POLITECNICO DI TORINO

Corso di Laurea Magistrale

in Ingegneria per l'ambiente e il territorio

Post – aeration of anaerobically digested sludge: optimization of the process and performance analysis

Relatore

Prof. Marichiara Zanetti

Prof. Deborah Panepinto

Candidato

Marta Di Marco

A.A. 2017/2018

Acknowledgements

Vorrei innanzitutto ringraziare la Prof. Deborah Panepinto non solo per avermi proposto questo progetto di tesi e avermi dato la possibilità di vivere questa esperienza, ma anche per la sua continua disponibilità e per avermi supportato durante tutto il percorso.

I would like to thank Marie for all the help with my thesis and the experiments, and all my lab mates for cheering my days up.

My sincere thanks go to Prof. Pavel Jenicek, for offering me this opportunity.

Ringrazio Mery e Valeria, le mie ragazze di Invalidovna, senza le quali questa avventura non sarebbe mai stata la stessa. Grazie a voi Praga è diventata la mia seconda casa.

I would also like to thank my friend Anil, who stayed by my side through this journey.

E non posso non ricordare i miei compagni del Politecnico: Laura e Lorenza, con me fin dal primo giorno, Marco e Tony.

E un grazie anche alle mie colleghe della "Sapienza" a Roma, che mi sono state accanto nella mia avventura precedente ma che senza le quali non avrei raggiunto neanche questo obiettivo: Giulia, Concetta, Michela, Serena e Marcella.

E infine, il ringraziamento piu grande va alla mia famiglia: ai miei genitori per tutto l'aiuto e il supporto, a mia nonna, per tutto il cibo e le chiamate sempre puntuali alle 7 di sera, e soprattutto a Francesca, perchè non avrei potuto desiderare una sorella migliore con cui crescere.

Contents

Abstract 1

1. Introduction 3

  1.1 Anaerobic digestion 3

    1.1.1 Description of the process 3

    1.1.2 Advantages and disadvantages 6

  1.2 Aerobic digestion 7

    1.2.2 Description of the process 7

    1.2.2. Advantages and disadvantages 8

  1.3 Sequencing Batch Reactor (SBR) 8

    1.3.1 Main characteristic 8

    1.3.2 Advantages and disadvantages 10

  1.4 Nitrogen removal 10

    1.4.1 Nitrogen forms 10

    1.4.2 Nitrification process 11

    1.4.3 Denitrification process 12

    1.4.4 Impacts of nitrogen in water 12

    1.4.5 Literature review: nitrogen removal by combined anaerobic – aerobic digestion 13

  1.5 Organic compounds removal 14

    1.5.1. Chemical Oxygen Demand (COD) 14

    1.5.2 Total Organic Carbon (TOC) 14

    1.5.3 Total Solids (VS) and Volatile Solids (VS) 14

    1.5.4 Literature review: organic compounds removal by combined anaerobic – aerobic digestion 15

  1.6 Improvement of the dewatering properties 16

    1.6.1. Distribution of the water in the sludge 16

    1.6.2 Capillary Suction Time 17

    1.6.3 Centrifugation method 18

1.5.4 Literature review: improvement of the dewaterability properties by combined aerobic – anaerobic digestion 18
2. Objectives 20
3. Methods 21
3.1 Materials 21
3.2 Experiments and procedures 22
3.3 Analytical techniques 23
3.3.1 pH and temperature 23
3.3.2 Total solids analysis 23
3.3.3 Total Ammonia Nitrogen (TAN) 25
3.3.4 Nitrite and nitrate nitrogen 26
3.3.5 Chemical Oxygen Demand (COD) analysis 26
3.3.6 Total Organic Carbon (TOC) analysis 27
3.3.7 Capillary Suction Times (CST) analysis 27
3.3.8 Centrifugation method 27
4. Results 28
4.1 Post – aerobic digestion: previous experiments 28
4.1.1 Nitrogen removal 28
4.1.2 Organic compounds removal 32
4.1.3. Water removal 36
4.2 Experiment 1 38
4.2.1. Nitrogen removal 38
4.2.2 Organic compounds removal 42
4.2.3 Water removal 46
4.3 Experiment 2 47
4.3.1 Nitrogen removal 48
4.3.2 Organic compounds removal 51
4.3.3 Water removal 55
5. Discussions 57
5.1 Previous experiments 57
5.1.1. Nitrogen removal 57

5.1.2 Organic compounds removal 58

5.1.3. Water removal 60

5.2 Experiment 1 61

5.2.1 Nitrogen removal 61

5.2.1 Organic compounds removal 62

5.2.3 Water removal 64

5.3 Experiment 2 66

5.3.1 Nitrogen removal 66

5.3.2. Organic compounds removal 66

5.3.3. Water removal 68

6. Conclusions 70

References 73

Abstract

Sludge stabilization represents one of the most crucial aspects in sludge management. Anaerobic digestion is generally the most widespread method for sludge stabilization in large wastewater treatment plants, mainly because of the high energy recovery obtained by the biogas production. However, the digested sludge produced must be often treated with the aim of quality improvement. Several studies have highlighted the advantages of a post – aerobic stage following the conventional anaerobic digestion to improve the sludge properties.

In this study, a post – aeration treatment of anaerobically digested sludge is proposed. This stage could successfully reduce TAN and organic compounds concentration, and improve the dewaterability properties. The sludge utilized for the experiments was collected at the Prague Central WWTP and the experiments were carried out at the University of Chemistry and Technology in Prague.

Two experiments were conducted in a continuously mixed and aerated Sequencing Batch Reactor operating under different conditions, by changing SRT and intensity of aeration rate. In the first experiment, the following operating conditions were set up: during the first phase, the reactor operated at SRT of 4 days and aeration rate of 600 L/h, while during the second one the parameters were respectively equal to 2 days and 900 L/h. In the second experiment, a SRT of 2 days was maintained through all the experiment, while the air flow was increased sequentially in three steps: 600 L/h, 1200 L/h and 2000 L/h.

As part of the same project, previous experiments were conducted, and their results are reported in order to have a complete background and a deeper understanding of the topic. The previous experiments were characterized by the following parameters: SRT of 8 and 6 days and aeration rate of 300 L/h; SRT of 4 days and aeration rate of 300 L/h, 600 L/h and 900 L/h.

The parameters chosen to evaluate the efficiency of the treatment are: Total Ammonia Nitrogen concentration, nitrite and nitrate nitrogen concentration, Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), Capillary Suction Time (CST), pH, Total Solids (TS) and Volatile Solids (VS) concentration.

In order to determine the dewaterability properties of the sludge, a new analysis, alternative to the more utilized CST one, was proposed: the centrifugation method. The comparison between the results obtained from the different tests was very interesting.

Overall, the post-aerobic stage significantly reduced TAN concentration in all the experiments, with removal efficiencies up to 59%. The centrifugation test reported good results, showing the potentialities of the method to increase the percentage of water that could be removed from the

sludge. On the other hand, the CST test led to completely different conclusions, indicating in most of the experiments an aggravation of the dewatering characteristics of the sludge. The reduction of organic compounds (COD, TOC and VS) resulted effective only at 8 days SRT.

1. Introduction

Sludge stabilization is one of the most important phases in sludge management, since its performance significantly affects the amount of sludge produced and its quality.

Overall, anaerobic digestion has been generally preferred to the aerobic one, mainly for the possibility to recover part of the energy consumed by the biogas production. However, this kind of digestion is far more difficult to manage, and it is considered economically advantageous only for medium – high size plants: an indicative economical limit value is 30,000 PE (Tomei and Carozza, 2014). Aerobic digestion is characterized by a higher energy demand for the aeration but is surely more effective for the sludge sanitation.

In order to merge the advantages of both the process, combined aerobic – anaerobic digestion has been investigated and demonstrated a valid alternative to improve the sludge stabilization process.

Several studies have highlighted the advantages of a post – aerobic stage following the conventional anaerobic digestion. It could significantly reduce Total Ammonia Nitrogen with a great efficiency and thereby reduce the amount of nitrogen recycled in the whole wastewater treatment process. It also improves the sludge properties, particularly the dewatering characteristics. The reduction of the amount of sludge to be dewatered could bring several economic advantages. In these conditions, also the decomposition of organic matter hard to degrade in a single anaerobic stage is deepened. Stabilized sewage sludge is mainly composed by particulate organic matter that needs to be hydrolyzed in order to allow the biological degradation of the sludge. The addition of a further aerobic stage resulted effective to obtain optimal conditions for the degradation of the Volatile Solids fraction present in the sludge and COD and TOC reduction.

1.1 Anaerobic digestion

1.1.1 Description of the process

Anaerobic digestion is the process by which bacteria degrade organic matter in the absence of oxygen. The main product of this process is called biogas, which is mainly composed of methane and carbon dioxide.

It occurs naturally in marshes, sediments, wetlands and the stomach of ruminants. It is also the principal degradation process in landfills.

The digestion process can be divided in four main stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Below each step is discussed in the details:

- Hydrolysis: the enzymes released by fermentative microorganisms transform insoluble higher molecular mass compounds present in the water into soluble and less complex ones, making them more suitable for being utilized as source of energy from the bacteria. The bacteria involved in this phase are called hydrolytic bacteria – acidogens. The general equation of this phase is shown below:

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + H_2$$

- Acidogenesis: the compounds dissolved in the first step are converted into intermediate compounds, characterized by a lower molecular mass, like volatile fatty acids (VFAs), alcohols, lactic acid, CO_2, H_2, NH_3, H_2S and new cell material. The general equations of this phase are shown below:

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 3H_2 + H^+$$

- Acetogenesis: the volatile fatty acids produced during the previous step are converted by acetogens bacteria into acetate, hydrogen (H_2), CO_2 and new cell material. The general equations of this phase are shown below:

$$CH_3CH_2\,CO\ \ {}^{-} + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HC\ \ {}_{3}^{-} + 3H_2$$

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 3H_2 + H^+$$

- Methanogenesis: conversion operated by methanogenic bacteria of intermediate compounds into simpler products like methane, CO_2 and new cell material. The general equations of this phase are shown below:

$$CH_3COOH \rightarrow CH_4 + CO_2$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$$

The main product is called biogas, which is mainly composed by methane and carbon dioxide.

In the Figure 1.1 the main steps previously described are shown.

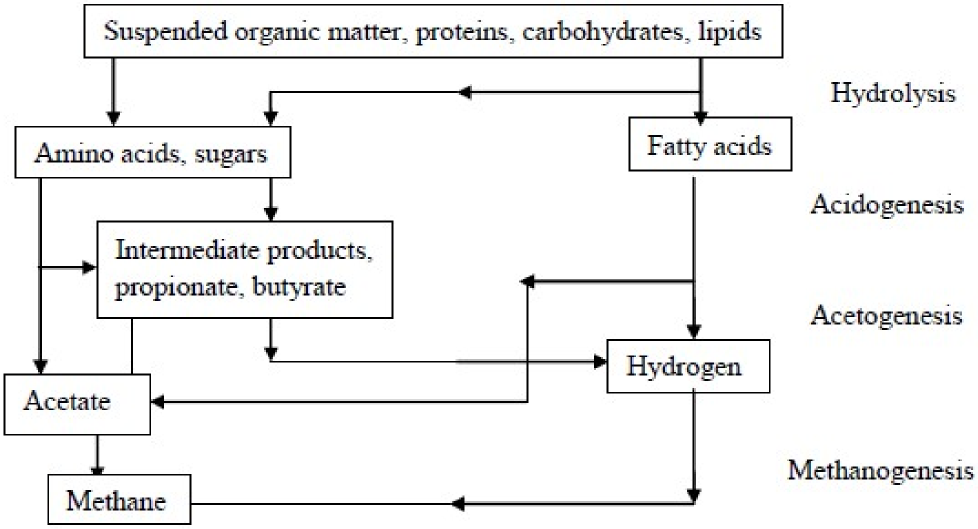

Figure 1.0.1 - Phases of the anaerobic digestion

Overall, the efficiency of the process depends by the following parameters:

- characteristics of the organic matter;
- environmental factors;
- SRT;
- intensity of mixing, which promotes the contact between bacteria and organic matter;
- specific organic loading rate.

Regarding the environmental factors, the main parameters to take into account are pH and temperature.

Methanogenic microorganisms are extremely sensitive to pH fluctuation. The optimum pH range for the methane production is considered between 6.6 and 7.6. The non-methanogenic bacteria, instead, are not extremely influenced from environmental conditions and are able to operate in a range of pH from 5 to 8.5.

Anaerobic digestion is generally operated either at mesophilic (35ºC) or thermophilic (55-60ºC) conditions. Overall, mesophilic digestion is usually more utilized since its lower energy demand and the higher stability of the process. The thermophilic one, instead, is more efficient in terms of organic matter removal, methane production and sanitation.

Another important aspect to consider is the stability of the whole process. The digestion can get instable for several reasons such as the rapid increase in the concentration of volatile acids in the first stage of the reaction or a low pH with a corresponding reduction in methane gas production. The instability can be reduced by allowing the bacteria to sufficiently acclimatize. The acclimatization process, in fact, enables the bacteria to stand stressful conditions. Usually the acclimatization of the microbes to a substrate may take 3 to 8 weeks.

It is also important to consider the presence of toxic compounds in the system, such as sulphides, than can inhibit the whole process. An increase in the concentrations of ammonia, higher than 0.5 – 0.6 g/L could also affect the system since it could be absorbed by the bacteria membranes. The ratio between Volatile Fatty Acids and Total Alkalinity, instead, should be between 0.3 and 0.4.

1.1.2 Advantages and disadvantages

The main advantages of the process are:

- less space required in comparison to other conventional systems;
- reduction of solids to be handled;
- a high degree of waste stabilization;
- energy recovery by the production of methane, which has a definite economic value as a fuel, and it is used as a source of energy for both heat and electric power;
- nutrients (nitrogen, phosphate and potassium) are almost completely detained;
- the fact that no oxygen is required highly reduce the energy demand;
- if the reactor is not fed for few months the system is not consistently affected and this makes this treatment an attractive option for seasonal industrial wastewater treatment;
- while the aerobic processes are restricted in maximum organic loading rate by the inability to transfer oxygen at the rate sufficient to satisfy the oxygen demand of the systems, the anaerobic process do not have this limitation in terms of organic loading rate;
- high pathogens reduction by the thermophilic anaerobic process.

This process, however, has also several disadvantages:

- complex and unstable operation;
- since the anaerobic microorganisms (especially methanogens) are characterized by a low growth rate, the first start-up period of an installation can be very long;
- the methanogenic bacteria are really sensitive to the presence of a large number of chemical compounds;
- the sludge produced has often bad dewaterability properties.

1.2 Aerobic digestion

1.2.2 Description of the process

Aerobic digestion is a process defined as the biological oxidation of organic matter under aerobic condition. During this process, the microorganisms (heterotrophic bacteria), consume organic matter and convert it into carbon dioxide, water and active biomass. The final acceptor in the oxidation process is the oxygen.

This kind of digestion is far less utilized than the anaerobic one but, it has the advantage to stabilize the sludge in shorter time.

Aerobic heterotrophic microorganisms use the fermentation process to reduce complex organic compounds to simple organic forms. The fermentation is an exothermic reaction, during which the soluble organic compounds are broken down. As shown in the equations below, it does not depend on the presence of dissolved oxygen. This process can be divided in two stages: acid fermentation and methane fermentation. During the acid fermentation volatile fatty acids (VFA) and alcohols are produced. Since in this phase most of the carbon is still in an organic form, just a small reduction of BOD occurs. During methane fermentation, a portion of the products of the acid fermentation are converted to methane and carbon dioxide, providing in this way a reduction of the BOD.

$$organic\ compounds\ \rightarrow VFA + CO_2 + \ H_2O + CH_4 + energy + residuals$$

During the respiration step, aerobic microorganisms transform the VFA into carbon dioxide, water and additional energy. As shown in the equation, this phase requires oxygen to occur.

$$VFA + \ O_2 \rightarrow CO_2 + \ H_2O + energy + residuals$$

Through the biosynthesis, new cells are produced. For this process precursors (that provide essential elements present in the cellular structures, like nitrogen, carbon and hydrogen) and adenosine triphosphate (ATP) are required.

$$simple\ precursors \rightarrow C_5H_7NO_2$$

Eventually, with the process called endogenous respiration, that occurs when the substrate starts lacking, the microorganisms start to nourish on each other, using cell material as carbon source.

1.2.2. Advantages and disadvantages

The main advantages of aerobic digestion are:

- the process is easy to handle and it requires less qualified management;
- less daily maintenance;
- lower capital costs;
- aerobically digested sludge usually has good dewatering characteristics;
- supernatant liquors from aerobic digestion have a lower BOD than those from anaerobic digestion;
- it produces a highly stable end product, suitable for subsequent utilization in a variety of processes (e.g. agriculture);
- end - products are basically odorless.

The process has also negative aspects:

- higher power requirements than anaerobic digestion, since oxygen is required;
- the energy recovered is much lower than anaerobic digestion (no methane is produced);
- no sufficient sanitation efficiency (pathogens removal) at low SRTs.

1.3 Sequencing Batch Reactor (SBR)

1.3.1 Main characteristic

Sequencing batch reactors (SBR) are a type of activated sludge wastewater treatment. In this kind of reactors, equalization, aeration and clarification processes occur sequentially in a single tank.

The SBR operates following the basic steps, described below:

1. Fill: the wastewater to be treated is added to the reactor. During this phase the air flow could be turned on or off, depending on the operational conditions, that could be static, mixed or aerated fill:
    - static fill: the reactor is not mixed or aerated;
    - mixed fill: the reactor is mixed but not aerated;
    - aerated fill: the reactor is mixed and aerated;
2. React: in the reactor continuously aerated and mixed the reactions start. The react phase can be mixed or aerated: in the first case there would be anoxic conditions, in the second case just aerobic ones;
3. Settle (Sedimentation/Clarification): the separation of biosolids from the effluent occurs without any influent or effluent currents;
4. Draw (Decant): the clarified effluent is discharged from the reactor through several types of withdrawal mechanisms, like a pipe placed at a certain depth with the flow regulated by an automatic valve or a pump;
5. Idle: this is the step between the draw and the fill phase.

In the Figure 1.2 all the steps described above are shown.

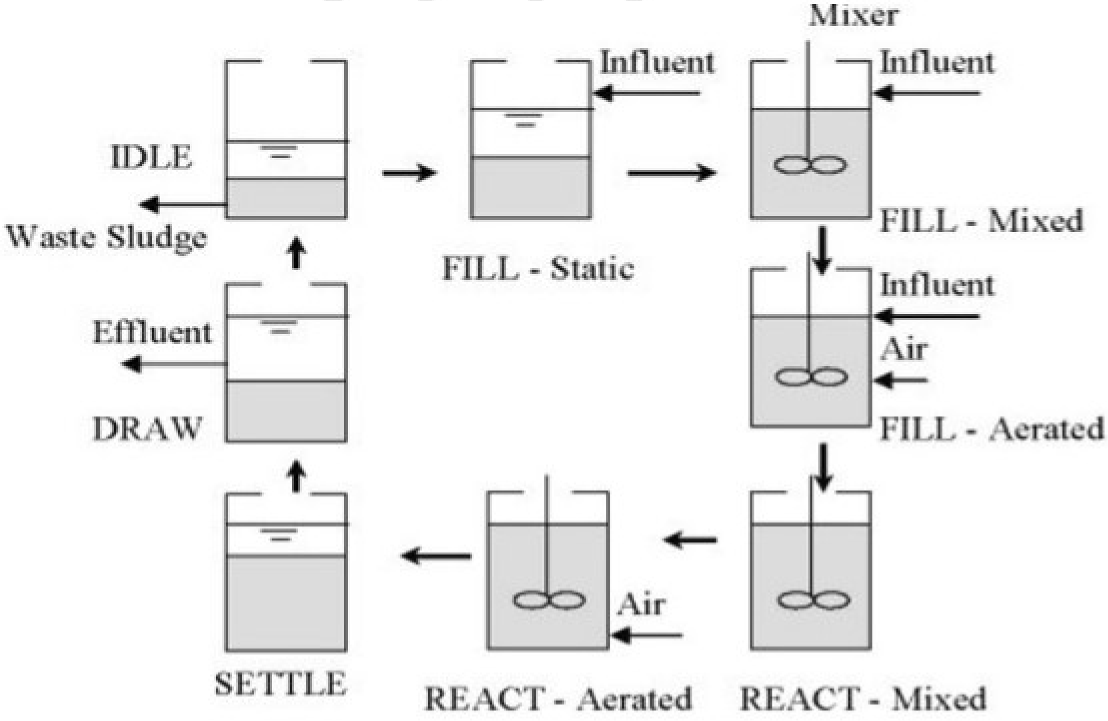

Figure 1.0.2 - Main phases of a Sequencing Batch Reactor

1.3.2 Advantages and disadvantages

The main advantages of this reactor are:

- economic savings by merging different phases (equalization, biological treatment and clarification) in one reactor;
- flexible technology.

This technology, however, compared to conventional systems, especially in the case of larger plants, requires a higher level of sophisticated control and more maintenance, because of the presence of automated mechanisms (e.g. valves).

1.4 Nitrogen removal

1.4.1 Nitrogen forms

Nitrogen exists in several forms: Total Nitrogen, Total Kejeldahl Nitrogen (TKN), Ammonia, Organic Nitrogen, nitrate and nitrite nitrogen. Concentrations are reported in mg/L.
The Total Nitrogen concentration is determined as:

$$Total - N = TKN + NO_3 + NO_2$$

Total Kejeldahl Nitrogen (TKN) includes Total Ammonia Nitrogen (TAN) and Organic Nitrogen:

$$TKN = TAN + org - N$$

The Total Ammonia Nitrogen is given by the sum of ammonia (NH_3) and ammonium (NH_4^+), while Organic Nitrogen is organically bound nitrogen in the trivalent state.
The ammonification is a processed carried out by heterotrophic bacteria, in which the organic nitrogen is converted to ammonia nitrogen. Ammonia nitrogen is present in water as either free ammonia nitrogen (NH_3) or ammonium (NH_4^+). NH_3 is a gas representing the undissociated form of ammonia and that can be found, in certain concentrations, dissolved in the water. It can be toxic for certain microorganisms since is permeable from the membranes. The NH_4^+ is the dissociated form. The two species are in equilibrium accordingly to the following equation (pKa = 9.3 and T = 25 ºC):

$$NH_4^+ \leftrightarrow NH_3 + H^+$$

When the pH of the wastewater is below 7, the majority of the nitrogen can be found like ammonium (NH_4^+). Instead, when the pH increases over 7, the nitrogen is mostly ammonia (NH_3). Above pH 12, mostly all the ammonia will be present as dissolved gas, in a percentage increasing with temperature and pH. The relationship between these two forms can be expressed as follows:

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$$

1.4.2 Nitrification process

The nitrification is the biological process in which the ammonium is converted to nitrate nitrogen. The main bacteria operating the nitrification processes are the *Nitrosomonas* and *Nitrobacter*, which are autotroph bacteria, since they use as source of energy inorganic nitrogen and carbon (CO_2) compounds, rather than organic compounds.

The whole process can be divided in two phases:

1. *Nitrosomonas* convert ammonia and ammonium to nitrite (the general equation is shown below);

$$NH_4^+ + 1.5O_2 \rightarrow 2H^+ + H_2O + NO_2^-$$

2. *Nitrobacters* eventually converts nitrite to nitrate (the general equation is shown below).

$$NO_2^- + 0.5O_2 \rightarrow NO_3^-$$

The general reaction is the following one:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

The parameters to take into account for this process are the following:

- Dissolved oxygen: nitrification occurs only under aerobic conditions at dissolved oxygen levels of 1.0 mg/L or more. At dissolved oxygen concentrations lower than 0.5 mg/L, the growth rate is extremely slow;
- Sludge Retention Time: from 2 to 20 days;

- Temperature: this is not a parameter that considerably affects the process but a reduction of temperature below 15ºC could negatively affect the growth yield of the bacteria;
- pH: the optimum range is between 6.5 and 8.6;
- Alkalinity: since it is consumed during the process, it is important to maintain sufficient alkalinity in the wastewater, in order to prevent a decrease in the pH;
- Organic load: an excessive organic load quickens the heterotrophic growth yield and the sludge production, resulting in a decrease of the amount of nitrifiers present in the system.

1.4.3 Denitrification process

The denitrification is the biological reduction, under anoxic conditions, of nitrate nitrogen (NO_3) to nitrogen gas (N_2) by facultative heterotrophic bacteria. The nitrogen gas can eventually escape from solution to atmosphere, but gaseous forms are not considered to have an environmental impact.

The denitrifying microorganisms are ubiquitous heterotrophic bacteria: in an oxygen-free environment they use nitrite and nitrate nitrogen as final electron acceptors for the oxidation of the organic matter.

The formula describing the process follows:

$$6NO_3^- + 5CH_3OH \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^-$$

The parameters to take into account for this process are:

- pH: it must be between 6 and 8;
- Temperature: it significantly affects the growth yield of the bacteria. The process can occur between 5 and 30ºC, it will proceed at reduced rates at temperatures below 5ºC;
- Dissolved oxygen: since the process is performed under anoxic conditions, the dissolved oxygen concentration in the system must be less than 0.5 mg/L (ideally less than 0.2 mg/l);
- Carbon concentration: there must be sufficient organic matter to support the reaction.

1.4.4 Impacts of nitrogen in water

Nitrogen is a nutrient naturally present in the aquatic ecosystems, so it cannot be considered dangerous when present in water. A surplus of nitrogen, however, may cause eutrophication, a process that occurs in presence of a considerably high concentration of nutrients in the water which causes an excessive plant and algal growth.

The main effects of eutrophication are:

- limited light penetration;
- reduced gases (also oxygen) exchange with the atmosphere;
- when the plants eventually die, a consequent reduction of oxygen occurs because of the decomposition process, and also a release of substances like ammonia, methane and hydrogen sulfide;
- water turbidity;
- unpleasant smell.

Regarding human health problems, nitrate can be converted to nitrite, which combines with hemoglobin in the blood to form methemoglobin, which does not absorb oxygen. With reduced capacity of the blood to absorb oxygen, death from lack of oxygen can result.

1.4.5 Literature review: nitrogen removal by combined anaerobic – aerobic digestion

In this study the potentiality to remove ammonia nitrogen by a continuously aerated reactor has been investigated. The ammonia nitrogen is removed through the nitrification process, with the following production of nitrite and nitrate nitrogen.

Unfortunately there are not so many studies investigating just the nitrification process operated by a post – aerobic treatment of anaerobically digested sludge: the majority of the articles investigate the effect of an aerated stage with intermittent aeration in order to determine anoxic periods inside the reactor to promote the denitrification process for a complete nitrogen removal. In our case, it has been decided to not set periodically anoxic conditions since several kinetic tests highlighted the fact that the substrate present was not enough to sustain the denitrification process.

However, a study performed by Kim and Novak (2011) showed a 97% reduction of ammonia nitrogen from the effluent of the anaerobic system, after treated it with an aerobic reactor operating at SRT of 5 days and room temperature.

In another experiment carried out at the University of Chemistry and Technology of Prague by PhD student Marie Vojtiskova and Prof. Pavel Jenicek, the highest percentage of ammonia nitrogen removal (96%) was reached during a batch experiment lasted 12 days at the temperature of 36^0C.

1.5 Organic compounds removal

1.5.1. Chemical Oxygen Demand (COD)

Chemical oxygen demand (COD) is a measurement of the total quantity of oxygen required to oxidize all organic material into carbon dioxide and water. It is usually expressed in mgO_2/l. COD is an important water quality parameter because it provides an index to assess the effects that the discharged wastewater will have on the receiving environment. An excessive concentration of COD could lead to a reduction of the DO levels, which can causes anoxic conditions in the water system.

1.5.2 Total Organic Carbon (TOC)

The Total Organic Carbon (TOC) is a measurement of the amount of organic carbon present in water. It represents one of the main parameters to determine the organic pollution of water.

It is expressed as:

$$TOC = TC - TIC$$

Total Carbon (TC) includes both inorganic and inorganic sample constituents.

The Total Inorganic Carbon (TIC) represents the amount of inorganic carbon forms in the sample (carbon dioxide, carbonic acid, bicarbonate and carbonate).

It can be also equal to:

$$TOC = NPOC + POC$$

The POC (Purgeable Organic Carbon) represents the volatile organic fraction presents in the sample, which can be purged by injecting inert gas in the acidified sample.

The NPOC (Non-Purgeable Organic Carbon) represents the fraction that cannot be purged. Usually it represents almost the totality of the TOC.

1.5.3 Total Solids (VS) and Volatile Solids (VS)

Total Solids (TS) are the total of all solids in a sample. They include the total suspended solids, total dissolved solids, and volatile suspended solids.

The Volatile Solids represent the organic fraction. They are measured as difference between the Total Solids (obtained by evaporation of the sample at 105°C) and the residual after further combustion in a furnace at 550°C (at this temperature the organic fraction is completely oxidized).

1.5.4 Literature review: organic compounds removal by combined anaerobic – aerobic digestion

The concentration of soluble COD is correlated to the presence of biopolymers, such as proteins and polysaccharides. They are released during the hydrolysis process in the anaerobic digestion and degraded during the aerobic one. Parravicini (2008) reported a 25% reduction of the COD concentration treating anaerobically digested sewage sludge (mesophilic stabilization) with an aerated reactor operating at SRT of 5 days and at 30^0C.

The concentration of COD is also related to the dewaterability properties of the sludge: and high COD usually corresponds to bad dewatering properties.

Regarding the TOC, there are not so many articles analyzing the correlation between this parameter and the post – aeration treatment but, the results obtained by this study, show that the pattern of the TOC is usually similar to the COD one. However, a study performed by Mantas et al. (2007), reported that aerobic stabilization led to a TOC reduction of approximately 75%.

Regarding the VS fractions present in the sludge, Novak (2004) proposed the following classification:

1. Aerobically degradable fraction;
2. Anaerobically degradable fraction;
3. A fraction degradable under aerobic or anaerobic conditions;
4. A non – degradable fraction.

The combined anaerobic – aerobic digestion can remove the first three fractions, which cannot be removed just only by one of these types of digestion. With this combination, a greater reduction of VS is achieved.

The SRT seems the main parameter to keep into account in order to promote the removal of VS: as the SRT increase, more VS are removed. Kim and Novak (2011) reported an additional VS reduction of 14% from anaerobically digested sludge, by setting in the continuously aerated reactor a SRT of 5 days. Another study, performed by Kumar (2006), showed that the combined system characterized by a SRT of 3, 6 or 9 days, led to a further 10% reduction of VS.

1.6 Improvement of the dewatering properties

The dewatering process of the sewage sludge is one of the main challenges to be faced in a treatment plant. The sludge is often dewatered in order to reduce the total volume leading is this way, in a lowering of the management costs (e.g. transportation).

The main parameters to consider for improving the sludge dewatering properties are: nature of the sludge to be treated and technology adopted to remove the water.

It is also important to determine which parameter should be utilized to evaluate the dewaterability properties. In this study two methods have been investigated: centrifugation and Capillary Suction Time test.

1.6.1. Distribution of the water in the sludge

Accordingly to the most used categorization, in the sludge four kinds of water can be identified (Figure 1.3):

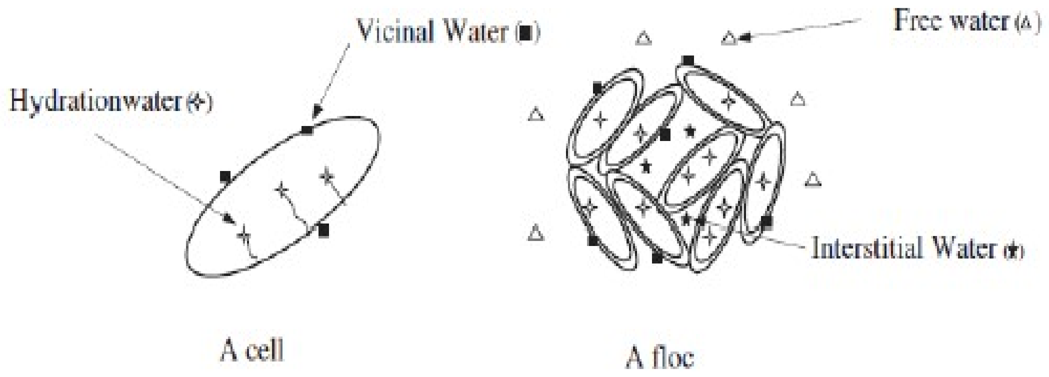

Figure 1.3 - Distribution of the water in the sludge

- Free water: it is not attached to solid particles and that can be easily removed by gravity settling;
- Interstitial water: it is trapped between particles and it can be extracted by mechanical dewatering machines (e.g. vacuum filters or centrifuges);

- Vicinal water: water gripped to the surfaces of molecules by adsorption and adhesion. This water is really difficult to be removed, except maybe by drying process;
- Hydration water: water chemically bound to the molecules that can be removed only by high temperatures (above 105ºC).

1.6.2 Capillary Suction Time

Baskerville and Gale (1968) developed the CST test as an alternative to the most used Specific Resistance to Filtration (SRF) test. The instrumentation is composed by the following parts: two plastic rectangular blocks, a small steel cylindrical tube, filter paper (Whatman No. 17), two electrodes connected to an electrical timer. The test is executed by spilling approximately 5 ml of sludge into the tube. The capillary pressure led the sludge flowing radially through the filter paper. The timer starts to calculate the time when the sludge reaches the first two sensors. It stops once the third sensor is reached. The CST value is expressed in seconds. CST is an easy and automatic measurement, characterized by a quick interpretation of the data. For these reasons it became one of the most widely utilized methods to assess the dewatering properties of the sludge. The CST test is used to determine the proper conditioning dose to improve the sludge dewaterability (Figure 1.5).

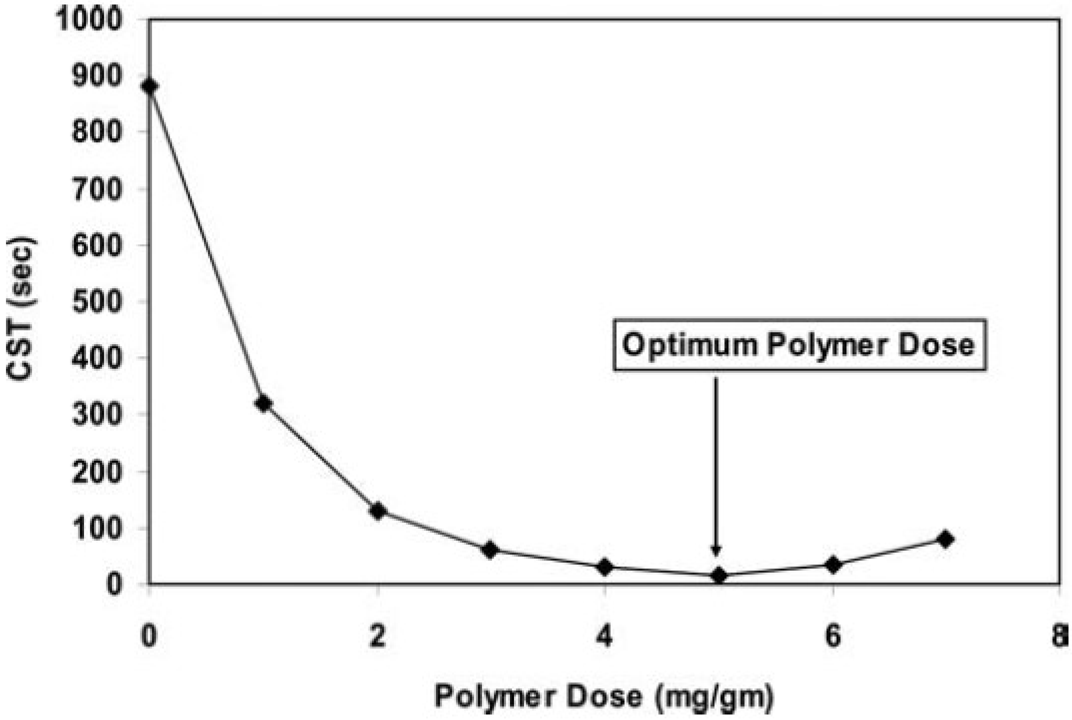

Figure 1.4 - Correlation between CST and Polymer Dose

As shown is the following formula, CST can be affected by several parameters such as filter paper, instrumentation and sludge properties:

$$CST = \emptyset\left[\frac{\mu C}{\chi}\right]$$

where $\emptyset$ is a constant depending from the utilized instrumentation (adimensional); C is the solid concentration, χ is the filterability constant.

1.6.3 Centrifugation method

Although CST method is widely used, it turns out not to be very suitable for practical use at WWTP if the sludge is dewatered by centrifugation. Therefore, also the centrifugation method has been investigated to determine the dewaterability characteristics of the sludge.

1.5.4 Literature review: improvement of the dewaterability properties by combined aerobic – anaerobic digestion

The anaerobically digested sludge is often characterized by extremely poor dewatering properties and this is a main concern because of the additional costs for the further treatments to be carried out.

Novak (2003) suggested that one of the main reasons of the deterioration of the dewatering properties is due to the release of soluble biopolymers, such as proteins and polysaccharides, into solution during the hydrolysis phase of the anaerobic digestion. Since these polymers have high affinity with water, the dewatering characteristics of the sludge are worsened. The aerobic stage could reduce the concentration of proteins and, in this way, facilitate the dewatering processes. Kumar (2006), through a post - aerobic stage (SRT 6 days), reported a 80% reduction of proteins and polysaccharides and a consequent improvement of CST values from the sludge coming from thermophilic anaerobic digestion.

Braguglia et al. (2014), in another study (room temperature, SRT of 12 days and mesophilic anaerobic digested waste sludge), reported a 25% reduction of the CST value.

Tomei and Carozza (2014) also performed a study of a combined mesophilic (37ºC) anaerobic reactor, fed with WAS or mixed sludge, and an aerobic reactor operating at room temperature and at SRT of 12 days. The CST measurements showed an increase of CST after anaerobic stage from 30±10 to 470±45 s for WAS and from 154±53 to 538±78 s for mixed sludge. After the aerobic stage, instead, the CST decreased to 350±60 to 253±72 s for WAS and mixed sludge respectively. Also a decrease in the COD concentration has been observed. In fact, during the aerated digestion, the degradation of biopolymers occurs, reducing the soluble COD and releasing of bound water.

2. Objectives

The aim of the present project is the optimization of a post-aerobic treatment of anaerobically digested sludge. Post-aeration is a proven technique to achieve further stabilization of digested sludge and to improve its dewaterability properties.

For the study, a SBR has been chosen. The reactor, continuously mixed and aerated, operated in room temperature conditions. Sludge used for the experiments was collected from the Central WWTP of Prague.

The variables changed through all the study in order to determine the best operating conditions were Sludge Retention Time and aeration rate. The chosen parameters to estimate the post-aeration treatment efficiency accordingly to the main literature are: Total Ammonia Nitrogen concentration, nitrite and nitrate concentration, Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), Capillary Suction Time (CST), pH, Total Solids (TS) and Volatile Solids (VS) concentration.

In particular, the experiments were focused on the following achievements: ammonia nitrogen removal, organic compounds removal, improvement of the dewatering properties of the sludge.

The main scope of this study is to obtain preliminary results of the effect of the mentioned variables to the system.

Also, the results obtained can provide a comparison between the two methods (Capillary Suction Time and centrifugation) utilized to assess the dewaterability properties of the sludge.

3. Methods

3.1 Materials

The sludge utilized for all the experiments was collected at the Central WWTP of Prague. In the Table 3.1 the main characteristics of the plant are shown.

Capacity	Type	Sludge Stabilization
1,500,000 PE	Mechanical-chemical-biological, activation process	Anaerobic thermophilic

Table 3.1 - Characteristics of Central WWTP of Prague

In the Figure 3.1 the flow diagram is shown.

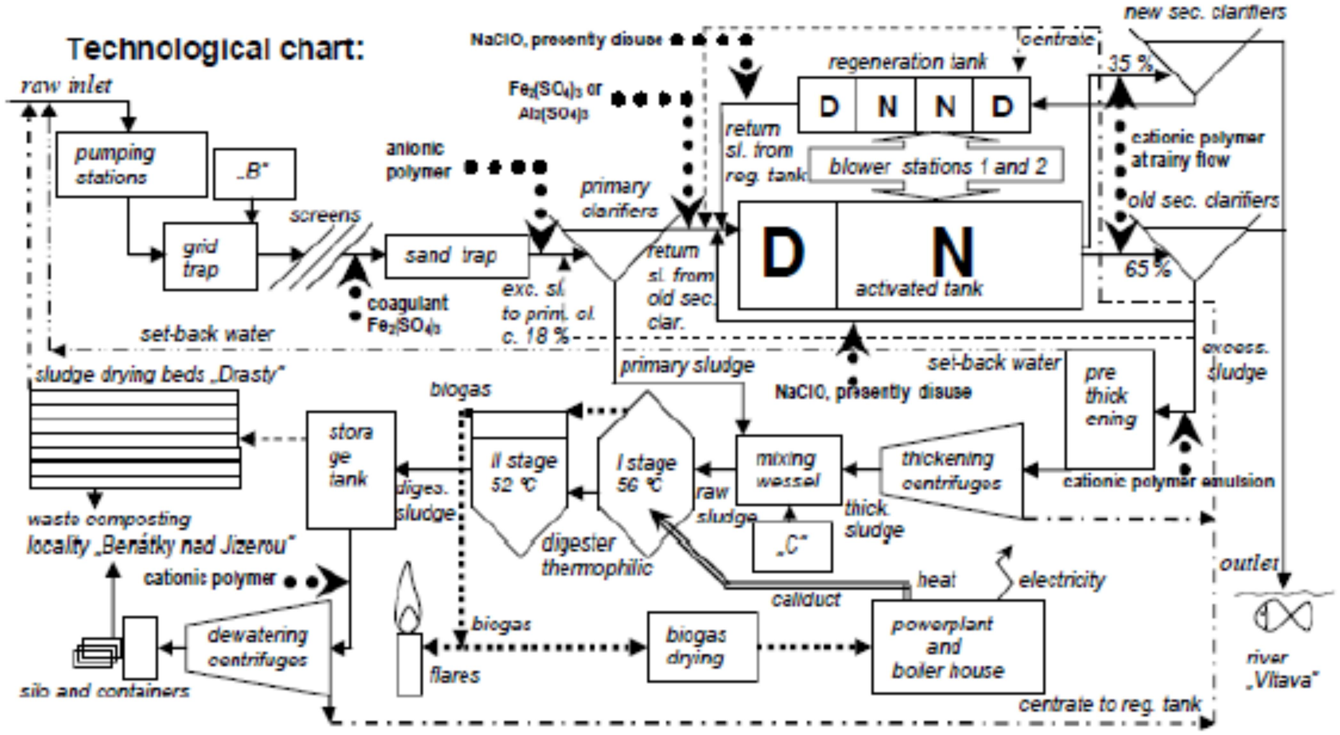

Figure 3.1 - Flow diagram of Central WWTP of Prague

The sludge was stabilized through a two stages anaerobic digestion in thermophilic conditions:

1. Mixed and heated digesters (55ºC);
2. Mixed and non-heated digesters (52ºC);

Each digester is characterized by a volume of 5000 m^3. Real hydraulic retention time through the digesters is 16 - 20 days.

After the sampling, the sludge was subsequently stored in 5 L tanks and put in a fridge at the temperature of about 4ºC.

In the Table 3.2 the main characteristics of the sludge used in the study are summarized.

TS	**VS**	**pH**	**COD**	**TAN**	**NO_2**	**NO_3**
g/L	**g/L**	**-**	**mg/l**	**mg/l**	**mg/l**	**mg/l**
22.4 ± 8.6	33.2 ± 13.6	8.9 ± 7.5	2525 ± 1087	1552 ± 981	21.6 ± 0	0.062 ± 0

Table 3.2 - Characteristics of anaerobically digested sludge utilized for the study

It must be pointed out that the characteristic of the sludge vary a lot because the samples were collected in different time periods.

3.2 Experiments and procedures

A lab-scale SBR (8L) cylindrical shaped was used. The rector is shown in Figure 3.2.

Content of the reactor (3.2 L of digested sludge) was mixed by magnetic stirrer and aerated. The mixers operated continuously, except during the short time allowed for settling and draining. The mixer switches were also operated manually.

The SBR operated in aerobic conditions: it was aerated also during the fill and react phase. The only phases were the air flow was turned off were the settle and draw ones. All the experiments were conducted in room temperature conditions (20 - 25ºC).

Reactor was fed daily (except weekends) and analyses were performed three times a week.

For all the experiments it was considered that the reactor started to work at the best conditions after a start-up period equal to 4 times the set SRT. The experiments were executed also during that period but, for the motivation mentioned before, the results cannot be considered completely reliable.

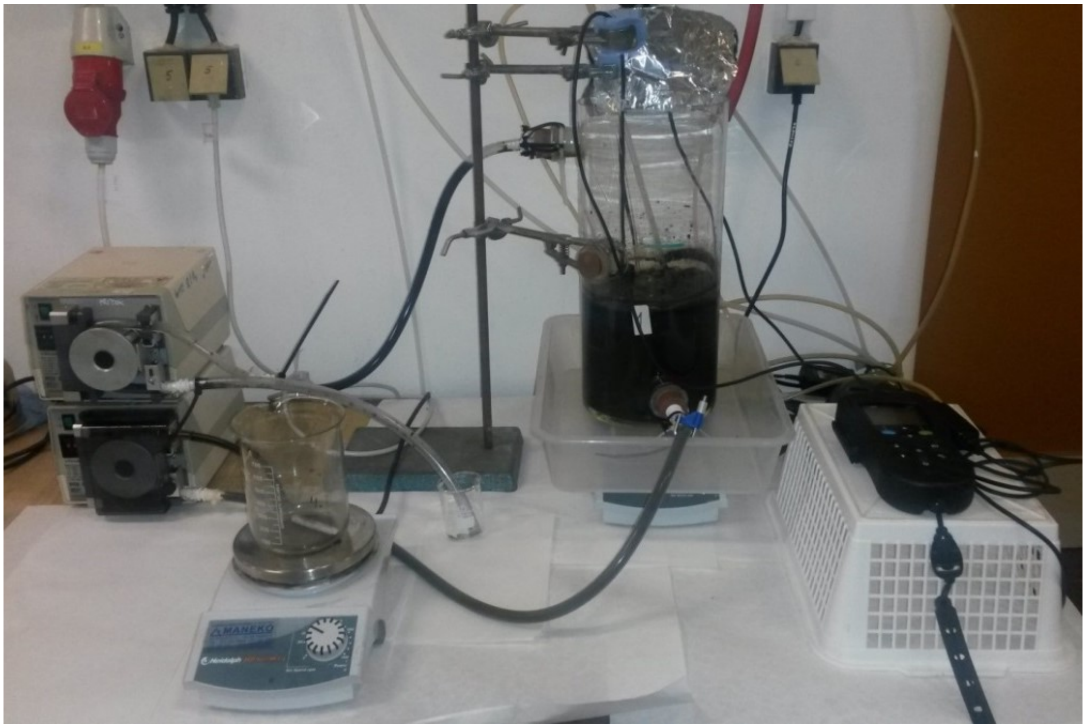

Figure 3.2 - Sequencing Batch Reactor used for the experiments

3.3 Analytical techniques

Analyses were performed according to standard methods or Czech standards.

3.3.1 pH and temperature

The pH and the temperature were determined using a daily calibrated pH meter (SENTRON - SI4007400 – 010).

3.3.2 Total solids analysis

For the TS determination, the following procedure has been adopted:

1. mixing properly with a magnetic stirrer both effluent and influent sludge;
2. preparation of containers for the sludge with aluminium foils;

3. weighting the dishes;
4. putting 10 ml of well-mixed sludge into the dishes (there were prepared 2 samples for the effluent and 2 samples for the influent);
5. drying the samples in a drying chamber at 105ºC for 24 hours.

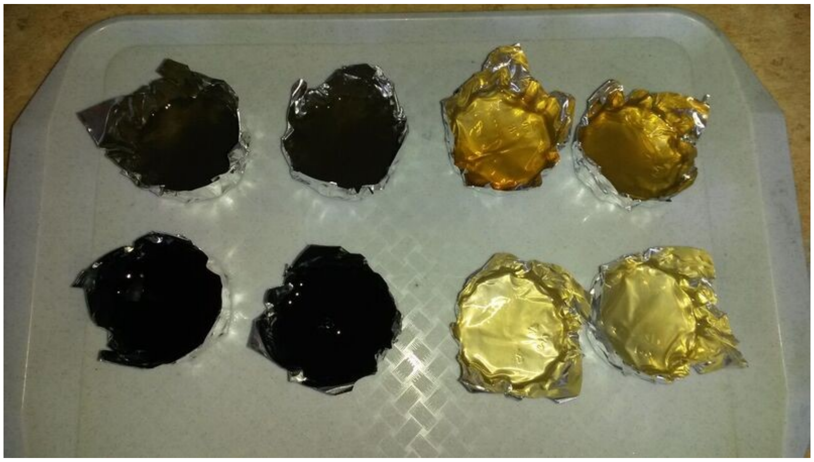

Figure 3.3 - Samples after the drying process at 105 °C

Total Solids were determined as difference between the weight of the samples after the drying process and the weight of the aluminium dishes.

The Volatile Solids (VS) were determined by further combusting the solid samples in a furnace at 550ºC for 1 hour.

The inorganic matter was determined as difference between TS and VS.

The Total Dissolved Solids (TDS) instead, were determined with the following procedure:

1. inserting 3 samples for both effluent and influent into a centrifuge for 10 minutes at 13000 min^{-1}, in order to separate the liquid part from the solid one;
2. preparation of the dishes with aluminium foils;
3. weighting the dishes;
4. putting 10 ml of the liquor obtained after the centrifugation into the dishes (there were prepared 2 samples for the effluent and 2 samples for the influent);
5. drying the samples in a drying chamber at 105ºC for 24 hours;

Total Dissolved Solids were determined as difference between the weight of the samples after the drying process and the weight of the aluminium dishes.

The Total Dissolved Volatile solids were determined after further combustion of the dried liquor in a furnace at 550ºC for 1 hour.

3.3.3 Total Ammonia Nitrogen (TAN)

The Total Ammonia Nitrogen (TAN) was determined by using a Manual Distillation Unit K-350 Buchi (Figure 3.4), a machine suitable for determining nitrogen using the Kjeldahl (TKN; Total Kjeldahl Nitrogen) method.

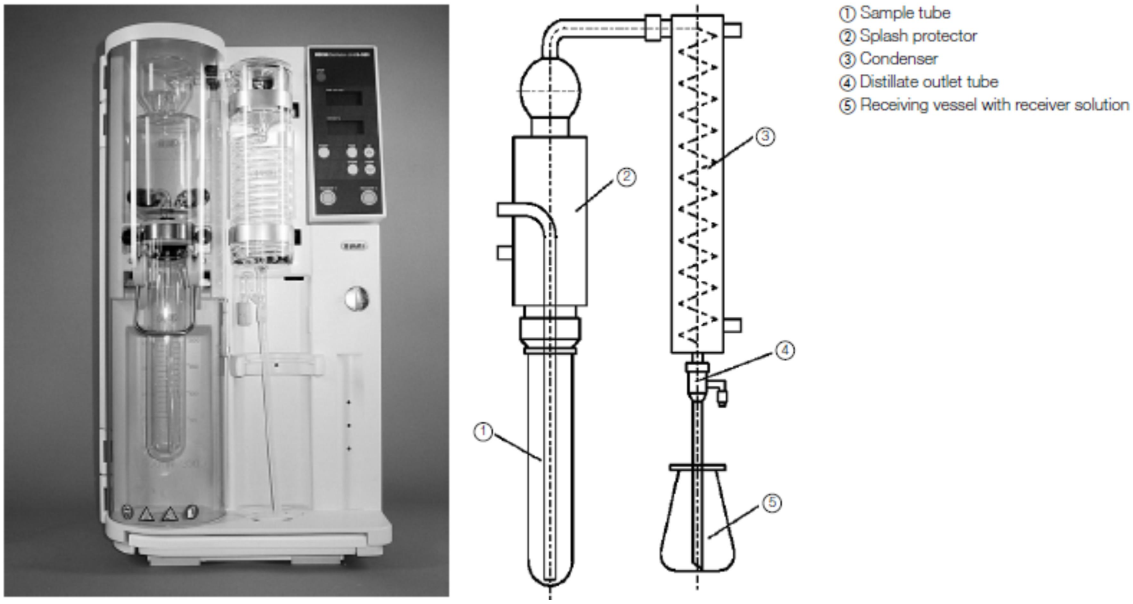

Figure 3.4 - Manual Distillation Unit K-350 Buchi

Procedure:

1. filtration in a filter paper (0.45 μm) of the liquor obtained by the previous centrifugation for removing all the impurities;
2. introduction of 5 ml of liquor and 45 ml of water into the sample tube;
3. steam is introduced into the sample solution to drive out the ammonia;
4. after condensation (in the condenser) the condensate is collected in a receiver solution (50 ml of boric acid);
5. the amount of ammonia is then determined by the titration with sulfuric acid, with the use of the following equation:

$$TAN\ (^{mg}/_{l}) = \frac{(V_{sulfuric\ acid} - V_{blank}) \cdot 14 \cdot 1000 \cdot 2 \cdot C_{sulfuric\ acid}}{V_{blank}}$$

3.3.4 Nitrite and nitrate nitrogen

The nitrite nitrogen was determined accordingly to standard ISO 6777:1984, through the following procedure:

- 5 ml of samples;
- 125 µl of SANED (diazotized sulfanilamide with N-(1-naphthyl)-ethylene-diamine dihydrochloride);
- 1,1 ml of distilled water.

After waiting for 20 minutes, the concentration was determined by measuring the absorbance of the samples with a spectrometer (Spectroquant NOVA 60 Merck) at wavelength equal to 550 nm.

The nitrate nitrogen was determined using standard ČSN 757455, through the following procedure:

- 0,5 ml of sample;
- 50 µl of sulfamic acid;
- 3,5 ml of acid mixture ($H_2SO_4 + H_3PO_4$);
- 0,5 ml of dimethylphenol.

After waiting for 10 minutes, the concentration was determined by measuring the absorbance of the samples with a spectrometer at wavelength equal to 340 nm.

3.3.5 Chemical Oxygen Demand (COD) analysis

The methodology to measure the COD follows the standard ISO 15705: 2002, which specifies the method for assessing the amount of oxygen consumed in total chemical oxidation of the organic constituents present in the water. The principle of this method is that 2 ml of the samples are oxidized by digestion in sulphuric acid and potassium dichromate in presence of silver sulphate and mercury (II) for 2 hours at 140ºC in a high temperature thermostate (Hach Lange HT200S). Silver acts as a catalyst to oxidize the more refractory organic matter and mercury reduces interferences caused by the presence of chloride ions. The amount of dichromate used in the oxidation of the sample is then determined by measuring absorbance of the Cr(III), it corresponds to the amount of oxygen. The wavelength to carry out the analysis was 605 nm according to the methodology.

3.3.6 Total Organic Carbon (TOC) analysis

For the TOC measurements, the Shimadzu Total Organic Carbon Analyzer (TOC-VCPH) was utilized.

3.3.7 Capillary Suction Times (CST) analysis

The capillary suction time was measured using a CST4 FIMA (Brno) and Whatman17 as filter paper (Figure 3.5).

Figure 3.5 - CST4 FIMA (Brno)

The sludge used for CST measurements was accurately mixed in order to achieve proper homogenization.

3.3.8 Centrifugation method

About 25 mL of the sludge was poured into a pre-weighed centrifuge tube and then weighed again. The sample was centrifuged (13,000 min^{-1} for 10 min) and the sludge liquor was decanted for further analysis. The quantity of removed water was calculated as the difference in weight of the total sample and the weight of the sludge cake remaining in the tube after centrifugation.

4. Results

4.1 Post – aerobic digestion: previous experiments

Previous experiments regarding the post – aerobic treatment were conducted at the Department of Water Technology of the University of Chemistry and Technology (Prague). The study was carried out by the PhD students Marie Vojtíšková and Barbora Šátková, under the supervision of the Professor Pavel Jeníček. It has been decided to report the results of this study in order to have a complete background of the argument.

In the Table 4.1 all the information related to the experiments are shown.

Number of experiment	Phase	Duration [d]	SRT [d]	Aeration rate [L·h^{-1}]	Aeration regime	Temperature [°C]	Type of the sludge
1	-	80	8	300	continuous	20 - 25	thermophilic
2	-	65	6	300	continuous	20 - 25	thermophilic
3	1	67	4	300	continuous	20 - 25	thermophilic
	2	19		600			
	3	5		900			

Table 4.1- Experiment description

4.1.1 Nitrogen removal

In the Figure 4.1 the Total Ammonia Nitrogen, nitrite and nitrate nitrogen concentration and pH in the effluent are shown.

The nitrification process took approximately 20 days to occur. The nitrite nitrogen reached its maximum values in correspondence with the minimum in the ammonia nitrogen concentration because of the oxidation process. Overall, 7 peaks are visible: on day 35 (216 mg/l), 70 (393 mg/l), 121 (378 mg/l), 155 (127 mg/l), 176 (119 mg/l), 219 (352 mg/l), 235 (238 mg/l). As expected, the treatment resulted less effective with a SRT of 6 and 4 days and an aeration rate of 300 L/h, so also the nitrite nitrogen concentration was lower. In the first phase of the experiment 3 (SRT of 4 days and aeration rate of 300 L/h), in fact, for three weeks (between day 185 and 205), the nitrification did not occur.

The nitrate nitrogen has a similar pattern to the nitrite one, but overall the concentration measured was characterized by lower values.

In general the pH declined with an increase in the ammonia nitrogen oxidation and rose when the rate of process decelerated. The minimum in the pH trend occurred on day 70 (6.25), when the highest peak in the nitrite nitrogen concentration was found.

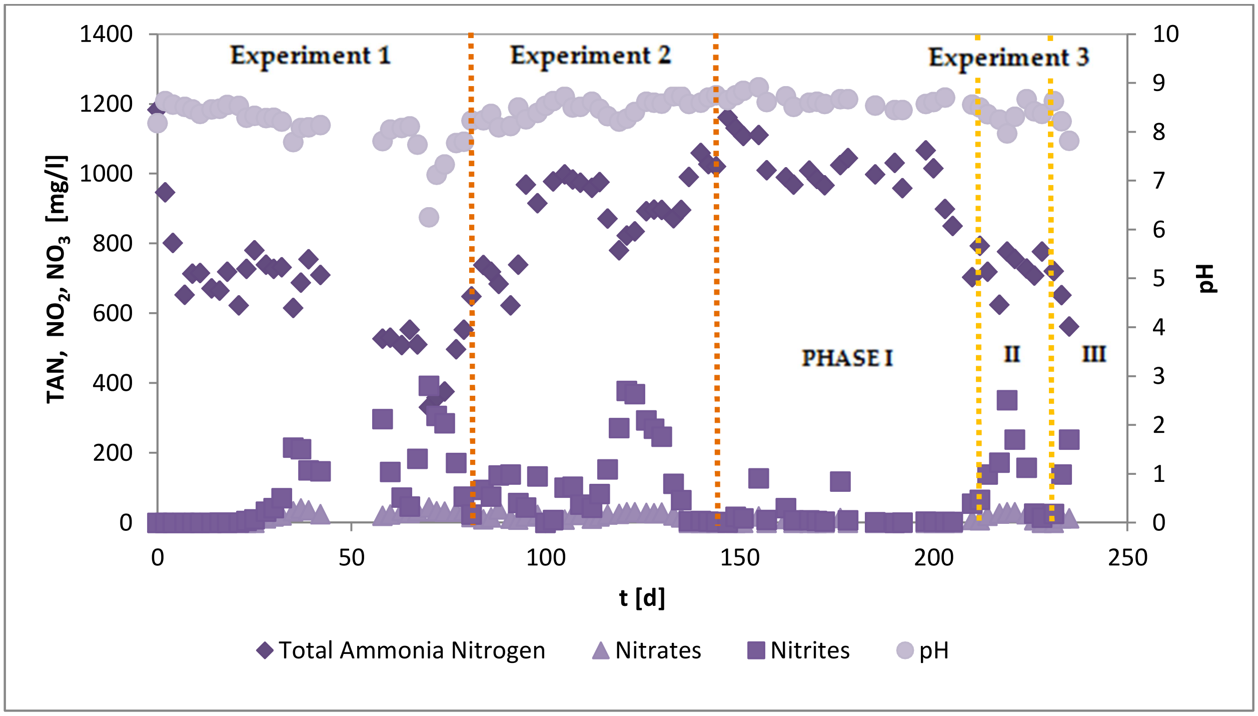

Figure 4.1 - Concentration of Total Ammonia Nitrogen, nitrites, nitrates and pH in the effluent

In the Figure 4.2, 4.3, 4.4 and 4.5 the Total Ammonia Nitrogen, nitrite and nitrate nitrogen concentration and pH in the effluent compared with the ones in the influent are respectively shown.

The treatment resulted effective in all the experiments, since the concentration of ammonia nitrogen in the treated effluent showed always a reduction in comparison with the influent. The major achievements were achieved in the first experiment and in the second phase of the third one, where the concentration decreased, respectively, from 1295 mg/l to 561 m/l and from 1349 mg/l to 726 mg/l (the values just reported represent an average on the concentrations in the influent and the effluent).

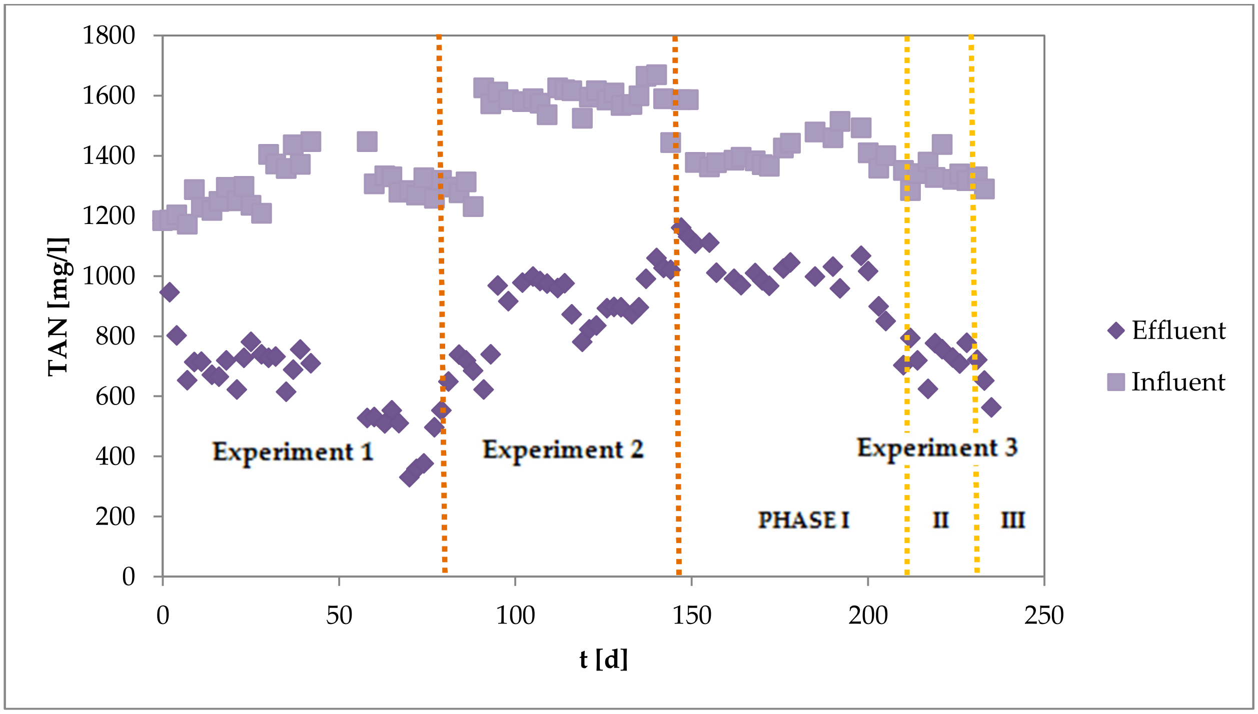

Figure 4.2 - Concentration of the Total Ammonia Nitrogen in the effluent and in the influent

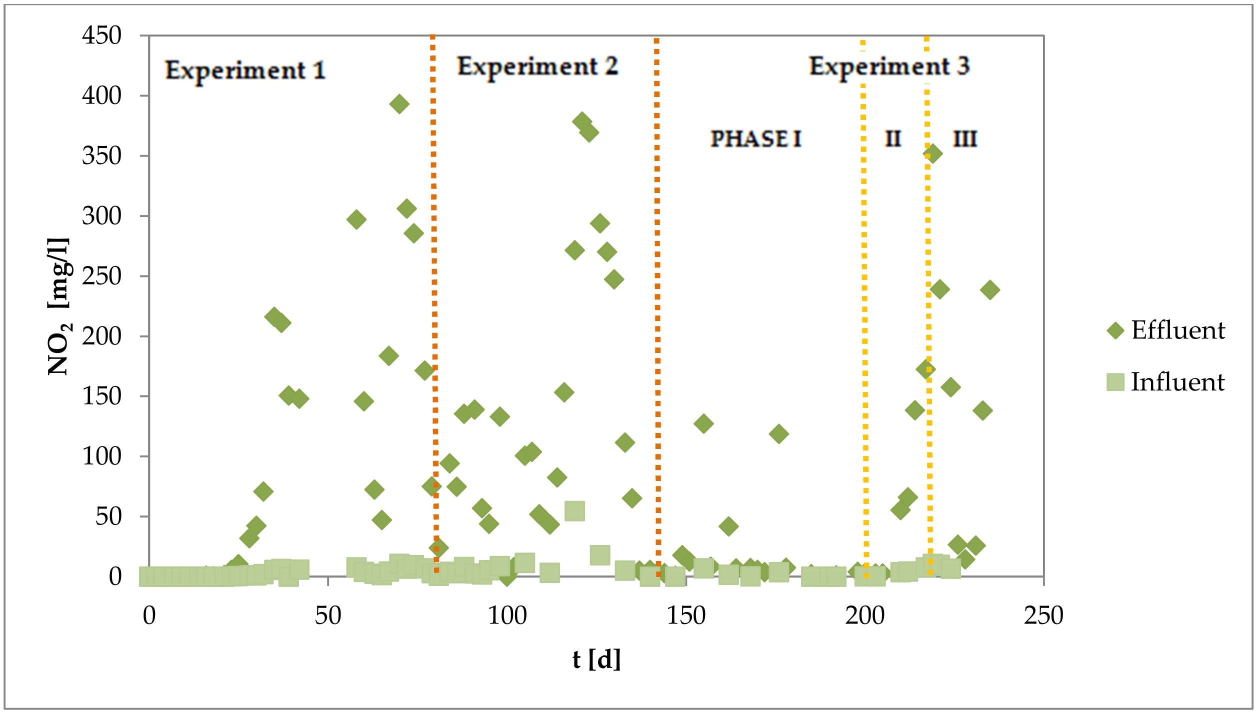

Figure 4.3 - Concentration of nitrite nitrogen in the effluent and in the influent

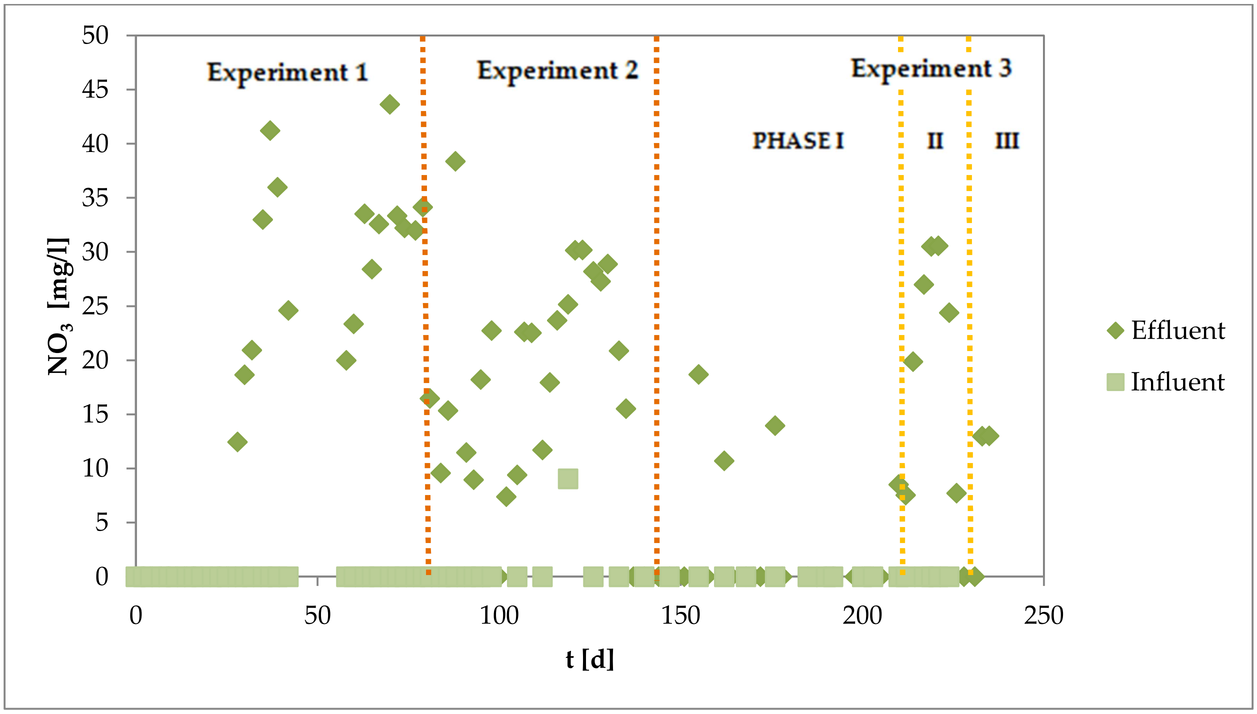

Figure 4.4 - Concentration of nitrate nitrogen in the effluent and in the influent

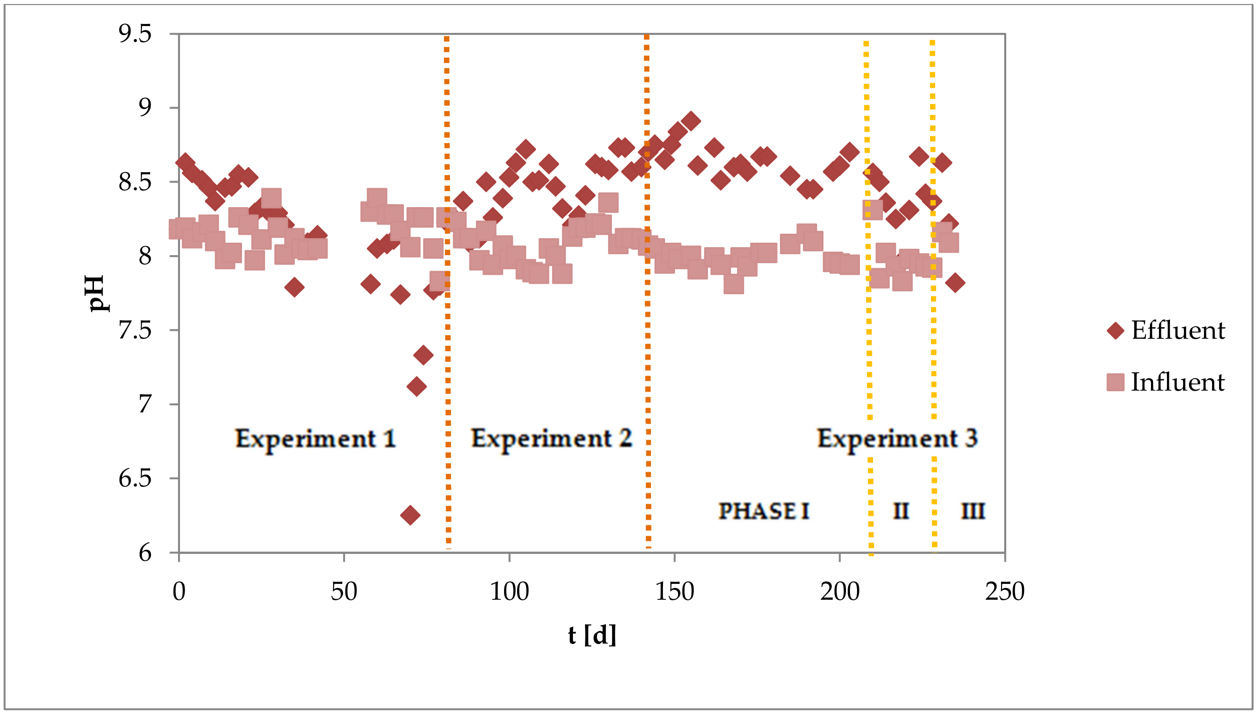

Figure 4.5 - pH in the effluent and in the influent

As expected, the nitrite and nitrate nitrogen concentration was always higher in the effluent, because the ammonia nitrogen was successfully oxidized. The value reported in the influent are for both the parameters always extremely low, with an exception on day 119, when both the nitrogen forms showed a peak.

While the pH in the influent remained stable through all the experiments (in a range of 7.31 – 8.39), in the effluent, as described before, the values changed accordingly with the fluctuations in the trends of the different nitrogen forms.

4.1.2 Organic compounds removal

In the Figure 4.6 the concentration of COD and TOC in the effluent are shown.

As expected, the COD and the TOC have a similar pattern, but the concentration of the second parameter was always smaller.

The results obtained during second experiment, characterized by a SRT of 6 days, unfortunately cannot be considered reliable since, in the Central WWTP of Prague, after the anaerobic digestion, a flocculant agent was added, and this completely compromised the results.

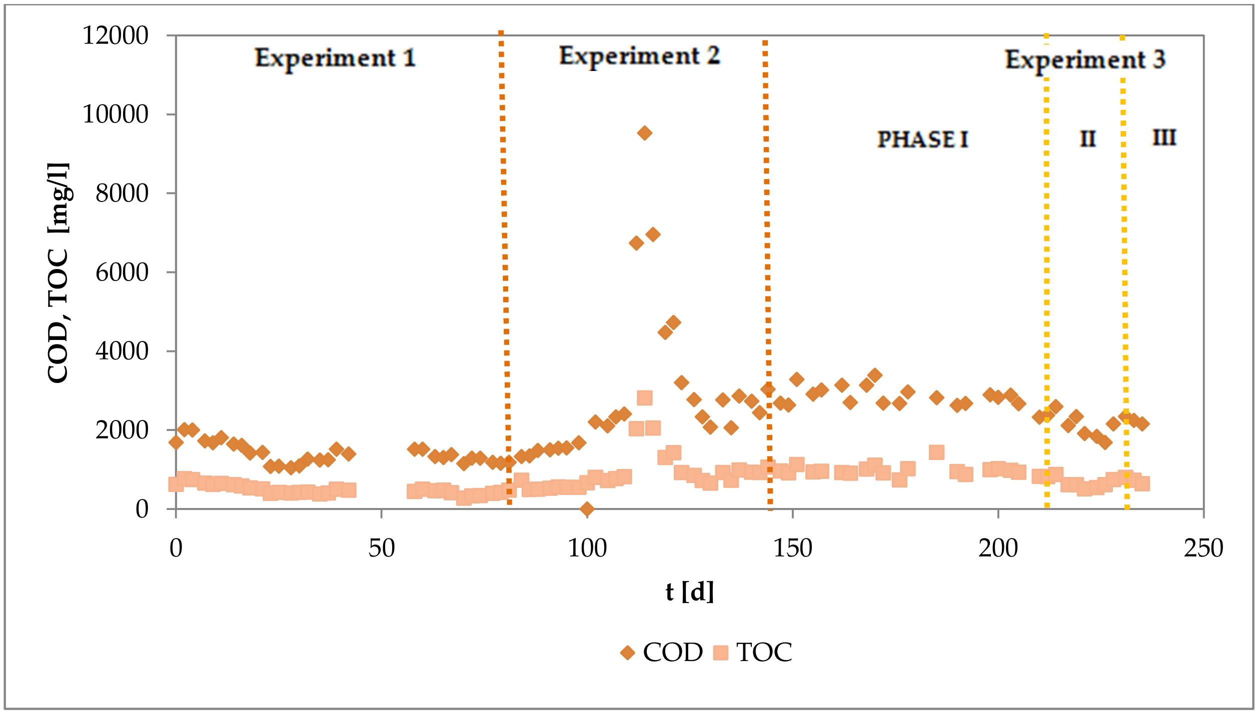

Figure 4.6 - COD and TOC concentration in the effluent

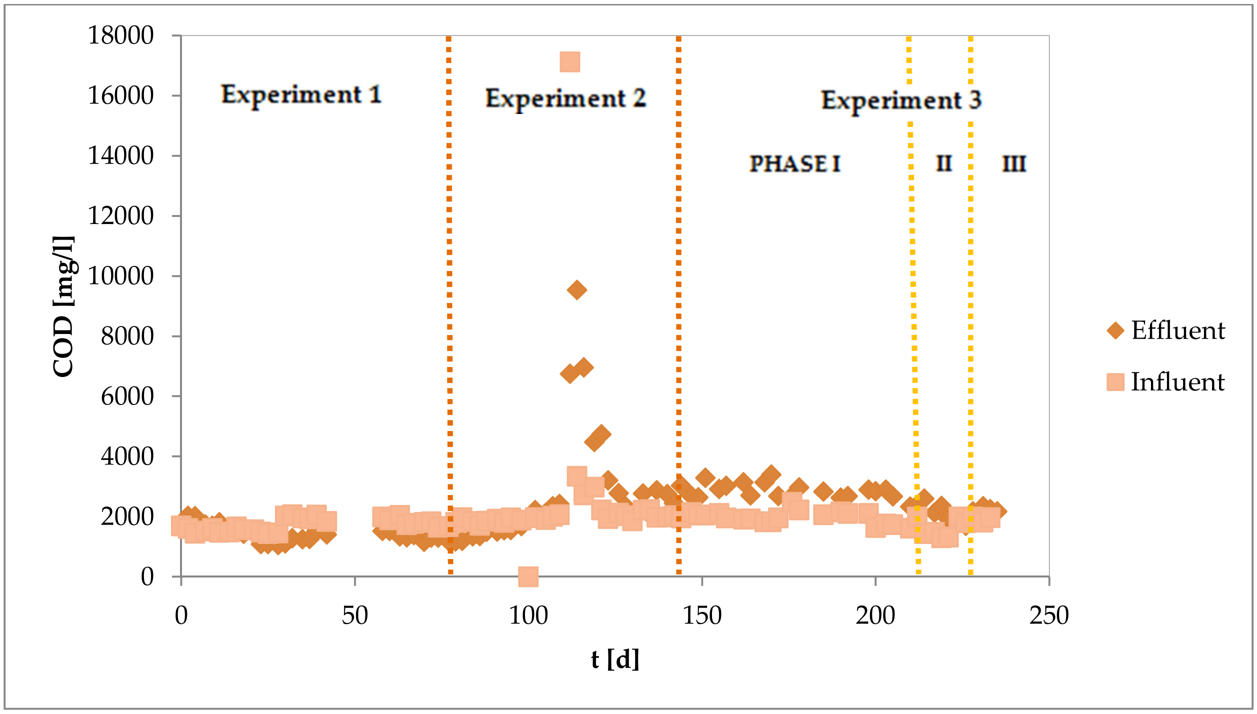

Figure 4.7 - COD concentration in the effluent and in the influent

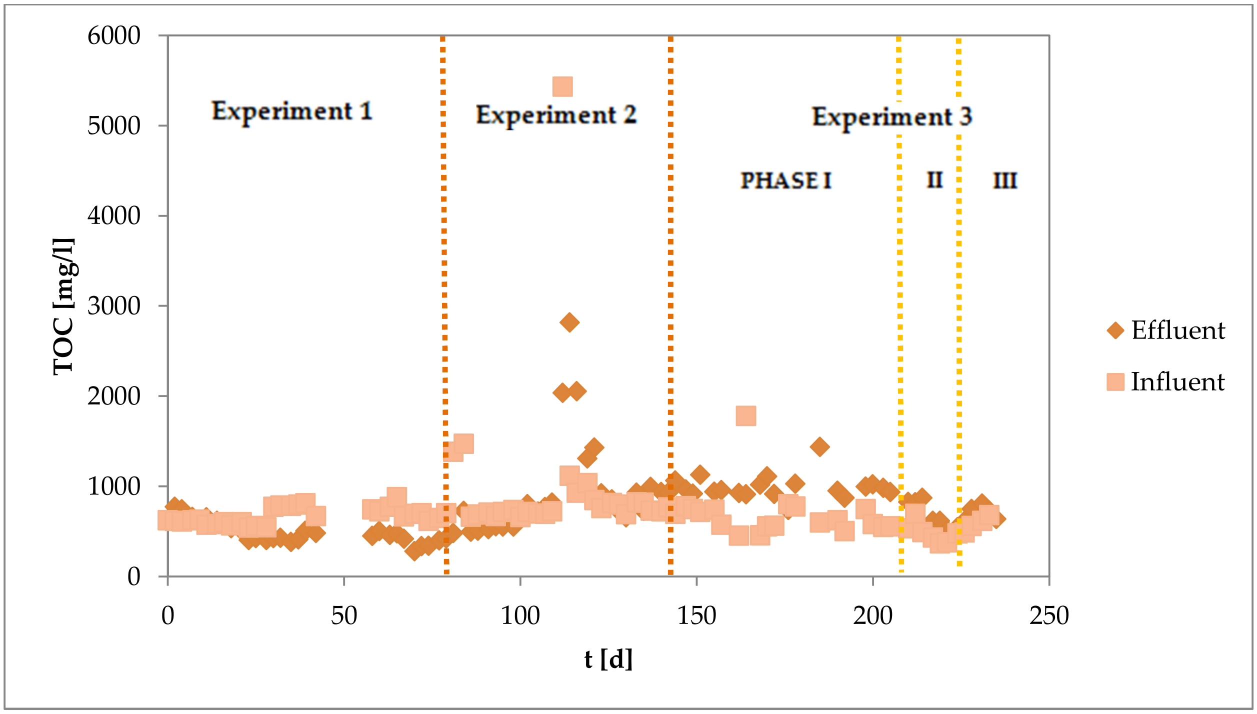

Figure 4.8 - TOC concentration in the effluent and in the influent

In the Figure 4.34 and 4.35 the COD and TOC in the effluent compared with the ones in the influent are respectively shown.

The treatment resulted effective in the first experiment, when the concentration decreased as follows: from 1725 mg/l to 1308 mg/l for the COD and from 673mg/l to 422 mg/l for the TOC. During the other experiments the concentration in the effluent rose.

In the Figure 4.9 the concentrations of Total Solids and Volatile Solids in the effluent are shown and in the Figure 4.10 and 4.11 they are compared with the ones in the influent.

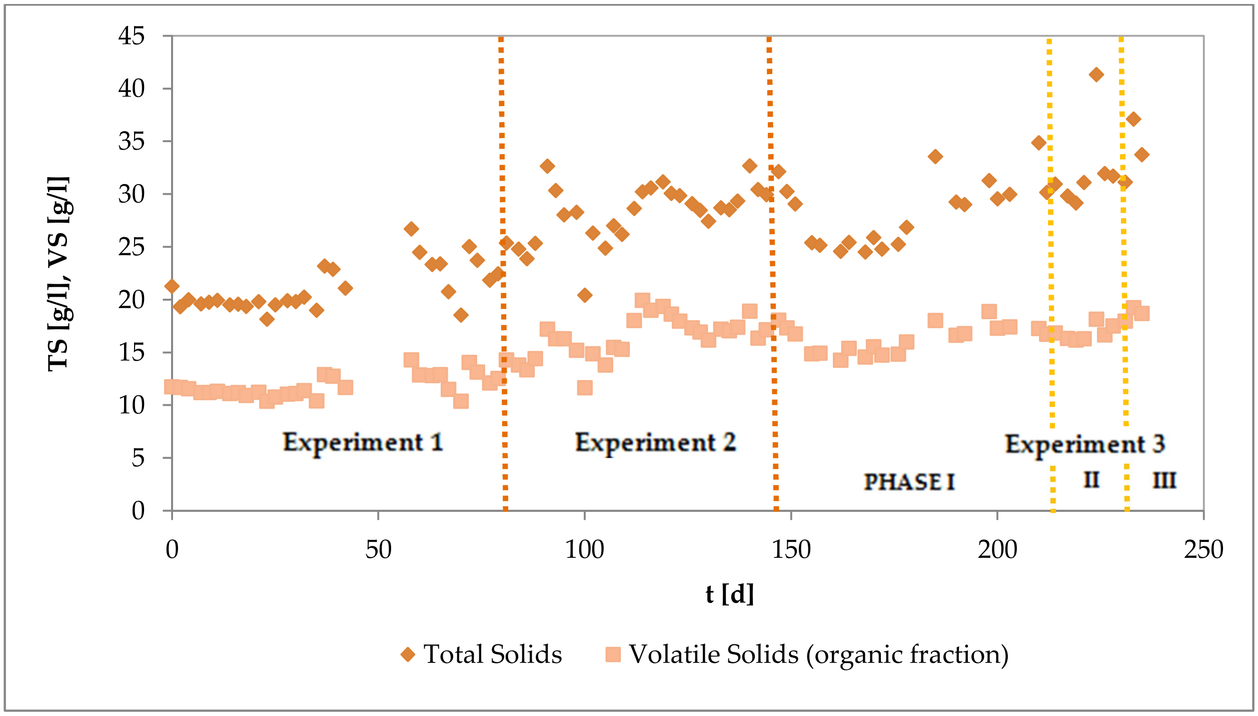

Figure 4.9 - TS and VS in the effluent

During the first phase of the experiment the concentration of the Total Solids and the Volatile Solids was slightly lower in the effluent than in the influent. It changed, respectively, from 25 g/l to 21 g/l and from 14 g/l to 12 g/l. This trend remained similar also at the beginning of the second experiment, until the addition of the flocculant agent which altered the results of the experiment. Also in this case, measurements were completely affected by this interference, and the actual removal efficiencies could not be calculated. During the third phase (SRT of 4 days) the concentration in the effluent rose, despite the increase in the aeration rate.

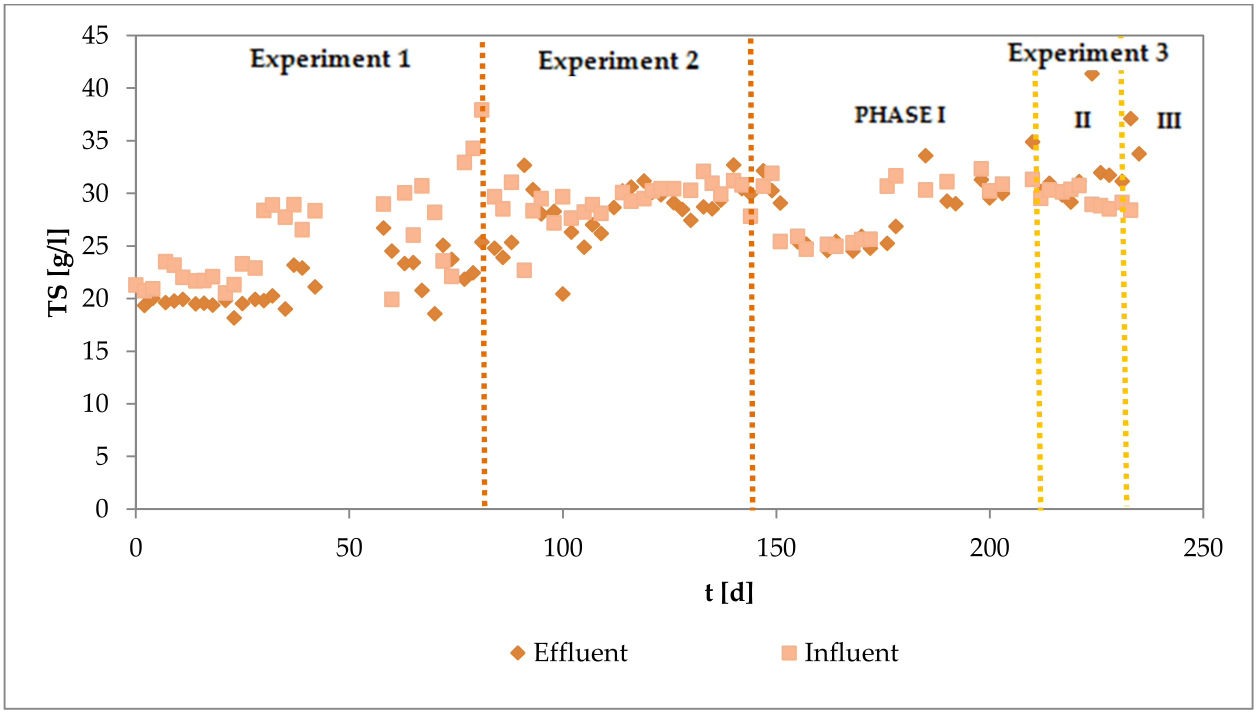

Figure 4.10 - TS in effluent and influent

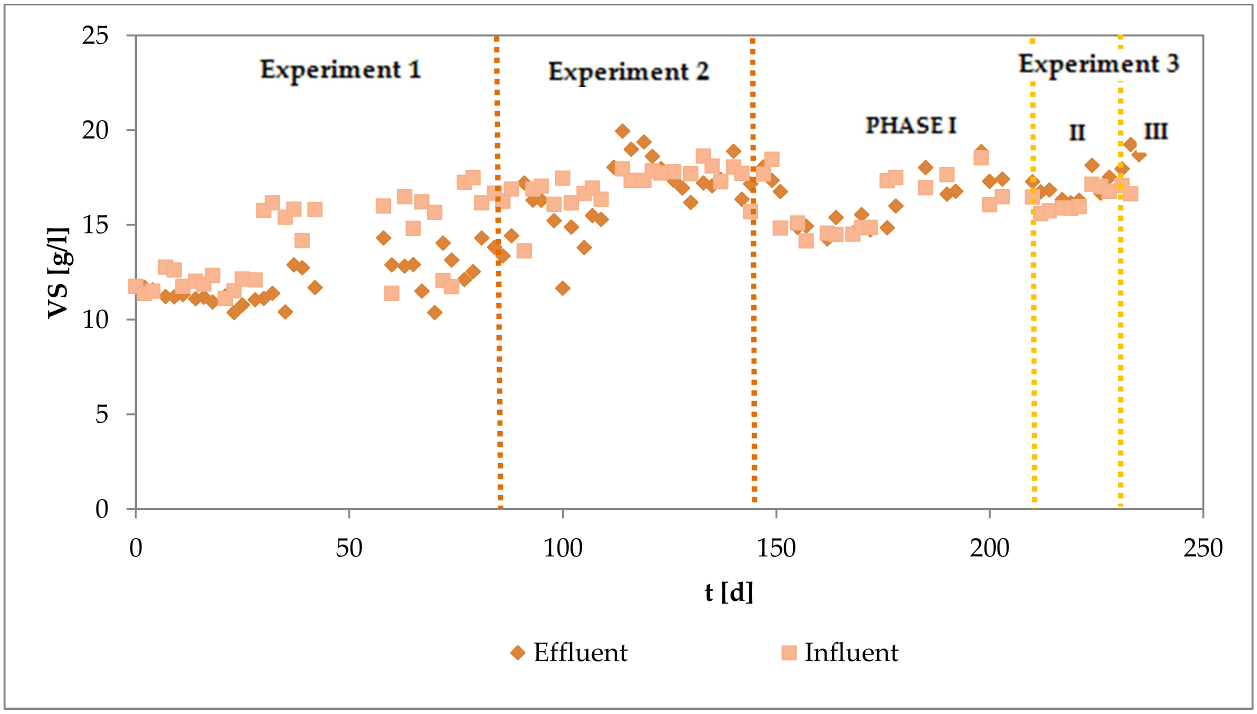

Figure 4.11 - VS in effluent and influent

4.1.3. Water removal

In the Figure 4.12 the dewaterability analysis in terms of Capillary Suction Time (CST) and Sludge Cake for the effluent are respectively shown. The Sludge Cake represents the percentage over the total sample of residual sludge after centrifugation.

Also in this case the addition of the flocculant agent completely affected the measurements of the second experiment.

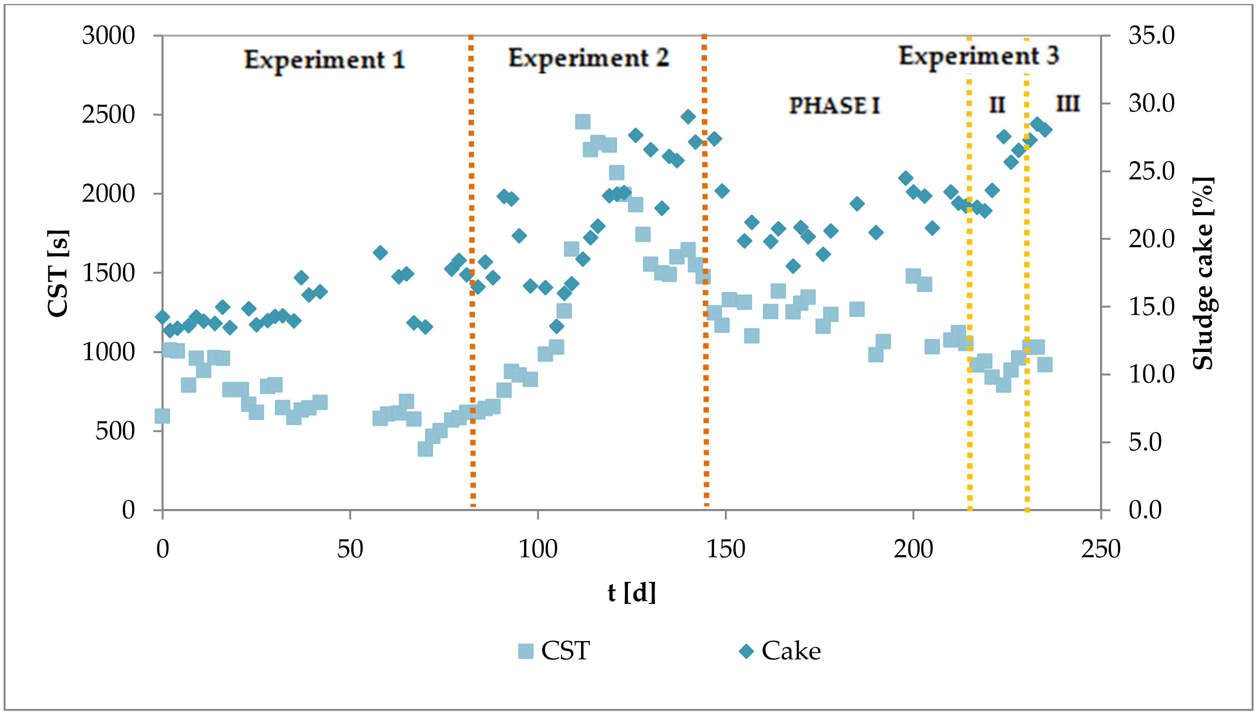

Figure 4.12 - CST and Sludge cake in the effluent

In the Figure 4.13 and 4.14 the CST and the Sludge cake in the effluent are compared with the ones in the influen.

The dewaterability properties, analyzed in terms of the CST parameter, moderately improved only in the first phase, dropping from an average initial value of 709 s to 597 s.

The Sludge Cake, instead, was always lower in the effluent, especially in the first experiment and in the first phase of the third study.

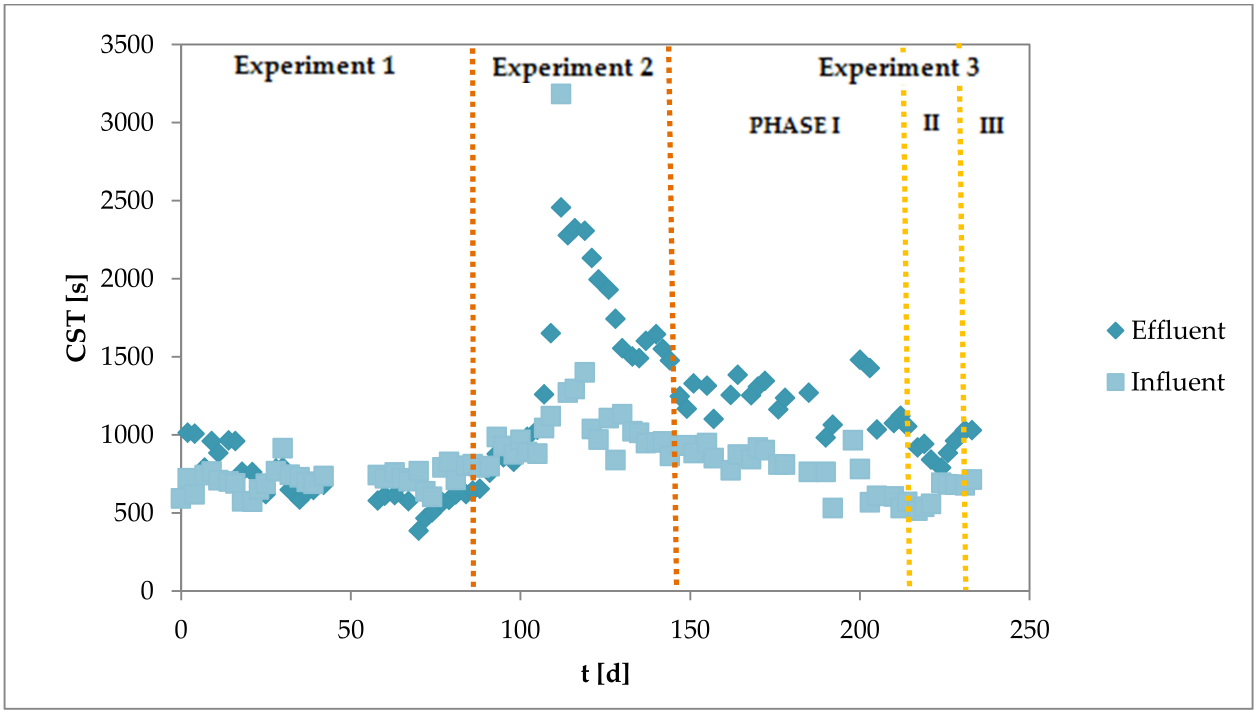

Figure 4.13 - CST in the effluent and in the influent

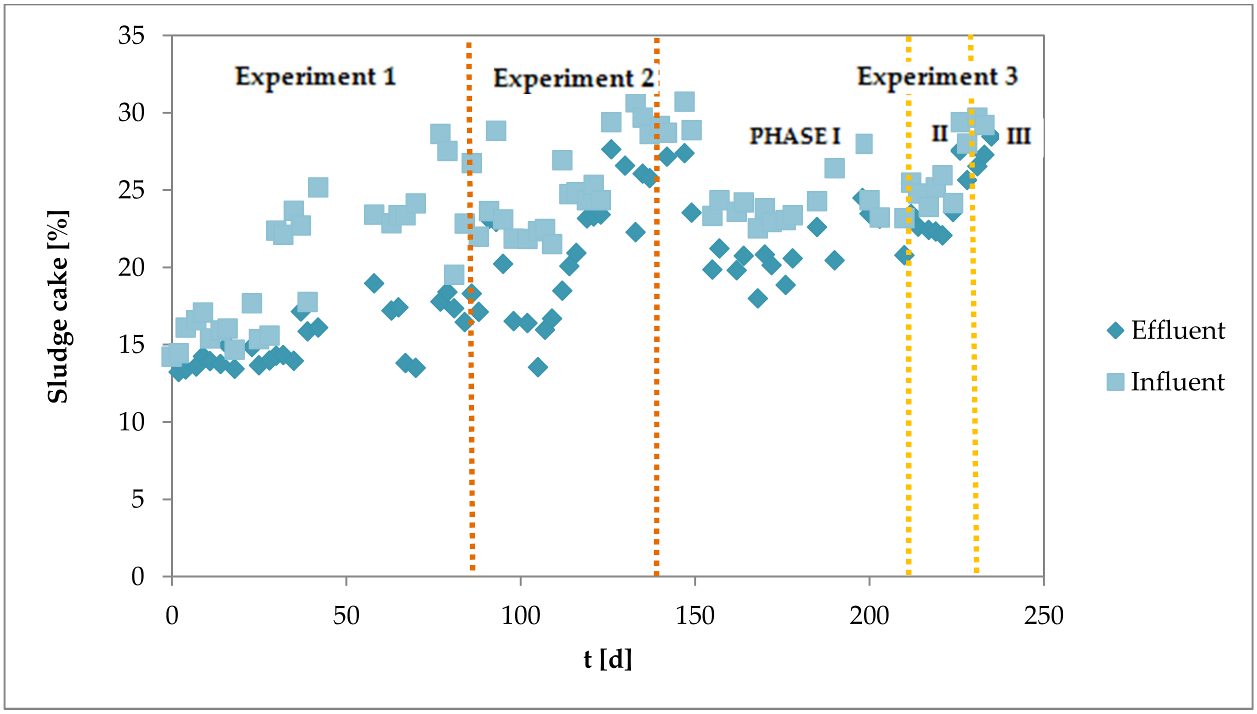

Figure 4.14 - Sludge cake in the effluent and in the influent

4.2 Experiment 1

Since the promising results obtained in the previous study with a SRT of 4 days and an aeration rate of 600 L·h^{-1}, which represented the best combination of technical and economic advantages, it was decided to investigated further this operational conditions, which were maintained for 91 days inside the reactor in the first phase of this experiment. After that, for the last 25 days of the experiment, the SRT was reduced to 2 days and the aeration rate increased to 900 L·h^{-1}.

In the Table 4.2 all the information related to the experiments are shown.

Number of experiment	Phase	Duration [d]	HRT [d]	Aeration rate [L·h^{-1}]	Aeration regime	Temperature [°C]	Type of the sludge
1	1	91	4	600	continuous	20 - 25	thermophilic
	2	25	2	900	continuous	20 - 25	thermophilic

Table 4.2 - Experiment description

4.2.1. Nitrogen removal

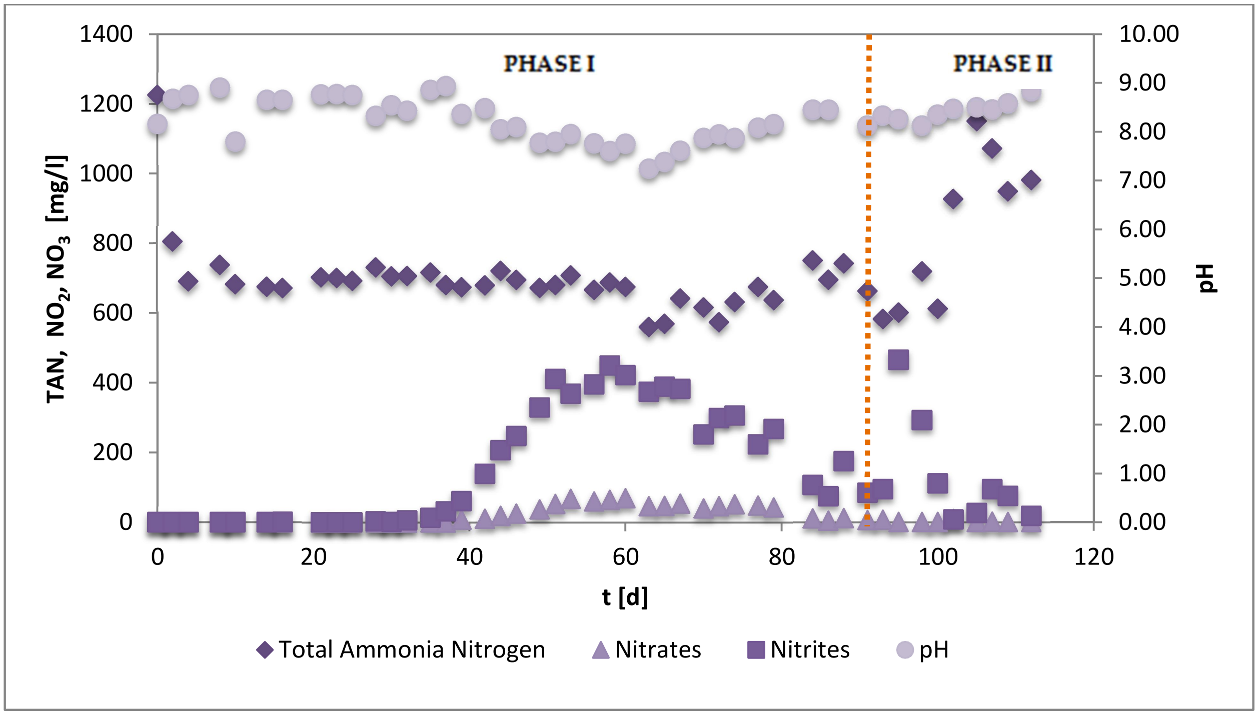

Figure 4.15 - Concentration of Total Ammonia Nitrogen, nitrite nitrogen, nitrate nitrogen and pH in the effluent

In the Figure 4.15 the Total Ammonia Nitrogen, nitrites and nitrates concentration and pH in the effluent are shown.

Since the trend of nitrite and nitrate in the effluent during the first experiment could signify that a denitrification process was occurring, a kinetic test was carried out in order to verify this assumption. A batch reactor continuously mixed with a magnetic stirrer and operating under anoxic conditions was used. Sludge was sampled every hour, for a total of 11 samples during the first day and one sample at the end of the experiment (after 27 hours from the beginning). The following parameters were determined: temperature, pH and nitrite nitrogen concentration, with the analytical techniques described in the *Methods* chapter. In the Figure 4.16 the nitrite nitrogen concentration and the pH are shown.

The nitrite decreased through all first eleven hours and only after 27 hours they reached a value closer to the initial one. Clearly, the denitrification process did not occur, probably because there was not enough substrate to sustain the process.

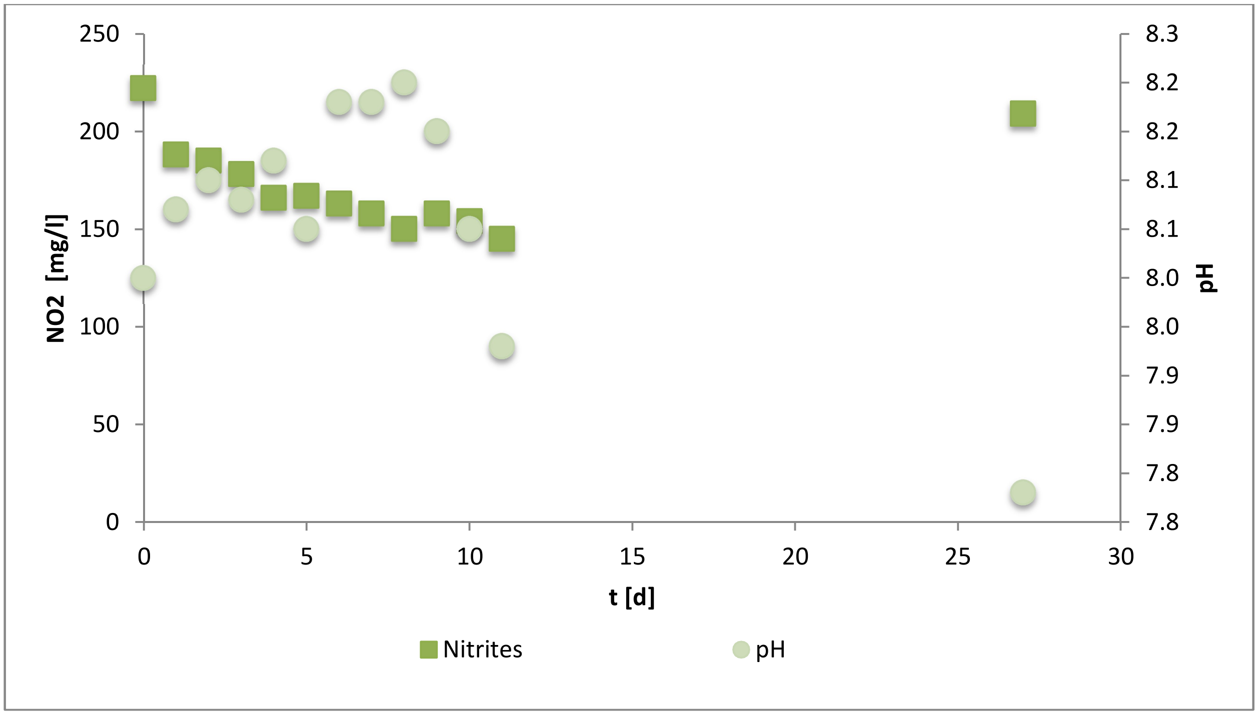

Figure 4.16 – pH and nitrite nitrogen concentration during the kinetic test

The production of nitrite nitrogen in the effluent started after 30 days of experiment. Until that day, the TAN was rather stripped out than biologically removed due to high pH value of the sludge. The nitrite nitrogen concentration rapidly climbed, until reaching the maximum at day

58, with a concentration of 449 mg/l. After, it dropped again, until the value of 74 mg/l at day 86. While it was decreasing, the removal of the ammonia occurred by stripping, as mentioned before. It rose again after the increase in the aeration rate, but after a peak on day 95 (465 mg/l), it dropped until the end of the experiment.

The concentration of nitrate nitrogen, as expected, followed a similar pattern.

The lowest value of pH (7.24) was reached at day 63, around the peak of nitrites and nitrates concentration. In the rest of the experiment it remained generally above 8, indicating the fact the most of the ammonia was removed by the stripping process.

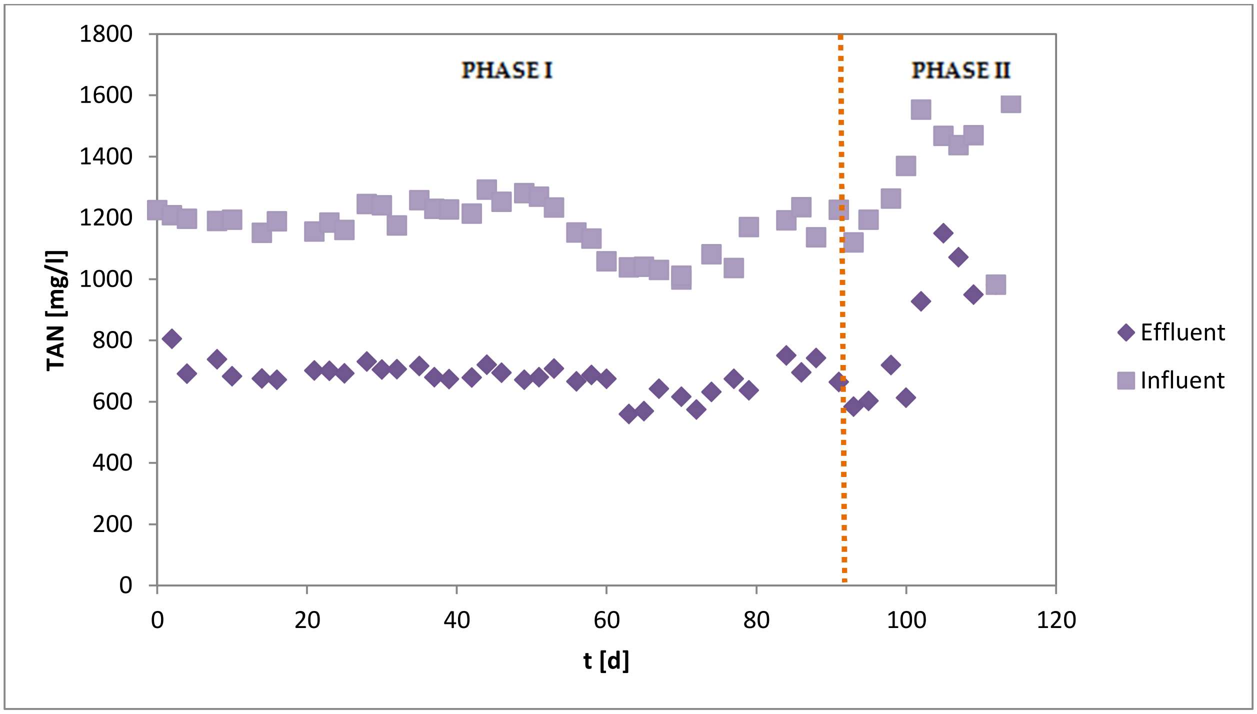

Figure 4.17 - Concentration of the Total Ammonia Nitrogen in the effluent and in the influent

In the Figure 4.17, 4.18, 4.19 and 4.20 are respectively shown the Total Ammonia Nitrogen, nitrites and nitrates concentrations and pH in the effluent compared with the ones in the influent.

The ammonia nitrogen concentration in the effluent was always smaller, so also in this case the post - aerobic stage was effective. The treatment removed more ammonia in the first experiment, when it decreased from 1162 mg/l to 695 mg/l.

Overall, setting a higher SRT resulted more effective than rising the air flow.

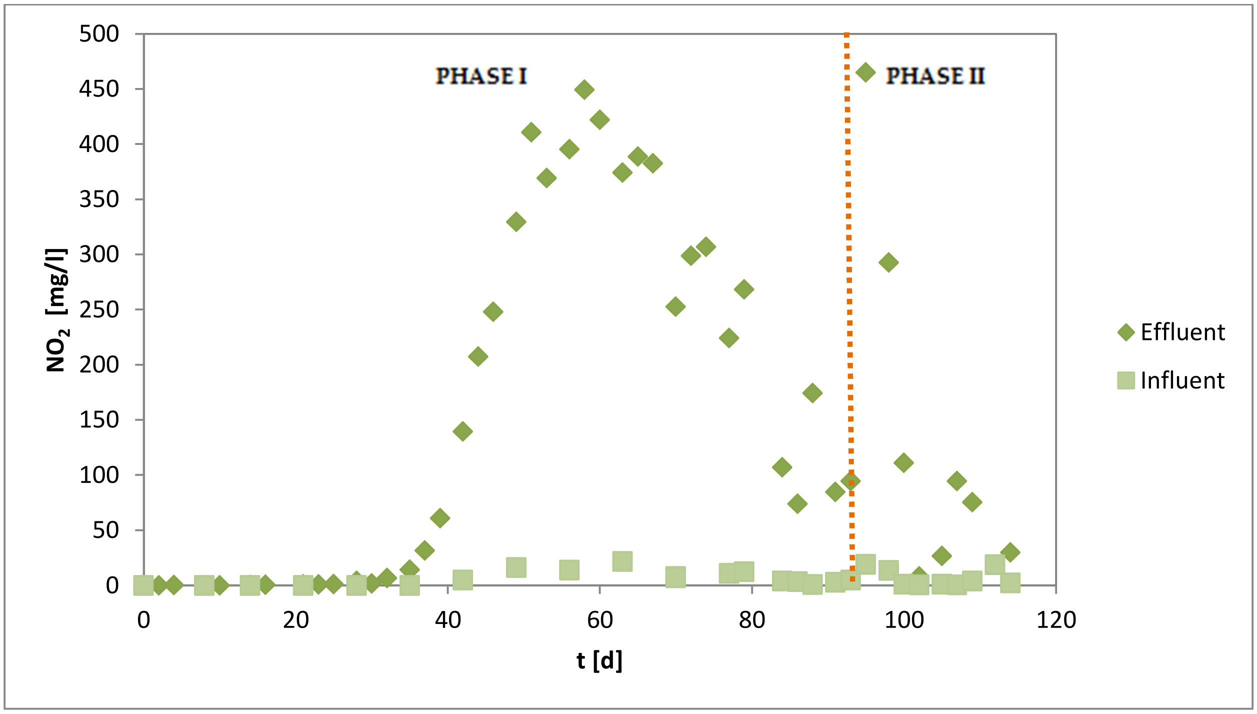

Figure 4.18 - Concentration of nitrite nitrogen in the effluent and in the influent

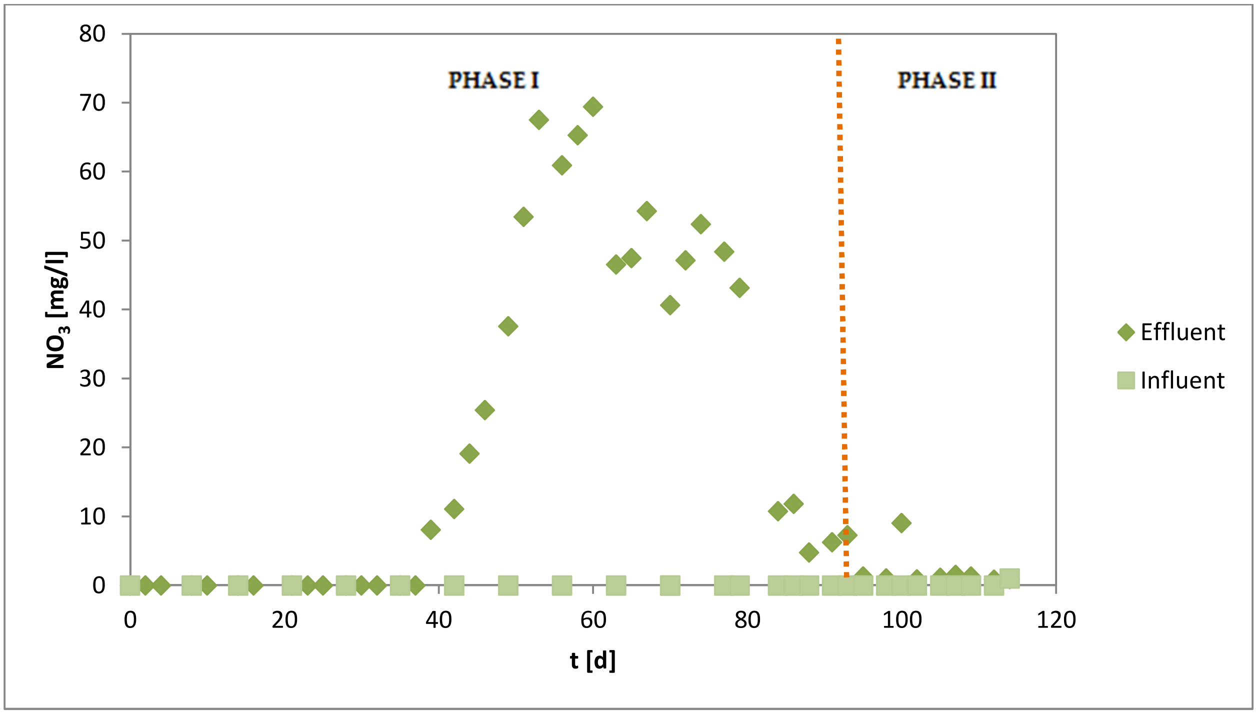

Figure 4.19 - Concentration of nitrate nitrogen in the effluent and in the influent

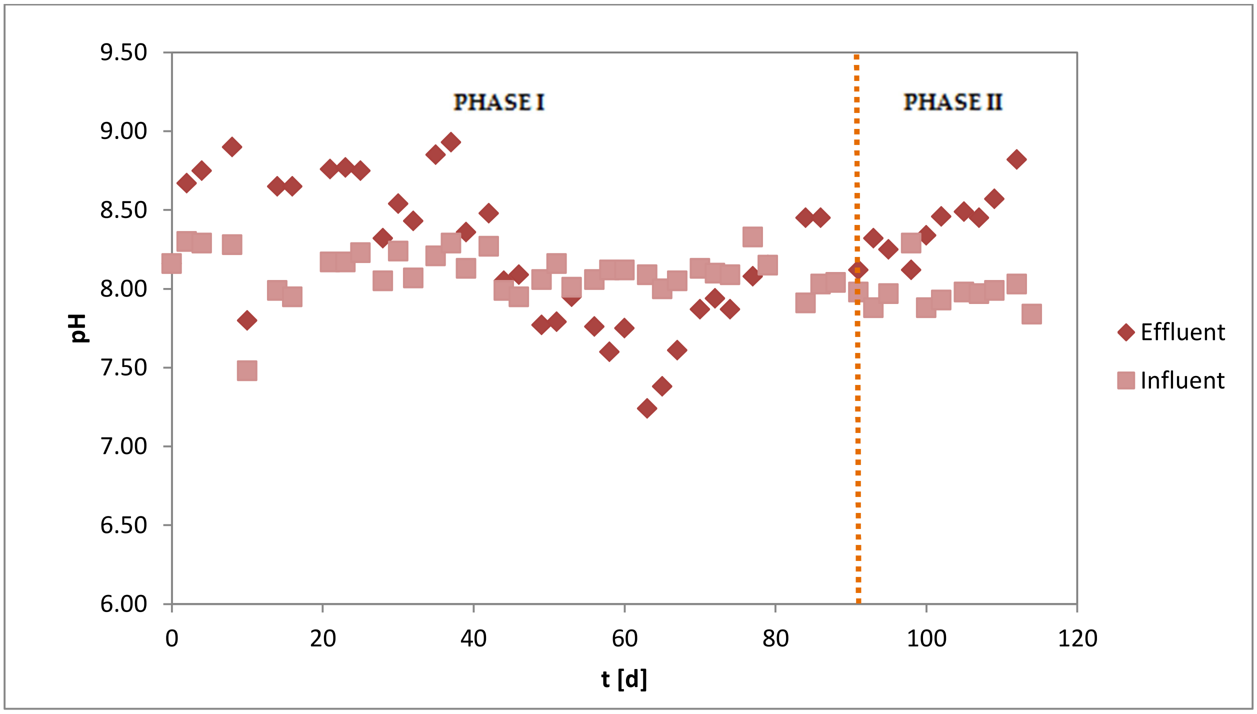

Figure 4.20 - pH in the effluent and in the influent

4.2.2 Organic compounds removal

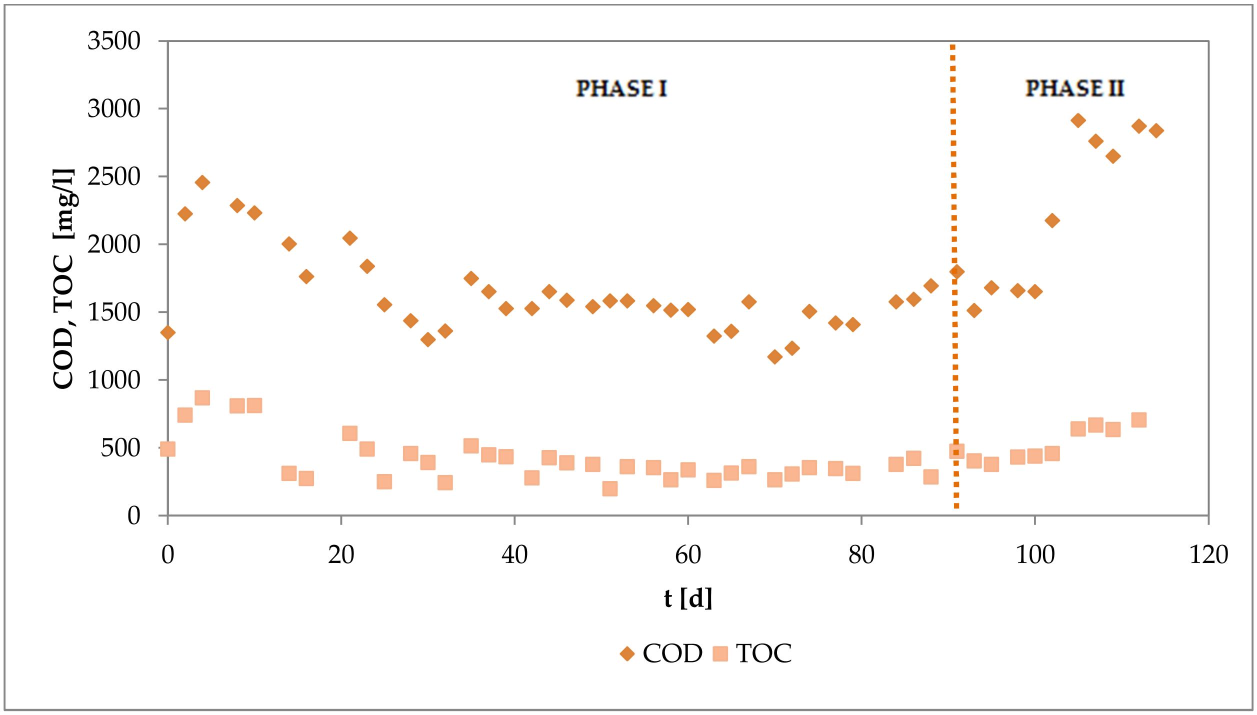

Figure 4.21 - COD and TOC concentration in the effluent

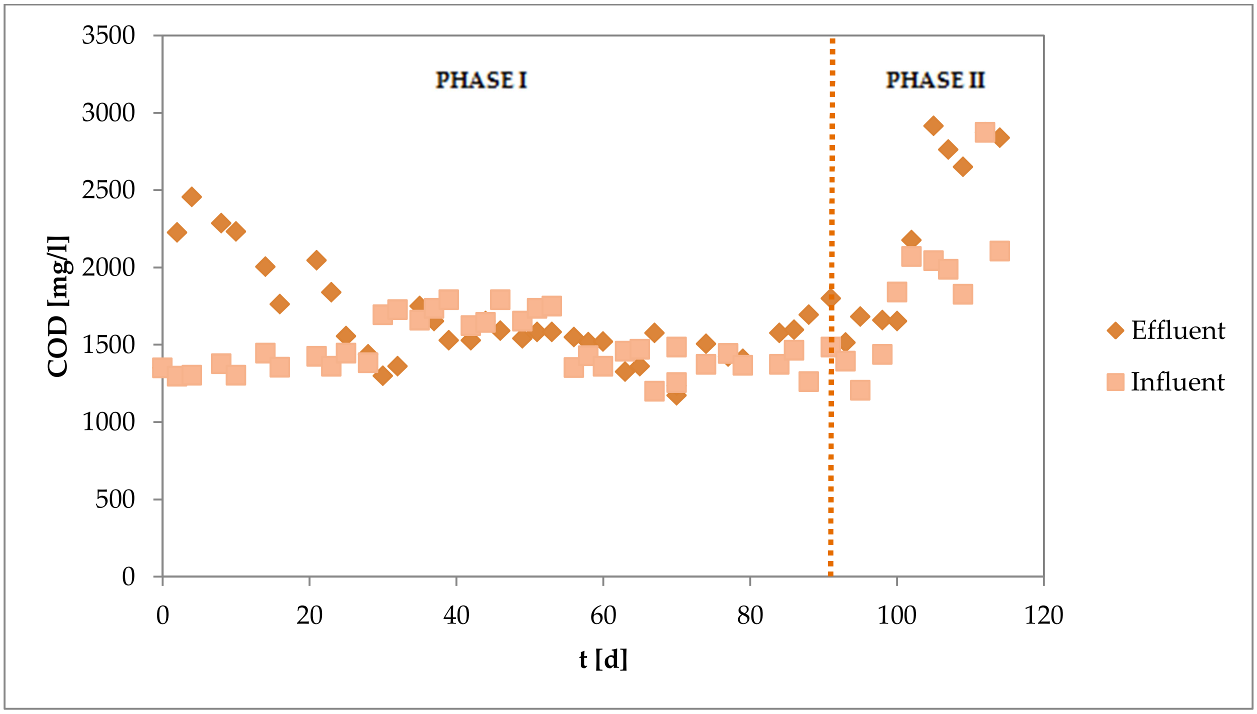

Figure 4.22 - COD concentration in the effluent and in the influent

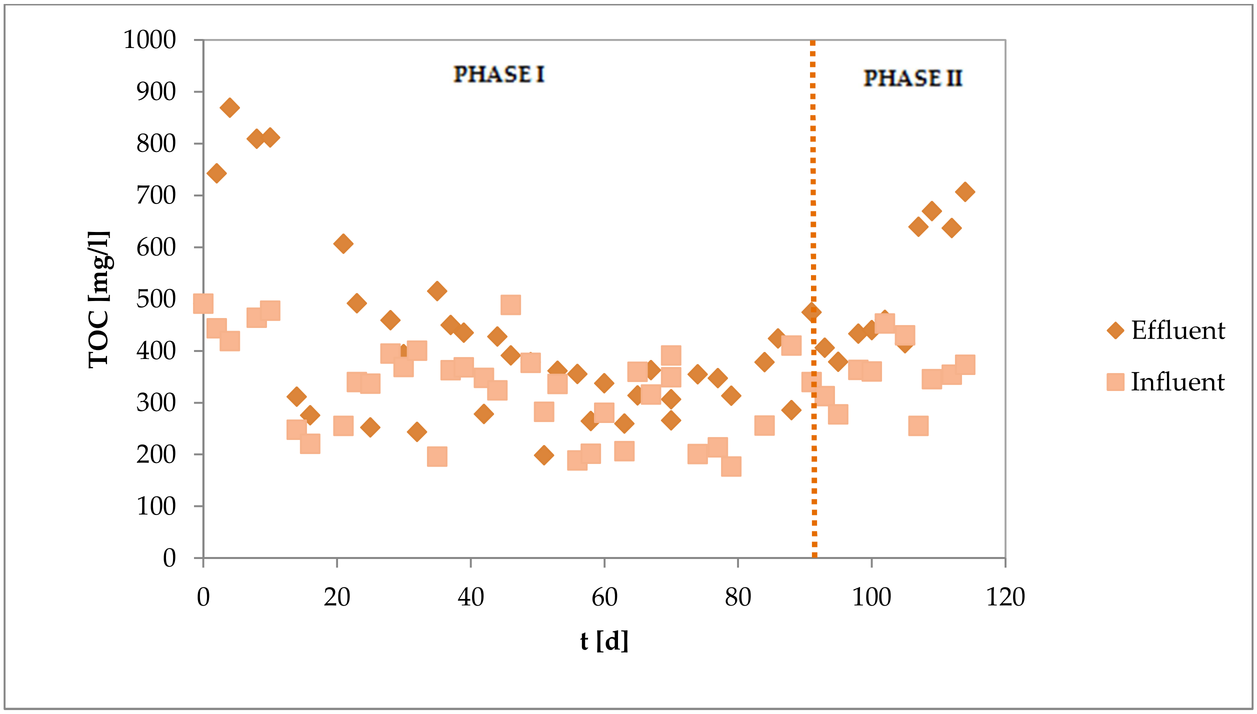

Figure 4.23 - TOC concentration in the effluent and in the influent

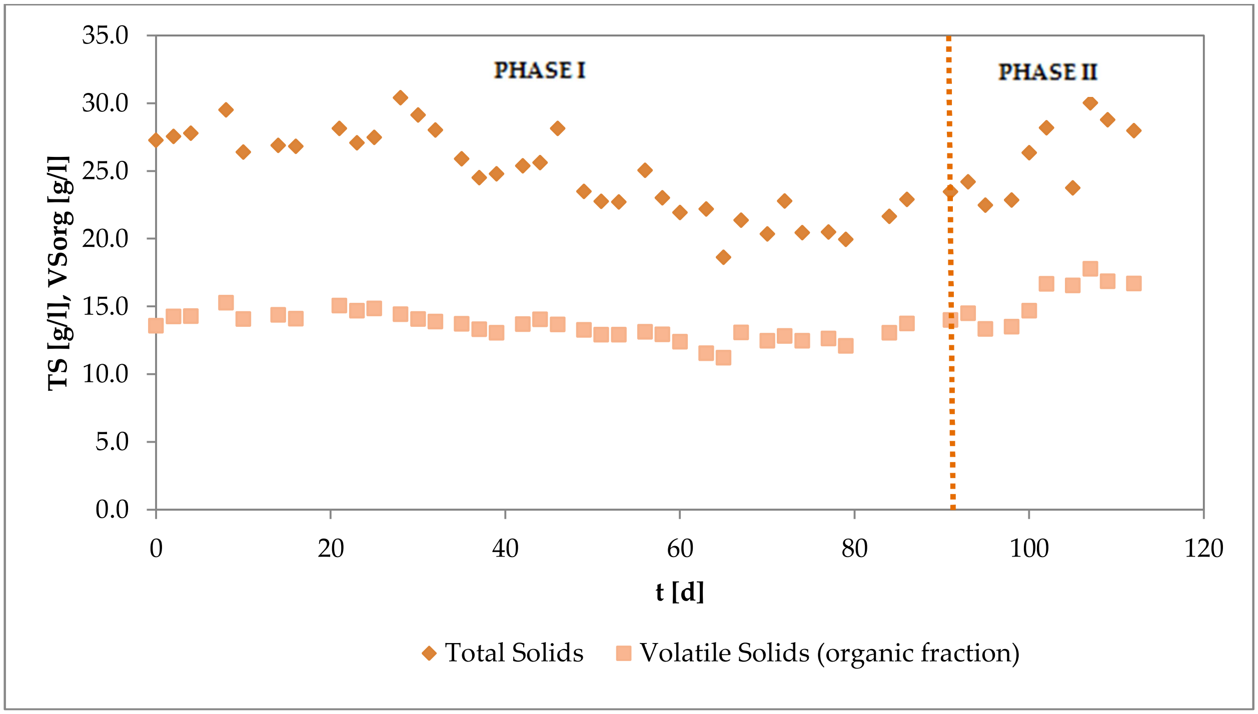

Figure 4.24 - TS and VS in the effluent

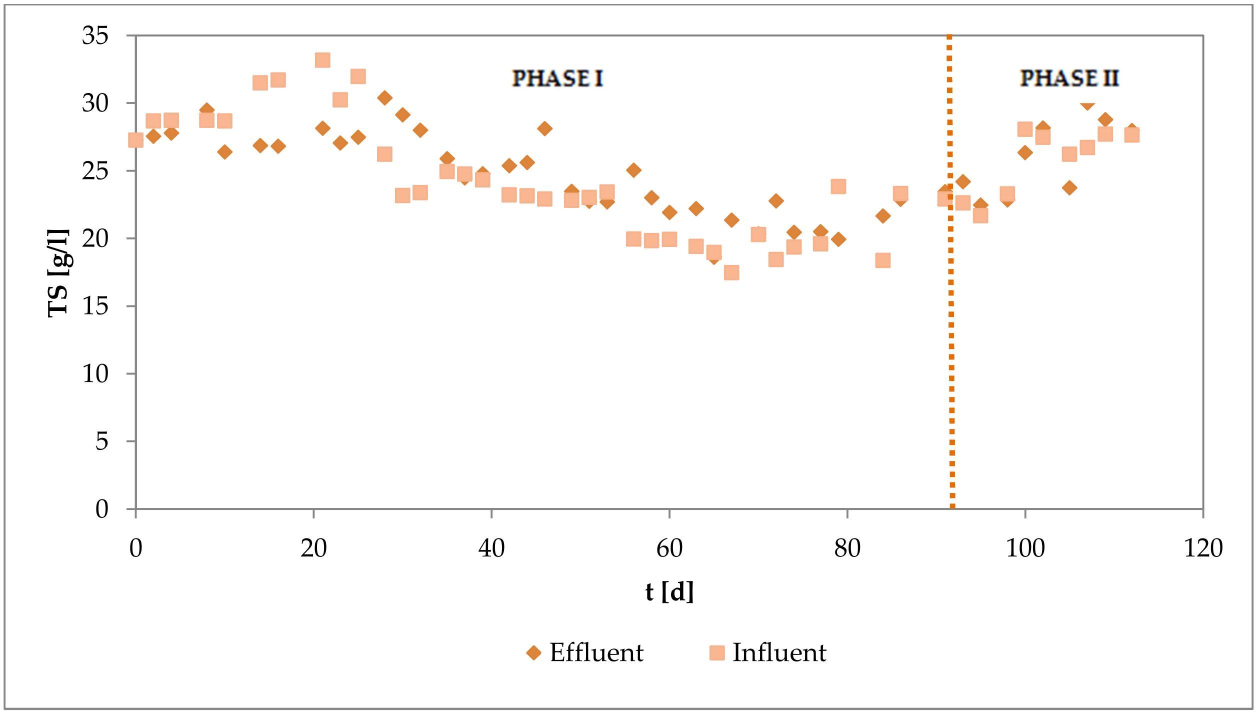

Figure 4.25 - TS in effluent and influent

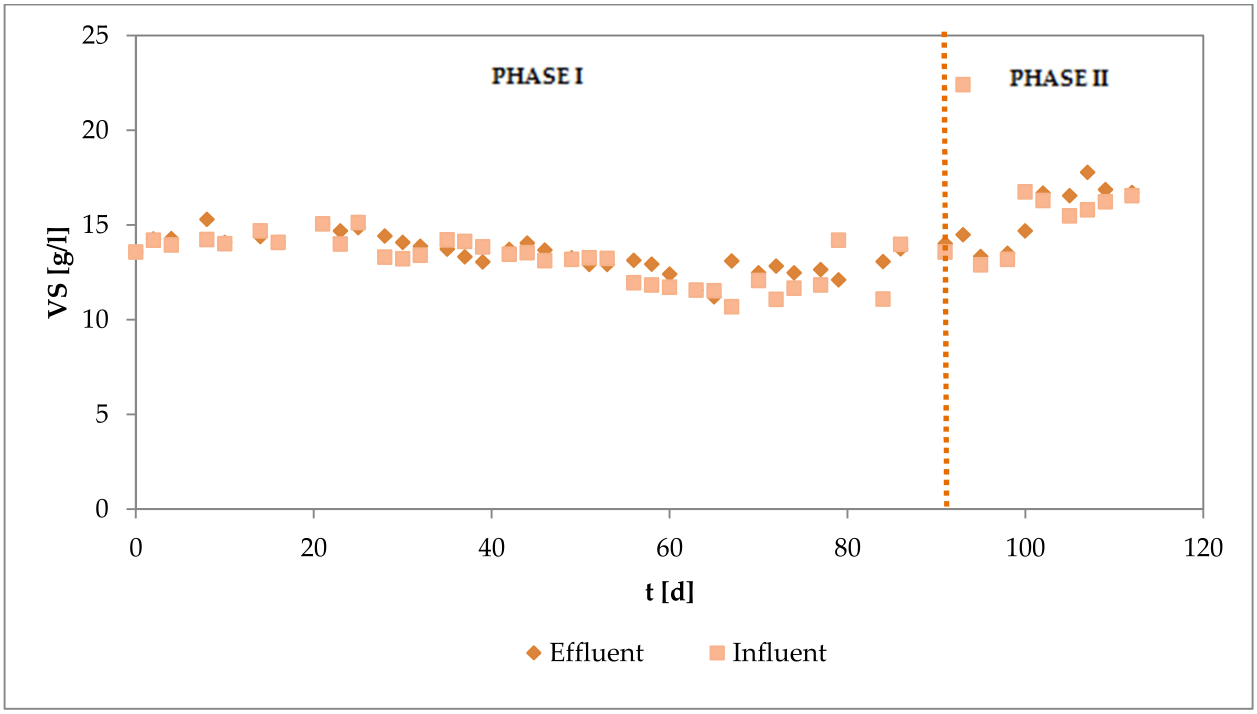

Figure 4.26 - VS in effluent and influent

In the Figure 4.21 the concentration of COD and TOC in the effluent are shown and in the Figure 4.22 and 4.23 they are compared with the ones in the influent.

In the first 25 days of the experiment the concentrations of both the parameters were considerably higher in the effluent. After, the situation improved but not enough to consider the treatment effective, since the COD and TOC kept increasing in the treated water, especially in the second phase.

The worst results in the second phase are probably caused by the addition of a anti-foaming agent characterized by a COD concentration of 1000 g/L.

In the Figure 4.24 the concentration of Total Solids and Volatile Solids in the effluent are shown. As expected, the Volatile Solids show a pattern similar to the one of the Total Solids.

In the Figure 4.25 and 4.26 the concentration of Total Solids and Volatile Solids in the effluent is compared with the ones in the influent.

Also in this case, the treatment did not reduce the VS and TS fractions, which climbed through all the experiments. An interesting aspect that should be pointed out is that, while the soluble organic compounds climbed more with a lower SRT and a higher aeration rate, the opposite occurred in the case of TS and VS.

4.2.3 Water removal

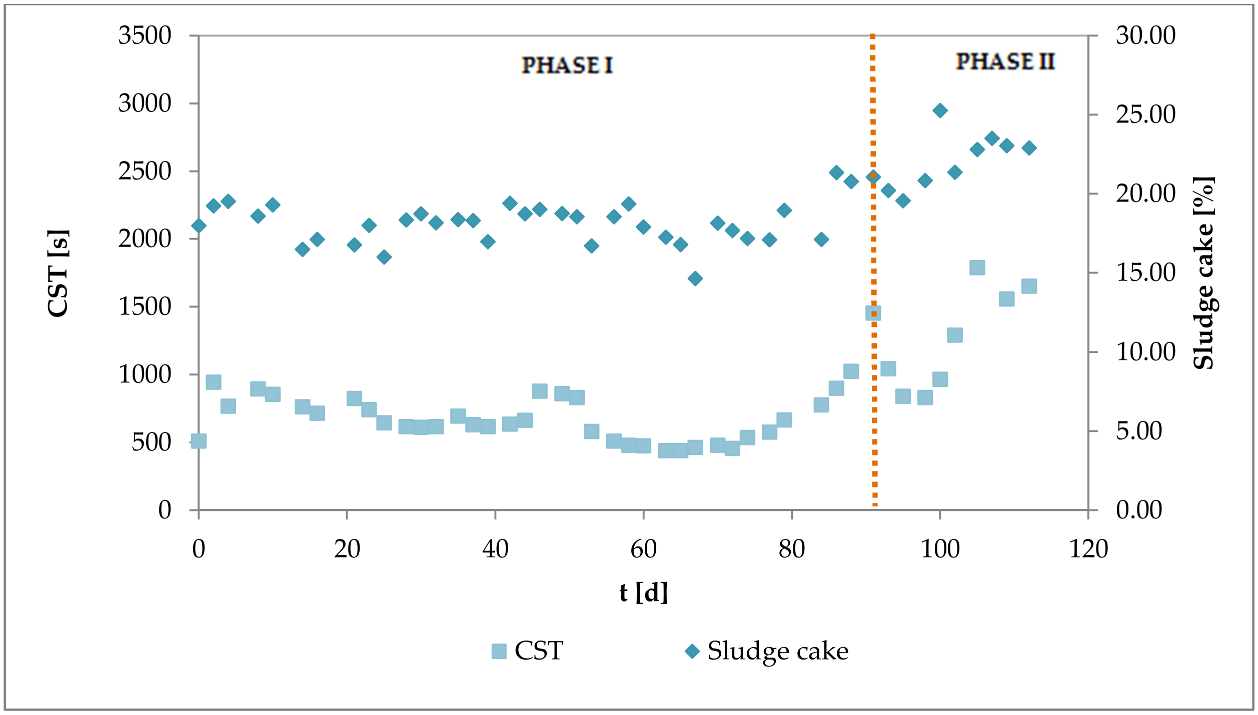

Figure 4.27 - CSTs and sludge cake dry mass in the effluent

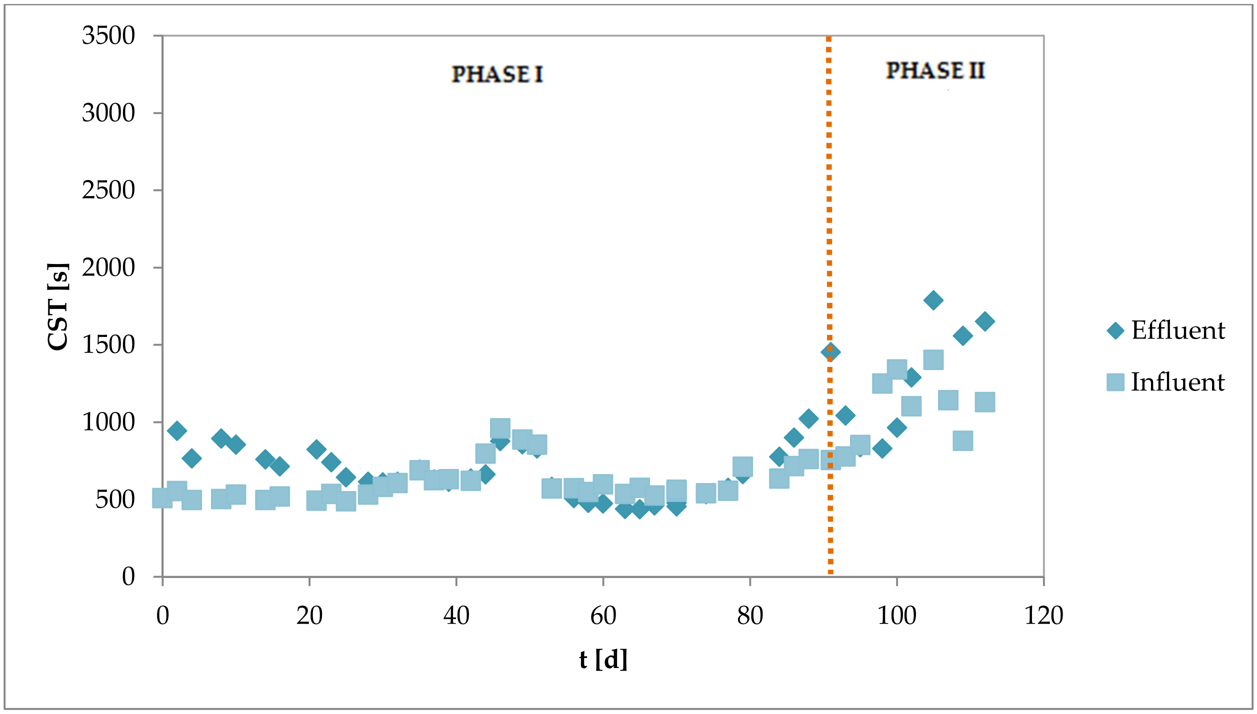

Figure 4.28 - CST in the effluent and in the influent

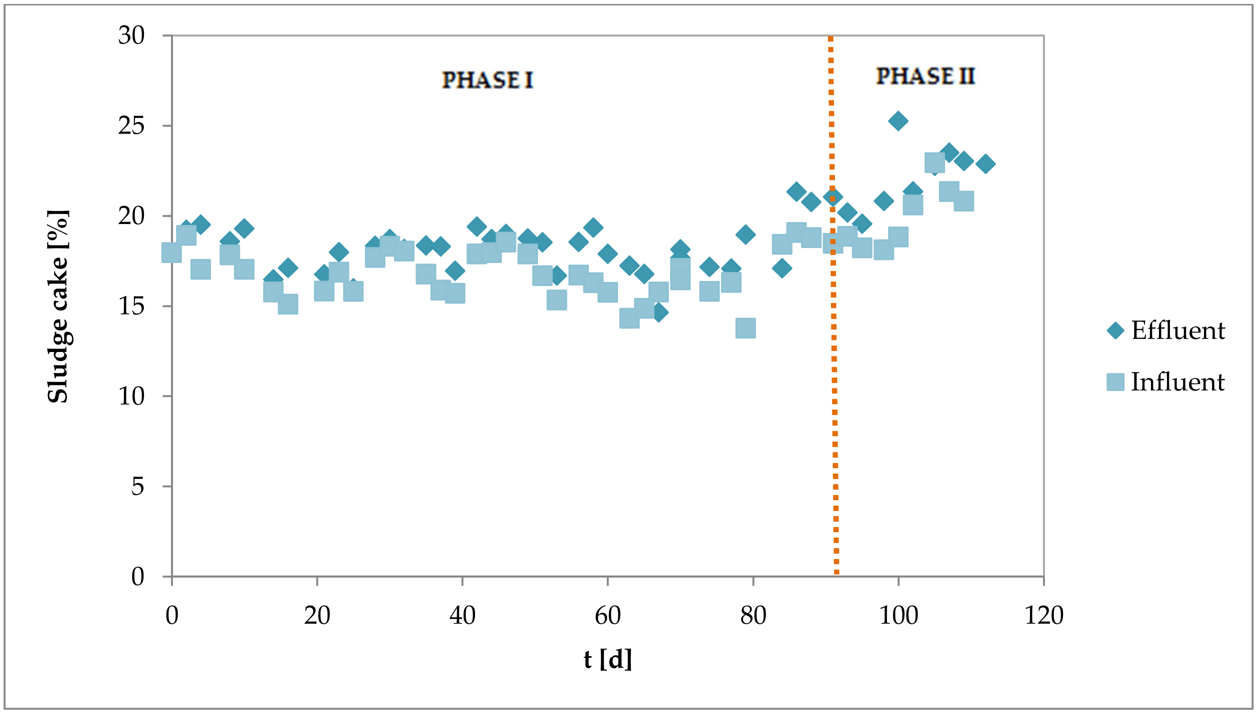

Figure 4.29 - Sludge cake in the effluent and in the influent

In the Figure 4.27 the dewaterability analysis in terms of, respectively, Capillary Suction Time and Sludge cake for the effluent are shown, while in the Figure 4.28 and 4.29 those values are compared with the ones in the influent.

The CST parameter generally worsened, especially in the second phase. It rose from 611 s to 689 s in the first experiment and from 1097 s to 1449 s in the second one. The addition of the anti – foaming agent after the increase of the air flow could be the reason of this pattern.

The Sludge cake, instead, slightly improved, mainly in the first experiment.

In this case, setting a higher SRT in the reactor, rather than increasing the aeration rate, led to better results.

4.3 Experiment 2

During the second experiment the SRT was constantly maintained at 2 days, while the aeration rate was sequentially increased: 600 L·h^{-1} for the first 14 days, 1200 L·h^{-1} for other 37 days and 2000 L·h^{-1} for the last 20 days of the experiment.

In the Table 4.3 all the information related to the experiments are shown.

Number of experiment	Phase	Duration [d]	HRT [d]	Aeration rate $[L\cdot h^{-1}]$	Aeration regime	Temperature [°C]	Type of the sludge
2	1	14	2	600	continuous	20 - 25	thermophilic
	2	37	2	1200	continuous	20 - 25	thermophilic
	3	20	2	2000	continuous	20 - 25	thermophilic

Table 4.3 - Experiment description

4.3.1 Nitrogen removal

In the Figure 4.30 the Total Ammonia Nitrogen, nitrite and nitrate nitrogen concentration and pH in the effluent are shown.

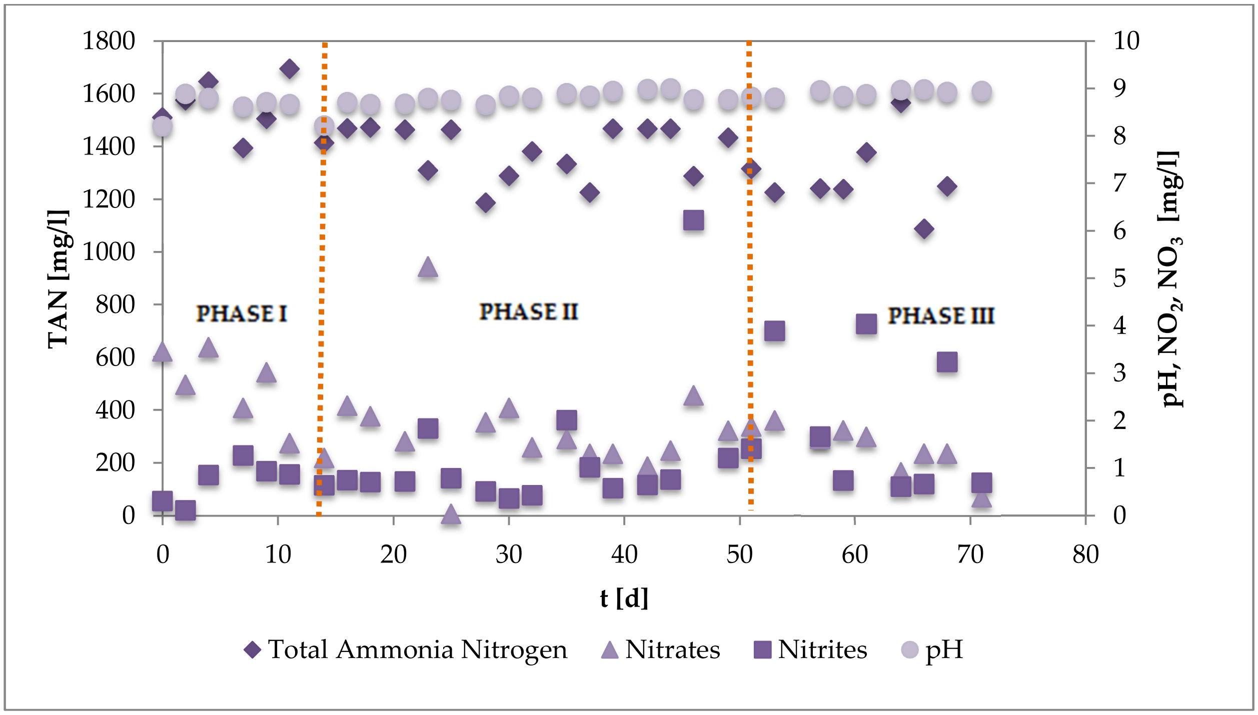

Figure 4.30 - Concentration of Total Ammonia Nitrogen, nitrite nitrogen, nitrate nitrogen and pH in the effluent

A minimum concentration of nitrite nitrogen was already observed at day 1 (0.309 mg/l). It grew until day 7 (1.268 mg/l), for lessening again until day 14, because of the increase in the TAN concentration. After the increase in the aeration rate, the pattern remained more or less stable until day 39, with the exception of two peaks reached on day 23 (1,832 mg/l) and 25 (2,006 mg/l) in correspondence with the ones in the TAN concentration. After, it started to climb again, more sharply after the further variation in the aeration. But, overall, the concentration of nitrite nitrogen in all the samples was extremely low compared to the previous experiment. In this case the nitrate nitrogen was present in higher concentrations than the nitrite nitrogen, maybe because they were already present in the influent (this did not happen in the previous experiments) or for the increased air flow that facilitated the oxidation process.

The pH moderately grew through all the experiment, showing that the nitrification was not occurring at an elevated rate.

In the Figure 4.31, 4.32, 4.33 and 4.34 the Total Ammonia Nitrogen, nitrite and nitrate nitrogen concentrations and pH in the effluent compared with the ones in the influent are respectively shown.

The ammonia nitrogen overall was reduced, but the efficiency removal worsened in comparison with the previous experiments. It decreased as follows: from 1534 m/l to 1224 mg/l in the first phase, from 1381 mg/l to 926 mg/l in the second and from 1287 mg/l to 754 mg/l in the third. Overall the rise in the air flow improved the results.

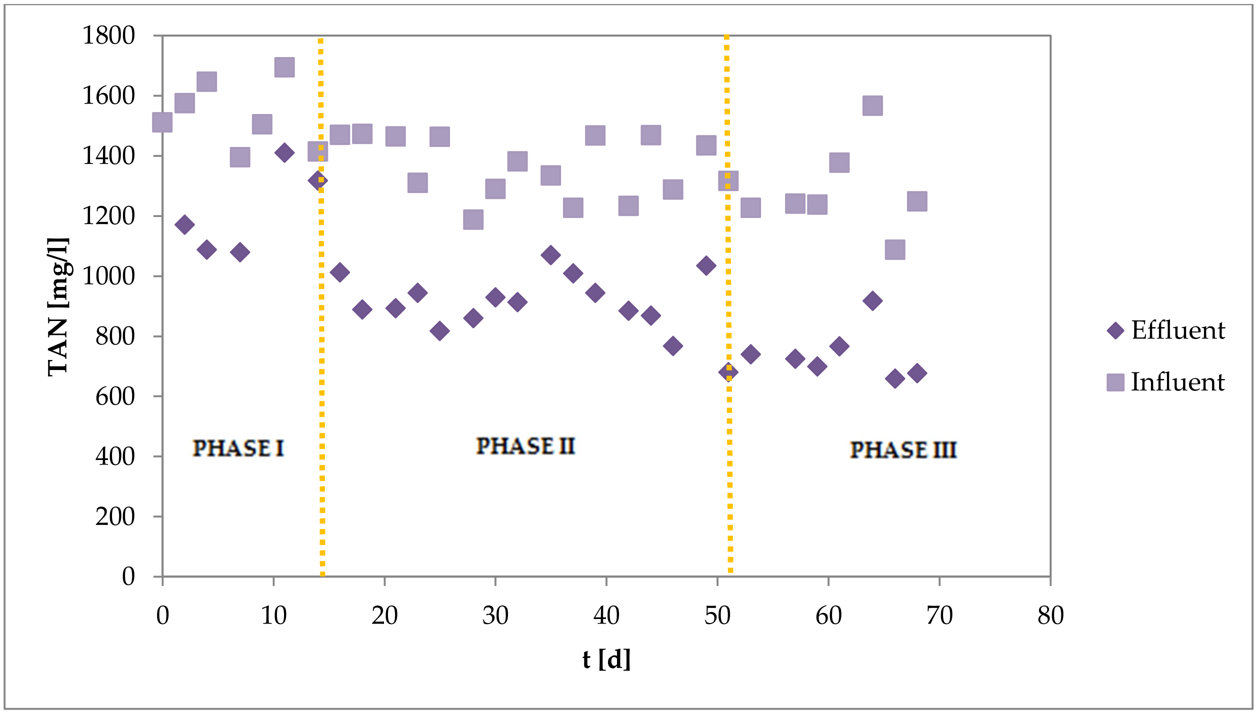

Figure 4.31 - Concentration of the Total Ammonia Nitrogen in the effluent and in the influent

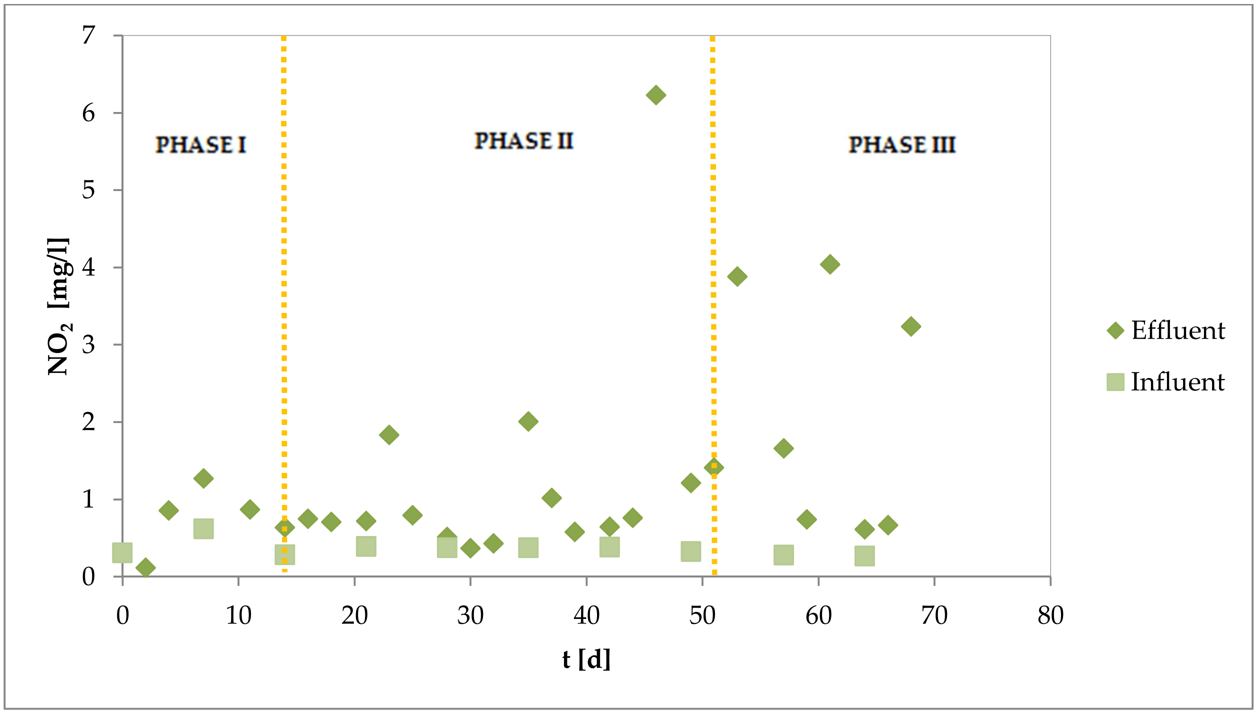

Figure 4.32 - Concentration of nitrite nitrogen in the effluent and in the influent

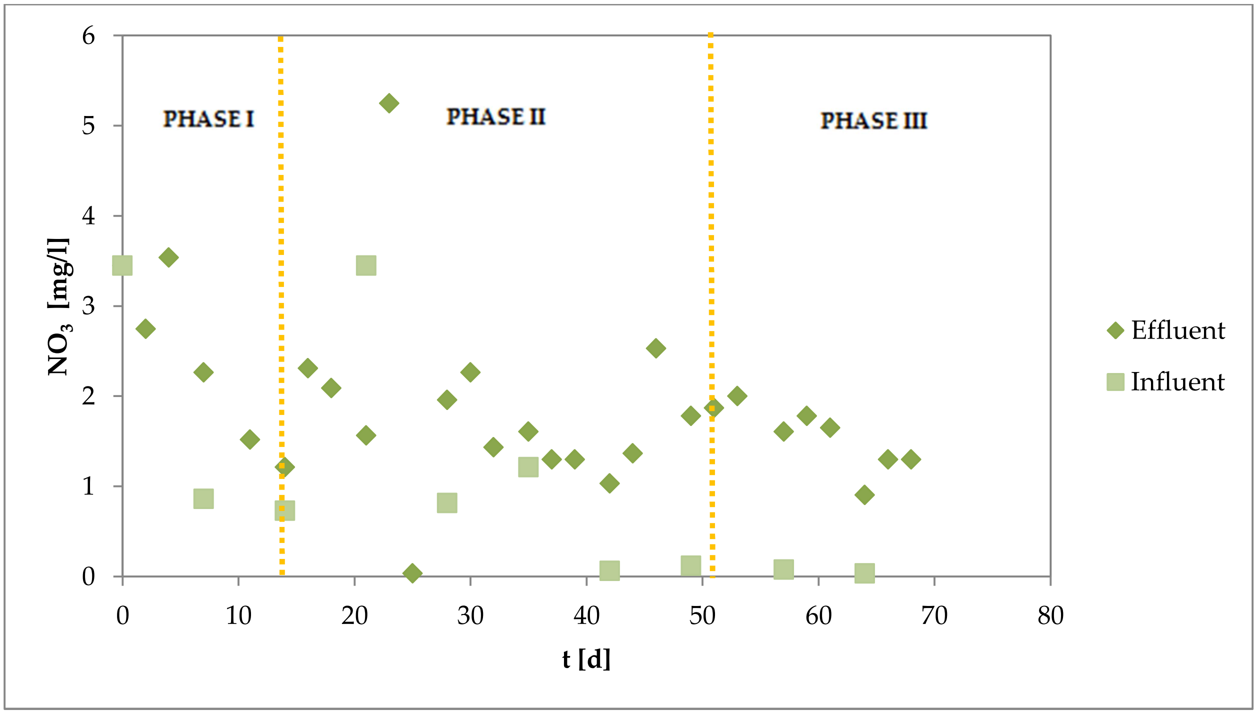

Figure 4.33 - Concentration of nitrate nitrogen in the effluent and in the influent

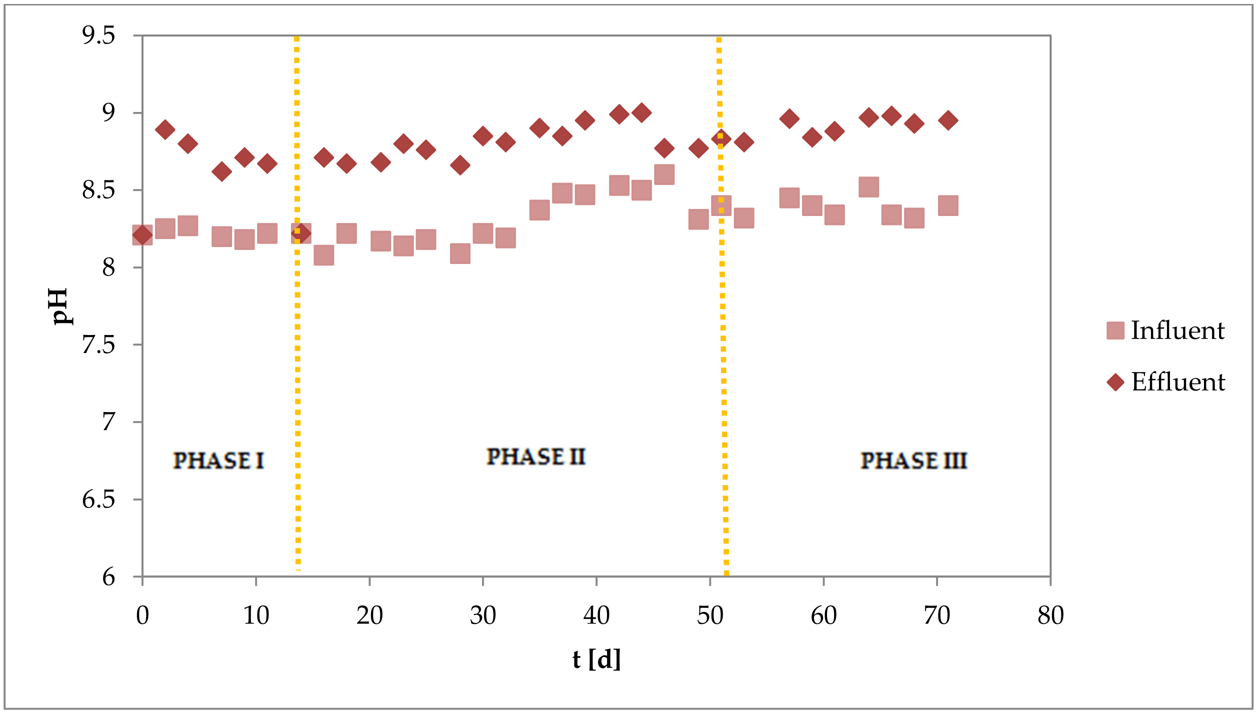

Figure 4.34 - pH in the effluent and in the influent

4.3.2 Organic compounds removal

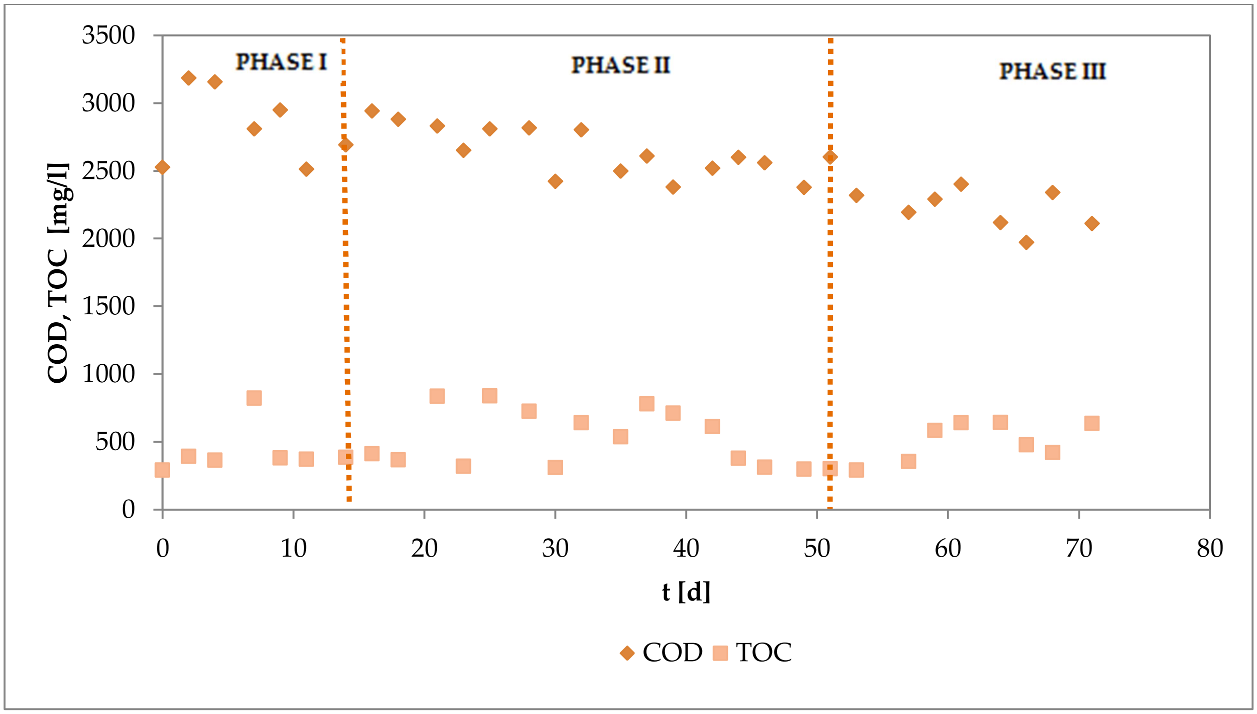

Figure 4.35 - COD and TOC concentration in the effluent

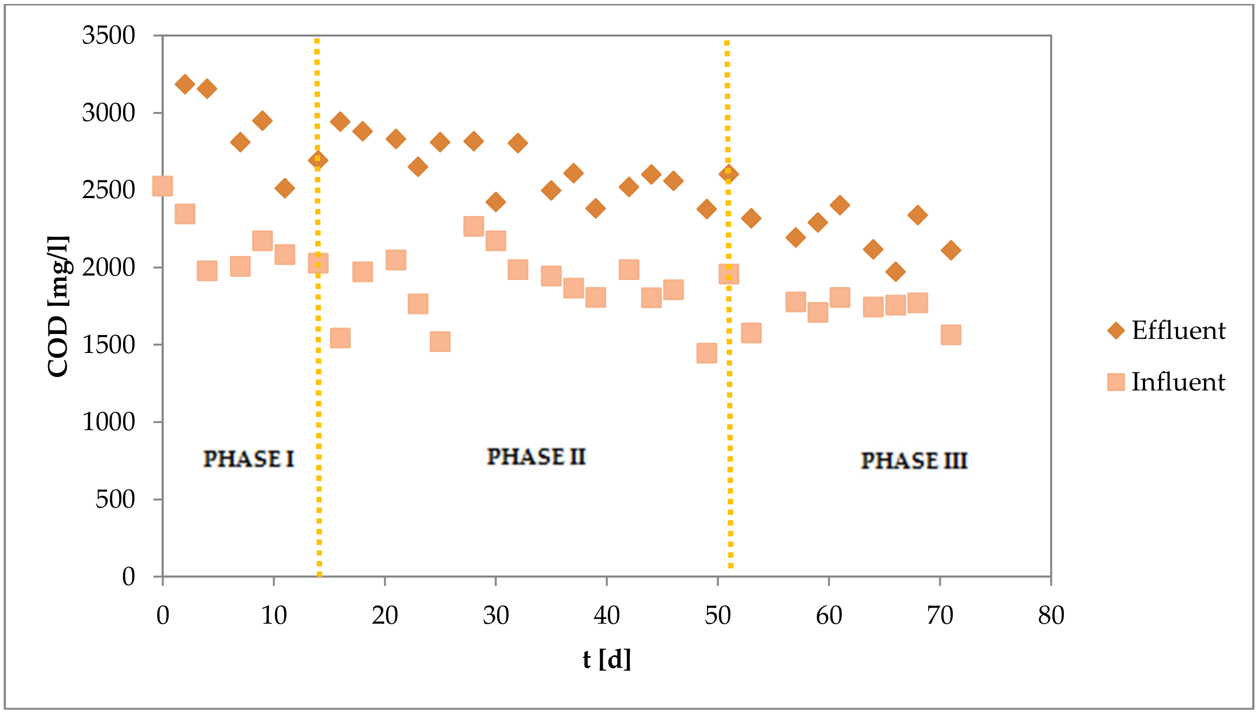

Figure 4.36 - COD concentration in the effluent and in the influent

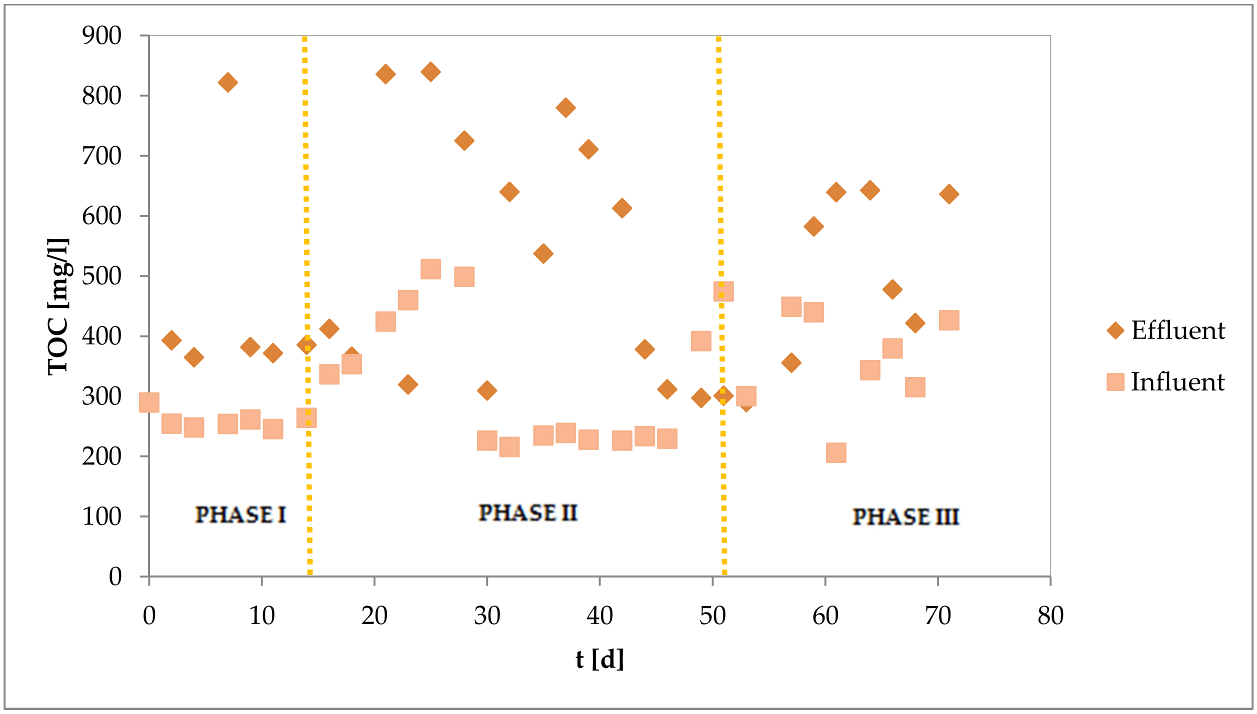

Figure 4.37 - TOC concentration in the effluent and in the influent

In the Figure 4.35 the concentrations of COD and TOC in the effluent are shown, while in the Figure 4.36 and 4.37 they are compared with the ones in the influent.

The COD increased as follows: from 2163 mg/l to 2833 mg/l in the first phase, from 1853 mg/l to 2637 mg/l in the second and from 1740 mg/l to 2260 mg/l in the third one.

The TOC, as well, worsened from 260 mg/l to 430 mg/l (first phase), from 321 mg/l to 538 mg/l (second phase) and from 371 mg/l to 483 mg/l (third phase).

Overall, the worst results were obtained in the second phase and the best in the first one, when the aeration rate was lower.

In the Figure 4.38 the concentration of Total Solids and Volatile Solids in the effluent are shown and in the Figure 4.39 and 4.40 they are compared with the ones in the influent.

Also in this case the aerobic stage produced more solids and the TS and VS concentration in the treated effluent rose, especially in the second phase. For these organic forms as well the first phase was the better.

These results were unexpected, since the increase in the aeration rate should improve the efficiency of the treatment. It can be explained with the addition of an agent used to avoid an excessive foam formation when the air flow was rose, and this probably altered the final values.

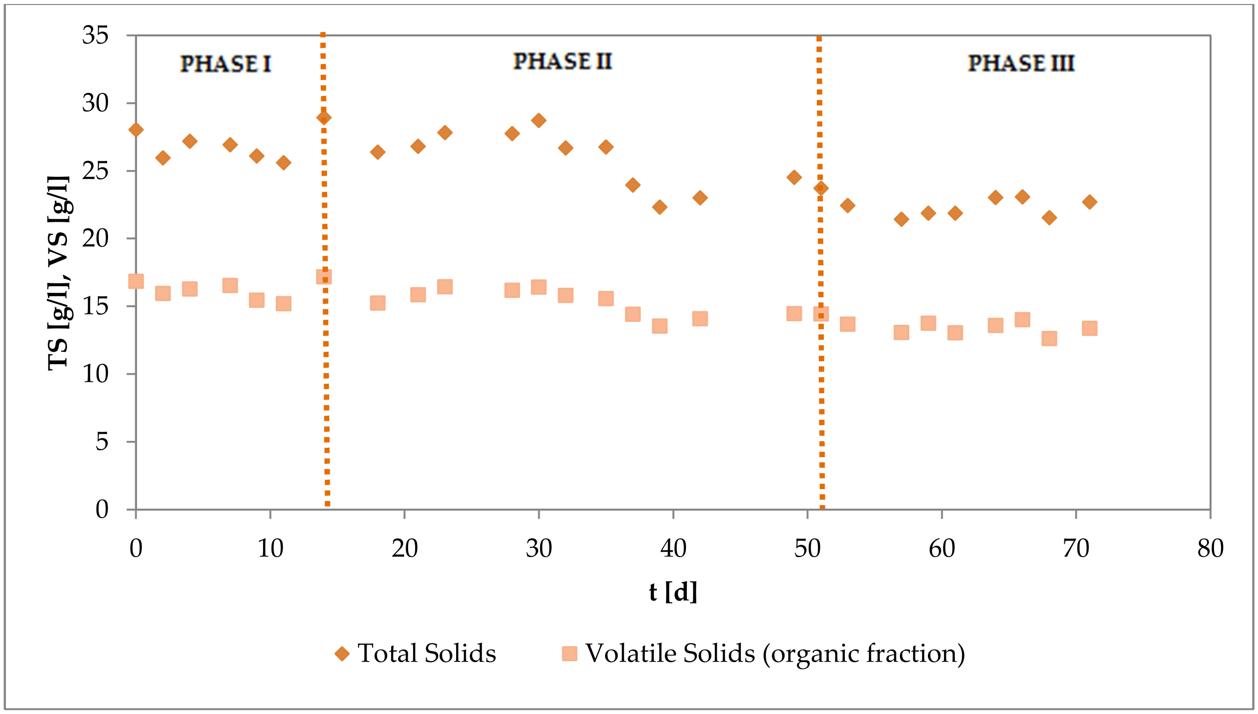

Figure 4.38 - TS and VS in the effluent

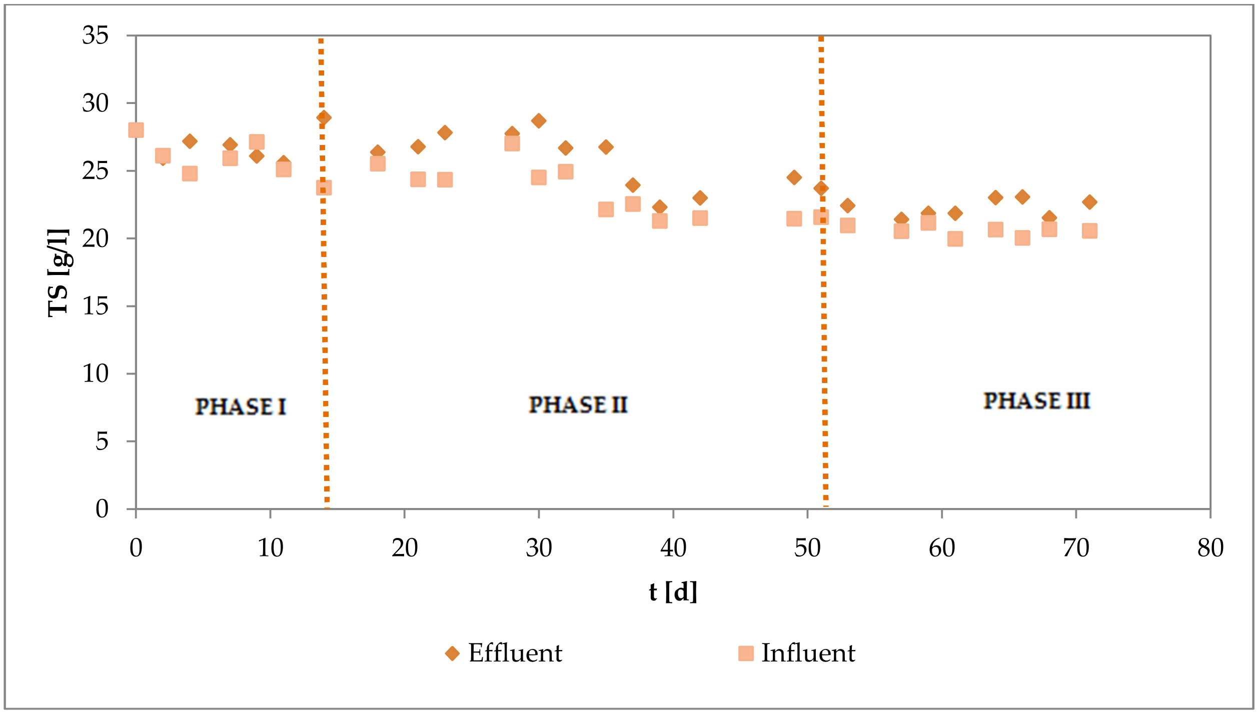

Figure 4.39 - TS in effluent and influent

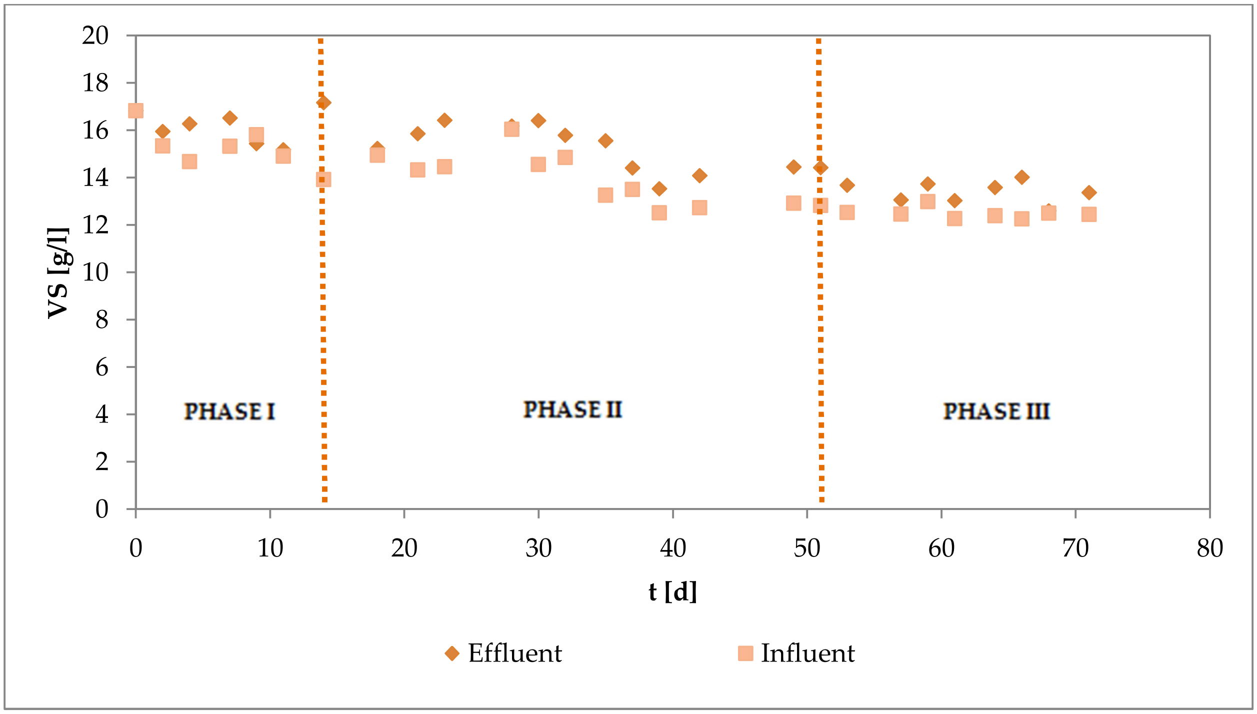

Figure 4.40 - VS in effluent and influent

4.3.3 Water removal

In the Figure 4.41 the dewaterability analysis in terms of Capillary Suction Time and Sludge cake are respectively shown and in the Figure 4.42 and 4.43 those values are compared with the ones in the influent.

The CST worsened sequentially with the increase of the air flow: from 1039 s to 1314 s in the first phase, from 857 s to 1194 s in the second one, from 654 s to 992 s in the last part.

The amount of water removed with the centrifuge method was less in this experiment in comparison with the previous ones, but the best results were achieved in the first phase.

This could be correlated with the addition of the anti-foaming agent containing an elevate concentration of COD. As mentioned in the *Introduction*, the COD is a parameter strictly connected with the dewatering properties of the sludge and that external substance probably interfered with the CST and centrifuge tests results.

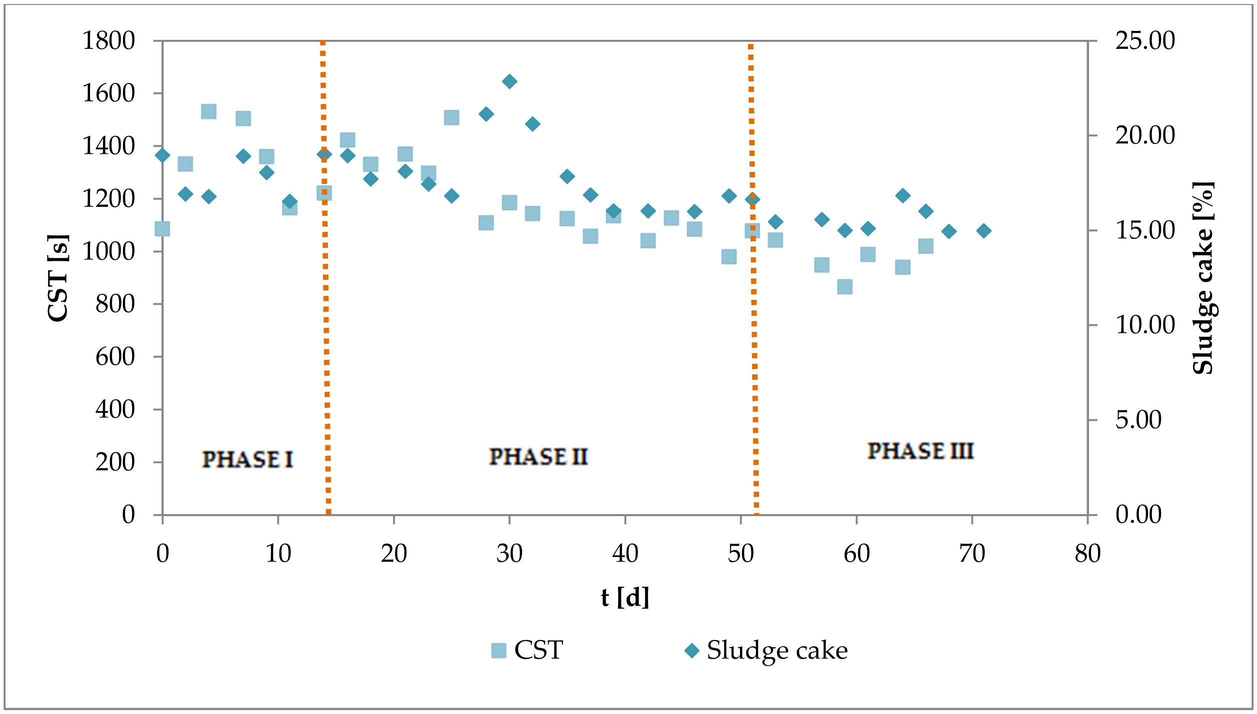

Figure 4.41 - CST and Sludge cake in the effluent

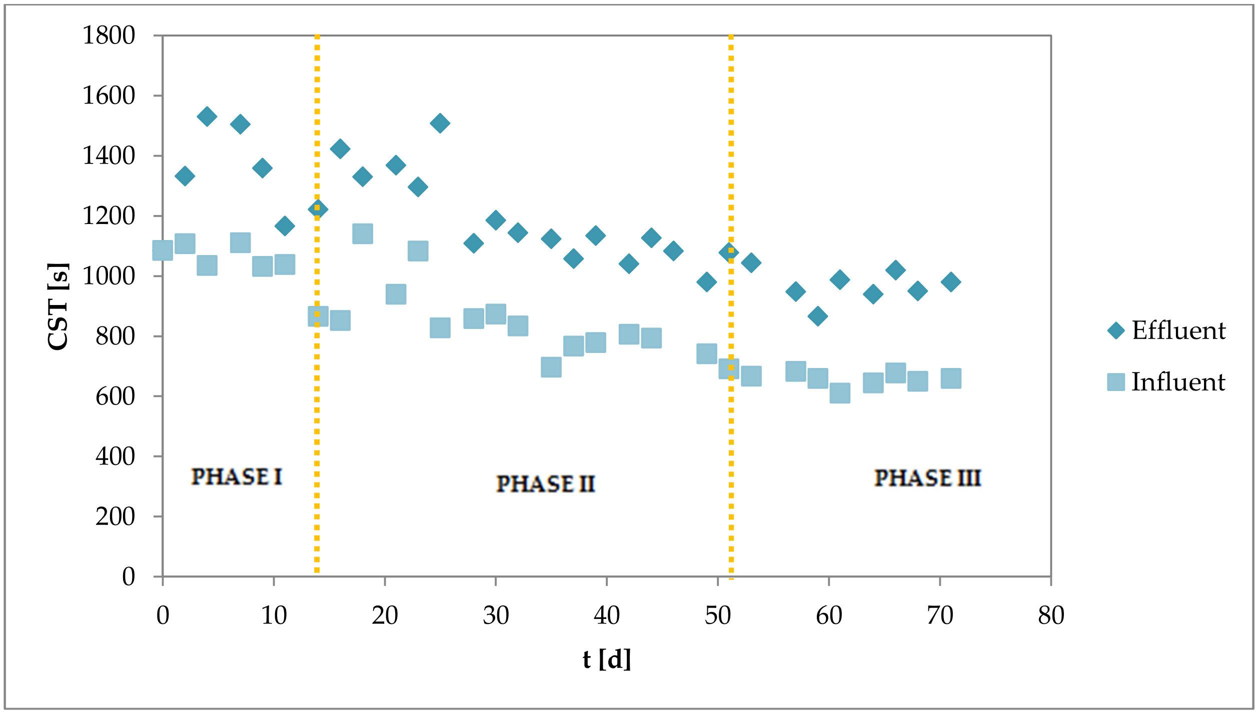

Figure 4.42 - CST in the effluent and in the influent

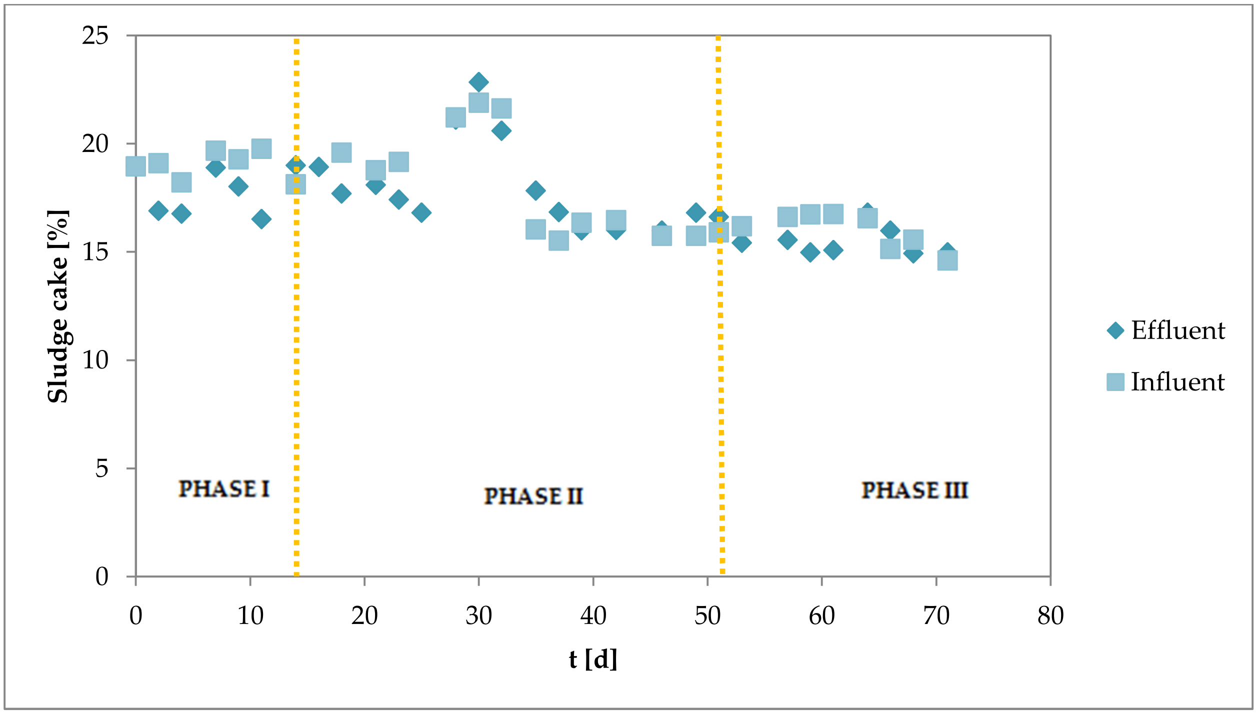

Figure 4.43 - Sludge cake in the effluent and in the influent

5. Discussions

5.1 Previous experiments

5.1.1. Nitrogen removal

Starting from an average removal efficiency of 59 % (SRT of 8 days and aeration rate of 300 L/h), the efficiency of the treatment consistently decreased with the reduction of the SRT value. With a SRT of 4 days and aeration rate of 300 L/h, the average removal was equal to 30%.

After, the aeration was increased, and the efficiency started to rise again. The average values of the efficiency reported were, respectively, 46 % with an aeration rate of 600 L/h, and 47.6 %, with 900 L/h.

Overall, considering the economic costs of maintaining a high SRT and aeration rate in a WWTP, the best solution is definitely the one with an SRT of 4 days and an aeration rate of 600 L/h.

In general the obtained results are certainly good but, in the literature, Kim and Novak (2011) achieved 97 % ammonia nitrogen removal efficiency with an aerobic reactor operating at SRT of 5 days and room temperature. It must be pointed out that the sludge used for the treatments was anerobically digested in mesophilic conditions (35^{0}C).

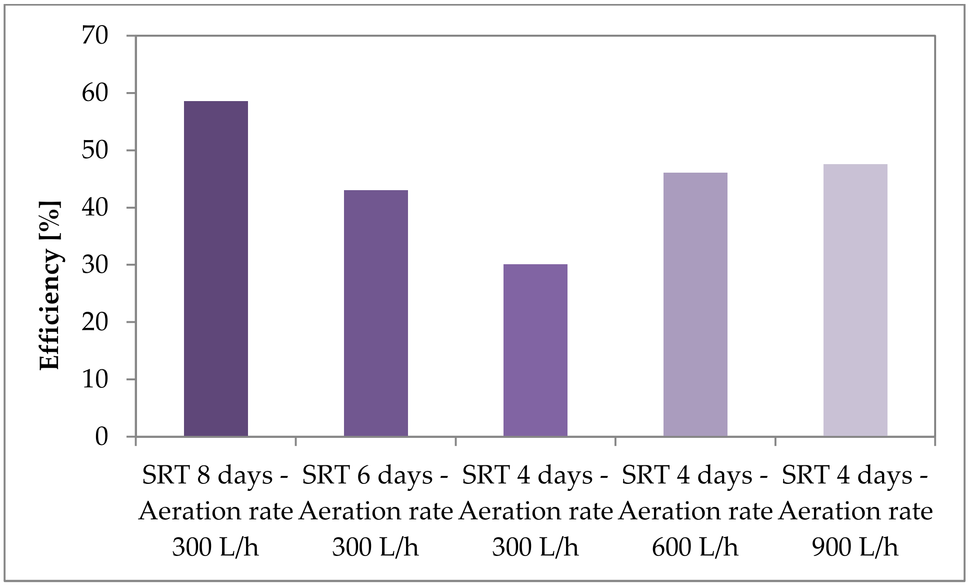

Figure 5.1- Ammonia nitrogen removal efficiency

5.1.2 Organic compounds removal

For what concern the organic compounds removal, the efficiency rate regarding the SRT of 6 days will not be reported, since the results were affected by the addition of the flocculant agent added at the Prague Central WWTP.

A reduction in the COD concentration was observed only in the first phase, characterized by an SRT of 8 days and an aeration rate of 300 L/h. The average efficiency in that case was equal to 30.1%. After that, the COD only increased in comparison to the influent.

An increase in the aeration rate, while maintaining a lower SRT of 4 days, slightly improved the efficiency value. The COD, in fact, remained negative in any case. Tested sludge in these experiments was probably stabilized only partially and during its post-aeration some organic compounds were degraded and transformed into soluble COD.

Parravicini (2008) reported a 25% reduction of the COD concentration treating anaerobically digested sewage sludge (mesophilic stabilization) with an aerated reactor operating at SRT of 5 days and at 30^{0}C. It may be possible that the higher temperature deepened the COD degradation process.

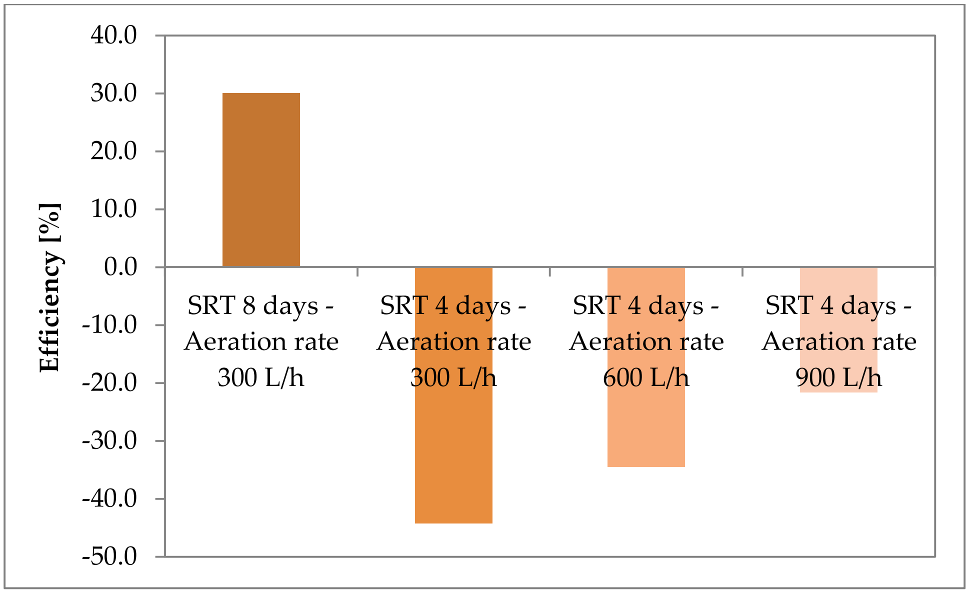

Figure 5.2 - COD removal efficiency

The TOC, as expected, showed a similar pattern: the only positive removal efficiency, equal to 43%, was achieved in the first phase. Subsequently, the efficiency was always negative, but it was improved with the air flow.

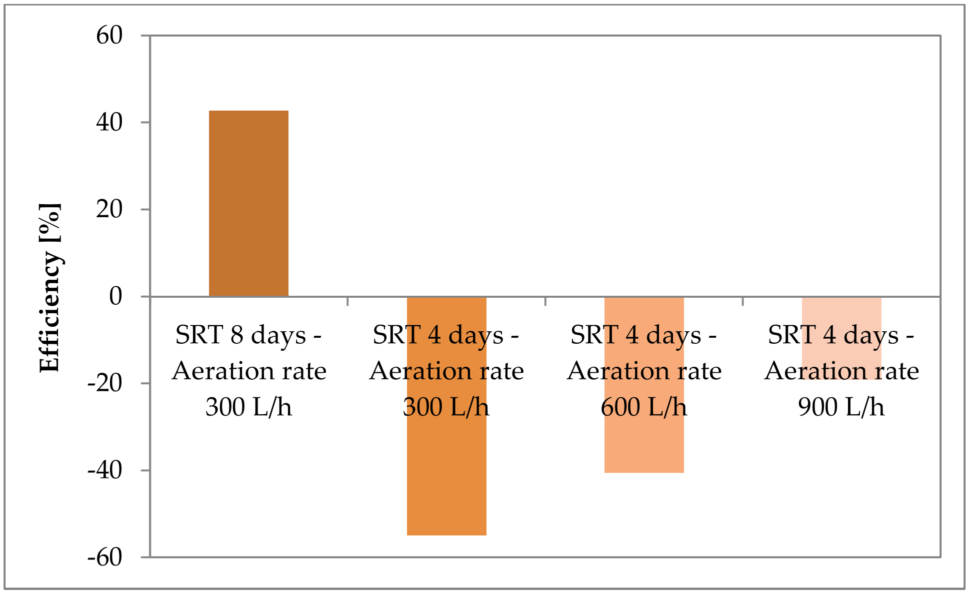

Figure 5.3 - TOC removal efficiency

The treatments led to a 18.1 % reduction of the TS with a SRT of 8 days and just 0.6 % with a SRT of 4 days, with the same aeration rate of 300 L/h. Subsequently the increase in the aeration rate worsened the trend.

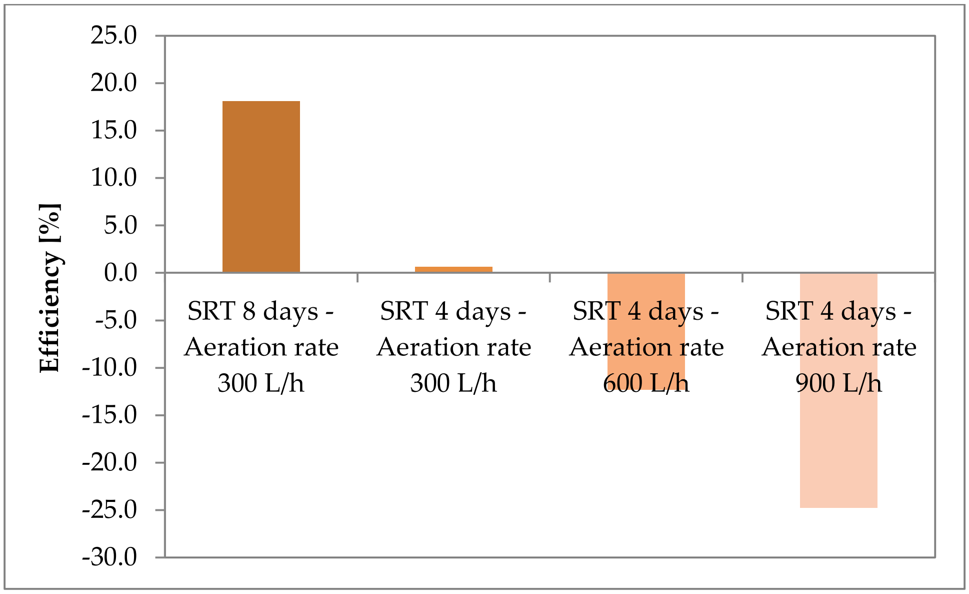

Figure 5.4 - TS removal efficiency

The trend for the Volatile Solids is the same, with the exception that the efficiency was already negative with an SRT of 4 days and an aeration rate of 300 L/h.

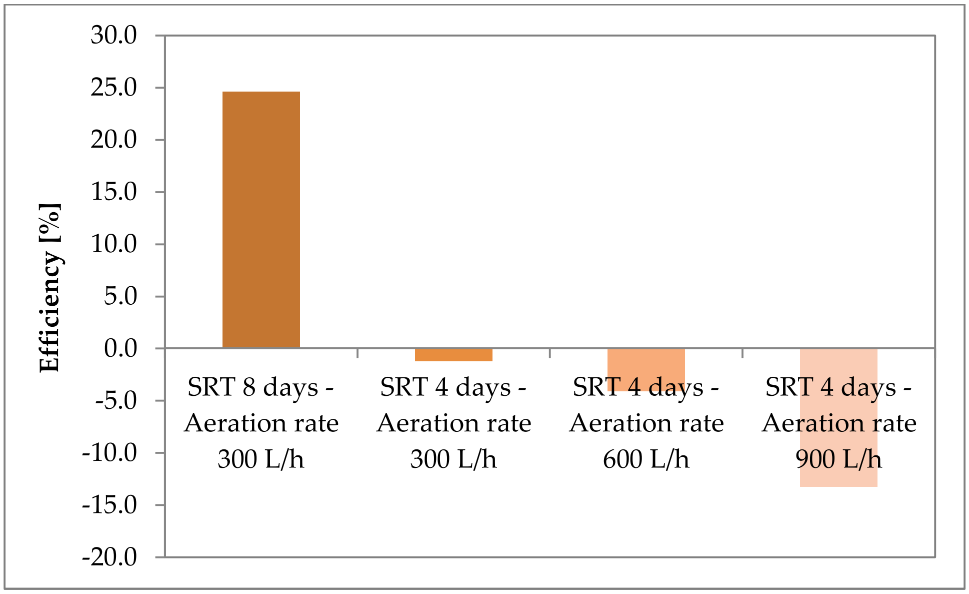

Figure 5.5 - VS removal efficiency

5.1.3. Water removal

The efficiency measured with the CST parameter was positive only at SRT 8 days (18.8%). After that the SRT was changed from 8 to 4 days the efficiency dropped. The increase in the aeration rate slightly improved the results, but not enough to consider the treatment efficient.

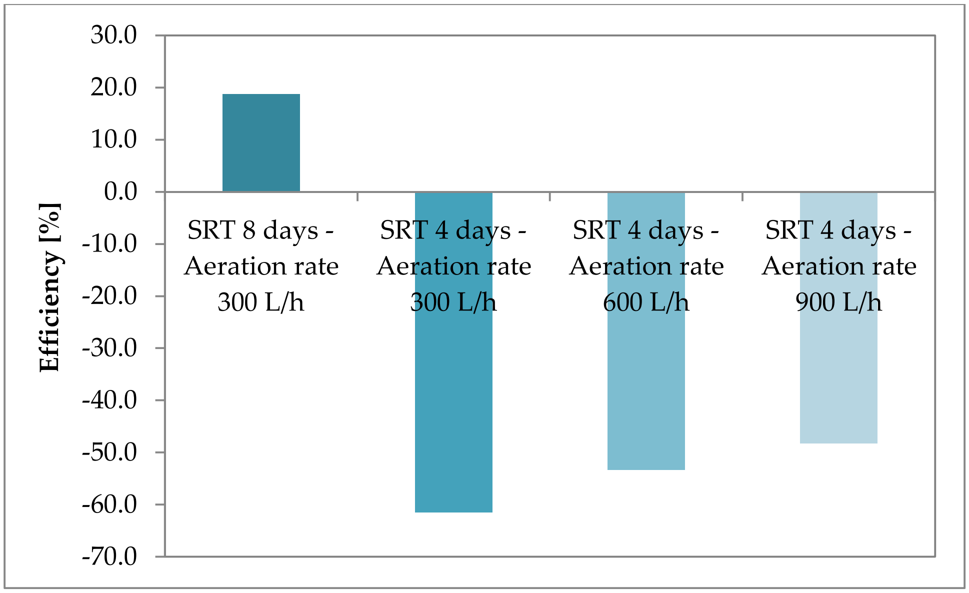

Figure 5.6 - CST improvement efficiency

Looking at the results obtained with the centrifuge method, the efficiency was always positive, but the trend reported was completely the opposite in comparison with the CST method. As expected, also in this case the best results (efficiency of 31.4%) were obtained with a SRT of 8 days. Subsequently, the increase in the air flow worsened the trend. The results of the centrifuge method are strictly connected with the trend in the TS and VS concentration, so the efficiencies obtained, overall, are coherent.

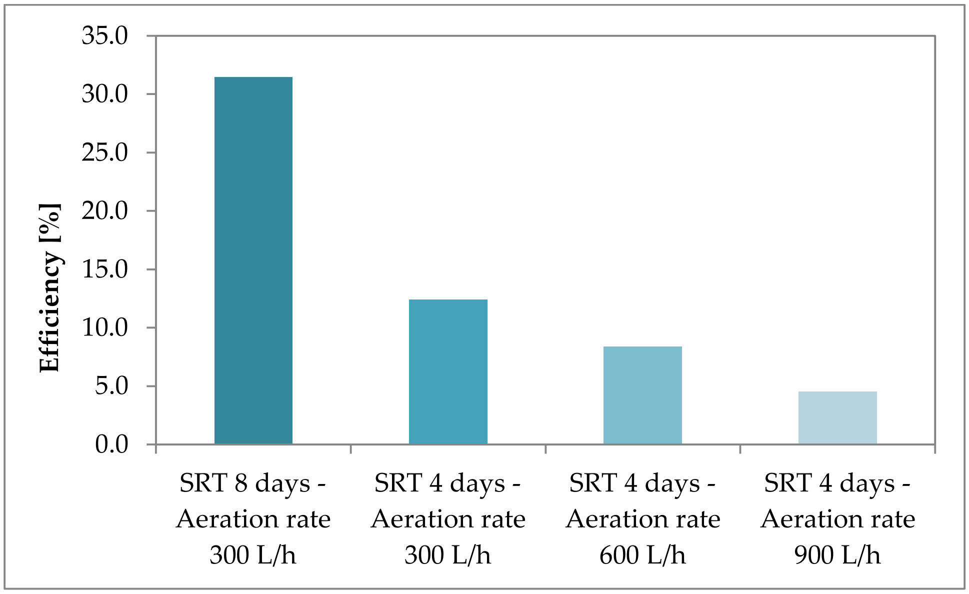

Figure 5.7 - Sludge Cake reduction efficiency

5.2 Experiment 1

5.2.1 Nitrogen removal

During the first phase of the experiment, characterized by a SRT of 4 days and an aeration rate of 600 L/h, the average efficiency of removal of the Total Ammonia Nitrogen was 40.8 %.

During the second phase of the experiment, characterized by a SRT of 2 days and an aeration rate of 900 L/h, the average efficiency of removal of the Total Ammonia Nitrogen was 30.6 %.

Overall, despite the increase in the aeration rate in the second part, the highest SRT value set up in the first phase led to a higher nitrogen removal.

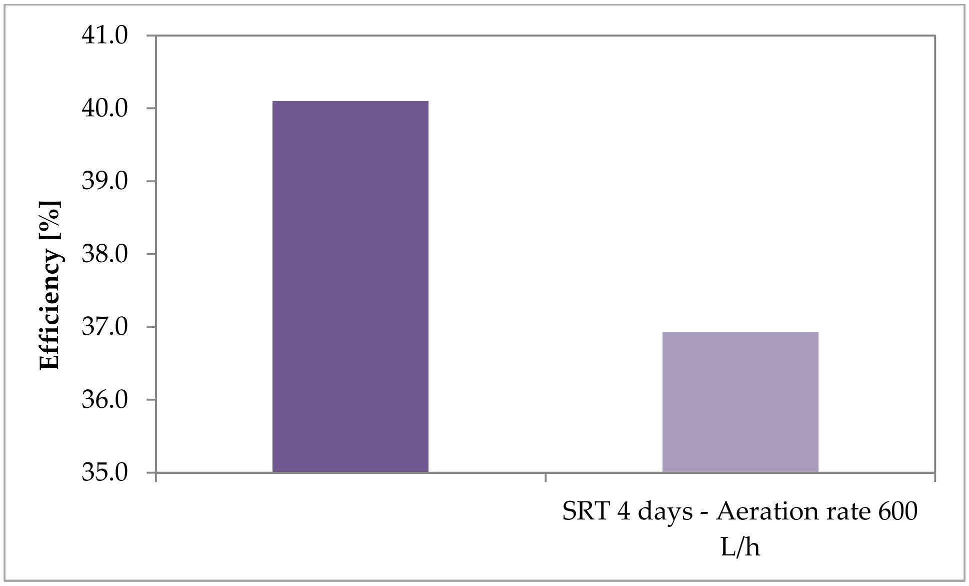

Figure 5.8 - Ammonia nitrogen removal efficiency

5.2.1 Organic compounds removal

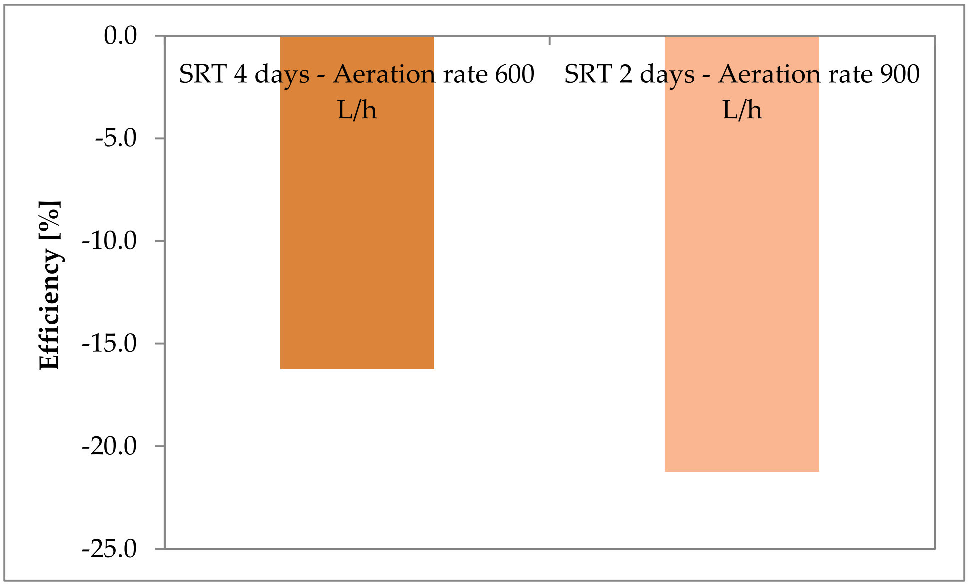

Figure 5.9 - COD removal efficiency

The COD, overall, was not removed through all the experiment: in the second phase, in particular, the efficiency was the worse: - 21.3%. So, even by increasing the aeration, the treatment did not lead to satisfying results. It must be pointed out that, during this experiment, the reactor started to foaming and for this reason about 1 ml of anti- foaming agent was added. Since it was characterized by a COD of 1000 g/L, this interfered with the results and the numbers obtained cannot be considered completely reliable. As expected, the TOC showed a similar pattern, but the efficient is the second phase was worst: -58%.

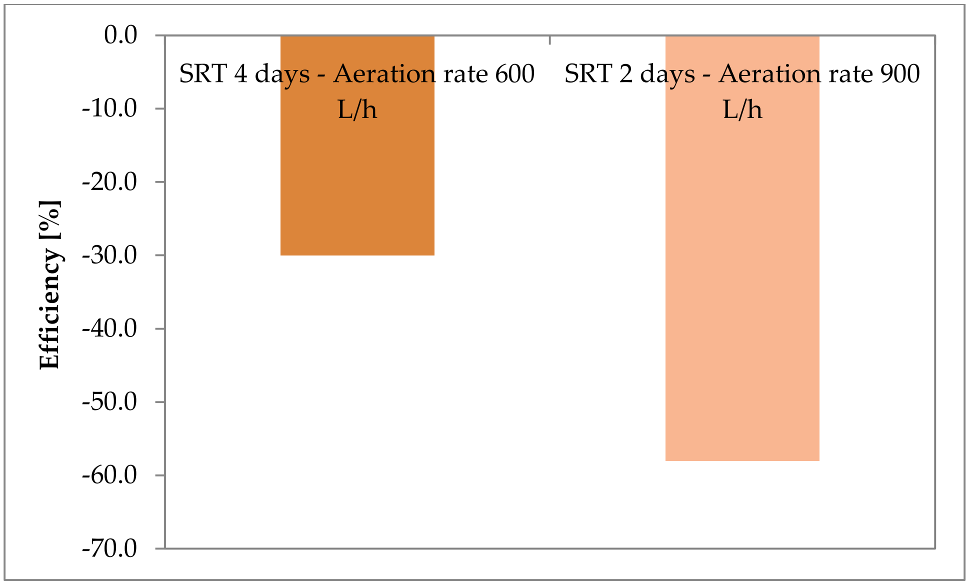

Figure 5.10 - TOC removal efficiency

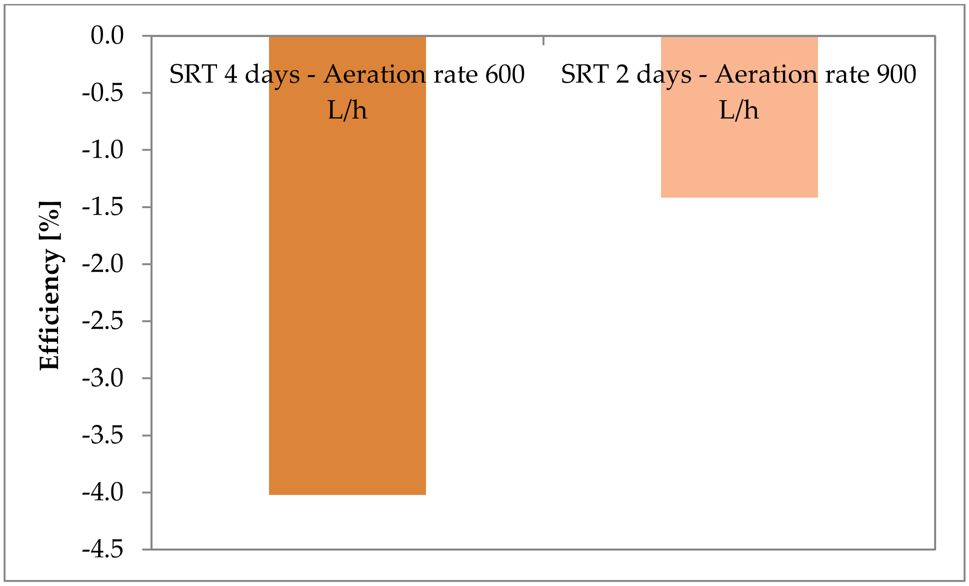

Figure 5.11 - TS removal efficiency

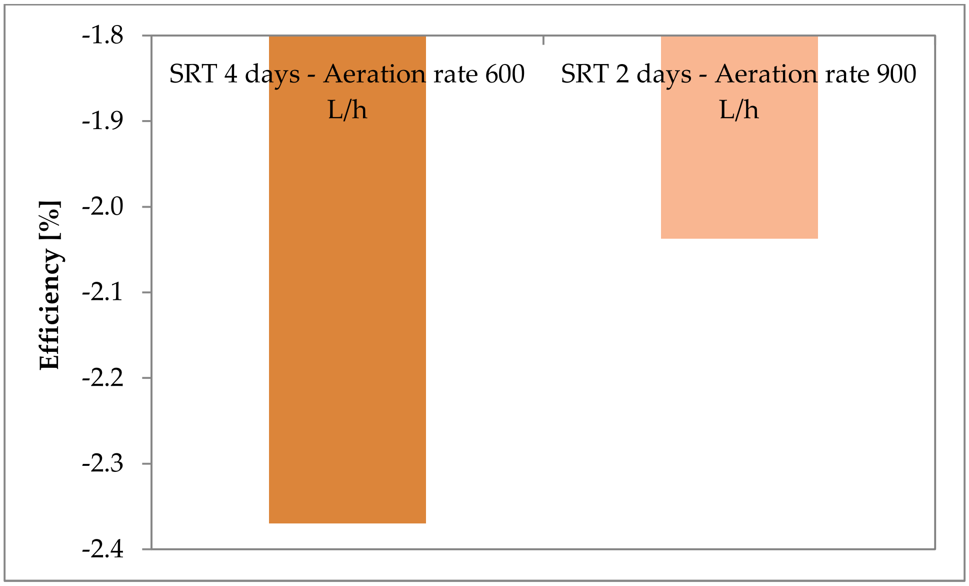

Figure 5.12 - VS removal efficiency

For what concern the dry mass analysis, the overall efficiency was negative, but in both cases it improved with the increase in the air flow, even with a lower SRT. This fact is in contrast with what reported is the previous experiment, but is also possible that, due to the scarcity of the results of the second experiment (16 days), the average efficiency could not be considered completely reliable.

5.2.3 Water removal

The CST parameter in the effluent just increased, more sharply after the decrease of the SRT. So the higher air flow did not deepen the efficiency of the treatment.

The Sludge cake in the effluent always decreased, testifying instead a positive effect of the treatment. But, also in this case, the results consistently worsened with the lower SRT.

The two different methods so, led to different results but, overall, the treatment resulted more effective in the first phase.

In this case, strangely, the centrifuge method results seemed to not be connected with the TS and VS ones.

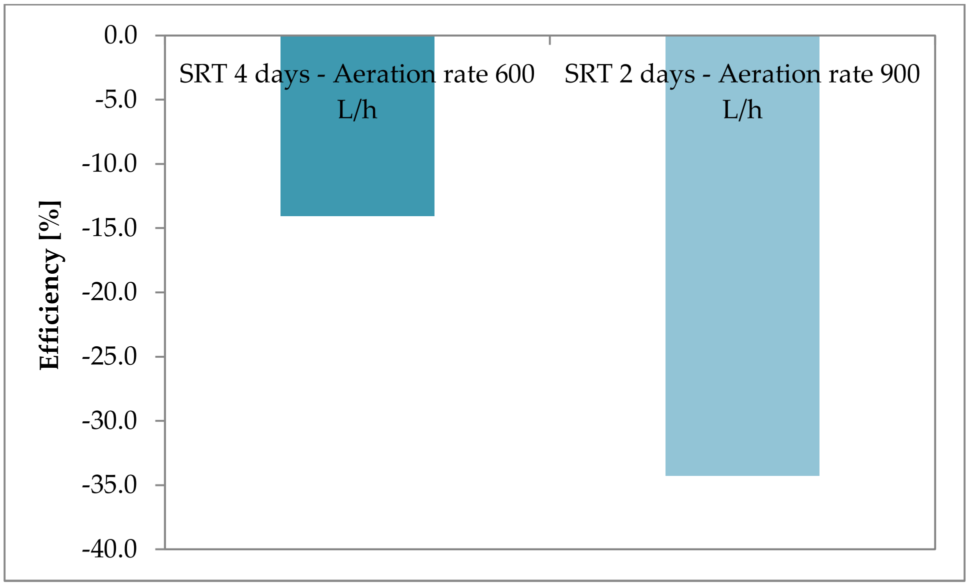

Figure 5.13 - CST improvement efficiency

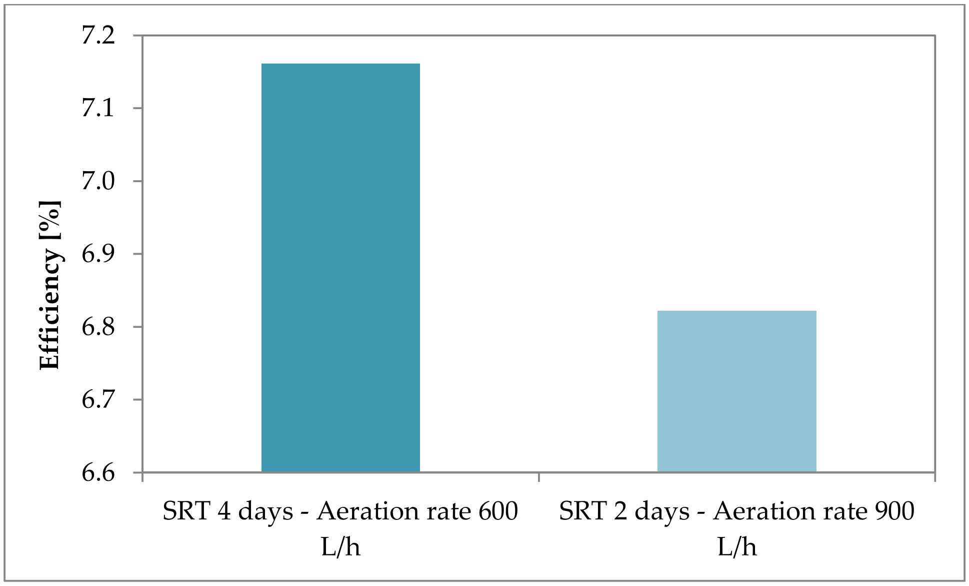

Figure 5.14 - Sludge Cake reduction efficiency

5.3 Experiment 2

5.3.1 Nitrogen removal

The average efficiency in the ammonia nitrogen removal climbed with the increase in the aeration rate, while the value of SRT was maintained the same (2 days). As shown in the Figure 5.15, the average efficiencies were the following ones: 20 % with an aeration of 600L/h, 32.6 % with 1200 L/h and 43 % with 2000 L/h.

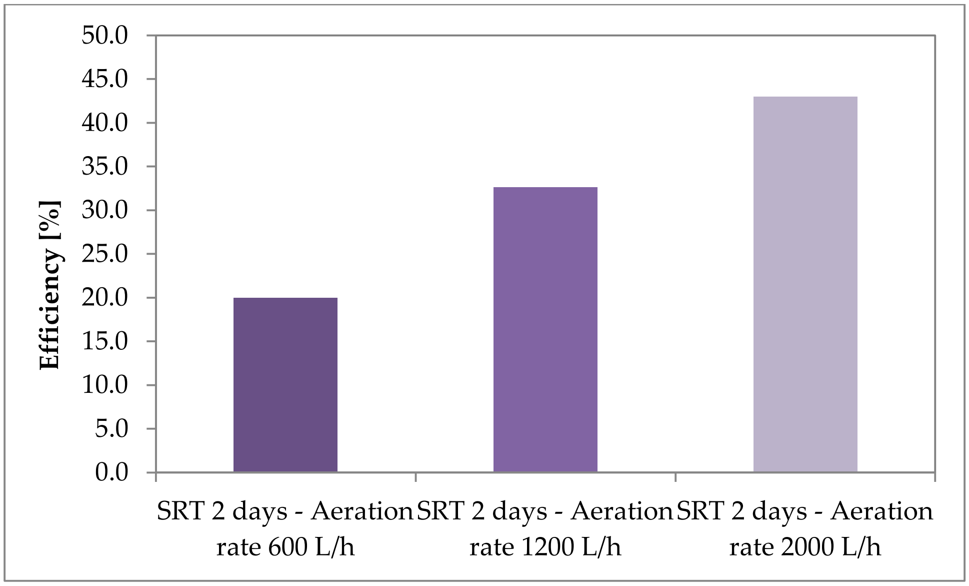

Figure 5.15 - Ammonia nitrogen removal efficiency

5.3.2. Organic compounds removal

Overall the treatment did no result effective in the COD removal: it actually increased during all the three experiments. The lowest average efficiency (-44.4 %) was observed in the second phase, while the highest (- 30.1 %) in the third one. This could connected to the anti-foaming agent addition.

The TOC, as expected, showed a similar pattern.

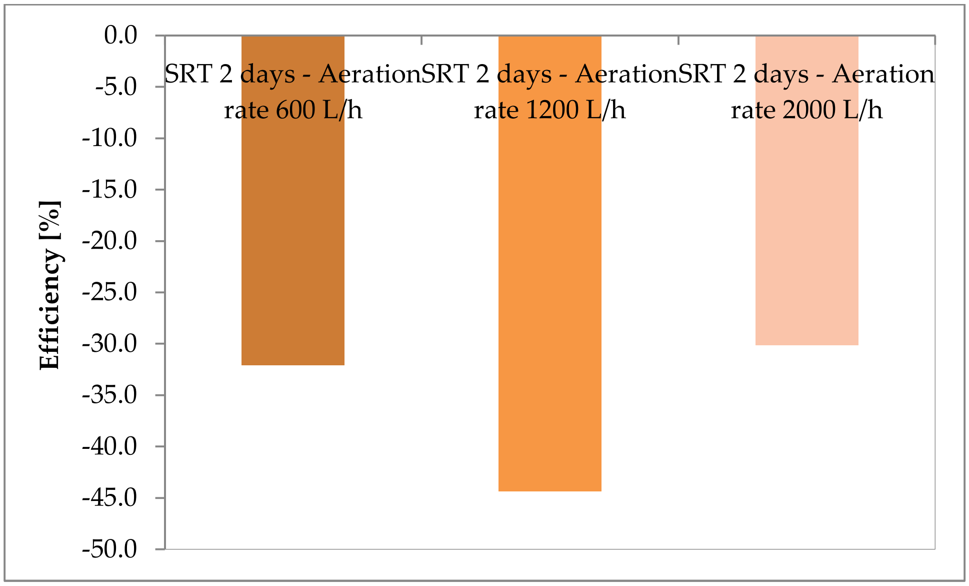

Figure 5.16 - COD removal efficiency

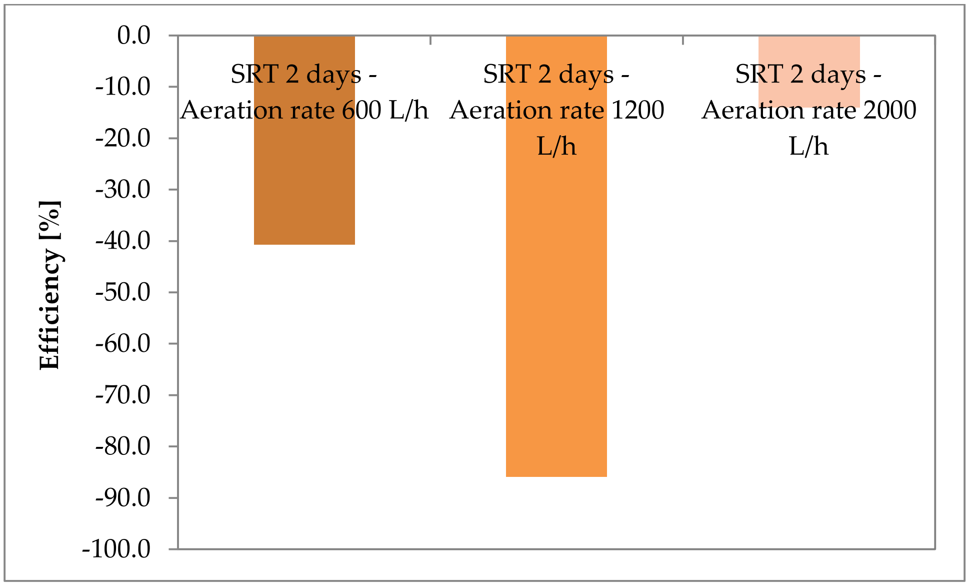

Figure 5.17 - TOC removal efficiency

For what concern the dry mass analysis, the lowest efficiency rate occurred in the second phase as well: respectively – 8.6 % and – 8.2 % for Total Solids and Volatile Solids. Regarding the rest, they increased also in the other two phases, but less in the first one. Overall, the treatment did not result effective also in this case.

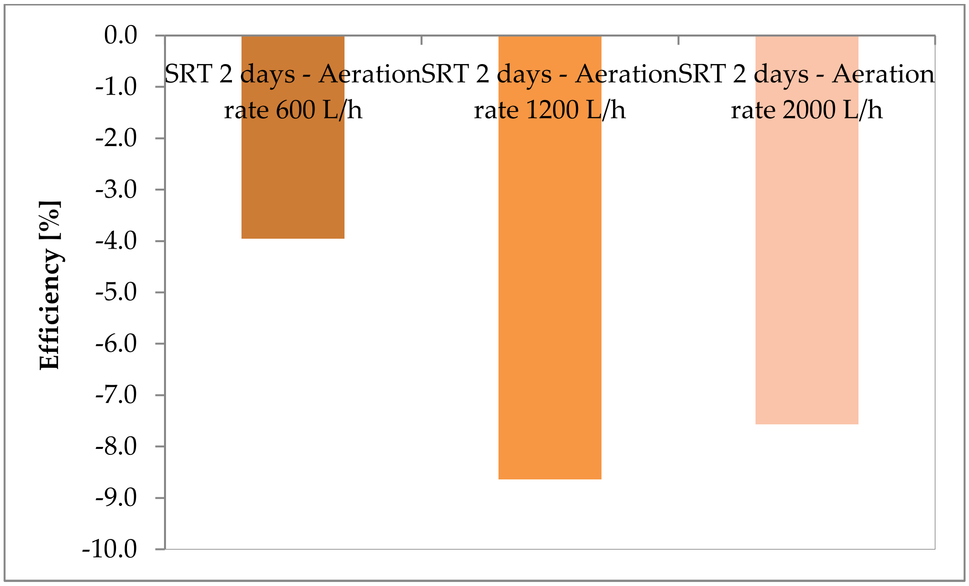

Figure 5.18 - TS removal efficiency

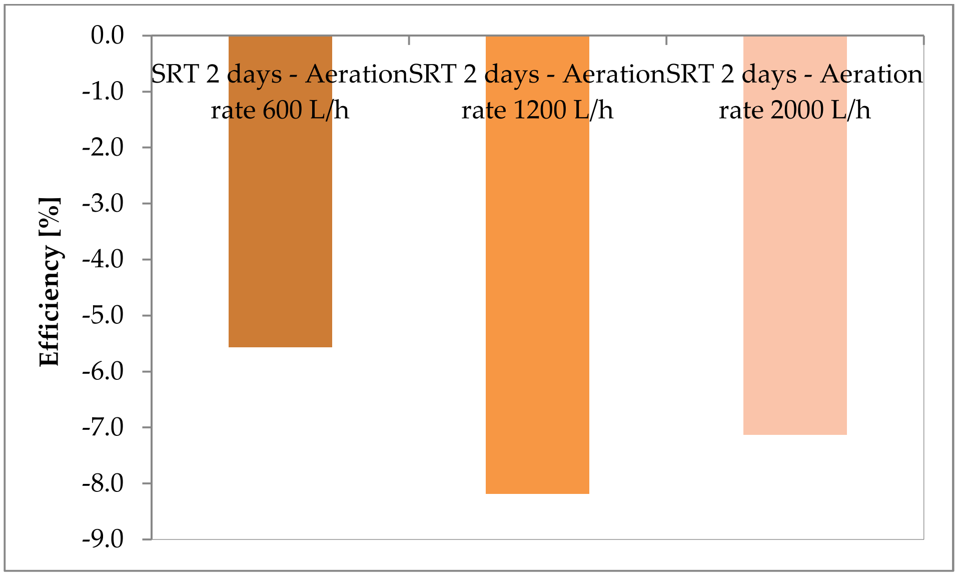

Figure 5.19 - VS removal efficiency

5.3.3. Water removal

The results obtained for the dewaterability analysis, from the CST and centrifuge test, were completely different. In fact, while the efficiency of the centrifuge analysis was always positive, the one in the CST analysis was always negative. In particular, the CST worsened with the increase in the aeration rate, while the Sludge cake was lower in the first phase and highest in the second one. Overall, an aeration rate excessively high did not improve the dewaterability properties of the sludge.

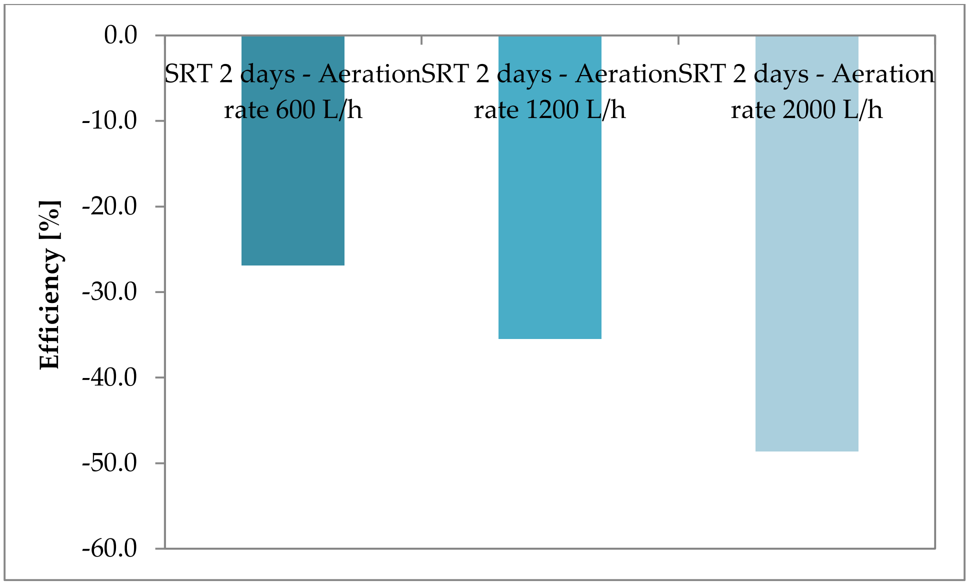

Figure 5.20 - CST improvement efficiency

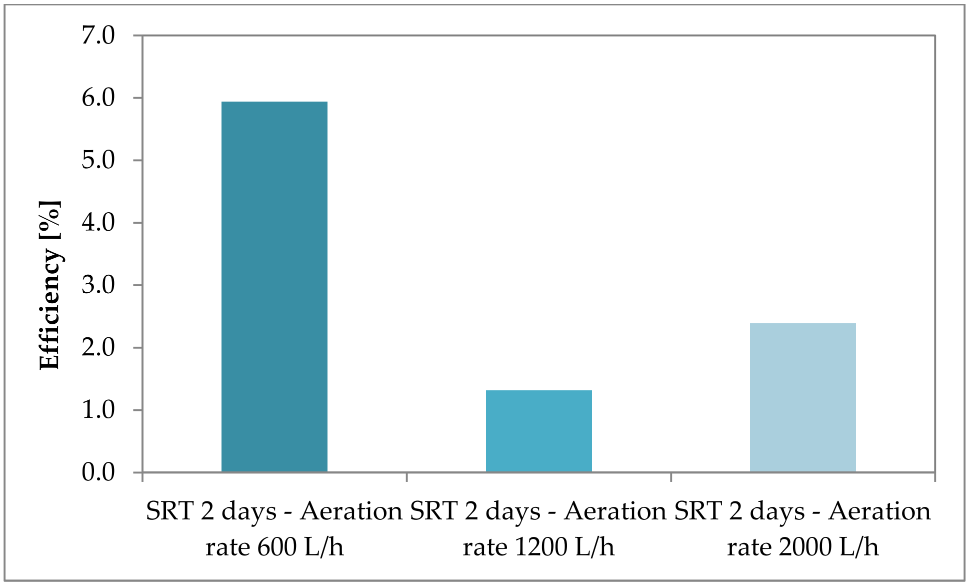

Figure 5.21 - Sludge Cake reduction efficiency

6. Conclusions

A post – aeration treatment was operated on anaerobically digested sludge to quantify the efficiency of the treatment for ammonia nitrogen removal, organic compounds removal and improvement of the dewaterability propertie. In order to determine the operating conditions for the achievement of the best results from the treatment, the following technical parameters were changed through all the study: SRT and aeration rate, while the temperature remained always constant (room temperature).

Two experiments were performed to determine the potentiality of a post-aerobic stage, but also the results of a previous study conducted as part of the same project has been evaluated, in order to have a complete comprehension of the topic.

The general conclusions of the previous study are the following:

- The highest ammonia nitrogen removal efficiency, 49%, was achieved with a SRT of 8 days and aeration rate of 300 L/h. Similar results were obtained with a SRT of 4 days and increased air flow: 46 % with an aeration rate of 600 L/h and 47.6 % with 900 L/h. Considering the economic costs to maintain an elevated SRT in the reactor, the best operating solution was the one with SRT of 4 days and air flow of 600 L/h;
- Regarding the organic compounds removal, the average efficiencies achieved are the following:
    - The COD and the TOC has been effectively reduced only with a SRT of 8 days, with an average efficiency, respectively, of 30.1% and 43%;
    - The TS and VS, as well, were removed only in that case, with removal efficiencies of 18.1% and 24.6%.

- The characterization of the dewatering properties through the CST and centrifugation methods led to completely different results:
    - The efficiency calculated with the CST parameter was positive only in the first experiment (18.8%), instead after the trend worsened, and the increase in the aeration rate just slightly improved the results;
    - On the contrary, the dewatering properties improved with the centrifuge test. Overall, more water was removed with the highest SRT (8 days) and the subsequent increase in the air flow reduced the dewaterability.

Regarding the first experiment, these are the conclusions:

- The highest ammonia removal (40.8 %) was reported with the SRT of 4 days and aeration rate of 600 L/h, but the treatments resulted effective (36.9%) also with a SRT of 2days and aeration rate of 900 L/h;
- The COD and TOC were not removed. A decrease in the SRT worsened further the pattern, despite an increase in the air flow to 900 L/h;
- The TS and VS were not reduced as well, but a higher aeration led to better results;
- Regarding the dewatering properties characterization, the results were considerably different for both the methods: negative with the CST test and positive with the centrifuge one. The trend observed with the first method was similar to the one of the soluble organic compounds (the efficiency decreased in the second phase); while the centrifuge test reported a pattern coherent with the TS and VS one (it improved in the second phase).

The last experiment was conducted to evaluate whether the treatment could result effective even with an extremely low SRT (2 days), while the air flow was sequentially increased. The conclusions are summarized below:

- The best ammonia nitrogen removal efficiency was reached with the highest aeration rate: 43% with an air flow of 2000 L/h;
- The treatment did not resulted effective for the COD and TOC removal;
- The TS and VS was not successfully reduced;
- Also in this case, the results obtained with the dewaterability analysis were completely different: while the efficiency of the centrifuge analysis was always positive, and higher with the lowest aeration rate, the ones obtained with the CST analysis was always negative, especially when the air flow was rose.

In general, the most important achievements of this study are:

- Post – aerobic treatment can effectively remove the Total Ammonia Nitrogen, since it has been reduced with good removal efficiency in all the experiments. Overall, a high reduction can be achieved by increasing the SRT or the aeration rate. The best solution was considered the one with the reactor operating at SRT of 4 days and aeration rate of 600 L/h, representing a good compromise between economical and technical advantages.
- The potentiality to reduce the COD and the TOC has been shown only with an SRT of 8 days, but the addition of an anti-foaming agent could have compromised the subsequent results;
- The removal efficiency for TS and VS, as well, was positive only with a SRT of 8 days;

- As shown from the centrifugation method, post-aeration has the potential to improve the dewatering properties of the sludge;
- The CST method reported generally unfavorable results, with the exception if the SRT of 8 days. Probably better results could be obtained by working at higher temperature, because more colloidal and organic matter is release in the medium while working under higher temperatures conditions.

Future studies regarding this topic could investigate more these aspects:

- With this study a new method, alternative to the CST one, has been investigated: the centrifuge method. Since the extremely different results obtained with the two process, their correlation should be studied deeply;
- Instead of operating the reactor in continuous aeration conditions, intermittent aeration could be set up. In this study it was decided to set this conditions up because previous kinetic tests showed that probably in the sludge utilized for the experiment the substrate present was not enough to sustain the denitrification process;
- Since a part of the ammonia nitrogen was removed by the stripping process, it could be interesting to investigate the potentiality to recover part of that nitrogen released in the atmosphere;
- The potentiality in the COD and TOC removal must be studied deeply as well, since the addition of an anti-foaming agent during the experiments, which surely interfered with the results;
- The effect of the temperature, which has not been evaluated in this study, should be investigated: a higher temperature could significantly deepen the organic compounds removal.

References

Akrama Mahmoud, Aurora Fernandez, Toma-Mihai Chituchi, Patricia Arlabosse. Thermally assisted mechanical dewatering (TAMD) of suspensions of fine particles: Analysis of the influence of the operating conditions using the response surface methodology, *Chemosphere, Elsevier* (2008), 72 (11), 1765-1773.

C. M. Braguglia, N. Carozza, M. C. Gagliano, A. Gallipoli, A. Gianico, S. Rossetti, J. Suschka, M. C. Tomei and G. Mininni. Advanced anaerobic processes to enhance waste activated sludge stabilization, *Water Science & Technology* (2014), 69(08), 1-8

C. M. Braguglia & A. Coors & A. Gallipoli & A. Gianico &E. Guillon & U. Kunkel & G. Mascolo & E. Richter & T. A. Ternes & M. C. Tomei & G. Mininni. Quality assessment of digested sludges produced by advanced stabilization processes, *Environmental Science and Pollution Research* (2014), 22(10), 7216–7235

E. Smidt, V. Parravicini. Effect of sewage sludge treatment and additional aerobic post-stabilization revealed by infrared spectroscopy and multivariate data analysis, *Bioresource Technology* (2009), 100, 1775–1780

Elif Pehlivanoglu-Mantas, Didem Okutman Tas, Guclu Insel, Egemen Aydin, Duygu C. Ozturk, Tugba Olmez, Erdem Gorgun, Emine Ubay Cokgor, Derin Orhon. Evaluation of Municipal and Industrial Wastewater Treatment Sludge Stabilization in Istanbul, Clean (2007), 35 (6), 558 – 564

H. M. Jang, S. K. Park, J. H. Ha and J. M. Park. Combined mesophilic anaerobic and thermophilic aerobic digestion process for high-strength food wastewater to increase removal efficiency and reduce sludge discharge, *Water Sci Technol.* (2014), 69(8), 1768-74

Hyun Min Jang, Jeong Hyub Ha, Jong Moon Park, Mi-Sun Kim, Sven G. Sommer, Comprehensive microbial analysis of combined mesophilic anaerobic - thermophilic aerobic process treating high-strength food wastewater, *Water Research* (2015), 73, 291-303

James Diak, Banu Örmeci, Kevin J. Kennedy. Effect of micro-aeration on anaerobic digestion of primary sludge under septic tank conditions, *Bioprocess Biosyst Eng.* (2013), 36(4), 417-24

John T. Novak. Dewatering of Sewage Sludge, *Drying Technology* (2006), 24, 1257–1262

John T. Novak. The Role of Organic Colloids in Dewatering, *Drying Technology* (2010), 28, 871–876

Jules B. Van Lier, Nidal Mahmoud, Grietje Zeeman. *Biological Wastewater Treatment: Principles, Modelling and Design*, 401 – 442.

Kari F. Brisolara. Biosolids and Sludge Management, *Water Environment Research* (2012), 84 (10)

Kim, Jongmin, Novak, John T. Combined Anaerobic/Aerobic Digestion: Effect of Aerobic Retention Time on Nitrogen and Solids Removal, *Water Environment Research* (2011), 83(9); 802

M. Concetta Tomei & Nicola Antonello Carozza. Sequential anaerobic/anaerobic digestion for enhanced sludge stabilization: comparison of the process performance for mixed and waste sludge, *Environ Sci Pollut Res* (2015), 22, 7271–7279

M. C. Tomei, N. A. Carozza, D. Mosca Angelucci. Post-aerobic digestion of waste sludge: performance analysis and modelling of nitrogen fate under alternating aeration, *International Journal of Environmental Science and Technology* (2016), 13 (1), 21–30

M. V. Kevbrina, Y. A. Nikolaev, D. A. Danilovich and A. Ya. Vanyushina. Aerobic biological treatment of thermophilically digested sludge, *Water Science & Technology* (2011), 63(10)

Mikel Morras, J. Dosta, J. L. Garcia-Heras. Aerobic/anoxic post-treatment of anaerobically digested sewage sludge as an alternative to biological nitrogen removal from reject water, *Bioprocess Biosyst Eng* (2015), 38, 823–831

Miklas Scholz. Review of Recent Trends in Capillary Suction Time (CST) Dewaterability Testing Research, *Ind. Eng. Chem. Res.* (2005), 44, 8157-8163

N. Bernet, N. Delgenes, J. C. Akunna, J. P. Delgenes, R. Moletta. Combined anaerobic–aerobic SBR for the treatment of piggery wastewater, *Water Research* (2000), 34(2), 611-619

Nicholas P. Cheremisinoff. Nitrification and Denitrification in the Activated Sludge Process, *Biotechnology for Waste and Wastewater Treatment* (1996), 151 - 188

Nitin Kumar, John T. Novak, Sudhir Murthy. Effect of secondary aerobic digestion on properties of anaerobic digested biosolids, *Water Environment Foundation* (2006)

S. Vigneswaran, M. Sundaravadivel, D. S. Chaudhary. Sequencing Batch Reactors: Principles, Design/Operation and Case Studies, *Water and wastewater treatment technologies*

Sepideh Kasiri, Fraser Mah, Chonggang Zhang, Melissa Haveroen, Scott Ellsworth, Ania Ulrich. Anaerobic Processes, *Water Environment Research* (2012), 84 (10)

V. Parravicini, K. Svardal and H. Kroiss. Post-aeration of anaerobically digested sewage sludge for advanced COD and nitrogen removal: results and cost-benefit analysis at large-scale, *Water Sci Technol.* (2008), 57(7), 1087-94

Vu Hien Phuong To, Tien Vinh Nguyen, Saravanamuth Vigneswaran and Huu Hao Ngo. A review on sludge dewatering indices, *Water Sci Technol.* (2016), 74(1), 1-16