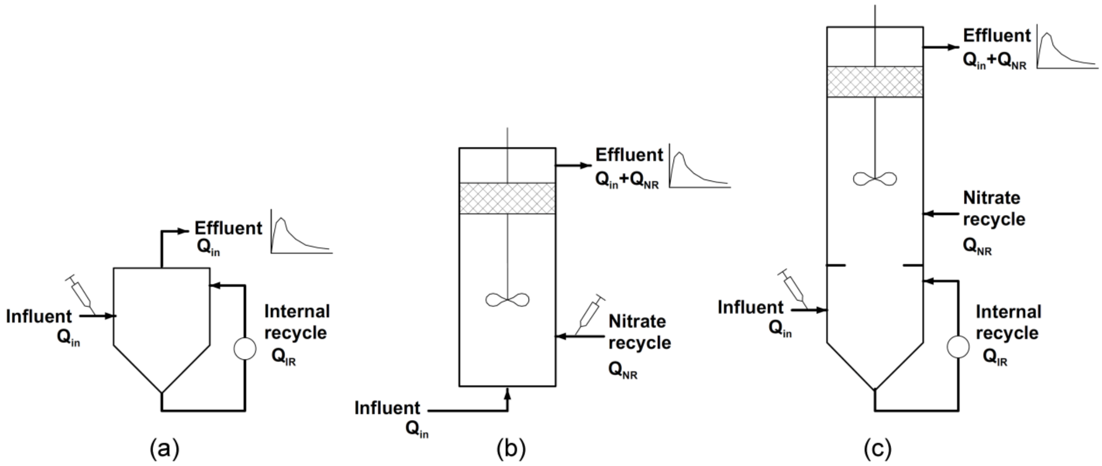

Figure 5-2 Schematic diagram of the three RTD experimental setups: (a) anaerobic zone, (b) anoxic and clarification zones, and (c) overall AnoxAn reactor

Table 5-1 Residence time distribution experimental conditions

RTD experiment	V (L)	Q_{in} (L h^{-1})	R_{IR} (Q_{IR}/Q_{in})	Anaerobic volume turnover rate ($Q_{IR}/V_{anaerobic}$; h^{-1})	R_{NR} (Q_{NR}/Q_{in})
RTD1 (anaerobic zone)	12.4	10.8	3.33	2.9	-
RTD2 (anaerobic zone)	12.4	10.8	5.56	4.8	-
RTD3 (anaerobic zone)	12.4	10.8	7.78	6.8	-
RTD4 (anoxic and clarification zones)	36.0	10.6	-	-	3.13
RTD5 (overall reactor)	48.4	10.4	5.77	4.8	2.98

5.2.3. Hydraulic reactor model

Based on the results of the RTD experiments, a hydraulic model for the reactor was set up and implemented in AQUASIM (Reichert, 1994). Several alternatives to represent the physical compartments and thus mimic hydraulic behaviour of the reactor were tested through trial-and-error. The anaerobic zone was represented as a single CSTR or a series of two or three CSTRs, with different volumes, connections and recycle streams. For the anoxic and clarification zones, several combinations of CSTRs and PFR with axial dispersion were tested. The selected setups for the anaerobic zone on the one hand and the anoxic and clarification zone on the other hand were combined to form the hydraulic model for the overall AnoxAn reactor, while adding an additional interconnection between the anoxic and anaerobic zones. The total volume of these compartments was set equal to the total reactor volume (48.4 L).

The best model was identified based on the calculation of χ^2, i.e. the sum of the squares of the weighed deviations between measurements and simulation results, as follows:

$$\chi^2(\mathrm{p}) = \sum_{\mathrm{i}=1}^{\mathrm{n}} \left(\frac{\mathrm{y_i(p)} - \mathrm{y_{meas,i}}}{\sigma_{\mathrm{meas}}}\right)^2 \quad (5\text{-}1)$$

Where:

$y_{meas,i}$ = measured tracer concentration at time i

σ_{meas} = global standard deviation of the measured tracer concentration

$y_i\ (p)$ = the ith simulated value at time i

$p = (p_1,\ldots, p_m)$ = the model parameters

n = the number of data points

Furthermore, the coefficient of determination R^2 was calculated for each model, as follows:

$$R^2 = 1 - \frac{SS_{err}}{SS_{tot}} \quad (5\text{-}2)$$

$$SS_{err} = \sum_{i=1}^{n} \left(y_i - y_{meas,i}\right)^2 \quad (5\text{-}3)$$

$$SS_{tot} = \sum_{i=1}^{n} \left(\overline{y_{meas}} - y_{meas,i}\right)^2 \quad (5\text{-}4)$$

Where:

SS_{err} = residual sum of squares

SS_{tot} = total sum of squares (proportional to the sample variance)

$\overline{y_{meas}}$ = average value of measured tracer concentration

The optimum values for the parameters p, being the input tracer concentration, the diffusion coefficient in the axial dispersion model and the interconnection flowrate between the anoxic and anaerobic zones, were obtained by fitting the model results to the experimental RTD data. The best models were selected as constituting a compromise between model complexity (number of compartments) and data fit (low χ^2).

Finally, the obtained model was used to evaluate the hydraulic separation between the two zones of the reactor (anoxic-anaerobic). Similarly to the experimental tracer test performed with biomass inside the reactor, the continuous injection of a tracer component in the nitrate recycle was simulated to study the effect of a nitrate-rich stream coming from the subsequent aerobic reactor, by comparing the resulting steady tracer concentrations throughout the reactor. The extent of the separation was evaluated not taking into consideration the biological activity, i.e. only due to hydraulic separation. Subsequently, a saturation type (Monod equation) (Tchobanoglous et al., 2003) denitrification model was included in the anoxic zone in order to assess the influence of the nitrate consumption:

$$\frac{dC_{NO3}}{dt} = -k \cdot \frac{C_{NO3}}{K_{NO3}+C_{NO3}} \cdot X_H = -\frac{1-Y_H}{2.86 \cdot Y_H} \cdot \mu_H \cdot \eta_{NO3} \cdot \frac{C_{NO3}}{K_{NO3}+C_{NO3}} \cdot X_H \qquad (5\text{-}5)$$

Where:

C_{NO3} = nitrate concentration (mgN L^{-1})

k = denitrification rate (mgN $gVSS^{-1}$ day^{-1})

K_{NO3} = half saturation constant for nitrate (mgN L^{-1})

X_H = heterotrophic biomass concentration (mgVSS L^{-1})

Y_H = heterotrophic yield coefficient (dimensionless)

μ_H = maximum growth rate on substrate (day^{-1})

η_H = reduction factor for denitrification (dimensionless)

The denitrification kinetics (Eq. 3-5) were adapted from the Activated Sludge Model ASM2d (Henze et al., 1999), assuming substrate, nutrients, and alkalinity to be present in non-limiting amounts, in the absence of dissolved oxygen. Typical values for the kinetic (K_{NO3}, μ_H, η_H) and stoichiometric (Y_H) parameters were used as proposed in the ASM2d (Henze et al., 1999).

5.3. Results and discussion

5.3.1. Residence time distribution tests

The residence time distribution profiles for the three experiments performed in the anaerobic zone at different internal recycle rates (RTD1, RTD2 and RTD3) are illustrated in Figure 5-3. The goal of these tests was to identify the lowest internal recycle rate which still guarantees good mixing. RTD1 shows a significant delay in the peak, which is attributed to slow mixing. Both RTD2 and RTD3 give rise to a sharp peak, which is similar to the hydraulic behaviour of a CSTR. Between the latter options, an internal recycle ratio of 5.56, as performed in RTD2 experiment, was chosen since it involves the least energy consumption. This internal recycle ratio corresponds with a turnover rate of the reactor of 4.8 times per hour, which is higher than the practical design value of 3 times per hour (Water Environment Federation, 2010). This rate should be high enough to accomplish sufficient mixing and low enough to prevent unwanted oxygen transfer from the atmosphere due to excessive turbulence. However, in the AnoxAn reactor configuration, the latter is prevented by its own design, as the anaerobic zone is not exposed to the atmosphere.

The delay of approximately 4 minutes in the sharp peak of RTD2 compared to the theoretical CSTR profile can be explained by the fact that the internal recycle is pumped from the bottom to the top of the anaerobic zone, producing a countercurrent downflow and in this way slightly delaying the arrival of the tracer in the outlet.

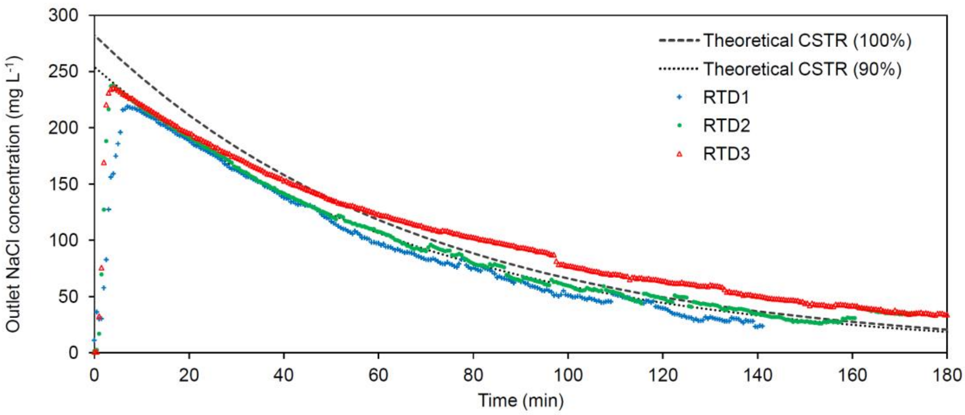

Figure 5-3 Residence time distribution profiles for anaerobic zone experiments RTD1 (R_{IR}=3.33), RTD2 (R_{IR}=5.56), RTD3 (R_{IR}=7.78) and theoretical CSTR with 100% and 90% tracer recovery

To characterize the flux in the anoxic zone and the influence of the clarification zone, a tracer pulse was injected in the nitrate recycle flow (with rate Q_{NR}). The resulting outlet tracer concentration profile (RTD4 in Figure 5-4(b)) shows a sharp peak followed by a long tail, similar to the behaviour of a CSTR, but with shift forward of approximately 18 minutes, possibly caused by the influence of the upper clarification zone. The baffle inserted between the anoxic and clarification zones impedes an immediate and complete mixing of the upper part of the reactor. The delay in the rise of the RTD profile can be attributed to non-ideal plug-flow behaviour in the volume under the influence of the baffle and the clarification zone, which can be described by means of an axial dispersion model consisting of an ideal PFR with a diffusive component in the axial direction. The remaining volume of the reactor, which represents the anoxic zone, is assumed to be completely mixed by the impeller.

The global RTD profile for the overall AnoxAn reactor is displayed in Figure 5-4(c) (RTD5). The outlet tracer concentration trend shows a complex non-ideal flux type, which should be represented by the combination of the setups proposed for the individual anaerobic and anoxic plus clarification zones. The tail of the RTD shows a slight cyclical pattern, which may be due to the presence of an internal recycle as explained in Levenspiel (1999). However, since the amplitude of these oscillations is relatively small, they were neglected in order not to increase the model complexity.

The amount of tracer recovered in the individual experiments was calculated and related to the theoretical amount of tracer injected. A tracer recovery of 81.8%, 79.7% and 75.4% was obtained for the experiments RTD2, RTD4 and RTD5, respectively. The incomplete tracer recovery could be attributed to inaccuracies during the tracer solution preparation and manipulation (syringe injection).

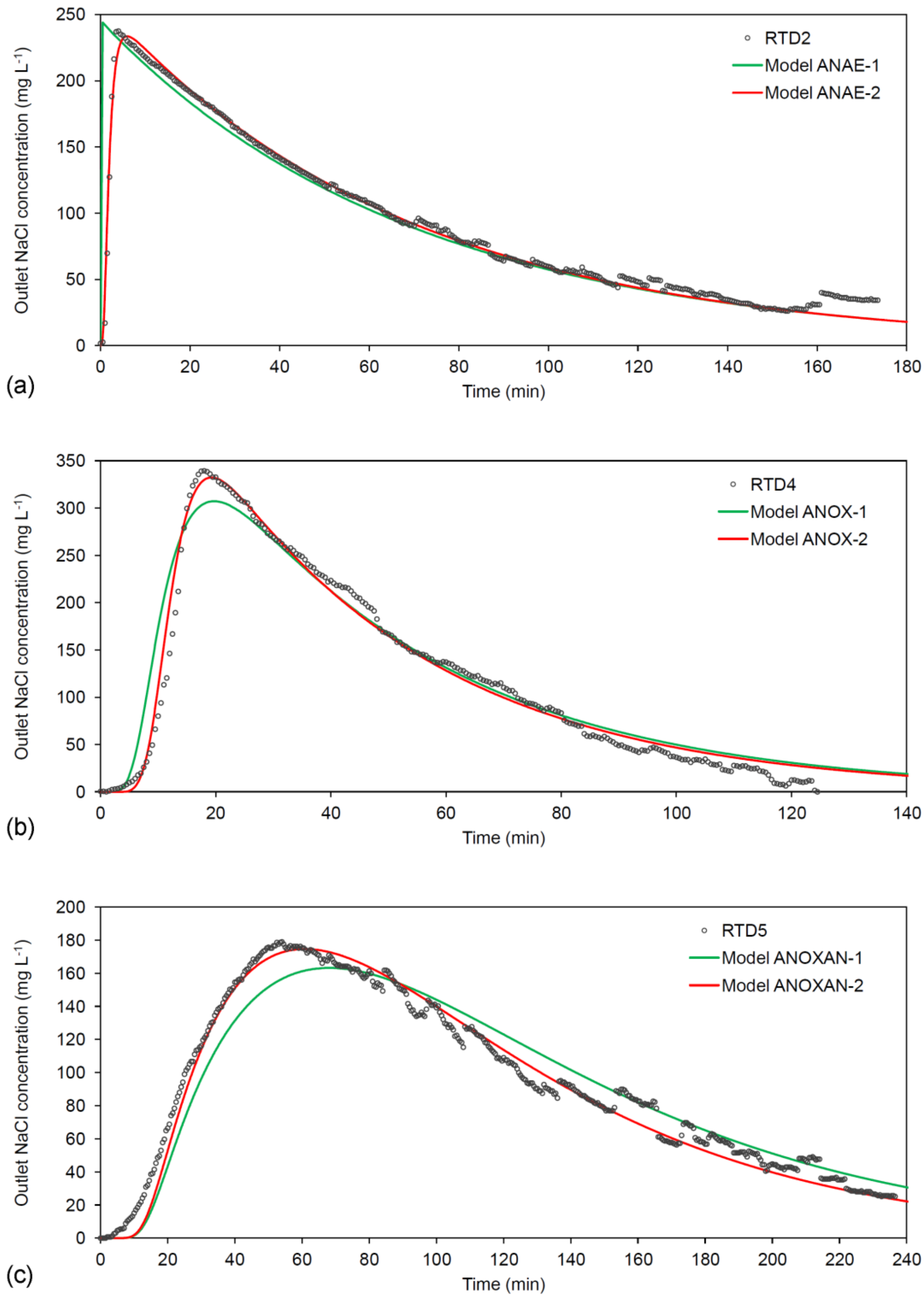

Figure 5-4 Comparison of experimental (circles) and simulated (lines) RTD for the three experimental setups: (a) anaerobic zone, (b) anoxic and clarification zones, and (c) overall AnoxAn reactor. Simulations -1 and -2 refer to two different model setups presented in the next section

5.3.2. Hydraulic reactor model

Anaerobic zone

Several alternatives were implemented to represent the anaerobic zone in the hydraulic model. Two of them are presented together with the experimental RTD2 in Figure 5-4(a). Model setup ANAE-1 consists of a single mixed reactor compartment. The second setup ANAE-2 is represented in Figure 5-5(a) and consists of a combination of 3 mixed reactor compartments in series, representing the main anaerobic zone (compartment 1, 10.6 L), the hopper at the bottom of the reactor (compartment 2, 1.4 L) and the upper layer receiving the internal recycle (compartment 3, 0.4 L). The second setup allows simulating the effect of the internal recycle pumped from the bottom compartment to the top compartment, on its turn providing a downflow in the anaerobic zone. The latter was represented through a bifurcation from the outlet of the top compartment (3) to the main compartment (1). Its flowrate Q_{31} was defined as a fraction of the influent flowrate Q_{in}:

$$Q_{31} = Q_{IR} - Q_{in} = \left(\frac{Q_{IR}}{Q_{in}} - 1\right) \cdot Q_{in} = (R_{IR} - 1) \cdot Q_{in} = f_1 \cdot Q_{in} \qquad (5\text{-}6)$$

The parameter f_1 was calculated as R_{IR}-1=4.56 to represent the actual internal recycle flow.

The fit between the model simulation and the experimental results was significantly improved with the 3 compartments model (ANAE-2) compared to the single mixed reactor compartment (ANAE-1), as it is clear from Figure 5-4(a) and from the χ^2 values shown in Table 5-2, achieving a coefficient of determination R^2 of 0.99.

A parameter estimation was carried out in order to estimate the amount of tracer input. The results are displayed in Table 5-2. The tracer recovery estimated from the ANAE-2 model fit was somewhat higher than the amount of tracer recovered experimentally (87.1% versus 81.8%), which may be due to the limited duration of the experimental measurements. It also suggested that the reduced experimental tracer recovery may be due to overestimation of the actual amount of tracer injected during the tests.

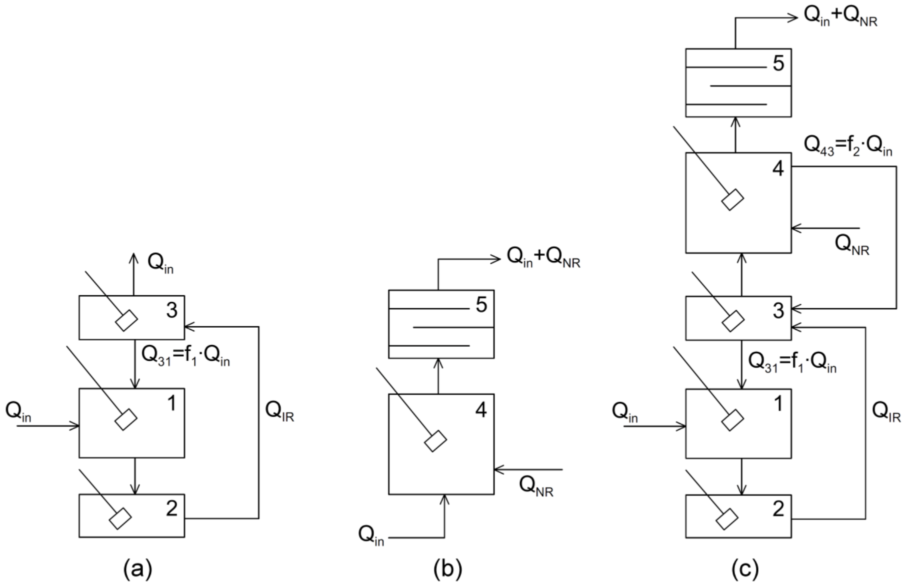

Figure 5-5 Schematic diagram of the final hydraulic models: (a) anaerobic zone ANAE-2, (b) anoxic and clarification zones ANOX-1/ANOX-2 and (c) overall AnoxAn reactor ANOXAN-1/ANOXAN-2

Table 5-2 Hydraulic model parameters and resultant χ^2 and R^2

Setup	**f_1**	**f_2**	**D ($m^2\ s^{-1}$)**	**Tracer input (%)**	**χ^2**	**R^2**
ANAE-1	-	-	-	86.2[a]	33.7	0.95
ANAE-2	4.56	-	-	87.1[a]	3.7	0.99
ANOX-1	-	-	$8.9\cdot10^{-6}$ [a]	89.4[a]	12.4	0.95
ANOX-2	-	-	$3.6\cdot10^{-6}$ [a]	86.8[a]	3.9	0.99
ANOXAN-1	4.77	0	$3.6\cdot10^{-6}$	83.6[a]	31.6	0.93
ANOXAN-2	4.77	0.402[a]	$3.6\cdot10^{-6}$	78.8[a]	10.8	0.98

[a] Obtained by parameter estimation

Anoxic and clarification zones

Among several alternative hydraulic models to represent the anoxic and clarification zones, a configuration consisting of a mixed reactor followed by an advective-diffusive compartment was selected. Different values were tested for the volumes of these reactors (compartments 4 and 5 in Figure 5-5(b)) which were set at 30 L and 6 L for ANOX-1 and at 28.8 L and 7.2 L for ANOX-2 (corresponding to the same total volume). ANOX-1 represents the clarification zone and the volume occupied by the baffle by means of a PFR with axial dispersion, while ANOX-2 considers non-ideal PFR for the clarification zone and the baffle plus 1.2 L volume under the baffle influence.

A parameter estimation was carried out in order to determine the diffusion coefficient D of the non-ideal PFR and the amount of tracer (Table 5-2). The diffusion coefficient D was estimated at $8.9 \cdot 10^{-6}$ m^2 s^{-1} and $3.6 \cdot 10^{-6}$ m^2 s^{-1} for setup ANOX-1 and ANOX-2, respectively. The corresponding Peclet number (Pe):

$$Pe = \frac{U \cdot L}{D} \qquad (5\text{-}7)$$

in which U is the upflow velocity (m s^{-1}) and L is the length of the compartment (m), is a characteristic for the axial dispersion. A large Pe number indicates low back-mixing (recall that an ideal PFR corresponds with Pe=∞, while Pe=0 for a CSTR). It was calculated as 5.1 and 15.2, for ANOX-1 and ANOX-2 respectively. Taking Pe≤5 as the criterion of greater back-mixing (CSTR) and Pe≥50 as small back-mixing (PFR) (Sarathai et al., 2010; Ji et al., 2012; Levenspiel, 1999), both alternatives tended to intermediate between PFR and CSTR. It is clear from Figure 5-4(b) that the fit between the simulations and the experimental data is better for the second volume distribution option (ANOX-2), achieving a high value for the coefficient of determination, R^2, of 0.99 (Table 5-2). A relatively longer PFR compartment with a lower diffusion coefficient seems to better represent the upper calm zone of the reactor.

The estimated amount of tracer for setup ANOX-2 was somewhat higher than the one recovered experimentally (86.8% versus 79.7%), similarly to the previous anaerobic zone simulations.

Overall AnoxAn reactor

The model setups ANAE-2 and ANOX-2 were combined (ANOXAN-1) and compared to a configuration with additional mixing between the anoxic and anaerobic zones (ANOXAN-2, Figure 5-5(c)). For the latter purpose, a bifurcation was included from the anoxic zone (compartment 4) to the anaerobic upper layer (compartment 3). A parameter f_2, termed mixing coefficient, was used to define the flowrate Q_{43} diverted from compartment 4 to compartment 3:

$$Q_{43} = f_2 \cdot Q_{in} \quad (5\text{-}8)$$

This approach is similar to the one of Heertjes and van der Meer (1978), who proposed a model for upflow anaerobic sludge blanket reactors including return flow or back-mixing between stirred compartments.

The diffusion coefficient D was set to the value determined previously, during the evaluation of the anoxic and clarification zones, and f_1 was set to 4.77 (equal to R_{IR}-1) to represent the actual internal recycle during the experiment RTD5. A parameter estimation was carried out in order to determine the amount of tracer and the mixing coefficient f_2 (Table 5-2). The fit was clearly improved considering the mixing between both zones (ANOXAN-2, Figure 5-4(c)) achieving a coefficient of determination R^2 of 0.98. The estimated amount of tracer was again slightly higher than the one recovered experimentally (78.8% versus 75.4%). The mixing coefficient f_2 was estimated at 0.402 (mixing flowrate 40.2% of Q_{in}), which is lower than typical anoxic recycle ratio (from the anoxic to the anaerobic reactor) in several conventional BNR configurations, such as UCT (Tchobanoglous et al., 2003). This indicates no excessive mixing takes place, which is desired in the AnoxAn reactor to avoid the loss of the anaerobic condition, since nitrate presence in the theoretically anaerobic zone will prevent EBPR.

The ultimate model, ANOXAN-2, is considered a reliable hydraulic model for the AnoxAn prototype tested in this study, making it possible to evaluate the feasibility of the novel configuration prior to scaling up and studying the biological performance of the reactor.

To evaluate the hydraulic separation between the two zones of the ANOXAN-2 configuration, a continuous injection of a constant concentration of tracer (5, 10, 15 and 20 mg L^{-1}) in the nitrate recycle was simulated. This tracer injection represents a nitrate-rich stream recycled from an ideal subsequent aerobic nitrifying reactor, corresponding to influent wastewater ammonium concentration approximately in the range of 20-80 mgN L^{-1}. The simulations were performed with the same experimental conditions of the RTD test for the overall reactor, that are Q_{in}=10.4 L h^{-1}, R_{IR}=5.77 and R_{NR}=2.98. Figure 5-6(a) displays the obtained steady state tracer (nitrate) concentrations in the five reactor compartments. The tracer (nitrate) concentration in the anoxic zone (compartment 4) was observed to be 4.3 times higher than the concentration in the anaerobic zone (compartment 1), only due to hydraulic separation. No significant hydraulic separation was observed between the anoxic and clarification zones (compartments 4 and 5) on the one hand and the bottom, middle and top compartments of the anaerobic zone (compartments 1, 2 and 3) on the other hand.

While the nitrate concentration in the anaerobic zone may still be too high for EBPR, it was drastically reduced when denitrification in the anoxic zone was taken into account in the presence of biomass, even with a continuous nitrate injection of 20 mgN L^{-1} in the recycle stream, as can be observed from Figure 5-6(b). Nitrate consumption due to biological activity led to reduced nitrate concentration in the anoxic zone, while the ratio between nitrate concentrations in the anoxic and anaerobic zones was the same (about 4.3), indicating that denitrification did not affect the extent of hydraulic separation. However, it is clear from Figure 5-6(b) that it is required a minimum concentration of biomass (1.2 g L^{-1}), which is considered achievable, to maintain negligible concentration of nitrate in the anaerobic zone (less than 0.1 mgN L^{-1}), making possible the existence of an actually anaerobic zone below the anoxic one. The denitrification model was only incorporated in the anoxic zone (not in the anaerobic one) in order to assess the required nitrate disappearance in the anaerobic zone, not being influenced by biological activity in such a zone.

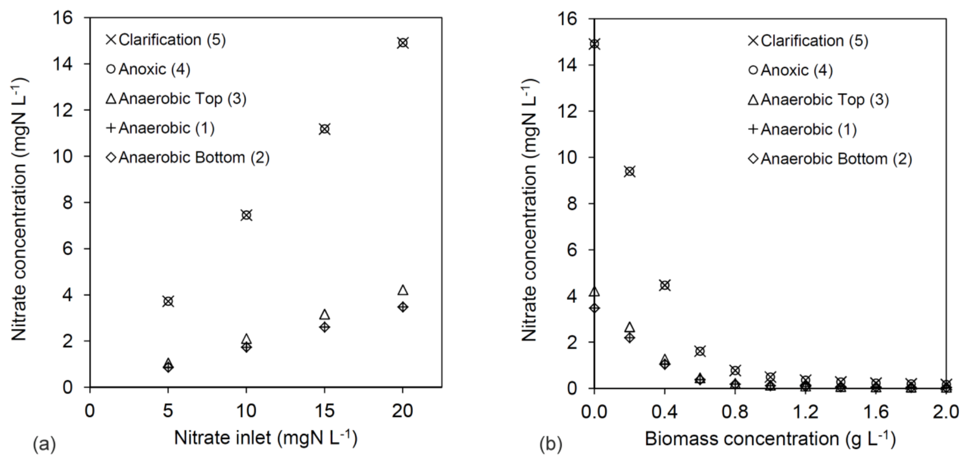

Figure 5-6 Tracer (nitrate) concentration in the five model compartments: (a) for different tracer (nitrate) injections in the nitrate recycle inlet not taking into account denitrification and (b) including denitrification model in the anoxic zone with a tracer (nitrate) injection in the nitrate recycle inlet of 20 mgN L^{-1}

The subsequent tracer test with biomass, carried out after several months of reactor operation, once the concentration of total suspended solids (TSS) amounted to approximately 5 g L^{-1} in the anoxic zone and 10 g L^{-1} in the anaerobic one, allowed to assess the influence of biomass on the reactor hydrodynamics. The comparison between the tracer (Li) concentrations in the anoxic and anaerobic zones, resulting from the continuous injection of the tracer (Li) in the nitrate recycle, and the simulation results obtained for identical operational conditions without biomass, are shown in Figure 5-7. It shows that the hydraulic separation is somehow benefitted from the presence of biomass.

In particular, the experimental and simulated lithium concentration profiles in the anoxic zone matched very well. For the anaerobic zone, the measured concentrations were slightly overpredicted through simulation, which suggests that the presence of biomass further increase the hydraulic separation between the anoxic and anaerobic zones. It is attributed to the different TSS concentration in both zones. The lower TSS concentration in the anoxic zone can be imputed mainly to the nitrate recycle stream, which enters the AnoxAn reactor with high flowrate and lower concentration of TSS, thus provoking TSS dilution in the anoxic zone. Due to these different concentrations, different densities in each zone have slightly enhanced the hydraulic separation.

When compared to similar studies, the influence of biomass on the hydrodynamics of bioreactors was shown to have a notable effect for reactors with high biomass concentration and without mechanical mixing, as it is the case for upflow anaerobic sludge blanket reactor, UASB (Lou et al., 2006; Ren et al., 2008). In these reactor types, the produced biogas bubbles disturb the sludge blanket and lead to mixing, thus affecting the hydrodynamics of the reactor. In the AnoxAn reactor however, the envisaged biomass concentration is higher than the typical value of 3 g L^{-1} in conventional activated sludge processes (Tchobanoglous et al., 2003), but still relatively low compared to sludge concentration in UASB reactors, which could exceed 80 g L^{-1} (Heertjes and van der Meer, 1978). And what is more, mechanical devices continuously mix each zone avoiding the compacting of the sludge mass and limiting the influence of gas bubbles, thus explaining the minor influence of biomass in the AnoxAn reactor hydrodynamics compared to other sludge blanket reactors such as UASB.

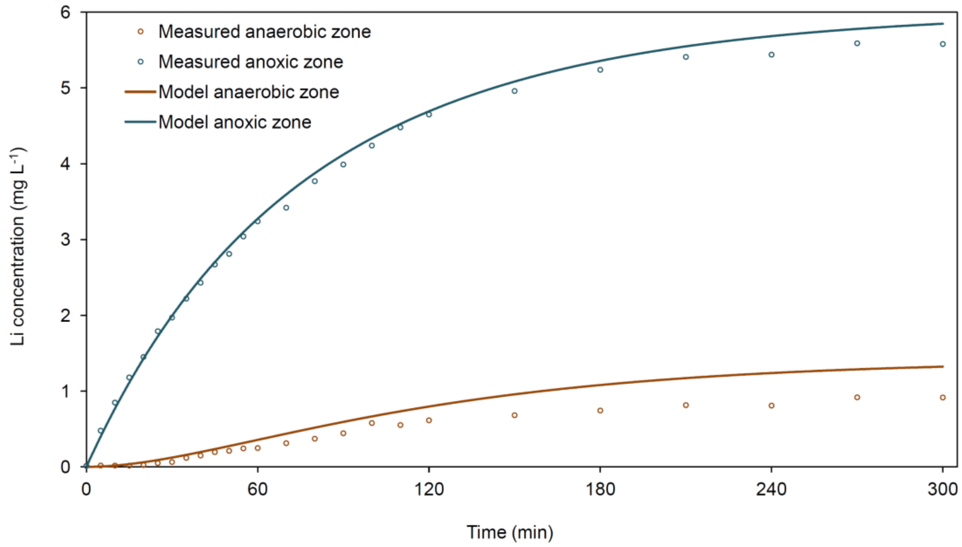

Figure 5-7 Tracer (lithium) concentration in the anoxic and anaerobic zones with tracer (lithium) injection in the nitrate recycle inlet of 11.15 mgLi L^{-1}. Comparison between experimental data (with biomass) and simulation results (without biomass)

5.4. Conclusions

A novel anaerobic-anoxic upflow reactor, AnoxAn, is presented as an innovative technology for BNR. The required environmental conditions to achieve EBPR and denitrification imply hydraulic separation between the anaerobic and anoxic zones inside the reactor. Such specific hydraulic behaviour inside the reactor has been tested experimentally at bench-scale and through numerical simulation in order to assess the feasibility of the novel reactor configuration, leading to the following main conclusions:

The hydraulic behaviour of an AnoxAn prototype has been characterized by means of RTD analysis of the individual anaerobic and anoxic zones, as well as of the overall reactor. Adequate mixing was achieved for each zone.

A hydraulic model describing the zoning of the reactor has been built up and fitted to the RTD test results. The ultimate setup consists of a combination of four CSTR compartments and one PFR with axial dispersion compartment and will form the basis for the inclusion of biological conversion processes in future.

The simulation results showed that the desired hydraulic behaviour was achieved, involving little mixing between the anoxic and the anaerobic zones of the AnoxAn reactor. The mixing flowrate between both zones was estimated to be only 40.2% of influent flowrate.

When denitrification in the anoxic zone was taken into account, the ratio between nitrate concentrations in the two zones remained the same and, more important, it resulted in negligible nitrate concentration (less than 0.1 mgN L^{-1}) in the anaerobic zone (as desired) for biomass concentrations of 1.2 g L^{-1} or higher. The established hydraulic separation makes the AnoxAn concept ready for further research addressing the performance of the reactor in the removal of organic matter and nutrients from wastewater.

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Chapter 6

Performance evaluation of a novel anaerobic-anoxic sludge blanket reactor for biological nutrient removal treating municipal wastewater

Part of this chapter is under revision as:

Díez-Montero, R.; De Florio, L.; González-Viar, M.; Herrero, M.; Tejero, I. Performance evaluation of a novel anaerobic-anoxic sludge blanket reactor for biological nutrient removal treating municipal wastewater. Submitted to Bioresource Technol (2015)

6.1. Introduction

Nitrogen and phosphorus are the main nutrient elements discharged with wastewaters whose presence in the receiving water bodies is a significant contributor to eutrophication. Biological nutrient removal (BNR) processes avoid the use of chemicals and chemical sludge disposal but conventional configurations require complex and large treatment systems providing anaerobic, anoxic and aerobic compartments. An aerobic reactor sufficiently large to establish nitrification is required, which should be coupled with additional non-aerated (anoxic and anaerobic) reactors, resulting in a significant volume increase compared to the one needed for organic matter removal only. In the anoxic reactor, denitrification takes place where nitrate serves as an electron acceptor allowing organic matter consumption. In the anaerobic one, phosphate is released through the phosphate accumulating organisms (PAO) metabolism, while the subsequent accumulation of phosphate by PAO takes place in excess of metabolic requirements, under aerobic conditions. Phosphate uptake is also feasible under anoxic conditions using nitrate as sole electron acceptor, instead of oxygen (Vlekke et al., 1988), through the denitrifying phosphate accumulating organisms (DPAO) metabolism, which can lead to savings in plant operational costs due to energy savings for aeration, less sludge production and maximal influent organic substrate exploitation (Kuba et al., 1993; Oehmen et al., 2007).

In order to reduce the BNR system complexity and volume requirements, compact and efficient aerobic reactors have been proposed, as well as the inclusion of the anaerobic and/or anoxic zones into the same aerobic reactor. In a different approach, aimed at making it easier to prevent the undesired intrusion of oxygen into the anoxic and anaerobic zones, the anaerobic and anoxic zones are unified in a single non-aerated reactor. This approach takes advantage of the complete separation from the aerobic reactor. For instance, Ahn et al. and Song et al. (Ahn et al., 2003; Song et al., 2009; Song et al., 2010) proposed anaerobic and anoxic sequential conditions in a single reactor, avoiding the construction of separate tanks. Intermittent recirculation of the nitrate-rich effluent from the aerobic zone to the sequencing anoxic/anaerobic reactor provides the alternation of anoxic and anaerobic conditions. However, the separation in time of the anaerobic and anoxic conditions while keeping continuous wastewater inflow may hinder the achievement of both high nitrogen and phosphorus removal efficiencies. Better efficiencies may be attained through the separation of the anaerobic and anoxic conditions in space. Few studies have been found compacting the anaerobic and anoxic zones in a single suspended sludge reactor. Kwon et al. (Kwon et al., 2005) proposed an upflow multi-layer suspended sludge bioreactor, in which raw wastewater was fed into the reactor together with a nitrate-rich stream recycled from the subsequent aerobic reactor. This flow generates an anoxic zone, followed by an upper anaerobic one (where nitrate is depleted). However, in such configuration, the availability of biodegradable substrate needed for phosphate release in the anaerobic zone is limited due to consumption during denitrification in the previous anoxic zone. For this reason, configurations with an anaerobic zone preceding an anoxic one are preferred for biological phosphorus removal.

In this framework, the AnoxAn reactor configuration was conceived and patented by Tejero et al. (2010) with the objective of unifying the non-aerated zones (anoxic and anaerobic) in a continuous upflow sludge blanket reactor. The unification of the anaerobic and anoxic compartments in a single reactor leads to a simple layout, compared to conventional configurations for BNR. Furthermore, energy savings for mixing are attained due to upflow operation. The setup, with an anaerobic zone at the bottom prior to an anoxic zone above, avoids the use of chemicals and the need for additional source of organic matter for BNR by means of enhanced biological phosphorus removal (EBPR) and pre-anoxic denitrification, as it is in the configurations A^2/O, Modified Bardenpho, UCT and VIP (Tchobanoglous et al., 2003). A calm zone at the top of the reactor avoids the escape of large amounts of biomass, thus promoting high sludge concentration in the sludge blanket, leading to a better exploitation of the reactor volume. In addition, the alternate anaerobic-anoxic conditions promote DPAO activity and anoxic phosphate uptake. Overall, the novel configuration claims anaerobic phosphate release, anoxic denitrification and phosphate uptake in a single reactor, providing high compactness and efficiency.

The hydraulic separation is required in order to establish separate anoxic and anaerobic conditions inside the reactor, that is to keep negligible nitrate concentration in the anaerobic zone. Previous studies were aimed at the hydraulic behavior evaluation and optimization of an AnoxAn reactor prototype (Díez-Montero et al., 2015). It was proved the feasibility of anoxic-anaerobic hydraulic separation while achieving adequate mixing conditions in the two zones and keeping the continuous influent flow up-way through it.

The biological anaerobic-anoxic functioning of AnoxAn is meant to be coupled with an aerobic reactor (for the removal of residual organic matter, phosphate uptake, and nitrification) and a secondary sedimentation unit (or a final filtration step), as to complete the BNR treatment train. In this study AnoxAn was coupled with an aerobic hybrid membrane bioreactor (HMBR) in order to evaluate the performance of the novel reactor in the removal of organic matter and nutrients from wastewater. The configuration of the HMBR was previously patented (Tejero and Cuevas, 2005) and tested for organic matter and nitrogen removal at different scales

(Rodríguez-Hernández et al., 2012; Rodríguez-Hernández et al., 2014). The proven efficient and stable nitrification in the HMBR facilitates the AnoxAn evaluation, reducing the influence of the aerobic reactor operation in the AnoxAn performance. Besides, coupling a biofilm reactor with a suspended biomass reactor leads to an integrated process, which has the additional advantage of enabling separate control of different biomasses. The slower-growing nitrifying biomass preferentially takes place on biofilms, while the faster-growing heterotrophic biomass, including denitrifiers and PAO, usually resides in the suspended activated sludge. This feature facilitates the optimization of simultaneous nitrogen and phosphorus removal processes (Onnis-Hayden et al., 2011).

This chapter reports the performance evaluation of the AnoxAn reactor in the removal of organic matter and nutrients from municipal wastewater. The expected advantages of the novel reactor were tested in the very first experimental campaign ever carried out with the AnoxAn reactor, which is presented in this chapter. The specific objectives of the study were to assess the organic matter, nitrogen and phosphorus removal efficiencies, to reveal the underlying mechanisms controlling BNR, and to describe the key features of the novel reactor.

6.2. Materials and methods

6.2.1. Experimental setup

The setup of the bench-scale pilot plant is illustrated in Figure 6-1. It consists of two reactors, AnoxAn and HMBR, made of polymethyl methacrylate (PMMA).

The 48.4 L AnoxAn reactor, with internal square section of 0.20 x 0.20 m^2 and a height of 1.30 m, is vertically divided up into an anaerobic zone at the bottom (26% of total volume), an anoxic zone above (66%) and a transition calm zone at the top (8%). A nitrate-rich stream, set to about 3 times the influent flowrate, is recycled from the subsequent aerobic reactor to the anoxic zone of AnoxAn with a dosing pump. Mechanical mixing in the anoxic zone was obtained by means of an impeller (300 rpm) while continuous internal recycle of the anaerobic zone was carried out by means of a peristaltic pump (turnover rate of the anaerobic volume 4.2 h^{-1}). The same peristaltic pump provided intermittent recycling from the anaerobic to the anoxic zone performing repeating sequences of anoxic/anaerobic recirculation (t_{anox}/t_{anae}) in order to enhance the suspended biomass circulation inside the reactor being exposed to the alternating anaerobic and anoxic conditions. The hydrodynamic reactor behaviour was further optimized introducing an expanded polyvinyl chloride (PVC) baffle of 0.040 m width along the wall, between the anoxic and anaerobic zones. A baffle of a rigid horizontal polyethylene (PE) net of 0.039 m height was inserted 0.10 m below the water surface to establish the upper transition zone.

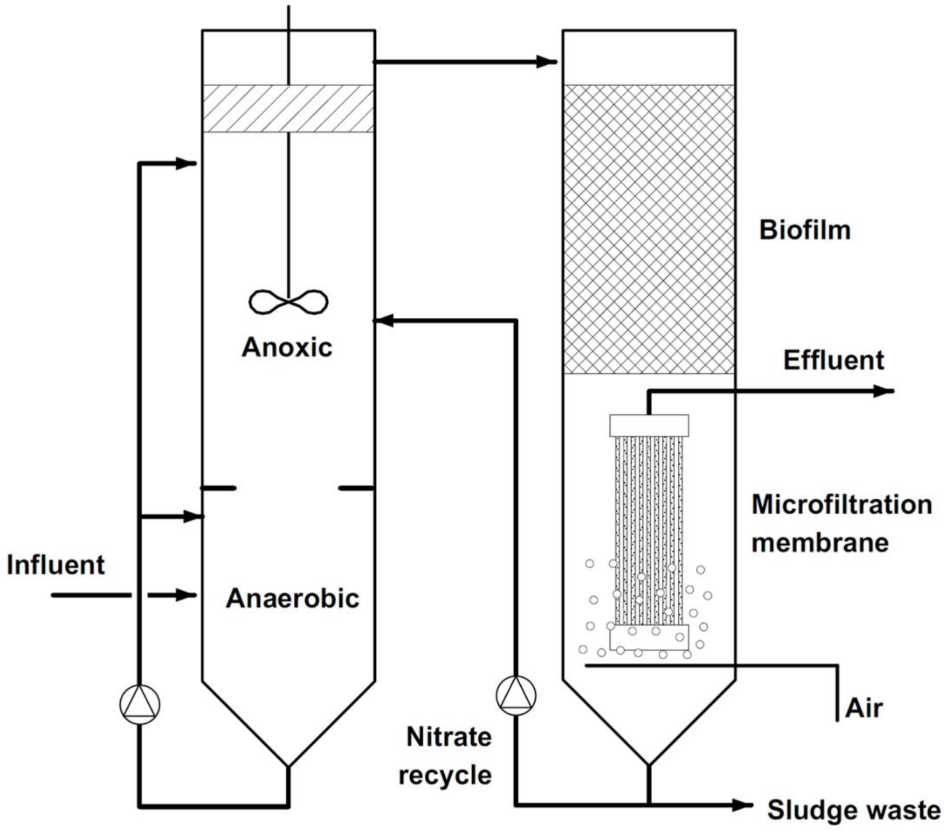


Figure 6-1 Schematic diagram of the experimental system

The 69.0 L HMBR, with internal square section of 0.20 x 0.20 m^2 and a height of 1.80 m, was partially filled with a sponge type biofilm support (polyurethane pieces of 2 x 1 x 1 cm^3) occupying 46% of the total reactor volume. A polyvinylidene difluoride (PVDF) hollow fibre microfiltration membrane module (2 m^2 filtering surface, produced by Porous Fibers, Spain) was placed underneath the biofilm bed, as described in Rodríguez-Hernández et al. (2012). An automatic backwashing was conducted using permeate water for 4 minutes every 45 minutes, according to manufacturer instructions. At the bottom of the reactor a coarse bubble air diffuser was placed. The air supply (14 L min^{-1}) was set in order to provide sufficient and continuous stirring in the membrane zone, eventually controlling membrane fouling rate. This air flowrate resulted in a bulk liquid oxygen concentration of about 5 mg L^{-1}.

6.2.2. Wastewater and operational conditions

The study was performed in a municipal wastewater treatment plant, located in Santander (North coast of Spain), with a population equivalent of about 428,000 p.e., combined sewer system and average flow of 7,668 m^3 h^{-1}. Pre-treated wastewater (coarse screen, 2-mm fine screen, grit and grease removal) was fed into the bench-scale pilot plant. The composition of the influent wastewater showed high fluctuations due to wet weather and it was characterized by high salinity as typical for coastal area with combined sewer system. The operational conditions during the experimental campaign are reported in detail in Table 6-1. The mixed liquor solids retention time (SRT) was set at 39 days through sludge wastage from the HMBR. The recirculation sequence t_{anox}/t_{anae} was set to 3 min / 9 min in order to tackle progressive sedimentation and to improve the alternation of anaerobic-anoxic conditions.

Table 6-1 Operating conditions of the AnoxAn pilot plant

		Average ± SD
Run time (day)		88
Influent flowrate Q_{in} (L h^{-1}) [a]		11.9 ± 1.7
HRT (h) [a]	Total	10.1 ± 1.9
	AnoxAn	4.2 ± 0.8
	HMBR	5.9 ± 1.1
OLR [a]	kgBOD_5 m^{-3} day^{-1}	0.59 ± 0.17
	kgCOD m^{-3} day^{-1}	0.87 ± 0.34
C/N (gCOD gTN^{-1}) [a]		10.6 ± 2.2
C/P (gCOD gTP^{-1}) [a]		89.3 ± 25.3
SRT (day) [a]		39
Internal recirculation sequence t_{anox}/t_{anae} (min min^{-1})		3 / 9
Temperature (ºC) [a]		18.0 ± 3.2

[a] not including start-up (days 1-15)

6.2.3. Analytical procedures

6.2.3.1. Analytical methods

24-h composite samples were collected two or three times a week and kept cool until laboratory analysis. The sample points were: influent wastewater, HMBR effluent, nitrate-recycle stream, and anaerobic zone, anoxic zone and effluent from the AnoxAn reactor. Total and filtered chemical oxygen demand (COD and fCOD), biochemical oxygen demand (BOD_5), total and volatile suspended solids (TSS and VSS), ammonium (NH_4), total nitrogen (TN) and total phosphorus (TP) were measured according to the Standard Methods (APHA, 2005). Ion-chromatography (761 COMPACT-IC METROHM) was used for nitrite (NO_2), nitrate (NO_3) and phosphate (PO_4). Dissolved oxygen concentration, temperature and electrical conductivity were measured using portable meters (HACH HQ40d meter with LDO101 and CDC40103 probes).

6.2.3.2. Characterization of functional microorganisms

Activated sludge grab samples were taken from the anoxic zone of the AnoxAn reactor, while biofilm samples were extracted from the biofilm support at three different locations: top, middle and bottom of the biofilm zone. The sponge pieces were immersed in phosphate buffer solution (PBS), centrifuged and strongly vortexed to extract the biofilms as in Chae et al. (2012).

Microbial activity batch tests

The biological potential activity was evaluated by means of batch tests, determining the following specific rates: (i) ammonium uptake rate (AUR) of biofilm extracts; (ii) nitrate uptake rate (NUR) and phosphate release and uptake rates (PRR and PUR) of the AnoxAn activated sludge samples. The AUR and NUR tests were performed according to Kristensen et al. (1992), while the PRR and PUR were determined as described in Wachtmeister et al. (1997). The fraction of DPAO out of PAO was also estimated using the approach proposed by Wachtmeister et al. (1997), as the ratio between the PUR under anoxic and aerobic conditions (PUR_{anox}/PUR_{aero}). A set of batch tests for each specific rate were performed during the experimental campaign.

FISH analysis

The identification and abundance of specific microorganisms present in the activated sludge samples and biofilm extracts of the reactors were analysed by fluorescent in-situ hybridization (FISH) analysis as specified by (Amann, 1995). The samples were subject to gentle sonication before fixation. Afterwards, immobilization and hybridization using selected probes were carried out. To visualize all the cells the microscope slides were counterstained with DNA stain 4', 6'-diadimino-2-phenylindol (DAPI). The target organisms were detected by the examination of their characteristic fluorescence using an epifluorescence Leiz Laborlux D microscope in combination with a digital camera Leica DCF42 and software LAS (v3.7.0) from Leica Microsystems. The probes used in this study were: Nso_1225 for ammonia oxidizing bacteria (AOB); Ntspa_662 and Nit_3 for nitrite oxidizing bacteria (NOB); Pao_462 for Accumulibacter phosphatis (PAO); and Amx_368 for anammox bacteria (anaerobic AOB). The target cells were counted to determine the fraction of FISH positive out of the total DAPI count.

6.2.3.4. Statistical analysis

Results of the performance evaluation of the pilot plant are expressed with average values and the standard deviation. Results of concentrations close to zero and removal efficiencies close to 100% are clearly skewed and do not correspond to a normal distribution, nevertheless the standard deviation was determined in order to represent the spread of the results. Regarding the results of the microbial activity batch tests and FISH analysis, statistical analysis was performed in order to assess the significance of differences between results obtained in different samples, using the single-factor analysis of variance followed by multiple comparisons by means of post hoc tests (Tukey's method when variances were equal or Games-Howell's method when variances were unequal). The Kolmogorov-Smirnov test was used to test the normality of the distributions.

6.2.4. Mass balances analysis

Mass balances analysis was performed in order to better understand the removal mechanisms of the process and to reveal some key features of the novel AnoxAn reactor, as detailed below, and according to the nomenclature reported at the end of this chapter.

The fate of organic matter in the AnoxAn reactor was determined taking into account the COD inputs and outputs. The mass of soluble COD entering the AnoxAn reactor per day is given by:

$$AnoxAn\ input\ COD = Q \cdot fCOD_{inf} + Q_{NR} \cdot fCOD_{NR} \quad (6\text{-}1)$$

Similarly, the mass of soluble COD leaving the AnoxAn reactor is accounted by:

$$AnoxAn\ output\ COD = (Q + Q_{NR}) \cdot fCOD_{AnoxAn\ eff} + M_{COD,den} + M_{COD,P} \quad (6\text{-}2)$$

This output estimation considers independent routes of organic matter consumption for denitrification and phosphate uptake. Organic matter consumption through denitrification was estimated according to the amount of nitrate reduced, while uptake for phosphorus removal was determined assuming that 10 g of soluble COD are required to remove 1 g of phosphorus (Tchobanoglous et al., 2003):

$$M_{COD,den} = NO_{denitrified} \cdot \frac{2.86}{1-1.42 \cdot Y_{obs}} \quad (6\text{-}3)$$

$$M_{COD,P} = 10 \frac{g\, fCOD}{g\, P_{removed}} \cdot Q \cdot \left(PO_{inf} - PO_{eff} - \Delta P_{assim}\right) \quad (6\text{-}4)$$

The nitrate removal efficiency in the anoxic zone was determined taking into account the nitrate recycle flowrate and concentrations as given by:

$$NO_{RE} = 100 \cdot \frac{(Q \cdot NO_{inf} + Q_{NR} \cdot NO_{NR}) - (Q + Q_{NR}) \cdot NO_{AnoxAn\, eff}}{(Q \cdot NO_{inf} + Q_{NR} \cdot NO_{NR})} \quad (6\text{-}5)$$

The extent of simultaneous nitrification and denitrification in the aerobic HMBR, expressed by the parameter SND, was determined through nitrate mass balance in the HMBR. The amount of nitrate denitrified in the HMBR is given by the difference between the theoretical amount of nitrate produced in the system (considering complete nitrification of the influent ammonium except nitrogen removal through bacterial assimilation) and the actual nitrate output from the HMBR. Then, the SND is defined as the ratio between the amount of nitrate denitrified in the HMBR and the theoretical amount of nitrate produced in the system, as given by:

$$SND = \frac{Q \cdot (NH_{inf} - \Delta N_{assim}) - (Q_{NR} \cdot NO_{NR} + Q \cdot NO_{eff})}{Q \cdot (NH_{inf} - \Delta N_{assim})} \quad (6\text{-}6)$$

An SND value of 0 indicates no occurrence of simultaneous nitrification and denitrification, while an SND of 1 indicates complete removal of nitrate in the HMBR through simultaneous nitrification and denitrification.

The amount of phosphate and nitrate consumed in the anaerobic and anoxic zones of the AnoxAn reactor were calculated through mass balances schematically represented in Figure 6-2, according to the following formulas:

$$M_{C,anae} = Q \cdot C_{inf} + Q_{mix} \cdot C_{anox} + Q_{IR} \cdot C_{anox} \cdot \frac{t_{anox}}{t_{anae} + t_{anox}} - (Q + Q_{mix}) \cdot C_{anae} - Q_{IR} \cdot C_{anae} \cdot \frac{t_{anox}}{t_{anae} + t_{anox}} \quad (6\text{-}7)$$

$$M_{C,anox} = (Q + Q_{mix}) \cdot C_{anae} + Q_{NR} \cdot C_{NR} + Q_{IR} \cdot C_{anae} \cdot \frac{t_{anox}}{t_{anae} + t_{anox}} - (Q + Q_{mix} + Q_{NR}) \cdot C_{anox} - Q_{IR} \cdot C_{anox} \cdot \frac{t_{anox}}{t_{anae} + t_{anox}} \quad (6\text{-}8)$$

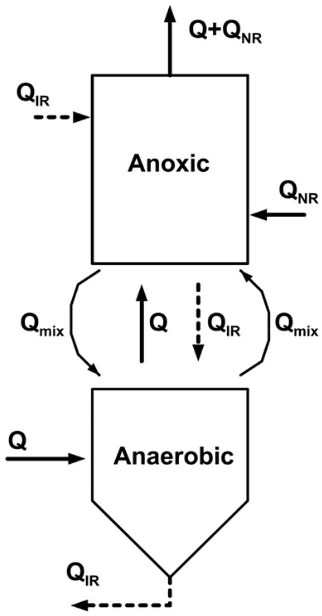


Figure 6-2 Schematic diagram indicating nutrients mass balances in the AnoxAn reactor (dashed lines corresponds to flow only during t_{anox})

A mixing current (Q_{mix}) between the anoxic and the anaerobic zones was considered in the mass balance, which has been previously identified and quantified through hydraulic characterization experiments and model simulation as described in Díez-Montero et al. (2015). The capability of the AnoxAn configuration to establish two hydraulically separated zones inside the single reactor was observed and the mixing current between both zones was estimated at 40.2% of the influent flowrate, which has been included in the present mass balances.

The sludge yield was estimated as the amount of biomass wasted through the sludge waste (including sample collection), divided by the cumulative COD removed, as given by:

$$Y_{obs} = \frac{\sum V_{waste} \cdot TSS_{waste} \cdot {}^{VSS}/_{TSS}}{\sum Q \cdot (fCOD_{inf} - fCOD_{eff}) \cdot t} \quad (6\text{-}9)$$

Nitrogen and phosphorus removal through bacterial assimilation are estimated according to Tchobanoglous et al. (2003), as given by the following formulas:

$$\Delta N_{assim} = Y_{obs} \cdot N_{biomass} \cdot (fCOD_{inf} - fCOD_{eff}) \quad (6\text{-}10)$$

$$\Delta P_{assim} = Y_{obs} \cdot P_{biomass} \cdot (fCOD_{inf} - fCOD_{eff}) \quad (6\text{-}11)$$

6.3. Results and discussion

6.3.1. Start-up and development of the anaerobic-anoxic sludge blanket

The support medium was acclimatized treating municipal wastewater in the same location before the start-up, thus a nitrifying biofilm was already developed at the beginning of the experimental campaign. On the other hand, the AnoxAn reactor was not inoculated. During the start-up, the system was fed with municipal wastewater so that the sludge blanket suspended solids concentration progressively rose, as can be observed in Figure 6-3 where TSS concentrations in the different compartments of the system are plotted. Eventually, TSS concentration up to 10 g L^{-1} was reached in the anaerobic zone and 5 g L^{-1} in the anoxic one. To achieve such sludge blanket concentrations, high mixed liquor SRT (39 days) was maintained which is not typical for EBPR even though phosphorus removal feasibility at SRT as high as 50 and 80 days has been already proved (Patel et al., 2006; Song et al., 2009; Song et al., 2010). Biological nutrient removal activity became significant after day 15, which was considered the start-up period.

Once developed the sludge blanket, TSS concentration in the anaerobic zone was considerably higher than that in the anoxic zone. This is due to the fact that the anoxic zone is fed with the recycle from the subsequent aerobic reactor, with high flowrate (approximately 3 times the influent flowrate) and lower TSS concentration than in the anaerobic zone, provoking the dilution of the sludge blanket, as by reactor design. Besides, mixing in the anoxic zone was found good enough to maintain a steady TSS concentration, while the sludge blanket in the anaerobic zone was apparently not stabilized, gradually increasing to a peak value of 10 g L^{-1} and decreasing thereafter. It could be due to the incapability of the mixing pump to prevent occasional compacting of the sludge mass. Mixing in the anaerobic zone could be improved in order to keep the sludge blanket steadily and uniformly spread in the whole zone. Finally, despite that the upper transition zone did not avoid the escape of biomass from the reactor, TSS concentration in the AnoxAn effluent was lower than those in the anaerobic and anoxic zones of the reactor, indicating that the biomass was retained to some extent.

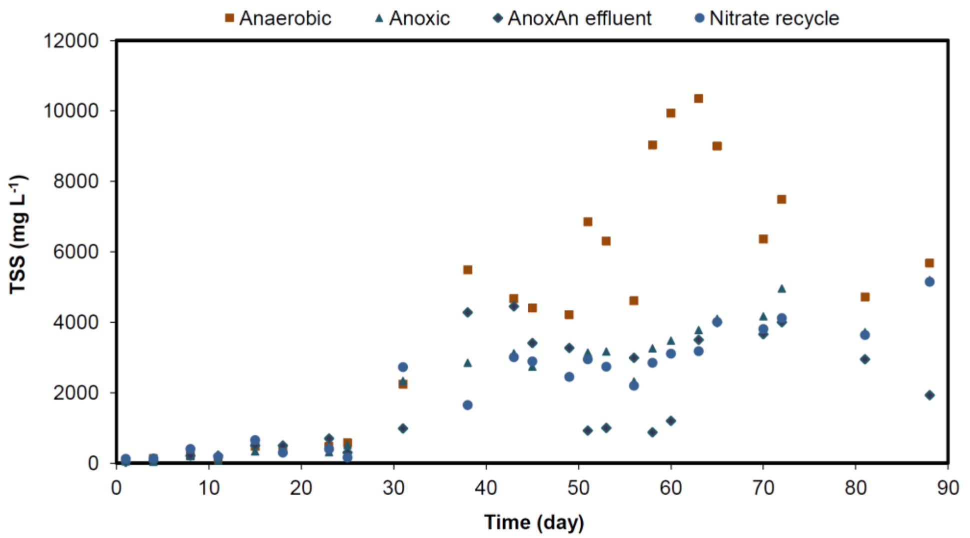


Figure 6-3 Evolution of TSS concentration during the experimental period

The observed yield (Y_{obs}) of the overall system was estimated by a solid mass balance incorporating the total biomass wasted through the sludge waste including sample collection, versus the cumulative COD removed. The observed yield was estimated at 0.25 gVSS gfCOD^{-1}, which was used for the subsequent mass balances calculations.

6.3.2. Organic carbon removal

The overall system performed steadily with reference to organic matter removal (results are summarized in Table 6-2). Influent organic load fluctuations were buffered in the system and didn't affect significantly the removal efficiencies of COD and BOD_5.

Within the AnoxAn reactor, organic matter removal to certain extent is expected due to retention of particulate substrate, consumption through denitrification and uptake during phosphate release. Nevertheless, soluble COD production by means of hydrolysis of particulate COD is expected to occur under anaerobic and anoxic conditions. The soluble COD output of the AnoxAn reactor estimated through mass balances including the effluent load, consumption for denitrification, and consumption for phosphate release, as described in section 2.4, resulted to be 1799 g m^{-3} day^{-1}, (based on the AnoxAn reactor volume). However, the soluble COD input taking into account the influent and nitrate recycle loads, resulted as low as 1218 g m^{-3} day^{-1}. It suggests that certain amount of soluble COD was produced by means of hydrolysis within the AnoxAn reactor, estimated at an average of

581 g m^{-3} day^{-1}, which corresponds to 42% of the average influent particulate COD. It has been previously reported that while good total COD balances are to be expected in aerobic reactors, systems incorporating anaerobic or anoxic zones tend to exhibit differences between COD inputs and outputs due to fermentation processes taking place in the anaerobic and anoxic zones (Barker and Dold, 1995). This feature would be beneficial for BNR, since readily biodegradable organic matter is needed for phosphate release and denitrification. This concept has been already applied in some bioreactors, for instance in the anaerobic upflow bed filter proposed by Shin et al. (2005), where hydrolysis in an anaerobic zone enhances denitrification in an anoxic bed, by means of organic acids production.

Nevertheless, the average soluble COD concentration in the AnoxAn effluent was as low as 62.0 mg L^{-1}, which is considered advantageous for feeding the subsequent aerobic HMBR in order to avoid overloading (Santamaría, 1998).

Table 6-2 Biological performance of the pilot plant, not including start-up (days 1-15)

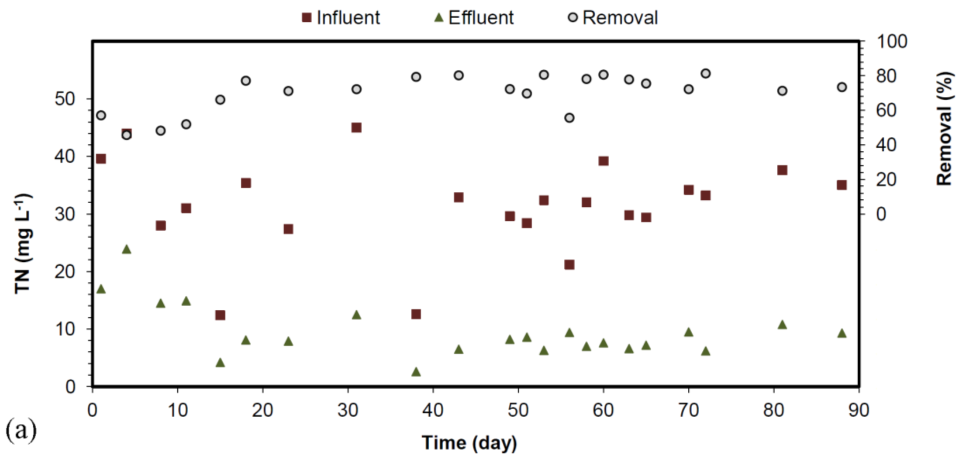
Parameter	Units	Influent[a]	Overall effluent[a]	Efficiency (%)[a,b]
COD	mg L^{-1}	351.8±123.6	40.7±28.6	88.7±8.9
fCOD	mg L^{-1}	120.1±92.9	26.1±15.8	79.9±11.7
BOD_5	mg L^{-1}	241.1±67.0	5.6±11.4	98.1±3.1
TSS	mg L^{-1}	173.5±43.5	5.9±6.7	97.7±2.2
NH_4-N	mg L^{-1}	21.9±4.6	0.3±0.6	98.6±3.2
NO_3-N	mg L^{-1}	0.3±0.0	4.1±2.1	NA
TN	mg L^{-1}	31.5±7.2	7.9±2.2	74.6±6.2
TP	mg L^{-1}	4.0±0.8	0.5±0.5	88.7±11.2

[a] Average value ± standard deviation
[b] Overall efficiency calculated as the average of sample efficiencies
NA: Not Applicable

Summarizing, the AnoxAn reactor provided a suitable effluent for feeding the subsequent nitrifying reactor, while producing partial hydrolysis of the particulate organic matter beneficial to the performance of BNR.

6.3.3. Nitrogen removal

The influent and effluent ammonium, nitrate and total nitrogen concentrations are reported in Table 6-2. Almost full nitrification was observed throughout the whole experimentation, with effluent ammonium concentration close to zero and removal efficiency close to 99%. Nitrate was reduced to an average effluent concentration of 4.1 mgN L^{-1}, providing a stable effluent TN concentration below 10 mg/L after the 15 days start-up period, as observable in Figure 6-4(a).



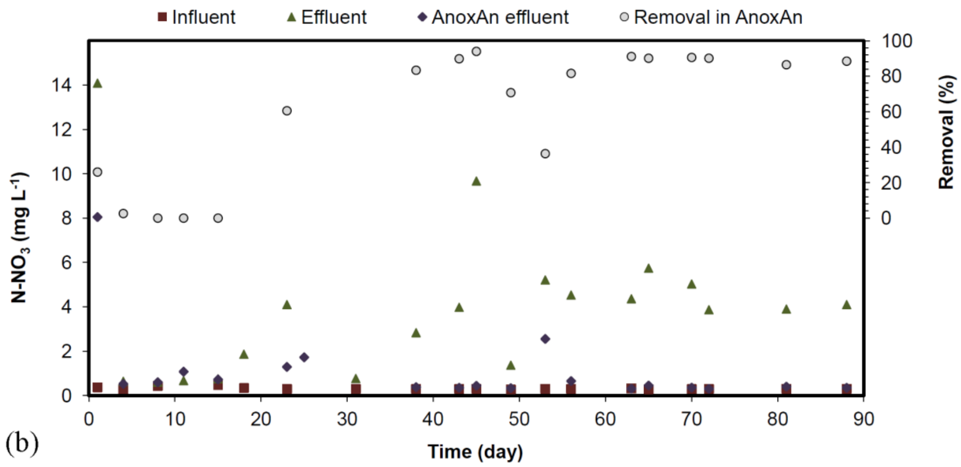


Figure 6-4 (a) Influent and effluent total nitrogen concentrations and removal efficiency in the overall system; and (b) Nitrate concentration and denitrification efficiency in the AnoxAn reactor

Nitrification is considered to be attributable to the HMBR, according to previous studies with the same HMBR setup (Rodríguez-Hernández et al., 2012). It was also confirmed through the determination of the AUR in batch tests performed with biofilm samples, which are displayed in Table 6-3. The rates resulted to be in the range 1.2-2.6 mgN $gVSS^{-1}$ h^{-1}, comparable to other studies performing successful nitrification (Kristensen et al., 1992). Additionally, nitrifying bacteria were identified in the biofilm samples through FISH analysis, confirming the presence of AOB (Nitromonas spp.) and NOB (Nitrospira spp.), as shown in Table 6-4. A significantly minor amount of both AOB and NOB was also detected in the activated sludge. The presence of anaerobic AOB (Anammox) was negligible in either the biofilm or the suspended biomass.

Table 6-3 Suspended biomass and biofilm nitrifying and denitrifying activity rates obtained from batch tests (AS: AnoxAn activated sludge; TBf: top biofilm zone; MBf: middle biofilm zone; BBf: bottom biofilm zone; NA: not analyzed)

Biological activity batch test	**Units**	**Rate [a]**				**Literature**
		AS	**TBf**	**MBf**	**BBf**	
AUR	mgN $gVSS^{-1}$ h^{-1}	NA	1.9±0.2[c]	2.6±0.1[d]	1.2±0.2[e]	1.1-9.0 [b]
NUR	mgN $gVSS^{-1}$ h^{-1}	3.5±0.8	NA	NA	NA	1.1-7.4 [b]

[a] Average value ± standard deviation
[b] Kristensen et al. (1992)
[c, d, e] Averages values with different letters presented significant differences

Denitrification was expected to occur in the AnoxAn reactor, and it actually took place therein once nitrification became steady in the aerobic reactor and the AnoxAn sludge blanket was developed. An average nitrate concentration in the AnoxAn effluent of 0.7 mgN L^{-1} was achieved. Nitrate concentrations in the influent wastewater, AnoxAn effluent and overall effluent are displayed in Figure 6-4(b), together with the nitrate removal efficiency obtained through a mass balance within the AnoxAn reactor. High denitrification efficiency was observed with an average value of 81%, in spite of some reduced efficiency scattered data, which did not undermine the effluent quality. The specific denitrification rate (SDNR) obtained with the same mass balance, considering the volume and the biomass concentration in the anoxic zone of AnoxAn, resulted in 1.9 mgN $gVSS^{-1}$ h^{-1}. Besides, the NUR obtained in the biological activity batch tests, which represent the potential rate of the AnoxAn biomass in ideal conditions for denitrification, was 3.5 mgN $gVSS^{-1}$ h^{-1} (Table 6-3).

This rate is comparable to those obtained in activated sludge nitrogen removal processes at full-scale (1.1-7.4 mgN $gVSS^{-1}$ h^{-1}) and pilot scale (3.4-4.8 mgN $gVSS^{-1}$ h^{-1}) (Kristensen et al., 1992), as summarized in Table 6-3. The high biomass concentration in the AnoxAn reactor together with this specific denitrifying biological activity account for the excellent denitrifying capability, providing almost complete denitrification with an anoxic average hydraulic retention time (HRT) of 2.7 hours.

Table 6-4 Average percentage of FISH positive out of the total DAPI count (AS: AnoxAn activated sludge; TBf: top biofilm zone; MBf: middle biofilm zone; BBf: bottom biofilm zone; ND: not detected)

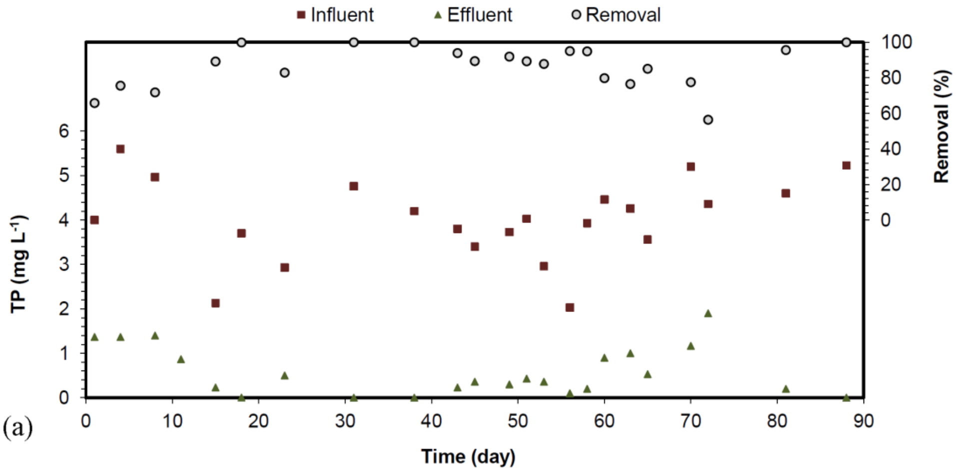
Probe	**Target organisms**	**Sample**			
		AS	**TBf**	**MBf**	**BBf**
Nso_1225	AOB *(Nitromonas spp.)*	0.12^{a}	1.39^{b}	1.45^{b}	0.91^{c}
Ntspa_662	NOB *(Nitrospira spp.)*	0.12^{a}	0.36^{b}	0.27^{b}	0.66^{c}
Nit_3	NOB *(Nitrobacter spp.)*	ND	ND	ND	ND
Pao_462	PAO *(Accumulibacter phosphatis)*	4.1	ND	ND	ND
Amx_368	Anaerobic AOB *(Anammox)*	ND	ND	ND	ND

$^{a, b, c}$ Averages values with different letters presented significant differences

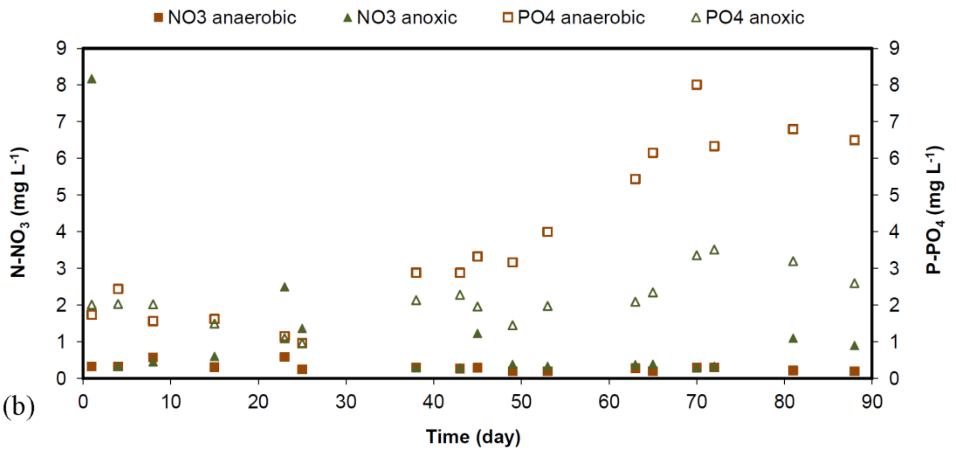
Simultaneous nitrification and denitrification in the HMBR could contribute to the overall nitrogen removal, but it was considered to occur to a minor extent since better conditions for denitrification were provided in the AnoxAn reactor. Nevertheless, in order to confirm the reduced extent of simultaneous nitrification and denitrification in the HMBR, the SND ratio was calculated, taking into account the experimental Y_{obs} (0.25 gVSS $gfCOD^{-1}$) and the average nitrogen content of bacteria of 0.12 gN $gVSS^{-1}$ (Tchobanoglous et al., 2003). The average SND resulted in 0.13. This indicates that only 13% of the potential nitrate produced was not recirculated to the AnoxAn reactor, confirming minor involvement of the HMBR in nitrate removal through simultaneous nitrification and denitrification.

6.3.4. Phosphorus removal

Total phosphorous (TP) removal evolution during the whole period is presented in Figure 6-5(a). Similarly to denitrification, stable and satisfactory removal efficiency was achieved once the AnoxAn sludge blanket was developed. The average TP removal efficiency was 89%, producing an effluent TP concentration below 1 mg L^{-1}.



(a)



(b)

Figure 6-5 (a) Influent and effluent TP concentration and overall removal efficiency; and (b) Nitrate and phosphate concentration within the two zones (anaerobic and anoxic) of the AnoxAn reactor

Phosphorus removal through bacterial assimilation (ΔP_{assim}) taking into account the experimental Y_{obs} (0.25 gVSS gfCOD^{-1}) and the average phosphorus content of bacteria of 0.02 gP gVSS^{-1} (Tchobanoglous et al., 2003), resulted in 0.5 mgP L^{-1}.

Compared to the average phosphorus removal, this indicates an average contribution of phosphorus assimilation of only 15%, thus confirming the occurrence of EBPR and indicating the important role EBPR played in the overall phosphorus removal. Phosphate release in the anaerobic zone followed and increasing trend during the experimental period, as observable in Figure 6-5(b) in which the content evolution of nitrate and phosphate in the two zones of AnoxAn are plotted. It appears that significant EBPR activity came up from day 40 and was stabilized since day 60.

The evolution of the PAO and DPAO biological activities along the experimental period was measured through batch tests, as summarized in Table 6-5. The phosphate release and uptake rates (PRR and PUR) obtained in batch tests represent the potential activity of the AnoxAn sludge in ideal conditions to biologically remove phosphorus (Wachtmeister et al., 1997). Regarding phosphate release, the rate increased during the experimental period, achieving a PRR of 3.18 mgP-PO_4 $gVSS^{-1}$ h^{-1} at the end of the experimentation. The resulting PRR was slightly lower than the ones obtained in other investigations with full and pilot scale activated sludge BNR processes, as summarized in Table 6-5. Such result could be attributed to the lack of primary sedimentation, allowing the entrance of particulate organic matter to the reactor and the long SRT of the system (39 days), reducing the removal of particulate organic matter as well as the products of biomass lysis and decay from the reactor. These conditions entail an increase of the actual VSS concentration, and hence a reduction of the biological activity rates. Eventually, the high biomass concentration in the AnoxAn sludge blanket compared to conventional activated sludge (about 3 g L^{-1}) may explain the satisfactory phosphorus removal efficiencies observed, despite the relatively low biomass activity.

Regarding phosphate uptake, the PUR under aerobic conditions (PUR_{aero}) increased more than five times after 75 days, achieving 10.74 mgP-PO_4 $gVSS^{-1}$ h^{-1}. This accounts for an increasing EBPR activity throughout the pilot plant operation, thus confirming the aforementioned observations based on the extent of phosphate release in the anaerobic zone. The measured DPAO phosphate uptake activity was lower than that of PAO, as expected. The rate of phosphate uptake under anoxic conditions is generally lower than under aerobic conditions, considering that there are two different groups of PAO: (i) DPAO, which possesses the ability to use nitrate and/or nitrite as an electron acceptor for P removal instead of oxygen, and (ii) non-DPAO (Oehmen et al., 2007). The PUR under anoxic conditions (PUR_{anox}) also increased throughout the experimental run from 0.60 to 4.58 mgP-PO_4 $gVSS^{-1}$ h^{-1}. The DPAO fraction (PUR_{anox}/PUR_{aero}) varied along the experimental period, however this variation did not show a clear trend, suggesting that in spite of the increasing EBPR activity, the DPAO fraction was neither promoted nor hampered over time.

The resulting fractions fluctuated around an average value of 49%, which appears to be comparable with typical DPAO fractions in conventional EBPR systems, as shown in Table 6-5. This indicates the ability of the AnoxAn sludge to simultaneously denitrify and uptake phosphorus under the ideal conditions of the batch tests, i.e. no limiting nitrate and negligible readily biodegradable organic matter.

Table 6-5 Evolution of PAO and denitrifying PAO activity along the experimental period

Parameter	Units	Day 15	Day 40	Day 65	Day 90	Literature
PRR	mgP-PO_4 gVSS^{-1} h^{-1}	1.04	1.13	2.88	3.18	3.97-20.9 [a]
PUR_{aero}	mgP-PO_4 gVSS^{-1} h^{-1}	1.85	2.44	6.96	10.74	3.62-19.2 [b]
PUR_{anox}	mgP-PO_4 gVSS^{-1} h^{-1}	0.60	1.69	3.64	4.58	1.2-6.0 [c]
%DPAO	%	32	69	52	43	12-50 [d]

[a] Tykesson et al. (2005); Tykesson et al. (2006); Puig et al. (2008); Monclús et al. (2010); Kapagiannidis et al. (2009); López-Vázquez et al. (2008); Kuba et al. (1997)

[b] Puig et al. (2008); Monclús et al. (2010); Wang et al. (2009); Kapiagiannidis et al. (2009); López-Vázquez et al. (2008); Kuba et al. (1997)

[c] Monclús et al. (2010); Wang et al. (2009); Kapiagiannidis et al. (2009); López-Vázquez et al. (2008); Kuba et al. (1997); Meinhold et al. (1998)

[d] Monclús et al. (2010); Wang et al. (2009); Kapiagiannidis et al. (2009); López-Vázquez et al. (2008); Kuba et al. (1997)

However, under the conditions of the present study, simultaneous denitrification and phosphate uptake by means of DPAO did not achieve the desired phosphorus removal efficiency. It can be observed in Figure 6-5(b) how nitrate was depleted in the anoxic zone, because of the denitrification activity, while phosphate was not fully taken up. The phosphate concentration in the anoxic zone was kept between 2.0 and 3.5 mgP L^{-1} during the last 25 days. This entails that the aerobic stage was necessary to complete the phosphate uptake. The operation of AnoxAn, allowing the escape of certain amount of biomass resulted essential for the achievement of such low overall effluent TP concentration.

PAO population, detected by FISH analysis on activated sludge samples of the anoxic zone of AnoxAn was estimated as 4.1% of the total cells (Table 6-4). Such percentage of PAO was low compared to those obtained at full-scale EBPR activated sludge plants (5.7 to 20%), as reported by Saunders et al. (2003); Tykesson et al. (2006); López-Vázquez et al. (2007); and López-Vázquez et al. (2008). This result is consistent with the aforementioned PRR and is attributed to the long SRT of the system, taking into account that the determination of the total amount of cells by DAPI includes all DNA present in the sludge sample.

6.3.5. Fate of nutrients in the AnoxAn reactor

Phosphate and nitrate mass balances were performed in the anaerobic and anoxic zones in order to analyze the fate of nutrients in the AnoxAn reactor and to better understand the removal mechanisms carried out in each zone. The mass balances are schematically represented in Figure 6-2 and were based on experimental data of the influent, anaerobic and anoxic zones, and nitrate recycle characteristics. The internal recycle Ax/An was also considered in the mass balance, as well as a mixing current between the anoxic and the anaerobic zones as described in section 2.4. The average nutrient removals obtained through the mass balances have been divided by the influent flowrate in order to be expressed as concentration.

The resulting equivalent concentrations are depicted in Figure 6-6. Phosphate release in the anaerobic zone achieved an equivalent concentration of 8.0 mgP L^{-1}, while phosphate uptake in the anoxic zone resulted negligible (< 0.1 mgP L^{-1}). This corroborates the occurrence of EBPR and the inability of DPAO to achieve the desired phosphate effluent concentration, under the conditions of the present study. In addition, this result supports the assumption of independent routes of organic matter consumption for phosphate uptake and denitrification, used for the evaluation of the fate of organic matter within the AnoxAn reactor, as explained in section 2.4.

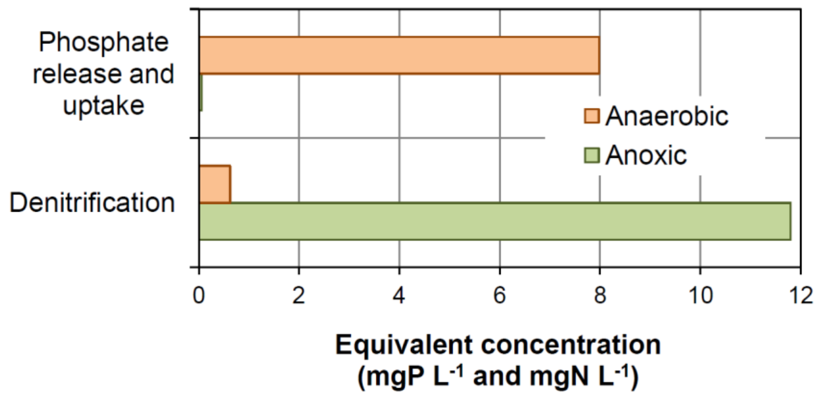


Figure 6-6 Nutrients uptake and release in the anaerobic and anoxic zones, expressed as equivalent concentrations based on the influent flowrate

Despite the DPAO potential activity evaluated through batch tests, the net phosphate uptake under anoxic conditions resulted negligible. This was attributed to the competition for nitrate of conventional denitrifying heterotrophs and DPAO. The influent wastewater characteristics, with no limiting organic matter availability (C/N > 10 gCOD gN^{-1} and C/P > 80 gCOD gTP^{-1}), led to a relatively low nitrate loading to the anoxic zone, where the limited exposure of organisms to nitrate possibly could have hindered anoxic phosphate uptake (Barker and Dold, 1996). Another possible explanation is the overlapping activities of DPAO and PAO in the anoxic zone as explained by Meinhold et al. (1998). DPAO are responsible for anoxic phosphate uptake while phosphate release occurs under anoxic conditions due to the non-denitrifying PAO if there is organic matter availability.

The negligible net phosphate uptake under anoxic conditions did not result detrimental for the overall TP removal efficiency, since the aerobic period proved to be long enough to complete the phosphate uptake. This indicates that the AnoxAn operation, allowing the escape of certain amount of biomass, entails high flexibility to treat wastewaters with different characteristics, specifically C/N ratio, although it still requires evaluation and optimization of the process. The ability of the AnoxAn setup to promote DPAO activity would be crucial for the treatment of low C/N ratio wastewaters, with limiting organic matter availability for both nitrogen and phosphorus biological removal. Further research is needed addressing this aspect.

Regarding nitrate mass balances, nitrate removal based on the influent flowrate was estimated at 11.8 mgN L^{-1} and 0.6 mgN L^{-1} in the anoxic and anaerobic zones, respectively. Only 5% of the nitrate entering the AnoxAn reactor was removed in the anaerobic zone, thus confirming the different biological role of the two zones as well as the hydraulic separation between the anoxic and the anaerobic zones of AnoxAn.

6.4. Conclusions

A novel upflow anaerobic-anoxic sludge blanket reactor, AnoxAn, was tested at pilot scale treating municipal wastewater in order to evaluate its performance for BNR, coupled with an aerobic HMBR. The AnoxAn sludge blanket was developed, while maintaining separate anoxic and anaerobic conditions in the single reactor. Such multi-environment allowed performing several functions with an HRT of 4.2 hours: biomass retention, achieving TSS concentration up to 10 g L^{-1}; hydrolysis of influent particulate organic matter, which could boost BNR processes; phosphate release with an anaerobic HRT of 1.1 hours; and nearly complete denitrification with an anoxic HRT of 2.7 hours.

Mass balances nomenclature

C_{anae} = Anaerobic zone nutrient concentration (mg L^{-1})

C_{anox} = Anoxic zone nutrient concentration (mg L^{-1})

C_{inf} = Influent nutrient concentration (mg L^{-1})

C_{NR} = Nutrient concentration in the nitrate recycle (mg L^{-1})

ΔN_{assim} = Nitrogen assimilated for biomass synthesis (mgN L^{-1})

ΔP_{assim} = Phosphate assimilated for biomass synthesis (mgP L^{-1})

$fCOD_{AnoxAn\ eff}$ = AnoxAn effluent soluble COD (mg L^{-1})

$fCOD_{eff}$ = Effluent soluble COD (mg L^{-1})

$fCOD_{inf}$ = Influent soluble COD (mg L^{-1})

$fCOD_{NR}$ = Soluble COD in the nitrate recycle (mg L^{-1})

$M_{C,anae}$ = Mass of nutrients consumed in the anaerobic zone (mg day^{-1})

$M_{C,anox}$ = Mass of nutrients consumed in the anoxic zone (gm day^{-1})

$M_{COD,den}$ = Mass of soluble COD consumed for denitrification (mg day^{-1})

$M_{COD,P}$ = Mass of soluble COD consumed for phosphorus removal (mg day^{-1})

$N_{biomass}$ = Average nitrogen content of bacteria (gN $gVSS^{-1}$)

NH_{inf} = Influent ammonium (mgN L^{-1})

$NO_{AnoxAn\ eff}$ = AnoxAn effluent nitrate (mgN L^{-1})

$NO_{denitrified}$ = Mass of nitrate denitrified in the AnoxAn reactor (mgN day^{-1})

NO_{eff} = Effluent nitrate (mgN L^{-1})

NO_{inf} = Influent nitrate (mgN L^{-1})

NO_{NR} = Nitrate in the nitrate recycle (mgN L^{-1})

NO_{RE} = Nitrate removal efficiency within the AnoxAn reactor (%)

$P_{biomass}$ = Average phosphorus content of bacteria (gP $gVSS^{-1}$)

PO_{eff} = Effluent phosphate (mgP L^{-1})

PO_{inf} = Influent phosphate (mgP L^{-1})

Q = Influent flowrate (L day^{-1})

Q_{IR} = Internal recycle flowrate (L day^{-1})

Q_{mix} = Mixing current between anoxic and anaerobic zones (L day^{-1})

Q_{NR} = Nitrate recycle flowrate (L day^{-1})

SND = Simultaneous nitrification and denitrification ratio

t = Time span between consecutive sample collection and analysis (day)

TSS_{waste} = Total suspended solids of each sludge waste including sample collection (mg L^{-1})

VSS/TSS = Ratio VSS to TSS

V_{waste} = Volume of each sludge waste and sample collection (L)

Y_{obs} = Observed sludge yield (gVSS $gfCOD^{-1}$)

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Chapter 7

Model-based evaluation of an anaerobic-anoxic primary clarifier for a trickling filter facility upgrade to biological nutrient removal

Part of this chapter is under revision as:

Díez-Montero, R.; Casao, M.; Tejero, I. Model-based evaluation of a trickling filter facility upgrade to biological nutrient removal. Submitted to Water Environ Res (2015)

7.1. Introduction

Nitrogen and phosphorus are the main nutrient elements discharged along with wastewaters, whose presence in the receiving water bodies is a contributor to eutrophication. The need for nutrient removal is pursued by stringent regulation for the protection of water bodies, such as Directive 91/271/EEC in Europe. In addition, due to the reviews of the water quality objectives, there are an increased number of areas being declared as sensitive to eutrophication which therefore require nitrogen and phosphorus removal from wastewater before it is discharged into such areas. This fact implicates a need for upgrades or retrofits for a great number of wastewater treatment plants (WWTP) for nutrient removal or recovery. Conventional configurations for biological nutrient removal (BNR) require anaerobic and anoxic compartments, in addition to aerobic ones which must be large enough to establish nitrification. This results in a large increase in complexity of wastewater treatment configurations when compared to those needed for organic matter removal only.

Facilities based on trickling filters have been widely used in many countries for organic matter removal. The benefits inherent to the trickling filter process comprise operational simplicity, resistance to toxic and shock loads, and low energy requirements (Daigger and Boltz, 2011). Therefore, these features make trickling filter facilities suitable for small and medium-sized communities, as is the case presented in this chapter. Many trickling filter facilities have been upgraded because they have become undersized due to increasing influent loadings, and were therefore upgraded by incorporating suspended growth reactors, realizing combined or coupled processes, such as the trickling filter/solids contact (TF/SC) and the roughing filter/activated sludge (RF/AS). However, most of those processes face only organic matter removal and in some cases nitrification, but seldom total nitrogen or phosphorus removal (Harrison et al., 1984; Harrison and Lum, 1994; Harrison, 2014). Parker et al. (1998) proposed and tested a TF/SC process to achieve organic matter removal and nitrification, while phosphorus removal was carried out by means of chemical precipitation.

For total nitrogen removal, facilities must also be upgraded for denitrification, which can be achieved by means of pre or post-anoxic suspended growth or biofilm reactors (Mehlhart, 1994). For pre-anoxic suspended growth denitrification, an intermediate settling tank is usually required between the anoxic reactor and the trickling filter, while for post-anoxic denitrification, an additional carbon source is usually required. Dai et al. (2013) integrated pre-anoxic denitrification in a primary settling tank to enhance nitrogen removal in a trickling filter facility. By recycling the nitrified effluent from the trickling filter to the primary settling tank, an improvement of nitrogen removal was achieved through denitrification in the activated settling tank. Furthermore, Vanhooren et al. (2003) observed that at high organic loading rates with insufficient oxygen supply to the biofilm, denitrification could be induced in trickling filters by providing the biofilm with external nitrate. Indeed, several full-scale case studies have been reported in literature using trickling filters for denitrification. In some cases the trickling filters were covered and the aeration openings were impounded (Dorias and Baumann, 1994), or the trickling filters were flooded (Nasr et al., 2000), to provide anoxic conditions for denitrification.

However, additional anaerobic tanks are needed for enhanced biological phosphorus removal (EBPR). Moreover, alternate anaerobic-aerobic/anoxic conditions are required to promote the growth of phosphate accumulating organisms (PAO), responsible of EBPR, which is more difficult to achieve in biofilm than in suspended growth systems. Few studies have been found which address both nitrogen and phosphorus biological removal at full-scale trickling filter facilities. Most of them have proposed the extension of the trickling filter process with additional anaerobic, anoxic and aerobic activated sludge tanks (Christensen, 1991; Morgan et al., 1999) or converting the trickling filters into suspended growth reactors (Dichtl et al., 1994). A different scheme was implemented at the Daspoort Wastewater Treatment Plant, South Africa, where an existing trickling filter process was integrated with a BNR activated sludge system according to the external nitrification BNR activated sludge system (ENBNRAS) (Muller et al., 2004; Muller et al., 2006).

In the case study hereby presented, the objective of the upgrading is to achieve nitrogen and phosphorus effluent standards, and the main constraint for the process selection is the limited available space. It should be also considered that the WWTP serves a medium-sized community of less than 20,000 inhabitants, so that alternatives involving low investment and operating costs will be prioritized. In this framework, several alternatives have been analyzed and the proposed configuration consists of a modification of the existing primary clarifier to host an anaerobic-anoxic sludge blanket reactor. The main goals of this alternative are to achieve BNR (i.e. no need for chemicals and low sludge production) and to reuse the existing facilities (i.e. no need for construction of new tanks or reactors). However, in spite of the apparent suitability of such a process, there are no full-scale examples of this configuration. A model-based approach is proposed for the feasibility evaluation and preliminary design of the facility upgrade. The capabilities of mathematical models for assessing and comparing different alternatives have proven their usefulness to make decisions about existing facilities' retrofits (Hvala et al., 2002). In addition, model simulations have been shown to be useful for design, optimization and upgrading of WWTP, aiding to estimate the optimal design configuration, reactor sizes and operational parameters, and providing an estimation of the expected response (Daigger and Nolasco, 1995; Salem et al., 2002; Seco et al., 2004). Furthermore, modelling is of particular interest in BNR processes due to the large number of interacting phenomena. Therefore, it has been considered a useful tool for the case study hereby presented.

The objective of this study is to assess the feasibility and to preliminarily design and optimize a novel process for the retrofit of an existing trickling filter WWTP for nutrient removal, by means of mathematical model simulations. The configuration of this novel process consists of an anaerobic-anoxic sludge blanket reactor hosted in the primary clarifier, followed by the existing trickling filters and clarifiers.

7.2. Materials and methods

7.2.1. Case study

The existing WWTP began operations in 2005. It serves a Spanish community with a population of approximately 15,000 inhabitants, discharging into the Ebro river basin. The wastewater treatment scheme, consisting of a two-stage trickling filter process with intermediate clarification, is shown in Figure 7-1. The process consists of preliminary treatment (5-mm screening and grit removal), primary clarification, first stage trickling filter, intermediate clarification, second stage trickling filter and secondary clarification. The trickling filters are filled with a random plastic media type (specific surface area 100 m^2 m^{-3}; void space 95%), occupying a volume of 3,181 m^3 in each filter. The three clarifiers (primary, intermediate and secondary) are identical, with an individual volume of 1,823 m^3.

The influent and effluent available data are summarized in Table 7-1. These values were obtained from the operation of the WWTP during 2013. Satisfactory organic matter removal and nitrification were achieved, while denitrification and phosphorus removal did not occur. The new discharge permit will require both nitrogen and phosphorus removal with an annual average effluent TN and TP concentration of 15 mg L^{-1} and 2 mg L^{-1}, respectively.

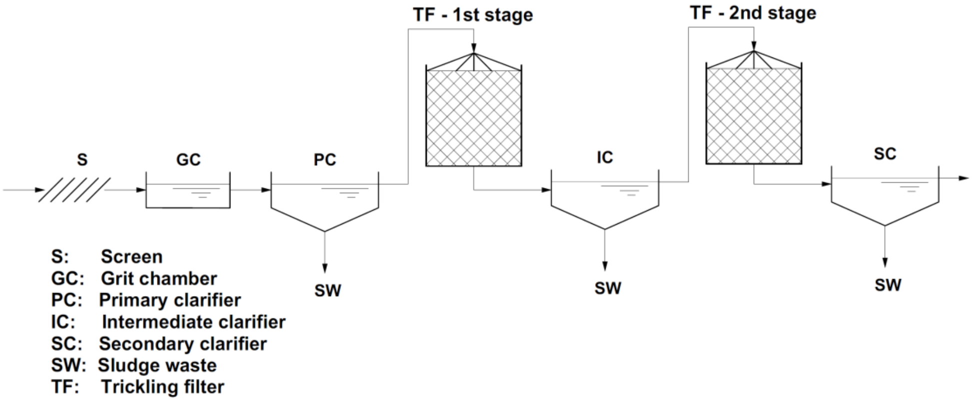

Figure 7-1 Wastewater treatment scheme of the current WWTP

Table 7-1 Current WWTP influent and effluent flow and concentrations (year 2013)

	Influent	Effluent
Flow rate (m^3 day^{-1})	5239	
Total COD (mg L^{-1})	524	43
Soluble COD (mg L^{-1})	204	32
TN (mg L^{-1})	37.3	24.7
NH_4-N (mg L^{-1})	21	0.6
NO_3-N (mg L^{-1})	0.1	21.3
NO_2-N (mg L^{-1})	0.0	0.4
TP (mg L^{-1})	4.7	3.2
TSS (mg L^{-1})	267	7

COD = Chemical Oxygen Demand; TN = Total Nitrogen;
TP = Total Phosphorus; TSS = Total Suspended Solids

7.2.2. Process selection and description

A number of alternatives were proposed and analyzed in order to upgrade the existing facility for nutrient removal. The first alternative, comprising of post-anoxic denitrification in biofilters and chemical precipitation of phosphorus, corresponds to conventional and consolidated technology and makes it possible to reach a good quality effluent. However, the main drawbacks of this alternative are the implementation of an additional post-treatment, and the need for an external carbon source and chemical addition for denitrification and phosphorus precipitation, respectively.

Several alternative technologies were proposed, such as pre-anoxic denitrification in the first trickling filter or pre-anoxic denitrification in the primary clarifier. Those alternatives do not require an external carbon source addition and do not imply the construction of new tanks or reactors for nitrogen removal, while phosphorus should be removed by chemical precipitation. In order to avoid the need for chemicals, EBPR must be carried out, providing the alternate anaerobic-aerobic/anoxic conditions required to promote the growth of PAO. Thus, a plant extension including anaerobic suspended growth reactors is required, which could imply a major renovation of the existing plant.

In this case study, the ultimate alternative proposed is based on the reuse of the existing primary clarifier to accommodate an anaerobic-anoxic sludge blanket reactor, as depicted in Figure 7-2(a). The overall treatment scheme proposed, (shown in Figure 7-2(b)), claims that both nitrogen and phosphorus biological removal using the existing facilities avoids the construction of new tanks or reactors, and does not require an external carbon source or the addition of chemicals. At first glance, the primary clarifier volume, with an average hydraulic retention time (HRT) of 8.4 hours, seems to be large enough for the anaerobic and anoxic zones. The anaerobic-anoxic modified primary clarifier would provide the environmental conditions needed for phosphate release and denitrification (with the corresponding organic matter removal), while the existing trickling filters would provide the aerobic stage for the removal of remaining organic matter, phosphate uptake and nitrification. Mainly, the first trickling filter is aimed at organic matter removal and phosphate uptake operating as a hybrid process (biofilm and suspended biomass coexisting in the same reactor), while the second filter is aimed at nitrification. Coupling the existing trickling filters with a suspended biomass reactor (the original primary settling tank) leads to an integrated process. It has the additional advantage of enabling separate control of both the slower-growing nitrifying biomass, which usually prefers to reside on biofilms, and the faster-growing heterotrophic biomass including denitrifiers and PAO, which would reside in the suspended activated sludge. This feature facilitates the optimization of simultaneous nitrogen and phosphorus removal processes (Onnis-Hayden et al., 2011).

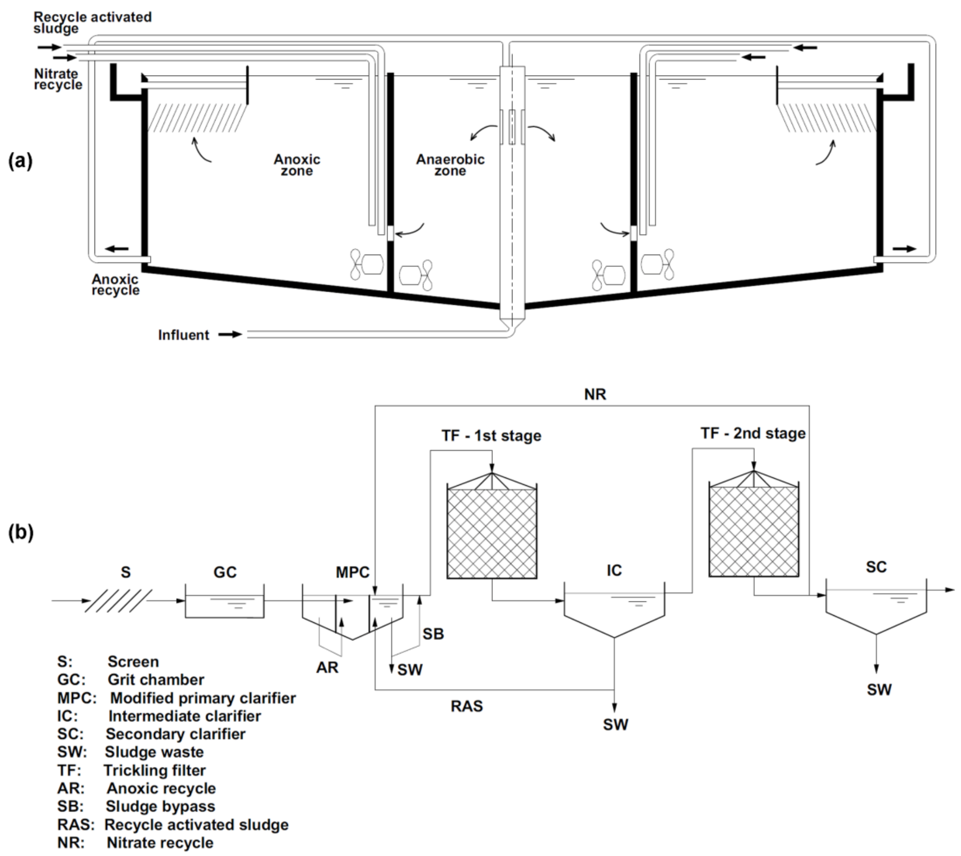

Figure 7-2 (a) Primary settling tank modification for anaerobic-anoxic sludge blanket reactor, and (b) Wastewater treatment scheme of the WWTP upgrading for BNR

The modification of the primary clarifier is based on an anaerobic-anoxic sludge blanket reactor for BNR, named AnoxAn, which was proposed by Tejero et al. (2010). The AnoxAn reactor was conceived with the objective of unifying the anaerobic and anoxic zones of a wastewater treatment process for BNR in a single reactor, aimed at achieving high compactness and efficiency. A clarification zone at the top of the reactor avoids the escape of large amounts of biomass, thus promoting high sludge concentration in a sludge blanket type reactor. Moreover, simultaneous denitrification and phosphate uptake could be achieved. Overall, the AnoxAn configuration claims anaerobic phosphate release, anoxic denitrification and phosphate uptake in a single reactor. The feasibility of the desired hydraulic behavior was assessed in an upflow AnoxAn prototype (Díez-Montero et al., 2015). However, due to the shape and dimensions of the primary clarifier in this case study (26 m diameter and 3.0 m depth), a concentric configuration was proposed instead of a vertically compartmentalized upflow reactor. The primary clarifier modification can be materialized by means of a cylindrical wall dividing the clarifier into two different zones: (i) central anaerobic zone with a volume of 800 m^3, and (ii) outer anoxic zone with a volume of 1,013 m^3. The influent wastewater is fed into the anaerobic zone, where it is mixed with activated sludge recycled from the anoxic zone (AR). A submersible mixer would provide mixing in the anaerobic zone, and the mixed liquor would flow to the anoxic zone through openings in the cylindrical wall. A nitrate rich stream (NR) recycled from the second stage trickling filter would enter the anoxic zone together with the sludge recycled from the intermediate clarifier (RAS), where submersible mixers provide intermittent mixing. The effluent would then be withdrawn through submerged outlet tubes. Underneath the outlet tubes, a set of lamellas would be assembled to provide a final clarification zone. The intermittent mixing in the anoxic zone would therefore cause settling cycles, reducing the amount of biomass escaping from the modified clarifier. The biomass will alternate anaerobic and anoxic environmental conditions, so that denitrifying PAO would be promoted. Furthermore, a certain amount of activated sludge would be bypassed (SB) from the anoxic zone to the first stage trickling filter in order to provide aerobic conditions to the PAO and enhance the phosphorus removal efficiency. Finally, the inclusion of an aerobic zone in the modified primary clarifier (MPC) has also been considered, correspondingly reducing the available anoxic volume. This additional aerobic volume would be needed to improve the EBPR and to achieve the desired phosphorus removal efficiency. The aeration could be performed in a specific volume of the anoxic zone, by means of submerged air diffusers, therefore reducing the actual anoxic volume. Besides, aeration could be carried out continuously or intermittently, depending on the oxygen demand.

7.2.3. Mathematical model

In order to assess the feasibility of the process and to preliminarily design and optimize the upgrading of the facility, mathematical model simulations were carried out. A model of the current WWTP was implemented in BioWin Process Simulator v4.0 (EnviroSim Associates Ltd., Ontario, Canada), as shown in Figure 7-3. All of the biological processes have been described according to the default BioWin General Model (ASDM) and the default model parameters and values. The settling tanks have been implemented as ideal clarifiers. Steady-state simulation results have been compared with the operational results of the WWTP during 2013. Some model parameters have been adjusted in order to improve the fit between predicted (simulations) and observed (current WWTP operating performance) results. Subsequently, the model has been modified to represent the proposed upgrade for BNR, as shown in Figure 7-3, while the model parameters have been unchanged. The primary clarifier was divided into two chambers to host the anaerobic and anoxic zones, or three chambers to host anaerobic, anoxic and additional aerobic zones. A final settling tank has been included at the end of the MPC, to consider the clarification zone. The AR from the anoxic to the anaerobic zone and the NR from the second stage trickling filter to the anoxic zone were set to 2 and 3 times the influent flowrate, respectively, while the RAS from the intermediate clarifier to the anoxic zone flowrate was set equal to the SB. The waste activated sludge in the simulations were adjusted in order to achieve suitable biomass concentration in the MPC, compared to conventional activated sludge systems, not exceeding TSS concentration of approximately 3 g L^{-1}. The biomass concentration in the MPC was kept fairly similar in all the simulations, making a comparison between the different analyzed scenarios possible. A set of steady-state simulations have been performed covering a range of different configurations and operational conditions: Run001-Run011 for different SB; Run101-Run188 for different combinations of additional aerobic volume and SB; and Run201-Run207 for different dissolved oxygen (DO) concentration in the additional aerobic zone.

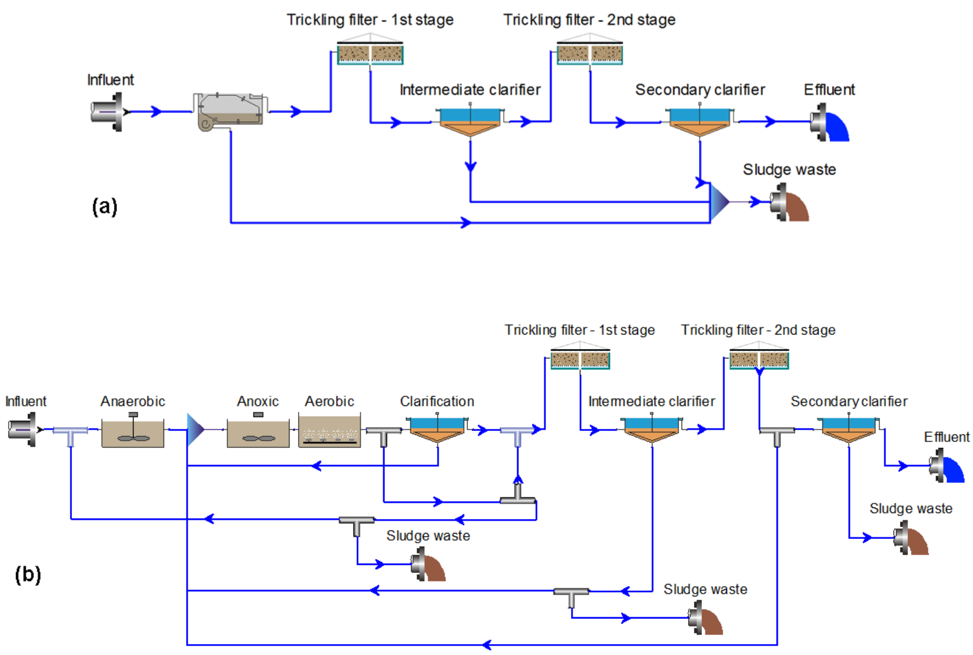

Figure 7-3 BioWin flowsheet of: (a) the current WWTP; and (b) the modified treatment train for BNR

7.3. Results and discussion

7.3.1. Current WWTP performance simulation

The steady-state effluent quality predicted by the model with the default values of the model parameters was slightly better compared to the effluent quality observed during operation in 2013. A few model parameters needed to be adjusted in order to better represent the real plant behavior. The model nitrifying and denitrifying activities and the biological phosphate uptake were reduced by means of model parameters adjustment, as shown in Table 7-2, avoiding overly optimistic simulation results.

Table 7-2 Model parameters adjustment

Model Parameter	Default value	Adjusted
OHO anoxic yield	0.54	0.90
P in biomass AOB, NOB, OHO (mgP $mgCOD^{-1}$)	0.022	0.012
P in endogenous residue (mgP $mgCOD^{-1}$)	0.022	0.012
AOB maximum specific growth rate μ (d^{-1})	0.9	0.5
AOB half-saturation coefficient K_N (mgN L^{-1})	0.7	1.0

OHO = Ordinary Heterotrophic Organisms
AOB = Ammonia Oxidizing Bacteria
NOB = Nitrite Oxidizing Bacteria

7.3.2. Anaerobic-anoxic modified primary clarifier and influence of the sludge bypass

The overall effluent quality obtained with the modified treatment train is displayed in Table 7-3, along with the MPC effluent nitrate concentration and the TSS concentration in the hybrid trickling filter, and in the anaerobic and anoxic zones of the MPC. The simulated SB, expressed as a percentage of the influent flowrate, covered a range from 0 to 50%. Satisfactory nitrogen removal was achieved with effluent TN concentration lower than 15 mgN L^{-1} in all of the simulated scenarios. Nitrate concentration in the MPC effluent resulted to be negligible (< 0.1 mgN L^{-1}), confirming that pre-anoxic denitrification performed successfully in the MPC, which could be attributed to a sufficiently high anoxic HRT (4.7 h) with moderate suspended sludge concentration (up to 2,869 mgTSS L^{-1}). However, increasing the bypass of biomass from the anoxic zone to the first stage trickling resulted in an increase of the effluent TN concentration. Effluent ammonium concentration rose from 2.9 mgN L^{-1} (Run001) to 6.6 mgN L^{-1} (Run011), denoting that nitrification was adversely affected.

For this reason, configurations with SB higher than 50% of the influent flowrate have not been implemented and simulated.

The lower nitrification efficiency obtained for higher SB is attributed to the increasing particulate and soluble COD concentration in the nitrifying trickling filter influent (second stage trickling filter). The importance of maintaining low influent suspended solids and biodegradable organic matter to achieve good performance in nitrifying trickling filters has been previously reported (Parker et al., 1989; Logan and Parker, 1990; Parker et al., 1995; Mofokeng et al., 2009; Dai et al., 2013). In these investigations it has been suggested that the influence of influent biodegradable organic matter on nitrification is due to the development of a heterotrophic population, which competes with the nitrifiers for oxygen, thereby reducing nitrification rates (Logan and Parker, 1990; Parker et al., 1995). The simulations showed that the organic loading rate to the nitrifying trickling filter (second stage) was increased compared to the one obtained with the existing WWTP flowsheet. Such an increase, regarding biodegradable soluble COD loading rate, ranged from 2.5 (Run001) to 3.9 (Run011) times the loading rate in the existing WWTP, which was detrimental to nitrification. In addition, the BOD_5 and TKN volumetric loading rates recommended by the German standard for the dimensioning of trickling filters with nitrification were exceeded in the second stage trickling filter in runs with SB higher than 15% (Run005-Run011), confirming the inability to perform successful nitrification (DWA, 2001).

Regarding phosphorus removal, the desired effluent TP concentration was not achieved in the simulations of the modified WWTP, and was not improved by increasing SB. Negligible phosphate release in the anaerobic zone (results not shown) confirmed that EBPR did not take place. This could be attributed to the short HRT under aerobic conditions in the hybrid (first stage) trickling filter, which does not occur in other types of hybrid processes, such as integrated fixed film activated sludge (IFAS) reactors.

Table 7-3 Overall effluent quality, MPC effluent concentration of nitrate, and TSS concentration in the modified treatment train for BNR

		Total suspended solids (mg L^{-1})			Overall effluent (mg L^{-1})						MPC effluent (mg L^{-1})
	SB (%)	Anaerobic zone	Anoxic zone	Hybrid trickling filter	Total COD	Soluble COD	TN	NH_4-N	NO_3-N	TP	NO_3-N
Run001	0	1959	2798	90	34.8	30.3	9.5	2.9	4.5	3.2	0.07
Run002	5	1838	2615	195	35.3	30.8	9.4	2.9	4.4	3.2	0.05
Run003	10	1917	2734	234	35.3	30.6	9.4	3.0	4.3	3.2	0.04
Run004	15	1950	2784	270	36.2	30.2	10.6	4.5	3.9	3.2	0.04
Run005	20	2001	2861	307	36.7	30.0	11.2	5.4	3.6	3.2	0.03
Run006	25	2007	2869	338	37.3	30.0	11.6	6.0	3.5	3.2	0.03
Run007	30	1987	2839	364	37.8	30.1	11.7	6.2	3.4	3.2	0.03
Run008	35	1952	2786	385	38.4	30.3	11.9	6.4	3.3	3.2	0.03
Run009	40	1908	2721	403	39.0	30.6	11.9	6.5	3.2	3.1	0.02
Run010	45	1860	2649	417	39.6	30.9	12.0	6.6	3.2	3.1	0.02
Run011	50	1810	2572	430	40.2	31.2	12.0	6.6	3.1	3.1	0.02

SB: sludge bypass from the anoxic zone to the first stage trickling filter, expressed as percentage of the influent flowrate
MPC: modified primary clarifier

7.3.3. Anaerobic-anoxic modified primary clarifier with additional aeration

In order to increase the aerobic HRT for the suspended growth biomass, an additional aerobic reactor should be included in the treatment train. Due to the large size of the primary clarifier and the excellent denitrification capability shown in the aforementioned simulations, the use of a section of the anoxic zone of the MPC to provide aerobic conditions has been proposed. To represent the aerobic zone, an additional aerobic reactor has been included in the model next to the anoxic one, with a DO concentration of 2.0 mg L^{-1}. This alternative could be performed, and has been assessed, in combination with the SB previously discussed. Several aerobic volumes (AV) have been simulated, from 100 m^3 to 800 m^3 (accordingly reducing the anoxic volume), which correspond to 9.8% to 78.2% of the original anoxic volume. A range of combinations (AV – SB) was analyzed. Three-dimensional surface plots of the effluent TN and TP concentrations for each combination of AV and SB are shown in Figure 7-4. It could be observed that most of the scenarios analyzed fulfilled the required effluent quality. The effluent TN, NH_4-N, NO_3-N and TP concentrations, NO_3-N concentration in the MPC effluent, and TSS concentration in the anaerobic zone, anoxic zone and hybrid (first stage) trickling filter, for each simulation (Run101-Run188), can be found in the supplementary information at the end of this chapter.

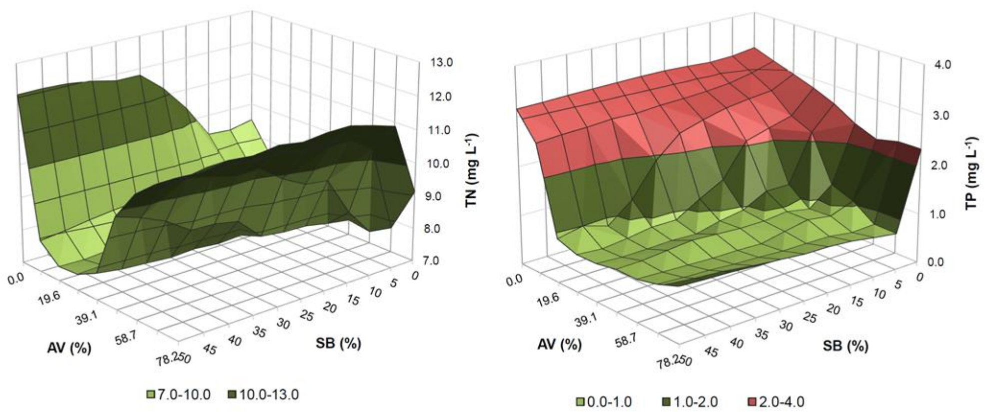

Figure 7-4 Effluent TN (left) and TP (right) concentration of the modified treatment plant for BNR for each combination of aerobic volume (AV) and sludge bypass (SB)

Excellent nitrogen removal was obtained, with an effluent TN concentration lower than 15 mgN L^{-1} in all of the simulated scenarios. However, the extent of nitrification and denitrification varied depending on the AV – SB combination. Without the additional aerobic zone, it was discussed previously how nitrification was deteriorated as the SB was increased, due to an excessive organic loading into the nitrifying trickling filter (second stage). This issue was improved by including an aerobic zone in the anoxic zone of the MPC, where a certain amount of organic matter was removed. An AV as small as 100 m^3 (corresponding to 9.8% of the original anoxic volume) was enough to reduce the biodegradable soluble COD loading rate into the nitrifying trickling filter by 25.5% compared to the simulations without AV, as well as to fulfill the BOD_5 and TKN volumetric loading rates recommended by the German standard for dimensioning of trickling filters with nitrification (DWA, 2001). Larger AV volumes provided higher organic loading decreases. Furthermore, it was observed that an aerobic volume higher than 48.9% of the original anoxic volume had an adverse effect on denitrification, thereby increasing the nitrate concentration in the MPC effluent (up to 4.3 mgN L^{-1}) and the TN concentration in the overall effluent (up to 11.7 mgN L^{-1}). In such scenarios denitrification was not complete, which was attributed to the reduced anoxic volume wherein the aerobic zone replaced more than 48.9% of the original anoxic volume. Under the conditions of the present case study, the minimum anoxic volume that guarantees suitable denitrification is 523 m^3, which provides an HRT of 2.4 hours and corresponds to an aerobic occupancy of 48.9% of the anoxic original volume. Therefore, the implementation of large aerobic volumes is not recommended on account of the fact that the TN effluent quality is slightly deteriorated due to the reduction of denitrification ability.

Regarding phosphorus removal, effluent TP concentration exceeded 2 mgP L^{-1} in several runs, all of them characterized by low AV and/or low SB. This indicates that EBPR could not be achieved by means of only SB or only AV. When no additional AV was implemented, the EBPR failure was attributed to the reduced aerobic HRT provided for suspended biomass in the trickling filter. On the other hand, when an excessively large AV was added, the increasing nitrate concentration in the anoxic zone due to incomplete denitrification led to nitrate recycle into the anaerobic zone, hampering or avoiding the occurrence of EBPR. Nonetheless, excellent phosphorus removal was achieved by the combination of AV and SB. The effluent TP concentration was reduced as both the AV and the SB were increased, and eventually most of the scenarios analyzed provided an effluent TP concentration below 2 mgP L^{-1}, which is the requirement in this case study. This effluent TP concentration came along with significant phosphate release in the anaerobic zone (results not shown), thus confirming the occurrence of EBPR, which was attributed to the increase of the aerobic HRT for suspended biomass, provided by the combination of the hybrid trickling filter (first stage) and the additional AV included in the MPC.

Overall, a broad range of combinations of AV and SB was found fulfilling the required removal of both nitrogen and phosphorus (effluent TN and TP below 15 mgN L^{-1} and 2 mgP L^{-1}, respectively) using the existing facilities, without the construction of new tanks or reactors. This range is depicted in green in Figure 7-5. Moreover, there is an optimal range of combinations AV – SB able to achieve more restrictive requirements (effluent TN and TP below 10 mgN L^{-1} and 1 mgP L^{-1}, respectively), which is displayed in light green in Figure 7-5. In addition, biomass concentration in the anoxic/aerobic zone ranged between 2,475 and 3,107 mgTSS L^{-1}, which appears to be moderate enough to allow for a final clarification of the MPC effluent. Furthermore, an increase of the biomass concentration could lead to achieve higher efficiency and compactness. The MPC fluid dynamics and the physical behaviour of suspended solids have not been analyzed in this study, and should be addressed when developing a detailed design of the MPC, mixing devices and strategy. Further research will focus on this topic.

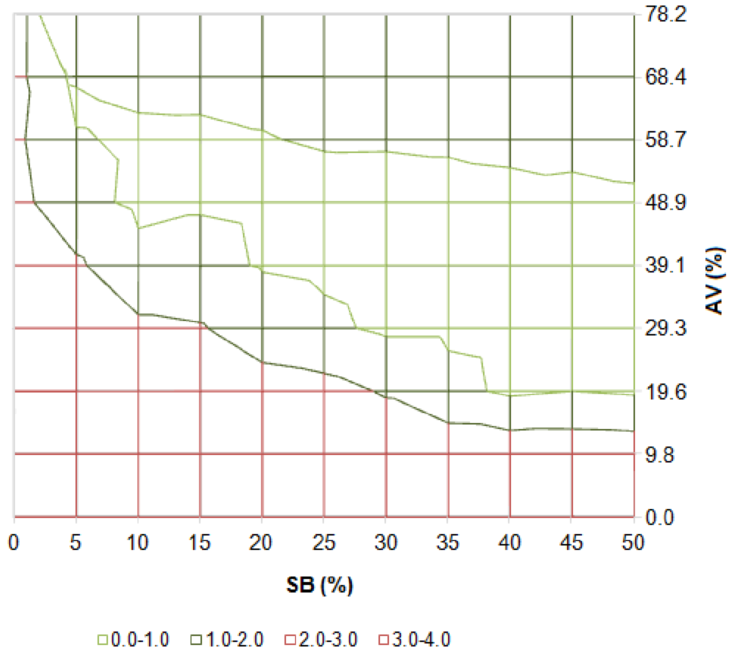

Figure 7-5 Range of combinations of aerobic volume (AV) and sludge bypass (SB) of the modified treatment plant for BNR fulfilling the required effluent quality (green, TN < 15 mgN L^{-1} and TP < 2 mgP L^{-1}) and more restringing requirements (light green, TN < 10 mgN L^{-1} and TP < 1 mgP L^{-1})

Finally, in order to optimize the aeration in the additional aerobic volume, further simulations have been performed reducing the DO concentration in the aerobic zone from 2.0 mg L^{-1} to 0.01 mg L^{-1} (Run201-207). The configuration implemented in Run140 (39.1% of AV and 30% of SB) has been selected as one of the optimal solutions, and has been used as the basis for the following simulations. Results are depicted in Figure 7-6.

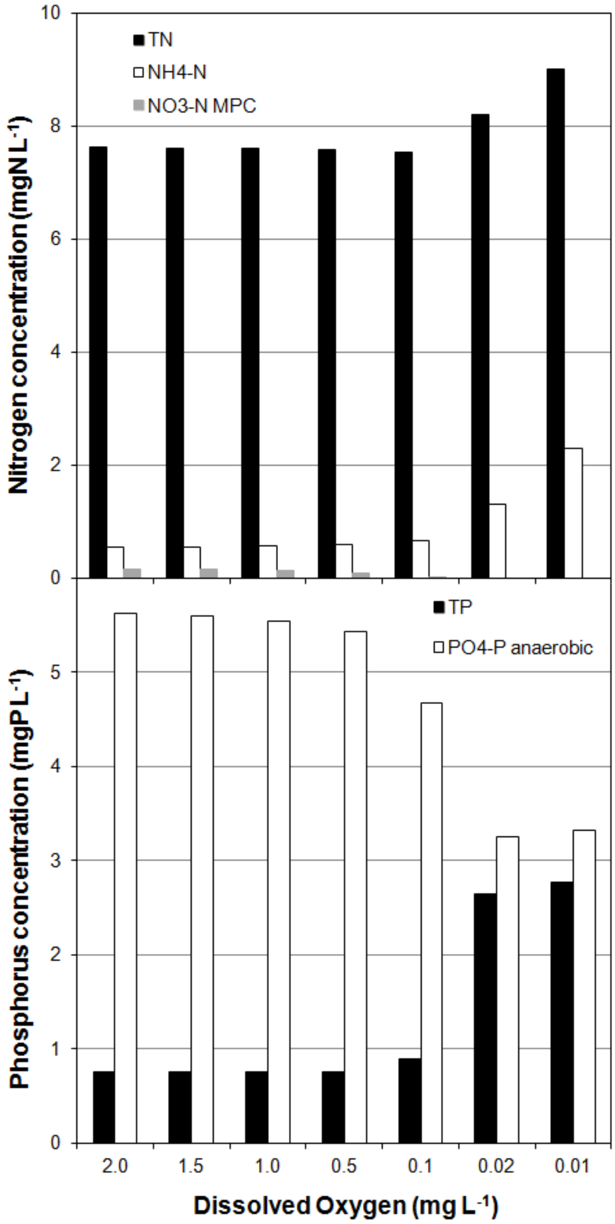

Figure 7-6 Overall effluent TN, NH_4-N and TP concentration, MPC effluent NO_3-N concentration, and PO_4-P concentration in the anaerobic zone, versus DO concentration in the aerobic zone of the modified treatment plant for BNR

Excluding the simulations with 0.02 and 0.01 mg L^{-1}, it was observed that the effluent TN and TP concentrations were similar to those obtained with DO concentration of 2.0 mg L^{-1}. BNR performed successfully with DO concentration as low as 0.1 mg L^{-1}, while it was deteriorated when the DO was further reduced due to the loss of nitrification and the reduction of PAO activity, similarly to the simulations without aerobic zone. These results imply that the aerobic reactor could be operated with low DO concentration and support the viability of including the aerobic zone inside the anoxic zone by means of intermittent aeration of a partial volume of the anoxic zone, and of controlling the DO concentration to a low set point during the aeration period, thereby allowing oxygen transfer efficiency to be optimized and the energy requirement reduced.

7.4. Conclusions

In this study, several alternatives have been assessed for the upgrading of an existing trickling filter WWTP for BNR, based on an anaerobic-anoxic sludge blanket reactor. The proposed treatment train makes use of the existing facilities in the current plant, avoiding the need for new tanks or reactors. Specifically, a large primary clarifier is proposed to be modified in order to host the anaerobic and anoxic zones required for BNR. The feasibility, preliminary design and optimization of the upgrading have been assessed by means of mathematical modelling and simulations, leading to the following main conclusions:

- The conversion of the existing primary clarifier in an anaerobic-anoxic reactor allows for nitrogen removal. The required TN effluent concentration of 15 mgN L^{-1} was achieved in all the simulated scenarios, being lower than 10 mgN L^{-1} is most cases. The anoxic zone performed satisfactorily with an HRT of 4.7 hours and TSS concentration of approximately 2.7 g L^{-1}. Good denitrification was maintained when the anoxic volume was reduced up to 2.4 hours. Further reduction of the anoxic volume led to incomplete denitrification.
- In the scenarios analyzed in this case study, phosphorus removal was not achieved by solely alternating anaerobic and anoxic conditions. Bypassing activated sludge from the anoxic zone to the first stage trickling filter, in order to provide aerobic conditions to the PAO biomass, did not succeed in the removal of phosphorus which was attributed to the short retention time for suspended biomass in the trickling filter.
- An additional aerobic zone was required to achieve EBPR, which should be combined with the sludge bypass from the anoxic zone to the first stage trickling filter. A reduction of the anoxic volume to host an aerobic

zone in the same modified primary clarifier was found to achieve EBPR with several combinations of aerobic volume – sludge bypass, while maintaining excellent nitrogen removal. Furthermore, there is an optimal range of combinations of aerobic volume and sludge bypass able to achieve more restrictive requirements (effluent TN and TP below 10 mgN L^{-1} and 1 mgP L^{-1}, respectively). By means of this facility upgrade, BNR resulted feasible by using the existing facilities in the current WWTP, with no need for new reactors.

- Additionally, a low DO concentration set point in the aerobic zone was able to achieve both nitrogen and phosphorus removal. Specifically, DO concentration as low as 0.1 mg L^{-1} resulted as sufficient to achieve a similar effluent quality to the one obtained with 2.0 mg L^{-1}, which could lead to significant energy savings. The aerobic zone could be implemented by means of intermittent aeration in the anoxic zone, with the air flowrate and the duration of the aeration as the key parameters for process control.

Supplementary information

Table 7S-1 Overall effluent quality, MPC effluent concentration of nitrate, and TSS concentration in the modified treatment train (SB: sludge bypass from the anoxic zone to the first stage trickling filter, expressed as percentage of the influent flowrate MPC: modified primary clarifier)

			Total suspended solids (mg L^{-1})			Overall effluent (mg L^{-1})				MPC effluent (mg L^{-1})
	AV (%)	SB (%)	Anaerobic zone	Anoxic zone	Hybrid trickling filter	TN	NH_4-N	NO_3-N	TP	NO_3-N MPC
Run101	9.8	0	1951	2783	89	8.6	1.5	4.9	3.1	0.10
Run102	9.8	5	1966	2805	207	8.5	1.6	4.7	3.0	0.05
Run103	9.8	10	2134	3055	259	8.6	1.8	4.5	2.9	0.04
Run104	9.8	15	2093	2992	285	8.6	1.8	4.5	2.8	0.03
Run105	9.8	20	2112	3021	320	8.5	1.7	4.5	2.8	0.03
Run106	9.8	25	2096	2996	348	8.4	1.6	4.5	2.8	0.03
Run107	9.8	30	2153	3081	389	8.3	1.4	4.5	2.7	0.03
Run108	9.8	35	1998	2849	388	8.2	1.4	4.5	2.7	0.03
Run109	9.8	40	2017	2877	420	8.1	1.3	4.5	2.7	0.03
Run110	9.8	45	2037	2907	451	8.0	1.2	4.5	2.7	0.03
Run111	9.8	50	2041	2912	478	7.9	1.1	4.5	2.6	0.03

			Total suspended solids (mg L^{-1})			Overall effluent (mg L^{-1})				MPC effluent (mg L^{-1})
	AV (%)	**SB (%)**	**Anaerobic zone**	**Anoxic zone**	**Hybrid trickling filter**	**TN**	**NH_4-N**	**NO_3-N**	**TP**	**NO_3-N MPC**
Run112	19.6	0	1943	2771	87	8.2	1.1	5.0	3.0	0.12
Run113	19.6	5	2122	3037	221	8.0	1.1	4.8	2.7	0.05
Run114	19.6	10	2070	2957	248	8.0	1.0	4.7	2.7	0.05
Run115	19.6	15	2015	2874	271	7.9	1.0	4.7	2.6	0.04
Run116	19.6	20	1996	2843	296	7.7	0.9	4.6	2.5	0.03
Run117	19.6	25	1957	2783	312	7.4	0.7	4.5	2.3	0.03
Run118	19.6	30	2003	2856	351	7.4	0.7	4.5	1.9	0.03
Run119	19.6	35	2046	2917	390	7.4	0.7	4.5	1.3	0.06
Run120	19.6	40	2074	2960	426	7.5	0.7	4.6	0.9	0.04
Run121	19.6	45	1991	2836	435	7.4	0.7	4.5	1.0	0.04
Run122	19.6	50	2008	2862	466	7.4	0.7	4.5	0.9	0.04

			Total suspended solids (mg L^{-1})			Overall effluent (mg L^{-1})				MPC effluent (mg L^{-1})
	AV (%)	**SB (%)**	**Anaerobic zone**	**Anoxic zone**	**Hybrid trickling filter**	**TN**	**NH_4-N**	**NO_3-N**	**TP**	**NO_3-N MPC**
Run123	29.3	0	1931	2752	85	8.0	0.9	5.0	2.8	0.14
Run124	29.3	5	2145	3067	212	7.4	0.6	4.7	2.4	0.04
Run125	29.3	10	2172	3107	250	7.5	0.6	4.7	2.2	0.04
Run126	29.3	15	2061	2940	268	7.5	0.6	4.7	2.1	0.04
Run127	29.3	20	2053	2929	301	7.5	0.6	4.7	1.4	0.05
Run128	29.3	25	2016	2875	326	7.5	0.6	4.7	1.2	0.06
Run129	29.3	30	2075	2964	368	7.5	0.6	4.7	0.9	0.07
Run130	29.3	35	2002	2855	382	7.5	0.6	4.7	0.9	0.07
Run131	29.3	40	2032	2900	418	7.5	0.6	4.7	0.8	0.08
Run132	29.3	45	2061	2946	453	7.5	0.6	4.7	0.7	0.09
Run133	29.3	50	1970	2809	458	7.5	0.6	4.7	0.8	0.09

			Total suspended solids (mg L^{-1})			Overall effluent (mg L^{-1})				MPC effluent (mg L^{-1})
	AV (%)	**SB (%)**	**Anaerobic zone**	**Anoxic zone**	**Hybrid trickling filter**	**TN**	**NH_4-N**	**NO_3-N**	**TP**	**NO_3-N MPC**
Run134	39.1	0	1918	2731	83	7.7	0.7	4.9	2.6	0.14
Run135	39.1	5	2089	2982	206	7.5	0.6	4.8	2.2	0.06
Run136	39.1	10	2124	3037	246	7.6	0.6	4.9	1.2	0.08
Run137	39.1	15	2018	2879	265	7.6	0.6	4.9	1.2	0.09
Run138	39.1	20	2014	2873	296	7.6	0.6	4.9	1.0	0.11
Run139	39.1	25	1980	2822	320	7.6	0.6	4.9	0.9	0.12
Run140	39.1	30	2040	2914	362	7.6	0.5	4.9	0.8	0.15
Run141	39.1	35	1970	2809	376	7.6	0.6	4.9	0.8	0.16
Run142	39.1	40	2002	2858	412	7.6	0.5	4.9	0.8	0.20
Run143	39.1	45	2036	2909	447	7.7	0.5	5.0	0.7	0.26
Run144	39.1	50	2062	2949	481	7.8	0.5	5.1	0.8	0.37

			Total suspended solids (mg L^{-1})			Overall effluent (mg L^{-1})				MPC effluent (mg L^{-1})
	AV (%)	**SB (%)**	**Anaerobic zone**	**Anoxic zone**	**Hybrid trickling filter**	**TN**	**NH_4-N**	**NO_3-N**	**TP**	**NO_3-N MPC**
Run145	48.9	0	1900	2703	79	7.5	0.7	4.7	2.4	0.13
Run146	48.9	5	2046	2921	203	7.6	0.5	5.0	1.2	0.13
Run147	48.9	10	2086	2984	243	7.7	0.5	5.1	0.9	0.19
Run148	48.9	15	1987	2833	261	7.7	0.5	5.1	1.0	0.22
Run149	48.9	20	1988	2837	292	7.8	0.5	5.2	0.9	0.33
Run150	48.9	25	2103	3009	342	8.5	0.5	5.9	0.9	1.01
Run151	48.9	30	2040	2914	361	8.7	0.5	6.0	0.9	1.18
Run152	48.9	35	1972	2811	376	8.7	0.5	6.0	1.0	1.26
Run153	48.9	40	2011	2869	412	9.2	0.5	6.5	0.9	1.74
Run154	48.9	45	2047	2923	449	9.5	0.5	6.8	0.9	2.07
Run155	48.9	50	2071	2960	482	9.7	0.5	7.0	0.9	2.31

	AV (%)	SB (%)	Total suspended solids (mg L^{-1}) Anaerobic zone	Anoxic zone	Hybrid trickling filter	Overall effluent (mg L^{-1}) TN	NH_4-N	NO_3-N	TP	MPC effluent (mg L^{-1}) NO_3-N MPC
Run156	58.7	0	1861	2644	73	7.4	0.6	4.7	2.2	0.14
Run157	58.7	5	2027	2894	202	8.2	0.5	5.7	1.1	0.71
Run158	58.7	10	2088	2986	243	9.4	0.5	6.8	0.9	1.85
Run159	58.7	15	1990	2837	261	9.5	0.5	6.9	1.0	1.94
Run160	58.7	20	1993	2842	293	9.8	0.5	7.2	0.9	2.34
Run161	58.7	25	2094	2995	341	10.4	0.5	7.7	0.8	2.86
Run162	58.7	30	2030	2897	359	10.3	0.5	7.7	0.8	2.86
Run163	58.7	35	2082	2975	399	10.5	0.5	7.9	0.8	3.07
Run164	58.7	40	2118	3030	436	10.7	0.5	8.0	0.8	3.21
Run165	58.7	45	2027	2893	444	10.5	0.5	7.9	0.8	3.14
Run166	58.7	50	2050	2927	476	10.6	0.5	7.9	0.9	3.23

			Total suspended solids (mg L^{-1})			Overall effluent (mg L^{-1})				MPC effluent (mg L^{-1})
	AV (%)	**SB (%)**	**Anaerobic zone**	**Anoxic zone**	**Hybrid trickling filter**	**TN**	**NH_4-N**	**NO_3-N**	**TP**	**NO_3-N MPC**
Run167	68.4	0	1796	2546	67	7.8	0.5	5.3	2.3	0.32
Run168	68.4	5	2021	2883	202	10.4	0.5	7.9	0.8	2.90
Run169	68.4	10	2070	2957	241	10.8	0.5	8.3	0.7	3.32
Run170	68.4	15	1972	2810	259	10.8	0.5	8.2	0.8	3.29
Run171	68.4	20	1973	2811	289	10.9	0.5	8.3	0.8	3.41
Run172	68.4	25	2071	2957	336	11.1	0.5	8.5	0.8	3.62
Run173	68.4	30	2007	2861	354	11.0	0.5	8.4	0.8	3.59
Run174	68.4	35	2057	2937	393	11.1	0.5	8.5	0.9	3.70
Run175	68.4	40	2093	2990	430	11.2	0.5	8.6	0.9	3.78
Run176	68.4	45	2004	2856	437	11.1	0.5	8.5	0.9	3.72
Run177	68.4	50	2025	2888	470	11.2	0.5	8.5	1.0	3.78

	AV (%)	SB (%)	Total suspended solids (mg L^{-1}) Anaerobic zone	Anoxic zone	Hybrid trickling filter	Overall effluent (mg L^{-1}) TN	NH_4-N	NO_3-N	TP	MPC effluent (mg L^{-1}) NO_3-N MPC
Run178	78.2	0	1750	2475	66	9.1	0.5	6.7	2.3	1.55
Run179	78.2	5	1997	2847	199	11.3	0.5	8.8	0.7	3.82
Run180	78.2	10	2045	2918	237	11.5	0.5	9.0	0.8	3.98
Run181	78.2	15	2101	3002	278	11.7	0.4	9.1	0.9	4.12
Run182	78.2	20	2088	2982	308	11.7	0.4	9.1	0.9	4.14
Run183	78.2	25	2045	2917	331	11.6	0.5	9.0	0.9	4.13
Run184	78.2	30	2113	3020	374	11.7	0.4	9.1	1.0	4.23
Run185	78.2	35	2031	2897	387	11.6	0.5	9.0	1.0	4.18
Run186	78.2	40	2066	2949	423	11.7	0.4	9.0	1.1	4.25
Run187	78.2	45	1979	2817	431	11.6	0.5	8.9	1.1	4.18
Run188	78.2	50	2000	2849	463	11.6	0.5	9.0	1.1	4.23

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Chapter 8

Conclusions and recommendations

The novel anaerobic-anoxic reactor conceived within this study and presented in this thesis has been proved as a novel technology for biological nutrient removal (BNR) from wastewater. The experimental and theoretical results, obtained by means of pilot plant operation, modelling and simulations, demonstrate the feasibility of the novel reactor concept, its applicability for wastewater treatment, and the feasibility of prospective retrofit of existing wastewater treatment plants (WWTP). Several uncertainties have emerged from the study and should be faced, mainly about the performance of the reactor under particular operational conditions and the scalability to medium and large-scale. Thus, the major findings of this thesis are presented below, together with some suggestions for further research, and structured according to the main objectives of the thesis.

Conception and design of a novel anaerobic-anoxic reactor for BNR from wastewater, aimed at achieving high compactness and efficiency

Conventional configurations for BNR require complex and large treatment systems providing anaerobic, anoxic and aerobic compartments in order to carry out nitrification, denitrification and phosphate release and uptake. To avoid the construction of multiple separate tanks, the anaerobic and anoxic zones could be unified in a single non-aerated reactor, which takes advantage of the complete separation from the aerobic reactor preventing the undesired intrusion of oxygen into the anoxic and anaerobic zones. The AnoxAn reactor is presented as an innovative technology for BNR, consisting in a continuous upflow sludge blanket reactor, with an anaerobic zone at the bottom prior to an anoxic zone above. A clarification zone at the top of the reactor avoids the escape of large amounts of biomass, thus promoting high sludge concentration in a sludge blanket reactor type. The biological anaerobic-anoxic functioning of AnoxAn is meant to be coupled with an aerobic reactor and a secondary sedimentation unit (or a final filtration step), in order to complete the treatment train.

The main specific features of the AnoxAn reactor are: (i) upflow operation; (ii) hydraulic separation between the anoxic and anaerobic zones; and (iii) suspended solids retention. Such characteristics aim at achieving high compactness and efficiency, reducing the surface requirement and the energy consumption. The upflow operation contributes to energy saving for mixing, plug-flow and sustainable high sludge concentration. The hydraulic separation is required in order to establish separate anoxic and anaerobic conditions, that is to keep negligible nitrate concentration in the anaerobic zone. Specific mechanical mixing devices and baffles are implemented in order to achieve the desired hydraulic separation, while keeping the influent flow up-way through the reactor. The suspended solids retention is aimed at achieving a high biomass concentration inside the reactor. The upflow setup leads to biomass retention to some extent due to suspended solids settling, and it is assisted by means of an additional baffle or set of lamellas at the top of the reactor. Some escape of suspended solids is expected in order to provide alternating anaerobic-aerobic conditions to perform enhanced biological phosphorus removal (EBPR) by means of phosphate accumulating organisms (PAO). Additionally, a periodic recirculation of suspended solids is carried out from the anaerobic to the anoxic zone, in order to avoid excessive biomass accumulation in the anaerobic zone and to enhance biomass circulation inside the reactor being exposed to alternating anaerobic-anoxic conditions. This setup encourages phosphate uptake using nitrate as electron acceptor, instead of oxygen, by means of denitrifying phosphate accumulating organisms (DPAO). Overall, the AnoxAn configuration claims anaerobic phosphate release, anoxic denitrification and phosphate uptake in a single reactor with high biomass concentration and low energy consumption.

The reactor complied with the characteristics of novelty and inventive, therefore it was registered as a patent. The main advantages of the invention are:

- ✓ Simplicity, high efficiency and compactness compared to conventional configurations for BNR, due to the unification of the anaerobic and anoxic compartments in a single reactor and the high biomass concentration.
- ✓ No need for chemicals addition by means of pre-anoxic denitrification and EBPR.
- ✓ Energy savings for mixing due to upflow operation.
- ✓ Energy savings for aeration, less sludge production and ability for wastewater treatment with low C/N ratio, due to the promotion of simultaneous denitrification and phosphate uptake under anoxic environmental conditions.

In order to assess the potential economic savings of the implementation of the AnoxAn reactor, an economic analysis of a hypothetical realization was been carried out. The results showed remarkable differences between the novel AnoxAn compared to the equivalent anaerobic and anoxic stages of a conventional BNR treatment system (specifically UCT). The investment cost of the AnoxAn reactor, not including the land cost, was estimated 23% higher than that of the equivalent UCT system, mainly due to the additional cost of lamellas or baffles. However, the energy savings for mixing of the AnoxAn reactor led to an operational cost lower than half of that of the UCT system. Eventually, the total annualized equivalent cost (including investment and operation) of the AnoxAn reactor resulted from 20 to 26% lower than the one of the equivalent UCT system, considering an electricity cost from 0.10 to

0.14 € per kWh. This indicates the significance of the potential energy savings of the AnoxAn reactor and the corresponding economic benefit.

Feasibility evaluation and optimization of the anoxic-anaerobic hydraulic separation, based on hydrodynamic characterization and modelling

The required environmental conditions to achieve EBPR and denitrification in the novel anaerobic-anoxic upflow reactor, AnoxAn, imply hydraulic separation between the anaerobic and anoxic zones inside the reactor. Such specific hydraulic behaviour has been tested experimentally in a bench-scale prototype (48.4 L reactor volume). A hydraulic model describing the observed behaviour was built up and calibrated with the experimental results. The feasibility of the novel reactor configuration was assessed by means of the hydrodynamic characterization and numerical model simulations.

Tracer tests in clean water were performed for residence time distribution analysis in order to characterize the hydraulic behaviour of the individual anaerobic and anoxic zones, as well as of the overall reactor. Adequate mixing was achieved for each zone. In the anaerobic zone, a hydraulic behaviour similar to a continuous stirred tank reactor (CSTR) was achieved with a turnover rate of the reactor volume of 4.8 times per hour. This rate, which should be high enough to accomplish sufficient mixing and low enough to prevent unwanted oxygen transfer from the atmosphere due to excessive turbulence, is higher than the practical design value of 3 times per hour. However, in the AnoxAn reactor configuration, the oxygen transfer from the atmosphere is prevented by its own design, as the anaerobic zone is not exposed to the atmosphere. The hydraulic behaviour in the anoxic plus clarification zones resulted similar to a CSTR but with shift forward of approximately 18 minutes, which was attributed to non-ideal plug-flow behaviour in the volume under the influence of the baffle and the clarification zone. Finally, the global residence time distribution profile for the overall AnoxAn reactor showed a complex non-ideal flux type, which was represented by the combination of the setups proposed for the individual anaerobic and anoxic plus clarification zones.

The hydraulic behaviour observed in the experimental tests was described by means of a model consisting of a combination of several compartments. Several model configurations were tested and fitted to the experimental results. The best models were selected as constituting a compromise between model complexity and data fit. The ultimate setup consisted of a combination of four CSTR (three of them describing the anaerobic zone and the last one representing the anoxic zone) and one plug-flow reactor (PFR) with axial dispersion (representing the clarification zone and the volume under the influence of the baffle). A back-mixing stream between the anoxic and anaerobic zones of the reactor was incorporated in the model and the fit was clearly improved. This model setup will form the basis for the inclusion of biological conversion processes in future.

The model was used for the feasibility evaluation of the anoxic-anaerobic hydraulic separation inside the reactor. The simulation results showed that the desired hydraulic behaviour was achieved, involving adequate mixing in each individual zone (anaerobic and anoxic) and little mixing between both zones. The back-mixing flowrate was estimated to be only 40.2% of influent flowrate, which is lower than typical anoxic recycle ratio (from the anoxic to the anaerobic reactor) in several conventional BNR configurations, such as UCT. When the denitrification process was incorporated to the model (in the virtual presence of biomass), nitrate concentration was drastically reduced, even with a continuous nitrate injection of 20 mgN L^{-1} in the recycle stream. The ratio between nitrate concentrations in the two zones remained the same, indicating that denitrification did not affect the extent of hydraulic separation. And more important, the occurrence of denitrification resulted in negligible nitrate concentration (less than 0.1 mgN L^{-1}) in the anaerobic zone (as desired) for biomass concentration of 1.2 g L^{-1} or higher.

Finally, a tracer test was performed with biomass inside the reactor: total suspended solids (TSS) concentration of approximately 5 g L^{-1} in the anoxic zone and 10 g L^{-1} in the anaerobic one; in order to assess the influence of biomass on the reactor hydrodynamics. The experimental results were compared to those obtained through hydraulic model simulation. The experimental and simulated tracer concentration profiles in the anoxic zone matched very well. However, for the anaerobic zone, the measured concentrations were slightly overpredicted through simulation, which suggests that the presence of biomass further increase the hydraulic separation between the anoxic and anaerobic zones. It is attributed to the different TSS concentration in both zones. The lower TSS concentration in the anoxic zone can be imputed mainly to the nitrate recycle stream, which enters the AnoxAn reactor with high flowrate and lower concentration of TSS, thus provoking TSS dilution in the anoxic zone. Due to these different concentrations, different densities in each zone have slightly enhanced the hydraulic separation.

It should be pointed out that the hydrodynamic characterization has been performed in an AnoxAn prototype with specific dimensions. According to the setup, it is expected that such type of reactor could be applied for small-sized wastewater treatment. The implementation in medium and large-scale WWTP would entail the construction of multiple modular units of the AnoxAn reactor, which could be far from the optimum from the technical and economic points of view. This suggests the interest in developing new AnoxAn configurations, maintaining the same features but with different dimensions. Such new configurations and its shapes could mimic typical primary clarifiers, activated sludge reactors, etc., aimed at making the AnoxAn concept readily applicable at full-scale, for instance for existing WWTP upgrade. Thus, there is a need for hydrodynamic assessment of new AnoxAn full-scale setups, which could be performed with the aid of computational fluid dynamic (CFD) tools.

Performance evaluation of the novel reactor in the removal of organic matter and nutrients from municipal wastewater

The prototype of the AnoxAn reactor was tested at pilot scale treating municipal wastewater in order to evaluate its performance for BNR, coupled with an aerobic hybrid membrane bioreactor (HMBR). The AnoxAn sludge blanket was developed achieving TSS concentration up to 10 g L^{-1} in the anaerobic zone and 5 g L^{-1} in the anoxic one. The upper clarification zone did not avoid the escape of biomass from the reactor; however TSS concentration in the AnoxAn effluent was lower than those in the anaerobic and anoxic zones of the reactor, indicating that the biomass was retained to some extent. Thus, the denomination transition zone should be used to refer to the upper zone of the reactor (instead of clarification) under these operational conditions.

Denitrification successfully occurred in the AnoxAn reactor, with an average nitrate concentration in the AnoxAn effluent as low as 0.7 mgN L^{-1}. The overall total nitrogen (TN) removal efficiency averaged 75%, with a nitrate recycle flowrate about 3 times the influent flowrate. The overall phosphorus removal was also satisfactory, with an average total phosphorus (TP) removal efficiency of 89%. However, under the conditions of the present study, simultaneous denitrification and phosphate uptake by means of DPAO did not achieve the desired phosphorus removal efficiency. Nitrate was depleted in the anoxic zone, due to the denitrification activity, while phosphate was not fully taken up. This entails that the subsequent aerobic stage was necessary to complete the phosphate uptake, achieving an effluent TP concentration below 1 mg L^{-1}. The operation of AnoxAn, allowing the escape of certain amount of biomass resulted essential for the achievement of such low overall effluent TP concentration. It was observed partial hydrolysis of the particulate organic matter in the AnoxAn reactor, estimated at 42% of the average influent particulate organic matter, according to mass balances. This feature would be beneficial to the performance of BNR, since hydrolysis produces readily biodegradable organic matter which is needed for phosphate release and denitrification. Nevertheless, the AnoxAn reactor provided and effluent with low enough soluble organic matter concentration (62.0 mg L^{-1}), suitable for feeding the subsequent nitrifying reactor.

Separate anoxic and anaerobic conditions were maintained in the single multi-environment reactor, confirming the different biological roles of the two zones. Phosphate release in the anaerobic zone confirmed the occurrence of EBPR and was possible thanks to the preservation of anaerobic conditions. And according to nitrate mass balances, 95% of the nitrate entering the AnoxAn reactor was removed in the anoxic zone, being only the remaining 5% removed in the anaerobic one. Summarizing, the novel setup allowed performing several functions in the single reactor with a hydraulic retention time (HRT) of 4.2 hours: biomass retention; hydrolysis of influent particulate organic matter; phosphate release with an anaerobic HRT of 1.1 hours; and nearly complete denitrification with an anoxic HRT of 2.7 hours.

Further research is proposed aimed at promoting simultaneous denitrification and phosphate uptake by means of DPAO, in order to take advantage of the energy savings for aeration, less sludge production and maximum influent organic matter exploitation derived from the activity of these organisms. This is of particular interest for wastewater treatment with limiting organic matter availability (low C/N and C/P ratios), which could be insufficient for BNR conventional processes. In this study, despite the DPAO potential activity, which was evaluated through batch tests during the experimental campaign, the net phosphate uptake under anoxic conditions resulted negligible. This was attributed to the competition for nitrate of conventional denitrifying heterotrophs and DPAO. The influent wastewater characteristics, with no limiting organic matter availability (C/N > 10 gCOD gNT^{-1} and C/P > 80 gCOD gTP^{-1}), led to a relatively low nitrate loading to the anoxic zone, where the limited exposure of organisms to nitrate possibly could have hindered anoxic phosphate uptake. It suggests that further research could be performed treating wastewater with low C/N and C/P ratios, by means of pilot plant operation complemented by means of mathematical model simulations. The adaptability of the AnoxAn reactor to variable influent wastewater characteristics, controlling the biomass escape to the subsequent aerobic reactor, could be the subject of further research.

Feasibility evaluation and preliminary design of an existing WWTP upgrade to BNR based on the novel anaerobic-anoxic reactor, by means of mathematical model simulations

Facilities based on trickling filters have been widely used for wastewater treatment. However, most of them face only organic matter removal and in some cases nitrification, but seldom TN or TP removal. In this thesis, a real case study was presented aimed at upgrading an existing trickling filter WWTP to achieve nitrogen and phosphorus effluent standards. The main constraint for the process selection was the limited available space. Therefore, the proposed treatment train made use of the existing facilities in the plant, avoiding the need for new tanks or reactors. Specifically, a large primary clarifier (average HRT of 8.4 hours) was proposed to be modified in order to host the anaerobic and anoxic zones required for BNR, based on the anaerobic-anoxic sludge blanket reactor, AnoxAn. The feasibility evaluation, preliminary design and optimization of the upgrading were addressed through mathematical modelling and simulations.

The required TN effluent concentration of 15 mgN L^{-1} was achieved in all the simulated scenarios, being lower than 10 mgN L^{-1} is most cases. The anoxic zone performed satisfactorily with an HRT of 4.7 hours and TSS concentration of approximately 2.7 g L^{-1}. Good denitrification was maintained when the anoxic volume was reduced up to 2.4 hours. Regarding phosphorus removal, it was not achieved by solely alternating anaerobic and anoxic conditions, in the scenarios analyzed in this case study. This was attributed to the competition for nitrate of conventional denitrifying heterotrophs and DPAO, due to the influent wastewater characteristics with no limiting organic matter availability. This entailed that a subsequent aerobic stage was necessary to complete the phosphate uptake. An activated sludge bypass from the anoxic zone of the modified primary clarifier (MPC) to the trickling filter was included in order to provide aerobic conditions to the PAO biomass, but did not succeed in the removal of phosphorus. Negligible phosphate release in the anaerobic zone confirmed that EBPR did not take place. This was attributed to the short HRT under aerobic conditions in the hybrid trickling filter, which does not occur in other types of hybrid processes, such as integrated fixed film activated sludge (IFAS) reactors. In order to increase the aerobic HRT for the suspended growth biomass, an additional aerobic reactor was included in the treatment train, and simulated in combination with the sludge bypass from the anoxic zone to the first stage trickling filter. A reduction of the anoxic volume to host an aerobic zone in the same MPC was found to achieve EBPR with several combinations of aerobic volume – sludge bypass, while maintaining excellent nitrogen removal. There is a range of combinations of aerobic volume and sludge bypass able to achieve TN and TP effluent concentrations clearly fulfilling the Directive 91/271/EEC requirements. The best alternatives were found around a compartmentalization of the primary clarifier providing HRT of 3.7, 2.4 and 2.3 hours in the anaerobic, anoxic and aerobic zones, respectively.

Finally, the influence of the dissolved oxygen (DO) concentration in the MPC aerobic zone was evaluated, and it was obtained that a low DO set point was able to achieve both nitrogen and phosphorus removal. DO concentration as low as

0.1 mg L^{-1} resulted as sufficient to achieve a similar effluent quality to the one obtained with 2.0 mg L^{-1}, which could lead to significant energy savings. This suggests that the aerobic zone could be implemented by means of intermittent aeration in the anoxic zone, with the air flowrate and the duration of the aeration as the key parameters for process control.

In conclusion, by means of this facility upgrade, BNR resulted feasible by using the existing facilities in the current WWTP, with no need for new reactors. Nevertheless, pilot studies are recommended before the implementation at full-scale. The experimental results could be used for the calibration of the model, providing a more reliable tool to assess the performances of the proposed treatment train under different operational conditions. Furthermore, the MPC clarifier fluid dynamics and the physical behavior of suspended solids have not been analyzed in this study, and should be addressed when developing a detailed design of the MPC, and mixing devices and strategy. Further research will focus on this topic.

Conclusiones y recomendaciones

El reactor anaerobio-anóxico concebido en este estudio y presentado en esta tesis ha sido probado como una tecnología innovadora para eliminación biológica de nutrientes (EBN). Los resultados experimentales y teóricos, obtenidos mediante operación de una planta piloto, modelización y simulaciones, demostraron la viabilidad del concepto del reactor, su capacidad tratando agua residual urbana, y la viabilidad de su posible aplicación para ampliación de estaciones depuradoras de aguas residuales (EDAR) existentes. A partir del estudio han surgido algunas incertidumbres que permanecen pendientes de ser resueltas, principalmente sobre el funcionamiento del reactor bajo condiciones operacionales específicas y sobre su escalabilidad a media y gran escala. Por lo tanto, junto a las principales conclusiones, que se presentan a continuación, se muestran también las recomendaciones para futuras investigaciones, estructuradas de acuerdo a los principales objetivos de esta tesis.

Concepción y diseño de un novedoso reactor anaerobio-anóxico para EBN de aguas residuales, con elevada compacidad y eficiencia

Las configuraciones convencionales para EBN requieren grandes y complejos sistemas incluyendo compartimentos anaerobios, anóxicos y aerobios para llevar a cabo la nitrificación, desnitrificación y liberación y acumulación de fosfato. Para evitar la construcción de múltiples tanques independientes, las zonas anaerobia y anóxica se pueden combinar en un único reactor no aireado, lo cual aprovecha la completa separación del reactor aerobio evitando al indeseada intrusión de oxígeno en las zonas anóxica y anaerobia. Se presenta el reactor AnoxAn como una tecnología innovadora para EBN, que consiste en un reactor continuo de lecho de fango y flujo ascendente, con una zona anaerobia en la parte inferior seguida de una zona anóxica por encima. Una zona de clarificación en la parte superior del reactor evita el escape de sólidos en suspensión, permitiendo conseguir una elevada concentración de biomasa dando lugar a un reactor de lecho de fango. El funcionamiento biológico anaerobio-anóxico de AnoxAn se ha de combinar con un reactor aerobio y una sedimentación secundaria (o filtración final) para completar el tren de tratamiento de EBN.

Las características principales del reactor AnoxAn son: (i) flujo ascendente; (ii) separación hidráulica entre las zonas anóxica y anaerobia; y (iii) retención de sólidos en suspensión. Estas características están orientadas a conseguir una elevada compacidad y eficiencia, reduciendo el requerimiento de superficie y el consumo energético. El flujo ascendente contribuye al ahorro de energía para mezcla, favorece el flujo pistón y permite mantener una elevada concentración de fango. La separación hidráulica es necesaria para establecer condiciones anóxicas y anaerobias por separado, es decir, mantener una concentración despreciable de nitrato en la zona anaerobia. Para conseguir la separación hidráulica mientras se mantiene el flujo ascendente de agua en el reactor, se dispone de equipos de mezcla y deflectores específicos. La retención de sólidos en suspensión tiene como objetivo lograr una elevada concentración de biomasa en el interior del reactor. La configuración en flujo ascendente implica cierta capacidad de retención de biomasa debido a la sedimentación de los sólidos, y es complementada mediante un deflector-tranquilizador adicional o la instalación de lamelas en la parte superior del reactor. Se ha de permitir cierto escape de sólidos en suspensión con la intención de proporcionar condiciones alternas anaerobias y aerobias a la biomasa y así fomentar la eliminación biológica de fósforo (EBF) mediante los organismos acumuladores de fosfato (OAF). Adicionalmente, se lleva a cabo periódicamente una recirculación desde la zona anaerobia a la anóxica, con el objetivo evitar una excesiva acumulación de biomasa en la zona anaerobia y para favorecer la circulación de biomasa dentro del reactor, siendo expuesta a condiciones alternas anaerobias y anóxicas. Esta configuración estimula la acumulación de fosfato en condiciones anóxicas, utilizando nitrato como aceptor de electrones en vez de oxígeno, mediante los organismos acumuladores de fosfato desnitrificantes (OAFD). De manera global, la configuración de AnoxAn permite liberación de fosfato en condiciones anaerobias, y desnitrificación y acumulación de fosfato en condiciones anóxicas, en un único reactor con elevada concentración de biomasa y baja demanda energética.

El reactor se ajusta a los requisitos de innovación y capacidad inventiva, por lo que fue registrado como patente. Las principales ventajas de la invención son:

- ✓ Sencillez, elevada eficiencia y compacidad, comparado con configuraciones convencionales para EBN, debido a la combinación de los compartimentos anaerobio y anóxico en un único reactor y la elevada concentración de biomasa.
- ✓ No se necesita adición de reactivos al llevar a cabo desnitrificación pre-anóxica y EBF.
- ✓ Ahorro energético en mezcla debido al flujo ascendente.
- ✓ Ahorro energético en aireación, menor producción de fango y capacidad para tratar aguas residuales con baja relación C/N, debido al fomento de la desnitrificación y acumulación de fosfato simultáneas en condiciones anóxicas.

Para cuantificar el potencial ahorro económico de la implantación de AnoxAn, se ha llevado a cabo el análisis económico de una hipotética realización del reactor a escala real. Los resultados fueron comparados con los correspondientes a las etapas anaerobia y anóxica equivalentes de un sistema de EBN convencional (en concreto UCT). Se observaron notables diferencias entre AnoxAn y el sistema equivalente

UCT. El coste de inversión de AnoxAn, sin considerar el coste del terreno ocupado, resultó un 23% superior al correspondiente al sistema UCT, principalmente debido al coste adicional de lamelas o deflectores. Sin embargo, el ahorro energético en mezcla del reactor dio lugar a un coste operacional menor de la mitad del correspondiente al sistema UCT. El coste anual equivalente total (incluyendo inversión y operación) del reactor AnoxAn resultó entre un 20 y 26% menor que el correspondiente al sistema equivalente UCT, considerando un precio de la energía eléctrica entre 0.10 y 0.14 € por kWh. Este resultado demuestra la importancia del potencial ahorro energético del reactor AnoxAn y su correspondiente beneficio económico.

Evaluación de la viabilidad y optimización de la separación hidráulica entre zonas anóxica y anaerobia, mediante caracterización hidrodinámica y modelización

Las condiciones ambientales necesarias para EBF y desnitrificación en AnoxAn implican la necesidad de separación hidráulica entre las zonas anóxica y anaerobia en el interior del reactor. Este específico comportamiento hidráulico ha sido analizado experimentalmente en un prototipo a escala de bancada (reactor de 48.4 L de volumen). A partir de los resultados experimentales se ha construido y calibrado un modelo hidráulico, representando el comportamiento observado. La viabilidad de la configuración del reactor se ha evaluado mediante la caracterización hidrodinámica y simulaciones del modelo.

Se realizaron ensayos de trazadores en agua limpia para analizar la distribución de tiempos de residencia y caracterizar el comportamiento hidráulico de cada una de las zonas individualmente (anaerobia y anóxica), así como del reactor completo. Se consiguió una mezcla adecuada en cada zona. En la zona anaerobia, el comportamiento hidráulico resultó similar a un compartimento de mezcla completa (MC), con una tasa de renovación del volumen del reactor de 4.8 renovaciones cada hora. Esta tasa, que debe ser suficiente para proporcionar una mezcla adecuada y suficientemente baja para prevenir la indeseada transferencia de oxígeno desde el aire debido a una turbulencia excesiva, es mayor que el valor recomendado de diseño de 3 renovaciones a la hora. Sin embargo, en la configuración de AnoxAn, la transferencia de oxígeno desde el aire se evita por el propio diseño del reactor, ya que la zona anaerobia no está expuesta a la atmósfera. El comportamiento hidráulico en la zona anóxica y de clarificación resultó similar a un compartimento MC pero con un retraso de aproximadamente 18 minutos, lo cual fue atribuido a un flujo pistón (FP) no ideal en el volumen bajo la influencia del deflector-tranquilizador y de la zona superior de clarificación. Por último, el perfil de distribución de tiempos de residencia del reactor global mostró un complejo flujo no ideal, el cual fue representado mediante la combinación de las configuraciones propuestas para las zonas individuales anaerobia, y anóxica más clarificación.

El comportamiento hidráulico observado experimentalmente fue descrito mediante un modelo que consistió en la combinación de varios compartimentos. Se analizaron diferentes configuraciones del modelo y se ajustaron a los resultados experimentales. Se seleccionaron los mejores modelos de acuerdo a un compromiso entre la complejidad del modelo y el ajuste de los datos. La configuración definitiva consistió en una combinación de cuatro compartimentos MC (tres de ellos describían la zona anaerobia y el último representaba la zona anóxica) y un FP con dispersión axial (describiendo la zona de clarificación y el volumen bajo la influencia del deflector-tranquilizador). Se incorporó al modelo una corriente de retro-mezcla entre las zonas anóxica y anaerobia y el ajuste mejoró significativamente. Este modelo será la base para la incorporación en el futuro de los procesos biológicos.

El modelo se utilizó la evaluar la viabilidad de la separación hidráulica entre zonas anóxica y anaerobia en el interior del reactor. Los resultados de las simulaciones mostraron que se alcanzó el comportamiento hidráulico deseado, implicando mezcla adecuada en cada zona (anaerobia y anóxica) y baja mezcla entre ambas zonas. Se estimó el caudal de la corriente de retro-mezcla en sólo un 40.2% del caudal afluente, el cual es menor que el típico ratio de recirculación anóxica (desde el reactor anóxico al anaerobio) en varias configuraciones convencionales de EBN, como el sistema UCT. Cuando se incluyó el proceso de desnitrificación en el modelo, en presencia teórica de biomasa, la concentración de nitrato se redujo drásticamente, incluso con una inyección continua de 20 mgN L^{-1} en la corriente de recirculación. El ratio entre las concentraciones de nitrato en ambas zonas se mantuvo sin cambios, indicando que la desnitrificación no afectó el alcance de la separación hidráulica. Sin embargo, la incorporación de la desnitrificación en el modelo dio lugar a una concentración despreciable de nitrato en la zona anaerobia (menor de 0.1 mgN L^{-1}), tal y como se deseaba, con concentraciones de biomasa a partir de 1.2 g L^{-1}.

Finalmente se realizó un ensayo de trazador con biomasa en el reactor: concentración de sólidos en suspensión (SST) de aproximadamente 5 g L^{-1} en la zona anóxica y 10 g L^{-1} en la zona anaerobia; con el objetivo de determinar la influencia de la biomasa en la hidrodinámica del reactor. Los resultados experimentales se compararon con los obtenidos mediante simulaciones del modelo hidráulico. Los perfiles simulados y experimentales de concentración de trazador en la zona anóxica coincidieron adecuadamente. En cambio, en la zona anaerobia los resultados experimentales fueron pronosticados con un ligero exceso mediante el modelo, lo cual indica que la presencia de biomasa incrementó la separación hidráulica entre las zonas anóxica y anaerobia. Esto pudo ser debido a las diferentes concentraciones de SST en ambas zonas. La menor concentración en la zona anóxica fue atribuida principalmente a la corriente de recirculación de nitratos, la cual entra al reactor AnoxAn con elevado caudal y baja concentración de SST, provocando por lo tanto cierta dilución de SST en la zona anóxica. La ligera diferencia de densidades del fango activo entre ambas zonas, debida a las diferentes concentraciones de SST, podría causar el aumento de la separación hidráulica.

Cabe destacar que la caracterización hidráulica se ha llevado a cabo en un prototipo de AnoxAn con unas dimensiones específicas. De acuerdo a la configuración, se estima que un reactor de ese tipo podría ser aplicado en sistemas de depuración de pequeña escala. La implantación en EDAR de mediana y gran escala implicaría la construcción de varias unidades modulares del reactor AnoxAn, lo cual puede no ser óptimo desde el punto de vista técnico y económico. Esto incita a desarrollar nuevas configuraciones de AnoxAn, manteniendo el mismo concepto y características, pero con diferentes formas y dimensiones. Las nuevas configuraciones podrían imitar típicas formas de decantadores primarios, reactores de fangos activos, etc., con el objetivo de hacer el concepto AnoxAn fácilmente aplicable a escala real, por ejemplo en el caso de ampliación de EDAR existentes. Por lo tanto, hay una necesidad de análisis hidrodinámico de nuevas configuraciones de AnoxAn a escala real, para lo cual el empleo de herramientas de simulación CFD (Computational Fluid Dynamics) puede resultar de gran ayuda.

Evaluación del funcionamiento del reactor AnoxAn para eliminación de materia orgánica y nutrientes de aguas residuales

El funcionamiento del prototipo de AnoxAn fue analizado tratando agua residual urbana, combinado con un reactor biológico de membranas híbrido aerobio a escala piloto. El lecho fango se desarrolló en el reactor, alcanzando concentraciones de SST de 10 g L^{-1} en la zona anaerobia y 5 g L^{-1} en la anóxica. La zona superior de clarificación no evitó el escape de biomasa del reactor, pero la concentración de SST en el efluente de AnoxAn fue menor que la del interior del reactor, indicando que se produjo cierta retención de biomasa. Por lo tanto, se considera que la zona superior del reactor puede denominarse de transición o tranquilización (en vez de clarificación) cuando el reactor se opere en esas condiciones.

El proceso de desnitrificación tuvo lugar de manera satisfactoria en AnoxAn, con una concentración media de nitrato en el efluente de AnoxAn de tan sólo 0.7 mgN L^{-1}. El rendimiento medio global de eliminación de nitrógeno total (NT) fue del 75%, con un caudal de recirculación de nitratos de aproximadamente 3 veces el caudal afluente. La eliminación global de fósforo también fue satisfactoria, con un rendimiento medio de eliminación de fósforo total (PT) del 89%. Sin embargo, en las condiciones de este estudio no se consiguió la eliminación de fósforo a través de desnitrificación y acumulación de fosfato simultáneas en AnoxAn, mediante OAFD. El nitrato prácticamente se agotó en la zona anóxica, debido a la actividad desnitrificante, mientras que el fosfato no fue acumulado. Esto indica que la etapa posterior aerobia fue necesaria para completar la acumulación de fosfato, alcanzando una concentración efluente de PT menor de 1 mg L^{-1}. El modo de operación de AnoxAn, permitiendo el escape de cierta cantidad de biomasa, resultó determinante para lograr una concentración efluente de PT tan baja. Por otra parte, en AnoxAn se produjo hidrólisis de parte de la materia orgánica particulada, estimada de acuerdo a balances de masa en un 42% de la materia orgánica particulada afluente. Esta característica pudo ser favorable para el funcionamiento de EBN, ya que la hidrólisis produce materia orgánica fácilmente degradable que es necesaria para los procesos de liberación de fosfato y desnitrificación que tienen lugar en AnoxAn. A pesar de ello, el efluente del reactor AnoxAn presentó una baja concentración de materia orgánica disuelta (62.0 mg L^{-1}) lo cual resultó adecuado para alimentar al siguiente reactor aerobio, con biopelícula.

Se comprobó el carácter multi-ambiente del reactor AnoxAn, ya que se consiguieron condiciones anaerobias y anóxicas, desarrollándose las diferentes actividades biológicas en cada zona. La liberación de fosfato en la zona anaerobia confirmó la eliminación de fósforo por vía biológica y fue posible gracias al mantenimiento de condiciones anaerobias. Y de acuerdo a balances de masa de nitrato, el 95% del nitrato entrante en AnoxAn fue eliminado en la zona anóxica, siendo sólo el 5% restante eliminado en la zona anaerobia. En conclusión, la novedosa configuración permitió llevar a cabo diversas funciones en un único reactor con un tiempo de retención hidráulico (TRH) de 4.2 horas: retención de biomasa; hidrólisis de materia orgánica particulada afluente; liberación de fosfato con un TRH anaerobio de 1.1 horas; y desnitrificación con un TRH anóxico de 2.7 horas.

Se recomienda continuar la investigación del funcionamiento de AnoxAn fomentando la desnitrificación y acumulación de fosfato simultáneas mediante OAFD, con el objetivo de comprobar la posibilidad de aprovechar el ahorro energético en aireación, la menor producción de fango y el máximo aprovechamiento de la materia orgánica afluente derivados de la actividad de estos organismos. Esto es de especial interés para el tratamiento de aguas residuales con disponibilidad limitada de materia orgánica (bajo ratio C/N y C/P), que podría ser deficitaria para llevar a cabo EBN con procesos convencionales. En el estudio presentado en esta tesis, a pesar de la actividad potencial de los OAFD, que fue evaluada mediante la realización de ensayos discontinuos a lo largo de la experimentación, la acumulación neta de fosfato en condiciones anóxicas resultó despreciable. Este hecho fue atribuido a la competición por nitrato entre organismos heterótrofos desnitrificantes convencionales y OAFD. Las características del agua afluente, sin limitación de materia orgánica (C/N > 10 gDQO gNT^{-1} y C/P > 80 gDQO gPT^{-1}), provocaron que la carga de nitrato a la zona anóxica fuera relativamente baja, donde la limitada exposición a nitrato de los organismos pudo dificultar la acumulación de fosfato. Esto sugiere que se podrían continuar las investigaciones en esta línea tratando aguas residuales con baja relación C/N y C/P mediante operación a escala planta piloto, lo cual puede ser complementado mediante simulación de modelos matemáticos. Analizar la flexibilidad de AnoxAn ante características variables del agua residual afluente, controlando el escape de biomasa al posterior reactor aerobio, puede ser el objetivo de futuras investigaciones.

Evaluación de la viabilidad y diseño preliminar de la ampliación de una EDAR existente para EBN basada en el innovador reactor anaerobio-anóxico, mediante modelización

El proceso de lechos bacterianos se ha utilizado ampliamente para el tratamiento de aguas residuales. Sin embargo, se trata de un proceso que en la mayoría de los casos sólo lleva a cabo eliminación de materia orgánica y en algunos casos nitrificación, pero raramente eliminación de NT y PT. En esta tesis, se ha presentado un caso real cuyo objeto era ampliar una EDAR existente de lechos bacterianos para cumplir nuevos requerimientos de nitrógeno y fósforo en el efluente. La principal restricción para la selección de alternativas era la disponibilidad limitada de espacio. Por lo tanto, el tren de tratamiento propuesto utilizaba las instalaciones existentes en la EDAR, evitando la necesidad de construir nuevos tanques o reactores. Concretamente, se propuso adaptar un gran decantador primario (TRH medio de 8.4 horas) para alojar las zonas anaerobia y anóxica necesarias para EBN, inspirado en el reactor anaerobio-anóxico de lecho de fango AnoxAn. Mediante modelización y simulación de diversos escenarios se evaluó la viabilidad de la propuesta, y se llevó a cabo el diseño preliminar y la optimización del proceso.

La concentración efluente de NT cumplió el requisito de 15 mgN L^{-1} en todos los escenarios simulados, resultando menor de 10 mgN L^{-1} en la mayoría de los casos. La desnitrificación tuvo lugar satisfactoriamente en la zona anóxica con un TRH de 4.7 horas y una concentración de SST de aproximadamente 2.7 g L^{-1}. Se mantuvo una buena desnitrificación incluso reduciendo el volumen anóxico hasta un TRH de 2.4 horas. En cuanto a la eliminación de fósforo, no se consiguió mediante la alternancia de sólo condiciones anaerobias y anóxicas, en los escenarios analizados. Esto pudo ser debido a la competencia por nitrato entre organismos heterótrofos desnitrificantes convencionales y OAFD, debido a las características del agua residual afluente, sin limitación de materia orgánica. Esto conllevó a la necesidad de incluir una etapa aerobia para completar la acumulación de fosfato. Se incorporó un bypass de fango activo desde la zona anóxica del decantador primario modificado (DPM) al lecho bacteriano para proporcionar condiciones aerobias a los OAF, pero no resultó suficiente para lograr la eliminación de fósforo. La liberación de fosfato en la zona anaerobia, prácticamente despreciable, confirmó la no ocurrencia de EBF. Esto fue atribuido al reducido TRH de la biomasa en suspensión en el lecho bacteriano, comparado con otros tipos de procesos híbridos como los reactores IFAS (reactores de biopelícula y fango activo integrados). Para aumentar el TRH aerobio de la biomasa en suspensión, se incluyó una zona aerobia adicional en el DPM. El volumen anóxico se redujo correspondientemente para alojar la zona aerobia, y se combinó con el bypass de fango activo al lecho bacteriano. Se simularon diversos escenarios y se encontraron numerosas combinaciones de volumen aerobio – caudal de bypass que lograban activar la EBF, manteniendo una excelente eliminación de nitrógeno. Se obtuvo un rango de combinaciones de volumen aerobio y caudal de bypass capaz de cumplir los requisitos de concentración efluente de NT y PT indicados en la Directiva 91/271/CEE. Las mejores alternativas que se obtuvieron se encontraban en torno a una compartimentación del DPM en volúmenes anaerobio, anóxico y aerobio con un TRH de 3.7, 2.4 y 2.3 horas, respectivamente.

Finalmente se evaluó la influencia de la concentración de oxígeno disuelto (OD) en la zona aerobia del DPM, y se observó que con una baja concentración era posible mantener la eliminación de nitrógeno y fósforo. Una concentración de OD de tan sólo 0.1 mg L^{-1} resultó suficiente para conseguir una calidad del efluente similar a la obtenida con 2.0 mg L^{-1}, lo cual puede conllevar un importante ahorro energético. Esto sugiere que la zona aerobia podría ser incorporada mediante aireación intermitente en la zona anóxica, o en una parte de la zona anóxica, siendo el caudal de aire y la duración del periodo de aireación los parámetros clave para el control del proceso.

Se puede concluir que mediante la modificación propuesta de la EDAR se podría conseguir la EBN utilizando las instalaciones existentes, sin necesidad de construir nuevos reactores. Sin embargo, se recomienda la realización de estudios a escala piloto antes de la implementación a escala real. Los resultados experimentales se podrían utilizar para la calibración del modelo, proporcionando una herramienta más fiable para confirmar el funcionamiento del tren de tratamiento propuesto bajo diferentes condiciones. Además, en el presente estudio no se ha analizado el comportamiento hidrodinámico del DPM ni el comportamiento de los sólidos en suspensión, lo cual debería ser afrontado para el diseño de detalle del DPM y los equipos y estrategia de mezcla. Futuras investigaciones se centrarán en este aspecto.

Annex

Reactor biológico anóxico-anaerobio para la eliminación de nutrientes de aguas residuales

This annex has been published as the following patent:

Tejero, I.; Díez, R.; Esteban, A.L.; Lobo, A.; Temprano, J.; Rodríguez, L. Reactor biológico anóxico-anaerobio para la eliminación de nutrientes de aguas residuales. Spanish patent ES2338979

Título

"Reactor biológico anóxico-anaerobio para la eliminación de nutrientes de aguas residuales"

Descripción

Sector de la técnica

La invención corresponde al sector técnico de procesos de depuración de aguas residuales, más concretamente en el relativo a los sistemas biológicos de eliminación de nutrientes (nitrógeno y fósforo) de aguas residuales.

Estado de la técnica

El fenómeno conocido como eutrofización, designa el enriquecimiento en nutrientes de un ecosistema provocando una abundancia anormalmente alta. En los ecosistemas acuáticos los nutrientes nitrógeno y fósforo constituyen los principales factores limitantes para el desarrollo de la biomasa. La abundancia de estos nutrientes origina un crecimiento desordenado y molesto de plantas acuáticas con importantes consecuencias sobre la composición, estructura y dinámica del ecosistema, lo que conduce de manera general a un aumento de la biomasa, un empobrecimiento de la diversidad, y en definitiva, el deterioro de la calidad del agua.

Las corrientes procedentes de las cuencas fluviales aportan continuamente nutrientes disueltos a ríos y lagos de forma natural, pero la actividad humana provoca la descarga continua de aguas residuales con un contenido importante de nutrientes, acelerando drásticamente el proceso de eutrofización de los ecosistemas acuáticos. Las principales aportaciones antropogénicas de nutrientes provienen de la descarga continua, directa o indirecta, de aguas residuales urbanas, agrícolas e industriales. Los vertidos de agua residual urbana, si no hay una depuración previa de nutrientes, aportan nitrógeno orgánico, fósforo orgánico, amonio y fosfato procedentes de las aguas fecales y los detergentes. La contaminación agropecuaria aporta nitratos, amonio y fosfatos procedentes de los fertilizantes y los excrementos animales. Los efluentes industriales, especialmente del procesado de productos alimenticios, también pueden aportar importantes cantidades de nutrientes.

Tanto a nivel nacional como europeo y mundial hay una preocupación importante y creciente en la Administración sobre el estado eutrófico de ríos, embalses, etc. Por ello se prevé una progresiva definición de zonas declaradas como sensibles a la eutrofización que implicaría la remodelación de muchas Estaciones Depuradoras de Aguas Residuales (EDAR) existentes, con el fin de capacitarlas para la eliminación de nitrógeno y fósforo, además de las nuevas que restan por construir para el cumplimiento de la normativa vigente.

Eliminar el nitrógeno y/o el fósforo antes de la descarga del agua al medio receptor es necesario además de para evitar la eutrofización, para evitar la toxicidad directa de diversos compuestos nitrogenados, y para permitir la recarga de acuíferos y otras aplicaciones de reutilización.

La eliminación del nitrógeno en una EDAR puede ser parte integral del tratamiento biológico o un proceso añadido a los tratamientos existentes. Para ello se precisa la existencia de una zona anóxica en el proceso biológico de tratamiento del agua residual, además de la zona aerobia, en una variedad de posibles configuraciones. En la zona aerobia se produce la oxidación de los compuestos de nitrógeno hasta la forma de nitratos, empleando oxígeno como oxidante, mientras que en condiciones anóxicas se produce la oxidación de sustrato carbonoso utilizando los nitratos como agente oxidante. De esta manera se obtiene nitrógeno gas molecular.

La eliminación de fósforo del agua residual implica la incorporación de los fosfatos a los sólidos en suspensión, con la posterior retirada de dichos sólidos. El fósforo se puede incorporar a precipitados químicos mediante la adición de sales metálicas o cal en diversas localizaciones dentro del diagrama de flujo del proceso de depuración. Por otra parte, el fósforo se puede incorporar a sólidos biológicos, resultando un proceso con menor coste de operación y menor producción de fango. En los últimos 30 años se han utilizado varias configuraciones de procesos biológicos de fango activo para la eliminación del fósforo. Todas ellas incluyen una zona anaerobia, en la que las bacterias acumuladoras de fósforo (PAOs) liberan fósforo al agua, previa a la zona aerobia o anóxica en la que se produce la acumulación biológica del fósforo en las mismas bacterias PAOs. La mayoría de estas configuraciones incluyen la zona anaerobia en la propia línea principal de agua, mientras que otras lo hacen en la línea de recirculación de fango.

La eliminación biológica conjunta de nitrógeno y fósforo de las aguas residuales urbanas creció notablemente en la década de 1980-1990 y se implantó empleando procesos como A^2/O, UCT, Johannesburgo y Bardenpho 5-etapas. Estos procesos incluyen zonas o etapas aerobias, anóxicas y anaerobias para desarrollar las actividades anteriormente descritas. También existen procesos SBR para la eliminación de nutrientes, que funcionan de manera discontinua utilizando un mismo volumen para las diferentes etapas.

La selección de un proceso específico para la eliminación biológica de nutrientes depende de las condiciones y características propias del lugar, de los procesos y equipos existentes y de las necesidades u objetivos del tratamiento. Cada configuración ofrece unas ventajas y limitaciones, pero a modo general, se puede resumir que los procesos biológicos convencionales para eliminación de nutrientes, basados en fangos activos en suspensión, presentan las siguientes desventajas:

- Amplias necesidades de espacio, ya que se requiere aproximadamente cuatro veces el volumen que precisaría el mismo tratamiento sin eliminación de nutrientes. En muchos casos, especialmente en ampliaciones de EDAR existentes, existe un problema de limitación de espacio si se mantiene el proceso convencional de fangos activos.

- Proceso propenso a la generación de bulking filamentoso, fenómeno de mala sedimentabilidad del fango que origina importantes problemas en la explotación de las EDAR.

- Elevado consumo energético, ya que los procesos de nitrificación y acumulación biológica de fósforo aumentan las necesidades de oxígeno del proceso.

Las nuevas tecnologías para la eliminación biológica de nutrientes pretenden mejorar los procesos convencionales aumentando los rendimientos de eliminación de nutrientes, reduciendo los requerimientos de espacio y energía, y/o aumentando la fiabilidad del proceso. Algunas de estas nuevas tecnologías optan por el empleo de un único reactor desempeñando las funciones de reactor anaerobio y anóxico, consiguiendo una importante reducción de las necesidades de espacio. Además este tipo de reactores generalmente permite la ampliación de EDAR existentes de una manera más sencilla y viable que si se utilizaran procesos convencionales. Como ejemplo de esta alternativa se encuentras las siguientes investigaciones:

Kyu-Hong Ahn et al., según el artículo "*Enhanced biological phosphorus and nitrogen removal using a sequencing anoxic/anaerobic membrane bioreactor (SAM) process*" Desalination (2003), desarrollaron e investigaron el proceso SAM (Sequencing anoxic/anaerobic membrane bioreactor) para mejorar la eliminación de fósforo obtenida por otros procesos de eliminación de nutrientes. El proceso incluye una zona aerobia, continuamente aireada, para la nitrificación y la fijación de fósforo, con una membrana sumergida para la separación sólido-líquido. El licor mezcla de esta zona aerobia se recircula intermitentemente a la zona secuencial anóxica/anaerobia (a la cual llega el caudal afluente) para alternar las condiciones anóxica para desnitrificación y anaerobia para la liberación de fósforo. Se obtuvieron unos rendimientos de eliminación de fósforo y nitrógeno del 93% y 60% respectivamente.

Park et al., según el artículo "*Small sewage treatment system with an anaerobic-anoxic-aerobic combined biofilter*" Water Science and Technology (2003), emplearon un digestor anaerobio de flujo vertical con filtro anóxico alimentado con el agua residual bruta y con la recirculación del efluente de un posterior reactor aerobio. Se obtuvo una eliminación de DQO del 71% en el digestor anaerobio y del 20% en el filtro anóxico. La eliminación de nitrógeno total fue del 70% con una recirculación del efluente nitrificado del 300%. En cambio el trabajo no muestra resultados de eliminación de fósforo, ya que se empleó la zona anaerobia como digestor para reducir la producción de sólidos.

Kwon et al., según el artículo *"Pilot study of nitrogen and phosphorus removal system in municipal wastewater using upflow multi-layer bio reactor (KNR System)"* Journal Korean Society of Environmental Engineering (2003), desarrollaron el proceso KNR para la eliminación de N y P de agua residual urbana con un reducido ratio C/N. El proceso consiste en un reactor UMBR (upflow multi-layer bio reactor) sustituyendo al habitual decantador primario, seguido de un proceso de fangos activos con reactor biológico y decantador secundario. El UMBR es un reactor de flujo vertical ascendente alimentado por el agua residual afluente junto con la recirculación de fango activo del decantador secundario y la recirculación de nitratos de la zona aerobia. La alimentación se produce por la parte inferior a través de distribuidores rotatorios. Una ligera agitación permite que se produzca un flujo pistón creando diferentes condiciones ambientales en función de la altura. Por debajo de los distribuidores de alimentación se produce el espesamiento del fango. La zona intermedia es anóxica debido a la presencia de nitratos procedentes de la recirculación de la zona aerobia. Una vez que los nitratos han sido desnitrificados completamente, se produce en la parte superior una zona anaerobia donde se lleva a cabo la liberación de fósforo. Según este diseño la disponibilidad de materia orgánica carbonosa para liberación de fósforo en la zona anaerobia está limitada dependiendo del consumo producido en la zona anóxica. Además el lecho de fango producido en el reactor supone una elevada concentración de sólidos en suspensión en la zona anóxica, mientras que esta concentración será baja en la zona superior anaerobia, disminuyendo la eficiencia en la eliminación de fósforo. Por lo tanto, el reactor UMBR ofrece dos importantes limitaciones para conseguir elevados rendimientos de eliminación de fósforo.

Kwon et al., según el artículo *"Biological nutrient removal in simple dual sludge system with an UMBR (upflow multi-layer bio reactor) and aerobic biofilm reactor"*, Water Science and Technology (2005), estudiaron un proceso compuesto por un reactor biológico multicapa de flujo vertical UMBR como reactor anóxico y anaerobio con biomasa en suspensión y un posterior reactor aerobio biopelícula con decantador lamelar. Los rendimientos de eliminación de DQO, DBO, sólidos en suspensión (SS), nitrógeno total (NT) y fósforo total (FT) fueron 92.7%, 96.4%, 96.4%, 74.9% y 76.5%, respectivamente. Los rendimientos de eliminación de NT y PT confirman las limitaciones indicadas en el párrafo anterior. Además, según los autores, la eliminación de fósforo tuvo lugar por la sedimentación y adsorción a través del lecho de fango en el UMBR, proceso a su vez favorecido por la baja relación entre fosfato y fósforo total que presentó el agua residual afluente.

Como patentes relacionadas con la presente invención se pueden citar:

La patente GB 2456836-A *Reactor for biological treatment of feedwater stream such as a municipal wastewater stream, comprises feedwater inlets, sludge outlets, effluent outlets, an anoxic/anaerobic reaction zone, and an aerobic reaction zone* (2009) muestra un reactor compacto anóxico/anaerobio y aerobio, donde la zona anóxica/anaerobia es compartida para alojar sucesivamente los ambientes anóxicos y anaerobios.

En las patentes DE4409435 *Waste water treatment appts. by biological elimination of phosphorus and nitrogen* (1994), DE3301643 *Phosphate removal from waste water – by alternate anaerobic and aerobic treatment using moving bed of sludge carrier* (1984) y US2008053897 *System for biological nutrient removal in raw wastewater feed stream to remove carbon/nitrogen/phosphorus* (2008) se describen procesos de eliminación de nutrientes que utilizan reactores biológicos anóxicos y anaerobios, pero en configuraciones diferentes a la presente invención, es decir, no utilizan un reactor compacto anóxico-anaerobio.

Las patentes KR460462 *The advanced wastewater treatment system using the marsh filter bed* (2004) y KR460463 *The garden typed advanced wastewater treatment system* (2004) muestran sistemas de tratamiento de aguas residuales que emplean un reactor biológico multicapa de flujo vertical que reúne las funciones de decantador primario, reactor anaerobio, anóxico, y espesador de fango. Este reactor, denominado UMBR, ha sido descrito en párrafos anteriores, y es la invención que se ha encontrado más similar a la presente, pero tiene las limitaciones citadas anteriormente, que son objeto de mejora en la presente invención.

Problema técnico planteado

Objetivo: eliminar o reducir el contenido de nutrientes (nitrógeno y fósforo) de aguas residuales antes de su vertido al medio o de su reutilización una vez regeneradas, mediante un reactor compacto anóxico-anaerobio integrado en el proceso biológico de una EDAR, que mejore la técnica de tratamiento biológico convencional con eliminación de nutrientes de aguas residuales.

De cara a optimizar los rendimientos de eliminación de nutrientes y al mismo tiempo disminuir los costes del proceso de depuración, se han planteado los siguientes objetivos parciales:

- Utilizar un reactor que aloje las zonas anóxica y anaerobia con elevada concentración de biomasa para magnificar los efectos físicos y biológicos obteniendo una elevada eficiencia.

- Disminuir la necesidad de espacio para la implantación de las zonas anóxica y anaerobia, mediante la utilización de un único reactor compacto anóxico-anaerobio.

- Reducir el consumo energético del proceso de depuración del agua residual mediante el empleo de las zonas anóxica y anaerobia.

- Reducir el consumo de reactivos, al eliminar biológicamente el fósforo y no precisar aporte externo de sustrato carbonoso para la desnitrificación.

La presente invención se basa en el conocimiento de los procesos de eliminación biológica de nitrógeno y fósforo, la cual se lleva a cabo en un reactor compacto anóxico-anaerobio que ha de acompañar a un proceso o reactor aerobio nitrificante y aerobio heterótrofo para afino de la oxidación de materia orgánica, en su caso, sea del tipo que sea. El objeto de la presente invención es el reactor biológico anóxico-anaerobio en el que, mediante la optimización de su configuración y de su modo de operación, se pretende compartimentar en un único reactor las dos condiciones ambientales (anóxica y anaerobia) de una manera compacta, innovadora y con elevada eficiencia. Para ello en el diseño se incluyen las características explicadas a continuación en comparación con las habituales de los tratamientos biológicos convencionales para eliminación de nutrientes por fangos activos:

1. Los procesos biológicos de eliminación de nutrientes como etapa terciaria posterior al tratamiento biológico de eliminación de materia orgánica carbonosa precisan instalaciones adicionales a los sistemas generalmente presentes en una EDAR. Para poder reducir las necesidades de espacio e instalaciones, y facilitar la ampliación de plantas existentes, la presente invención permite la eliminación de nutrientes de manera integrada en el tratamiento biológico de la planta.

2. Los procesos biológicos para la eliminación de nitrógeno con zona anóxica posterior a la zona aerobia (post-desnitrificación) precisan generalmente la

adición de sustrato carbonoso. Para evitar esta necesidad, la presente invención sitúa la zona anóxica previamente a la aerobia.

3. En los procesos químicos de eliminación de fósforo se precisa la adición de reactivos. La presente invención permite la eliminación biológica de fósforo sin necesidad de reactivos.

4. En los procesos biológicos de eliminación de nutrientes se disponen, al menos una zona anóxica y una anaerobia, además de la zona aerobia, en diferentes tanques o reactores. Ello precisa una importante ocupación de espacio e instalaciones complementarias. Frente a esto, la presente invención se caracteriza por disponer de una sola zona anaerobia y otra anóxica en un único reactor con un elevado aprovechamiento del espacio.

5. Los procesos convencionales de fangos activos para eliminación de nutrientes operan normalmente con concentraciones de sólidos en suspensión alrededor de 3.000 mg/L. La presente invención opera con concentraciones superiores de sólidos en suspensión, permitiendo un mayor aprovechamiento del volumen del reactor.

6. Los procesos convencionales de fangos activos retiran o purgan el fango en exceso desde un decantador con una concentración de sólidos en suspensión normalmente igual o inferior a 8.000 mg/L, precisando un posterior espesamiento. La presente invención permite obtener mayor concentración de sólidos en suspensión su zona inferior, desde donde se puede realizar la purga de fango, obteniendo un fango al menos parcialmente espesado.

7. Las instalaciones convencionales de fangos activos normalmente disponen de un decantador primario para eliminar parte de la materia orgánica e inorgánica del agua residual afluente, y alimentar al tratamiento biológico con menor carga orgánica y de sólidos. En cambio, la presente invención puede sustituir a dicho decantador primario, al permitir una importante eliminación de materia orgánica e inorgánica. Por lo tanto, la presente invención desempeña también la función de decantador primario, permitiendo la concentración y purga de sólidos inorgánicos y del fango en exceso, con una zona superior de clarificación, que permite alimentar al posterior tratamiento con baja carga de sólidos.

8. Los procesos biológicos que utilizan biopelícula ofrecen varias ventajas frente a los procesos de fangos activos (mayor concentración de biomasa en el

reactor, menor sensibilidad ante variaciones de carga orgánica y temperatura, etc.) y son especialmente eficientes para aguas residuales con baja carga. Uno de los inconvenientes de los procesos biopelícula es el riesgo de atascamiento del lecho. Frente a esto, el efluente de la presente invención es un agua clarificada y con baja carga, lo cual favorece el desempeño de un proceso posterior aerobio del tipo biopelícula.

9. Los procesos de separación sólido-líquido por membranas de filtración pueden sustituir al decantador secundario de un proceso biológico convencional, obteniendo un efluente de calidad muy elevada, normalmente susceptible de ser reutilizado. Los principales inconvenientes de la utilización de membranas son los elevados costes de inversión y la necesidad de controlar el ensuciamiento o fouling de las mismas. Esto último implica frecuentes limpiezas con su correspondiente consumo energético y de reactivos. Como ya se ha indicado, el efluente de la presente invención está lo suficientemente clarificado para favorecer un correcto funcionamiento de las membranas, reduciendo el ensuciamiento de las mismas.

10. A pesar de las características presentadas en los dos puntos anteriores, la presente invención puede emplearse como reactor previo a cualquier otro proceso aerobio nitrificante.

11. En los procesos biológicos convencionales con eliminación de fósforo, la acumulación de fósforo por parte de las bacterias PAOs se produce en ambiente aerobio. En cambio, la presente invención produce un secuestro parcial de las bacterias acumuladoras de fósforo, favoreciendo el fenómeno simultáneo de desnitrificación y acumulación de fósforo, o defosforación desnitrificante. Esto permite la eliminación de fósforo y nitrógeno con un consumo mínimo de materia orgánica, ya que se utiliza simultáneamente para dos fines (desnitrificar y acumular fósforo), un consumo mínimo de oxígeno, ya que la acumulación de fósforo se produce utilizando nitratos como oxidante, y una producción mínima de fango en exceso.

Descripción detallada de la invención

La presente invención consiste en un reactor biológico compartimentado verticalmente con flujo ascendente y de funcionamiento continuo. Se puede emplear en procesos de tratamiento de agua residual para eliminación de nutrientes, precediendo a otro reactor o proceso biológico aerobio nitrificante y aerobio heterótrofo para la oxidación de la materia orgánica residual.

Esta invención se distingue por ser un reactor que alberga varios compartimentos o zonas en su interior, y cumplir varias funciones en un solo reactor. Estas zonas son: zona Anaerobia, zona Anóxica, y zona de Clarificación.

La zona Anaerobia se sitúa en la parte inferior del reactor y se caracteriza por presentar una elevada concentración de sólidos en suspensión, lo que lo convierte en un lecho suspendido de fango. Esta zona dispone de un sistema de mezcla intensa que favorece la resuspensión y homogeneización del lecho de fango, y evita la formación de zonas muertas y caminos preferenciales para el flujo de agua. En esta zona se produce la hidrólisis del material particulado y la liberación de fósforo, en forma de fosfatos, por parte de las bacterias acumuladoras de fósforo (PAOs). Además en esta zona tiene lugar la acumulación y concentración de sólidos en exceso del proceso, pudiendo realizarse por su parte inferior la purga de fango. Opcionalmente puede realizarse la purga desde la zona Anóxica para reducir el contenido en fósforo disuelto del fango purgado. Se puede también realizar la purga conjuntamente desde el posterior reactor o etapa aerobio y el reactor anóxico-anaerobio.

El siguiente compartimento, en sentido ascendente, es la zona Anóxica. No existe una separación física entre las zonas Anaerobia y Anóxica, aunque para evitar caminos preferenciales y dificultar la mezcla entre ambas zonas se pueden instalar deflectores y/o tranquilizadores. Esta separación no debe impedir la circulación ascendente del agua y tampoco puede suponer una superficie sobre la que se depositen sólidos sedimentados. El volumen de la zona Anóxica es el mayor de los diferentes compartimentos del reactor, suponiendo aproximadamente el doble del volumen de la zona Anaerobia.

El sistema de mezcla de la zona Anóxica consiste en agitación mecánica a bajas revoluciones de giro para evitar la rotura de los flóculos biológicos. Además de proporcionar la suficiente mezcla en la zona Anóxica y favorecer el contacto entre los sólidos biológicos y el agua residual, la agitación mecánica tiene otras dos funciones. Por una parte reduce la sedimentación o pérdida de sólidos, aumentando su tiempo de residencia en la zona Anóxica y manteniendo la concentración de sólidos en suspensión. La concentración de sólidos en suspensión deseada en la zona Anóxica es similar o superior a la habitual en un fango activo convencional. Por otra parte la agitación mecánica proporciona la separación entre las zonas anóxica y anaerobia, ya que la separación real tiene lugar por la superficie del lecho suspendido de fango de la zona Anaerobia. Diferentes velocidades de giro del agitador permiten crear diferentes intensidades de mezcla y turbulencia, pudiendo seleccionar dicha velocidad de acuerdo a la altura del lecho suspendido de fango anaerobio deseado, y en función de la morfología exacta del reactor. Dependiendo de la superficie en planta del reactor, se puede precisar la instalación de varios agitadores repartidos por toda la superficie actuando cada uno sobre un área de influencia, y funcionando cada uno de ellos como se ha descrito anteriormente.

Las condiciones anóxicas en esta zona se producen debido a la entrada de la recirculación del efluente nitrificado de un posterior reactor o etapa aerobia, a una altura próxima a la ubicación del agitador mecánico. De esta manera, en esta zona tiene lugar el fenómeno de desnitrificación, consumiendo como sustrato la materia orgánica carbonosa del agua residual afluente con los nitratos procedentes de la recirculación como agente oxidante. Además, dado que la presencia de una zona de Clarificación reduce la concentración de sólidos en suspensión del efluente del reactor, se produce el secuestro de las bacterias PAOs en el interior del reactor, favoreciendo la defosforación desnitrificante.

Aunque la agitación mecánica reduce el paso de sólidos de la zona Anóxica a la zona Anaerobia por decantación, no lo evita completamente, produciéndose una reducción progresiva de la concentración de sólidos en la zona Anóxica, aumentando la concentración y altura del lecho suspendido de fango anaerobio. Para mantener estables las concentraciones de sólidos en suspensión en ambas zonas se dispone una recirculación de sólidos desde el fondo del reactor (zona Anaerobia) hasta la parte superior de la zona Anóxica. El propósito de esta recirculación es doble, ya que además de mantener las concentraciones de sólidos favorece la exposición alterna de bacterias PAOs a las condiciones anóxicas y anaerobias.

La zona de Clarificación, ubicada en la parte superior del reactor, ocupa un pequeño volumen comparado con las otras zonas (aproximadamente el 10% del volumen del reactor). La tranquilización se consigue por la distancia que separa esta zona del agitador mecánico de la zona Anóxica, y se favorece por la colocación de un medio de soporte fijo de biopelícula y separador sólido - líquido entre las zonas Anóxica y Clarificación. Este medio soporte y separador proporciona un medio para el crecimiento de biopelícula y además actúa como filtro para las partículas que fluyen ascendentemente. La biopelícula estaría colonizada por organismos desnitrificantes aumentando la concentración útil de biomasa en la zona Anóxica. Como medio de soporte y separador se puede utilizar cualquier soporte fijo utilizado como base para el crecimiento de biopelícula, incluido módulos de decantación lamelar.

La salida final del reactor se produce por la parte superior del mismo, en la zona de Clarificación, y se puede llevar a cabo a través de una conducción lateral, vertedero perimetral o canaletas de recogida de agua clarificada.

Descripción del Equipo

El presente invento consta de los siguientes elementos (aunque en determinadas condiciones puede no emplearse alguno de ellos o emplearse algún otro): depósito compartimentado verticalmente abierto por su parte superior al que llamamos reactor (1), resistente a la corrosión, que posee un fondo inclinado (5) para la concentración de sólidos, un deflector o tranquilizador (6) situado entre la zona Anaerobia (2) y la zona Anóxica (3), y un medio soporte para biopelícula y separador sólido – líquido (7) situado entre la zona Anóxica (3) y la zona de Clarificación (4).

El sistema de mezcla y agitación está formado por: una bomba de recirculación (9), una válvula automática NA (10), otra válvula automática NC (11), y un agitador mecánico de bajas revoluciones (8). En su lugar, el sistema de mezcla puede utilizar agitadores sumergidos.

El sistema de purga de fango en exceso utiliza la misma bomba de recirculación (9) y una válvula automática NC (12). En su lugar, se puede utilizar una bomba independiente para la purga, con las correspondientes válvulas automáticas temporizadas o controladas.

Las conexiones de entrada/salida del reactor (1) son: entrada (13) de agua residual afluente en zona Anaerobia (2), salida (14) de agua efluente desde zona de Clarificación (4), y recirculación (15) de efluente nitrificado de una posterior etapa aerobia a zona Anóxica (3).

El sistema de control está compuesto por: medidor de altura (17) del lecho suspendido de fango (sensor óptico o de ultrasonidos), medidor de concentración de sólidos en suspensión (16) en zona Anóxica (3) (sonda de sólidos en suspensión o turbidez), controlador automático (18) para registro de datos y apertura y cierre de válvulas automáticas, y regulador de velocidad de giro (19) del agitador mecánico (8) (Ver Figura 1). Este sistema puede estar formado por otros sensores, controladores y actuadores que en todo caso realicen las funciones necesarias, descritas a continuación.

Descripción del funcionamiento

El agua residual bruta, previamente pretratada (desbaste, tamizado y desarenado-desengrasado) se introduce en el reactor (1) por la conexión de entrada (13), accediendo a la zona Anaerobia (2). El sistema de mezclado de esta zona funciona de manera continua proporcionado una mezcla completa y formando un lecho suspendido de fango anaerobio que ocupa la zona Anaerobia (2).

La única posibilidad de evacuación del agua de la zona Anaerobia (2) es por su parte superior accediendo así a la zona Anóxica (3) por flujo ascendente. Entre la zona Anaerobia (2) y Anóxica (3) se dispone un deflector o tranquilizador (6) que interrumpe las corrientes preferenciales del fluido sobre la pared del depósito, de manera que se evita el mezclado entre las dos zonas. Además, este deflector o tranquilizador (6) facilita la formación de la superficie del lecho suspendido de fango anaerobio, produciéndose desde la parte superior del deflector (6) la mezcla de la zona Anóxica (3) mediante el agitador mecánico (8), que puede ser de eje vertical o de eje horizontal. En esta zona Anóxica (3) se produce el mezclado con el efluente nitrificado de una posterior etapa aerobia, que accede por la conexión de recirculación (15).

Mediante el regulador de velocidad (19) se selecciona la velocidad de giro del agitador mecánico (8) que proporciona la altura del lecho suspendido de fango anaerobio en el nivel deseado, facilitado por el deflector o tranquilizador (6). Esta agitación mantiene los sólidos en suspensión en la zona Anóxica (3) retardando su decantación hacia el lecho suspendido de fango anaerobio, pero sin evitar la progresiva reducción de la concentración de sólidos en suspensión en la zona Anóxica (3). Por ello, periódicamente se produce la apertura de la válvula NC (11) y el cierre de la válvula NA (10), resuspendiendo la cantidad de sólidos necesaria para restituir la concentración deseada en la zona Anóxica (3). A continuación se vuelve a la posición cerrada de la válvula NC (11) y abierta de la válvula NA (10). El sistema de resuspensión de sólidos descrito utiliza la bomba (9) de mezcla y agitación de la zona Anaerobia (2), pero también puede utilizar una bomba independiente para realizar la función de resuspensión de sólidos.

La circulación ascendente provoca el paso del agua a través del soporte fijo y separador sólido - líquido (7) y la biopelícula formada sobre el mismo, accediendo a la zona de Clarificación (4) con baja concentración de sólidos en suspensión. La salida (14) del agua efluente se produce por la parte superior del reactor (1) a través de una conducción lateral, de un vertedero perimetral o de canaletas de recogida del agua clarificada.

Mediante el sistema de purga de fango se retira el fango en exceso del proceso. Esta purga se puede realizar desde el fondo del reactor (1), mediante la bomba de recirculación (9) y la apertura de la válvula NC (12) comandada por el controlador (18). Para la acumulación de sólidos se dispone de un fondo inclinado (5) en la zona Anaerobia (2). El sistema de acumulación de fango puede disponer también de rasquetas que concentran el fango en el fondo del reactor (1). Opcionalmente se puede hacer la purga desde la zona Anóxica (3), de manera que aunque el fango purgado tenga menor concentración de sólidos en suspensión, no tendrá fósforo disuelto en alta concentración. En este caso la zona Anóxica (3) puede disponer de concentradores de fango.

El controlador automático (18) registra los valores obtenidos por el medidor de altura (17) del lecho suspendido de fango y el medidor de concentración de sólidos en suspensión (16) en zona Anóxica (3). De esta manera se permite conocer la evolución del funcionamiento del reactor (1) en cuanto a la concentración de biomasa en las zonas Anóxica (3) y Anaerobia (2). La orden de apertura y cierre de la válvula automática NC (11) y la válvula automática NA (10) respectivamente, dada por el controlador (18) para llevar a cabo la recirculación de biomasa de la zona Anaerobia (2) a la Anóxica (3) puede producirse de manera temporizada, o bien mediante el control de la concentración de sólidos en suspensión en la zona Anóxica (3) llevado a cabo por el medidor de concentración (16), tomando como consigna para llevar a cabo la recirculación de biomasa un valor mínimo de concentración de sólidos en suspensión. La purga de fango también se puede llevar a cabo de manera temporizada mediante la apertura de la válvula automática (12) por orden del controlador (18), o bien a partir de la altura del lecho suspendido de fango indicada por el medidor de altura (17) y registrada en el controlador (18).

Se ha comprobado la viabilidad técnica de la idea mediante la experimentación en un reactor a escala de bancada de 49 litros de volumen con un caudal afluente de 10 L/h en la cual se analizaron las necesidades de resuspensión de sólidos. Se obtuvo como resultado que para mantener unas concentraciones de sólidos en suspensión de 3.000 y 8.000 mg/L en las zonas Anóxica (3) y Anaerobia (2) respectivamente, se precisaría el funcionamiento de la resuspensión de sólidos mediante una bomba (9) de caudal 60 L/h durante aproximadamente 50 segundos cada 10 minutos.

Ventajas

Las ventajas del reactor descrito, debidas fundamentalmente a la utilización de un único reactor, su configuración y su modo de operación son:

1. Reducción y simplificación de las instalaciones necesarias en el proceso global de tratamiento en una EDAR, al reunir en un único reactor compacto las funciones de decantador primario, zona anaerobia, zona anóxica y espesamiento de fango.

2. Viabilidad para ampliación de EDAR existentes, sustituyendo al decantador primario.

3. Eliminación del consumo de reactivos al no precisar aporte de sustrato carbonoso para la desnitrificación y al eliminar el fósforo biológicamente.

4. Optimización en el aprovechamiento de la materia orgánica del agua residual, lo que hace que el proceso sea aplicable a aguas residuales con bajas relaciones C/N y C/P.

5. Reducción del consumo energético para mezclado al funcionar por flujo ascendente.

6. Reducción del consumo de oxígeno del tratamiento posterior, al favorecer la desnitrificación y acumulación de fósforo simultáneas en la zona Anóxica.

7. Obtención de una elevada eficiencia en comparación con otras tecnologías empleando el mismo volumen, al operar con elevada concentración de biomasa, o bien necesidad de menor volumen de reactor para obtener los mismos resultados.

8. Reducción del espacio necesario para la implantación de un proceso de eliminación biológica de nutrientes.

9. Obtención de un efluente con baja carga contaminante, ya que la mayor parte de la materia orgánica biodegradable y de los sólidos en suspensión se elimina en el reactor.

10. Mejora del funcionamiento de un posterior reactor aerobio biopelícula al reducir el riesgo de atascamiento y permitir su especialización como nitrificante. No obstante, el tratamiento posterior al reactor biológico anóxico-anaerobio puede ser cualquiera del tipo aerobio nitrificante y aerobio heterótrofo para afino de materia orgánica.

11. Mejora de un posterior proceso de separación sólido-líquido por membrana al reducir el ensuciamiento y las necesidades de limpieza de la misma. No obstante, el tratamiento posterior al reactor biológico anóxico-anaerobio puede ser cualquiera del tipo aerobio nitrificante y aerobio heterótrofo para afino de materia orgánica.

Breve descripción de los dibujos

Figura 1:

1. Depósito (Reactor)
2. Zona Anaerobia
3. Zona Anóxica
4. Zona de Clarificación
5. Fondo inclinado
6. Deflector/Tranquilizador
7. Soporte fijo y separador sólido-líquido.
8. Agitador mecánico de bajas revoluciones
9. Bomba de recirculación
10. Válvula automática NA para recirculación y mezcla de zona Anaerobia
11. Válvula automática NC para recirculación de biomasa desde la zona Anaerobia a la Anóxica
12. Válvula automática para purga de fango
13. Entrada de agua residual afluente
14. Salida de agua tratada
15. Entrada de recirculación de efluente nitrificado en una posterior etapa aerobia
16. Medidor de concentración de sólidos en suspensión en zona Anóxica
17. Medidor de altura de lecho suspendido de fango en zona Anaerobia
18. Controlador para registro de datos, automatización y control de válvulas automáticas
19. Regulador de velocidad de giro del agitador mecánico

Bomba

⋈ Válvula

Válvula automática

Conducciones hidráulicas

Línea de captación de datos

Circuito de mando eléctrico

Reivindicaciones

1. Reactor biológico anóxico-anaerobio para la depuración y la eliminación de nutrientes de aguas residuales que comprende: un depósito (1) compartimentado verticalmente en orden ascendente en tres zonas: Anaerobia (2), Anóxica (3) y Clarificación (4), con entrada de agua residual afluente (13) en zona Anaerobia (2), salida de agua tratada (14) desde zona de Clarificación (4) y entrada de recirculación (15) del efluente nitrificado de una posterior etapa aerobia en la zona Anóxica (3), un sistema de mezcla de la zona Anaerobia (2), un sistema de mezcla de la zona Anóxica (3), un sistema de acumulación de fangos en la zona Anaerobia (2), un sistema de recirculación de biomasa mediante bombas desde la zona Anaerobia (2) a la zona Anóxica (3) y un sistema de purga de fangos.

2. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, caracterizado por la posibilidad de emplear tanto deflectores (6) como otros elementos tranquilizadores para favorecer la separación entre la zona Anaerobia (2) y la zona Anóxica (3).

3. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, caracterizado por disponer de un soporte fijo y separador sólido - líquido (7) para la formación de biopelícula, para favorecer la separación de los sólidos arrastrados por el flujo de agua y para tranquilización o reducción de la transmisión de turbulencia de la zona Anóxica (3) a la zona de Clarificación (4).

4. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, en el que el sistema de mezcla de la zona Anaerobia (2) utiliza bombas externas de recirculación (9) o bien agitadores sumergidos.

5. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, en el que el sistema de mezcla de la zona Anóxica (3) comprende agitadores mecánicos (8) de eje vertical de bajas revoluciones, o bien agitadores sumergidos de eje horizontal.

6. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, en el que la recirculación de biomasa desde la zona Anaerobia (2) a la zona Anóxica (3) se realiza mediante las bombas externas (9) del sistema de mezclado de la zona Anaerobia (2) y válvulas automáticas (10, 11), permitiendo el accionamiento intermitente temporizado o controlado tanto del mezclado como de la recirculación.

7. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, en el que el fondo (5) del reactor (1) está inclinado con cierta pendiente para favorecer la acumulación de sólidos.

8. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, en el que la acumulación de fangos se realiza mediante rasquetas radiales de fondo, bien de accionamiento central o periférico, o mediante rasquetas a lo ancho de accionamiento por puente o por cadenas.

9. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, en el que el sistema de purga de fangos utiliza bombas propias o bien las bombas (9) del sistema de mezclado de la zona Anaerobia (2) y válvulas automáticas (12) temporizadas o controladas.

10. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, en el que el sistema de purga de fangos se realiza mediante bombas o válvulas temporizadas o controladas que extraen el fango mediante tuberías que parten de concentradores de fangos colocados en la zona Anóxica (3).

11. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con las reivindicaciones 1, 4 y 5, caracterizado porque mediante la velocidad de giro de los agitadores (8) se establece la altura del lecho suspendido de fango de la zona Anaerobia (2).

12. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, caracterizado por disponer de un sistema de medida de la altura del lecho suspendido de fango de la zona Anaerobia (2) mediante un sensor (17) óptico o por ultrasonidos.

13. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con la reivindicación 1, caracterizado por disponer de un sistema de medida de la concentración de sólidos en suspensión en la zona Anóxica (3) mediante una sonda (16) de sólidos suspendidos o de turbidez.

14. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con las reivindicaciones 1, 6 y 13, caracterizado porque mediante el sistema de recirculación de biomasa controla la concentración de sólidos en suspensión de la zona Anóxica (3), medida por la sonda de concentración (16).

15. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con las reivindicaciones 1, 9, 10 y 12, caracterizado porque mediante el sistema de purga de fango controla la altura del lecho suspendido de fango de la zona Anaerobia (2), medida por el sensor de altura (17).

16. Dispositivo para la eliminación de nutrientes de aguas residuales, de acuerdo con las reivindicaciones 1, 6, 9, 10, 11, 12, 13, 14 y 15, caracterizado por disponer de captación de los datos de los sensores, tratamiento de los mismos y automatización y control de las válvulas automáticas, bombas y agitadores.

Dibujos

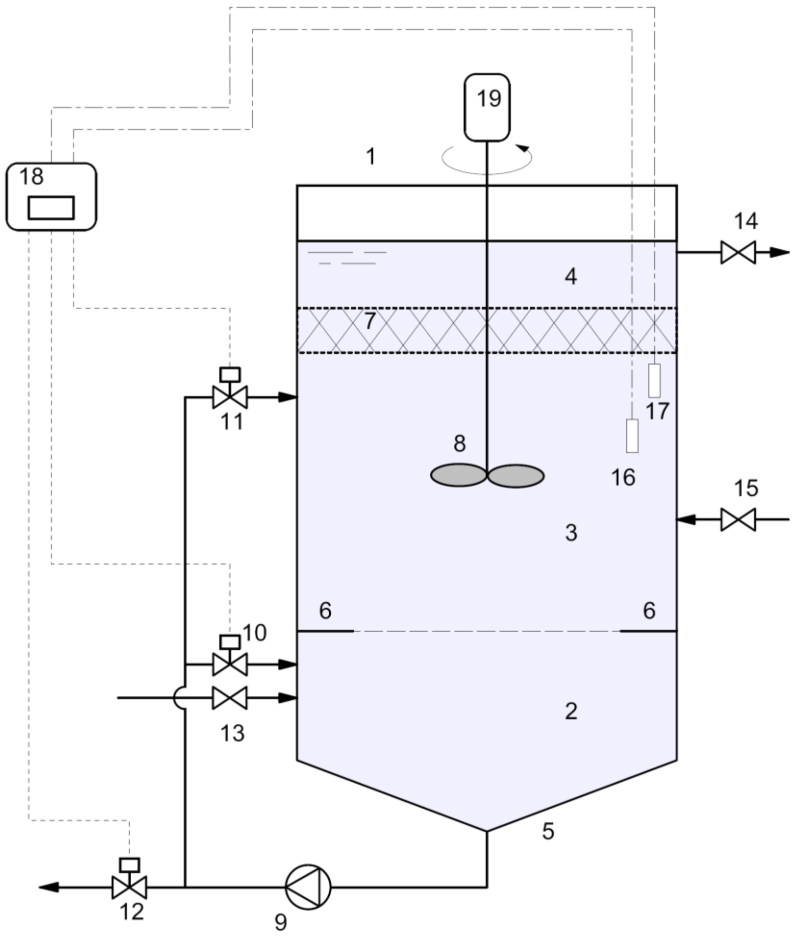

Figura 1