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Nitrogen removal from municipal wastewater using aerobic granules

Impact on the energy consumption and potential for the WWTP optimization

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SUMMARY

The electrical energy consumption of Swiss Waste Water Treatment plants (WWTP) is substantial, approximately 450 GWh per year. Recent studies show an interesting optimization potential of 188 GWh per year. About 40% of the electricity is consumed by the aeration for the biological process. The proposed project offers a new approach to upgrade municipal and industrial WWTPs, using aerobic granular biomass for a more energetically efficient (energy reduction around 10-20%) and a biologically active wastewater treatment process.

The project was carried out in field conditions using on-site pilot plants in order to compare the Puratis aerobic granular process ARGUS with a conventional activated sludge process under continuous and batch conditions. The results obtained were used to prepare a mathematical model, which describes the process and evaluates the energy efficiency potential of the ARGUS process.

The crucial element in the ARGUS process is the quality of the microbial community, which directly affects the process and energy efficiency. A higher percentage of nitrifying community is the principal factor influencing the competitiveness and energy-advantage of the ARGUS process compared to the conventional activated sludge process.

Taking into the account that nitrification needs about 5% of the aeration energy the mean energy consumption for nitrification will then be 9 GWh per year when all WWTPs in Switzerland will be equipped with a nitrification process.

With the ARGUS process, it is possible to reduce the energy demand for nitrification in about 50% or 4.6 GWh per year in case that all WWTPs in Switzerland install ARGUS process. Additionally, a 10% of COD reduction might increase the saving potential to 40-50 GWh per year in case that all municipal plants apply ARGUS process.

Even though these numbers are hypothetical, they reflect the potential of the ARGUS process to contribute to the energy saving in the municipal domain and not only a more process-efficient but also an energy-efficient wastewater treatment process can be achieved.

This report provides the overview of all achieved results on the course of the project and evaluates the potential of the ARGUS process. The results also serve as the technical basis for a future project follow-up.

GLOSSARY:

ARGUS - Puratis aerobic granular process
COD – Chemical Oxygen Demand
D.O. – Dissolved Oxygen
gPROMS - advanced process modeling
GWh - Giga Watts per hour
GHG- Green House Gas
HRT – Hydraulic Retention Time
MLSS – Mixed Liquor Suspended Solids
NEREDA – RoyalHaskoning DHV aerobic granular process
NH_4-N – Ammonia Nitrogen
NO_2-N – Nitrite Nitrogen
NO_3-N – Nitrate Nitrogen
PE – Person Equivalent
SBR – Sequencing Batch Reactor
SS - Suspended Solids
WWTP – Waste Water Treatment Plant

CONTENT

1 Project basis

Waste Water Treatment Plants (WWTPs) are one of the most expensive public industries in terms of energy requirements, accounting for more than 1% of consumption of electricity in Europe. EU Water Framework Directive (WFD) 91/271/CEE made obligatory the wastewater treatment for cities and towns. Now within the EU-27, the total number of WWTPs is estimated as 22.558, for which the total energy consumption is 15,021 GWh per year. Although most of the objectives of the WFD in relation to water protection have been achieved, most of these aging plants show unsustainable energy consumption and must be optimized to the maximum and renovated accordingly. Here we present more facts regarding the electric energy consumption in EU countries (ENERWATER, 2015):

- In the United Kingdom, where roughly 3% of generated electricity is used by the water industry alone, energy efficiency is also of growing interest. Besides, some recent studies have highlighted the importance of greenhouse-gas (GHG) emissions coming from energy use in the water sector. They show that water-related energy use in the US accounts for nearly 5% of total GHG emissions, and the proportion is even higher in the UK.

- In Italy, the energy consumption of the integrated water service is about 7.5 billion of kWh/year.

- In Spain the three major sources of consumption in the public sector are: 1. Street lighting; 2. Drinking water supply & wastewater treatment, 3. Water desalination.

- Within the EU-27, the total number of Urban Wastewater Treatment plants is 22.558 (agglomerations>2.000 PE), where 96% of them include secondary, nutrient removal or more stringent treatments. A similar ratio applies to wastewater in EU big cities, with 586 big cities that comprise 250.2 million PE.

Taking into account that the total population in the EU-27 is around 500.7 million and assuming an energy intensity use from the urban wastewater treatment of 30 kWh/PE·per year, we can estimate a total energy consumption associated to this sector of 15,021 GWh per year.

The electrical energy consumption of Swiss Waste Water Treatment plants (WWTPs) is substantial, approximately 450 GWh per year. Recent studies show an interesting optimization potential of 188 GWh per year (BAFU Bundesamt für Umwelt (OFEV) and Holinger AG Ingenieurunternehmung, 2012) About 40% of the electricity is consumed by the aeration for the biological process, which is thea target point in this project.

The aim of the project was to evaluate a biotechnological approach to upgrade municipal and industrial WWTPs, using the Puratis Sàrl aerobic granular biomass process (ARGUS) for a more energetically efficient and biologically active wastewater treatment process.

2 Project objectives and the achieved results

The objective of the proposed project was to reduce the electricity consumption of biological wastewater treatment in conventional WWTPs by an estimated 10-20% through the following means:

1. Integrating aerobic granular biomass with the existing activated sludge systems forming a “hybrid biology”, which aims to increase the biological system activity for nitrogen removal of non-nitrifying WWTPs. The expected reduction in energy consumption is 15%.

2. A higher carbon compounds removal efficiency of the hybrid biological process will contribute to the additional 5% energy saving in an existing WWTP.

3. The process improvement and process control will be supported and optimized by the integration of the adapted mathematical model developed to be integrated in the existing modeling software package.

The results of the project can be summarized as follows:

1. Two different approaches were used: a hybrid system (combination of activated sludge and ARGUS granular biomass) and pure ARGUS granular biomass in order to test the process efficiency and energy efficiency. The results achieved showed that up to 1/3 of the hydraulic retention time can be reduced and in average 15-25% of energy for the oxidative processes (nitrification) can be reduced.

2. The ARGUS granular biomass principally increases the nitrification activity due to an enrichment of the nitrifying community in the granules and in a lower proportion decreases the COD. The decrease of the COD contributes to an additional 5-7% overall energy savings.

3. Based on the qualitative analysis, the Puratis ARGUS granular biomass process is similar to the activated sludge process, with the exception that an initial biomass concentration has to be specified to run the simulations. A batch reactor model including a 1D biofilm model to represent the granules was developed for this project. The results of the model-based calculations correspond to the results obtained from the pilot plants tests. This model could be used as a tool to evaluate the composition of granules depending on the characteristics of the water in which they are grown. It could also be used to evaluate the long-term stability and the modification of the composition of granules.

A more detailed description of the project execution and achieved results are presented in the following chapters.

3 Technical basis of the project

3.1 Aerobic granular biomass in wastewater treatment

Aerobic granules technology is a novel approach for the biological treatment of high strength industrial wastewater. Compared to conventional bioflocs with their loose structure and comparatively poorer settling properties and density, granular biomass has a strong structure and excellent settling properties (Lettinga *et al.*, 1984). Granular sludge was first described for strictly anaerobic systems in 1984 by Lettinga and collaborators (Lettinga *et al.*, 1984) and only later other groups adapted and used this principle for the formation and application of aerobic granules (Leenheer *et al.*, 1982; Stuermer *et al.*, 1982; Inizan *et al.*, 2005). The granular sludge improves settling characteristics, greatly facilitating the solid-liquid separation. This has as a consequence the need of smaller settlers (Adav *et al.*, 2008; EPA-US, 2013). Compact structured aerobic sludge granules with wide diverse microbial species has a high biomass retention and tolerance to toxicity (EPA-US, 2013). The process of granulation of microorganisms occurs under specific process conditions, facilitated by the excretion of microbial biopolymers that are used for microgranulation of selected microorganisms. In further stages, microgranules are merged into granules (Liu *et al.*, 2004; Zhang *et al.*, 2007).

Aerobic granules are commonly known to exhibit attributes of:

1) Regular, smooth and nearly round in shape
2) Excellent settleability
3) Dense and strong microbial structure
4) High biomass retention
5) Ability to withstand at high organic loading
6) Tolerance to toxicity

The team of the company Puratis Sàrl developed the ARGUS (**A**e**r**obic **G**ranules **U**pgrade **S**ystem) process for highly loaded, toxic, hardly biodegradable industrial wastewater in order to remove high nitrogen loads and difficult biodegradable compounds.

After years of laboratory and pilot plant testing, the right mechanism of granulation and maintenance of granules on industrial wastewater was found, which resulted in a new aerobic granular process. The ARGUS process has been successfully applied in four pharmaceutical industries, two chemical industries and a landfill leachate treatment plant. The achieved full-scale results indicate significant process advantages over conventional activated sludge systems.

Granulation of microorganisms, which provides strength and stability to the system, occurs under specific process conditions, which facilitate the excretion of microbial biopolymers that are used for microgranulation of selected microorganisms and later the formation of granules (Figure 1 and Figure 2.).

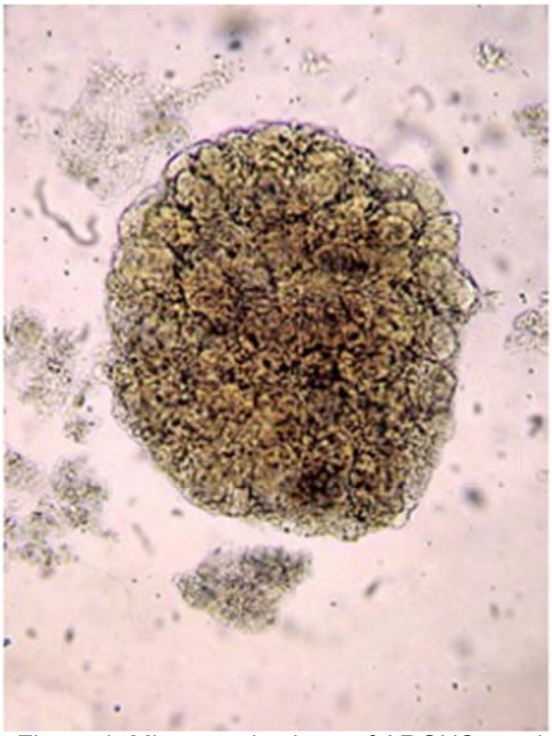


Figure 1. Microscopic photo of ARGUS aerobic granule applied on pharmaceutical industry Krka d.d., Novo mesto, Slovenia (magnification 400x).

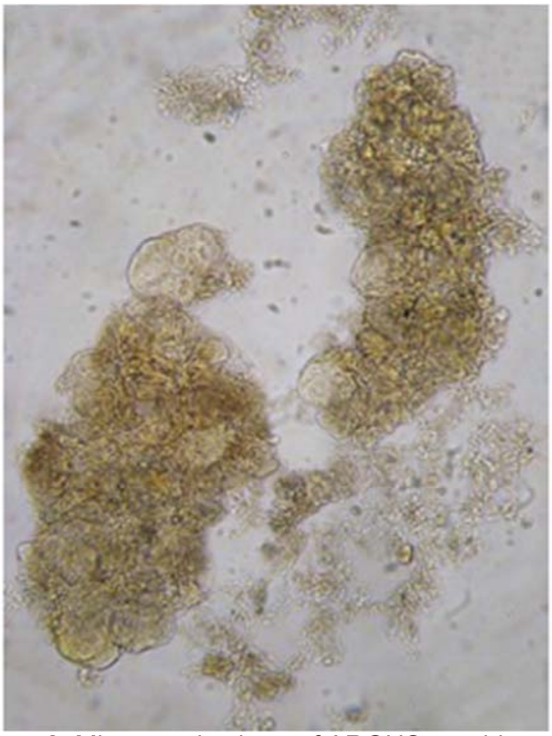


Figure 2. Microscopic photo of ARGUS aerobic granules on OLAZ landfill leachate, The Netherlands (magnification 400x).

The ARGUS process is not the only aerobic granular process on the market. NEREDA, an aerobic granular process developed by the company DHV Water (now RoyalHaskoningDHV, The Netherlands), together with the University of Delf, offers a benchmark for the granular processes in wastewater treatment. In contrast with the ARGUS process, which uses selected microorganisms, the NEREDA granular process is based on activated sludge granulation. In the following illustrations, a comparison between the ARGUS and NEREDA processes is presented (Figure 3 and Figure 4).

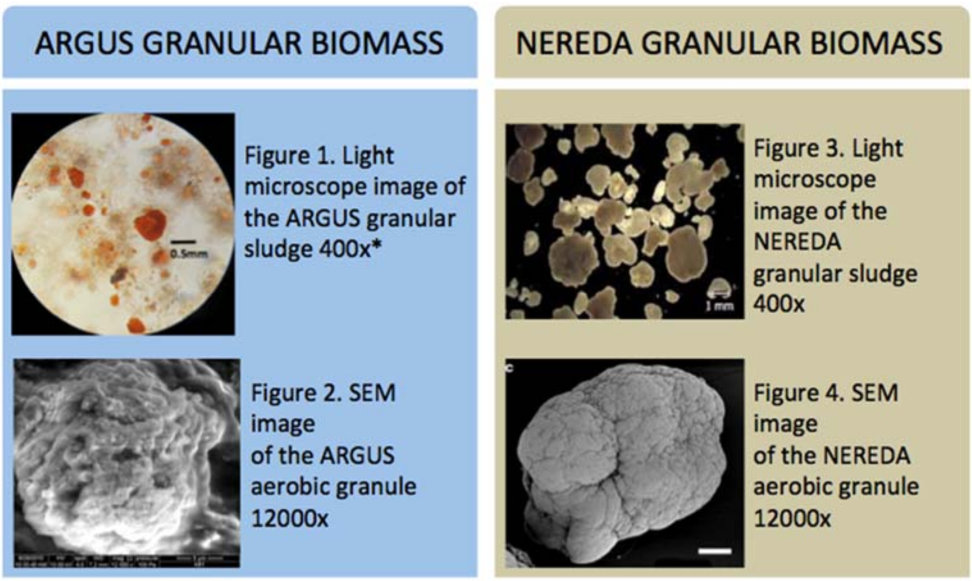


Figure 3. Microbiological and morphological differences between the ARGUS and NEREDA aerobic granular processes.

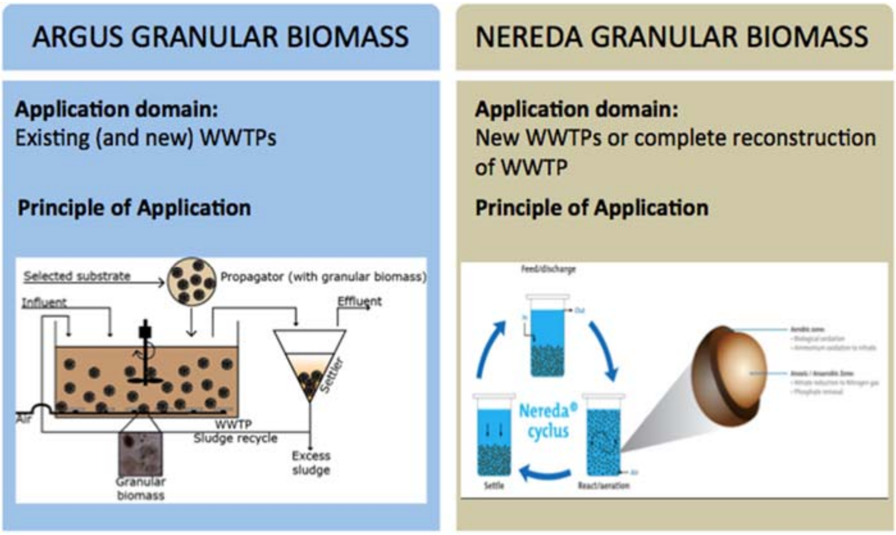


Figure 4. Application differences between the ARGUS and NEREDA aerobic granular processes.

Three main differences between ARGUS and NEREDA can be outlined:

1. Microbiology
2. Morphology and size
3. Application

Microbiology

The ARGUS process distinctive characteristic lies in its microbiological basis, that is, the microbial community forming the granules. During the granulation process, pre-selected microorganisms are used to form granules. The microorganisms are isolated using selective media, which is based on the compounds to be treated in the wastewater. The NEREDA granules are formed using activated sludge, as the basis for granulation.

Morphology and size

Due to the specialized microbial community used to form the granular biomass, ARGUS granules are smaller in size comparing with NEREDA granules, which have higher a biodiversity. However, the limited biodiversity in the ARGUS granules provides them with a higher compactness and stability of the granular form over a longer period of time.

Application

The market approach of the ARGUS granular process is directed to the upgrade of existing wastewater treatment plants, principally using the existing infrastructure with minimum technical changes. ARGUS granules are prepared in on-site bioreactors (corresponding to a 2-5% of the main biological tank size) and dosed in a specific percentage to the WWTP. On contrast, the NEREDA granular process has to be applied on completely new WWTPs.

The NEREDA process is further referenced for comparative purposes.

3.2 Mathematical modeling in wastewater treatment

In wastewater treatment, we have to deal with a complex modeling framework, which is represented schematically on the Figure 5.

It is important to consider at the same time all the relevant physical phenomena and their coupling to build representative models of the treatment processes.

Simulation and process modeling are powerful tools to optimize complex biological processes. In order to take full profit of the process optimization potential, the project proposes to integrate the development of an adapted mathematical model for granular and hybrid biological systems in an existing software tool. The simulation software will allow a better process understanding and simplified dimensioning for the validation of the applicability and replication of the new technology to different WWTP in the future.

The level of complexity of the models used should be chosen accordingly to the objective of the engineering project and the application that is looked for (design, control and optimization) (Hauduc *et al.*, 2013).

For that reason, Bluewatt Engineering Sàrl has developed a flexible and modular modeling framework called gWater. These models are implemented under a specialized advanced mathematical environment (gPROMS) where they are combined (with all the required expertise) to represent a wide range of process units: from a simple mass balance model to a detailed reactor including control simulation up to a plant-wide flow-sheet model including the water and the sludge treatment line.

Different level of detail concerning the biochemistry modeling and the wastewater characterization are implemented in gWATER. Available biological models range from the standard IWA ASM (Henze *et al.*, 1999) models to more complex plant-wide models, which are able to give a complete representation of a plant by including the anaerobic digestion process and the sludge line processes (Descoins *et al.*, 2012).

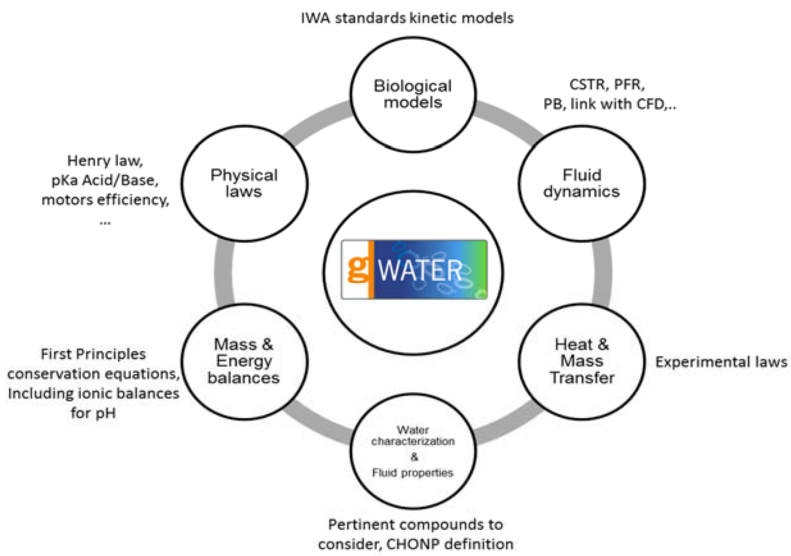


Figure 5. gWater Modular Modeling Structure.

Customized biological models can also be constructed based on lab-scale or pilot-scale experiments, for example if a specific chemical compound needs to be considered because of its impact on the biology. The open and flexible structure of gWATER allows to easily building new biological models from existing ones.

Developments have also been made to describe a more complex and more representative microbial ecosystem that is involved in nitrogen transformation processes (including for example anammox bacteria), based on the scientific literature and the current progress in wastewater treatment modeling (Ni *et al.*, 2013).

Indeed, there is a growing number of technologies that rely on an improved usage of the nitrogen-related microbial species naturally present in water to deal with high N-load effluent. These technologies are more and more frequent in wastewater treatment, and it is becoming important to have a mathematical representation of these specialized treatments for engineering purposes (design, control design and operation). Modeling can also be a good tool for technology providers to further understand and improve the design and operation of these processes.

Concerning granular sludge, mathematical modeling has proven to be particularly useful because of the complexity of the various phenomena involved in aerobic granular sludge systems (Beun *et al.*, 2001; Lübken *et al.*, 2005). It has been shown that many factors like substrate diffusion inside granules, biological conversion rates, granule size, biomass spatial distribution, etc., influence each other and render the experimental study extremely challenging.

A good computational model for the granular sludge process provides significant insight in the most important factors that affect the nutrient removal rates and in the distribution of different microbial populations in the granules. Furthermore the use of representative models within an optimization and experiment design platform (like gPROMS) is a good way to estimate various control strategies linked to operating conditions of the reactors. The energy consumption and the nitrogen removal performances can be deeply investigated, and the numerical simulations can be used to further improve the experimental campaign and the use of the pilot. Noticeably, the models can also be used to compare in a rigorous way the performance of this technology with more classical WWTP configurations (already available in gWATER).

The granular sludge model that was developed during this project is based on the state-of-the art of the scientific knowledge on this topic; see (Beun *et al.*, 2001; Lübken *et al.*, 2005; de Kreuk *et al.*, 2007)for instance.

4 Project execution and evaluation of work packages

4.1 Project execution

The project was structured in 3 well-integrated work packages (WPs) distributed over the period of 24 months. Work package 1 (WP1) is related to the laboratory activities in order to obtain, isolate and select microorganisms and prepare the starting aerobic granular biomass and evaluate the crucial process parameters for aerobic granular process modeling. Work package 2 (WP2) is dedicated to the pilot plant tests on the selected locations such as the municipal WWTP Broc and WWTP Orbe. The pilot plant tests were executed in order to simulate parallel treatment process lines, that is, one line containing the conventional activated sludge treatment and the second with the ARGUS aerobic granular biomass. As part of the WP2 the preliminary energy requirements for the aeration and ammonia oxidation were calculated. Work package 3 (WP3) aimed to evaluate and validate the mathematical model concept prepared in WP1, which should provide the information regarding the energy efficiency of aerobic granular biomass for nitrogen removal compared with the conventional activated sludge process.

4.2 Project work packages

In the following description, the work packages with their main objectives are shortly presented.

Workpackage 1: Laboratory tests in order to determine process parameters for the aerobic granular process.

Objectives:
- Adaptation of granular biomass to the specific conditions on selected WWTP
- Determination of the biokinetic parameters
- Definition of the process configuration
- Determination of operational and process parameters
- Determination of key process parameters for mathematical modeling
- Implementation of mathematical modeling for aerobic granular process

Workpackage 2: Pilot plant simulation of the activated sludge improvement with the aerobic granular biomass

Objectives:
- Setting up the pilot plants at selected WWTP
- Determination of microbial stability
- Determination of process stability
- Determination of energy requirements for the aeration and ammonia oxidation
- Comparative study of the existing activated sludge and hybrid system efficiency for the nitrogen removal concerning technical and economical aspects
- Protocol for fast aerobic granules start up process
- Operation and maintenance protocols of aerobic granular sludge

Workpackage 3: Energy analysis of the proposed process

Objectives:

- Data preparation in view of model calibration
- Model calibration
- Model validation and assessment.
- Model-based energy evaluation of the proposed technology compared to main-stream treatment

A more detailed depiction of the activities, results and outcomes are presented in the following sections.

WORKPACKAGE 1: LABORATORY TESTS IN ORDER TO DETERMINE PROCESS PARAMETERS FOR THE AEROBIC GRANULAR PROCESS

The lab equipment and materials required to cover this WP were prepared during the first month of work (April 2015). The equipment included a rotary shaker, an incubator and a stereomicroscope.

The materials required for this activity included growth media chemicals, ammonia (NH_4), nitrite (NO_2) and nitrate (NO_3) standard solutions, NH_4 measurement kits (Merck®), glass lab-scale bioreactors, etc. (more detailed information about the media composition and process parameters were included in the Progress Report 01).

Using standard and proprietary selective media for isolation of nitrifying microorganisms (GSN), on Petri dishes, the sample of activated sludge from WWTP Broc was used and cultivated in order to prepare the isolates for the granulation. A few colonies that grew on GSN media using apparently only the ammonia as nutrient, and that had seemingly different colony morphology were selected to determine its identity (Figure 6). After further purification on plates, four different colonies were selected and sequenced to arrive to a full identification. The results of the sequencing are presented in Table 2. It is evident that the bacteria selected with our growth media show characteristics of either nitrifying bacteria or bacteria resistant to harsh compounds such as heavy metals and aniline.

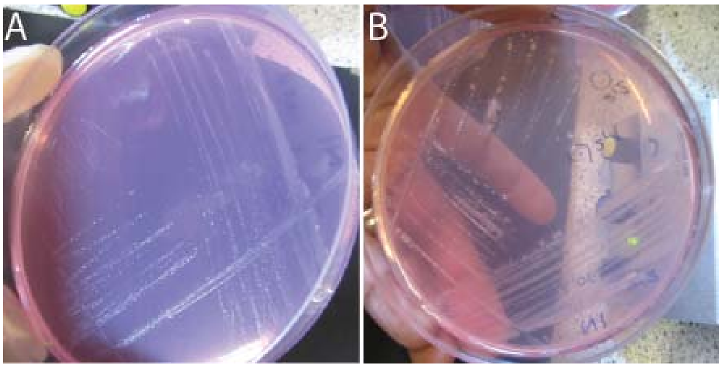


Figure 6. Strain 1 (**A**) and strain 2 (**B**) isolated after several passages on GSN media.

In order to validate the nitrification activity of the selected bacterial strains, additionally the bacterial biomass grown on solid microbiological media was transferred to liquid media consisting of a 200ml flask containing 50ml of GSN media (100x dilution) and the culture was incubated in a rotary shaker at 180 rpm and room temperature (≈ 24°C). The confirmation of nitrification activity was done using pH indicators (phenol red), which changes the media color from red to yellow.

When the culture media in flasks turned from red to yellow, it was taken as an indication of the acidification of the media due to nitrification activity (Figure 7).

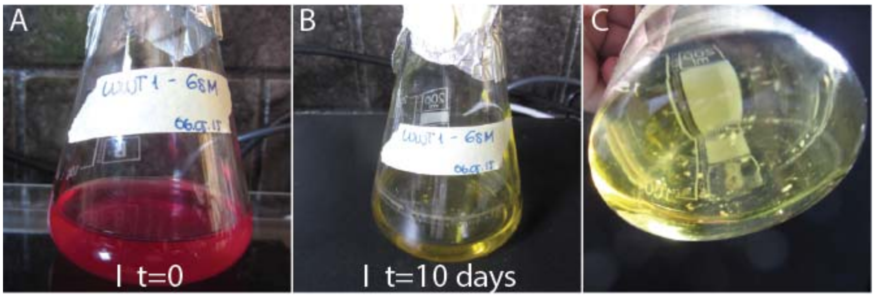


Figure 7. Flasks containing 50ml of GSN media and preselected NH_4 degraders at the starting point of the culture (**A**) and end of the growth period after 10 days (**B**). View of the bottom of the flask after a 10-day incubation period, shows flocks or aggregates formed during the culturing (**C**).

Table 1. Result of the sequencing of the strains isolated from nitrifying media where ammonia was the only energy source available.

Clone	Sequencing result	% Identity	Characteristics
1-1	Pseudomonas sp.	98%	Heavy metal resistant bacteria
1-2	Stenotrophomonas sp.	89%	Nitrate reducing-Denitrifying bacteria
2-1	Uncultured bacterium clone	96%	Bacteria associated with plant secondary compounds in PCB-contaminated soil
2-2	Comamonas testosteroni strain P1	99%	Aniline (aromatic amine) degrading bacteria

To start the lab-scale granulation process a glass bioreactor with a working volume of 600ml was used (Figure 8). The bioreactor has three inlets, which were used for the pH probe, the air diffusor and the sampling. The bioreactor has a pH control system (pH analog Controller, Hanna Instruments) coupled to an acid (H_2SO_4) and base (NaOH) solutions pump to maintain the pH around 7.5, which is optimal for the nitrifying communities.

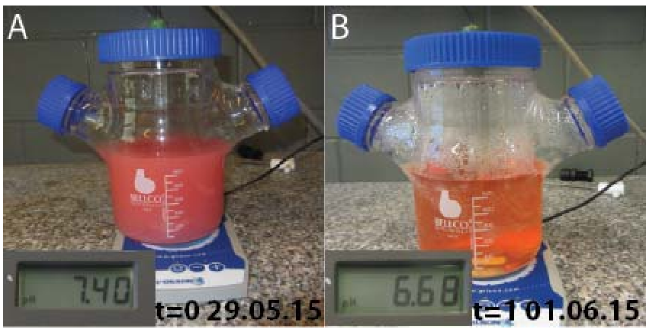


Figure 8. Glass bioreactor containing a culture of pre-enriched nitrifiers on GSN media at the starting point (**A**) and when the culture was stopped after 5 days (**B**). The image corresponds to the measurements of the pH probe.

This lab-scale setting allowed us to recover a population of isolated nitrifying biomass and start the granulation process. When observing the cells under the microscope growing in the bioreactor (Figure 9), small aggregates were seen.

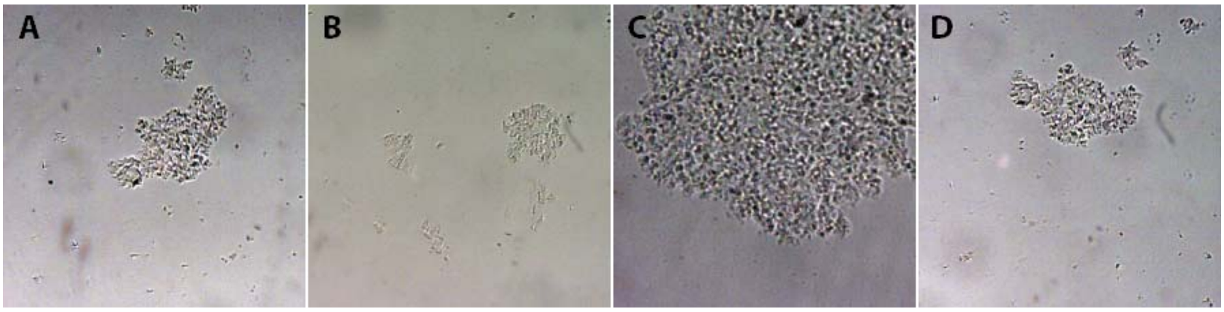


Figure 9. Microscopical observations of the granule formation of the biomass coming from the incubations on the glass bioreactor (Figure 9D). A 40x objective was used (400x amplification).

The selected nitrifying biomass was transferred to a 1L bioreactor (Figure 10) in order to continue with the granulation process and cultivate sufficient quantity of granular biomass for laboratory tests and further on for the pilot plant.

Figure 10. Glass column bioreactor of 1L used to favor the process of granular biomass cultivation.

A part of the cultivated granular biomass was used to set up laboratory batch tests in a reaction vessel of 2L (Figure 11).

The substrate (influent wastewater) for the biotests was taken from WWTP Morges, WWTP Roche and WWTP Broc. As input data for the model, different parameters of water quality were measured (COD, Ammonia, pH). Since the slowest kinetic data were obtained from the WWTP Roche, these results can be taken as the worst-case scenario. In order to avoid granular biomass adaptation on the wastewater, for each of the batch tests carried out, non-adapted granular biomass was used, previously cultivated on mineral salts (sodium acetate and di-ammonia sulfate). In addition, as a wastewater source, low-loaded municipal wastewater was used. The batch was then aerated during a minimum of 10h. This experimental procedure is based on previously published data concerning the evaluation and the mathematical modeling of granular sludge technologies.

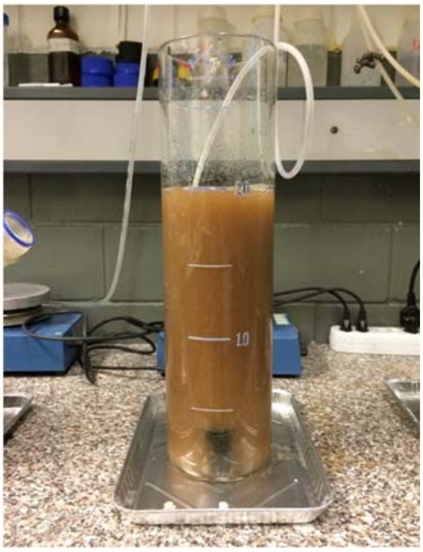


Figure 11. Glass column bioreactor of 2L for lab-scale batch experiments (biotests) with granular biomass.

The parameters measured using the influent WWTP Roche are reported in the Table 3. As shown, the temperature was maintained constant around 19 °C, pH constant around 8.3 and COD, $N\text{-}NH_4$, $N\text{-}NO_2$ and $N\text{-}NO_3$ concentrations evolving as a function of oxidation and nitrification rates.

Table 2. Results obtained from the biotest growing the granular biomass (batch) on water coming from WWTP Morges.

Item/Time (hours)	0	2	4	6	8	10	12	14
COD mg/L	550	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	164
COD filtr mg/L	420	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	145
NH_4-N mg/L	62	52	36	36	27	14	7	3
NO_3-N mg/L	17	15	15	16	19	27	38	55
NO_2-N mg/L	2.4	3.2	3.9	5.1	5.6	6.7	7.3	7.4
pH	8.2	8.6	8.5	8.5	8.5	8.5	8.4	8.3
T °C	19.2	19.1	19.2	19	19.6	19.6	19.5	19.6
D.O. mg/L	6.52	6.42	6.39	6.26	6.22	6.25	6.22	6.21

As shown, there is a discrepancy between the data provided and a simple nitrogen balance during the course of the experiment. What we should normally see is a constant amount of nitrogen during the experiment (assuming first no denitrification occurs). At this point, we see mostly three possibilities to explain the results:

- There is a substantial denitrification process occurring in the reactor, which is in contradiction with the oxygen level reported. To favor the denitrification process, we should have oxygen levels below 1 mg/L in the liquid phase of the reactor, while we observed a constant value of 6 mg/L.

- Some simultaneous nitrification/denitrification processes could also occur inside the granules. Given the characteristic sizes of the Puratis granules (around 50 microns), it is very unlikely that an anoxic zone is created inside the granules.

- There is a substantial biomass growth during the course of the batch test, which could lead to nitrogen assimilation inside the biomass (not measured in this case). This explanation seems to be unlikely given the short duration of the batch test (12h) in comparison with the typical kinetic of the biomass (order of days).

Based on the observed results, the first step to be carried out was to construct the Puratis Granular sludge model. This model intends to describe the measurements obtained by Puratis during the batch experiments evaluated in WP1.

Biological model selection

As ammonium (NH_4), Nitrite (NO_2), Nitrate (NO_3) measurements are available within the datasets provided, we decided to use a two-step nitrification model, taking into account Ammonium Oxidizing Bacteria (AOB), Nitrite Oxidizing Bacteria (NOB) and Heterotrophic Bacteria (HB).

This biological model is available in gWATER as a predefined component and should be able to describe the evolution of NH_4, NO_2, NO_3 and COD components within the batch reactor. All stoichiometric and kinetics parameters are retrieved from the scientific literature and used as such unless accurate and specific experimental data are available.

Biofilm model selection

Another question concerns the representation of the mass transfer within the granule. Granules are usually represented as spheres of varying radius, by opposition to flocs of biology usually encountered in traditional activated sludge process (see Figure 12).

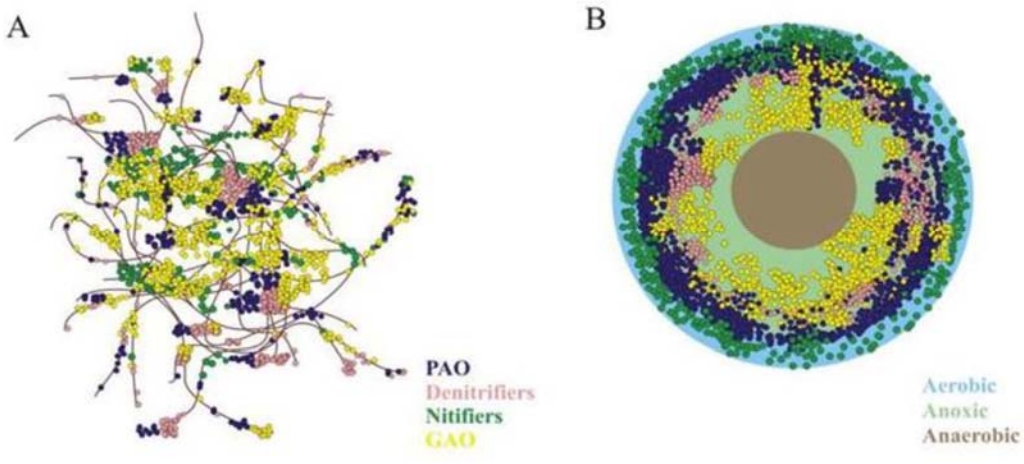


Figure 12. Granules geometry compared to flocks [16]. Flocks are represented at the left where granules are represented at the right.

Generally speaking, granular sludge is considered to consist of granules of sizes ranging between 600 and 1200 microns, while Puratis granules are much smaller (around 50 microns).

Big granules can have zones in their internal structures with different characteristics, as shown in the Figure 12. This is due to a diffusion-limited mass transfer inside the granules, which can lead ultimately to a non-homogenous biomass distribution and the formation of aerobic, anoxic and anaerobic zones within their depth. These specific morphologies can explain simultaneous nitrification/denitrification processes occurring in an aerobic water environment surrounding the granules. In the case of Puratis granules, the small size shouldn't lead to strong biomass stratification, as the oxygen should be able to penetrate the whole granule. The consequence is that Puratis granules should behave similarly to a flock, with a specific biomass composition. Each biomass fractions will have in this case an equal access to oxygen and substrates within the surrounding water (see Figure 12).

To further determine if a model that takes into account mass transfer limitations within the Puratis Granules was necessary we performed two simulations using our dynamic biofilm model available within gWATER. This model is based on a set of equations.

The idea is to compare a granule of a size around 50 microns (Puratis granules) with a granule of a size around 1000 microns (1 mm) and to check whether or not a biomass stratification could be observed in the case of the Puratis granules. The 1D biofilm model was run with the two-step nitrification biological model selected to investigate the characteristics of the Puratis granular sludge.

The comparative results for a normal Swiss wastewater composition with a concentration of dissolved oxygen close to 6 mg/L are presented below.

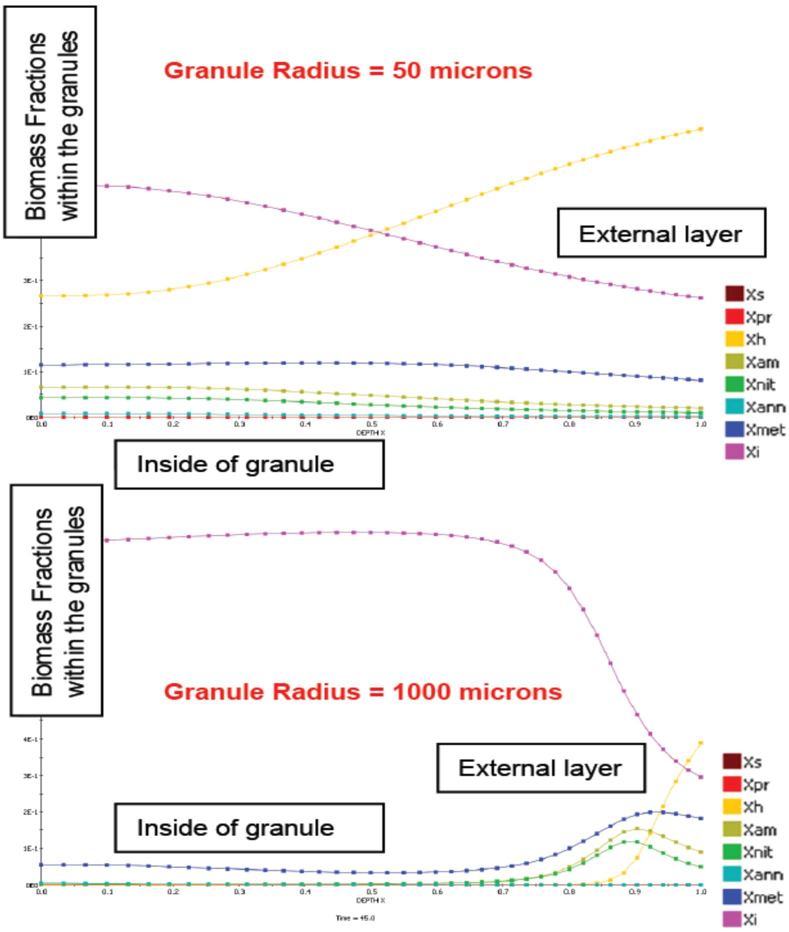


Figure 13. Model-based estimation of the biomass distribution within a granule depending on its mean size.

As shown in Figure 13, a characteristic size of around 50 microns doesn't imply a strong stratification of biomass within the granule (the biomass distribution within the granule is almost flat).

A characteristic size of 1000 microns can however lead to a stronger stratification (depending on the environmental conditions for the granules growth), with eventually the formation of successive aerobic, anoxic and anaerobic zones within the granule depth (see Figure 13).

Given this first qualitative analysis using our 1D biofilm model, it was decided to model the Puratis process similarly to an activated sludge process, with the exception that an initial biomass concentration will be specified to run the simulations.

A batch reactor model including a 1D biofilm model to represent the granules was also developed for this project. After the first testing runs the results suggested that the simplest model was the best choice to reproduce the Puratis data; consequently, the batch reactor model involving the 1D biofilm was not used in the parameter estimation strategy.

Batch reactor model construction

The Puratis batch experiment can be modeled by combining all relevant sub-model components. This consists in assembling the fundamental model components representing Biological reactions, Electrolytes equilibrium (pH calculations), mass & energy balances, intra-granules diffusion and gas to liquid mass transfer correlations so the batch tank can be simulated.

The Figure 14 below is a schematic representation of the components involved in the batch model:

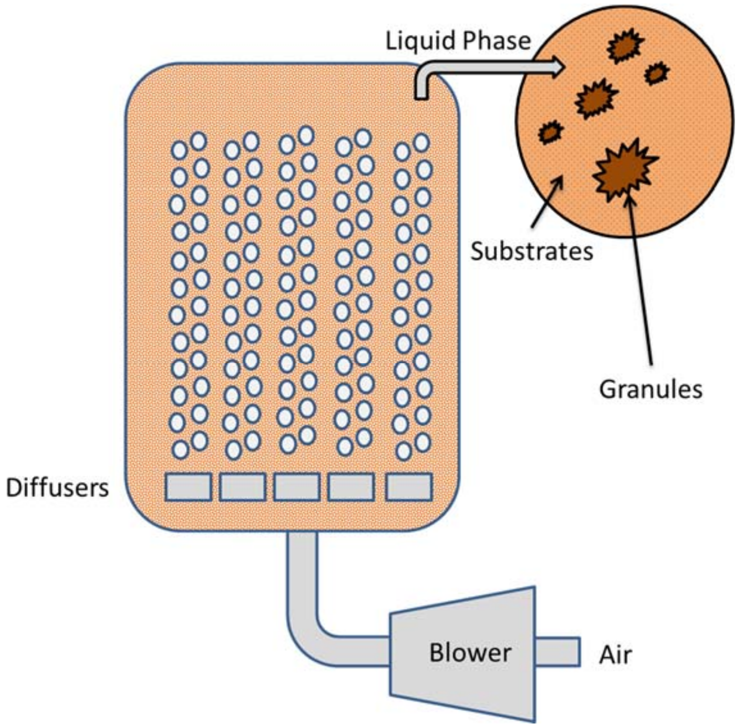


Figure14. Models components involved for the Batch experiment modeling.

The batch reactor model was build using the following components model:

- A blower model that translate the air flow-rate in electricity consumption

- A simple mass transfer coefficient model was used to describe the gas/liquid mass transfer (aeration). Others models are available and can be selected by the user.
- A batch reactor model has been developed specifically for this project. It consists of a volume initially fed with some wastewater, which has specifics characteristics (specified by the user).
- A biological model that represents the biochemical transformations linked to the biomass concentration in the reactor. It is important to note that the biological model is active both in the liquid phase (similarly as an activated sludge model), but also in the biofilm model if this module is activated.
- A biofilm model. Here a static 0D model (zero degree model) has been used and could represents the additional effect of Puratis granules on the biological activity. This module was not used in the Parameter Identification task.

WORKPACKAGE 2: PILOT PLANT SIMULATION OF THE ACTIVATED SLUDGE IMPROVEMENT WITH THE AEROBIC GRANULAR BIOMASS

Following the laboratory tests, the subsequent activities included the cultivation of sufficient pre-selected biomass in granular form for the pilot plant start up. Since each line of the pilot has 1250L and the target concentration of MLSS (Mix Liquor Suspended Solids) in the pilot plant is approx. 3 g/L (mixture of activated sludge and granular bimass) the target quantity of granular biomass to be cultivated was between about 1kg of granular biomass. The first granular biomass cultivation phase was carried out in laboratory, on adapted reaction vessel of 320 L (Figure 15).

Figure 15. The 320L PVC tank used for aerobic granular biomass cultivation.

The reaction tank was equipped with a pumping, aeration and a mixing system. Further cultivation was directly on-site in 150L, which was used to cultivate granular biomass, adapted on the influent wastewater and dosed into the pilot plant (Figure 17).

Figure 16. The 150L process tank used for aerobic granular biomass on-site cultivation.

In parallel to the granular biomass cultivation, the assembly of the pilot plant was carried out. The pilot plant was constructed as a mobile container unit, equipped with aeration, mixing and pumping units and completely automatized for process control and monitoring (Figure 17). Two lines of the pilot plant provided the parallel tests with aerobic granular biomass and activated sludge from the testing location.

Figure 17. The container pilot plant unit prepared for the present project .

Continuous pilot plant testing

The specifications (see the scheme in Figure 18) for the continuous process pilot plant were as follows:

- Stainless steel container with total volume of biological system: 2250L (1125 L per line)
- Number of process lines: 2
- HRT (Hydraulic Retention Time) per process line: 3.7-48 hours (depending on the installed pumps capacity)
- Pre-anoxic Volume per line: 375 L (optional or as aerobic zone)
- Aerobic Volume per line: 750 L
- Settling tank per volume: 375 L
- Design MLSS in Aerobic Tank: 0.5-5.5 g/L

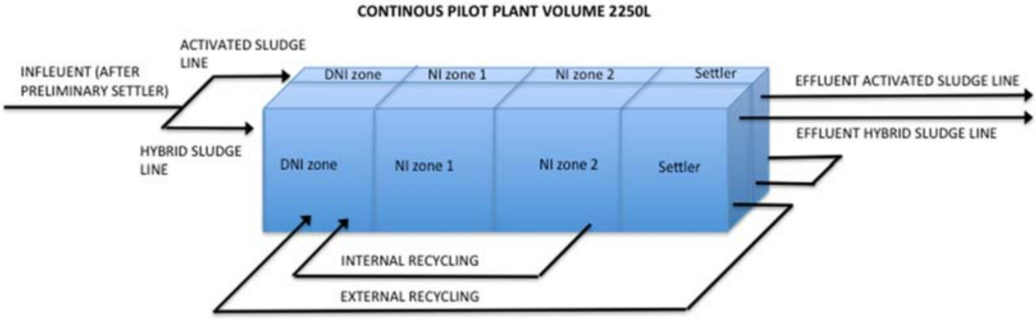


Figure 18. Simplified scheme of the continuous pilot plant.

One line ran as the conventional activated sludge line, whereas the parallel line was a hybrid system comprised of activated sludge enriched with granular biomass (the percentage defined in the lab-scale experiments in WP1). The treatment process ran continuously in order to simulate optimal treatment process conditions and measure energy consumption in both lines (Figure 19).

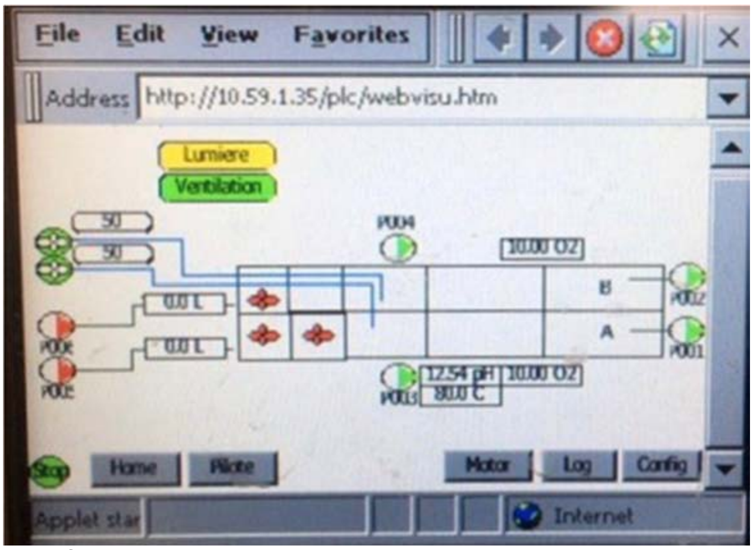


Figure 19. Screen shot of the automatisation unit.

Continuous pilot plant tests were carried out in WWTP Broc, jointly with the engineering company Alpha Wassertechnik AG (Nidau). The goal of the pilot plant was to evaluate the potential to upgrade the existing municipal wastewater treatment plant with Puratis aerobic granular process (ARGUS).

Parallel tests were carried out controlling and measuring the process and operational parameters and energy consumption in three periods:

- **a)** Both pilot plant lines with existing (from the WWTP) activated sludge,
- **b)** One pilot plant line with existing activated sludge while the second contained activated sludge enriched with granular biomass inoculated from the on-site propagator.
- **c)** One pilot plant line with existing activated sludge while the second contained the granular biomass enriched-activated sludge from stage **b** once the granular biomass was partially washed out due to the sludge floating.

Comments on the results:

The aerobic granular biomass was well integrated into the activated sludge as it is presented on the Figure 20.

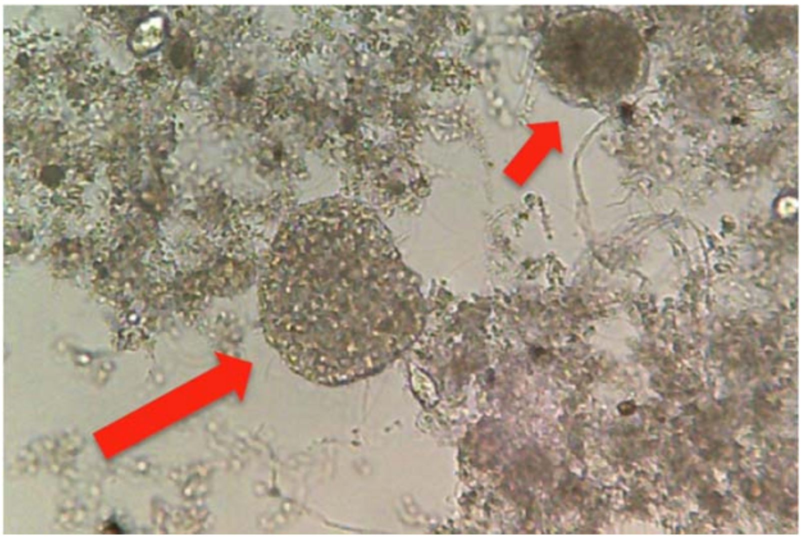


Figure 20. Microscopic image of activated sludge from biological stage WWTP Broc enriched with granular biomass (magnification 400x). The granular biomass is indicated in red arrows, while the rest is the loose activated sludge.

The effect of addition of aerobic granular biomass was measured and in the Table 4 the compared results of the three testing periods are presented.

Table 3. The target compounds reduction in the corresponding periods with and without granular biomass inoculation.

Period	Reduction COD_{tot} %	Reduction NH_4-N %
Period: 24.08 - 10.09.2015 Average with both lines containing activated sludge **(a)**	67	52
Period: 11.09 - 22.09.2015 Average with granular biomass inoculation **(b)**	70	85
Period: 23.09 - 09.10.2015 Average activated sludge after granular biomass washout **(c)**	75	66

Even though, no significant decrease in COD with granular biomass addition was achieved (17% of increase), the addition of granular biomass significantly augments the nitrification process in 33%.

SBR pilot plant testing

The specifications (see the scheme in Figure 21) of the batch process pilot plant were as follows:

- Stainless steel container with total volume of biological system - 2250 L *i.e.* 1125 L per line
- Number of process lines – 2
- HRT per process line – VARIABLE set to 0-6 hours
- Aerobic Volume per line – 375 L
- Design MLSS in Aerobic Tank – 0.5-5.5 g/L

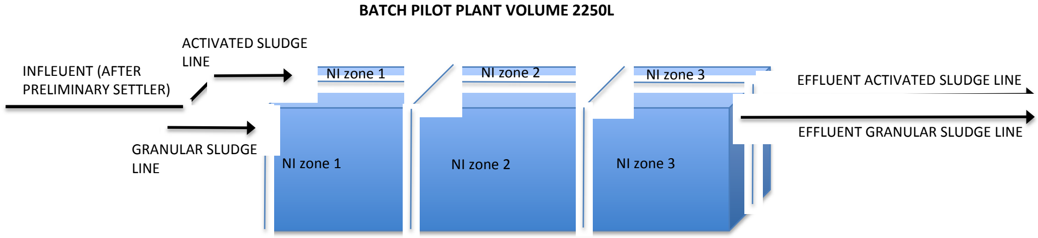


Figure 21. Simplified scheme of the batch pilot plant.

The batch pilot plant tests were carried out in WWTP Orbe performing the aerobic granular biomass adaptation on-site using the plant's influent wastewater.

Each line of the pilot plant was controlled separately and ran as SBR according to the following regimes:

Sedimentation	Decanting	Filling	Aeration
30 min	15 min	5 min	6 hours

The batch pilot plant tests were controlled and monitored by:
- Process efficiency and operational parameters
- Morphological changes in granular biomass quality
- Consumption of energy for the aeration

Comments on the results:

Process efficiency and operational parameters

Based on the carried out measurements, the achieved results obtained by the A-line (activated sludge line) and B-line (granular biomass line) are presented in table 5 and 6:

Table 4. The comparison of the results achieved on COD reduction between activated sludge line (A-line) and granular biomass line (B-line) on the pilot plant within 6 hours of hydraulic retention time

A-line Activated sludge line	**B-line Granular biomass line**
Reduction COD_{tot} %	Reduction CODtot %
43	50

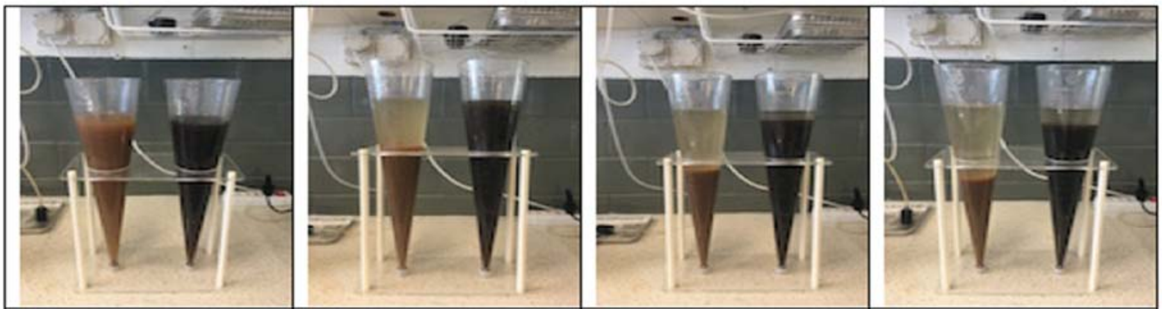
Table 5. Comparison of the results achieved on NH_4-N oxidation (nitrification process) between activated sludge line (A-line) and granular biomass line (B-line) on the pilot plant within 5 hours of hydraulic retention time

A-line Activated sludge line	**B-line Granular biomass line**
Reduction NH_4-N %	Reduction NH_4-N %
71	95

The obtained results from batch pilot plant with the granular biomass-containing line confirmed a significant increase in the nitrification activity around 25% comparing with the activated sludge line. However the reduction in COD was not significantly impacted and these results were similar to the results obtained with the continuous pilot plant tests.

Sedimentation measurements

On the other hand, the aerobic granular biomass demonstrated significantly better settling properties, which results in better SVI (Sludge Volume Index)(see Figure 22).



0 min	5 min	10 min	30 min
	V_GB 450 mL V_AS 950 mL	V_GB 350 mL V_AS 900 mL	V_GB 250 mL V_AS 800 mL
			SVI_GB 55 mL/g SVI_AS 285 mL/g

Figure 22. Sedimentation results of the existing activated sludge (AS), the cones on the right with the dark suspension compared with granular biomass (GB) the cones on the left with the light brown suspension.

Morphological changes in granular biomass quality

During the eight-week period of the pilot plant testings, the granular biomass maintained a steady and similar morphology, confirming that during the two months of pilot plant testing the granular form remains unchanged and stable.

The Figure 23 presents comparative microscopic photos of the activated sludge line compared with granular biomass line at the beginning and at the end of the pilot plant tests.

The comments on the energy consumption are evaluated in the following chapter (WP3).

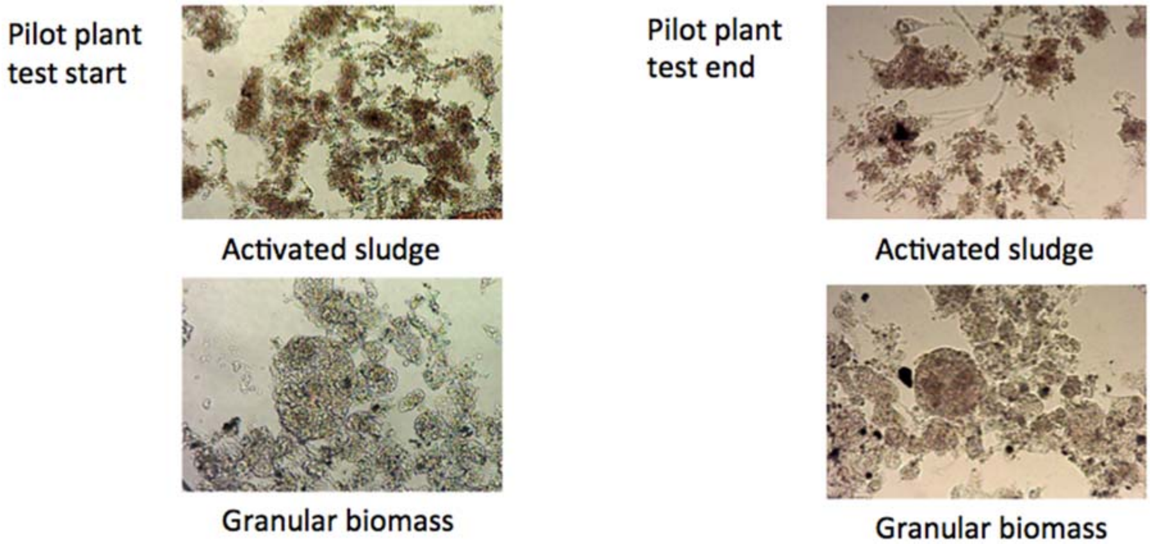


Figure 23. Microscopic photos of the activated sludge line compared with granular biomass line at the start of the test and after 8 weeks of cultivation (magnification 400x).

WORKPACKAGE 3: ENERGY ANALYSIS OF THE PROPOSED PROCESS

Introduction

Energy consumption during pilot plant tests was measured automatically based on the main energy consuming components:

- Blowers
- Influent and recycle pumps, and mixers

Other pilot plant energy consuming components, such as light, ventilation, on-site granular biomass cultivation, were not taken into consideration.

The energy consumption was controlled and monitored in real time and compared in both lines in parallel using the process automatisation unit. In Figure 24, a screenshot of the automatisation unit presents the on-line electric energy consumption measurements.

In the following sections the mathematical modeling and effect on the process and energy efficiency is described in detail.

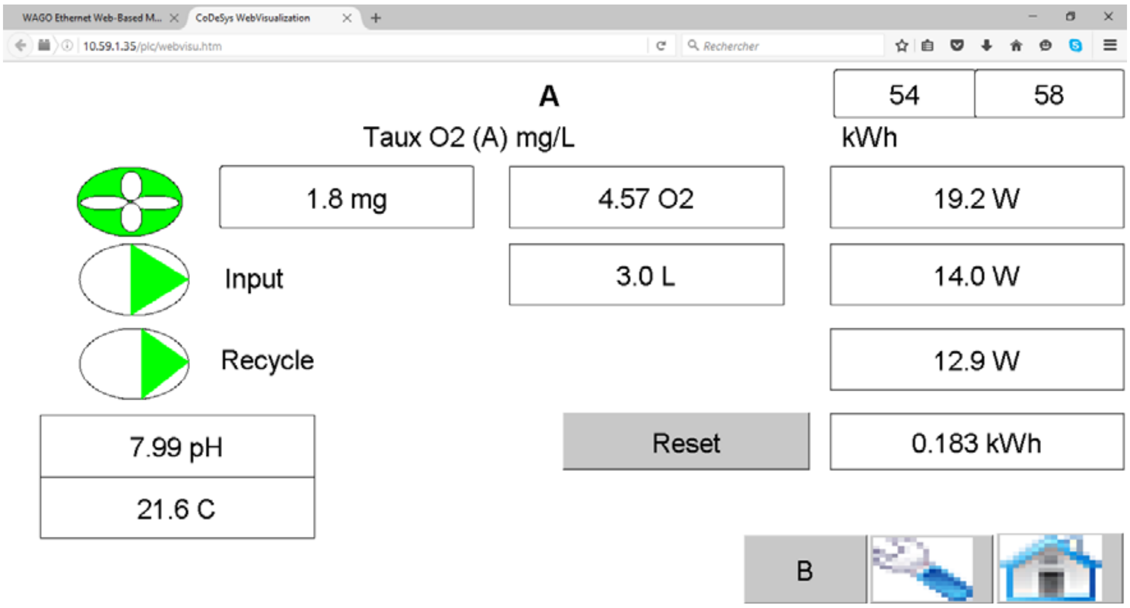


Figure 24. The energy consumption of the main process equipment

Model calibration and validation based on pilot plant data

We introduced in this section the comparisons done taking into account the experimental data available as well as the model selection.

Model calibration strategy

A screenshot of the model implemented under our platform is given in Figure 25.

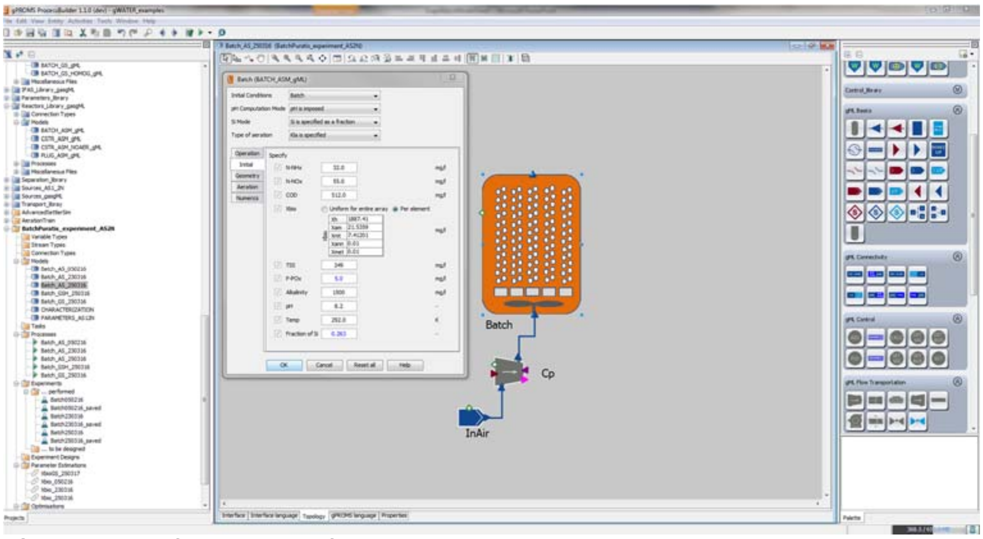


Figure 25: Screenshot of the model of the batch Puratis experiment as implemented under the gWATER environment.

This model was used to perform several simulation activities:

- Dynamic simulations. These simulations will reproduce the batch experiments.
- Parameter identification: The objective here is to identify some unknown models parameters in order to reproduce the experimental data.

The first task was to define a strategy to calibrate the model using the experimental data generated by Puratis. The following calibration strategy was adopted:

The initial granular biomass concentration was around 2.2-2.5g SS/L. This initial composition has a strong influence on the dynamic evolution of the nitrogen compounds concentration during the batch experiment, because it defines the initial quantities of each type of biomass present in the reactor during the aeration period.
Consequently, it was decided to include in the parameter estimation these initial quantities for each type of biomass considered in the model, so an approximate composition of the biomass could be deduced.

All the kinetics parameters involved in the biological model, as well as the aeration parameter (Kla) has been kept constant to their default values, as no additional data was available for the parameter identification.

Based on the laboratory batch tests carried out and data obtained, it was possible to identify a biomass composition that fits correctly to the data measured during the batch experiments.

The nitrite profiles adjustments were more difficult because the model does not accurately describe the mechanisms of nitrite formation and denitrification based on nitrite. The uncertainty regarding the nitrogen balance and possible denitrification also makes the complete model identification more difficult, since it is not possible to discriminate between experimental measurement error and model uncertainty. However the nitrification rate is correctly identified and gives a good idea of the nitrogen removal capabilities of the Puratis granules, which was the main objective of this work package.

Model-based energy evaluation of the proposed technology compared to main-stream treatment

Introduction

The biofilm model combined with an appropriate biological model can give an estimation of the composition of a granule as well as its dynamics concerning the process and energy efficiency. This model could be used as a tool to evaluate the composition of granules depending on the characteristics of the water in which they are grown. It could also be used as a tool to evaluate the long-term stability and the modification of the composition of the granules. In that sense, the model could be used as a tool to drive experimental and laboratory work.

However, it is also necessary to keep in mind the limitations of the models given the complexity of the various phenomena involved. The granules model (using a biofilm model or not) could be combined with the reactors model already available in gWATER to simulate and study the design of a biological process involving granules.

On Figure 26, the generic flow sheet, which is based on the VSA workbook in order to evaluate energy efficiency, is shown.

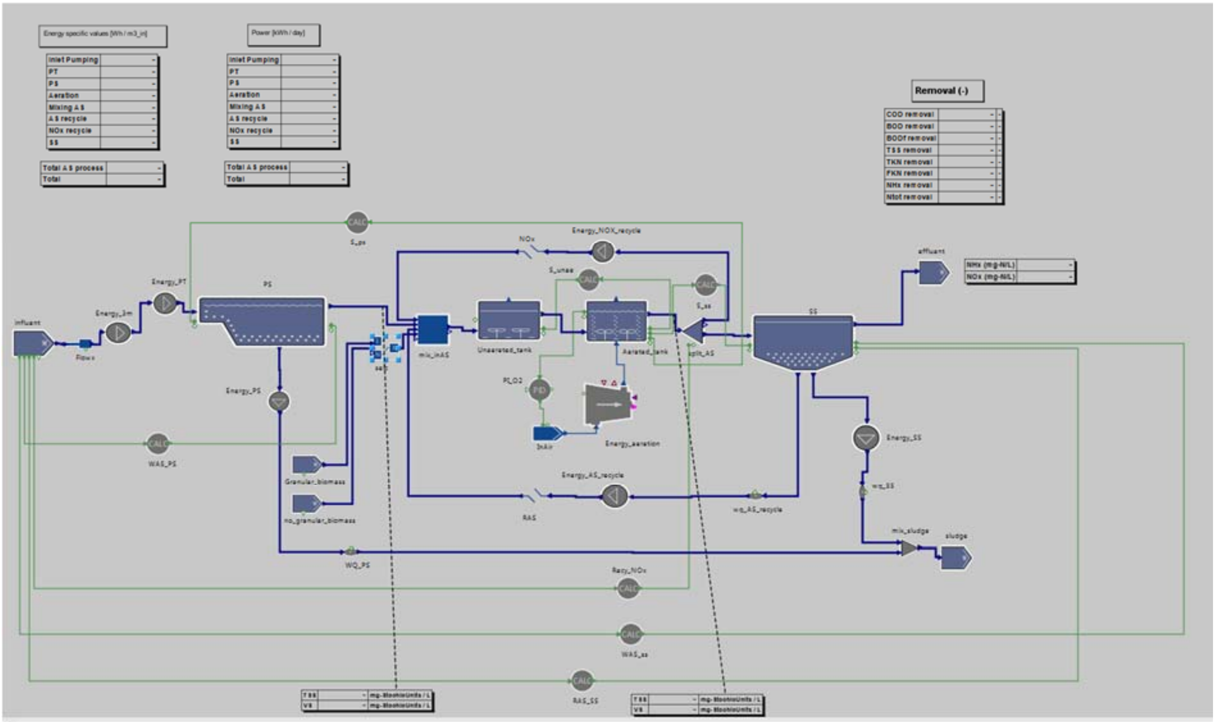


Figure 26: Generic flow sheet used to evaluate energy efficiency.

As mentioned in Work Package 1, the characteristic granular biomass size around 50 microns doesn't imply a strong stratification of biomass within the granule, which indicates that no aerobic, anoxic and anaerobic zones within the granule depth will be formed. However, Puratis granular biomass contains a very specific and selective microbial community, with a high enrichment of nitrifying bacteria, contrary to the conventional activated sludge.

The nitrifying community within Puratis granular biomass comparing with conventional activated sludge and NEREDA granular biomass (for which the sizes are in a larger range, up to few mm), is the main parameter that affects the energy consumption. During the pilot plant tests, under the same process and operational parameters, granular biomass line performed faster nitrification process, and to a lower extent decreased the COD. Faster oxidative processes result in decreased energy consumption.

The pilot plant data was used in modeling to evaluate the energy efficiency. The summary of the calculations using the different percentages of the nitrifying bacteria in granular biomass is presented in the table 7 and Figure 27 and Figure 28.

Table 6. Summary of the calculated values of process time (nitrification process) and energy consumption obtained with different percentages of nitrifying bacteria in granular biomass (Xa)

Xa% in GS		1	2.5	5	10	20
NI	(hours)	6.48	3.6	2.4	2.16	2.16
Energy consumption	(kJ per m3 of tank)	1826.209704	1014.560947	676.3739645	608.736568	608.736568
	(Wh per m3 of tank)	547.8629112	304.368284	202.9121893	182.6209704	182.6209704

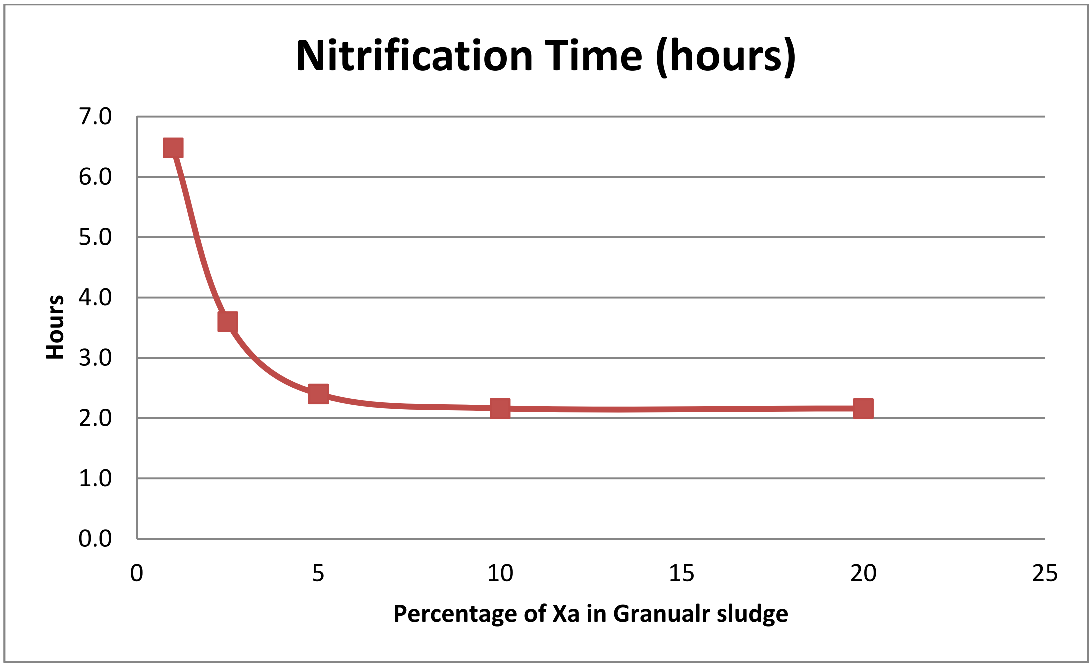


Figure 27. Calculated values of process time (nitrification process) obtained with different percentage of nitrifying bacteria in granular biomass (Xa)

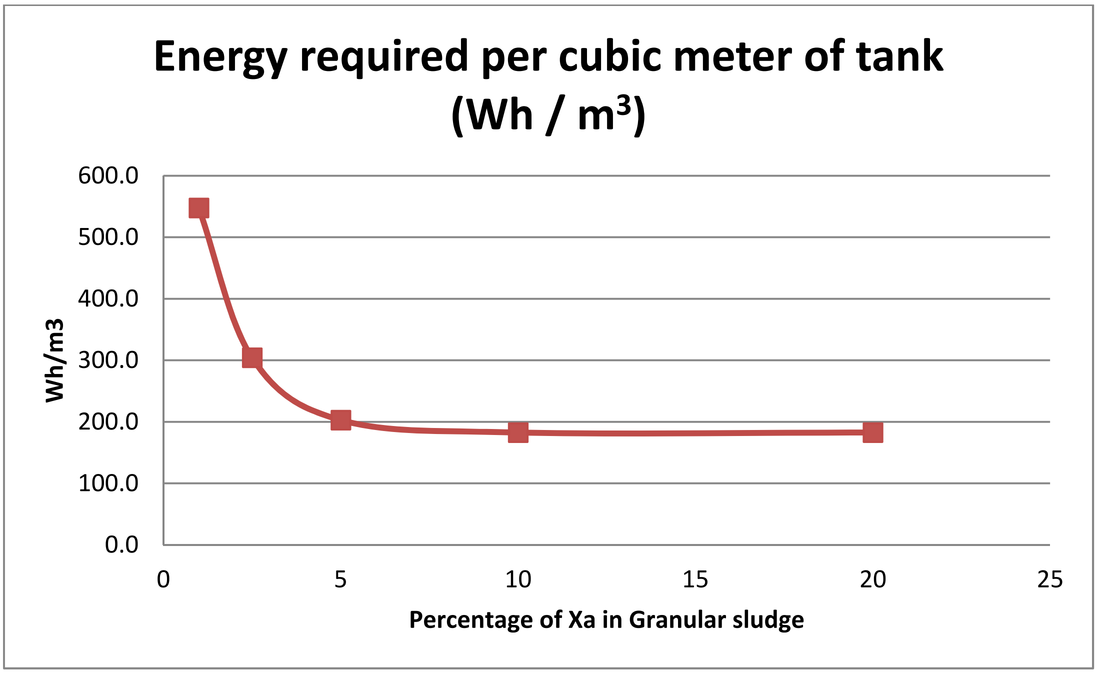


Figure 28. Calculated values of energy consumption obtained with different percentage of nitrifying bacteria in granular biomass (Xa)

The results of the model-based calculations correspond to the results obtained from the pilot plants tests. The process time and the energy consumption are directly correlated with the percentage of nitrifying community in granular biomass.

Figure 29 presents the microbial community analyses using Puratis granular biomass. The analyses show that the percentage of nitrifying microorganism (*Nitrosomonas sp.*) is increased in 7% thus, a shorter nitrification time and the lower energy consumption is expected.

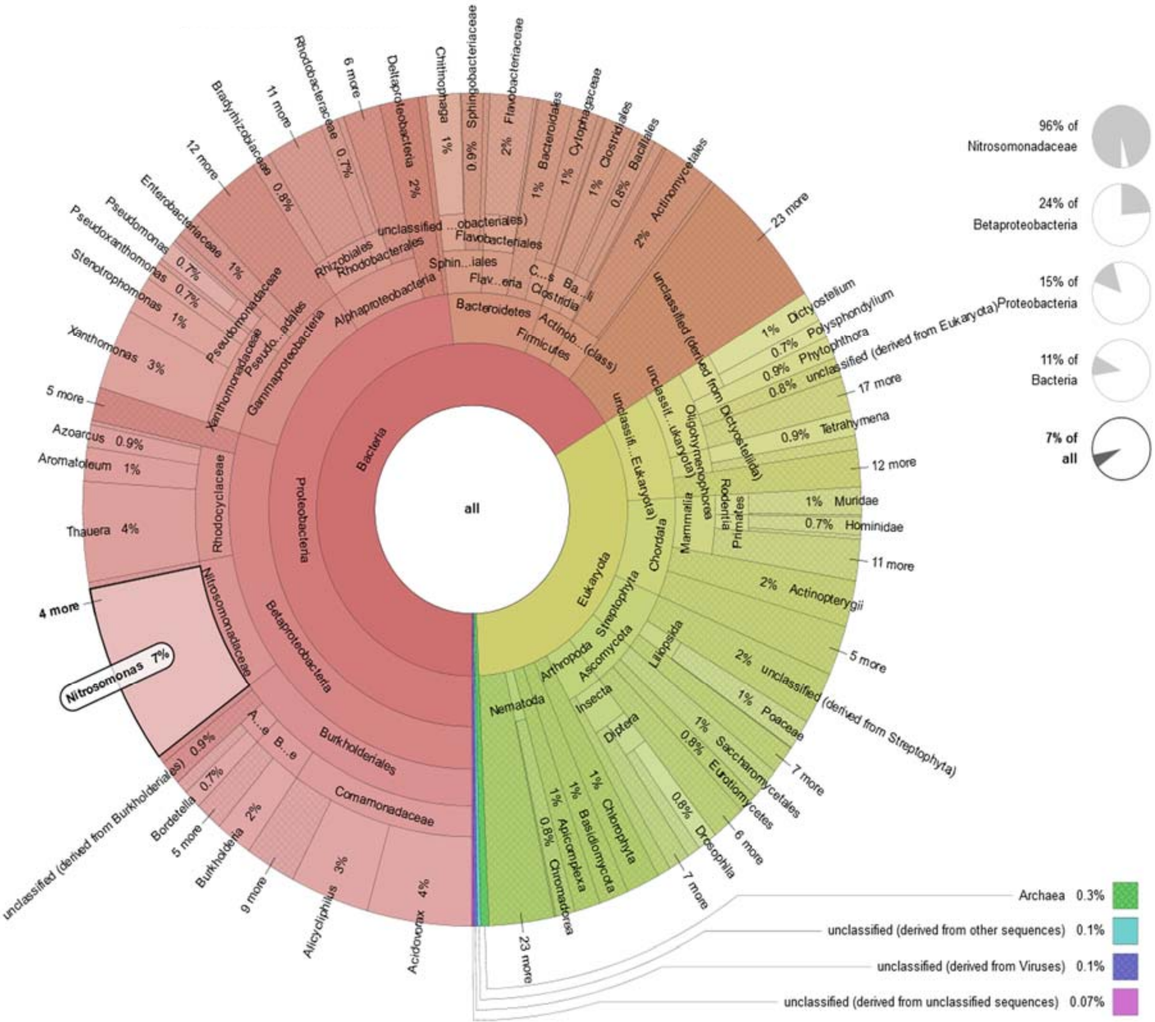


Figure 29. Microbial community analysis of activated sludge enhanced by ARGUS granular biomass (analyses performed by HEPIA Lullier)

4.3 Project results summary

The objectives of the present project established in the project proposal were:

1. Integrating aerobic granular biomass with the existing activated sludge systems forming so-called "hybrid biology", which aimed to increase the biological system activity for nitrogen removal of non-nitrifying WWTPs. The expected reduction in energy consumption is 15%.
   Achieved results: two different approaches were used: a "hybrid" system (combination of activated sludge and ARGUS granular biomass) and pure ARGUS granular biomass in order to test the process and energy efficiency. The results obtained showed that up 1/3 of the hydraulic retention time can be reduced and in average 15-25% of energy for the oxidative processes can be decreased, both as the "hybrid" system or pure aerobic granular system.

2. A higher carbon compounds removal efficiency of the "hybrid biological" process will contribute to an additional 5% energy saving in an existing WWTP.
   Achieved results: ARGUS granular biomass, due to a higher percentage of nitrifying community in the granules, increases mainly the nitrification process and in a lower extent the reduction of COD. The observed reduction in COD contributes to an additional 5-7% of overall energy savings. According to this result, both "hybrid" system and pure aerobic granular system can reach similar results.

3. The process development and process control will be supported and optimized by the integration and the development of an adapted mathematical model to be integrated in the existing modeling software package.
   Achieved results: Based on the qualitative analysis performed, the Puratis ARGUS granular biomass process is similar to the activated sludge process, with the exception that an initial biomass concentration has to be specified to run the simulations. A batch reactor model including a 1D biofilm model to represent the granules was developed for this project.

5 Conclusions

5.1 Introduction

The proposed project aimed to offer a new approach in the existing municipal and industrial wastewater treatment plants upgrade, using aerobic granular biomass as a biological tool for a more efficient wastewater treatment. The expected outcomes planned were:

1. Validation of the effectiveness of the new biological hybrid system, combining activated sludge systems and granular biomass
2. Measuring over a period of 10 month the efficiency of the biological treatment and the energy consumption.
3. Operational data collection for process validation and control and integrating the data in the simulation software.
4. Ecological and economical validation of the technology upgrade

Validation of the effectiveness of the new biological hybrid system, combining activated sludge systems and granular biomass

The results of the pilot plant tests showed that the granular biomass either as a “hybrid” system (continuous pilot plant) or as a pure granular biomass system (batch pilot plant) achieves more efficient oxidative processes, especially nitrification. The effect on the oxidative processes results in shorter process time that translates into a faster process. The nitrification was the principal biological reaction improved, as a result of the microbial community naturally selected in ARGUS granular biomass consisting of a highly enriched community of ammonia oxidizing bacteria.

Measuring over a period of 10 months the efficiency of the biological treatment and the energy consumption.

Two pilot plants were tested during the course of the project: a continuous pilot plant and pilot plant that runs as a SBR reactor. The pilot plants were assembled with two lines in order to control and monitor in parallel the biological processes performed with the existing activated sludge (WWTP Broc and WWTP Orbe) and the ARGUS granular biomass. The control and monitoring systems installed allowed on-line measurements of the process parameters and energy consumption of the main components: blowers, pumps and mixers.

Operational data collection for process validation and control and data integration into the simulation software.

The pilot plant data was collected and used for our modeling to evaluate the energy efficiency. The results of the model-based calculations correspond to the results obtained from the pilot plants tests. This model could be used, as a tool to evaluate the composition of granules depending on the characteristics of the water in which they are grown. It could also be used to evaluate the long-term stability and the modification of the granules’ composition. The model confirmed that the process’ time and the energy consumption are directly correlated with the percentage of nitrifying community in granular biomass.

Ecological and economical validation of the technology upgrade

In our results it was observed that due to the shorter process time needed with the ARGUS aerobic granules, there is a lower overall energy expense going to the oxidative processes (principally nitrification and in lower extent a reduction in COD). The process time and energy consumption is correlated with the quantity (percentage) of nitrifying bacteria integrated in the granular biomass. This fact distinguishes ARGUS granular process from NEREDA in which a biomass stratifications and zone stratification with different microbial communities is formed due to a higher granule size. On the contrary, within the ARGUS granules, a highly specialized biomass mainly consisting of nitrifiers, is naturally selected, which contributes to the process and energy efficiency.

There are potentially several domains of application for the ARGUS aerobic granular process in the municipal sector such as:

1) The upgrade of the existing municipal wastewater treatment plants or
2) Building new municipal wastewater treatment plants (completely new or new as the enlargement of the existing ones.

In the following sections, more ecological and economical outcomes are presented.

5.2 Market potential of ARGUS process application in Switzerland

The Swiss water infrastructure has been built mainly in the 1960s and 1970s, about a quarter of which has now substantial damage. The replacement value of all assets is estimated in 108 billion of CHF (KVU CCE, 2011).

The Swiss wastewater is treated in 759 large central treatment plants and additionally in more than 3’400 small-scale sewage treatment plants. 470 (62%) of central treatment plants are built for less than 10.000 PE (Person Equivalents) and treat 8% of the total wastewater. 81 treatment plants are for larger communities with more than 50.000 PE, and treat 62% of the total wastewater. Additionally, 65 plants are serving between 30.000 and 50.000 PE.

In Switzerland, the treatment plants are under the control and management of the local authorities. 2530 municipalities with a total of 7.28 million inhabitants are connected to the 759 central wastewater treatment plants. The total plant capacity is 16.7 million PE. Small sewage treatment plants, with an average load of 10,000 inhabitants, are loaded on average to 60%.

The average treatment capacity of the wastewater treatment plants is 88% based on COD removal and 84% based on total phosphorus removal. The ammonium nitrogen is removed on average up to 75% while for total nitrogen only 45% is removed. In wastewater treatment plants with 50.000 inhabitants, the spare capacity is only 15% and on average all Swiss wastewater treatment plants have 23% capacity left (KVU CCE, 2011).

Therefore, in the forthcoming years, a significant amount of treatment plants will have to be upgraded thus ARGUS process can be an interesting approach.

5.3 Energy saving potential in Switzerland with ARGUS process

Electricity consumption in Switzerland for wastewater treatment is about 448 GWh per year, of which 40% is used for aeration of the biological degradation process. In average, the treatment of one PE needs 39 kWh per year.

The amount of energy used for the biological step is 16 kWh per year for the aeration only. Taking into the account that nitrification needs about 5% of the aeration process energy, the energy saving for nitrification will then be 9 GWh per year when all WWTP will be equipped with nitrification process.

Applying the ARGUS process on all Swiss WWTPs will contribute to a reduction of the energy demand for nitrification to about 50% or 4.6 GWh per year. Additionally, a reduction of 10% of COD will increase the saving potential to 40-50 GWh per year.

These hypotheses are done based on the pilot plant results and taking into account the mathematical model output values, however the full potential of ARGUS process in municipal domain will be evaluated in full-scale conditions, once the process is applied on a selected municipal wastewater treatment plant.

As a follow up of this R&D project, a full-scale demonstration will be proposed and executed.

5.4 Collaborations during the project execution

The project was organized and carried by two partners Puratis Sàrl and BlueWatt Engineering Sàrl. The Companies Alpha WasserTechnik AG (CH) and Polychem GmbH (CH) contributed to the project with process equipment and the pilot plant units, respectively.

5.5 Dissemination of the project results

On the course of the project three publications was prepared:
Vogel, B., *Abwasser soll energieeffizienter gereinigt werden.* UMWELTTECHNIK SCHWEIZ, 2016. 3-4: p. 8-9
Vogel, B., *Energieeffizienter Klärschlamm*. AQUA & GAS, 2016 (11): p 62-65
Vogel, B., *Energieeffizienter Klärschlamm*. Kommunal Magazin, 2016 April/Mai (2): p 22-25

Additionally, the project results were presented in:
Soljan, V., *Energetische Optimierung der Abwasserreinigung mittels granulierter Biomasse.* Forschungstagung Bioenergie des BFEs am 10. Mai 2017

6 Literature

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7 List of Figures and Tables