UNIVERSITÀ POLITECNICA DELLE MARCHE
ENVIRONMENTAL ENGINEERING

MASTER DEGREE THESIS

“*Biopolymers recovery from municipal sewage sludge: sustainability assessment in large wastewater treatment plants*”

Supervisor
Prof. Francesco Fatone

Student:
Maria Elena Beccacece

Assistant supervisor
Ing. Anna Laura Eusebi

Assistant supervisor
Dott. Nicola Frison

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ABSTRACT

The main scope of this work is feasibility studies in real urban wastewater treatment plants for Volatile fatty acids (VFA) recovery and Polyhydroxyalkanoates production (PHA.)

A critical review of scientific literature on VFA and PHA recovery has been carried out in order to obtain an overall view of VFA Yield and PHA production. The feasibility studies have been carried out in three different plants located in different regions in Italy: Castelfranco Salvatronda WWTP (Veneto region), Modena Canale Navigli WWTP (Emilia Romagna region) and Castiglione WWTP (Piemonte region). The work is part of a project carried out in collaboration with the companies Hera, Ireti, Smat and A2A and the University of Verona.

Further, the life cycle assessment has been performed with the support of the Umberto software in order to evaluate the environmental impact of different scenarios. The LCA has been conducted in Castelfranco Salvatronda WWTP to support decision making for the new configuration plant and sludge valorization centre in order to recover Phosphorus and PHA from sludge. Moreover, feasibility study for PHA recovery have been made for Modena and Castiglione WWTPs using literature yield and production, and in order to evaluate the impacts of the rejected water from the sludge line on the water line, some models simulations have been implemented.

Finally, the experimental activity has included laboratory tests on the sludge samples from two WWTPs in order to compare literature VFA yield with experimental results. The tests were done at 5, 7 and 9 days of fermentation in order to control the variation of yields over time.

1. Introduction and thesis goal

The goal of the thesis work is to evaluate the feasibility study of PHA recovery in real urban wastewater treatment plants.

This work could be seen inside the aim of the bioeconomy. The bioeconomy comprises those parts of the economy that use renewable biological resources from land and sea – such as crops, forests, fish, animals and micro-organisms – to produce food, materials and energy.

It is in interesting and current issues, so much so that it is among the first problems that Europe wants to solve.

Europe is setting the pathway for a resource-efficient and sustainable economy. The goal is a more innovative and low-emissions economy, reconciling the sustainable use of renewable biological resources for industrial purposes.

To achieve this, the European Commission has set a Bioeconomy Strategy and action plan which focuses on three key aspects:

- developing new technologies and processes for the bioeconomy;
- developing markets and competitiveness in bioeconomy sectors;
- pushing policymakers and stakeholders to work more closely together.

Moreover, the Commission works on ensuring a coherent approach to the bioeconomy through different programmes and instruments including the Common Agricultural Policy, Horizon 2020, European environmental initiatives, the Blue Growth initiative for the marine sector and the European Innovation Partnership on Sustainable Agriculture.

This report is in line with the goal proposed by the European Union, which aims to exploit all types of resources in order to recover bio-based materials, replacing the use of fossil-based materials.

In line with what has been said so far, the feasibility analysis for the PHA and resource recovery is conducted in three plants.

Before starting the analysis of the plants for feasibility studies, an in-depth study was carried out on the production processes of biopolymers from different types of substrates. The study was focused on the different process steps, operating parameters, yields and, finally, the feasibility in the real plants.

The first plant is Castelfranco Veneto, which is located in Veneto and is managed by the Alto Trevigiano Servizi. For this plant the final design for the resource recover platform, that produces phosphorus as struvite and the biogas has been already planned.

The additional work that was done to this plant was to modify its flow scheme in order to add processes that had the purpose of exploiting the waste to recover resources. Once the technical-economic feasibility was assessed, a life cycle assessment and life cycle costing were carried out with the support of a software called Umberto, which is a software tool that helps to calculate the potential environmental impacts of products.

Life cycle assessment (LCA) can be used as a tool to evaluate the environmental impacts associated to WWTPs and improvement options. In this work it is applied to compare the environmental performance of different scenarios of wastewater treatment plants.

The work is part of a project carried out in collaboration with the companies Hera, Ireti, Smat and A2A and the Verona University. Indeed, the other plants were Modena Canale Navigli and Castiglione. The first plant is managed by Hera company, while the second is located near Turin and is managed by Smat utility.

For both the plants the study is conducted with the aim to evaluate the possibility of recovering PHA and biogas. For Modena, the analyses are conducted with the support of Advanced simulation platform, which is a wastewater treatment process simulator that ties together biological, chemical, and physical process models.

Finally, in order to have detailed information about the characterization of the supernatant and of the sludge, laboratory tests have been done on samples of Modena wastewater treatment plants and of another plant managed by the Hera company. Farther, the scope of the laboratory tests was to do fermentation tests on the sludge, since the fermentation is one of the most important process for the resource recovery.

The standard methods for the examination of water and wastewater is used to conduct the laboratory test.

2. State of the Art and literature discussion

2.1 Bioeconomy and European Commission agreement

Until now, the European economy and society were based on oil gas and other fossil resources that are dangerous for the environment and the climate change. There is a need to change the way in which the European citizens live in order to halt climate change and prevent global warming.

European Commission policies and strategies have the objective to support the development of innovative bio-based products.

There is the need to define a detailed description of the EU bio-based products sector: find information about the market dynamic indicators, in order to provide land footprint information and how they relate to statistical nomenclature.

According to the definition provided in the European Commission's Lead Market Initiative (EC, 2007):

Bio-based products refer to non-food products derived from biomass (plants, algae, crops, trees, marine organisms and biological waste from households, animals and food production). Bio-based products may range from high-value added fine chemicals such as pharmaceuticals, cosmetics, food additives, etc., to high volume materials such as general bio-polymers or chemical feedstocks. The concept excludes traditional bio-based products, such as pulp and paper, and wood products, and biomass as an energy source.

For the same purpose, in December 2019 the European Commission published a European Green Deal (Green Deal, 2019) with the aim to launch a challenge to European Union and its citizens. The idea was to turn an urgent challenge into a unique opportunity resetting the Commission's commitment to tackling climate and environmental-related challenges.

In other words, the European Green Deal is a new growth strategy with the aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from fossil fuels use. It wants to protect, conserve and enhance the EU's natural capital, and protect the health and well-being of citizens from environment-related risks and impacts.

Since it will bring substantial change, active public participation and confidence in the transition is needed, considering citizens in all their diversity, with national, regional, local authorities, civil society and industry working closely with the EU's institutions and consultative bodies.

It is known that the environmental ambition of the Green Deal will not be achieved by Europe acting alone. The collaboration of all the countries of the world is required in order to obtain an healthy planet without net emissions. Therefore, it means that EU must to use its influence on mobilize its neighbors and partners to join it on a sustainable path.

The first goal is to transform the EU's economy for a sustainable future.

To deliver the European Green Deal, policies needed to be rethought for clean energy supply across the economy, industry, production and consumption, large-scale infrastructure, transport, food and agriculture, construction, taxation and social benefits. In this direction, it is essential to increase the value given to protect and restore natural ecosystems, to the sustainable use of resources and to improving human health. Furthermore, the EU should also promote and invest in the necessary digital transformation and tools as these are essential enablers of the changes.

The figure below (Figure 1) illustrates the different elements of the Green Deal.

Figure: 1 Green Deal idea

At first, the Commission will propose the first European 'Climate Law' by March 2020, with the aim to will enshrine the 2050 climate neutrality objective in legislation, that ensure that all EU policies contribute to the climate neutrality objective and that all sectors play their part.

The EU has already started to modernize and transform the economy with the aim of climate neutrality. The Commission will, by June 2021, review and propose to revise where necessary, all relevant climate-related policy instruments. The Commission will propose to amend the Climate Law to update it accordingly. These policy reforms will help to ensure effective carbon pricing throughout the economy. This will encourage changes in consumer and business behavior and facilitate an increase in sustainable public and private investment.

The Commission will propose to revise the Energy Taxation Directive, focusing on environmental issues, because it is also essential to ensure that taxation is aligned with climate objectives.

Moreover, it is important to pay attention, because as long as many international partners do not share the same ambition as the EU, there is a risk of carbon leakage, either because production is transferred from the EU to other countries with lower ambition for emission reduction, or because EU products are replaced by more carbon-intensive imports. If this happens, there will be no reduction in global emissions, and this will cancel the efforts of the EU and of all its participants to meet the global climate objectives of the Paris Agreement.

Should differences in levels of ambition worldwide persist, the Commission will propose a carbon border adjustment mechanism to reduce the risk of carbon leakage. This would ensure that the price of imports reflect more accurately their carbon content.

As already said, the scope is to find a way to supply clean, affordable, and secure energy.

A power sector must be developed that is based largely on renewable sources, complemented by the rapid phasing out of coal and decarbonizing gas. At the same time, the EU's energy supply needs to be secure and affordable for consumers and businesses.

Member States presented their revised energy and climate plans at the end of 2019, so the Commission will assess the ambition of this plans and the need for additional measures if the level of ambition is not enough. This has the aim to increase climate ambition for 2030, for which the

Commission will review and propose to revise, where necessary, the relevant energy legislation by June 2021. Renewable energy sources will have an essential role for the clean energy transition. Increasing offshore wind production will be essential, building on regional cooperation between Member States. The integration of renewables, energy efficiency and other sustainable solutions across sectors will help to achieve decarbonization at the lowest possible cost.

Furthermore, it is important to address the risk of energy poverty for households that cannot afford key energy services to ensure a basic standard of living. With this goal, the Commission will produce guidance to assist Member States in addressing the issue of energy poverty.

The transition to climate neutrality also requires considering the use of smart infrastructure.

The regulatory framework for energy infrastructure, including the TEN-E Regulation, will need to be reviewed to ensure consistency with the climate neutrality objective. This framework should encourage the deployment of innovative technologies and infrastructure, such as smart grids, hydrogen networks or carbon capture, storage and utilization, energy storage, also enabling sector integration.

The full mobilization of industry is required to achieve a climate neutral and circular economy.

This transformation is taking place at a too slow pace with progress neither widespread nor uniform: the European Green Deal has the aim to support and accelerate the EU's industry transition to a sustainable model of inclusive growth.

The circular economy action plan will include a 'sustainable products' policy to support the circular design of all products based on a common methodology and principles: in this way, it will prioritize the reuse of the materials before recycling them. It will also include measures to encourage businesses to offer, and to allow consumers to choose, reusable and repairable products.

The Commission will continue to work on the 2018 plastics strategy focusing, among other things, on measures to tackle intentionally added micro plastics and unintentional releases of plastics, for example from textiles and tire abrasion. Farther, the Commission will develop requirements to ensure that all packaging in the EU market is reusable or recyclable in an economically viable manner by 2030, will develop a regulatory framework for biodegradable and bio-based plastics, and will implement measures on single use plastics.

Another important role of the Commission is to deal with false green statements. Companies making 'green claims' should substantiate these against a standard methodology to assess their impact on the environment. Digital tools can also help improve the availability of information on the characteristics of products sold in the EU.

A sustainable product policy also has the potentiality to reduce waste significantly. Waste must be avoided, but in cases where is not possible, its economic value must be recovered and its impact on the environment and on climate change avoided or minimized. To simplify waste management for citizens and ensure cleaner secondary materials for businesses, the Commission wants to propose an EU model for separate waste collection. It is important that the EU should stop exporting its waste outside of the EU and will therefore revisit the rules on waste shipments and illegal exports.

Digital technologies are important tools for attaining the sustainability goals of the Green deal in many different sectors.

The Commission wants to explore measures to ensure that digital technologies can accelerate and maximize the impact of policies to deal with climate change and protect the environment. Digitalization could have an important role because presents new opportunities for distance monitoring of air and water pollution, and for monitoring and optimizing the use of energy and natural resource.

To address the challenge of energy efficiency and affordability, the European Union should pay attention and effort in reconstruction of public and private buildings. It also could be a good method to increase the local job's opportunities.

The Commission will enforce the legislation related to the energy performance of buildings and will review the Construction Products Regulation to ensure that the design of new and renovated buildings at all stages is in line with the needs of the circular economy. Another task in this sector is to ensure that this Regulation lead to increased digitalization of the building stock.

Another important argument in this field is the transport. It accounts for a quarter of the EU's greenhouse gas emissions**,** and still growing, so, to achieve climate neutrality, a 90% reduction in transport emissions is needed by 2050.

A substantial part of inland freight carried today by road should shift onto rail and inland waterways. The Commission will propose measures to manage better and to increase the capacity of railways and inland waterways. Farther, it will also consider presenting a new proposal to revise the Combined Transport Directive to turn it into an effective tool to support multimodal freight operations.

The EU transport system and infrastructure will be made to support new sustainable mobility services that can reduce congestion and pollution, especially in urban areas.

Furthermore, the price of transport must reflect the impact it has on the environment and on health, so the Commission will analyze the As it is tax exemptions including for aviation and maritime fuels.

The EU should in parallel engage in production and deployment of sustainable alternative transport fuels.

Transport should become drastically less polluting, especially in cities, so more stringent air pollutant emissions standard for combustion vehicles must be proposed.

Regarding the food production, it still results in air, water and soil pollution, contributes to the loss of biodiversity and climate change, and consumes excessive amounts of natural resources, while an important part of food is wasted.

The Commission presented the 'Farm to Fork' Strategy that has the aim to formulate a more sustainable food policy.

The Commission's plans should lead to the use of sustainable practices, such as precision agriculture, organic farming, agro-ecology, agro-forestry and stricter animal welfare standards. These strategic plans will show an increased level of ambition to reduce significantly the use and risk of chemical pesticides and the use of fertilizers and antibiotics.

The Farm to Fork Strategy will also contribute to achieving a circular economy. It will aim to reduce the environmental impact of the food processing and retail sectors by taking action on transport, storage, packaging and food waste.

Lastly, this Strategy will stimulate sustainable food consumption and promote affordable healthy food for all. The Commission will explore new ways to give consumers better information, including by digital means, on details such as where the food comes from, its nutritional value, and its environmental footprint.

Another point about which the agreement pays attention is the health of the ecosystem. Ecosystems provide essential services such as food, fresh water and clean air, and shelter. Moreover, they mitigate natural disasters, pests and diseases and help regulate the climate. The EU and its global partners need to halt biodiversity loss, caused by changes in how land and sea are used, direct exploitation of natural resources, and climate change.

The biodiversity strategy will identify specific measures to meet these objectives. The Commission will identify the measures that would help to improve and restore damaged ecosystems to good ecological status. The biodiversity strategy will also include proposals to green European cities and increase biodiversity in urban spaces. All EU policies should contribute to preserving and restoring Europe's natural capital.

As a result of climate change, forest ecosystems are under increasing pressure. The EU's forested area needs to improve, both in quality and quantity, for the EU to reach climate neutrality and a healthy environment. In this direction, the Commission will prepare a new EU forest strategy covering the whole forest cycle to promote the many services that forests provide.

It will have as its key objective's effective afforestation, and forest preservation and restoration in Europe, to help to increase the absorption of CO2, reduce the incidence and extent of forest fires, and promote the bio-economy, respecting the ecological principles favorable to biodiversity.

A sustainable 'blue economy' will have to play a central role in alleviating the multiple demands on the EU's land resources and tackling climate change, indeed the role of oceans in mitigating and adapting to climate change is increasingly recognized. The idea is to improve the use of aquatic and marine resources, promoting the production and use of new sources of protein that can relieve pressure on agricultural land. The Commission will find solutions to manage maritime space more sustainably and to help tap into the growing potential of offshore renewable energy.

One of the ways to reach the Green Deal objective is to create a toxic-free environment. To protect Europe's citizens and ecosystems, the EU and Member States will need to look more systematically at all policies and regulations, so the Commission will adopt in 2021 a zero-pollution action plan for air, water and soil.

It is essential that the natural functions of ground and surface water must be restored, in order to preserve and restore biodiversity in lakes, rivers, wetlands and estuaries and to prevent and limit damage from floods. In addition, the Commission wants to propose measures to solve the problem of pollution from urban runoff and from new or particularly harmful sources, such as micro plastics and chemicals, including pharmaceuticals. It is important also to study and address the combined effects of different pollutants.

The Commission will propose to improve actions on monitoring, modelling and air quality plans to help local authorities achieve cleaner air. Farther, it will propose to revise air quality standards to align them more closely with the World Health Organization recommendations.

The chemicals strategy for sustainability, proposed to achieve a clean and toxic free environment, will help to protect citizens and the environment against hazardous chemicals and encourage innovation for the development of safe and sustainable alternatives. All parties should work together to combine better health and environmental protection and increased global competitiveness. This can be achieved by simplifying and strengthening the legal framework.

Achieving the ambition set by the European Green Deal requires significant investments. Calculations show that achieving the As it is 2030 climate and energy targets will require €260 billion of additional annual investment, that will need to be sustained over time. The Commission will present a Sustainable Europe Investment Plan to help meet the additional funding needs.

At least 30% of the InvestEU fund will contribute to fighting climate change.

The Commission will also work with the European Investment Bank (EIB) Group, national promotional banks and institutions and with other international financial institutions. The EIB set itself the target of doubling its climate target from 25% to 50% by 2025, thus becoming Europe's climate bank.

The Commission will propose a Just Transition Mechanism, to leave no one behind, in fact the most vulnerable people are the most exposed to the harmful effects of climate change and environmental degradation. The transition can only succeed if it is conducted in a fair and inclusive way.

At the same time, managing the transition will lead to significant structural changes in business models, skill requirements and relative prices. Not all Member States, regions and cities start the transition from the same point or have the same capacity to respond. These challenges require a strong policy response at all levels. This is the reason why the Commission will work with the Member States and regions to help them put in place territorial transition plans.

To find a solution for the long-term financing needs of the transition, the Commission will continue to explore, additional sources that could be mobilized and innovative ways to do so. The Commission will present a renewed sustainable finance strategy that will focus on a number of actions.

First, the strategy will strengthen the foundations for sustainable investment. This means that the European Parliament will adopt the taxonomy for classifying environmentally sustainable activities. As many companies still focus too much on short-term financial performance compared to their long-term development, sustainability should be further embedded into the corporate governance framework. Farther, companies and financial institutions will need to increase their disclosure on climate and environmental data so that investors could be fully informed about the sustainability of their investments.

Second, increased opportunities will be provided for investors and companies by making it easier for them to identify sustainable investments.

Third, climate and environmental risks will be managed and integrated into the financial system. This means better integrating such risks into the EU prudential framework. It will be an opportunity to examine how our financial system can help to increase resilience to climate and environmental risks.

The Commission will work with the Member States to screen and benchmark green budgeting practices. The review of the European economic governance framework will include a reference to green public investment in the context of the quality of public finance. This will open a debate on how to improve EU fiscal governance, that will form the basis for any possible future steps.

Evaluations are underway of the relevant State aid guidelines including the environmental and energy State aid guidelines. The guidelines will be revised by 2021 to develop the policy objectives of the European Green Deal.

New technologies and sustainable solutions are required to achieve the objectives of the European Green Deal. Horizon Europe will play a fundamental role in enhancement national public and private investments. Part of the budget of Horizon Europe will fund new relevant solutions for climate, indeed the available tools will help to support the research and innovation efforts needed. Four 'Green Deal Missions' will help deliver large-scale changes. Partnerships with industry and Member States will support research and innovation on transport, including batteries, clean hydrogen, low-carbon steel making, circular bio-based sectors and the built environment.

Giving importance to experimentation, and working across sectors and disciplines, the EU's research and innovation agenda will take the systemic approach needed to achieve the aims of the Green Deal. This program will also involve local communities in working to obtain a more sustainable future.

An important activity is the one related to the teaching and sensitization of the citizens. The first part of the population that can reach a good awareness for the future are the students.

Schools, training institutions and universities are fundamental to engage with pupils, parents, and the wider community. The Commission will provide support materials and facilitate the exchange of good practices in EU networks of teacher-training programs.

The Commission has been working to provide financial resources in order to make school buildings and operations more sustainable.

It is necessary that a global response is given to address he global challenges of climate change and environmental degradation. This is the reason why the EU will continue to promote and implement ambitious environment, climate and energy policies not only in Europe, but across the world. The Commission will work closely with Member States to promote more sustainable development, including the United Nations, the G7, G20, the World Trade Organization and other international organization.

The Paris Agreement will remain the indispensable multilateral framework for tackling climate change. Since the EU's global emissions are falling, increased efforts by other regions will be critical for addressing the global climate challenge. There is the need to engage more intensely with all partners to increase the effort and help them to revise and implement their contributions at national and global level.

Furthermore, the EU will increase the engagement with partner countries and establish innovative forms of engagement. The EU is also working with global partners to develop international carbon markets as a key tool to create economic incentives for climate action.

The ecological transition can be fully effective only if the EU's all the Members and the neighborhood also takes effective action. In this direction, the Western Balkans will work for a green future and there is an agreement with Africa, in order to make climate and environmental issues key strands in relations between the two continents.

In particular, the Africa-Europe Alliance for sustainable investment and jobs will seek to unlock Africa's potential to make rapid progress towards a green and circular economy including sustainable energy and food systems and smart cities. It is fundamental to close the energy access gap between the Europe and the Africa while delivering the required reduction in CO_2. Farther, the EU will launch a "NaturAfrica" initiative in order to address biodiversity loss: the idea is to create a network of protected areas to protect wildlife and offer opportunities in green sectors for local populations.

More generally, the EU will use its diplomatic and financial tools to guarantee green alliances with Africa and other partner countries and regions, particularly in Latin America, the Caribbean, Asia and the Pacific.

The EU should also reinforce As it is alliances and engage with countries on climate and environment issues.

The ecological transition will reshape geopolitics, including global economic, trade and security interests. The EU wants to work with all partners to increase climate and environmental resilience and to reach the Green Deal objective. Climate policy implications should become an integral part of the EU's thinking and action on external issues, including in the context of the Common Security and Defense Policy.

Trade policy must support the EU's ecological transition, to engage with partners on climate and environmental action. The Commission has also been increased efforts to implement the sustainable development commitments of EU trade agreements and will propose to make the respect of the Paris agreement an essential element for all future comprehensive trade agreements. The EU's trade policy must facilitate trade and investment in green goods and services and promotes climate-friendly public procurement. It can help address harmful practices such as illegal logging, enhance regulatory cooperation promote EU standards and remove non-tariff barriers in the renewable energy sector. All chemicals, materials, food and other products that are placed on the European market must fully comply with relevant EU regulations and standards. The partners have to design similar rules that are as ambitious as the EU's rules, to facilitate commercial activities and improve environment protection and climate mitigation.

The Commission wants to work on new standards for sustainable growth and to facilitate trade in environmental goods and services and in supporting open and attractive EU and global markets for sustainable products. It has the intention to collaborate with global partners to ensure the EU's resource security and reliable access to strategic raw materials.

To mobilize international investors, the EU will increase the efforts to set up a financial system that supports global sustainable growth. The EU will build on the International Platform on Sustainable Finance that was recently established to coordinate efforts on environmentally sustainable finance initiatives.

The involvement and commitment of the public and of all stakeholders is fundamental to the success of the Green Deal.

The Climate Pact will build on the Commission's on-going series of citizens' dialogues and citizens' assemblies across the EU, and the role of social dialogue committees. The European Urban Initiative will be proposed to provide assistance to cities to help them make best use of opportunities to develop sustainable urban development strategies. Assistance will be provided to cities and regions that want to commit to ambitious commitments on environmental, climate and energy issues. It will remain an essential platform to share good practices on how to implement change locally.

To conclude, it is important to remember that the European Commission with the Green Deal wants to become climate neutral by 2030. So, it calls on all the other institutions, bodies and agencies of the EU to work with it and come forward with similar ambitious measures.

In addition to the Climate Pact, the Commission and Member States will work to ensure that the national energy plans and the strategic national plans to implement the common agricultural policy will be followed and respected.

European funds will help rural areas to exploit sustainable opportunities in the circular and bio-economy. Trough the European Green Deal, the Commission will pay particular attention to the role of outermost regions, taking into account their vulnerability to climate change and the renewable energy sources. The Commission will continue the work on the Clean Energy for EU Islands Initiative to develop a framework to accelerate the clean energy transition on all EU islands.

The Commission will present a new action program to complement the European Green Deal with a new monitoring mechanism to ensure that Europe continue in a good way to reach its aim.

It will also monitor the progress in order to notice if the agreement is approaching the goal in a satisfaction way.

The Commission will also promote action by the EU, its Member States and the international community to step up efforts against environmental crime.

The bioeconomy comprises those parts of economy that use renewable biological resources from land and sea, such as crops, forests, fish, animals and micro-organisms, to produce food, materials and energy.

Thus, it includes primary production and industrial sectors using and processing biological resources, for instance the food, pulp and paper industries and parts of the chemical, biotechnological and energy industries. These elements are at the heart of a sustainable development that delivers strong communities by creating a flourishing economy that respects the environment. This is done by reducing dependence on fossil fuels and finite materials without overexploiting renewable resources, preventing biodiversity loss and land use change.

A waste management system that fully considers the potential of agricultural, forestry, and municipal (biogenic) wastes and residuals is essential to enable the circular economy.

The Italian Bioeconomy means integrating the sustainable production of renewable biological resources and converting these resources and waste streams into value added products such as food, feed, bio-based

products and bioenergy.

This strategy aims to provide a shared vision of the economic, social and environmental opportunities and

challenges associated with the creation of an Italian Bioeconomy based on longer, more sustainable and

locally routed value chains. It also represents a significant opportunity for Italy to enhance its competitiveness and role in promoting sustainable growth in Europe and the Mediterranean area.

The Bioeconomy strategy will be part of the implementation processes of the National Smart Specialization Strategy, focusing in particular on the areas of "Health, Food and Life Quality" and "Sustainable and Smart Industry, Energy and Environment". It will be implemented in synergy with the principles of the Italian National Strategy for the Sustainable Development for ensuring environmental sustainability and economic growth reconciliation.

2.1.1 International context

More than 40 nations worldwide are proposing actions and strategies to boost their bioeconomy.

In Europe, the bioeconomy is already worth EUR 2 trillion in annual turnover and accounts for more than 20 million jobs (Strategy for "Innovating for Sustainable Growth: A Bioeconomy for Europe", EC, 2012); it is expected to grow further, reaching a market value of EUR 40 billion and creating 90,000 new jobs by 2020 ("Growing the European bioeconomy" Third Bioeconomy Stakeholders' Conference, Turin, EC, 2014). Furthermore, the food industry is the largest in the EU and there is still potential for growth, with new businesses and industries emerging in both traditional and novel food and non-food sectors.

The EU Bioeconomy strategy, which is under revision, will unlock the potential of available bio-resources in the various bioeconomy and blue economy sectors in a sustainable and socially responsible way. The European Circular Economy Package will stimulate Europe's transition towards a circular economy, boosting global competitiveness, fostering sustainable economic growth and generating new jobs. It establishes a concrete and ambitious action program, including measures that will contribute to "closing the loop" of product lifecycles through greater recycling and reuse, bringing benefits for both the environment and the economy.

The Mediterranean area deserves a specific focus: it is characterized by high levels of hydric stress that, together with climate change, have a negative impact on agriculture. This has a negative influence on standards of living, with social and economic stress acting as a major cause of instability, which in turn contributes to migration, both internally, from rural to urban territories, and externally, in particular towards Europe. For food security reasons, a sustainable management of water provision and use and of food systems is required to provide clean water and affordable food for the region's inhabitants.

PRIMA is an initiative launched and coordinated by Italy, aimed to make water provision and food systems more efficient, cost-effective and sustainable, to solve bigger problems relating to nutrition, health and social wellbeing, and ultimately to address mass migration trends.

The BLUEMED Initiative together with the EUSAIR and WEST MED regional initiatives, aims to create new 'blue' jobs and sustainable economic growth in the marine and maritime sectors in the area.

The Mediterranean Sea is a basin with unique bio-geo-physical characteristics that contributes significantly to the EU economy by supporting 30% of global sea-borne trade. However, it is facing serious environmental challenges related to climate change, growing maritime traffic and pollution, the overexploitation of fish stocks, etc.

At the same time, local biodiversity and deep-sea resources, tourism, renewable energy production, marine aquaculture etc. are major local opportunities for ‘blue’ growth and the creation of jobs in areas that are As it isly underexploited.

The bioeconomy could therefore contribute greatly to the regeneration, the sustainable development and the political stability of the area and, in turn, to a reduction in the migration phenomenon.

2.1.2 National context

In Italy the entire Bioeconomy sector (including agriculture, forestry, fisheries, food and beverages production, paper, pulp and tobacco industries, textiles from natural fibers, leather, bio-pharmaceuticals, green chemistry, biochemicals and bioenergy) accounted for a total turnover of EUR 254 billion in 2015, and around 1.6 million employees.

Estimates of the Bioeconomy as a whole are based on National Accounts for most of the sectors involved, while it is worth noting that biochemicals are not easily accounted for, since (with the exception of biofuels) they are not included in the As it is statistical framework.

The science for policy report conducted in 2019 by the European Commission, (EuropeanCommission, Insights into the European market for bio-based chemicals, 2019), was published in order to provide evidence-based scientific support to the European policymaking process. The scope of the study is the EU market, so it includes certain bio-based chemicals that are produced in other countries and imported onto the EU market.

The most common issue observed for the biobased market in all categories is the higher cost of producing bio-based products. This problem is less pronounced in some product categories, such as cosmetics and personal care products, where there is more willingness among consumers to pay a premium.

For this reason, it is often argued that fossil-based products are priced too cheaply, since they do not internalize the costs of their environmental impact. A fossil carbon tax is seen by experts as a way of creating a level playing field for all products, promoting those that are more sustainable without prioritizing specific products.

Indeed, a better understanding of the market should help in developing strategies to increase consumer interest in more sustainable, bio-based products (which is also one of the key ideas behind the bioeconomy strategy).

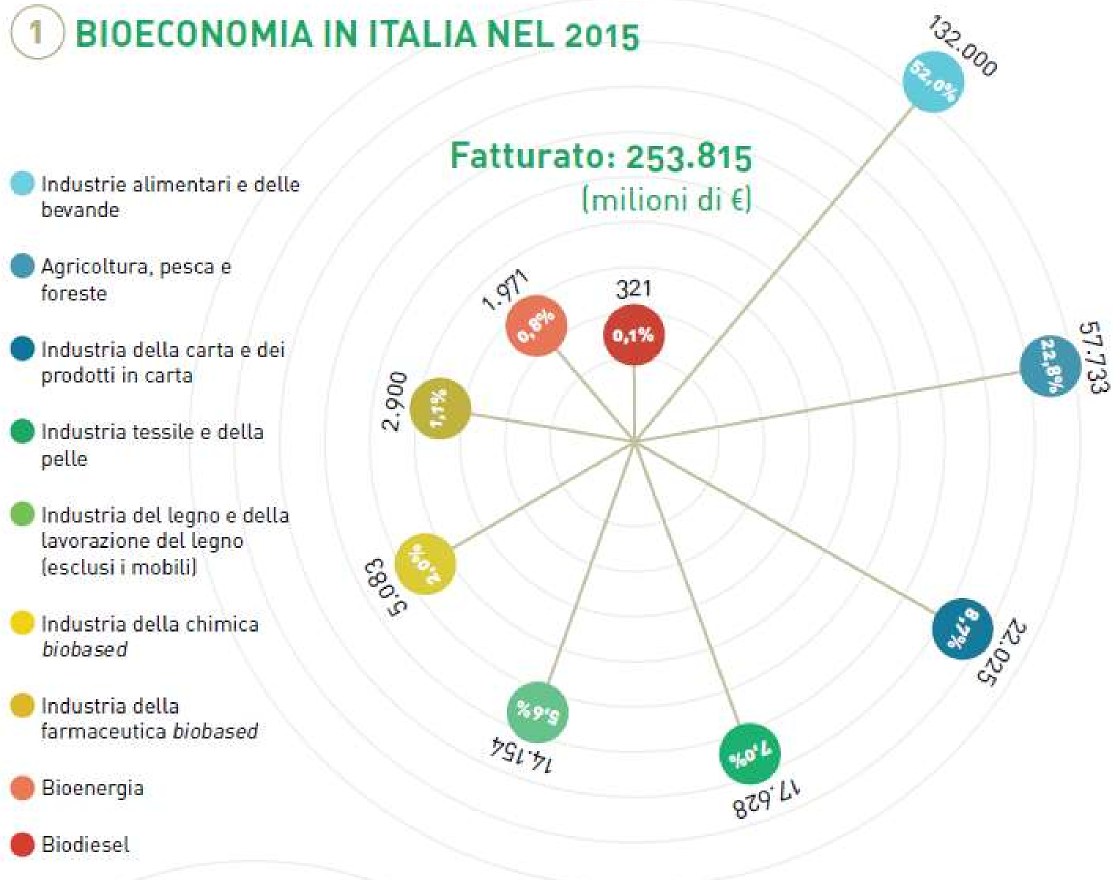


Figure: 2 Bioeconomy in Italy

The availability of local competitive biological feedstocks is an important requirement for bioeconomy industries.

Italian regions, at an individual level, have a high level of agricultural and natural landscape specificity linked to the biodiversity of cultivated plants, animals, related ecosystem services and their diverse cultural heritage.

The regions see great potential in the development of the bio-based industry. The potential is largely related firstly to the exploitation of food chain wastes, with the aim of reducing the environmental impact, and secondly to the development of industrial crops in marginal agricultural areas that do not compete with food production. Some territories host important projects for the reconversion of de-industrialized sites into biorefineries for the production of bioproducts and biochemicals from local renewable sources, leading to positive impacts on employment, environment, product profitability and integration with

regional agriculture systems.

The Italian regions are willing to establish a distributed bioeconomy system built on multiple concepts, by building cross territorial links.

From the environmental viewpoint, the bioeconomy raises both opportunities and challenges.

The opportunities are linked to the gradual shift in production processes from non-renewable to renewable resources in order to limit the environmental pressure on ecosystems. Higher value is placed instead on their conservation as, they can provide important services for the economy, - including the strategic importance of finding nature-based solutions to cope with climate change and hydrological risks. Furthermore, the bioeconomy implies the possibility of decreasing dependence on resources not widely available in Italy.

Producing more from renewables make the problem of waste management easier as these sources are more easily reabsorbed by the nature receptors.
However, the bioeconomy can also lead to a number of challenges. One necessary condition is the economic, environmental and social sustainability of products and processes.
To meet the challenge, a transition must take place from a social point of view, stimulating social awareness and dialogue, as well as better supporting innovation in social structures leading to more conscious behaviour.
Greater knowledge of what is being consumed - especially food products and processes - would lead to
improvements in health conditions and lifestyle, stimulating a demand pull on sustainable innovation by companies. For this reason, it is crucial to further develop ecolabeling.

Many EU regulations and National strategic plants are linked to the bioeconomy, to give opportunities to improve action plans and specific measures for the bioeconomy.
The Italian Bioeconomy Strategy is part of the implementation process of the National Smart Specialization Strategy (SNSI). The Smart Specialization Strategy aims to identify priorities for investment in research, development and innovation that complement the resources and productive capacity of territories to build comparative advantage and sustainable growth path in the medium and long term. (BIT, Bioeconomia in Italia, 2020).
In December 2015, the EU adopted the Circular Economy Package "Closing the loop - An EU action plan for the Circular Economy" defining ambitious targets and a timeline to reduce the pressure on natural resources and boost the market for secondary raw materials. The Circular Economy package introduced specific economic instruments and promoted industrial symbiosis, incentivizing other mechanisms to reduce future waste generation under a circular bioeconomy philosophy.
The aim of the Marine Strategy Framework Directive D.lgs n190/2010 is to achieve Good Environmental Status (GES) for the EU's marine waters by 2020 and to protect the resource base upon which marine- related economic and social activities depend. The Marine Strategy is the principal instrument to establish and promote an approach founded on sustainable development based on preserving and protecting marine biodiversity and finding solutions to As it is problems such as marine litter, pollution from contaminants, and the sustainability of fisheries.
Climate change strategy is a big challenge for the medium- and long-term future. In the meantime, it requires the transformation of the energy system in order to reduce GHG emissions into the atmosphere by increasing the share of clean and renewable energy, as well as the reduction of the energy intensity of the overall system.
On the other hand, it implies increasing the resilience and adaptive capacity to cope with climate change impacts.
The EU legislative framework for the first aspect (mitigation) is given by the Climate and Energy Package by 2030, that strengthens the Paris agreement which entered into force in November 2016, as well as the 2050 Low-Carbon Economy. With regards to the second pillar (adaptation), in 2013 the EU adopted the European Adaptation Strategy that, among other objectives, promotes adaptation measures in key vulnerable sectors.
Now consider the Italian legislation.
The Environmental Annex to the Stability Law 2014 ≪Measures for promoting the green economy and limiting the excessive use of natural resources≫18 defines the important milestones for future Italian environmental strategies. The main focus is on the green economy and the circular economy, in particular through: Green Public Procurement (GPP) with environmental minimum criteria for new purchases by the public sector defined also by Labelling and Certifications (Emas, Ecolabel, Environmental Footprints, Made Green in Italy); incentives for the purchase of post-consumption

materials, the management of specific waste fractions (including composting) and incentives to increase the share of collected waste; creation of a Natural Capital Committee, that can provide data on natural biomass consumption and monitor the impact of public policies on natural resources and ecosystem services conservation; the establishment of a system of Payment for Ecosystem and Environmental Services and the production of a catalogue on Environmental Harmful and beneficial Subsidies.

In this context and as part of the Lead Market initiative, introduced in 2006 to promote the spread of bio-based products on the market, the European Commission has entrusted the European Committee for Standardization (CEN) with the mandate to produce a series of common standardized rules. These include M/429 for the development of a standardization program for bio-based products and M/430 for biopolymers and lubricants.

One the most important aspects of the Environmental Annex is the update to the Sustainable Development

National Strategy, built upon the 2030 Agenda for Sustainable Development adopted by the UN in September 2015. Among the 17 Sustainable Development Goals (SDGs) of the UN agenda, some of them are strictly related to the bioeconomy.

The Green Public Procurement (GPP) National Action Plan (NAP) document outlines the strategy for the diffusion of GPP in Italy, the commodity categories, the reference environmental targets to be attained and the general methodological aspects.

Based upon the Code of Public Contracts, the GPP NAP aims to spread and implement nationwide the adoption of sustainable purchases in Italy.

The above mentioned Environmental Annex established, from 2016, the compulsory commitment for the

Italian Public Administration to the Code. Italy thus became the first country in the world to adopt such an obligation.

The new Code of Public Contracts22 has further reinforced the statement by defining more specifically the Environmental Minimum Criteria (EMC) for the eligibility of applicants to participate in public tenders.

Since 2011, a number of Decrees from the Ministry of Environment, Land and Sea have been issued to define EMC by commodity category.

With reference to waste, legislative decree 152/2006 sets the same 65% target on municipal waste as the EU within the Circular Economy package. The “National Program for Waste Reduction” also considers the target of 50% share of “green purchases” by the public sector, and defines specific measures for biodegradable waste, valorization of agro-industry byproducts and minimizing food waste. Specifically, regarding composting, the recent Decree of Ministries Council Presidency on 7 March 2016 defines the requirements for the Italian regions in terms of organic waste to be treated through composting.

The updates of the “National Energy Strategy” and the “National Plan for Climate and Energy” will provide the framework within which the different sources of energy will develop in order to achieve the targets on GHG emission reduction and renewable energy share. In addition, Italy has adopted a “National Adaptation

Strategy” and is putting into place the “National Adaptation Plan”. The bioeconomy can play a significant role in both senses, in terms of providing clean energy sources and ensuring a long-term conservation of natural resources and ecological systems, also through nature-based solutions.

The National Biodiversity Strategy (NBS), adopted in 2010, aims to integrate biodiversity conservation targets and the sustainable use of natural resources within sectoral policies, while the National ratification of Nagoya Protocol, on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization, is still in progress (although in 2014 the EU

Regulation 511/2014 “on compliance measures for users of the Nagoya Protocol Arising from their Utilisation in the Union“ entered in force at EU level).
The National Marine Strategy D.lgs n. 190/2010 was enacted to transpose the Marine Strategy Framework Directive at national level and with the aim of achieving the Good Environmental Status for the Italian marine waters within a sustainable development perspective.
In addition, in order to implement and make more effective the measures already provided for, by the As it is legislation to protect the environment, the ministerial decree of 03/26/2020 (MinisteroDell'Ambiente, 26/03/2020) proposes to pay particular attention to the following areas:

a) awareness raising measures for the promotion of the circular bioeconomy
b) measures aimed to increase the market penetration of bio-based products
c) incentives for the adoption of initiatives aimed at reducing food-waste and enhancing waste
d) Information campaigns on sustainable transition issues

Many programs at EU, national, regional and local level can fund and contribute to regulating bioeconomy actions. The monitoring strategy aims to relate the main sectors of the bioeconomy, to create longer and more sustainable value chains, thus offering Italy the opportunity to increase its competitiveness in promoting sustainable growth in Europe and in the Mediterranean area.
An Agenda for research and innovation is defined and some support measures are proposed to overcome possible obstacles and create the conditions for the developments of the bioeconomy. The general objective is to increase the As it is turnover and employment of the Italian bioeconomy by 2030.
The Italian bioeconomy has an important growth potential. Since the bioeconomy affects wide and diversified production chains, strong integrations between public and private operators, between different sectors and disciplines, starting from primary agricultural production up to advanced manufacturing, become necessary.
Furthermore, interconnecting the sectors of the bioeconomy means facilitating cooperation between those involved in education, research, innovation, communication and consumers, to create a socio-economic and technological context capable to guarantee the effective application and implementation of interdisciplinary innovation.
To measure the performance of the bioeconomy, indicators are needed. The bioeconomy includes a wide type and number of products, raw materials, intermediate goods and technologies. Furthermore, there is still a high rate of uncertainty about the components of its value chain. Much of its future developments will emerge from the convergence and transformation of markets and industries and the creation of new market phenomena for which statistics and indicators are not available. However, it is possible to relate the general objective of the Strategy with some of the key performance indicators (KPIs) developed at the European Union level for an initial monitoring of developments in the Bioeconomy, on the supply and demand side. These indicators are based on Eurostat and national data and allow the development of benchmarking analysis.
The indicators were selected according to the availability of data. There is a general problem of lack of data and lack of homogeneity in their quality, therefore, even the construction of monitoring tools remains subjected to an evolutionary process. Another set of indicators is constructed with reference to the sustainability dimension of the bioeconomy, in order to improve social dialogue on these issues. The sustainability indicators also refer to EU initiatives for the evaluation and monitoring of European Bioeconomy.
Some indicators that define, for example, the availability of biomass are:

- Production of agricultural biomass [kg per capita] – import of agricultural biomass
- Production of blue biomass [kg per capita] – import of blue biomass
- Production of forest biomass [kg per capita] – import of forest biomass
- Production of waste biomass (including OFMSW) – import of waste biomass

As already said several times, the bioeconomy is based on the principle of reducing dependence on non-renewable fossil fuels for all sectors of raw materials. In this scenario, plastic is at the center of attention, both for the environmental implications of packaging and for the real possibility, today, of developing the biorefinery supply chain on it. Research focuses on the development of chemical and physico-chemical technologies for facilitate the recovery and reuse of plastic. Another topic of great attention is the development of biodegradable and compostable plastics. The latter can be managed at the end of its life as organic material and therefore can follow the compostable chain of the waste fraction.

This thesis work fits into this context, with the aim to study the production processes of bioplastics from urban wastewater treatment plants and the consequent feasibility in three existing plants.

2.2 Recovery of VFA and PHA in wastewater plants

2.2.1 Process schemes

The goal of this chapter is to analyse in detail the polyhydroxyalkanoates (PHA) production process, considering the different process steps, operating parameters, yields and, finally, the feasibility in the real plants. Indeed, in the last years, the search for new materials that replace fossil fuel-based plastics has been focused on biopolymers with similar physicochemical properties to fossil fuel-based plastics (Rodriguez-Perez, 2017).
One of these materials is represented by PHAs, that are a class of renewable, biodegradable, and bio-based polymers, in the form of polyesters (Kourmentza, 2017).
Since the main carbon source for PHA synthesis and bacteria growing is the raw material, the in-depth study of this material is important, not only because it can replace fossil-based plastics, but also because it allows to consider a new way to manage the wastes, which are consequently considered a potential resource to be recovered, rather than only a problem to solve. This approach is crucial, because it exploits the potential to use the waste as a raw material for production of value-added chemical, reducing as such also the amount of waste. (Lee, 2013)
Most of the biotech products that have been successfully established, such as antibiotics, organic acids, technical enzymes, etc. are extracellular products. In contrast, PHAs are intracellularly produced. This has several severe consequences, and it causes limitations regarding not only the fermentative part of the production process but also the downstream processes to obtain the polyesters in a purified state (Madkour, 2020).
One consequence is the need of high cell density cultivations because the availability of space limits the amount of PHA that can be produced within the cells.
Much of the research on mixed microbial culture (MMC) PHA production has been performed at laboratory scale in three process elements as follows: (1) acidogenic fermentation to obtain a volatile fatty acid (VFA)- rich stream, (2) a dedicated biomass production yielding MMCs enriched with PHA-storing potential, and (3) a PHA accumulation step (Valentino, 2016).
The MMC three-step process presented in fig. 2 could be achieved through a variety of different bioprocess configurations. These variations depend on the type of wastewaters, flows and concentrations, effluent water quality demands, and the already existing infrastructure.

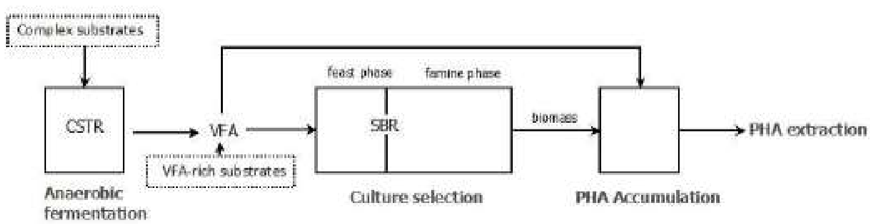


Figure: 3 Process scheme for VFA recovery and PHA production (Kourmetza, 2017)

The most important step is the step of PHA accumulation (third one) and this process element requires two essential raw ingredients:
1) feedstock rich in readily biodegradable organic matter. This feedstock is most preferably dominated by volatile fatty acids (VFA) and the VFA content may be maximized by an acidogenic fermentation of the raw feedstock (first step);
2) MMC biomass with significant PHA accumulation potential. This PHA-accumulating MMC can be enriched within and produced through a dedicated organic carbon removal bioprocess such as activated sludge (second step) whose feedstock may or may not have to be the same as used for process element 3.

The first step, the one in which the readily biodegradable organic matter is produced, occurs usually in a CSTR anaerobic fermenter, characterized by acidogenic PH and
In the second step, SBR reactors (sequential batch reactors) are used to select and enrich a microbial population with high PHA production capacity by applying transient conditions. In the last step, the culture from the SBR is subjected to conditions maximizing the PHA accumulation, from where cells are harvested for PHA extraction and purification when they reach maximum PHA content (Kourmentza, 2017).
A wide variety of solid and liquid wastes have been studied for VFA production.
Among them, sludge, food waste and organic fraction of municipal solid waste (OFMSW) are the three most investigated solid wastes while wastewaters generated from the agricultural, dairy, pulp and paper industries are the liquid wastes frequently utilized for VFA production. Besides these, mixtures of different types of wastes had also been explored to enhance the production of VFA. Primary sludge (PS) and waste activated sludge (WAS) generated from municipal wastewater treatment plant are frequently studied for VFA production because of the massive volumes generated from the widespread use of biological wastewater treatment (Lee, 2013).
Now, let's talk about the parameters influencing the PHA production.
The first is surely the waste carbon source. The main carbon source for PHA synthesis and bacteria growing is the raw material. Vegetal solid wastes, such as rice bran, chicory roots, potato peels, apple pomace, onion peels, animal farm waste, industrial waste, cheese way and olive oil effluent have been studied and represent most of the employed substrates. Other wastes are the one coming from the food: solid wastes such as coffee grounds and liquid waste such as used cooked oil. All industrial, not agro-alimentary wastes are generated by biodiesel manufacturing: crude glycerol.
Urban waste treatment plant wastes include carbon sources from both municipal solid and wastewater treatment plants: activated wastewater sludge, the organic fraction of municipal solid waste leachate, activated wastewater sludge combined with the organic fraction of municipal solid waste. Other feedstock considered by several authors is the synthetic substrate.
The physicochemical characteristics of the waste materials can make it necessary to include a previous preatment to adapt them to the requirements of the PHA production process. This phase might be used to increase the carbon sources available, dilute the concentration of organic matter, regulate the pH, control the temperature, sterilize waste material and/or remove suspended solids.
In order to increment the available carbon source, two technics have been used: chemical hydrolysis and anaerobic fermentation. Since this treatment is often used, it can be considered as the initial stage of the process, as mentioned in the previous pages.
Another parameter influencing the biopolymer production is the culture used for PHA production. The different cultures were classified as pure or mixed.
Mixed cultures for PHA production are more widespread because they are simpler and less costly than the process with pure cultures, since sterile conditions and infrastructure for an axenic bioprocess are not required.
The employment of wastewater activated sludge (WAS) from wastewater treatment plants was the most widespread, it could not be employed directly as culture for PHA production. It is necessary to fix nutrient and operation conditions for the selection of PHA accumulating cultures and their enrichment in the biomass.
Anyway, the use of WAS presents the additional advantage of integrating PHA production into the wastewater treatment processes.
This integration allows ensuring the continuous availability of mixed cultures, as well as organic matter from wastewater treatment plant effluent, which could be employed as substrates for PHA production.

Carbon source and total carbon load, nutrient concentration, C/N and C/P ratios, pH, and reactor environment are relevant parameters which influence the PHA production and the obtained compounds. In this sense, additional streams or chemicals were used in order to control them. (Rodriguez-Perez, 2017).

Since a great variety of expressions to report the production of PHA have been used in the literature, the comparison of the results is not easy. It is the reason why research studies should include some parameters such as PHA accumulation percentage in the biomass, PHA yield in relation to the added substrate and PHA yield in relation to the added waste.

2.2.2 VFA: process parameters and recovery yields

VFA are volatile fatty acids comprising groups of aliphatic monocarboxylic acids with chains of lengths up to six carbon atoms: formic, acetic, propionic, iso-butyric, n-butyric, isovaleric, n-valeric, iso- caproic, n-caproic acids (Raposo, 2013). They are generally produced in the acidogenic phase (ph <5) by degradation and decomposition of the complex organic substance.

The production of VFA can be aimed, in the purification sector, at the removal of nutrients (nitrogen and phosphorus) in conventional biological processes and in those of the EBPR type (enhanced biological phosphorus removal) as they favor the endocellular accumulation of polyphosphate (PO4), as well as being an additional carbon source for nitrogen denitrification.

Alternatively, the production of VFA is advantageous for the production of (bio) products and (bio) polymers, which have a higher market value than methane (CH4), alternative for the enhancement of the organic substance present in urban and industrial waste and/or in sewage sludge.

The production process of VFA biologically, using wastewater or organic waste of different origins, takes place in anaerobic conditions. There are two process phases, but usually they are carried out simultaneously within a single fully mixed fermentation reactor (Wee Shen Lee, 2014):

1. Hydrolysis phase, where complex organic compounds are broken down into simpler monomers;

2. Acidogenesis phase where the fermentation of monomers takes place and the production of VFAs including acetic acid, propionic acid and butyric acid.

Both require the presence of a complex consortium of anaerobic organisms such as Bacteriocides, Clostridia, Bifidoba cteria, Streptococci and Enterobacteriacei. It is specified that, for the recovery of VFA, a solid / liquid separation unit is required downstream of the fermentation reactor. Two methods are used for the anaerobic production of VFA from waste: 1) adherent growth biomass and 2) suspended growth biomass. The two modalities led to the development of different types of fermentation rector. The packed bed reactor works by using growth biomass adhered to ceramic filling materials, inserted into the reactor. This holds the biomass in the reactor, avoiding its runoff. However, the packed bed reactor has the disadvantage that it can become clogged due to the high concentrations of suspended solids in the matrix. To avoid clogging, a fluidized bed reactor was developed. In this reactor, the filling medium remains in suspension due to the upward flow. On the other hand, there are reactors with suspended growth biomasses including UASB reactors (upflow anaerobic sludge blanket) and CSTR (fully mixed reactors). When properly designed and managed, a CSTR is ideal for thoroughly mixing waste and microbial cultures in the presence of suspended solids in the waste, and therefore is the most commonly used type of reactor. In some cases, gravity separation is also used to separate and recirculate the biomass from the CSTR effluent. The packed bed, fluidized bed, UASB reactors and CSTR normally operate in continuous mode and therefore may not be suitable for reactions that require long retention times, such as fermentation (up to several days). For such slow reactions, some of these reactors can be converted into semi-continuous and/or sequential charge reactors with batch mode feeding (Wee Shen Lee, 2014).

The production yield of VFA represents the degradation and decomposition capacity of the complex organic substance into simple monomers and is expressed in gCOD (VFA) / gCOD (VSS). The productivity of the VFA, on the other hand, represents the performance of the specific process with respect to the time unit and the volume of the reactor, expressed in gVFA / L / d.

To deeply analyze the VFA production process, the data obtained from 164 case studies from the technical-scientific literature of the sector were studied and processed.

For each case study analyzed, the following categories of data were collected, where available:

• Process scale;
• Type and main characteristics of the fermentation reactor;
• Operating conditions of the process;
• Type and characteristics of the powered matrix;
• VFA yields and productions;
• Type and composition of the VFA produced;
• Economic value / market prices of the products obtained.

For the purposes of the analysis, the individual case studies were distinguished on the basis of the size of the reactor, defining laboratory-scale tests those carried out in a reactor with a volume of less than 5 liters and pilot-scale tests those with larger volumes, specifically higher than 80 Liters. Most of the case studies are applied on a laboratory scale (n° 142 analyzed) to which are added some examples on a pilot scale (n° 22 cases analyzed) (Table 1).

Table 1 Case studies and scale of application

SCALE	TRL	REACTOR SIZE	N° OF ANALYZED CASE STUDY
Laboratory	Up to 4	0.2 - 10 L	142
Pilot	Higher than 6	80-3000 L	22
Real*	Higher than 9	30000 L	1
TOTAL			165

* full-scale alkaline fermentation for the production of VFA, used as a carbon source for the removal of nutrients in the biological process A2O in the water line (He Liu, 2018).

Volatile fatty acids are short-chain acids composed mainly of C2-C6 carboxylic acids which, as said before, can be used in numerous applications (production of bioplastics, production of bio-energy and biological removal of nutrients from wastewater).

As it isly they are mainly produced chemically, however, the use of non-renewable petrochemicals as raw materials and the increase in the price of oil has renewed interest in their biological production.

As said before, usually waste is used to produce VFA, since the substrate to be used must be characterized by a high level of carbon source.

In general, it is not possible a priori to indicate which type of waste is most suitable for the production of VFA due to the different operating conditions adopted and the different performance evaluation criteria.

Substrate characterization is one of the most important factors influencing VFA production and product composition. The matrices commonly used for the fermentation process are rich in organic substance, and generally characterized by a COD (Chemical Oxygen Demand) content greater than

4000 mg/l. The ammonium content, on the other hand, should be lower than 5000 mg/l to avoid inhibition of VFA production, although this ammonium is an essential source of nitrogen for the growth of microorganisms (Wee Shen Lee, 2014).

Different types of waste, both liquid and solid, have been studied and tested. In particular, the case studies analyzed were divided according to the type of starting substrate (Figure 4 and Figure 5). The matrices identified are the following:

• industrial sludge,

• industrial waste,

• OFMSW,

• OFMSW combined with municipal sludge (OFMSW / organic waste + sewage sludge),

• wastewater,

• municipal sludge (sewage sludge).

The latter type of substrate has been further categorized into cellulosic sludge (cellulosic), primary and secondary mixed sludge (mix), primary sludge (primary) and secondary activated sludge (WAS).

As can be seen from Figure 4, on a laboratory scale, fermentation was mainly applied to purification sludge (53 cases), industrial matrices (37 cases) and OFMSW (31 cases). On a pilot scale (Figure 5) the most common application involves the use of OFMSW (10 cases) followed by sewage sludge (8 cases). It is therefore possible to deduce that the scale up is mainly to be focused on matrices such as sludge and OFMSW, while as regards the fermentation of industrial matrices, probably due to their variability in terms of chemical-physical characteristics and quantity of flows, it is As it isly in laboratory scale.

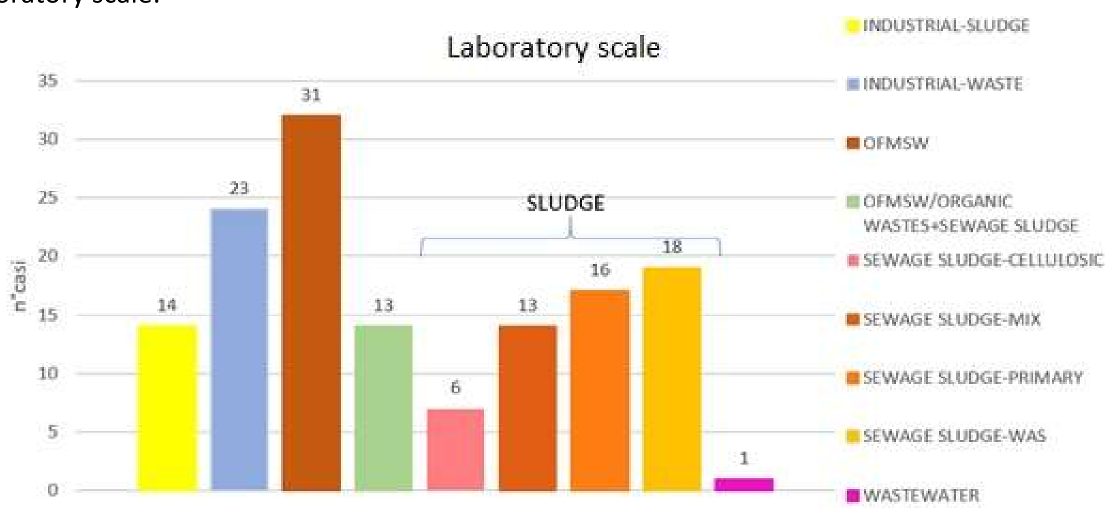


Figure: 4 Number of cases in laboratory scale, divided by matrix

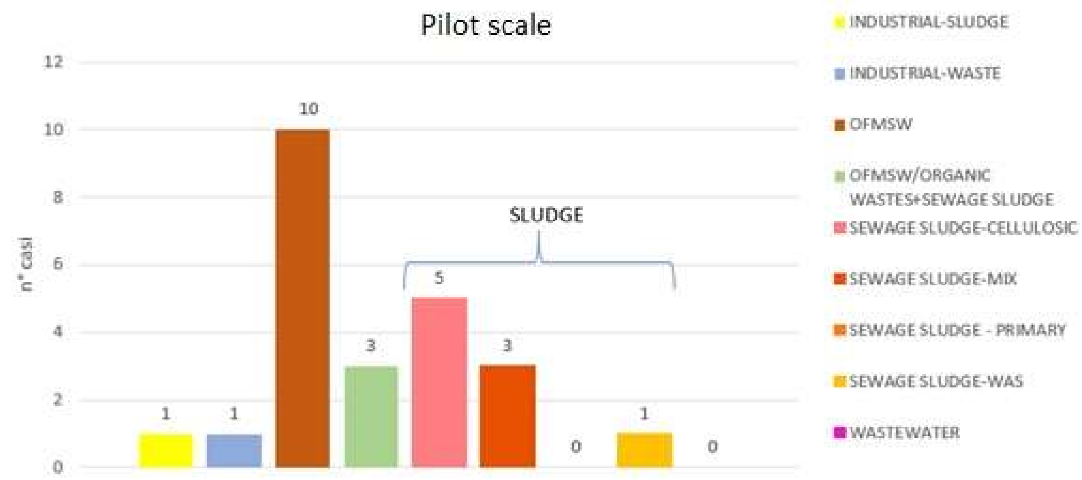


Figure: 5 Number of cases in pilot scale, divided by matrix

In the following paragraphs, the different matrices used for the production of VFA are described by macro-categories.

- <u>Industrial Sludge or Waste:</u>

The matrices associated with industrial processes and most commonly used for fermentation are wastewater generated by agriculture, the dairy, wood and paper industries (Wee Shen Lee, 2014). Several case studies (24) have used industrial waste, while 15 are the cases related to the industrial sludge.

In particular, whey permeate from the dairy industry and wastewater from paper mills were found to be suitable for this type of process, as they have a high, rapidly fermentable organic content (Wee Shen Lee, 2014) (Simon Bengtsson, 2008).

- <u>Organic Fraction Municipal Solid Waste (OFMSW):</u>

The use of urban waste for the production of VFA has been tested by several authors. This type of waste is produced in large quantities (22-54% of municipal waste on a European scale (Wee Shen Lee, 2014) and must necessarily undergo a treatment process in order to stabilize the material, reducing its environmental impact (Seong-Jin Lim, 2008).

Where there is no separate collection process of municipal solid waste, it may be necessary to apply specific treatments that allow to separate the organic fraction from other materials, such as glass, plastic and ferrous materials (Wee Shen Lee, 2014)

- <u>Combined matrices (OFMSW/organic wastes + sewage sludge)</u>

The combination of different types of waste has been tested in several case studies in order to maximize the production yields of VFA. Two main combinations of wastes emerged from the cases analyzed. First, the co-fermentation of municipal waste (sewage sludge) and OFMSW is considered. Furthermore, the combination of industrial wastewater rich in starch and sewage sludge has been tested by several authors (I. Maharaj, 2001) (A. Banerjee, 1999) highlighting how the production of VFA in the presence of industrial flows is higher than that in the presence of municipal sludge alone, respectively equal to 31 mgVFA/gVSS/d and 45 mgVFA/gVSS/d.

- <u>Sewage Sludge</u>

One of the most used matrices for the production of VFA is the sludge generated by municipal wastewater treatment plants. The VFAs produced by the anaerobic fermentation of sewage sludge can be used as an external carbon source in biological processes for the removal of nutrients or constitute the raw material necessary for the production of biodegradable plastics (PHA) (Su Jiang, 2007).

In the treatment plants, two main types of sludge are produced, with different biodegradable characteristics (HaiyanWu, 2009): 1) Primary sludge, characterized by a high portion of organic matter, consisting mainly of faeces, vegetables, fruit, fabrics and paper; 2) Activated sludge, containing small quantities of particulate matter that cannot be rapidly hydrolysed and biomass produced in the biological process.

Both these types of sludge, as well as their possible mixtures, if subjected to anaerobic fermentation processes can produce volatile fatty acids. Both primary sludge and activated sludge, in fact, are rich in organic matter, with COD ranges that vary between 14800 and 23000 mg/l. However, the soluble COD of the sludge is normally 10 to 100 times lower than the total COD. This condition slows down the production of VFA, with the hydrolysis process becoming limiting (Wee Shen Lee, 2014). Furthermore, some studies have tested the use of cellulosic sludge for the production of VFA. The cellulosic sludge is separated, for example, using a dynamic rotary filter that allows to obtain a concentrated and fiber-rich matrix of toilet paper (DaRos, 2020) and by controlling parameters such as temperature, pH and HRT (Hydraulic Retention Time) it is possible to maximize the production of VFA (DaRos, 2020) (Crutchik, 2018).

As said before, for the production of VFA, hydrolysis is often the limiting phase (Peng Zhanga, 2009). In order to increase the hydrolysis rate, it is possible to act in two distinct ways: 1) monitoring and control of some key parameters of the process, such as pH, temperature and HRT / SRT; 2) application of specific pre-treatments.

The production and composition of VFAs are influenced not only by the nature of the substrate and their organic content, but also by the pH, the process temperature, the hydraulic retention time of the process (HRT) and the fed organic load (OLR).

1. **pH**:

The pH parameter is one of the critical factors that controls the production of VFA in fermentation as it affects the metabolic activities of microorganisms. Most enzymes cannot tolerate hostile environments, both acidic (pH <3) and alkaline (pH> 12), optimal values, in fact, are generally between 5 and 11 (Wee Shen Lee, 2014).

From the analysis of the case studies (Figure 6) it is observed that in the case of industrial matrices tested in the laboratory, the pH does not present high variations, but always remains between a minimum of 6 and a maximum of 7. Furthermore, it is noted that, as regards the OFMSW, most of the case studies analyzed have a pH between 5 and 6 and in all cases the pH is controlled.

On the other hand, in the co-fermentation processes of OFMSW and municipal sludge, the pH is not controlled, and the ranges are between 5 and 6.In municipal sludge, a greater variability of pH is observed, also associated with a greater number of tests and laboratory tests performed. With the exception of the use of cellulosic sludge, in fact, most of the tests are carried out by imposing a pH control and testing values between a minimum of 3 and a maximum of 11. The variability with very alkaline pH is mainly associated with secondary sludge. Finally, as regards the tests carried out on a pilot scale, it is observed that in most cases (19 out of 24) the pH control was not imposed; however, the values do not show high variations as they are always included between a minimum of 4.5 and a maximum of 7.3.

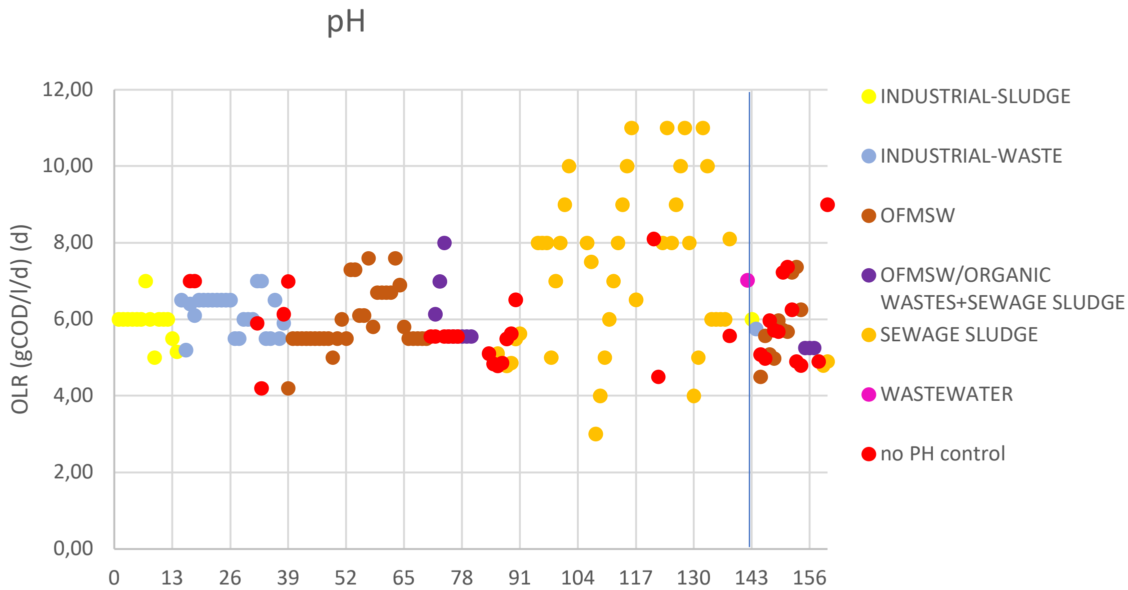


Figure: 6 Values of of pH in laboratory and pilot scale, divided by matrix

The following tables (Table 2 for the laboratory-scale case studies and Table 3 for the pilot-scale ones) show the average pH values and the relative standard deviations observed for each of the matrices identified. The number of cases with pH control is also specified for each category, equal to 85% of the total cases in the case of laboratory tests and equal to 29% for cases on a pilot scale.

Table 2 Average values and standard deviations of pH values in laboratory case studies

MATRIX (case studies in laboratory scale)	**pH**	**Total n° of case studies**	**Total n° of case studies with available pH value**	**Total n° of case studies with controlled pH value**
Industrial sludge	5.9±0.47	14	14	14
Industrial waste	6.17±0.51	24	24	20
OFMSW	5.95±0.79	32	32	31
OFMSW and sewage sludge	6.04±0.88	14	9	6
Cellulosic sewage sludge	5.12±0.36	7		1
Primary sewage slydge	7.08±2.36	17	12	16
Biological sewage sludge	7.94±2.27	19	16	18
Mixed sewage sludge	7.88±1.46	14	8	14

Wastewater	7	1	1	1
TOTAL		**142**	**116**	**121**
		100%	**82%**	**85%**

Table 3 Average values and standard deviations of pH values in pilot case studies

MATRIX (case studies in pilot scale)	**pH**	**Total n° of case studies**	**Total n° of case studies with available pH value**	**Total n° of case studies with controlled pH value**
Industrial sludge	6	1	1	1
Industrial waste	5.7	1	1	1
OFMSW	5.8±0.9	10	10	0
OFMSW and sewage sludge	5.2	3	3	3
Cellulosic sewage sludge	4.9±0.1	5		0
Biological sewage sludge	6	1	1	2
Mixed sewage sludge	6	3	3	0
TOTAL		**24**	**19**	**7**
		100%	**79%**	**29%**

2. **Temperature**

Temperature is an important operational factor for good VFA production as it influences the growth of microorganisms, the activity of enzymes and the rate of hydrolysis. Acidogenic fermentation can be carried out at different temperature ranges, based on the types of microorganisms selected:

• mesophilia, in which the temperature is between 35 °C and 45 °C;

• thermophilicity, in which the temperature is between 45 °C and 55 °C

• hyperthermophilia, with a temperature above 60 °C.

The mesophilic condition (35 °C) is considered the most favorable from an economic point of view even if it determines a production of VFA 10 times lower than the thermophilic condition (Jiang, 2013).

From the analysis of the different case studies, it is observed that as regards the laboratory scale cases (Figure 7), the fermentation of the OFMSW occurs mainly at temperatures between 35 and 40 °C. Industrial matrices works at constant temperatures, generally between 25 and 35 °C, with few cases at lower (20 °C) or higher (55 °C) temperatures. Greater variability is observed in the presence of municipal sludge, even if such matrices are combined with other types of waste. In fact, there are a large amount of cases at room temperature (20 °C), and several experiments with temperatures higher than 55-60 ° C.

Pilot scale cases operate at temperatures above 30 °C in most cases (90%), in particular between 30 and 50 °C, with an average value of 43 °C.

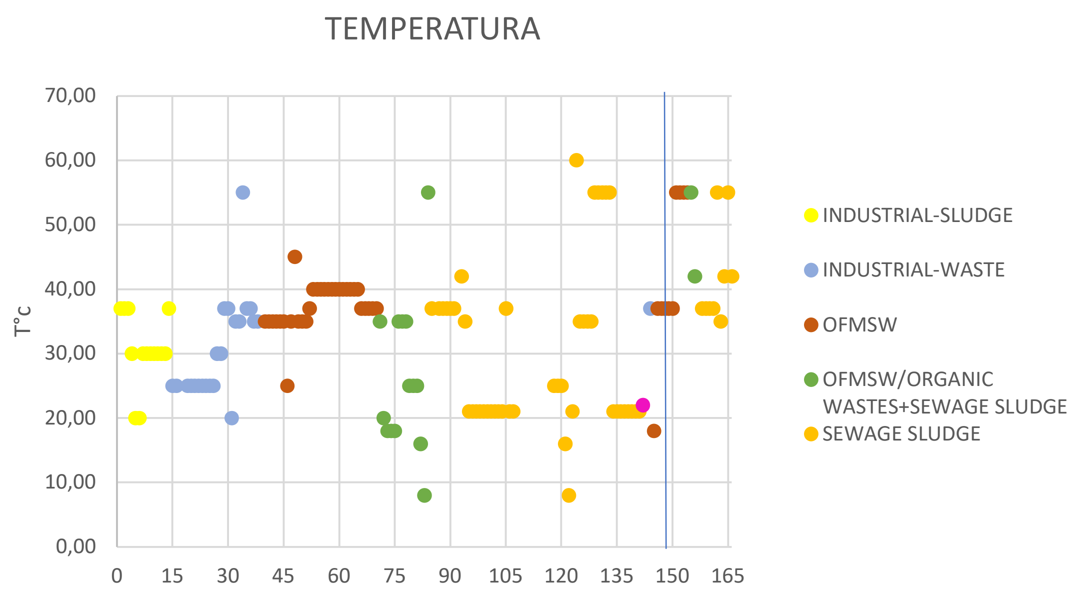


Figure: 7 Values of Temperature in Laboratory and pilot case studies, divided by matrix

The following tables show the average values and standard deviations associated with each matrix identified, both for case studies in laboratory scale (Table 4) and in pilot scale (Table 5). In both, the greatest number of applications is in the temperature range between 25 °C and 45 °C, with percentages of 49% and 71% respectively.

Table 4 Average values and standard deviations of Temperature values in Laboratory case studies

MATRIX (case studies in laboratory scale)	**T°C**	**Total n° of case studies**	**N° of case studies with T°C ≤25°C**	**N° of case studies with 25°C<T°C <45°C**	**N° of case studies with T°C ≥45°C**
Industrial sludge	31±5.4	14	2	12	0
Industrial waste	31±7.8	24	11	10	1
OFMSW	37.5±3.4	32	1	30	0
OFMSW and sewage sludge	24±8.5	14	11	4	0
Cellulosic sewage sludge	37	7	0	6	0
Primary sewage slydge	20±6.3	17	7	0	0
Biological sewage sludge	35±15	19	9	4	6
Mixed sewage sludge	25±7.6	14	10	3	0

Wastewater	22	1	1	0	0
TOTAL		**142**	**52**	**69**	**7**
		100%	**37%**	**49%**	**5%**

Table 5 Average values and standard deviations of Temperature values in pilot case studies

MATRIX (case studies in pilot scale)	T°C	Total n° of case studies	N° of case studies with T°C ≤25°C	N° of case studies with 25°C<T°C <45°C	N° of case studies with T°C ≥45°C
Industrial sludge	-	1	-	-	-
Industrial waste	37	1	0	1	0
OFMSW	42±12	10	1	5	4
OFMSW and sewage sludge	51±7.5	3	0	3	0
Cellulosic sewage sludge	41±8	5	0	4	1
Biological sewage sludge	42	1	0	1	0
Mixed sewage sludge	44±10	3	0	3	0
TOTAL		**24**	**1**	**17**	**5**
		100%	**4%**	**71%**	**21%**

3. **Retention times (HRT and SRT)**

The sludge and the hydraulic retention times are equal, in the case of fermenter, since there is no recircycle.

The retention time is established on the basis of the type of substrate and its rate of hydrolysis. Typically, a longer retention time leads to higher VFA production as the microorganisms stay in contact with the substrate for longer. In the fermentation process, HRT and SRT are equivalent in that, since there are no recycle, the substrate and biomass remain inside the reactor for the same time.

For industrial matrices, as well as OFMSW, it was observed that higher HRT were beneficial for the production of VFA. However, excessive increases lead to lower improvements, because is economically less sustainable, as they lead to the need for larger volumes (Wee Shen Lee, 2014).

Fang et al, 2000 reports that VFA production from dairy wastewater doubles from HRT of 4 hours to HRT of 12 hours, while the further increase to 16-24 hours improves production by only 6%. Similarly, the yield in OFMSW VFA production increases from an HRT of 96 hours to one of 192 hours, while no significant improvement is observed at HRT of 288 hours (Seong-Jin Lim, 2008).

In the fermentation of sludge, on the other hand, it is noted that shorter retention times are more advantageous as they prevent the predominance of methanogenic bacteria within the reactor. At the same time, however, a sufficiently long SRT must also be guaranteed to allow the hydrolysis process (Wee Shen Lee, 2014).

From the analysis, it is observed that for laboratory tests (Figure 8) with industrial-type matrices, the HRT adopted are very low and, only in one case, exceed two days, while in most case studies they are equal to or less than 24 hours. The fermentation of the OFMSW occurs at stable HRT, almost always corresponding to 8 days. Greater variability is observed for sewage sludge, with values that fluctuate, in most cases, between 5 and 8 days. In particular, lower HRTs were adopted for the primary sludge (4.2 ± 1.9 days), while the highest values were for the fermentation of secondary sludge (9 ± 4.6 days). Mixed sludge has intermediate values, equal to 6.5 ± 2 days. Mixed sludge has intermediate values, equal to 6.5 ± 2 days. The greater variability, however, is evident in the combined matrices in which retention times vary between a minimum of 1 and a maximum of 9 days.

As regards the case studies on a pilot scale, it is specified that the retention times are quite constant even between the different matrices and almost all of which are between 6 and 8 days. There are only one case with a higher HRT (equal to 14 days) for the fermentation of municipal sludge and two cases with a lower HRT (equal to about 2 days) for the fermentation of OFMSW.

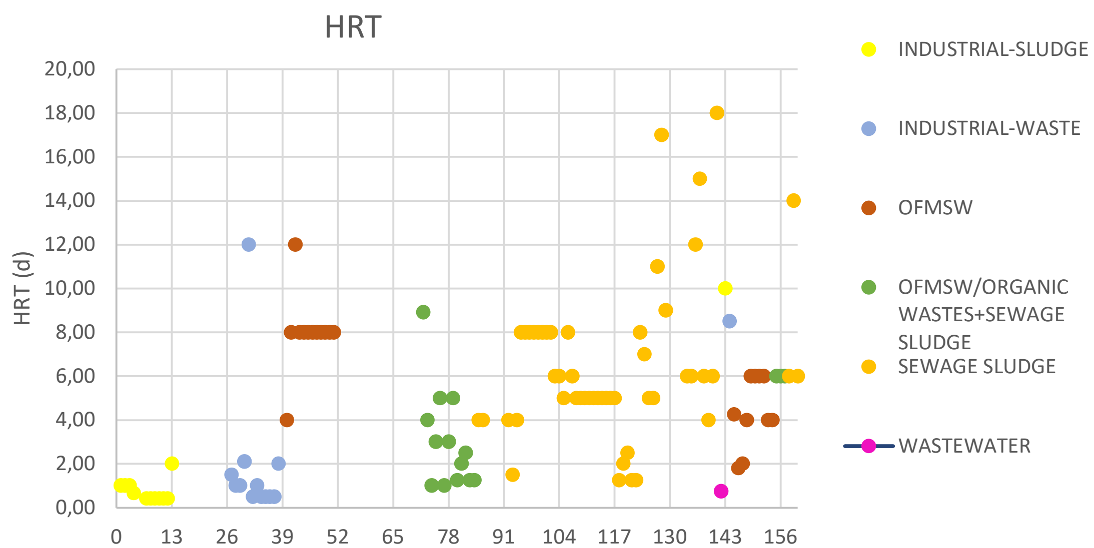


Figure: 8 Values of HRT in Laboratory and pilot case studies, divided by matrix

The following tables show the mean values and standard deviations divided by single matrix, both for the laboratory case studies (Table 6) and for the pilot scale case studies (Table 7). 49% of cases have an HRT between 5 and 10 days for laboratory tests, while in pilot scale 78% of applications have HRT below 10 days and, of the cases analyzed, 45% have an HRT less than 5 days.

Table 6 Average values and standard deviations of HRT values in lab case studies

MATRIX (case studies in laboratory scale)	HRT (d)	Total n° of case studies	N° of case studies with HRT ≤5d	N° of case studies with 5d <HRT <10d	N° of case studies with HRT ≥10d
Industrial sludge	0.74±0.5	14	11	0	0
Industrial waste	1.9±3.2	24	11	0	1

OFMSW	8±1.7	32	1	10	1
OFMSW and sewage sludge	3±2.3	14	13	1	0
Cellulosic sewage sludge	4	7	2	0	0
Primary sewage slydge	4.2±1.9	17	15	2	0
Biological sewage sludge	9±4.6	19	3	7	5
Mixed sewage sludge	6.5±2	14	4	10	0
Wastewater	0.75	1	1	0	0
TOTAL		**142**	**61**	**30**	**7**
		100%	**42%**	**49%**	**23%**

Table 7 Average values and standard deviations of HRT values in pilot case studies

MATRIX (case studies in pilot scale)	**HRT (d)**	**Total n° of case studies**	**N° of case studies with HRT ≤5d**	**N° of case studies with 5d <HRT <10d**	**N° of case studies with HRT ≥10d**
Industrial sludge	10	1	0	0	1
Industrial waste	8.5	1	0	1	0
OFMSW	4.4±1.6	10	6	4	0
OFMSW and sewage sludge	6	3	0	3	0
Cellulosic sewage sludge	6.4±4.5	5	2	0	0
Biological sewage sludge	-	1	-	-	-
Mixed sewage sludge	4.5	3	3	0	0
TOTAL		**24**	**11**	**8**	**1**
		100%	**45%**	**33%**	**4%**

4. **Organic loading rate**

The OLR represents the organic mass load fed daily and specified per unit of fermentation volume. From the analysis of the technical-scientific literature there is no clear influence of the OLR on the production of VFA. However, it is possible to identify optimal ranges, valid for each type of matrix (Wee Shen Lee, 2014). For example, in the study by Rincòn et al., the fermentation of solid residues of mills (industrial sludge) is tested at OLRs ranging from 3.2 to 15.1 gCOD/l/d, obtaining an optimal value equal to 12.9 gCOD/l/d (B. Rinco´n, 2008). The fermentation of starch-rich wastewater, on the other hand, is optimal with OLR equal to 32 gCOD/l/d (Yu, 2001). As regards the fermentation of the organic fraction of municipal solid waste, Lim et al., highlights the production of VFA increasing by increasing the OLR from 5 to 13 g / l / d. Once the value of 13 gCOD/l/d is exceeded, fermentation is particularly unstable as the fermentation liquid becomes viscous at high loads (Lim et al, 2008). In addition to the amount of waste fed into the reactor, the frequency of feeding can also influence the production of VFA (Wee Shen Lee, 2014). The study by Nebot et al. highlights that a feeding frequency of less than 3 times a day can lead to a higher concentration of VFA than a feeding equal to 24 times a day. Less frequent feeding also provides simpler reactor operation and reduces wear on feed pumps ((Nebot, 1995)).

From the analyzed case studies, it emerges that the organic load of the fermentation processes has values ranging between 4 and 25 gCOD/l/d. The fermentation of industrial matrices (liquid waste and/or sludge), OFMSW and primary cellulosic sludge generally operates at organic loads between 9 and 12.7 gCOD/l/d with comparable average values of 9.2 ± 7.5, 9.9 ± 3.3 and respectively 11 ± 5.4 gCOD/l/d (Table 8). It is also noted that, except for the case study applied to municipal mixed-type sludge, for all other fermented matrices, the process OLR is comparable and around 10 gCOD/l/d.

Table 8 Average values and standard deviations of OLR values

MATRIX	**OLR (gCOD/L/d)**	**Total n° of case studies**	**N° of cases with availability of OLR value**
Industrial sludge	12.7±2.7	15	5
Industrial waste	9.2±7.5	25	8
OFMSW	9.9±3.3	42	10
OFMSW and sewage sludge	-	17	0
Cellulosic sewage sludge	11±5.4	13	5
Primary sewage slydge	-	17	0
Biological sewage sludge	-	19	0
Mixed sewage sludge	25	15	1
Wastewater	-	4	0

For the organic fraction of municipal solid waste, the fermentation process for the production of VFA, operates at an average temperature of around 37 ° C, with HRT of about 8 days, and with an organic load fed on average equal to 10 gCOD/L/d. The pH, in this case and for all the other matrices analyzed, is on average between 5 and 7. Very similar values of Temperature and HRT also characterize the fermentation of the purification sludge, while, in this case, the OLR stands at values lower, on average equal to 1-2 gCOD/L/d. Industrial matrices are those with a higher organic load, equal to about 10-12 gCOD/L/d. In the latter case, the process HRTs are lower than the fermentation of the matrices described above and equal to 2-3 days. Temperatures are in the range of 25-30 ° C.

Analyzing the case studies on a pilot scale, for all the matrix types considered, the average pH values are again between 5 and 7 and the HRT between 5 and 10 days. The process temperature, on the other hand, is much more variable and probably associated with evaluations of the energy sustainability of the entire process and on average equal to 50 °C in the case of the combination of sewage sludge and FORSU, at 40 ° C in the case of sludge alone. purification and at 35 °C for industrial waste.

Sometimes the pre-treatments are required. They are useful, not only to increase the rate of hydrolysis, but also to optimize the biological process of producing VFA from waste matrices. The pre-treatments are divided into chemical, biological, physical and thermal processes. These can be applied both individually and in combined systems and have mostly been applied in laboratory scale to the OFMSW and in some cases to sewage sludge.

• Chemical treatments involve the use of reagents, commonly acids, alkalis, ozone and hydrogen peroxide.

• A further pre-treatment adopted to improve the solubilization of solid waste involves the use of biological agents such as hydrolytic enzymes. The use of biological agents has been applied on a laboratory scale only (Fdez-Güelfo, 2011).

• Among the physical pre-treatments, both microwave irradiation systems and ultrasound treatments are used. Microwave irradiation is electromagnetic radiation with a wavelength between 1 mm and 1 m, corresponding to an oscillation with a frequency of 0.3-300 GHz (Lise Appels, 2013). These pretreatments were applied in order to optimize the hydrolysis process. There are two main mechanisms that favor the process: 1) the rotation of dipolar molecules (water) in an electromagnetic field, 2) the alignment of the side chains of macromolecules (e.g. proteins) with the poles of the electromagnetic field, in order to breaking hydrogen bonds and destabilizing the structure of molecules.

• Alternatively, a thermal type pre-treatment can be applied in which the material is subjected to temperatures in the range of 60-180 ° C. (Wee Shen Lee, 2014). The thermal shock is effective in removing the microorganisms that consume hydrogen, protecting the bacteria responsible for the formation of spores, in this way, moreover, methanogenic activity is also inhibited (Elsayed Elbeshbishy, 2011).

Finally, the combined application of different pre-treatments to promote the synergistic hydrolysis of solid waste is common.

It is important, however, to underline that, among the numerous options listed, it is not possible to identify a system to be preferred over others; a method that is optimal in one study may be less efficient in a different case, this is due to a variability of the characteristics of the matrix and of the related impurities and/or the presence of compounds that can inhibit the hydrolysis phase (Elsayed Elbeshbishy, 2011).

The amount of VFA produced in a fermentation process depends on the degree of acidification of the substrate. It defined as the percentage of initial organic carbon, expressed as COD, converted into organic acids and other fermentation products. The degree of acidification therefore depends on the quantity of the easily fermentable organic fraction in the waste stream.
In terms of production yields (gCOD (VFA)/gCOD (VS)) and productivity of VFAs (gCOD (VFA)/L/d), it can be said that the matrices that on average have higher values, in the case studies in laboratory scale (Table 9), are the OFMSW and the cellulosic-type sewage sludge.

Table 9 VFA yield and production, divided by matrix for lab scale case studies

MATRIX (laboratory scale case studies)	YIELD gCOD(VFA)/gCOD(VS)	PRODUCTIVITY gCOD(VFA)/L/d
Industrial sludge	-	-
Industrial waste	0.17	-
OFMSW	0.45±0.11	2.2±0.78
OFMSW and sewage sludge		-
Cellulosic sewage sludge	0.5±0.17	-
Primary sewage slydge	0.31±0.16	0.5±0.17
Biological sewage sludge	0.3±0.18	0.27±0.1
Mixed sewage sludge	0.32±0.08	-
Wastewater	-	-

In the pilot scale case studies (Table 10), in terms of yields, where data are available, no high variability is observed. In particular, the combination of OFMSW and municipal sludge shows a yield of 0.5 ± 0.13 gCOD (VFA)/gCOD (VS), on average about 35% higher than the yields of individually fermented sewage sludge, showing a significant contribution in the yield due to the addition of organic material from municipal solid waste. Furthermore, OFMSW and its combination with municipal sludge also represent the matrices with the highest productivity, with values equal to 4.1 ± 2.6 gCOD(VFA)/L/d and 3.3 ± 0.3 gCOD(VFA)/L/d respectively . Also in this case, the sewage sludge (primary, secondary or mixed) follows with significantly lower average productivity (around 60%) and equal to 0.7 gCOD(VFA)/L/d.

Table 10 VFA yield and production, divided by matrix for pilot scale case studies

MATRIX (pilot-scale study)	RESA gCOD(VFA)/gCOD(VS)	PRODUTTIVITA' gCOD(VFA)/L/d
Industrial sludge	-	-
Industrial waste	-	-
OFMSW	-	4.1±2.6
OFMSW and sewage sludge	0.5±0.13	3.3±0.3
Cellulosic sewage sludge	0.29±0.11	0.7±0.7
Biological sewage sludge	0.39	-
Mixed sewage sludge	0.36±0.05	0.74±0.11

In terms of correlation between the process parameters, such as pH, temperature and HRT, and the production yields, it is possible to state that the highest values, equal to 0.55 gCOD/gCOD, are obtained with temperatures between 25 ° C and 45 ° C and with HRT less than 10 days.

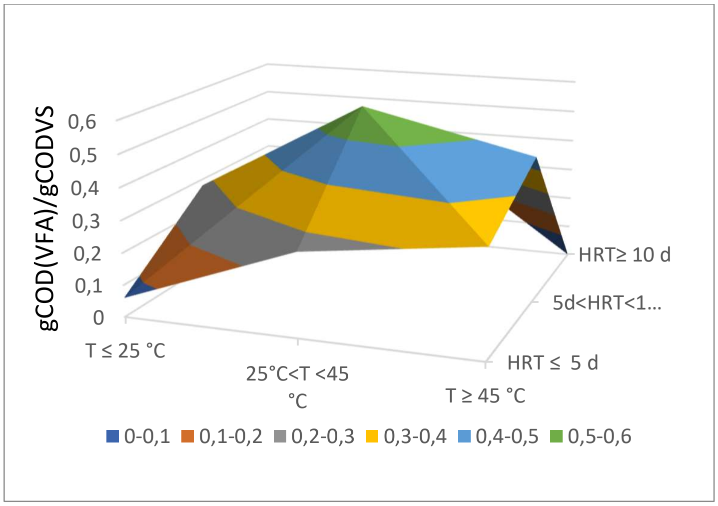


Figure: 9 VFA yield related to Temperature and HRT values

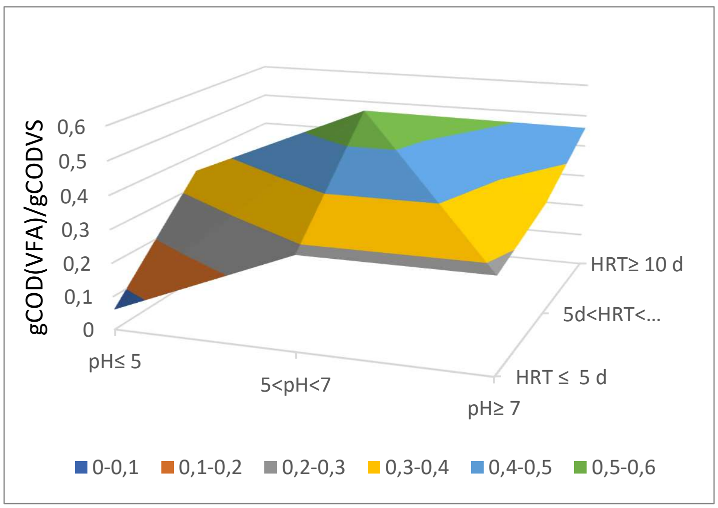


Figure: 10 VFA yield related to pH and HRT values

Furthermore, from Figure 10 it is possible to deduce that the maximum yields (0.55 gCOD / gCOD) are obtained at pH values between 5 and 7 and with HRT less than 10 days. The lowest values, around 0.1 gCOD / gCOD, are obtained with very acidic pH (<5) and HRT of less than 5 days.

The composition of the final fermented stream and of the VFA produced is not strictly dependent on the original type of matrix fed. As mentioned above, the most commonly produced VFAs are acetic, propionic, butyric acid and in smaller quantities, valeric, isovaleric, isobutyric and caproic acids (Sawyer, 2007).

It should be noted that in laboratory tests, the prevalent type is acetate regardless of the type of matrix, with a maximum percentage content of 67.5% for cellulosic sludge and a minimum of 34% for mixed sludge. In pilot-scale studies, acetate is again the main fermentation product for the OFMSW (65%) and secondary activated sludge (38%). Differently, for industrial sludges and for combined matrices (OFMSW + sludge) the main contribution is given by butyrate, with percentages of 50% and 33% respectively. Finally, the cellulosic sludge shows a prevalent propionate content, on average equal to 50%.

It is specified that the composition of the VFAs may affect the yield and composition of the PHAs produced in the subsequent phase. In particular, the composition of the VFAs, i.e. the relative proportions of acetate, propionate, butyrate and valeriate, directly influence the yield, productivity and monomer composition of the PHA produced.

Among the operational parameters, analyzed in paragraph 3.1, it should be noted that:

1) it is not possible to identify a clear correlation between the retention time and the composition of the VFA (Wee Shen Lee, 2014)

2) it is not even possible to identify a clear correlation between the process temperature and the composition of the VFA;

3) the technical scientific literature of the sector has revealed that the production of fatty acids is instead partially influenced by the pH value.

For what concerns the pH, the literature proposes conflicting visions. In fact, there is a variability in the relationship between the pH and the composition of the VFA produced, probably associated with the specific conditions of the case studies. However, it can be concluded that for most applications about 55% of the VFAs produced are acetic acid and its highest percentage was obtained at acidic pHs below 5 and / or at alkaline pH between 9 and 10.

To have a global idea about the VFA, it is necessary to consider also the market price. The market prices of VFAs recovered from waste matrices can vary from 506 to 3222 € / ton depending on the number of carbon atoms in the molecular structure, while biogas has a market value of 127 € / ton (Calt, 2015). In a recent study (Owusu-Agyeman, 2020) an economic comparison between the production of VFA and the production of biogas from sewage sludge is reported and the results showed that VFAs have a net profit of 7.7 € / m3, while biogas has a net gain of 3.1 € / m3 (He Liu, 2018).

FOCUS: FULL SCALE CASE STUDY - ALKALINE FERMENTATION

The case study that involves the application of full-scale fermentation is located in the city of Wuxi, China and treats 40,000 m3 / d of urban waste (He Liu, 2018). The plant includes 4 treatment stages: 1) the sludge pre-treatment system, 2) the alkaline fermentation, 3) the fermentation liquid separation system and 4) an anaerobic-anoxic-aerobic biological process (A2O). The fermentation of the sludge operates in a semi-continuous way, the pre-treatment of the sludge and the separation of the fermentation liquid are managed in batch mode, but the fermentation liquid is fed continuously to the A2O process. In particular, the secondary sludge is pumped into the thermo-alkaline pre-treatment tank of 1.9 m3, which is kept at a temperature always below 70 ° C and at pH 12. The organic load (OLR) of the fermenter is approximately 3 kg VS / m3 / d and the sludge is fermented at pH> 10 for a hydraulic retention time of 14 days. The solid / liquid separation of the fermented sludge takes place through a filter press.

The recovery yields of VFA are equal to 0.26 gCOD / gVSS, which assuming a theoretical COD / VSS ratio of 1.42, corresponding to 0.18 gCOD / gCOD. The improvement in the removal of nutrients in the biological process has reached percentages of 73% for nitrogen and 89% for phosphorus.

2.2.3 PHA: process parameters and recovery yields

This section is focused on the production of polyhydroxyalkanoates (PHAs). These polymers, which can be used as plastics, are thermoplastic, biodegradable and biocompatible materials. Generally, PHAs are distinguished on the basis of the length of the chain, distinguishing themselves in short-chain PHA (R = 1-5) and medium-chain PHA (R = 6-15). The great variability of the side chains and monomers gives these materials as much variability in physical characteristics (Jendrossek, 2002). In fact, they range from typically thermoplastic polymers, such as PHB (poly (3-hydroxybutyrate)) to rubbery materials such as polyhydroxyoctanoates (Valera, 2001).

As said in the process scheme paragraph, the PHA production can be distinguished by

1) Mixed microbial culture (MMC), or by applying operating conditions that favor the growth of bacterial communities capable of storing PHA in the presence of an easily assimilable carbon source, mainly volatile fatty acids (VFA);

2) Pure microbial culture (PMC), i.e. favoring the growth of a single previously selected microbial strain.

Some of the accumulating PHA microorganisms are naturally present in mixed bacterial cultures (MMCs), such as activated sludges, and their growth can be selectively favored by applying a feeding regime called feast-famine (FF) (Valentino, 2016). The condition in which the biomass assimilates the VFA by converting them into PHA is called "Feast", the one in which the PHAs are used for growth in the absence of other available substrates is called "Famine". The FF ratio is one of the key parameters for optimizing the biomass selection phase.

Selection (Stage II) is the downstream process of acidogenic fermentation (Stage I) and precedes the PHA accumulation stage (Stage III). As, highlighted in the previous chapter, the first stage involves the acidogenic fermentation of easily biodegradable organic substrates (industrial or municipal in nature) producing an effluent with a high content of volatile fatty acids (VFA). In the second stage, the microbial communities with a high PHA accumulation potential are selected starting from an activated sludge (MMC) in totally aerobic and/or aerobic/anoxic reactors with sequential charges (SBR) and operating in conditions called "Feast" and "Famine". The accumulation phase consists of a continuous succession of "feast" phases that allows PHA to accumulate within the bacterial cells.

During the research of technical-scientific literature, the following categories of data were collected in relation to the phases of acclimatization and accumulation of PHA, where available:

- Process scale;
- Type and main characteristics of the acclimatization and / or storage reactor;
- Operating conditions of the process;
- Type of microbial culture;
- Type and characteristics of the organic substrate;
- Biomass growth yields;
- PHA accumulation yields and productivity;
- Type and composition of PHAs produced.

For each type of inoculum used (MMC or CMP), 183 and 208 case studies were analyzed respectively, which in turn refer to studies conducted at laboratory and pilot scales as reported in Table 11 regarding the biomass selection / acclimatization phase.

Table 11 Case studies analyzed and scale of application for the selection phase and the accumulattion phase of PHA

Mixed microbial culture (MMC)		
SCALE	**REACTOR SIZE**	**N° OF ANALYZED CASE STUDY**
Laboratory	0.5 - 26 L	153
Pilot	120 – 2900 L	30
TOTAL		**183**
Pure microbial culture (CMP)		
SCALE	**REACTOR SIZE**	**N° OF ANALYZED CASE STUDY**
Laboratory	0.25-14 L	207
Pilot	70 L	1
TOTAL		**208**

From Table 12 it appears that the studies were carried out mainly on a laboratory scale, in particular for about 84% of cases for MMCs and for almost all (> 99%) in the case of PMC. The greater presence of pilot-scale studies for MMCs suggests a greater technological maturity compared to PMCs. However, the few industrial manufacturers that market PHA globally, including Tianan Biopolymer, BASF, Tepha, Biocycle, Biomer, use CMP processes.

As regards the accumulation phase, the majority of cases (77%) were carried out on a laboratory scale, i.e. in reactors that do not exceed 4 liters. Few cases, 37 out of 162 analyzed were applied on a pilot scale with maximum accumulation volumes equal to 1000 L.

Table 12 Case studies analyzed and scale of application in accumulation phase

SCALE	REACTOR SIZE	N° OF ANALYZED CASE STUDY
Laboratory	0.11-4 L	125
Pilot	70-1000 L	37
TOTAL		162

More than 60% of the studies carried out on a laboratory scale involved the use of mixtures of synthetic fatty acids, while about 40% experimented with the use of VFA produced by the acidogenic fermentation of scraps and waste of different composition and origin (Figure 11). In the case of studies conducted on a pilot scale (Figure 12), 15% of cases use VFA of synthetic origin, while 85% use scraps and waste of different composition and origin, consistent with the type of experimentation.

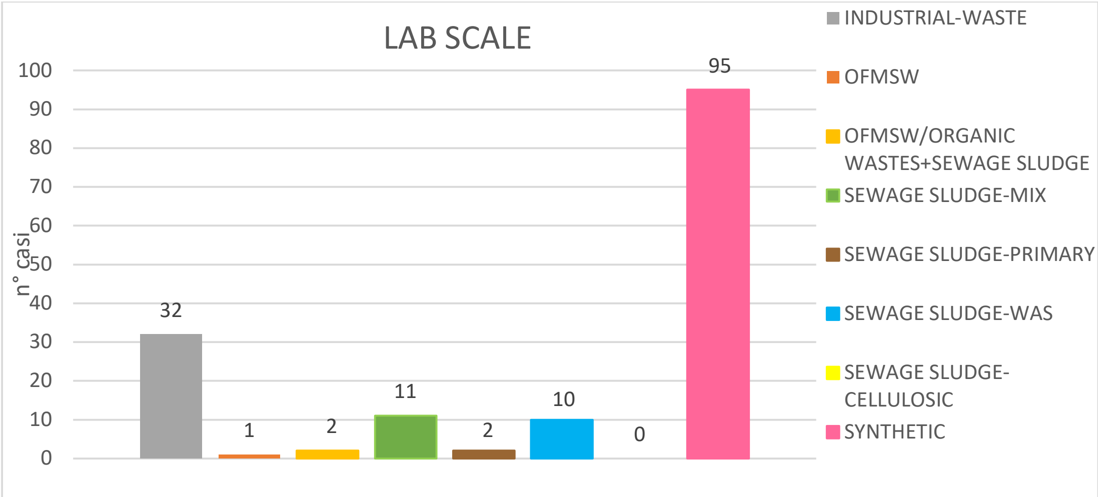


Figure: 11 Number of laboratory-scale case studies, divided by matrix

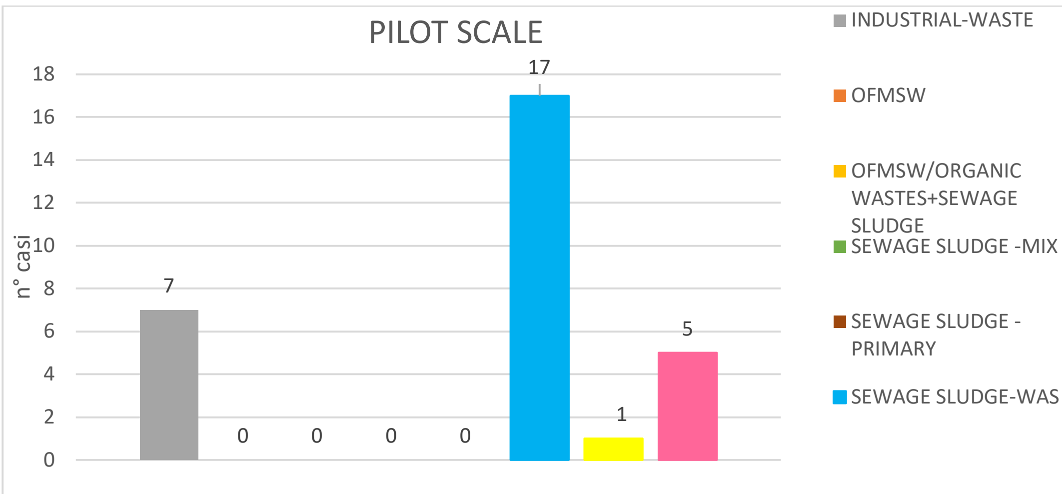


Figure: 12 Number of pilot-scale case studies, divided by matrix

As regards the type of waste used, the categories of fermented waste exposed in the previous chapter are used.

Now, the effects of the main process parameters necessary for the selection of accumulating PHA microbial communities starting from mixed cultures (MMC) are analyzed.

pH

During the selection process, the pH is a parameter that must be monitored. Table 13 and Table 14 below show the pH values for the laboratory and pilot scale case studies. From the tables it can be seen that about 60% of cases on a laboratory scale and only 30% of cases on a pilot scale report pH as a process data, demonstrating that pH is not a fundamental parameter.

The pH value during the biomass selection is given by the balance between the acidity of the wastewater used (e.g. concentration of VFA), by the removal of acidity by the biomass due to the assimilation of organic acids and by the buffering power given from the ammonium and bicarbonate ion in the reaction medium. From the analysis of the cases studied on a laboratory and pilot scale, it is observed that the pH values are generally in a range between 7 and 8.5, in relation to the type of wastewater used:

- The use of FORSU fermented or industrial liquid waste leads to the achievement of a higher pH than in the other cases studied (8-8.5). In this case, the pH control could become necessary when important phenomena of uncontrolled precipitation are observed (eg struvite);
- The use of purification sludge generally involves pH between 7 and 8.

Table 13 Mean and standard deviation for the pH value in laboratory case studies

MATRIX (laboratory scale)	pH	Total n° of case studies	Total n° of case studies with available pH value
Industrial waste	7.71±0.45	27	22
OFMSW	-	1	0
OFMSW and sewage sludge	8.5	2	1
Sewage sludge – primary	8.5±0	2	2
Sewage sludge – activated sludge	8.3	10	1
Sewage sludge – mixed	7±0	11	10
Synthetic	7.43±0.42	95	57
TOTAL		**153**	**93**
		100%	**60.78%**

Table 14 Mean and standard deviation for the pH value in pilot case studies

MATRIX (pilot scale)	pH	Total n° of case studies	Total n° of case studies with available pH value
Industrial waste	8±0.49	7	6
Sewage sludge – cellulosic	8	1	1
Sewage sludge – activated sludge	-	17	0
Synthetic	7±0	5	2
TOTAL		**30**	**9**
		100%	**30%**

Temperature

The temperature is a fundamental parameter as it influences the consumption rate of the substrate and therefore the growth rate of the biomass. Compared to the accumulation phase, during the selection phase, higher temperatures increase the degradation efficiencies of the PHAs and therefore increase the growth rate (productivity) of selected biomass for the same duration of the famine phase. In general, the temperatures observed at the laboratory scale are for 13% of cases below 20 ° C, while for the remaining cases the temperatures are between 20 and 25 ° C. Similar observations can be made for studies conducted on a pilot scale, where the observed temperatures are always between 25 and 30 °. In general, and with exceptions, the accumulation and selection processes do not require a heating system in order to keep the temperature constant. On the other hand, the temperature of the selection process is greatly influenced by the temperature of the liquid fermented, which for the most part comes from a fermentation process under mesophilic conditions (about 37 ° C). This effect is similarly visible during the accumulation phase.

Table 15 Average values, standard deviation and subdivision into bands for the value of the T ° C in the case studies on a laboratory scale

MATRIX (laboratory scale)	T°C	Total n° of case studies	N° of case studies with T°C ≤20°C	N° of case studies with 20°C<T°C <25°C	N° of case studies with T°C ≥25°C
Industrial waste	25.84±2.67	32	0	14	11
OFMSW	-	1	0	0	0
OFMSW and sewage sludge	23.5±0	2	0	1	0
Sewage sludge – primary	18±0	2	2	0	0
Sewage sludge – activated sludge	24±0	10	0	3	0
Sewage sludge - mixed	21±0	11	0	10	0
Synthetic	23.93±3.31	95	18	18	39
TOTAL		**153**	**20**	**46**	**50**
		100%	**13.07%**	**30.07%**	**32.68%**

Table 16 Average values, standard deviation and subdivision into bands for the value of the T ° C in the case studies on a pilot scale

MATRIX (pilot scale)	T°C	Total n° of case studies	N° of case studies with T°C ≤20°C	N° of case studies with 20°C<T°C <25°C	N° of case studies with T°C ≥25°C
Industrial waste	30	7	0	0	1
Sewage sludge – cellulosic	-	1	0	0	0
Sewage sludge – activated sludge	25	17	0	0	1
Synthetic	28.33±2.89	5	0	0	3
TOTAL		**30**	**0**	**0**	**5**
		100%	**0%**	**0%**	**16.67%**

SRT, OLR and Feast/Famine ratio

The retention time of solids (SRT) is one of the fundamental control parameters to be considered for the selection process as the SRT influences the process through two distinct mechanisms:

1) Feast/ famine ratio, which modifies the selective pressure of the accumulating PHA biomass;

2) Composition of the accumulating PHA biomass compared to other heterotrophic organisms.

From the laboratory-scale case studies analyzed, it can be seen that the SRT is for about 40% of cases under 5 days, while about 50% is between 5 and 15 days. Only in 3 cases the selection reactor was managed with SRT of more than 15 days (Table 17). In the studies conducted on a pilot scale, the SRT was maintained between about 4 and 7 days (Table 18).

Table 17 Average values, standard deviation and subdivision into bands for the value of the SRT in the case studies on a lab scale

MATRIX (laboratory scale)	SRT (d)	Total n° of case studies	Case studies with SRT≤5d	Case studies with 5d <SRT <15d	Case studies with SRT ≥15d
Industrial waste	7.57±3.92	32	9	18	1
OFMSW	25	1	0	0	1
OFMSW and sewage sludge	13±16.97	2	1	0	1
Sewage sludge – primary	5±0	2	2	0	0
Sewage sludge – activated sludge	8.3±7.35	10	1	1	0
Sewage sludge - mixed	5.73±0.9	11	1	10	0
Synthetic	4.93±3.92	95	49	42	0
TOTAL		**153**	**63**	**71**	**3**
		100%	**41.18%**	**46.41%**	**1.96%**

Table 18 Average values, standard deviation and subdivision into bands for the value of the SRT in the case studies on a pilot scale

MATRIX (pilot scale)	SRT (d)	Total n° of case studies	Case studies with SRT≤5d	Case studies with 5d <SRT <15d	Case studies with SRT ≥15d
Industrial waste	3.55±1.22	7	5	1	0
Sewage sludge – cellulosic	7	1	0	1	0
Sewage sludge – activated sludge	4.54±2.37	17	3	4	0
Synthetic	-	5	0	0	0
TOTAL		**30**	**8**	**6**	**0**
		100%	**26.67%**	**20%**	**0%**

It is specified that shorter SRTs lead to a reduction in the specific consumption of substrate and, therefore, longer "feast" phases and shorter "famine" phases, which can negatively affect the enrichment of accumulating PHA biomass.

The OLR represents the organic mass load fed daily with respect to the reactor volume. In general, the typical OLRs observed in the literature fall within a range between 0.2 and about 4 gCOD/L/d (Table 19). In particular, the OLR applied to the biomass selection process using industrial waste was observed on average equal to about 4 gCOD/L/d, of which only 30% consists of VFA. In the case of using OFMSW and / or fermented sewage sludge, the applied OLR is for both close to 2 gCOD/L/d. Only in one case was an OLR of 0.2 gCOD/L/d applied. In this case, the selection process was applied in the water line and therefore resulted in a low load compared to the previous cases.

Table 19 Average values and standard deviation for the OLR value in the case studies at any scale applied

MATRIX	OLR (gCOD/L/d)	Total n° of case studies	N° of cases with availability of OLR value
Industrial waste	4.05±3.03	39	12
OFMSW	0.2	1	1
OFMSW and sewage sludge	2.13±2.64	2	2
Sewage sludge – primary	-	2	0
Sewage sludge – activated sludge	2.05±3.38	27	11

In general, the OLR mainly affects the F/F ratio and therefore the degree of selection of the accumulating PHA biomass. It is now accepted by the scientific community that F/F ratios below 0.2 min / min demonstrate good selection of accumulating PHA biomass. A higher OLR applied leads to a higher initial concentration of VFA and a simultaneous one to a longer “feast” phase.

With the same cycle length, increasing the OLR would result in a corresponding decrease in the "famine" phase and therefore an increase in the F/F ratio, which negatively affects the selection of accumulating PHA biomass. As can be seen from Table 20, the type of waste used does not significantly affect the F/F ratio, as the analyzed cases show ratios ranging from 0.12 to 0.18 min/min.

Table 20 Average values and standard deviation for the F/F ratio

MATRIX	FF (FEAST-FAMINE)	Total n° of case studies	N° of cases with availability of FF value
OFMSW	-	1	1
OFMSW and sewage sludge	0.12±0.04	2	2
Sewage sludge – primary	-	2	0
Sewage sludge – activated sludge	0.18±0.06	27	9
Sewage sludge – mixed	-	11	0
Sewage sludge – cellulosic	0.15	1	1

Typically, the biomass growth yields observed in the various case studies analyzed vary from a minimum of 0.16 to a maximum of 0.49 gVSS/ gCOD (Table 21), the variation of which does not seem to depend on the type of waste but on the operating conditions. applied, like the SRT. In fact, the growth yields observed using synthetic mixtures of volatile fatty acids do not appear to be significantly different from those obtainable from VFA produced by acidogenic fermentation.

Table 21 Growth yields of biomass in the acclimatation phase divided by matrix

MATRIX (laboratory case study)	GROWTH YIELD (gVSS/gCOD consumed substrate)
Industrial waste	0.16±0.04
OFMSW and municipal sludge	0.49
Municipal sludge – activated sludge	0.23±0.14
Municipal sludge – mixed	0.16
Municipal sludge – cellulosic	0.35
SYnthetic	0.29±0.13

As discussed above, the accumulation stage is the final stage of the three-step process for producing PHA from MMC. This phase consists in subjecting the biomass selected during the selection phase to high quantities of VFA in "fed-batch" mode, or repeating different "feast" phases over time, in order to maximize the PHA concentration during the accumulation and the concentration of PHA within the cellular biomass, which influences the subsequent extraction and purification processes.

As regards the use of the carbon source, the use of synthetic VFA blends is the preferred strategy operating at a laboratory scale (62%), the use of industrial and/or fermented residues of FORSU and sewage sludge it is the most frequent practice operating on a pilot scale (54%). The use of synthetic carbon source is useful to minimise the contribution of nutrients (ammonia nitrogen and phosphates) during the accumulation phase, in order to maximize the PHA accumulation yields and to reduce the impurities associated with the use of fermented products (presence of salts, suspended solids, etc.) which can negatively affect the subsequent extraction and purification phases.

The following paragraph analyzes the effect of pH.

pH

As for the selection phase, also during the accumulation phase the pH is mostly around neutrality both for the case studies applied at the laboratory scale and for those on the pilot scale (Table 22 and Table 23). The pH can drop abruptly (<6) and reversibly inhibit the biomass when the amount of VFAs is greater than the buffer capacity of the selected biomass.

Table 22 Mean and standard deviation for the pH value in laboratory case studies

MATRIX (laboratory scale)	pH	Total n° of case studies
Industrial wastes	7.68±0.47	29
OFMSW	-	1
OFMSW and sewage sludge	-	1
Sewage sludge – primary	8.5	1
Sewage sludge – activated sludge	7	4
Sewage sludge – mixed	7±0	11
Synthetic	7.52±0.63	78
TOTALE		**125**
		100%

Table 23 Mean and standard deviation for the pH value in pilot case studies

MATRIX (laboratory scale)	pH	Total n° of case studies	Total n° of case studies with available pH value
Industrial wastes	7.1±0	7	5
OFMSW and sewage sludge	-	2	0
Sewage sludge – cellulosic	-	1	0
Sewage sludge – activated sludge	6.05±0.12	11	6
Synthetic	6.51±0.69	16	10
TOTALE		**37**	**21**
		100%	**56.76%**

From the analysis carried out, it seems clear that the PHA accumulation yield with respect to the COD consumed is closely linked to the duration of the phase itself. In general, high PHA production yields are observed when the batch cycle duration remains between 2 and 7 hours. With these durations, the accumulation yields are between 0.27 and 0.69 gCODPHA/gCOD of consumed substrate. In the case of batch cycle durations greater than 7 hours, the biomass converts the accumulated PHA into new cell growth, thereby reducing the PHA accumulation yield. From the literature analysis it was observed that for durations between 16 and 20 hours, the PHA accumulation yields do not exceed values of 0.28 gCODPHA / gCOD of consumed substrate.

As previously reported, the As it is production of PHA at industrial level takes place through the use of pure cultures, using high-purity substrates as a carbon source, namely glucose, synthetic VFA mixtures, etc. At the laboratory scale, about 30% of the cases analyzed reported the use of industrial residues or VFAs produced by the fermentation of OFMSW and purification sludge (Figure 13).

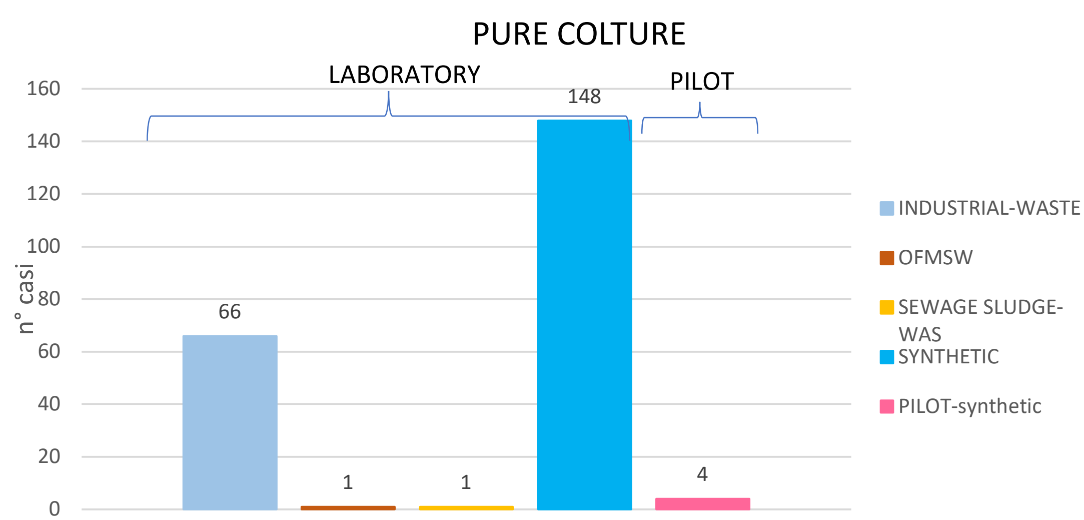


Figure: 13 Number of laboratory and pilot scale case studies, divided by matrix relating to the use of pure cultures

Currently, on an industrial level, PHA production consists in the fermentation of sugars extracted from sugar cane, beets, corn or molasses using selected strains under aerobic conditions. The advantages of PMCs are:

1) the phases of growth and accumulation of PHA take place in a single reactor;

2) PHA concentrations reach 80% of the dry cell weight;

3) the productivity of the PHAs are higher or equal to 2.5 g/L h.

However, the carbon source fed must be sterile to avoid contamination by exogenous microorganisms.

Unlike MMCs, CMPs have only one bacterial strain in the culture medium, therefore they require a bacterial growth phase and not a real selection phase. In fact, in the initial phase the bacterial strain is grown in sterile conditions in such a way as to have sufficient inoculum for the subsequent production of PHA. There are many species capable of producing PHA, one of the best known is the bacterium Cupriavidus necator (originally named Alcaligenes eutrophus, later renamed Wautersia eutropha and later Ralstonia eutropha). Several scientific literatures use this strain for the production of PHA, both for research purposes and for industrial production.

Another strain known and used for industrial production is C. acidovorans, which together with R. eutropha allows the production of the co-polymer P (3HB-co-4HB) which has a high crystallinity and is therefore usable as an elastomer.

The following paragraph analyzes the effect of operating parameters, which affect PHA production.

pH

As with MMCs, the pH in the PHA production process must be within physiological ranges to allow bacterial cells to grow. In most cases reported in the literature, the pH is around 7 for PMCs fed by synthetic VFA blends. PH values around neutrality are also obtained using liquid fermented products produced from industrial and municipal sludge. Only in the case in which OFMSW has been used, is recorded an alkaline pH of 10 (Table 24).

Table 24 Mean and standard deviation for the pH value in the case studies at any scale applied

MATRIX	pH	Total n° of case studies	Total n° of case studies with controlled pH value
Industrial sludge-lab	7.21±0.63	66	10
OFMSW-lab	10	1	1
Sewage sludge-lab	7	1	1
Synthetic-lab	7.06±0.37	148	72
Synthetic -pilota	6.9±0.54	4	4
TOTAL		**220**	**88**
		100%	**40%**

Temperature

Typically, the temperatures observed are in an average range between 30 and 38 ° C and preferably below 35 ° C. In particular, it is noted that for 48% of the cases analyzed the process temperatures are below 35 ° C and only 7% exceed 50 ° C.

Table 25 Average values, standard deviation and subdivision into bands for the value of the T ° C in the case studies at any scale applied

MATRIX	T°C	Total n° of case studies	N° of case studies with T°C ≤35°C	N° of case studies with 35°C<T°C <50°C	N° of case studies with T°C ≥50°C
Industrial sludge-lab	38.2±13.2	66	25	9	10
OFMSW-lab	37	1	0	1	0
Sewage sludge-lab	30	1	1	0	0
Synthetic-lab	35.6±5.4	148	80	6	7
TOTALE		**220**	**106**	**16**	**17**
		100%	**48%**	**7.3%**	**7.7%**

HRT

From the analysis carried out, in general it is noted that the PMCs have a relatively faster growth time when compared to the producer PHAs in MMC. This is reasonable considering that they do not compete for substrate availability. From the cases analyzed (Table 26), it is noted that the optimal hydraulic time using synthetic mixtures of VFA at the laboratory scale is 2.5 ± 2.4 days for 66% of the cases in which the data is indicated, while it is 2 days at scale pilot. Interestingly, the speed of growth using alternative sources of carbon does not affect the hydraulic time of the fermenter. In fact, about 30% of the cases with the available data operated with an HRT equal to 2.1 ± 1.1 days using fermented source from industrial sludge.

Table 26 Average values and standard deviation for the HRT value in the case studies at any scale applied

MATRIX	HRT (d)	Total n° of case studies	Total n° of case studies with controlled HRT value
Industrial sludge-lab	2.1±1.1	66	44
OFMSW-lab	-	1	0
Sewage sludge-lab	-	1	0
Synthetic-lab	2.5±2.4	148	92
Synthetic -pilota	2	4	3
TOTAL		**220**	**139**
		100%	**63.2%**

The PHA accumulation yields from pure microbial cultures, using liquid fermented products from industrial residues, OFMSW or sewage sludge, have not yet been fully validated on a pilot scale and often the data available are incomplete or unclear. Table 27 shows the yield data obtained from the literature analysis.

Table 27 PHA accumulation yields divided by matrix

MATRIX	ACCUMULATION YIELD OF PHA (gCODPHA/gCOD substrato)
Industrial sludge-lab	0.63±0.33
OFMSW-lab	-
Sewage sludge-lab	-
Synthetic-lab	0.28±0.28
Synthetic -pilota	-

Extraction process

The extraction process for the recovery of PHA from bacterial cells involves cell lysis as the first step, followed by the separation of the biopolymer from the rest of the cellular components. The extraction process remains among the limiting aspects of the entire PHA production chain, as it is still an impacting process from an economic point of view. The extraction of PHAs can require a significant consumption of reagents, such as chemical oxidants and/or solvents, as well as several washing and refinement steps necessary to achieve the high degree of purity (> 95%) required by the plastics industries. Furthermore, the extraction process can also affect the physical characteristics of the PHA on which applications depend.

The study by Hart et al., 2014 reports a complete process chain for the extraction of PHA consisting of the following unitary processes:

1) 2-phase extraction, using NaCl and NaOH in dosages of approximately 0.15 kgNaCl / kgPHA and 0.27 kgNaOH / kgPHA respectively, followed by centrifugal dehydration;

2) First washing of the dehydrated PHAs by resuspending them in water and subsequent dehydration in centrifuge;

3) Second washing of the dehydrated PHAs with ethanol and subsequent dehydration in centrifuge;

4) Drying.

The methods are calibrated in relation to the microbial strain used, the PHA concentration contained in the bacterial cells and the purity of the required product. The main extraction methods can be chemical (use of reagents and solvents), physical (mechanical destruction, use of ultrasound, etc.) or combined, sometimes preceded by heat treatments with temperatures up to 170 ° C.

It is noted that:

• Using chemical extraction methods, purities higher than 86% are obtained for PHA accumulated through CMP, comparable with those obtained for PHA accumulated by MMC, unless one case for which lower percentages and equal to about 50% have been obtained;

• The recovery of chemical reagents or solvents is very variable, with values between 28 and 100% for MMCs and between 37% and 99% for CMPs;

• The molecular weights of the extracted PHAs are in the range of 10 ^ 5-10 ^ 7 g / mol.

3. Materials and Methods

3.1 Summary of the state of the art

The goal of the work is to is to evaluate the feasibility of PHA recovery in real urban wastewater treatment plants. The analysed plants are the Castelfranco Veneto, Modena Canale Navigli and Castiglione plants. As already explained in the previous chapters, the polydroxyalkanoate is a well-known class of biodegradables polymers with great market potential thanks to them properties similar to conventional plastics. In addition to their complete biodegradability, PHAs can be produced from renewable resources, allowing a sustainable and closed-cycle process for the production and use of such polymers.

These are the reasons that have led to a great interest in the study of these biopolymers. Most of the cases studied, however, concern laboratory or pilot scale studies. On the contrary, there are few real case studies.

The analyses reveal that the higher value of VFA yields in terms of COD is the one related to the cellulosic sewage sludge at lab scale.

At pilot scale the higher one is the mixed substrate (OFMSW and sewage sludge).

Since in the case of Modena, the sludge used for the fermentation and PHA production is the secondary sludge, the interesting parameter is the biological sewage sludge data. Actually, since the study of a real plant has been conducted, the value used is the VFA yield of the real case study (0,18 gCOD/gCOD).

The other substrate used for the feasibility study is the mixed substrate, composed by the organic fraction of the municipal solid waste and the sewage sludge. Indeed, in Modena the second case studied is the scenario which considers the secondary sludge and the waste coming from other food industries. Actually, since the study applied to the real scale plant could be more reliable, that value is used increasing it by 10%.

In the case of Castiglione, the primary sludge yield is taken into account for the first case. For the second case, in which the mixed sludge is assessed for the feasibility study, the value 0.32 gCOD(VFA)/gCOD(VS) is considered.

Table 28 VFA growth yield in laboratory and pilot scale case studies

MATRIX	**YIELD gCOD(VFA)/gCOD(VS) (laboratory scale case studies)**	**YIELD gCOD(VFA)/gCOD(VS) (pilot-scale study)**
Industrial waste	0.17	-
OFMSW	0.45±0.11	-
OFMSW and sewage sludge	-	0.5±0.13
Cellulosic sewage sludge	0.5±0.17	0.29±0.11
Primary sewage sludge	0.31±0.16	-
Biological sewage sludge	0.3±0.18	0.39
Mixed sewage sludge	0.32±0.08	0.36±0.05

The selection of the microorganisms happens with yields listed in the table 29, depending on the type of substrate. For the activated sludge the yields used is 0,23 gVSS/gCOD, while for the for the substrate composed by OFMSW and sewage sludge the value is 0,49 gVSS/gCOD.

As assumption, the primary sludge is considered as cellulosic sludge substrate, so value 0,35 gVSS/gCOD is assumed.

Finally, the mixed sludge has a yield of 0,16 gVSS/gCOD.

Table 29 growth yield gVSS/gCOD consumed substrate (laboratory case study)

MATRIX (laboratory case study)	**GROWTH YIELD gVSS/gCOD consumed substrate (laboratory case study)**
Industrial waste	0.16±0.04
OFMSW and municipal sludge	0.49
Municipal sludge – activated sludge	0.23±0.14
Municipal sludge – mixed	0.16
Municipal sludge – cellulosic	0.35
Synthetic	0.29±0.13

Further, the PHA yield, listed in the following table (Table30), are 0.28 gCODPHA/gCODVSS and 0.3 CODPHA/gCODVSS for the WAS sludge and the mixed sludge (OFMSW+ Sewage sludge), respectively.

Finally, the data for the primary and mixed sludge are considered as 0.46 and 0.45 gCODPHA/gCODVSS, respectively.

Table 30 Yield gCODPHA/gCODVSS in laboratory and pilot scale case studies

	Yield gCODPHA/gCODVSS (Laboratory scale)	Yield gCODPHA/gCODVSS (Pilot scale)
(industrial-waste)	0,45	0,33
(OFMSW)	-	-
(OFMSW+ Sewage sludge)	-	0,3
(sewage sludge-mix)	0,45	-
(sewage sludge-primary)	0,46	-
(sewage sludge-was)	-	0,28
(sewage sludge-cellulosic)	-	0,23
(sintetico)	0,43	0,28

Starting from these values will be possible to evaluate the feasibility to recover PHA from the considered plants.

3.2 Configuration plant methodology

In this chapter, the methodology used to conduct the study will be explained.

Studying the papers, the yields have been found considering two important categories related to the volume size of the tanks. Indeed, the papers was divided between the laboratory scale test one and pilot scale.

The other important subdivision is given by the substrate rich in organic matter used in the tests.

As said in the previous chapters, the process can be divided in three steps:

- Fermentation of sludge in order to produce volatile fatty acids (VFA)
- Selection of biomass in SBR
- Accumulation of PHA in fed-batch

The yields related to each specific case (pilot/laboratory case, substrate type) are clearly explained in the chapter 3.1.

The idea, in the case of this work is to relate this process together with the method exposed on the scientific publication of Frison et al (2018). In its paper, he proposes to link the PHA recovery process together with the short cut of the nitrogen, exploiting the capability of the biomass to

In the configuration considered, the nitrogen removal through nitritation/denitritation and the PHA selection process occurred in a single reactor (SBR) by applying a feast and famine regime.

It means that in the same reactor, ammonium was oxidized to nitrate and the VFA converted in biolymers during the aerobic feast phase and the nitrite was reduced in nitrogen gas during the anoxic famine phase, using the PHA previously stored. Considering, ideally, that the aerobic conditions coincide with the feast and the anaerobic with the famine phase, he observed a good selection of PHA storing biomass decreasing the feast/famine ratio. However, the aerobic reaction should be long enough to ensure adequate availability of nitrite for denitritation.

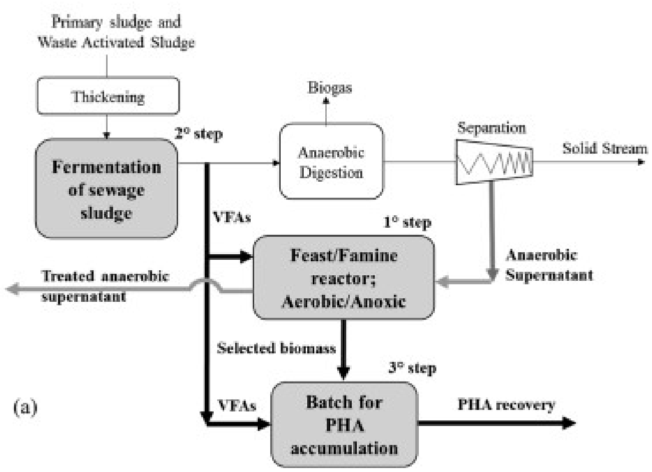


Figure: 14 Nitritation/denitritation and PHA selection process in a single reactor (SBR) (Frison, 2018)

The same idea can be applied in the case in which the nitritation reactor was separated with respect to the PHA storing biomass reactor.

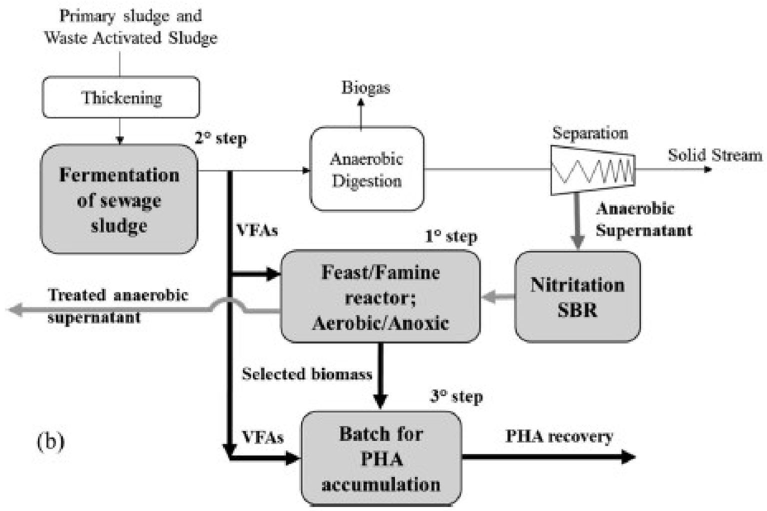


Figure: 15 Nitritation/denitritation and PHA selection process in two different reactors (SBR) (Frison, 2018)

Together with these studies, an accurate analysis of the plant was required in order to evaluate the best configuration for each plant.

The mass balance of the plants was carried out considering the real data given by the plant's managers and the utilities. Since some data have not yet been provided, some hypotheses have been necessary to complete the balance of the real case. To strengthen and prove the hypotheses, a software to simulate the plant (Advanced Simulation Platform) was used.

On the bases of these mass balances, the new design configuration for the feasibility study has been proposed and the calculation was carried out considering the literature yields previously found.

The configurations have been done following the method of Conca et al, (2020), that proposed an interesting way to recover both polyhydroxyalkanoates and biogas.

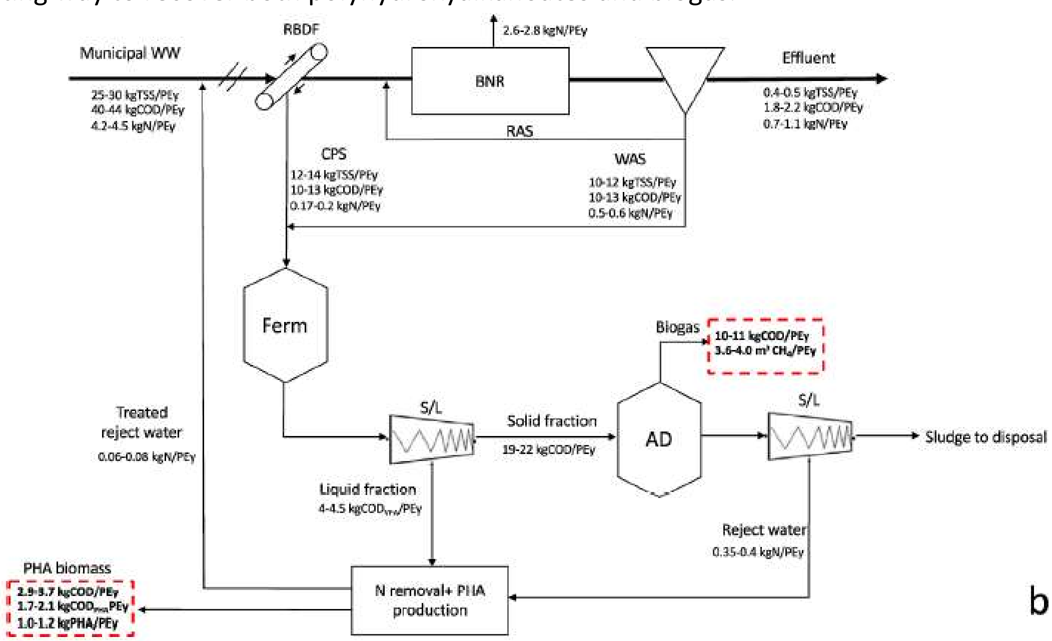


Figure: 16 Biogas and PHA recovery scenario (Conca, 2020)

Fermentation, required for the production of the volatile fatty acids is followed by a centrifuge to provide the solid liquid separation. The fermentation liquid, rich in VFA is sent to the nitritation and biomass selection, to remove nitrogen and select biomass, and to the PHA accumulation reactor to provide the biopolymers storage in the microorganisms. The sludge after the centrifuge can be sent in the anaerobic fermentation to exploit its high potential due to the presence of organic matter. The thickened and fermented sludge in anaerobic digestion is used to recover biogas.

So, Modena and Castiglione design scenario are built considering the feasibility to recover both the resources. In order to have an idea about the revenue of these PHA and Biogas recovery, an economic study was done.

Conca considers a CH4 market price of 0.12 €/m3 (0.04 €/kg CODCH4) and market price of PHA that ranges from 2 to 5 €/kg PHA.

Finally, the work ends with the life cycle assessment (LCA and LCC) in order to support decision making for the new configuration of Castelfranco Salvatronda WWTP and sludge valorization centre. Indeed, life cycle assessment (LCA) is a technique to quantify the impacts associated with a product, service or process from cradle-to-grave perspective (Corominas, et al., 2013).

The analysis was done, following the main standard steps proposed in the International Standards Organization (ISO) 14000 series: goal & scope, inventory, impact assessment and finally results interpretation.

The analysis was done with the support of the Umberto LCA+, which is a software tool that helps to calculate the potential environmental impacts of products. It uses graphic modelling of the product life cycle, and allows analyzing, assessing and visualizing the environmental impacts in different impact categories.

The goal and scope mean the reason why the LCA is conducted. Indeed, it can be done with different scopes as well as in different fields. It can be applied at a planning level, at design level, for optimization, or to develop new technologies.

In the case of Castelfranco, the goal is to support decision making, in order to enhance the sludge treatment and to develop the more suitable way to recover materials, reduce the impact due to the sludge disposal and improve the energy consumption.

The inventory was completed on the bases of the plant parameters, considering the functional unit (m3 of water treated) to make the values specific and comparable to each other. The support database uploaded in Umberto is ecoinvent: it provides well documented process data for thousand of products, helping to make truly informed choices about their environmental impact. In case in which the process required for this work is not implemented, some simplifications are needed. The assumptions done have been supported by the literature analysis.

Both temporal and physical boundary of the system must be defined. The temporal boundary is referred to 1 year of work at full capacity of the plant. The assumptions for the physical boundary are done considering the transports of all chemicals, products (sludge to composting plant) and by-products (screen ang grit to the landfill), the impacts caused by the chemicals production, the saving of fertilizers (due to for example, the production of compost) and the revenue due to the production of biopolymers and struvite.

In order to define the impact assessment category, a methodology for the LCA was chosen: the ReCiPe 2008. The categories that will be considered are the global warming potential (GWP), the freshwater eutrophication and the fossil depletion.

The interpretation of the results was done with the aim to compare the different Castelfranco scenario analyzed: the As it is configuration and the PHA recovery scenario.

3.3 Full scale plants and mass balances

3.3.1 Castelfranco Veneto

The wastewater treatment plant of Castelfranco Veneto is located in Salvatronda, in the eastern part of the municipal area of Castelfranco Veneto in the province of Treviso (Veneto). The plant is located in a flat area with an altitude of 34 m above the sea level. It was built in 1980 and it was subsequently modernized in several stages in response to the continuous evolution of environmental legislation.

Castelfranco Veneto wastewater treatment plant is managed by the Alto Trevigiano Servizi company, that manage the Servizio Idrico Integrato in Veneto.

The data for the description of the plant and for the mass and energy balance have been taken from the technical report of the plant both for the As it is that for the design scenario.

Description of the As it is configuration

The wastewater treatment plant (WWTP) of Castelfranco Veneto Salvatronda has a design treatment capacity of 73300 PE. The flow diagram of the plant can be seen in the appendix 1a. Wastewater partially come from a separated sewer network and partially from a mixed sewer. A pumping station feeds pre-treatment units of screening and aerated grit removal, followed by primary settling. Biologic treatment is characterized by a conventional CAS (MLE) with chemical precipitation of phosphorus (PAC dosage). From secondary sedimentation wastewater can be sent directly to the disinfection UV unit or pass before through a previous step of tertiary filtration.

Sludge line treats sludges from the wastewater stream of the plant, together with other pre-thickened sludges coming from other plants and sludges from settling tanks. Sludge treatment is made up by a thickening unit, anaerobic digestion (not operative at the moment), dewatering and drying beds. Actually, in Salvatronda WWTP, in addition to urban wastewater, also external liquid wastes are collected and treated in the sludge line, after being pre-treated by grit removals and biological process.

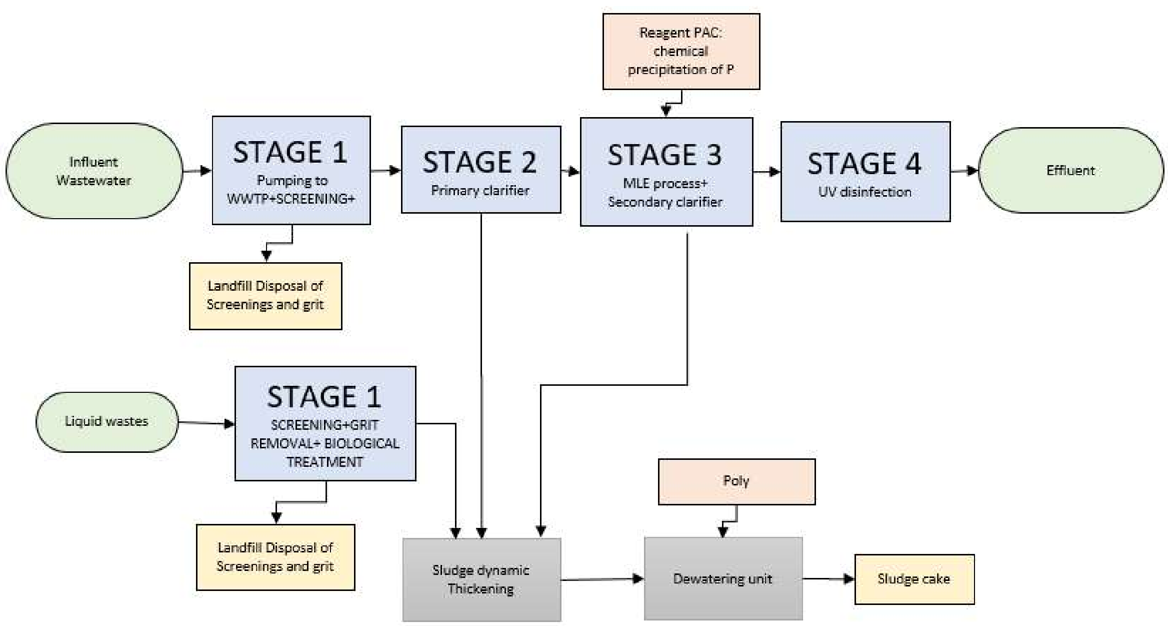


Figure: 17 Salvatronda WWTP as it is

At the moment, in addition to Salvatronda WWTP, 9 WWTPs in the nearby territory of Salvatronda are collecting their thickened sludge to composting plants and 79430 PE in the territory are not collected and not jet treated.

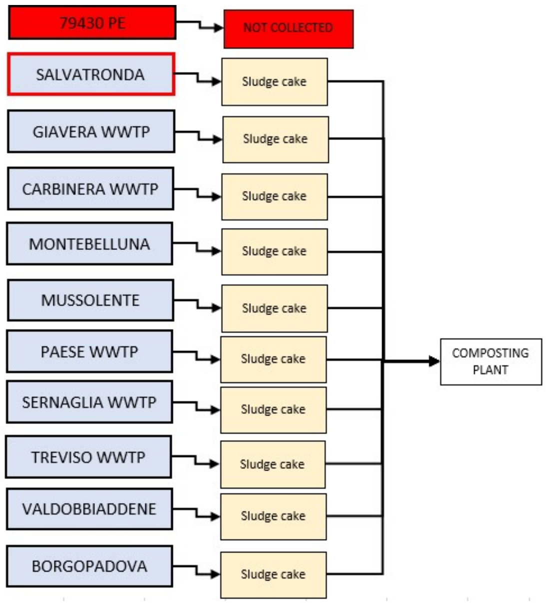


Figure: 18 Territorial scenario before the up-grade of Salvatronda sludge center

Table 31 Sludge quantity and Transport before the up-grade of Salvatronda sludge center

WWTps	Ton sludge/y	TS%	Ton TS/y	km/y (for disposal)
SALVATRONDA	6110	19	1161	41265
Giavera	951	14	133	7790
Carbonera	1733	22	381	12775
Montebelluna	3068	19	583	22477
Mussolente	665	18	120	7252
Paese	4232	25	1058	28684
Sernaglia	426	20	85	3655
Treviso	3419	23	786	29666
Valdobbiadene	655	16	105	4250
Borgopadova	2919	26	759	19479
			TOTAL	**177293**

Description of the design configuration

Plant upgrading will allow to reach a treatment capacity of 120000 PE in the wastewater stream, while the sludge line will become a centralized site for treatment and valorisation of sludge from other plants in the territory.

The sludge treatment line is designed with the aim to obtain the maximum reduction of the overall economic and environmental costs.

The planned pretreatment sections consist of an initial wastewater lifting station equipped with 4 Archimede screw pumps. The civil building is designed for the possible installation of an additional future pump. Downstream of the lift, the fine sieving system is provided with an opening of the holes of 5 mm n two independent channels. The screening material is sent to a washing and compacting press to be stored in a container.

The primary filtration system consists of self-cleaning belt filter units with high separation capacity of suspended solids present in wastewater. With a total useful filtration surface of 20 m^2 (10 filters with 2 m^2 area for each), they replace two primary settlers with a diameter of 26m and guarantee the removal of the TSS up to 50%, much higher than that of the primary sedimentation tank, equal to 30-35% (table 32).

Table 32 Characteristics of the primary filtration

Unit volume	2	
Cis	62,5	m3/m2/h
E% SST	50	%
E% COD	38	%
E% BOD5	37,5	%
E% TKN	13,1	%
E% P	32,4	%

The primary filtration system is installed inside a new closed building, with a total area of 375m^2. Downstream of the primary filtration, a flow deflector is provided for existing and design biological treatment lines: 60% of the flowrate and loads (72.000 PE) is sent to the existing biological treatment lines while 40% (38.000 PE) is sent to the new lines.

The design foresees the addition of two new independent activated sludge lines with pre-dentitrification and oxidation-nitrification process, which work in parallel with the existing lines of the plant.

The new biological treatment lines and the existing ones are sized and organized to be able to operate either according to the MLE scheme or with the Biological Nutrient Removal (BNR) process with intermittent aeration (IA).

Table 33 Characteristics of the bioreactor (MLE and BNR configurations)

		MLE	BNR
n° of lines		3	3
Total Anaerobic Volume		/	2210
Total Anoxic Volume	m3	11284	9074
Total Aerobic Volume	m3	10700	10700
Total Volume	m3	21984	21984
HRT	H	18	18
R ratio	-	1	1
IR ratio	-	4,8	4,8
FeCl3 40%	kg/d	2400	/
Acetate	Kg/d	/	4800

The BNR configuration requires the addition of external carbon to ensure the biological removal of the two main nutrients: nitrogen and phosphorus.

The MLE configuration needs the FeCl3 dosage for the chemical precipitation of phosphorus.

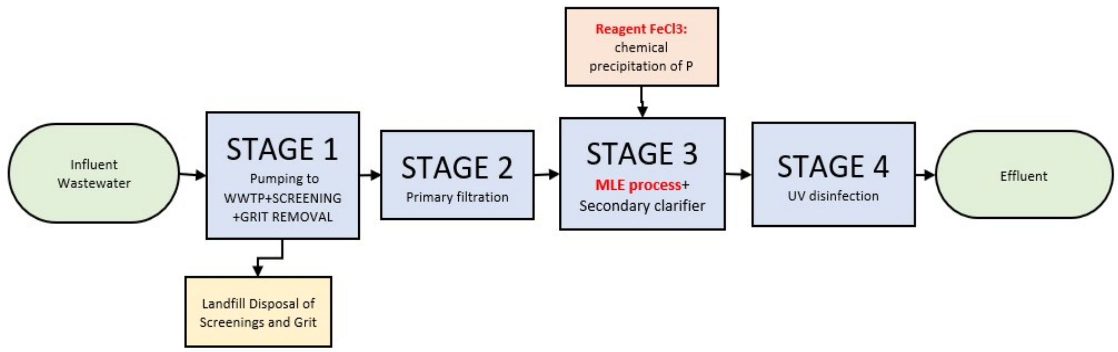


Figure: 19 MLE configuration of water line

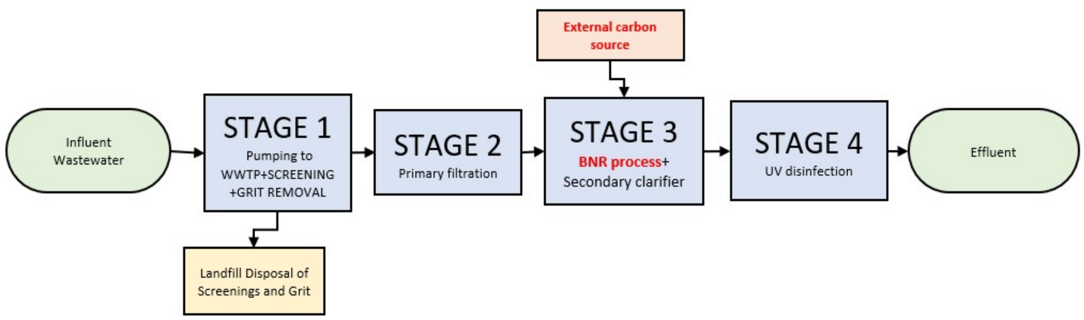


Figure: 20 BNR configuration of water line

The new biological treatment lines are organized through 6 reactors in series: the first is anaerobic, the next four operates with intermittent aeration (nitrification/denitrification) and the last reactor always works in oxidation conditions.

The two design biological lines are equipped with independent pumping station for the recirculation of the aerated mixture. The oxygen transfer to the nitrification process occurs thanks to insufflated air produced by a blower station that serves the two new treatment lines.

The plant is equipped with a flocculant storage and dosage system to integrate the process in case in which the plant does not reach the required phosphorus limit value. Furthermore, a storage and dosing plant of acetic acid (or other readily biodegradable carbon source) is foreseen to be dosed in the process if the carbon content in the wastewater is not enough for the removal of the necessary nitrogen. The dosage takes place in the flow divider at the biological treatment line.

The secondary sedimentation section is enhanced with 3 additional radial flow settlers with diameter 25 meters. Thus, the secondary sedimentation section will consist of 4 clarifiers with 25-meter diameter and 4 settlers with 20-meters diameter.

Table 34 Characteristics of the secondary clarifiers

n° of lines	8	
Total Volume	9755	m3
CIS(D=25m)	0,42	m3/m2/h
CIS(D=20m)	0,37	m3/m2/h
HRT (D=25m)	9,4	h
HRT (D=20m)	4,9	h
SRT	22	d

As in the case of the actual plant, the treated water, after the secondary settler section is measured with an electromagnetic induction flowmeter and, according to the content of suspended solids, it can be sent directly to disinfection and subsequently to discharge, or sent to the filtration section and from here to the disinfection. The final filtration section, As it isly equipped with 3 filters with 80 m^2 of surface each, is enlarged by installing additional 380 m^2 filters in the tanks.

The final disinfection system of the purified water is enhanced by installing an additional module in one of the other two channels already present in the building.

The treated water is finally discharged into the Salvatronda canal.

The design changes on the sludge line of the treatment plant aim to treat not only the sludge produced in the water line of the Salvatronda plant, but also all the dried sludges coming from the plants managed by Alto Trevigiano Servizi.

The idea is to reduce as far as possible the final amount of sludge to be disposed and maximize the biogas production and the energy availability for the facilities.

The sludge treatment line is composed by a new mechanized thickener for the primary sludge. It is characterized by 510 m^3 volume, 6.3 days HRT and a removal capacity of 100%.

The supernatant (8 m^3/d) is sent in the water line before the biological treatment, while the sludge continues in the sludge line entering in a 500m^3 fermenter. Here the sludge is fermented at 37-38 °C in order to produce a sludge rich in Volatile Fatty Acid (VFA) which is the most readily biodegradable carbon.

After the fermenter the sludge is sent to the dewatering to increase the solid percentage from 5% to 16,5%. The supernatant, rich in VFA, are sent to special storage tanks, while the sludge goes in another storage tank (300 m^3 volume) where it will be mixed with the other sludges (biological and treated ones).

On the other hand, the biological sludge, coming from the water line, meets at first two pre-thickeners, characterized by 100% of removal capacity and a total volume of 1000m^3, as summarized in the table (Table 35).

Table 35 Characteristics of the prethickeners

n° of lines	2	
unit volume	500	m3
E% SST	100	%

Now, the sludge enters in the dewatering process, where it is dewatered up to 16,5% of solid percentage to be subsequently stored in the storage tank where the primary sludge was accumulated.

As said before, the plant, according to the final design, must also treat the sludge coming from other plants managed by ATS. They, in particular, come from Treviso, Castelfranco Borgo Padova, Montebelluna S. Gaetano, Carbonera, Giaviera del Montello, Mussolente, Valdobbiadene e Semaglia della Battaglia, reaching a total of 16.063 ton tq/y, with 3.884,4 ton TSS/y.

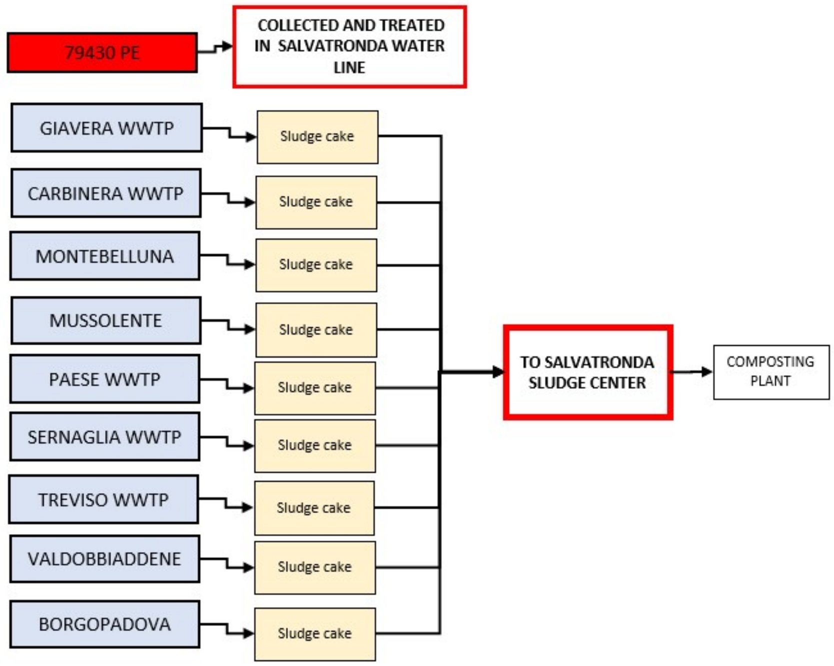


Figure: 21 Territorial scenario after the up-grade of Salvatronda sludge center

Table 36 Sludge quantity and Transport after the up-grade of Salvatronda sludge center

EXTERNAL SLUDGE	Ton sludge/y	TS%	Ton TS/y	km/y
Sludge of 9 WWTPs to Salvatronda	18288	22	4023	17483
Disposal from Salvatronda to composting plants	4560	90	4104	31893
			TOTAL	**49376**

Before entering the Thermal hydrolyzation process (THP) the sludge is subjected to a dosage of water (20m3/d).

The digestion occurs in 2 digestors characterized by a volume of 4000 m3 and at 39-40°C temperature. The energy requirement for maintaining the process temperature is guaranteed by the cooling heat of the sludge from the thermal hydrolysis process in the previously carried out heat exchange plant.

The amount of biogas corresponds to 5000 Nm^3/d (5280 Sm^3/d) with a percentage of methane equal to 50%.

The biogas is extracted from the dome of each digester and stored in two members gasometers for subsequent use inside the plant.

It can be used in two different configurations. If it is sent to the boiler (configuration R2a), it produces 25096 kWh/d of thermal energy. While if the biogas is used in the CHP-Combined Heat and Power (configuration R2b), it produces 7261 kWh/d of thermal energy and 13964 kWh/d of electric energy. Obviously, the amount of energy produced by the CHP is lower to the one produced by the heater because of the losses due to the cogeneration system.

Once it comes out of the digester, the sludge enters the phosphorus recovery system, composed by two tanks with a total volume of 120 m3. The HRT of the process is 13-14 h and the struvite recovery capacity amounts to 50% of the removed P-PO4. The MgCl3 (33% in solution) used for this process, has the aim to promote the precipitation of Magnesium-Ammonium-Phosphate.

The sludge is sent in an accumulation basin (518 m3 volume, 2,35 d storage time) before being sent to the centrifuge system composed by 1 decanter and 1 belt press, that have a removal capacity equal to 95% TSS. Finally, the sludge is dried with a thermal treatment characterized by a volume of 100m3 and an HRT of 10,4 h. The temperature used for drying the sludge I 140°C.

It is important, speaking about the sludge line, to describe also the supernatant treatments. The supernatant coming from the last centrifuge enters the Dissolved Air Flotation system (DAF), where the removal of the solids with a yield higher than 85% occurs. The DAF is a solid-liquid separation system with the dissolved air flotation method characterized by a low volume and low-profile flotation tank. The volume of the basin is 16,6 m3 and the HRT 97 min. The process system takes place with total or partial flow pressurization or with recirculation, according to the process requirements. The system is centrally feeded from the bottom part of the tank. A fixed central sector distributes the inlet flow radially, homogeneously and regularly over the entire area of the tank, allowing pre-constituted flocks enriched with air bubbles to float immediately on the surface. The formation of the floating layer on the surface begins in the center immediately after the rising water flow and extends immediately towards the external parts of the tank. The floating material is removed by means of a rotating collector located on a mobile bridge and conveyed by gravity to the central part of the flotator. The process occurs helped by a flocculant that is dosed in the tank in in quantities equal to 2-5 g/kg TS.

The water coming from the DAF system joins the water from dryer to enter the supernatant storage compartment (400 m3 volume). For the removal of the nutrients present in the anaerobic supernatants, in order to not overload the water treatment line of the plant, a “nitrite” pre-treatment system is planned on a biological SBR reactor. The nitrite pre-treatment system allows for the reduction of up to 85% of the nitrogen and phosphorus present in the water with a lower production of excess sludge and lower energy consumption for the oxidation of ammonia compared to the nitrification process. SCENA technology is provided for the biological pretreatment of supernatants (Short Cut Enhanced Nutrient Abatement) developed to full scale by Alto Trevigiano Servizi.

The sludge produced in this process is sent before the dewatering of the WAS sludge, while the treated water, low in nitrogen and phosphorus is sent before the biological treatment.

To avoid the propagation and emissions of disturbing odors, the potentially odorous treatment sections are equipped with covers or confined inside buildings and are kept under negative pressure.

In particular, the following treatment areas are covered:

- Arrival of sewage sludge and initial lifting with Archimedes screw pumps
- Fine screening
- Oil and sand removal treatment
- Primary filtration
- Mechanical dewatering
- Digested sludge accumulation tank
- Mechanical sludge centrifuge
- Storage tank and SBR reactor for pretreatment via nitrite of anaerobic supernatants
- Sludge dryer

All these elements, with the sole exclusion of the sludge dryer, which is equipped with its own air treatment system, are connected to an air intake and collection system, which keeps them under negative pressure, guaranteeing the suction of an hourly volume of air.

Mass and energy balance in the As it is configuration

Since the LCA requires the study of the plant and the organization of the inventory, the mass and energy balance must be conducted. The complete mass flow of the plant can be seen in appendix 1b.

Starting from the mass balance of the As it is configuration, the first element to be analyzed will be the *liquid waste line* from which 24.82 m^3/d of flowrate come in the plant in order to be treated.

Table 37: Liquid waste line characterization

FLOW	24,82	m3/d
COD	335,8	kgCOD/d
TP	2,5	kgTP/d
TKN	10,5	kgTN/d
TSS	298,2	kgTSS/d

The screen and the sand from the pretreatment processes of the *liquid waste line* are sent, together with the water line screen and sand, in the landfill, while the sludge is sent to the oxidation tank and then to the sludge line. The table 38 shows the characteristics of the liquid waste that enters in the thickener of the sludge line.

Table 38 Characteristics of the liquid waste that enters in the thickener of the sludge line

FLOW	24,82	m3/d
COD	404,5	kgCOD/d
TP	4,1	kgTP/d
TKN	8,0	kgTN/d
TSS	305,5	kgTSS/d

From the sewers, an amount of 12320m3/d of flowrate comes in the plant, characterized by the presence of COD, BOD and all other pollutants.

Table 39 Characterization of the wastewater

FLOW	12320	m3/d
COD	4868	kgCOD/d
BOD	2391	kgBOD/d
TN	519	kgTN/d
N-NH4	480	kg/N-NH4d
TP	77	kgTP/d
TSS	2667	kgTSS/d
E.coli	5050769	CFU/100 ml

After the pre-treatments (screening and degritting), the pretreated influent comes in the primary clarification tank. The total amount of screen is 84737 kg tq/d and the total amount of sand is 274460 kg tq/d.

The primary settler characteristics are unknown, so the removal percentage are calculated the literature proposed by Metcalf&Eddy:

$$R\%=\frac{1}{a+b*HRT}$$

Where

R%: expected removal efficiency

HRT: hydraulic retention time of the primary clarification tank a, b: empirical constants

Typical values for the empirical constants at 20°C are as follows:

Table 40 Typical values for the empirical constants at 20°C

	b	a
BOD	0,02	0,018
TSS	0,014	0,0075

The calculation gives these results, considering the removal efficiency of the COD equal to the one of the BOD.

Table 41 Removal efficiency of the primary settler

E% COD	35,1	%
E% BOD5	35,1	%
E% N	17,6	%
E% P	29,6	%
E% TSS	67,4	%
N%TS	4	%
P%TS	1	%

The effluent from this process enters in the biological reactor and has the following characteristics:

Table 42 Characteristics of the water entering in the bioreactor

FLOW	12.553	m3/d
COD	3.160	kgCOD/d
BOD	1551,9	kgBOD/d
TN	428	kgTN/d
N-NH4	480	kg/N-NH4d
TP	54	kgTP/d
TSS	1.106	kgTSS/d

The biological reactor is made by two denitrification tanks and four nitrification-oxidation tanks. This process has the aim to stabilize the organic matter and to remove the nitrogen which is subsequently released in the atmosphere in the form of N2. The phosphorus removal occurs chemically thanks to the dosage of the polyaluminium chloride (575.4 kg PAC/d). The internal recycle is important for the denitrification to take place.

After the biologic process the water enters in the secondary clarifier, where, with an HRT of 5 h the sludge settles. Part of this sludge recirculate in the bioreactor (24685,0 m3/d), the remaining part is the activated sludge that goes toward the sludge line to be treated (225 m3/d).

The water from the secondary clarifier is sent to the UV disinfection or to the filtration before it is released into the environment as water in the river. The output characteristics of the water must follow the regulations of the environmental framework D. Lgs 152/2006 ("Testo Unico Ambientale").

The amount of pollutants is schemed in the following table (Table 43):

Table 43 Characteristics of the ouflow

FLOW	2.553	m3/d
COD	249	kgCOD/d
BOD	64	kgBOD/d
TN	93	kgTN/d
TP	6	kgTP/d
TSS	64	kgTSS/d
N-NH4	8	kgN-NH4/d
N-NO3	54	kgN-NO3/d
E.coli	158	CFU/100 ml
Conc COD	19,8	mgCOD/l
Conc BOD	5,1	mgBOD/l
Conc TN	7,4	mgTN/l
Conc TP	0,45	mgTP/l
Conc TSS	5,1	mgTSS/l
Conc N-NH4	0,6	mgN-NH4/l
Conc N-NO3	4,3	mgN-NO3/l

It can be seen that these values are below the limits proposed by the law. Since the Water is released in the Salvatronda canal, that reach the Venice Lagoon, the limits to be followed are the ones proposed by the table 1 and table 2 of the "Testo Unico Ambientale".

The sludge from the liquid waste line, from the primary and secondary clarifier of the water line enter in the dynamic thickener, where the sludge is thickened before passing to the dewatering.

Table 44 Characteristics of the sludge that enters in the thickener

FLOW	290	m3/d
TSS	3.881	kgTSS/d
TS%	1,34	%

The thickener has a percentage of thickening of 86% so that the sludge that goes towards the dewatering amounts to 160m3/d. The sludge that has to be disposed, produced in this plant is 16739 kg tq/d (16.7 m3/d) with the characteristics showed in the following table (Table 45):

Table 45 Characteristics of the produced sludge

FLOW	16,7	m3/d
Quantity	16739	kg TQ/d
TSS	3160	kgTSS/d
TS%	18,9	%

The energy balance has been implemented knowing the electrical energy consumption of the machinery:

Table 46 Energy consumption

Electrical energy (entire liquid waste line)	82,4	kWh/d
Electrical energy (PAC dosage pumps)	219,0	kWh/d
Electrical energy (pumping and screening)	293	kWh/d
Electrical energy (sand and oil removal)	0	kWh/d
Electrical energy (pumps of primary clarifier)	61,9	kWh/d
Electrical energy (denitrification tanks)	1020,17656	kWh/d
Electrical energy (oxidation tanks)	1547,417	kWh/d
Electrical energy (secondary clarifier)	479,8926	kWh/d
Electrical energy (filtration unit)	16,93	kWh/d
Electrical energy (UV disinfection process)	290,9048	kWh/d
Electrical energy (dynamic thickener)	423,0838	kWh/d
Electrical energy (dewatering)	308,4	kWh/d
Total electrical energy consumed	**4743**	kWh/d

The complete energy flow of the plant can be seen in appendix 1c.

Mass and energy balance in the design configuration

Starting from the water line, it is important to say that the Castelfranco Veneto wastewater treatment plant is designed to ha a design capacity of 120.000 PE. The complete mass flow of the plant can be seen in appendix 1e.

The idea, as said in the previous chapter is to allow operation using either MLE (Modified Ludzack-Ettinger) or BNR (Biological Nutrient Removal) configuration, so the mass balance will be differentiated for these two scenarios.

Actually, the only difference that can be notice is that in the case of MLE, a dosage of $FeCl_3$ is required in order to remove the phosphorus in the water line. On the contrary, the other scenario is able to remove the phosphorus biologically, because is equipped with an anaerobic reactor, an anoxic reactor and finally, with an aerobic tank.

The biological phosphorus removal requires the presence of the Phosphorus Accumulating Organism (PAO), which are microorganisms able to release the P in the form of PO_4 (ortophsphate) in anaerobic environment and to uptake it in the aerobic environment. This kind of process needs also the presence of carbon source (readily biodegradable organic matter, such as VFA) that is uptaken in the anaerobic phase and use as source of energy to build the poly-P chain. This kind of bacteria are able to perform the same P uptake in anaerobic condition, together with the anoxic one. The only difference is that, instead of using oxigen, it uses nitrites as electron acceptors. These microorganisms are called Denitrifying Phosphorus Accumulating Organism (DPAO).

This process, called “luxury uptake”, is very important, because combining different reactors with different oxygen conditions (anaerobic+anoxic+aerobic), the removal of phosphorus, nitrogen and carbon is insured.

The wastewater coming from the sewer amounts to 30.000 m3/d and enters in the pretreatments.

Table 47 Wastewater coming from the sewer characteristics

FLOW	30.000	m3/d
COD	13.500	kg COD/d
TN	1.605	kgTN/d
N-NH4	1.194	kgN-NH4/d
TP	230	kgP/d
TSS	7.290	kgTSS/d

As said before, the biological reactor process is different for the two configurations. Indeed, the case in which the iron is dosed (MLE configuration), is the one characterized by a higher final phosphorus value. The reason is linked to the fact that the chemical phosphorus removal is less efficient with respect to the other biological method. The other different result is the nitrogen mass load. The removed nitrogen is higher in the case of BNR, maybe because the biological removal of phosphorus uses the nitrogen as electron acceptor in the anoxic phase, as explained in the initial part of this chapter.

These values are taken from the simulation done with the software Advanced Simulation Platform. Indeed, although there is still another process (UV disinfection) the concentration that are found after the secondary sedimentation are found in the effluent.

Table 48 Characteristics of the effluent

		MLE	BNR
FLOW	m3/d	30.167	30.167
COD	kg COD/d	347	347
TN	kgTN/d	291	205
N-NH4	kgN-NH4/d	14	2
TP	kgP/d	25	13
TSS	kgTSS/d	36	33

In fact, the UV disinfection is useful to reduce the level of coliforms in the water, but it does not modify the concentrations of pollutants.

Let's continue the description of the plant, talking about the energy balance of both the scenarios. Actually, they are the same, less the energy consumed by the bioreactors and the energy consumed for the iron (MLE configuration) and external carbon (BNR configuration). The following table (Table 49) shows the energy consumption values. Obviously, obviously the process in which more energy is consumed is biological process.

Table 49 energy consumed in the plant

		MLE	BNR
Pumping (energy consumed by the pumps)	kWh/d	1488,4	1488,4
Sand and oil removal (energy consumed for the aeration)	kWh/d	246,6	246,6
Sand CER 19 08 02 (energy consumed by the pumps)	kWh/d	12	12
Primary filtration (energy cosumed by the pumps)	kWh/d	213,2	213,2
Sludge line pretreated supernatant (energy consumed by the pumps)	kWh/d	5	5
Sludge line supernatant (no treated)	kWh/d	7,28	7,28
MLE bioreactor (energy consumed by the aeration)	kWh/d	5516	7394
FeCl3 (energy consumed by the pumps)	kWh/d	28,8	-
Acetate (energy consumed by the pumps)	kWh/d	-	24
Secondary clarifier	kWh/d	137,6	137,6
UV disinfection	kWh/d	794,4	794,4
TOTAL	kWh/d	8449,28	10322

These calculation and results are useful for the construction of the inventory required for the LCA. It will be the argument for the following chapters (paragraph 3.5.1).

The design configuration on the sludge line of the treatment plant, as already mentioned above, aim to treat not only the sludge produced in the purification processes at the Salvatronda treatment plant but also all dehydrated sludge from the purifiers managed by Alto Trevigiano Servizi.

The technologies envisaged in this final project allow to achieve the maximum reduction in the annual management costs of the purifiers, with particular regard to the costs of sludge disposal.

Indeed, design configuration involves the adoption of technologies aimed at obtaining the maximum reduction in the final quantities of sludge to be disposed and maximizing the production of biogas.

Both the type of sludges produced from the water line is treated in the thickeners. In particular, the primary sludge is sent in the mechanized thickener, characterized by a volume of 510 m3 and a percentage of TSS abatement of 100%, while the activated sludge, coming from the biological treatment, is thickened in 2 dynamic thickeners with a unit volume of 500m3.

The table (Table 50) below presents the characteristics of both the sludges.

Table 50 characteristics of the primary and biological sludge

		PRIMARY SLUDGE	WAS SLUDGE
Flow	m3/d	81	398
TS%	%	4,5	1
TSS	kgTS/d	3645	3980
N%TS	%	4,6	6,00
P%TS	%	2	5,00
N	kgN/d	168	238,8
P	kgP/d	73	199
COD	kgCOD/d	2624,4	2340

The thickeners have the goal to promote the solid-liquid separation of the material. The characteristics of the sludge after this treatment are listed in the following table (Table 51):

Table 51 Characteristics of the pre-thickened primary sludge and of the ore-thickened biological sludge

		PRE-THICKENED PRIMARY SLUDGE	PRE-THICKENED BIOLOGICAL SLUDGE
Flow	m3/d	72,9	159,2
TS%	%	5	3
TSS	kgTS/d	3645	3980

The supernatants from these processes come back to the water line, where they are treated together with the water that enters from the sewer. In partcular, they retrace the water line, starting from the biological treatment and amounts to 247 m3/d: 8 m3/d from I sludge and 239 m3/d from the biological one, with a concentration of TSS equal to 0.

The primary thickened sludge is used to produce the organic matter (VFA) useful for the biogas production. Indeed, it is sent in a fermentation tank with a 500 m3 volume, characterized by an HRT (hydraulic retention time) of 7 days and a working temperature of 35-40°C. The most important characteristic of this process is that, since there is no recycle, the HRT (hydraulic retention time) is equal to the (sludge retention time).

The following step, the dewatering process, requires the dosage of a chemical, called polyelectrolyte. It is able to promote flocculation by neutralize the electric charges of suspending particles in the water and unstabilize the particles. In particular, a polyelectrolyte at 0.2% of solution and quantity of 7,5 gPOLY/kgSS is dosed.

The dewatering process is characterized by a percentage of TSS abatement of 95%, so that the solids in the dewatered sludge is 3463 kgTSS/d.

The supernatant from this process is sent in an accumulation tank, where it is stored before entering in the anaerobic supernatant treatment.

Coming back to the biological sludge (tab26), it is treated in a dewatering process, after being mixed with the sludge from the anaerobic supernatant treatment, process that will explained in the following pages

This dewatering process has the same characteristics of the other, so a percentage of TS abatement of 95% and the required dosage of polyelectrolyte.

Table 52 characteristic of external sludges

Plant	**Flowrate (t/y)**	**%TS**	**VSS/TSS**	**TSS (t/y)**	**VSS (t/y)**
Paese	4088	27	67	1103,8	739,5
Treviso	3433	25	70	858,2	600,8
Castelfranco Borgo Padova	2587	22	80	569,1	455,3
Montebelluna S. Gaetano	2465	23	73	567	413,9
Caronera	1596	25	68	399	271,3
Giaviera del montello	555	20	75	111	83,3
Mussolente	536	21	80	112,6	90
Valdobbiadene	496	20	80	99,2	79,4
Sermaglia della Battaglia	307	21	73	64,5	47,1
Tot	16063			3884,4	2780,6

As already mentioned, the project also aims to create a platform for the treatment, minimization and valorization of the sludge produced at the Salvatronda treatment plant and of all the dewatered sludge produced by the treatment plants in the Alto Trevigiano Servizi area.

The table (Table 52) summarizes the sludge flows that comes from the external plants.

Therefore, all the sludge produced at the Salvatronda treatment plant and that delivered by the other plants are accumulated in a dehydrated sludge storage silo with a nominal volume of 300 m3. These are the characteristics of the mixed dewatered sludge + external sludge.

Table 53 Characteristics of the mixed dewatered sludge + external sludge

Flow	93,8	m3/d
TS%	19,5	%
TSS	18300	kgTS/d
N	888,9	kgN/d
P	485	kgP/d

Generally, the sludge is sent in the silo on five days a week while its emptying takes place on seven days a week because the operation of the THP thermal hydrolysis process takes place continuously 7 days a week for 24 hours a day. The volume of the silo therefore guarantees an autonomy of storage of more than 3 days.

All the sludge is sent to the thermal hydrolysis process (THP). It is a thermal and physical-mechanical treatment that hydrolyzes and disintegrates the pre-dehydrated sludge, transforming it into a sterilized and easy-to-digest product.

The THP process allows to obtain the following benefits and advantages:

▪ Increase in the efficiency of the anaerobic digestion process with greater production of biogas and lower quantities of digested sludge;

▪ Increase the dewatering capacity of the digested sludge which can reach a dry content higher than 30%

▪ Sterilization of sludge (temperature of 165 ° C for 25-30 minutes);

▪ Reduction of the amount of sludge sent to thermal drying with less water to evaporate and sludge to be disposed.

The thermal hydrolysis process is of the "batch" type, consisting of a system of reactors operating in sequence (Sequencing Batch Hydrolysis Reactors - SBHR), in which the sludge is subjected to heating and pressurization, followed by a contact time in reactors for at least 25-30 minutes at a temperature between 150 and 170°C and at a certain pressure, before carrying out a rapid pressure reduction of at least 3.5 bar.

The cooling water is taken from the water network of the industrial technical water of the plant (purified and disinfected water) fed by the pressurization unit installed in correspondence with the UV disinfection system.

For the anaerobic digestion of the sludge, two new anaerobic digesters are realized, each with a usable volume of 2,000 m3.

An average of 18.781 kgSST/d of hydrolyzed sludge is sent to the digestion process with a dry concentration of 6.1%.

The role of the digesters is twofold: on the one hand it must degrade the organic matter of the sludge, on the other it has the purpose of recovering biogas.

The digester works with an HRT (=SRT) equal to 18-20 days, in anaerobic condition, in order to promote the occurrence of the acetogenic and methanogenic phase. In this case the HRT of the digester is 19,2 days.

The recovered biogas with the anaerobic digesters is 5000 Nm3/d, with about 50% of methane inside. The biogas can be used for different scopes. At first it can be used in the boiler to produce the thermal energy needed for heating some processes, such as the fermenter, the digestor, the dryer or the THP. Actually, if all the biogas is transformed in heat, there will be 25096 kWh/y of thermal energy.

On the contrary, if the biogas is sent in the cogeneration plant, also the electric energy will be produced. In this case, there will be 7261 kWh/y of thermal energy and 13964 Kwh/y of electric energy.

In both cases an amount of external methane, to produce energy, will be necessary, since the energy produced by the plant is not enough.

In the sludge treatment process, the phosphates stored in the Bio-P process are re-dissolved with a significant increase in the content of orthophosphates in the sludge waters. The increase in the content of orthophosphates in the digested sludge, in addition to an increase in the phosphorus content that returns to the top of the plant, can cause problems due to the crystallization of PO4 in magnesium-ammonium-phosphate (MAP/Struvite) with the formation of encrustations in the pipes and systems, and with a reduction in the sludge dewatering efficiency (lower content of SST in the dewatered sludge).

To avoid the problems described above, downstream of the anaerobic digestion process, a plant for the reduction of orthophosphates present in the digested sludge is planned with the recovery of Struvite (MAP) in the form of macrocrystals.

The process reduces the content of orthophosphates in the filtrate by up to 95%, reduces deposits in pipes and systems and increases dehydration efficiency.

Table 54 Struvite recovery process

P-recovered	218	kgP/d
P molecular weight	31	g/mol
Struvite molecular weight	245	g/mol
STRUVITE	1727	kgMAP/d
E%TSS	4	%removed
E% P-PO4	90	%removed
P-recovered	45	%recovered
MgCl3	3,0	LMgCl2/m3sludge

As showed in the table, the recovered phosphorus in form of struvite amounts to 1727 mgMAP/d. It occurs in the tank thanks to the dosage of MgCl3 in order to increase the quantity of magnesium.

As expected, the level of the phosphorus, after the struvite recovery tank, is very low, as the table 54 shows.

After the P recovery, the sludge flows in the centrifuge, that has a percentage of abatement of solids equal to 95%. The sludge after the dewatering, 35 m3/d, goes into the dryer, where thanks to a belts system and hot air system is dried up to a concentration of 90%. The amount of the sludge to be disposed is 4560 ton/y, which correspond to a flowrate of 12-13m3/d.

Coming back to the centrifuge, the supernatant of the dewatering process is sent into the to dissolved air flotation treatment (DAF) where the removal of the solids present takes place with an efficiency higher than 85%. The DAF is a solid-liquid separation plant with the dissolved air flotation method characterized by a low-profile, low-volume circular flotation cell.

As a precaution, the removal efficiency of the incoming TSS is expected to be 70% for which the average daily quantity of sludge extracted from the flotator is equal to 578 kgSST/d. The sludge extracted from the flotator has a dry content of 3% for which the daily volume is equal to 19.3 m3/d.

The process is made more efficient thanks to the dosage of the flocculant (2-5 g/kg TS)

The effluent from the DAF is sent to the accumulation tank, where is mixed with the supernatant from the dryer.

The water in the accumulation tank, together with 52 m3/d of water coming from the treatment of the primary sludge, is sent to the anaerobic supernatant treatment.

For the removal of the nutrients present in the anaerobic supernatant wastewater, in order not to overload the water treatment line of the plant, a pre-treatment plant "via nitrite" on an SBR biological reactor is planned.

The pre-treatment plant via nitrite allows to obtain the reduction of up to 85% of the nitrogen and phosphorus present in the supernatants with a reduced production of excess sludge and a lower energy consumption for the oxidation of ammonia compared to the nitrification process.

For the biological pre-treatment of supernatants, S.C.E.N.A. (Short Cut Enhanced Nutrients Abatement) developed to full scale by ATS in collaboration with the Universities of Verona and Politecnica delle Marche, at the Carbonera treatment plant, is used.

The S.C.E.N.A. process consists of an SBR reactor with a useful volume of 1.000 m3. The process is an SBR (Sequencing Batch Reactor) type in which the following phases take place in sequence:

1. anaerobic supernatants loaded to the reactor;
2. Anaerobic process;
3. Aerobic process;
4. Anoxic process;
5. Sedimentation;
6. Discharge

The effluent water from this process is as followed characterized:

Table 55 Characteristics of the water treated in SCENA process

Flow	259	m3/d
TSS	325	KgTS/d
N	106	KgN/d
P	2,6	KgP/d

The external carbon required for the optimal operation of this process is equal to 400 kgCOD/d.

All the processes that are explained need the electric energy. In some cases, it is required only for the sludge or chemical transport (pumps), in other cases it is needed for the specific process. It is the case, for example, of the dewatering, in which the energy is used for the centrifuge.

The following table (Table 56) shows the energy consumption values. The first values listed are divided between the processes used for the primary sludge and those used for the secondary sludge. The other value, 1608 kWh/d is the one related to the pumps which have the purpose of transporting the sludge from the external sludge storage tank to the mixed sludge storage tank.

This value is higher with respect to the one of the other pumps, not only for the quantity of the sludge to be transferred, but also for its concentration.

Indeed, the external sludge flowrate is 50 m3/d with a solid concentration of 22% TS, while, for example, the primary sludge (for which the pumps use only 19.8 kWh/d) has a flowrate of 81 m3/d and a concentration of 4.5%.

Table 56 Electric energy consumption

	Primary sludge	Biological sludge	External sludge	
Sludge pumps (pumps to transport the sludge from water line to thickener)	19,8	31,86	-	kWh/d
Pre-thickening (energy consumed by pumps)	18	21,6	-	kWh/d
Fermenter (electric energy consumption)	230,9	-	-	kWh/d
First dewatering (electric energy consumption)	802,8	802,8	-	kWh/d
POLY (electric energy consumption due to the dosage pumps)	10,3	10,3	-	kWh/d
Pumps in the accumulation (to transport the supernatant into the anaerobic supernatant treatment)	385,9	-	-	kWh/d
Pumps in the external sludge accumulation tank (energy used to send the sludge in the accumulation tank where the mixed sludge tank)	-	-	1608	kWh/d
	Mixed sludge (I+WAS+Ext)			
Accumulation tank pumps (Energy used to transport the mixed sludge to THP pocess)	908,4			kWh/d
THP (electric energy consumption)	1248			kWh/d
Digestor (electric energy consumption)	694,4			kWh/d
P-recovery process (electric energy consumption)	4748,3			kWh/d
Second dewatering (electric energy consumption)	1277,8			kWh/d
POLY (electric energy consumption due to the dosage pumps)	28,3			kWh/d
Thermal treatment (electric energy consumption)	4840,8			kWh/d
DAF (electric energy consumption)	127,8			kWh/d
Flocculant (electric energy consumption due to the dosage pumps)	1,6			kWh/d
Pumps to transport the water from accumulation tank to Anaerobic supernatant treatment	37,9			kWh/d
Anaerobic supernatant treatment (electric energy consumption)	415			kWh/d
Exausted air to air treatment (electric energy consumption)	832			kWh/d
Biogas to CHP	16			kWh/d
TOT	**19118,56**			kWh/d

Let's consider the thermal energy consumed by the processes. It is used to heat the fermenter and the digestors that work with a temperature of 35-40°C, in order to produce organic matter.

Further, the THP uses thermal energy to sterilize the sludge at temperature of 165 °C. Anyway, the process that consumes the higher value of thermal energy is the thermal process, that while the sludge is transported along the dryer, remove the water contained in the sludge using a stream of hot air. The table (Table 57) shows the values of thermal energy consumed.

Table 57 Thermal energy consumption

Fermenter	2399	kWh/d
THP	12813	kWh/d
Digestor	1636,1	kWh/d
Thermal treatment	22198	kWh/d
TOT	**39046**	**kWh/d**

Part of this energy can be provided by biogas. Indeed, the biogas, which is recovered in the anaerobic digestor gasometer, can be sent to the boiler or to the cogeneration process.

In the first case, the boiler transforms all the biogas in thermal energy; in the second case part of these become thermal energy and part become electric one.
The following table (Table 58) resumes the production of energy from biogas in both of the cases.

Table 58 Energy consumption in case of boiler

Energy consumption in case of boiler

19119	kWh/d	electrical energy needed by the plant
39046	kWh/d	thermal energy needed by the plant
-25093	KWh/d	energy produced by the boiler
13953	**kWh/d**	**TOTAL thermal energy consumption in case of boiler**

Table 59 Energy consumption in case of CHP

Energy consumption in case of CHP

19119	kWh/d	electrical energy needed by the plant
39046	kWh/d	thermal energy needed by the plant
-7261	kWh/d	electrical energy produced by the CHP
-13964	kWh/d	thermal energy produced by the CHP
11858	**kWh/d**	**TOTAL electrical energy consumption in case of CHP**
25082	**kWh/d**	**TOTAL thermal energy consumption in case of CHP**

The complete energy flow of the plant can be seen in appendix 1f.

3.3.2 Modena

The Canale Naviglio wastewater treatment plant is located in Modena in the north-east part of the city. It is situated in the Emilia Romagna region, so it is managed by the HERA company.
It was built in 1983 and then in the following year it was modernized in order to meet the environmental legislation needs.
It has a nominal potentiality of 500.000 PE, but actually, basing the calculation on the actual inlet BOD5 value, it serves 91087 PE. The plant treats also an amount of industrial sludge that corresponds to 14113 PE.
The structure of the water line of Canale Naviglio plant develops according to the conventional sequence of operation unit, except for primary settle, that is used only as accumulation tank for the WAS sludge:

- Pre-treatments
- Biological treatment
- Secondary sedimentation
- Membrane filtration and disinfection

The analysis was conducted considering the average of three years, from 2017 to 2019. The data for the description and for the mass balance have been provided by the plant and the company that manage it.

Description

The wastewater coming from the sewage (83.383 m3/d) is treated at first in the pretreatment process. The coarse screening process is required to avoid breaking down the pipes and the pumps in the following steps. The water is then transported to the fine gritting and sand-oil removal process thanks to a lifting system composed by 1 screw pump and two centrifugal pumps.
The table 60 shows the characteristics of the pretreatment processes.

Table 60 characteristics of the pretreatments

Coarse screening		
n. of lines	n°	2
hole dimension	mm	50
Q of the pump	m3/h	3600
Fine screening		
n. of lines	n°	2
hole dimension	mm	6
Aerated gritting		
n. of lines	n°	2
length of the tank	m	37,5
width of the tank	m	4
high of the tank	m	4,7
Area	m2	300
extraction sand pumps	n°	2
Q of the pumps	m3/h	150

The water flow bypasses the primary clarifiers to reach directly the biological process, to keep COD and BOD5 in order to safeguard the biological removal of nitrogen. The biological sludge is sent to the primaries, therefore the sludge is extracted and sent to the sludge line. In the actual state, the primary settlers are destined to thicken the biological sludge and the influent is sent directly to the biological step.

Table 61 Characteristics of the primary sedimentation

Primary Sedimentation	n	4
Type	-	circular
Diameter	m	42
Single Area	m2	1385
Total Area	m2	5539
Average High	m	3,9
Total Volume	m3	21200
Bottom Slope	%	8

The plant does not adopt the biological phosphorus removal processes, that is strictly linked to the availability of "carbon" or to a high COD/Ntot ratio in input.

The plant is divided in two lines: the first one composed by 3 denitro-nitro bioreactors, feeded by 60% of the total flow wastewater and the other with 2 bioreactors. More detailed information are listed in the following table.

Table 62 Characteristics of the biological reactors (line 1 and line 2)

		Line1	Line 2
	n° reactors per line	3	2
Unit volume (aer+anox)	(m3)	7200	8150
Length of the reactors	(m)	57	60
Width of the reactors	(m)	28,6	30
High of the reactors	(m)	4,4	4,5
Total Volume (of all the bioreactors)	(m3)	21600	16300
Aerobic volume	(m3)	14400	10866,7
Anoxic volume	(m3)	7200	5433,3
Type of diffusers	-	Xylem EPDM S2	Xylem EPDM S2
Number of diffusers for each subline	n°	2838	2365
Total number of diffusers for each line	n°	8514	4730

The water coming from the biological reactors is settled in the secondary clarifier, in order to ensure the solid-liquid separation of the mixed liquor and the recovery of biological sludge sedimented. An amount of the recirculating sludge is sent to the primary clarifier, which works as thickner.

In the secondary clarifier, the chemical precipitation of the phosphorus occurs thanks to the dosage of 2334 kg solution/d of $FeCl_3$ at 40%.

Table 63 Characteristics of the secondary clarifier

Secondary sedimentation		Line1	Line 2
tanks per line	n°	3	2
Type		circular	circular
Diameter	m	43	43
Single area	m2	1451	1451
Average high	m	3	3
Single volume	m3	4350	4350
Total area	m2	4354	2903
Total volume	m3	13050	8700
Total volume lines 1 and 2	m3	21750	

Overall, 21750 m3 of volume, with 7257 m2 of surface are available for sedimentation. The flowrate of sludge recirculation amounted to 3000 m3/h for line 1 and 2000 m3/h for line 2. Each subline has a maximum IR flowrate of 2660 m3/h.

The tertiary processes are composed by the presence of a membrane filtration tank and of a disinfection process. Actually, only the flow that is treated in the second line is subjected to the membrane filtration process, so that the water coming out from this line has a TSS concentration equal to 0 mg/l. The other line (line 1) is characterized by the presence of the disinfection as single tertiary treatment process.

The disinfection occurs as last process of the water line of the plant thanks to the dosage of 13.7 kg/d of NaClO.

The secondary sludge, coming from the water lines, is sent to the gravitational thickener and to a dynamic thickener. Then is sent to the primary settler, used as accumulation tank.

After the sludge is thickened, it is sent to the anaerobic digestion process, which is composed by 3 digestors. Two of these have a volume of 4500 m3 a temperature of 35°C and an HRT of 22 d, while the other is characterized by a volume of 3000 m3 and 7 days HRT.

A gasometer of 800 m3 of useful volume completes the equipment.

Table 64 Characteristics of the digesters

Digesters 1-2		
n°		2
unit volume	m3	4500
HRT	d	22,0
T°C	°C	35
VSS in	kgVSS/m3/d	6767,6
Digester 3		
n°		1
unit volume	m3	3.000
HRT	d	7,3
T°C	°C	-
VSS in	kgVSS/m3/d	-

The biogas produced by the digestors is 1023 Nm3/d with an amount of methane equal to 685.3 Nm3/d (67%) of methane in the biogas.

The stabilized sludge is sent to the dewatering process, where 3 centrifuges dries the sludge up to a density of 25.9%TS.
The flowrates of the external sludge are minimal compared to the ones of the sludge line coming from the water line. The liquid wastes are subjected to fine screening treatment and then sent to the thickener of the sludge line thanks to a lifting system.

Mass balance

After having described the volumes and processes that characterize the Modena plant, we can move to the description of the mass balance of the entire plant. The complete mass flow of the plant can be seen in appendix 2a and 2b.

As said before, the analysis has been done on the basis of the data collected in three years (2017, 2018 and 2019), so the flowrates and the concentrations were all considered by taking the weighted average over the years.
From the sewer enters a flowrate of wastewater of 83.263, with concentrations and loads listed in the table 65.

Table 65 Wastewater characteristics

FLOW	83.263	m3/d
COD conc	126,3	mgCOD/L
BOD conc	57,0	mgBOD/L
TN conc	22,3	mgTN/L
N-NH4 conc	18,1	mgN-NH4/L
N-NO3	0,5	mgN-NO3/L
TP conc	2,1	mgP/L
TSS conc	58,0	mgTSS/L

Before entering the pre-treatments, another water flow joins the main one and it is the one due to the supernatants coming from the sludge line. It means that the flowrate is a little bit higher as well as the concentrations.
The pretreatments consist of a coarse screening process, a subsequent lifting plant, a fine screening process and finally a degritting and oil removal process. The pretreatments produce an amount of screen (CER code 190801) which is 321 kg/d and an amount of sand (CER code 190802) equal to 3982 kg/d.

The water is now divided between the two lines: line 1 is fed by 60% of the pre-treated water while the remaining 40% enters line 2.

As previous said, the primary treatment is bypassed, so the flow goes directly inside the biological reactors.

The table 66 shows the characteristics of the flow that comes out from the secondary treatment: despite the absence of primary treatments, the processes were efficient enough to remove suspended solids and nitrogen.

Table 66 characteristics of the flow that comes out from the secondary treatment (line 1 on the left and line 2 on the right)

FLOW	50.702,8	m3/d
TSS conc	3,5	mgTSS/L
N-NO3 conc	6,4	mgN-NO3/L

FLOW	33.801,8	m3/d
TSS conc	6,3	mgTSS/L
E. Coli	18450	UFC/100mL

The removal of the phosphorus occurs thanks to the dosage of the FeCl3 at 40% of solution: in particular the plant requires 2334 kg solution/d to be dosed in both the lines. The precipitation happens in the secondary clarifier, where the iron is dosed.

Before the flows join, the water of line 2 enters the membrane filtration process, where the TSS is completely eliminated, as well as the bacterial load ($\frac{UFC}{100ml}$= 0).

The last process to which the water is subjected is disinfection, that takes place with the dosage of NaClO in the tank (13.7 kg / d).

The water that is discharged in the environment (in the Naviglio canal) has the following characteristics.

Table 67 Characteristic of the treated water

FLOW	83.465	m3/d
COD conc	21,0	mgCOD/L
BOD conc	4,0	mgBOD/L
TN conc	8,8	mgTN/L
TP conc	0,6	mgP/L
TSS conc	5,7	mgTSS/L
N-NH4 conc	0,8	mgN-NH4/L
N-NO3 conc	7,0	mgN-NO3/L
E. Coli	5.065	UFC/100mL

Coming back to the biological treatment process, it produces the secondary sludge, that is stored in the primary settling tank which acts as sludge thickener. Here, the biological sludge is mixed with the external liquid wastes coming from other plants.

Before entering in the storage/accumulation tank the external sludge is subjected to fine screening process.

The biological sludge mixed with the external liquid waste presents these characteristics:

Table 68 Biological sludge mixed with the external liquid waste characteristics

FLOW	1.278	m3/d
TSS	12622	kgTSS/d
TS%	0,99	%
TVS/TS	0,62	
LP	269	kgP/d
TN	495	kgTN/d

In the sludge line there are two thickeners + one accumulation tank that works as a further thickener.

The thickening process increase the value of solids in the sludge up to 3,2%. The rejected water is sent in the water line, before pretreatment processes.

The sludge is now ready for the anaerobic digestion, so for the stabilization of the organic matter and for the biogas production.

The biogas produced by the digestors is 1023 Nm3/d with 67% of methane.

The calculated destroy percentage of TVS is a little bit lower than expected. Indeed, the general R%TVS is equal to 50%, while in this case is about 18%. This may mean that the kinetic parameters or the operating parameters are different to the ones known. For example, if the pH or the temperature are too low, the digester could work worse and produce less biogas.

Moreover, the secondary digester was subjected to ordinary maintenance works in 2017 which kept it off for partial durations of 65 days. This could be another reason for which the biogas production is so low.
The final process, the dewatering, increase the solids in the sludge up to 25,9%, using 241 kg POLY/d and producing 13196 tonTQ/y of sludge to be disposed.

Table 69 produced sludge

Flow	36,2	m3/d
TS%	25,9	%
TSS	9351,8	kgSS/d
TVS/TS%	0,56	-
Quantity	13196,2	ton tq/y
Quantity	36153,9	kg tq/d
LP	245,0	kgP/d
LN	436,7	kgN/d
P%TS	2,62	P%TS
N%TS	4,67	N%TS

The plant is also equipped with a system to treat the exhausted air, that needs the dosage of 16,4 kg NaOH/d.

3.3.3 Castiglione

The Castiglione Torinese wastewater treatment plant is the largest chemical, physical and biological treatment plant present in Italy, with a maximum capacity of 3,800,000 people equivalent (PE). It is located in north Italy near to Torino and it is managed by the SMAT company.
The Po river crosses a 38,000 km2 plain in which they live over 17 million inhabitants, equal to 30% of the Italian population.

Almost 1.5 million inhabitants and 1.000 productive activities, even to more than 2 million equivalent inhabitants, download annually over 200 million cubic meters of coming sewage from an area of approximately 450 km2.

The analysis was conducted considering the average of three years (2017, 2018 and 2019). The data for the description and for the mass balance have been provided by the plant and the company that manage it.

Description

The structure of the water line of Castiglione Torinese plant develops according to the conventional sequence of operation unit, except for primary settle, that is used only as accumulation tank for the WAS sludge:

- Pre-treatments
- Primary treatment
- Biological treatment
- Secondary sedimentation
- Tertiary treatment

The wastewater that enters from the sewer meets at first the pretreatments. They consist of a screening process and an aerated sand and oil removal tank. The pretreatments are important processes because it avoids the passage of coarse material which could damage pumps and pipes.

Table 70 pre-treatments characteristics

SCREENING		GRITTING		
n° of lines	4	n° of lines	1	
n° of gritting for each line	2	n° of aerated canals	8	
		HRT	45	min

After the pretreatments the water flux is divided in four modules. The modules 1, 2 and 3 are equal and can be divided again in 2 submodules.

Each submodules is equipped with 1 primary settler, 1 denitrification tank, 3 oxidation tank and finally by 3 sedimentation tank in parallel.

The internal recycle is present in these modules: it recirculates the nitrates and the oxygen from the oxidation tanks to the denitrification reactor. The internal recycle flowrate is activated only in the winter season. In the other periods of the year, the activated sludge recycle is switched off and the anoxic reactors become anaerobic tanks.

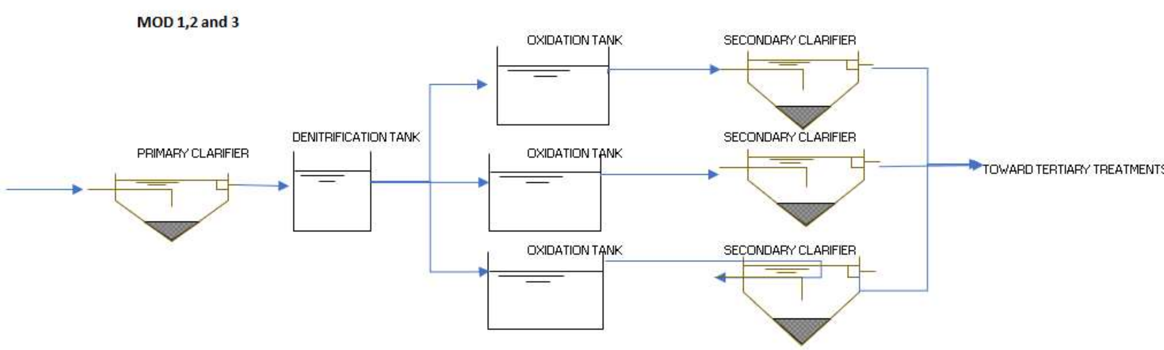


Figure: 22 Modules 1,2 and 3 flow scheme

It means that all the 3 lines together present six settlers whose characteristics are listed in this table (Table 71).

Table 71 Characteristics of the primary settlers

Number of lines	3	
Unit number for each line	2	
Unit volume	7430	m3
Total volume	44580	m3
Unit surface		m2
Total surface		m2
E%TS	58,3	%
E% COD	36,2	%
E% BOD5	45,9	%
E% TKN	16,1	%
E% P	10,0	%
HRT	2,4	h

Further, there are 6 denitrification tanks (1 for each submodule) and 18 aerobic reactors (3 for each submodule).

Table 72 characteristics of biological reactor (modules 1,2,3)

n° of lines	3	
n° anoxic tanks for each line	2	
n° of aerobic tanks for each line	6	
single anoxic volume	13500	m3
Total anoxic volume	81000	m3
Single aerobic volume	8736	m3
Total aerobic volume	157248	m3
Total volume	238248	m4
R ratio	1,0	-
IR ratio	1,3	-
SRT	30	d
h	6	m
Width (single anoxic reactor)	45	m
Width (total anoxic)	90	m
Width (single aerobiv reactor)	28	m
Width (total aerobic)	168	m

Secondary sedimentation is the last part of the biological treatment. Part of the activated sludge is extracted and pumped towards the line of sludge treatment. The dosage of iron salts in the activated sludge allows the phosphates removal, chemically. It is dosed only in winter when the internal recycle is activated; for the rest of the year there is no internal recycle and the anoxic tanks become anaerobic.

Table 73 characteristics of the secondary settler (modules 1,2,3)

n° of lines	3	
n° of settlers for each line	6	
Single volume	7328,7	m3
Total volume	131917	m3
SRT	23-32	d

Biological compartment of the 4th module works differently compared to modules 1 2 3. The operation is stepfeed with alternation in 3 steps of anoxic and aerobic phase. The flow rate is divided, as in the other modules, into 2 semimodules. Each submodule has 1 primary clarifier and a series of S-positioned bioreactors. The sequence is showed in the figure 23: anoxic-ox-anoxic-ox-anoxic-ox.

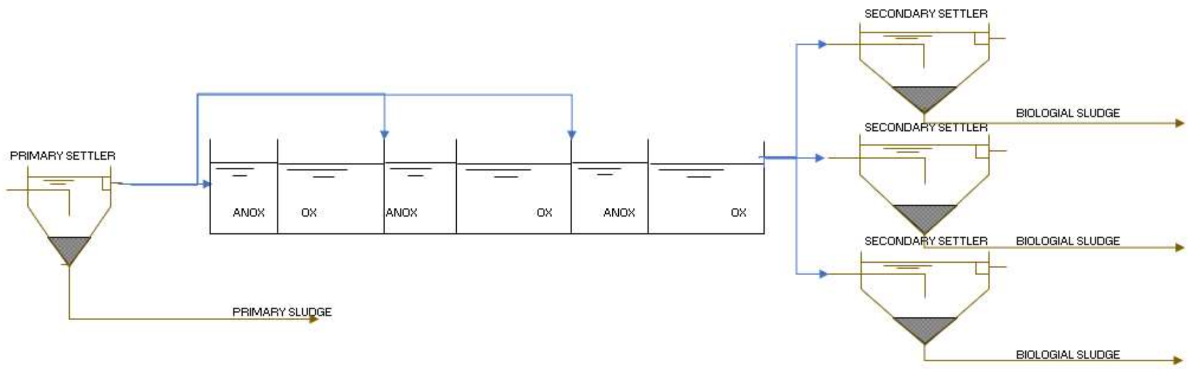


Figure: 23 Module 4 flow scheme

Finally, the water from the bioreactor sequence come into the secondary clarifiers.
Clarifiers (both the primary and the secondary) are equal to the ones described before. Biological reactor characteristics are listed in the following table (Table74).

Table 74 characteristics of the biological reactor (module 4)

n° of lines	1	
n° anoxic tanks for each line	6	
n° of aerobic tanks for each line	6	
Single noxic volume	4800	m3
Total anoxic volume	28800	m3
Single aerobic volume	9960	m3
Total aerobic volume	59760	m3
IR ratio	1,0	-
SRT	28	d
h	6	m
Width (single anoxic reactor)	20	m
Width 2 anoxic reactor in parallel	40	m
Width (single aerobiv reactor)	20	m
Width 2 aerobiv reactor in parallel	40	m

The flow rate to each half module is divided (not measured distribution) at the input to the 3 anoxic steps. So, the water is feeded not only at the primary denitrification tank but inside all the anoxic reactors.
In this case, there is no recirculation of the internal recycle, but only of the sludge.
The water is then sent toward the tertiary treatments. Part of the flux from the modules 1, 2 and 3 goes in the emergency chlorination, while the other part goes directly inside the final filtration process. After the water is treated there is a deflector that divided the water: a share goes toward the water body, while a share is subject to additional treatments that allow it to be reused in the drinking water plant.
The sludge produced in the water line are sent, separately into the sludge line. It goes into a static pre-thickener, where the sludge is subjected to a first thickening which increases its concentration. Cationic polyelectrolyte in emulsion is added to the secondary excess sludge.

The extraction of the thickened sludge takes place from the bottom. The sludge comes collected in an accumulation well and from there it is pumped to the subsequent phase of anaerobic digestion.

The wastewater, extracted through the upper weir of pre-thickeners, are collected, similar to water separated from the subsequent phases, in an accumulation tank from which they are sent to the head of the plant to restart the treatment purification.

Actually, there is another share of sludge that is treated inside the thickener together with the primary sludge: they are the external sludge with a concentration of solids of 2% TS and a mass load of 2242 kg/d.

Table 75 Characteristics of the primary and biological sludge

	I sludge	II sludge	
n° for each line	4	2	-
unit volume	1315	1315	m3
HRT	6-24	6-24	d
CSS	50	50	kgSS/m2

After the sludge reach a concentration of about 3%, it is stabilized in the anaerobic digestor.

The digestion phase carries out the transformation of part of organic matter present in the pre-thickened sludge, through the action of anaerobic bacteria that operate and develop at the temperature of 37 - 40 °C at which the sludge is kept inside the digesters. As the table 76 shows, there are 3 digesters for the primary sludge and 2 tanks for the biological one. Actually, there are 6 digesters, but one of these is not in use for maintenance works.

Table 76 digesters characteristics

	I sludge	II sludge	
n° for each line	3	2	
unit volume	10.000	10.000	m3
HRT	15-20	15-20	d
T°C	37-40	37-40	°C

The post thickener is not in use, so it is used only as accumulation tank.

The subsequent process is therefore mechanical dewatering, that occurs thanks to the presence of 4 centrifuges, with a percentage of abatement equal to 75%. The rejected water of the treatment is sent to the primary clarifier of the fourth module in water line.

A dryer with a volume of 230 m3 represents the last process of the sludge line. It works at a temperature of 105°C with an HRT of 6h. The percentage of abatement seems to be near to 100%, so that all the suspended solids remain in the sludge and the rejected water is completely discharged of solid pollutants.

Mass balance

The complete mass flow of the plant can be seen in appendix 3a and 3b.

The analysis has been done considering the data of three years: 2017, 2018 and 2019.

The influent flowrate in the wastewater treatment plant, coming from the sewer, amounts to 564239 m3/d characterized by the concentrations listed in the table below (Table 77).

Table 77 Characteristics of the wasteater

FLOW	564239	m3/d
COD conc	420	mgCOD/L
BOD conc	217	mgBOD/L
TN conc	34	mgTN/L
N-NH4 conc	21	mgN-NH4/L
TP conc	4	mgP/L
TSS conc	216	mgTSS/L

After the screening, which is the first process of the plant, the supernatant come from the sludge line and enter in the degritting process. Actually, the supernatant are the flows from the prethickener and the water from the back wash of the sand filter located at the exit of the water line.

After the sand and oil removal process, the water is divided into four lines as explained in the previous paragraph. The water flow entering the fourth line has an additional amount of water coming from the dewatering process of the sludge line.

The primary gravity settlers are 2 for each line, with a percentage of solids abatement of 58%, so that the sludge coming from this process amounts to 107111 kg TSS/d. Nitrogen and phosphorus are present in the sludge as pollutant related to the solids, so assuming the % of N and P in TS the amounts can be calculated.

Non-settling material is sent to biological reactors, where nutrients and organic carbon are removed. In particular the COD is removed for the 86% and the nitrogen for the 60% in the line 1, 2 and 3, while in the line 4 for the 90% and 62%.

The precipitation of the phosphorus takes place thanks to the chemical dosage of FeCl3 at 40% dilution. Actually, a quantity of 14175 kg solution/d is dosed only for the first three lines, because the third line is able to remove it biologically, thanks to the alternation of anoxic and aerobic tanks.

The water from the biological reactors enter in the secondary clarifiers, where the sedimentation of the activated sludge occurs. The sludge is, in part recirculated, in order to reach the optimal retention time, and in part sent to the sludge line. The SRT for the modules 1, 2 and 3 is 38 days considering the values in table 78 and 31 days for the fourth module.

Table 78 Operating parameters of the reactors

MODULES 1,2,3			MODULE 4		
FLOW	4197	m3/d	FLOW	2030	m3/d
MLSS in recirculation	7460	mg/l	MLSS in recirculation	8540	mg/l
MLSS in tank	4957	mg/l	MLSS in tank	6050	mg/l
Vbiologico	238248	m3	Vbiologico	88560	m3
SRT	38	d	SRT	31	d

The concentration of the secondary sludge is 0.78% (7800 mgTSS/l) while the nitrogen and phosphorus are calculated assuming the % related to the solids: 4.5 N%TS and 1.5 P%TS. Leaving the secondary settlers, the water flows from the lines join together showing the concentrations listed in the table 79.

Table 79 Characteristics of the secondary sludge

FLOW	741.172	m3/d
COD	27,5	mg/l
TN	9,1	mg/l
N-NH4	1,1	mg/l
N-NO2	0,1	mg/l
N-NO3	5,1	mg/l
TP	1	mg/l
TSS	15,5	mg/l

An emergency chlorination is present in the event that the outgoing flow was still too bacterially charged. The final sand filtration is thought for part of the exiting flow, so that only 363840 m3/d pass the filtration while the remaining amount bypasses the final process.

Only part of the treated water goes into the water body, because an amount of water goes in the disinfection process and is treated as drinking water.

The sludge line starts with the pre thickening of both the primary and the activated sludge. The primary sludge that enter in the thickeners is characterized by a concentration of 1.5%TS. Together with this sludge, also external sludge coming from the OLON pharmaceutical industry are collected. The sludge entering in the process presents the characteristics exposed in the table 80. Actually, there is another solids flux entering in the pre thickener, coming from the post thickener.

Table 80 Characteristics of the primary sludge entering in the prethickener

Flow	9008	m3/d
TS%	1,2	%
TSS	133969	kgTS/d

Unlike the primary, the activated sludge goes into the thickener with a lower concentration since the MLSS concentrations in the recirculation were 7460 mg/l for the modules 1,2 and 3 and 8540 mg/l for module 4.

Table 81 Characteristics of the activated sludge entering in the thickener

Flow	6227,0	m3/d
TS%	0,8	%
TSS	48646	kgTS/d
VSS/TSS	0,7	
VSS	35025	kgVS/d
N	2189,1	kgN/d
P	729,7	kgP/d

The solid liquid separation in the secondary prethickener is enhance by dosing 982 kg Polyelectrolyte/d.

Both the I and II thickened sludge that are sent into the digesters are characterized by solids concentration of about 3%TS. The efficiency of the digesters is different since the primary sludge has higher potential for the biogas production. The digesters of the primary sludge have a percentage of VSS destruction equal to 39,4% and a relative specific gas production (SGP)of 0.3 Nm3/VSSin. It means that the destroyed VSS are 18859 kgVSSdestroyed/d, that produce an amount of biogas of 22409Nm3/d.

On the contrary, the digesters of the WAS sludge produce 4793Nm3/d, since the percentage of destroyed VSS is equal to 17.4% and an SGP of 0.13 Nm3/VSSin.

The percentage of methane in the biogas is 63% for both the products.

After the digestion, the sludge is mixed together before entering in the post thickener.

Table 82 Characteristics of the sludge that enters in the post thickener

Flow	3117,8	m3/d
TS%	2,5	%
TSS	78768,2	kgTS/d
VSS	48109,7	kgVS/d

The thickener has a percentage of abatement equal to 69%TS, so the solids in the outgoing sludge are 54152 kgTSS/d. The lime and the iron salts are dosed in the thickener in order to improve the solid liquid separation. Part of the solids are recirculated before the pre-ticketing (1764 m3/d with 24616 kgTS/d.

The centrifuge treats the sludge coming from the post thickener. 163,8 kg Polyelectrolyte/d is dosed in the dewatering to improve the process. The sludge from the centrifuge is divided in two parts: 94,6 m3/d are treated in the dryer, while 113,6 m3/d bypass the dryer. The reason is related to the fact that the sludge is sent to the composting facility, that needs the wet characteristics of the sludge.

The sludge to be disposed presents the characteristics listed in the table 83.

Table 83 sludge to be disposed characteristics

Quantity	140594,3	kg/d
Flow	140,57	m3/d
TSS	53827,8	kgTSS/d
TS%	38,3	%
VSS/TSS	0,63	

3.4 Full scale plants modeling

3.4.1Advanced simulation platform

The advanced simulation platform is a wastewater treatment process simulator that ties together biological, chemical, and physical process models. It is used world-wide to design, upgrade, and optimize wastewater treatment plants of all types.

Thanks to the Advanced simulation platform user can define and analyse behaviour of complex treatment plant configurations with single or multiple wastewater inputs.

Most types of wastewater treatment systems can be configured thanks to this softare using the many process modules. These include:

- A range of activated sludge bioreactor modules – suspended growth reactors (diffused air or surface aeration), various SBRs, media reactors for IFAS and MBBR systems, variable volume reactors.
- Anaerobic and aerobic digesters.
- Various settling tank modules – primary, ideal and 1-D model settlers.
- Different input elements – wastewater influent (COD- or BOD-based), user-defined (state variable concentrations), metal addition for chemical phosphorus precipitation (ferric or alum), methanol for denitrification.
- Other process modules – holding tanks, equalization tanks, dewatering units, flow splitters and combiners.

A crucial component of Advanced simulation platform is the biological process model. It is unique in that it merges both activated sludge and anaerobic biological processes. Additionally, the model integrates pH and chemical phosphorus precipitation processes. It’s easy to use. The program has the look and feel of the many other Windows applications. When it is launched it comes up with the familiar interface and menu structure. Complex treatment plant schemes can be configured rapidly through "drag and drop" mouse actions. Functions are selected from the pull-down menus, using short cut keys, or by pointing the mouse and clicking on icons in the toolbar.

The user can also access many of the Windows functions usually embedded in a Windows application; for example, selecting and configuring the printer setup. Context-sensitive Help is built to provide on-line assistance, particularly for new users. Careful consideration has gone into the design of the package; for example, the hardware and software platforms, the object oriented software development system, the data structures, the user interface, and so on. A primary aim has been the production of a package structured to allow on-going development in years to come.

The simulator suite presently includes two modules:

- A **steady state** module for analysing systems based on constant influent loading and/or flow weighted averages of time-varying inputs. This unit is also very useful for mass balancing over complex plant configurations.
- An interactive **dynamic simulator** where the user can operate and manipulate the treatment system "on the fly". This module is ideal for training and for analysing system response when subjected to time-varying inputs or changes in operating strategy.

Modena WWTP in advanced simulation platform

Thanks to this software it is possible to simulate and analyse deeply the plant processes, evaluating the presence of any mistake and anomalies. Consequently, it allows to understand the way to intervene in case of malfunctions and to optimize the plant in case it is required.

The first step for the analysis of the plant is to draw the all the processes, choosing them one by one in the "configurations" menu at the top. The figure below (Figure 24) represents the water line, the details of which are detailed in paragraph 3.3.2

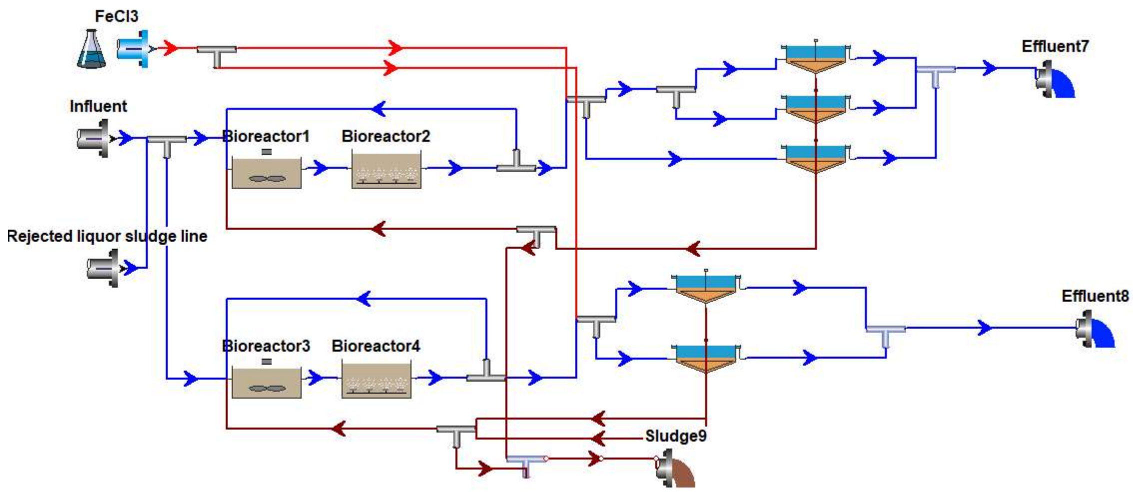


Figure: 24 Modena, Canale Navigli *water line*

The pre-treatments are not simulated in the software because of the negligibility of the waste masses (kg/d of screen and grit). So, due to the absence of the primary clarifiers, that are bypassed, the water flow enters directly into the biological process tank.

The water line is divided in two lines both equipped with denitrification/denitrification reactors. To represent the denitrification tank, the first tank is unaerated, while the second is aerated, with a concentration of the dissolved oxygen equal to 2 mg/l. Once entered the size of the tanks (volume), the secondary clarifiers can be analysed.

As the figure shows, there are 3 clarifiers in the primary line and 2 in the secondary line. Since the secondary settler is designed on the basis of some fundamental parameters, such as the Surface Overflow Rate (SOR) and the Solids Loading Rate (SLR), together with the HRT:

- SOR=$\frac{Q}{A}$; with Q influent flowrate and A the settling surface
- SLR=$\frac{(Q+Qr)X}{A}$; With Q influent flowrate, Qr the recycle flowrate, X the concentration and A the settling surface

the representation in the simulation tool must perfectly follow the actual volumetric dimensions. This is the reason why the settlers were not replaced, in the software, by a single large settler, as done for the bioreactors, but had to be represented in detail.

The type of secondary clarifier chosen is the one called “ideal settling tank”: the total volume is divided into two sub-volumes (a “thickened” or “sludge” volume and a “clarified” or “liquid” volume – the relative volume proportions are specified by the user). A constant or time-varying solid capture percentage also can be defined. The underflow also may be constant or time varying.

Now, all the recycle values has to be entered, together with the internal recycle of the bioreactors. The software gives the possibility to insert only the flowrate value [m3/d], while the concentration

Xr (concentration of the recycle flow) and the X (concentration of MLSS in tank) are calculated. The same is for the SRT: since it has all the parameters, the software can calculate it.
Anyway, there is the possibility to impose the SRT value for the bioreactor, in order to control the process starting from the retention time. Obviously, the consequence is the change of the other values, such as the recycle flow and the recycle concentration.
Some difficulties, due to calibration, were found in the implementation of the model, but they will be explained in more detail later (paragraph 4.2.2).
Finally, the water comes from the clarifier to the effluent. The choice to don't combine the two effluents is done for simplicity sake. Indeed, in the real plant, the line two of the water line is characterized by the presence of the membrane filtration before moving on the UV disinfection. Since the membrane filtration is not implementable in the advanced simulation platform, the idea is to compare the simulated values with the real values before the tertiary treatment processes.
The sludge coming from the clarifiers moves on the sludge line, which is implemented in another model, while the "rejected liquor sludge line" is the water that comes as supernatant in the water line from the sludge one. In particular it is the water that comes from the primary clarifier, used as thickener, the actual thickener and the final centrifuge.

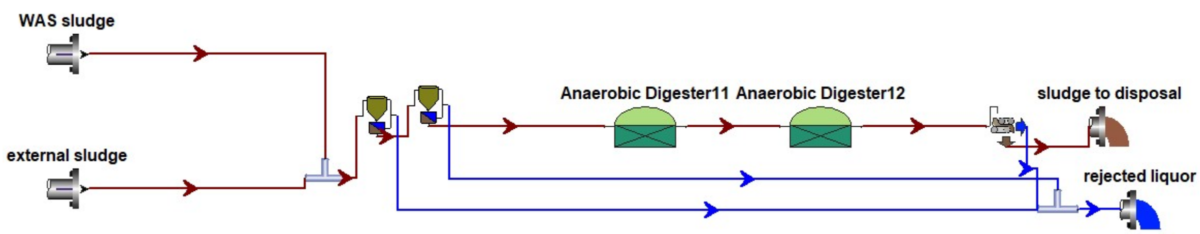


Figure: 25 Modena, Canale Navigli *sludge line*

As well as for the effluents, the choice to divide the water line from the sludge line is done for simplicity sake. Indeed, when the model is too high and complex, the software is not able to consider all the parameters and all the changes, so the final results appear unreliable and is more convenient to lighten the model, to make it more stable.
The sludge comes in the line from the water line, as biological sludge from the secondary settlers and from extra-sewage liquid waste delivered by tankers.
The sludge enters in the primary clarifiers, that are used as accumulation tanks. Actually, the clarifier acts as a thickener, as said before, so that the model has two thickener, represented by the so called "cyclone".
There are 3 anaerobic digesters, but since the first two are equal they are represented together with a volume that is two time big. The value of biogas produced and the amount of COD in outlet (higher than expected) make clear that the digesters don't start the methanogenesis phase, but remain in the acidogenic phase.
Finally, the dewatering process allow the solid-liquid separation. Some differences with the real sludge can be noted analyzing the characteristics of the sludge produced from the simulator.
Once the inlet values have been entered and the process scheme has been drawn, with all the parameters and characteristics added, it is possible to start the simulation in order to find the results.

3.5 LCA, LCC and simulation software

3.5.1 Life cycle assessment

Life Cycle Assessment is defined as "a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e. from raw material acquisition, via production and use stages, to waste management" (ISO 2006). This definition goes further the limited approach where only the manufacturing step was recognized as the pollution driver. Several purposes can be fulfilled with this kind of methodology: comparison of alternative products, processes or services; comparison of alternative life cycles for a certain product or service; or identification of parts of the life cycle where the greatest improvements can be made (Roy, et al. 2009)

The standard ISO 14040 establishes the framework and principles universally valid to plan and conduct an LCA. The LCA framework operates with four separate phases: Goal and scope definition, Inventory analysis, Impact assessment and Interpretation. The relationship between the phases is illustrated in **Errore. L'origine riferimento non è stata trovata.**.

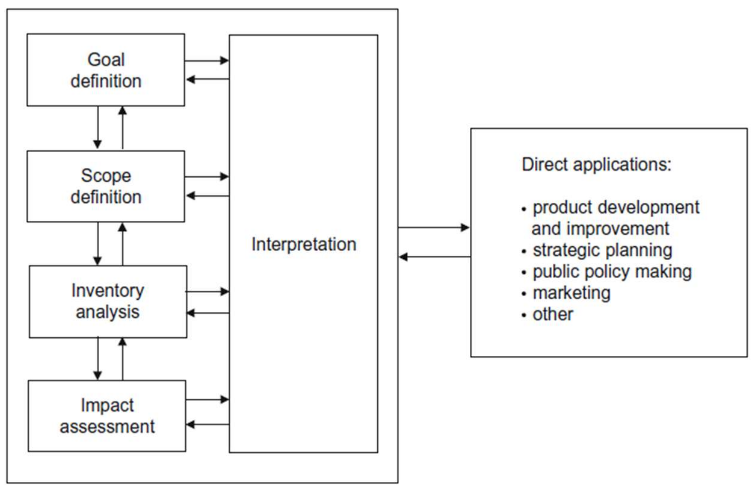


Figure: 26 Framework of LCA modified from ISO 14040 standard

The first essential step consists in the goal definition. It sets the context of the LCA study and is the basis of the scope definition primarily in terms of:

- Defining the functional unit
- Scoping the product system, deciding which activities and processes belong to the life cycle of the product that is studied (system boundaries definition)
- Selecting the assessment parameters
- Selecting the geographical and temporal boundaries

Indeed, a life cycle assessment can be applied at a planning level where alternative management strategies, conceptual designs, and long-term scenarios are analyzed. Or, it can be applied at a design level when preliminary designs plant, unit operations, or collection/reuse systems are generated and evaluated. Third, LCA can be applied to existing plants for operation, optimization, and retrofitting, enabling decision-makers to chart pathways to improve the environmental performance of a given system. Finally, LCA can also be applied during the development of new technologies to understand how best to advance an individual system. Therefore, the main purpose of the LCA will dictate the overall methodological approach and the level of detail required (Corominas, Byrne, et al. 2020).

As the second step, the inventory analysis collects information about the physical flows in terms of input of resources, materials, semi-products and products and the output of emissions, waste and valuable products for the product system. Six main categories of physical flows are identified:

Input flows:	Output flows:
1. Materials	4. Products
2. Energy	5. Waste to treatment
3. Resources	6. Emissions.

Resources and emission, since not exchanged between unit processes, are referred to as elementary flows. They are defined by ILCD (International Reference Life Cycle Data System) as "single substance or energy entering the system being studied that has been drawn from the ecosphere without previous human transformation, or single substance or energy leaving the system being studied that is released into the ecosphere without subsequent human transformation" (JRC, EU 2010).

Besides, it is useful to distinguish between unit processes belonging to the foreground and background system. The foreground system is commonly defined as comprising those processes of a product system that are specific to it. The foreground system is largely modelled using primary data, i.e. data collected first-hand by the LCA practitioner, e.g. obtained through the commissioner of the study. The background system, in contrast, is commonly defined as those processes of a system that are not specific to it. Such processes take part in numerous product systems besides the one studied. Examples are society's electricity supply, the production of metallic copper, or the waste management systems. The background system is typically modelled using LCI databases, which contain average industry data representing the process in specific nations or regions.

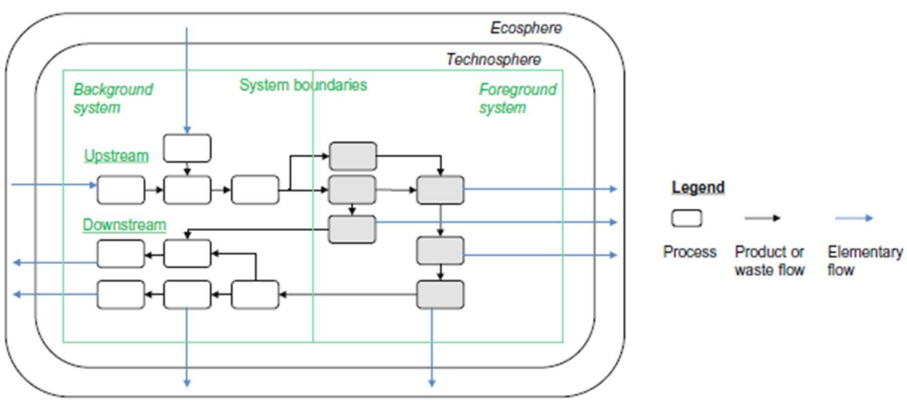


Figure: 27 LCI model for a generic product system. (Hauschild, Rosenbaum and Olsen 2018)

An LCI result is an inventory of the aggregated quantities of elementary flows, separated into resources and emissions, from all the unit processes within the system boundary. These elementary flow quantities must be correctly scaled to the assessed product by considering the extent to which the function of each unit process is required to deliver the studied product.

Several LCI databases are available to use in LCA software. The ecoinvent database is published and maintained by the ecoinvent Centre in Switzerland. It is the most renowned database for life cycle inventory (LCI) datasets. It contains approximately 4500-5000 harmonized, reviewed and validated datasets for use in Life Cycle Assessments (LCA). These datasets are all fully documented.

Once finalised the inventory, the impact assessment translates the physical flows and interventions of the product system into impacts on the environment using knowledge and models from environmental science. Impact assessment turns a Life Cycle Inventory into a Life Cycle Assessment.

Life cycle impact assessment (LCIA) translates emissions and resource extractions into a limited number of environmental impact scores by means of so-called characterisation factors.

It consists of five elements of which the first three are mandatory according to the ISO 14040 standard:

1. Selection of impact categories representative of the assessment parameters that were chosen as part of the scope definition. Which impacts do I need to assess?
2. Classification of elementary flows from the inventory by assigning them to impact categories according to their ability to contribute by impacting the chosen indicator. Which impact(s) does each LCI result contribute to?
3. Characterisation using environmental models for the impact category to quantify the ability of each of the assigned elementary flows to impact the indicator of the category. The resulting characterised impact scores are expressed in a common metric for the impact category. How much does each LCI result contribute?
4. Normalisation, e.g expressing LCIA results relative to those of a reference system. Is that much?
5. Grouping or weighting, e.g. aggregating several impact indicator results into a group.

In practice, the Life Cycle Impact Assessment (LCIA) phase is largely automated and essentially requires the practitioner to choose an LCIA method and a few other settings for it via menus and buttons in LCA software.

As the final step, the interpretation phase considers both results of the inventory analysis and the impact assessment elements characterisation and, possibly, normalisation and weighting. The interpretation must be done with the goal and scope definition in mind and respect the restrictions that the scoping choices impose on a meaningful interpretation of the results, e.g. due to geographical, temporal or technological assumptions. The results of the interpretation may lead to a new iteration round of the study, including a possible adjustment of the original goal.

3.5.2 LCA applied in the wastewater treatment field

Urban wastewater management requires large material, energy, economic and technological investments for the construction and operation of treatment plants. Energy consumption in WWT plants and the related greenhouse gas (GHG) emissions are also steadily increasing due to strict treatment requirements. Given the need to achieve long-term sustainability, the objectives of urban water systems need to go beyond the protection of public health and receiving bodies and also focus on strategies to reduce the impacts on natural resources, to optimize the use of energy and water and reduce waste generation. Therefore, urban systems should adopt innovative approaches to wastewater management to maximize the recovery of useful materials and/or energy and minimize emissions releases (Buonocore, et al. 2018).

Life cycle assessment (LCA) has been widely used to quantify environmental impacts associated with urban water infrastructure, including wastewater treatment plants (WWTPs) (Byrne, et al. 2017). The evaluation of the LCA results will help in the optimization of energy consumption and energy recovery processes, the enhancement of the efficiency of equipment and technology operation, and the good management of energy costs within WWTPs.

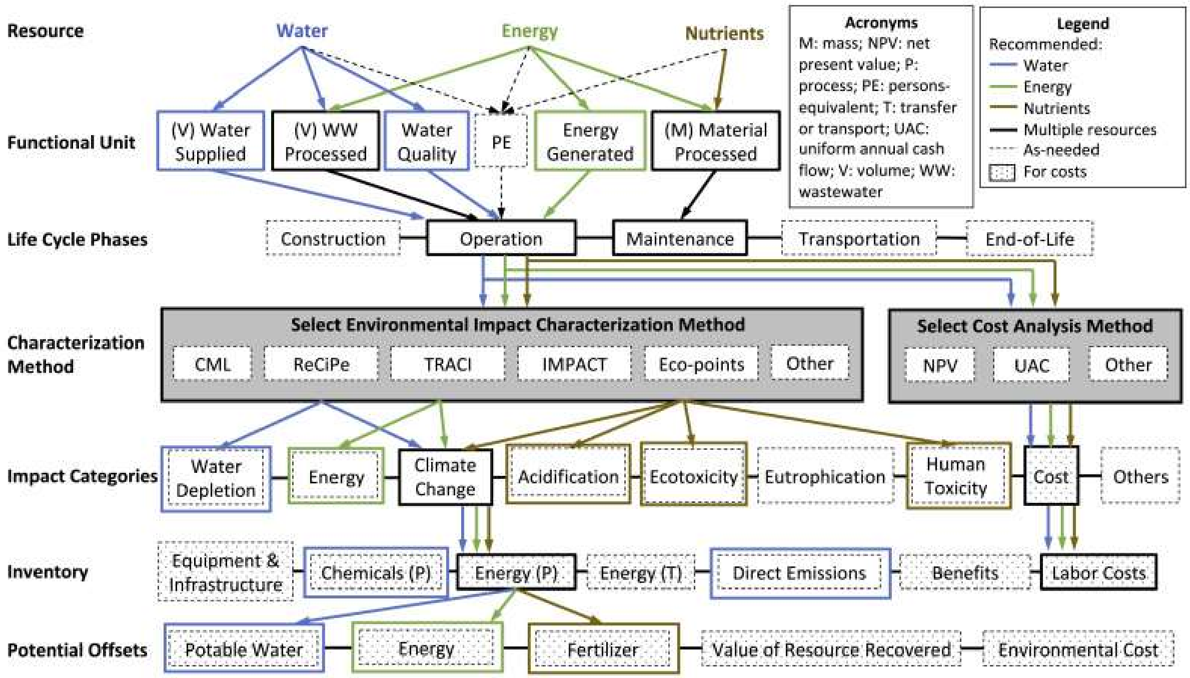


Figure: 28 Guidelines for life cycle assessments and economic analyses of resource recovery systems ((Diaz-Elsayed, et al. 2020)

The most commonly used functional unit in the case of a wastewater treatment plant is a volume unit of treated wastewater. However, this unit is not always representative, because it does not reflect the influent quality or the removal efficiency of the WWTP (Corominas et al. 2013). Nonetheless, the water quality should be explicitly stated (Diaz-Elsayed, et al. 2020). Some studies also add a temporal scope (e.g., 20 years of operation) to transparently account for the construction burden.

Depending on the goal and scope definition, the physical system boundaries have to expand beyond the fenceline of the WWTP (e.g., to include the agricultural water reuse or beneficial agricultural use of treated sludge). **Errore. L'origine riferimento non è stata trovata.** shows the physical system boundaries that are commonly applied in WWTP LCAs.

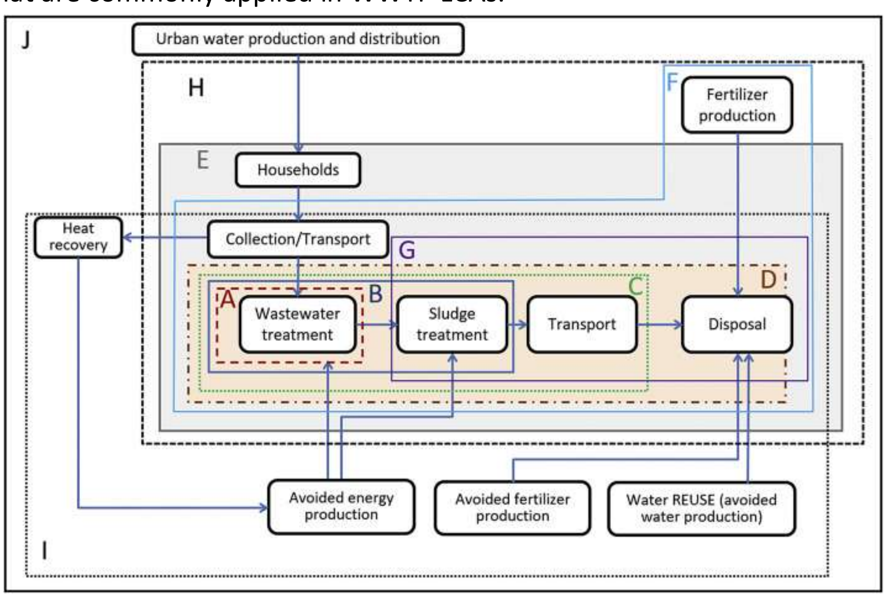


Figure: 29 Examples of physical system boundaries for WWTP LCAs. (Corominas, Byrne, et al. 2020)

The life cycle inventory elaboration is the most work-intensive and time-consuming phase compared to other phases in an LCA, mainly because of data collection. The foreground life cycle inventory (LCI) data is normally compiled directly from measurements, detailed design documents and vendor-supplied information. Background information (e.g. electricity generation systems, concrete and chemicals production processes) is normally provided by LCI databases, e.g. the EcoInvent (Corominas, Foley, et al. 2013).

Besides the data on civil works, it is recommended that large equipment (e.g., blowers, pumps, centrifuges, dewatering belt filters) be included by accounting for their primary materials (by mass) such as steel and copper (Morera et al., 2017). The most of papers accounting for the construction phase establishes a lifespan of 30 and 10-20 years for the infrastructure and the equipment, respectively.

Within the operation inventory, the main data to include are on direct emissions (to water, to air and soil), energy, chemicals and transport. Between the emission to water, the nutrients discharged are always considered. In recent years, there has been a growing interest in including organic micropollutants (Lorenzo-Toja et al., 2016) and even microbial pathogens (Harder et al., 2017) in LCA.The direct emission to air from the water and sludge lines, instead, are not always taken into account. Besides the N2O, CH4 and CO2 emissions are mostly estimated through secondary data depicting the accuracy.

On the contrary, not all chemicals will have corresponding LCI datasets available and in such cases, assumptions must be made. In any case, it is recommended not to exclude them, but rather identify and include suitable chemical analogues or surrogates. This can be done according to function or by identifying suitable alternate chemicals which have similar composition and/or background manufacturing processes (Corominas, Byrne, et al. 2020).

Concerning the impact assessment phase, midpoint indicators are preferred for wastewater systems. However, they should no provide adequate clarity for decision-making. At this regard, it may be advantageous to limit the number of indicators used for impact assessment: climate change, eutrophication, and ecotoxicity are recommended as key indicators for wastewater systems (Corominas, Byrne, et al. 2020).

Multiple LCIA methodologies exist at both the midpoint and endpoint levels and are available within existing LCA software (e.g., Umberto LCA+). The methodologies most employed are ReCiPe, CML and TRACI.

Depending on the defined goal and scope of the LCA, it may be appropriate to incorporate pathogen risk into life cycle impact assessment given the disproportionately local impact wastewater treatment has on reducing exposure to pathogens (Byrne, et al. 2017). One proposed option for this is the blending of LCA with quantitative microbial risk assessment (QMRA) (Harder et al., 2016), a decision-making tool used to quantify human health risks associated with multiple pathogens and exposure pathways. This approach typically involves using the common metric of disability-adjusted life years (DALYs) which requires the use of an endpoint methodology for LCIA and can therefore introduce additional uncertainty (Heimersson et al., 2014).

In all cases, the integration of pathogen risk in LCIA should be dependent on the LCA's goal and scope definition.

3.5.3 Life Cycle Costing

Together with the LCA, in recent years, two methodologies have been developed within life cycle thinking: Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) (Yago Lorenzo-Toja, 2016). Indeed, Kloepffer (2008) proposed the following scheme for Life cycle sustainability assessment: LCSA=LCA+LCC+SLCA.

LCC aims to quantify all costs associated with the life cycle of a product that is directly covered by one or more of the actors in that life cycle. S-LCA has the goal of assessing the social impacts of a product over its life cycle.

An important requirement of LCSA is that the three pillars of sustainability must be assessed using the same system boundaries, i.e. that the same elements of a product life cycle are considered in all three assessments.

Economic performance metrics can be divided into three categories based on life cycle phases: (a) project initiation and construction, (b) operation and maintenance (O&M), and (c) end-life costs. Project initiation and construction costs include equipment and area requirements, energy and labour costs during construction, external costs associated with construction as well as the capital expenditure (CAPEX) for treatment infrastructure.

Operation and maintenance (O&M) costs include chemicals and other consumables, equipment maintenance, licensing fees, administration, and training and labour requirements. Clearly, energy requirements also represent a significant operational cost; therefore, the energy data collected as an environmental performance indicator can be converted into energy cost in analyses of economic performance.

As the name suggests, LCC is a technique that assesses costs over the life cycle of a product or a system. Conducting an LCC can have different purposes. It may be used as a planning tool, an optimisation tool or to evaluate investment decisions.

A cost is normally considered as being synonymous with a price of something—it is the monetary value that someone has to pay for something. In an LCC, costs are identified over the life cycle of the product.

LCC can also include revenues which are considered as negative costs. Hunkeler et al. (2008) argue that there are no fundamental problems involved in adding the revenues in the analysis, as long as it is clear how it is being carried out, although for practical reasons they are frequently left out.

Since in LCC, costs are accumulated over a lifespan, one needs to consider that the monetary flows occur at different times. This complicates the analysis for two reasons.

The first is that prices of the product can change due to the market dynamics. The second complicating fact is that people are likely to have a time preference, and often prefer to spend money later rather than now. One solution to take these considerations into account in LCC when comparing future and present costs is discounting, that essentially weights impacts by assigning a lower weight to costs in the future than present costs (Hauschild, Rosenbaum, Olsen, "Life Cycle Assessment, theory and practice")

Hunkeler et al. (2008) provided a classification of LCC into three main approaches: Conventional (C-LCC), Environmental (E-LCC) and Societal Life Cycle Costing (S-LCC) mainly differing in terms of perspective, costs included, and potential uses (Menna, 2018).

Conventional LCC assess costs occurred during the life cycle of products, services, and technologies, focusing on the life cycle in its LCA-related meaning, rather than the product, service or investment life span.

E-LCC should have the same product system, functional unit, and system boundaries as LCA, while S-LCC further enlarges the boundaries of the analysis by assessing the overall direct and indirect costs covered by the society in a larger perspective (Menna, 2018)

Costs done by actors directly involved in the life cycle of the product are termed internal costs (interal or private costs). However, a product or system may involve other costs, borne by other actors indirectly influenced by the product life cycle. These are termed external costs.

External costs are value changes caused by a business transaction, which are not included in its price, or value changes caused as side effects of the economic activity (Dodds and Galtung 1997; Hunkeler et al. 2008).

For example, in the construction of a highway close to a residential area, one possible external cost that is not normally included in the life cycle costs of the highway is the value reduction of the houses close to the highway due to the increased noise levels. In conventional LCC, external costs are usually not included.

If the external costs are already expressed in some monetary unit, they can be included in the environmental LCC. In societal LCC, externalities can be monetarized and included in the assessment. The figure below (Figure 30) shows the comparison of the three different types of Life Cycle Costing.

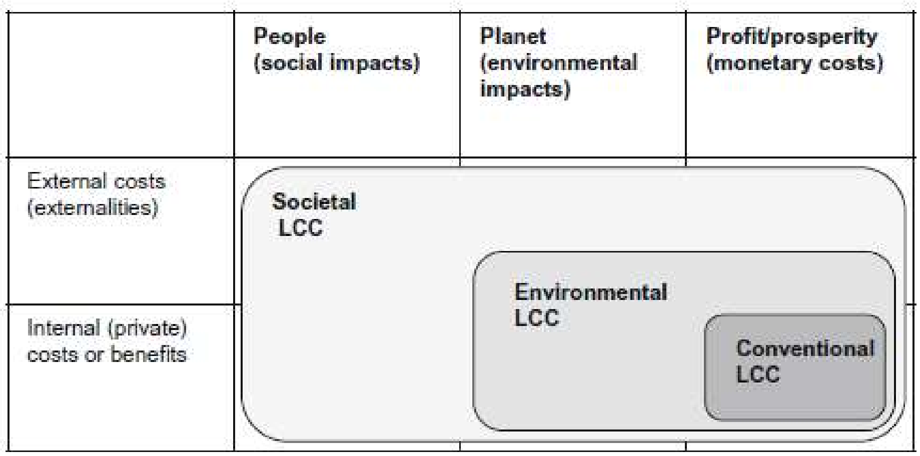


Figure: 30 Comparison of the three different types of Life Cycle Costing

The analysis in this work will focus on the study of the environmental LCC (E-LCC), since the system boundary coincide with the one of the LCA.

To conduct an eLCC in a consistent way and in parallel to an LCA, I must cover the same steps of the LCA:

1. Goal and Scope definition: in addition to the functional unit that needs to be defined as a reference for results, it is necessary to define a product system value, which, depending on the objectives of the study, may be functional, qualitative or monetary. For what concerns the system boundary, if the eLCC is conducted in parallel to an LCA, system boundaries for both must be equivalent and assume the same user perspective.

2. Data collection: In the inventory analysis, costs must be quantified in one currency (e.g. euro or US dollar) and be based on a common year.

3. Interpretation

In this work the LCC will be conduct in a wastewater treatment plant, so the focus is on the description of the analysis in a WWTP.

WWTPs life-cycle costs are highly constrained by operational costs and study demonstrated that annual equivalent costs linked to construction represents a minor contribution to total costs.

Lorenzo-Toya (2016) fixed the monetary unit for the system value as the cost of treating 1 cubic meter of wastewater. In this way, it is possible to compare the economic and environmental impacts of the WWTPs assessed.

The author, analyzing 22 WWTP, showed that, on average, 29% of the cost of operation and maintenance is related to energy consumption and 34% is due to personnel costs.

Operational costs per cubic meter of treated wastewater ranged from 0.044 to 0.344 €, with an average of 0.144 ± 0.074 €. Table 84 shows all the costs divided per phases, specified for the functional unit.

Table 84 Average of cost per category (Lorenzo-Toya et al., 2016)

Table 4
Average of costs per category.

	Annual costs (€/year)		Costs per F.U (€/m^3)	
Materials	47,599 €	±15.514 €	0.025 €	±0.010 €
Chemicals	16,795 €	±7463 €	0.007 €	±0.003 €
Energy	201,117 €	±92,449 €	0.110 €	±0.046 €
Personnel	212,713 €	±62,006 €	0.134 €	±0.049 €
Waste	41,778 €	±15,198 €	0.042 €	±0.024 €
Fees	102,509 €	±93,341 €	0.021 €	±0.018 €
Maintenance	140,583 €	±67,571 €	0.049 €	±0.021 €
Lab analyses	5621 €	±2587 €	0.004 €	±0.002 €

To consider the CAPEX, the study conducted by SMART-plant in the context of the Socio-economic assessment (Deliverable D4.5) is considered.

In order to choose the actual As it is CAPEX and OPEX in the municipal wastewater treatment sector, they considered data both from reports published by the European Commission and by scientific literature, as well as costs published in public tenders about new municipal WWTPs construction in 2019-2020 (see Figure 31 and Tables 85 and 86).

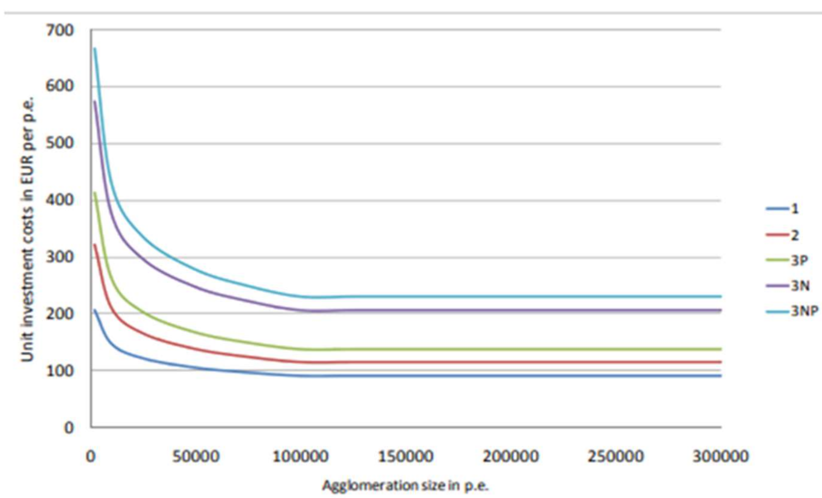


Figure: 31 Investment costs for wastewater treatment (EVALUATION of the Council Directive 91/271/EEC, concerning urban waste-water treatment, EC, Dec 2019)

Table 85 Investment costs for wastewater treatment plants and related references

COST ITEM	WWTP	PE	(€/PE)	References
CAPEX	activated sludge WWTP	500	426	Masotti, 2011, Campogialli WWTP
	activated sludge WWTP	600	450	Masotti, 2011, Pratolino WWTP
	activated sludge WWTP	1.000	350	Bid/tenders in Italy
	activated sludge WWTP	6.500	464	Bid/tenders in Italy
	activated sludge WWTP	8.000	270	Masotti, 2011, Impruneta WWTP
	BNR	46.700	290*	Bid/tenders in Italy
	advanced P-removal	50.000	180	(- EVALUATION of the Council Directive 91/271/EEC of 21 May 1991, concerning urban waste-water treatment, EC, Dec 2019)
	advanced N-removal	50.000	270	
	advanced N and P removals	50.000	300	
	activated sludge WWTP	56.000	235	Bid/tenders in Italy
	advanced P-removal	100.000	140	(- EVALUATION of the Council Directive 91/271/EEC of 21 May 1991, concerning urban waste-water treatment, EC, Dec 2019)
	advanced N-removal	100.000	200	
	advanced N and P removals	100.000	250	
	activated sludge WWTP	100.000	210-230	Bid/tenders in Italy
	advanced P-removal	250.000	140	EVALUATION of the Council Directive 91/271/EEC, concerning urban waste-water treatment, Dec 2019
	advanced N-removal	250.000	200	
	advanced N and P removals	250,000	230	

* cost doesn't include the sludge treatment line

Table 86 OPEX costs for wastewater treatment and related reference

		References					
COST ITEM	**Sub-category**	Costs of the Urban Wastewater Treatment Directive, EC, 2010	OPERATION COSTS OF WASTEWATER TREATMENT PLANTS, EMWATER 2005	EVALUATION of the Council Directive 91/271/EE, 2019	Benchmarking Yago Lorenzo-Toja et al.,2016 (elaborated)	Benchmarking M. Molinos-Senante et al., 2014 (elaborated)	Benchmarking of Municipal Wastewater Treatment Plants WWTP, Vienna University of Technology
OPEX	ENERGY	3% of CAPEX	10-30% of TOTAL OPEX	-	4-12 €/ PE.Y	6-17€/ PE.Y	-
	CHEMICALS	3% of CAPEX	5-7% of TOTAL OPEX	-	0.2-0.8 €/ PE.Y	0.7-2.2 €/ PE.Y	-
	MATERIALS		-	-	0.9-2.7 €/ PE.Y		-
	PERSONNEL		15-25% of TOTAL OPEX	-	5-14 €/ PE.Y	12-35 €/ PE.Y	-
	WASTE/SLUDGE DISPOSAL		15-50% of TOTAL OPEX	-	1.5-4,6 €/ PE.Y	1-3.2 €/ PE.Y	-
	MANTAINANCE		10-15% of TOTAL OPEX	-	1.7-5.3 €/ PE.Y	2.5-7.6 €/ PE.Y	-
	LAB ANALYSIS/OTHERS		-	-	0.1-0.4 €/PE.Y	3.6-11 €/ PE.Y	-
	TOTAL OPEX	**6% of CAPEX**	**26-28 €/PE.Y** (>50,000 PE)	**14-18 €/PE.Y** (>50,000 PE)- **13-16 €/PE.Y** (>100,000 PE)	**13-40 €/PE.Y**	**25-77 €/ PE.Y**	**22 €/PE.Y** (<5,000PE)- **10 €/PE.Y** (>50,000PE)

3.5.4 UMBERTO software

Umberto LCA+ is a software tool that helps to calculate the potential environmental impacts of products. It uses graphic modelling of the product life cycle, and allows analyzing, assessing and visualizing the environmental impacts in different impact categories.

To do a life cycle assessment analysis, the starting step plans to draw the life cycle model (or process map).

Processes represented by squares, are the most important element in the life cycle model. The processes have to be specified, so the relationship between input and output flows has to be defined. It is a prerequisite for a successful calculation of all material and energy flows of the system, and subsequently for the LCIA results, that all processes are specified.

A process specification can be made by entering materials on the input and output side of the process and specifying a coefficient for each entry. These coefficients don't have to be absolute values. Rather do they represent the size of flows on the input and on the output side in relation to each other.

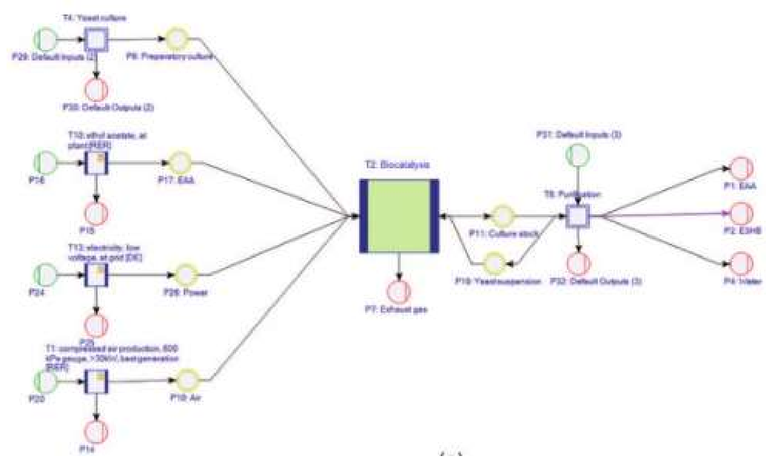


Figure: 32 Example of a graphic model in Umberto

The life cycle model can be displayed as Sankey diagrams, both for material and energy flows, as well as for weighted "impact flows", i.e. the environmental impact loads cumulated along the stages of the life cycle. Sankey diagrams are flow diagrams, where the width of the arrows represents the flow quantity. The Sankey diagrams are an integral part of Umberto LCA+, and the normal life cycle model view can be switched to a Sankey diagram view easily.

Unit process modules represent individual processes or single processing steps within the production chain. They present input and outputs of one production step with the coefficients representing the functional relationship between inputs and outputs. These inputs and outputs are the so-called intermediate exchanges since these flows are within the technosphere.

Between processes, life cycle phases are used to divide the entire cycle in categories.

The flows that run between the processes, within the technosphere, are called Intermediate Exchange. These could be flows that are outputs of a technical process, such as a product, a semi-finished product, processed goods or a component.

Intermediate exchanges do not play a role in life cycle impact assessment (LCIA) as they typically have no characterization factors. Intermediate exchanges can be defined by the user in the project as individual flows. It is possible to define a new intermediate exchange in the project clicking on the button 'New Material'. The exchange will be inserted in the material group that is As it isly marked. All information for the newly created intermediate exchange material can be edited in the Property Editor window when the material is selected in the material list. The material name and a description of the material can be entered, together with the unit type (unit of measure).

If this material is used as a reference flow for which the life cycle product model is to be calculated, the flag 'Material represents Functional Unit' can be set. Indeed, the life cycle model is typically calculated for one unit of product, which describes the delivery of the function of the product. It is also used in comparisons between products, to allow for a comparison based on the same function.

For the material type choose one of the three options: Good (green), Neutral (yellow), or Bad (red). The material type plays an important role in whether a flow of this material is considered an expense, or revenue. Generally speaking, all raw materials and energy should be set to green (Good). These are goods you are purchasing to run a process, to produce a good. Wastes and emissions of a process should be set to red (Bad). The revenue of a process, the intended output, must be set to green (Good) too. In multi-output processes the material type will also be used to determine the products and call for the allocation settings between the products of a process (main product, coproduct).

When calculating the product life cycle model, all material expenses (raw materials, energy, components) in the life cycle inventory are considered with their quantities, and their characterization factors for impact assessment. For newly defined intermediate exchanges, typically no such characterization factors exist, and the intermediate exchanges will most likely not appear in the life cycle impact assessment as contributing to environmental impacts.

In the 'Material Properties' panel the first field is labelled "Market Price" for materials that have a green material type ('Goods') and "Disposal Costs" for materials that have a red material type ('Bad').

Elementary Exchanges, on the contrary, are the flows that cross the system boundary, i.e. the border between technosphere and the natural environment. Typically, they are emissions to air, soil, and water (on the output side) or resources taken from nature (on the input side). Elementary exchanges play a central role in impact assessment as they do have characterization factors assigned, for which the contribution to an environmental impact is calculated. Typically, elementary exchanges are not defined by the practitioner as individual flows but are predefined in the master material databases.

When an elementary exchange is defined, there is the possibility to expand the flow in order to define the background process.

Umberto LCA+ is shipped with datasets from the following three system models:

- consequential system model. It uses different basic assumptions to assess the consequences of a change in an existing system.
- Allocation, at point of substitution (APOS) model. It follows the attributional approach in which burdens are attributed proportionally to specific processes.
- Allocation cut-off system model. It considers the producer as fully responsible for the disposal of its wastes, and so he does not receive any credit for the provision of any recyclable materials.

Several LCI databases are available for use in Umberto LCA+. The support database uploaded in Umberto is ecoinvent.

To use an activity dataset in your life cycle model simply drag the selected dataset (activity name with blue process icon in front) to an empty area in the editor.

Activity datasets from the master databases are "locked" to protect their original status. This is shown with a lock icon. To modify or adapt the process specification, the lock must be removed.

The activity dataset typically is available in different types (or "versions").

For a unit process this model stub has one input and an output place, to which elementary exchanges (should they exist in the unit process) will be assigned, and two connection places: one for the intermediate exchanges on the input side, and one for the intermediate exchange(s) on the output side (typically the reference flow).

Impact assessment is the part in LCA where predictions on environmental effects of the production system are made. For an impact assessment life cycle inventory, results are associated with specific environmental impact categories. The link between life cycle inventory results and impact categories are the characterization factors for each elementary flow, i.e. each flow across the system boundary that is not a product. The choice of impact categories, as well as the level of detail, depends on the goal and scope of the study. The other elements of an impact assessment are classification and characterization of the LCI results leading to the category indicator results (LCIA results).

One of the most important things to conduct the analysis is the choice of the method for the life cycle impact assessment that in this work in the ReCiPe 2008.

In Calculating the Life Cycle Model, is important to say that the product for which the life cycle model is built is represented by the reference flow of the system. In most cases there will be just one reference flow ("single product system"), but the models in Umberto LCA+ are also capable of handling several reference flows ("multi product systems"). This is the case, for example, when besides the main product there are also one or more co-products. In this case allocation must be made to properly assign process expenditures to the individual products.

After a model has been built up and all processes have been properly specified, it can be calculated. As a prerequisite to launch the calculation, it is required to enter at least one flow manually. This start flow can be located anywhere in the model, but it typically is the flow of one unit of product for which the model is calculated. As a result of the model calculation, ideally, all other flows will be determined.

The results of the LCA can be seen in different ways. The first way is the visualization through the Sankey diagram. Sankey diagrams are flow diagrams, where the width of the arrows represents the flow quantity.

It is a useful tool both to view the mass balance of the flows and the results in terms of impacts. The results can be seen depending on the product chosen. Indeed, the products in this configuration are the treated wastewater, which is also the functional unit, the compost from both the Salvatronda WWTP and the other 9 WWTPs and the effluent from the Imhoff tanks. The results can be seen also from the “main net” window in Umberto or could be extracted in the excel sheet, where they are schemed in tables.

Results are displayed graphically and in tables in excel files. The tables and the graphs are divided for impact categories and there is the possibility to choose to see only the impacts given by one product ore more products. If there is the need to see the results considering all the products, the software can do the calculations and sums up all the impacts together.

Umberto LCA+ include a managerial cost accounting feature. It allows calculation of costs based on the calculated materials and energy flows (material direct costs) and process costs. In the properties windows of the intermediate and elementary exchange it is possible to enter the prize per unit od product consider (i.e. Euro/kWh of energy).

Other costs are defined as entries under the Cost Types folder in the Project Explorer:

Energy Costs: In this cost type group one can define and manage cost types for electricity, fuels, heat, cooling, or compressed air.

System Costs: Under the system cost cost type group you can define cost types for other costs, such as taxes, depreciation, labour cost, maintenance or transport.

Waste Management Costs: This group can be defined to define cost types for management of waste. This includes costs for handling gaseous emissions, wastewater, solid waste, as well as for waste transport, waste storage and waste recycling activities.

There is the possibility to add new costs, defining also the cost type: they could be fixed or variable costs.

The costs results are available, after the model is run, in an excel table. Another presentation of calculated cost information can be with cost Sankey diagrams.

3.5.1 Data collection for LCI inventory for full scale plants

3.5.1.1 *Case of Casetelfranco Veneto wastewater treatment plant*

The life cycle assessment has been conducted in Castelfranco Salvatronda WWTP to support decision making for the new configuration plant and sludge valorisation centre.

It is a technique to quantify the impacts associated with a product, service or process from cradle-to-grave perspective (Corominas, et al., 2013) and it is a widespread analysis in the field of wastewater treatment.

As said in the methodology chapter, the LCA comprises 4 phases: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation.

During the first step, there is the need to define the scope of the study, since an LCA can be applied at different levels.

It is applied at planning level, in order to choose the wastewater management strategies and to enable to chart pathways to improve the environmental performance of technologies and processes. In particular, in the case of Castelfranco, the assessment is conducted in order to compare the As it is plant scenario, with the design one and to find the best way to design the resource recovery configuration. The result will be an important guideline to support the decision making.

The definition of the functional unit (FU) is a crucial issue for LCA studies. The most commonly used functional unit in literature is a volume unit of treated wastewater, but in some cases, to represent better the quality and the efficiency of the WWTP, other functional unit are chosen.

In this case, for simplicity sake, the treated water volume (4499750 m3/y in case of As it is scenario and 11024042.5 m3/y in case of PHA recovery configuration) is considered as functional unit, so all the values are specified with respect to this value.

Both temporal and physical boundary of the system must be defined in this phase. The temporal boundary is referred to 1 year of work at full capacity of the plant. The assumptions for the physical boundary are done considering the transports of all chemicals, products (sludge to composting plant) and by-products (screen ang grit to the landfill), the impacts caused by the chemicals production, the saving of fertilizers (due to for example, the production of compost) and the revenue due to the production of biopolymers and struvite.

The values used to execute the LCA are taken from the mass and energy balance of the plant, in such a way that it was possible to build the inventory for plant. The perimeter fences of the investigated WWTP are set as the physical system boundaries of the directly analyzed operation phases, while for the processes production of chemicals, electricity, waste disposal, transportation, anaerobic digestion and fertirrigation, the system boundaries were expanded by using case studies from the database and scientific literature.

The support database uploaded in Umberto is ecoinvent: it provides well documented process data for thousands of products, helping to make truly informed choices about their environmental impact. In case in which the process required for this work is not implemented, some simplifications are needed. The assumptions done have been supported by the literature analysis.

Impact categories and respective environmental indicators are selected based on experience from previous LCA studies in this field.

It is decided to stick to the ReCiPe 2008 methodology. The categories that will be considered are the global warming potential (GWP), the freshwater eutrophication and the fossil depletion.

The Global Warming Potential (GWP100) is an impact category considered in the methodology, related to the climate change and greenhouse gas emissions. Characterization factors are expressed as potential impact for a time horizon of 100 years in this case.

Direct global warming potentials (GWPs) are relative to the impact of carbon dioxide. GWPs are an index for estimating relative global warming contribution due to the atmospheric emission of a kg of a particular greenhouse gas compared to the emission of a kg of carbon dioxide. It is expressed in kgCO2eq.

The fossil (or abiotic resource) depletion includes depletion of nonrenewable resources, i.e. fossil fuels, metals and minerals. It is calculated as kg oil eq consumed in one year.

Eutrophication potential (EP) is defined as the potential to cause over-fertilisation of water and soil, which can result in increased growth of biomass. It can be divided into freshwater eutrophication (expressed in kg P released in one year) and marine eutrophication (defined as kg N released in one year).

Human toxicity potential (HTP) is calculated by adding the releases, which are toxic to humans, to three different media, i.e. air, water and soil and it is calculated as kg 1,4 DCB. The organic pollutants decachlorobiphenyl (DCB) are a group of persistent synthetic substances of high risk to human and environmental health (Rincón-Molina, 2019).

In general, the acidification potential (AP) is based on the contributions of SO2, NOx, HCl, NH3 and HF to the potential acid deposition, i.e. on their potential to form H^+ ions. The terrestrial acidification potential (TAP) is expressed as kg SO2 equivalent per year.

The water depletion (WDP) is another impact category that take into account the water use, since the water scarcity is one of the bigger problems in this last years.

3.5.1.2 Castelfranco Veneto As it is configuration

As said in the chapter 3.3.1, the As it is configuration of the plant is composed by pretreatments, primary clarifier, the biological reactors and the secondary settlers and finally by the filtration and UV disinfection process. The sludge line consists of dynamic thickener and dewatering. In this scenario, the sludge is then sent to the composting facility.

All these processes are resources and energy consuming, mainly due to the aeration and sludge treatment associated processes, since it uses the dynamic thickening and centrifuges.

From the figure below (Figure 33), it can be possible to understand how the plant looks and the system boundary considered. The production of the chemical and of the energy is not considered inside the system perimeter, while the transport is insert in ton*km.

The stages in the figure represents the phase in which the plant is divided in Umberto. It is an important detail for the visualization of the results.

Actually, the chemicals and the energy are studied and considered as “market for” in Umberto. A market activity is an activity that does not transform inputs, but simply transfers the intermediate exchange from one transforming activity to another transforming activities that consumes this intermediate exchange as an input.

The life cycle inventory (Appendix 4a) has been built starting from the real data of the plant, so the flowrate coming in the plant from the sewage and its characterization are data available and given by the plant manager. The material flows that are exchanged between one process and another within the plant are not considered as they have no impact on the environment. This is also underlined by the fact that these flows do not come from the database but can be created manually and entered for the convenience of the user of the software. Indeed, these are flows in which any type of assessment factor is absent.

As for the influent, the quantity of effluent and sludge that is produced by the sludge line plant is also known. The same occurs for the emission values that characterize the processes. However, they were calculated thanks to the carbon footprint, previously calculated on the Salvatronda plant. These values have been inserted creating materials manually and changing the impact assessment factor related to the climate change. For the carbon dioxide the value to be inserted is 1 kg CO2eq, for the methane and the nitrous oxide, the global warming potentials are 28 kg CO_{2e}/kg CH_4 and 265 kg CO_{2e}/kg N_2O respectively.

Concerning the electric energy, the technical reports have been able to provide interesting data for the study of LCA. The energy balance for the As it is scenario has been explained in the chapter 3.3.1 and the flow scheme can be seen in appendix 1c.

The electricity is added with the process taken from the Ecoinvent database called "market for electricity, low voltage". When a process is taken from the database, some different characteristics could be chosen. In particular, the geographic allocation is an important element to define. Since the plant is located in Italy, obviously the chosen process is related to the Italian characteristics.

There is the possibility also to define the type of process between Unit or Result. Unit process modules represent individual processes or single processing steps within the production chai, while result processes represent a whole life cycle inventory of products or services. By using a system terminated process module, the complete production chain with all process steps is included. Finally, the system model chosen is "allocation cut-off", that means it considers the producer as fully responsible for the disposal of its wastes, and so he does not receive any credit for the provision of any recyclable materials.

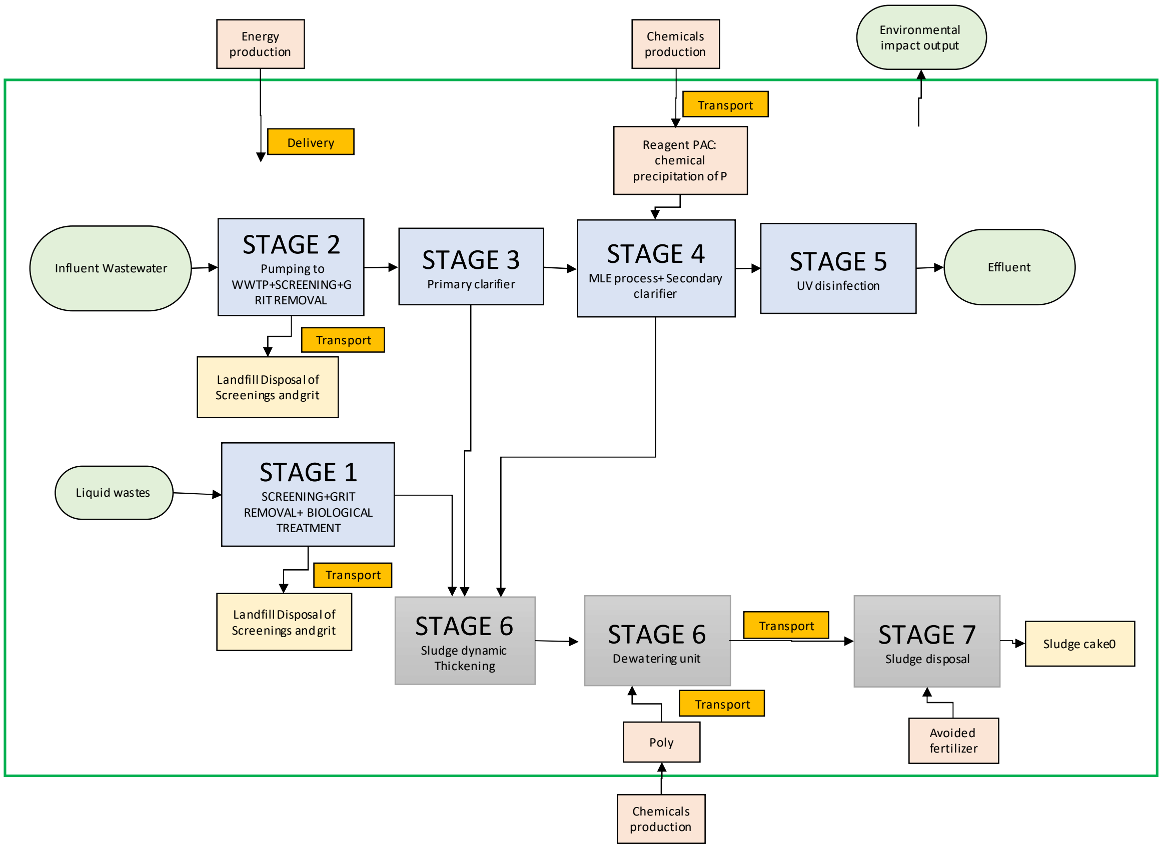


Figure: 33 System boundary of Castelfranco As it is

Also, the amount of the chemicals and the distance for the transport are known values provided by the plant or company that manages.

Polyaluminium chloride for the biological tank, is taken from the Ecoinvent. The value needed for the process is 575,4 kg PAC/d that, specified for the functional unit is 0.0467 kgPAC/m3 water treated.

Not all the chemicals are implemented in the database, so in some cases assumptions are required. In particular the polyelectrolyte has be implemented as polyacrylamide, which is a kind of polymer used for sludge coagulation (Yizhen Zhang, 2020).

The transport is defined in Umberto as the ton of material transported multiply for the distance to travel from the chemical production plant to the WWTP. The same calculation has been done for all the materials transport, i.e. the wastes from pretreatments (grit and screen) and sludge to be composted. The Umberto software gives the possibility to insert the transport taken from the database: depending on the size of the lorry, there is different emission related to the transport. It means that for each material, the weight of the truck must be known, in order to enter the right material from ecoinvent.

Also, the sand and the screen have to be insert doing some simplifications. Since they are composed mainly by inert material, they can be seen as inert waste, paper and plastic wastes. Indeed, with regards to grit disposal, the process “treatment of inert waste, sanitary landfill” was considered, while the processes “treatment of waste plastic, mixture sanitary landfill” was used to estimate the environmental burdens caused by the disposal of screening waste, assuming that such a waste is only composed by paper and plastic (Buonocore, Mellino, De Angelis, Liu, & Ulgiati, 2018).

The outflow from the water line is composed by the process “discharge”. The dissolved GHG and the effluent concentration of the pollutants are implemented in this element. As in the other cases, the gas emission is built manually, changing the emission factor value related to the climate change, while the nitrogen and the phosphorus flow is implemented taken them from Ecoinvent database.

The final part of the system is composed by the sludge disposal (stage 7), which represents the composting facility considering the transport of the sludge from the WWTP to the composting plant, the process itself and the spreading.

In the composting sludge process and in the spreading process, some assumptions are considered. The first is related to the decrease in the volume of sludge once transformed into compost. In this work, it is considered that 1 kg of sludge treated in the composting facility, become 0.5 kg of compost.

The emission due to the composting process are calculated considering the calculation done for the carbon footprint.

When the compost is spread in the soil, some elements have to be considered, starting from the chemical fertilizer that has not been produced, thanks to the production of compost. This concept can be considered in Umberto adding the materials “fertilizer as N” and “fertilizer, as P2O5”, with negative values (Almudena Hospido, 2005).

The emission from soil to air, to soil and to water must be calculate starting from the elements present in the compost.

At first, the carbon is about 294 kgC/tonTS so if the solids in the compost amounts to 1150 tonTS/y, the carbon in the soil is 339100 kgC/y. This value is useful in order to calculate the emission from soil to air. Indeed, considering the ratio 0.03 kgCO2/kgC (Bruun et al, 2006), the emission is 10173 kgCO2/y, that specified for the functional unit is 0.0023 kg CO2/m3. Another important data to be considered is the avoided emission due to the spreading of the compost. It is the carbon sequestration, which is the process involved in carbon capture and the long-term storage of atmospheric carbon dioxide. For the Salvatronda plant the value is -78kgCO2 eq/y.

Further, 0.02 kgN2O/kgN (Bruun et al, 2006) is the greenhouse gas from the soil spreading. This value must be multiplied for the quantity of nitrogen in the compost.

Loss of nitrogen and phosphorus through volatilization was included, assuming losses of 33% and 6%, respectively.

The study of Bengtsson (1997) shows that emission to soil due to the compost spreading are 50% for nitrogen and 30% of phosphorus, because the remaining part is taken from the vegetables and plants. For the emissions to the water, only the phosphorus is taken into account, considering a percentage of 2.2%.

The same pathway is followed for the composting plant that treats the sludge from the other external plants, without forgetting that the calculations must be performed on different volumes of sludge.

The life cycle assessment is conducted, as said previously, in order to compare the As it is configuration with the design one, so the study of the territorial scenario is required.

Indeed, at the moment, in addition to Salvatronda WWTP, 9 WWTPs in the nearby territory of Salvatronda are collecting their thickened sludge to composting plants and 79430 PE in the territory are not collected and not yet treated.

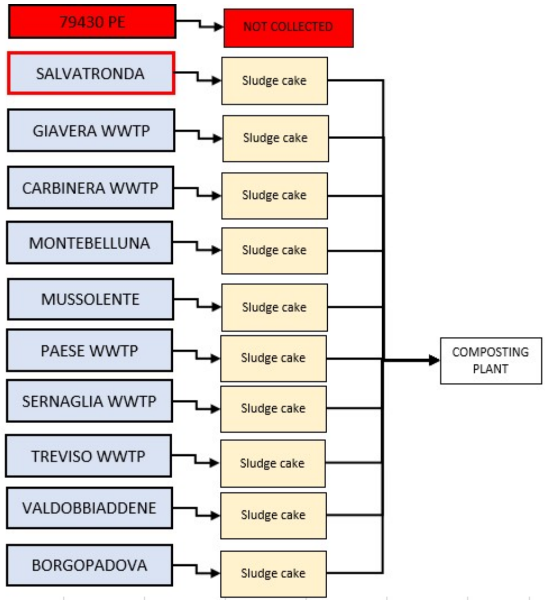


Figure: 34 Territorial scenario before the up-grade of Salvatronda sludge center

Table 87 Sludge quantity and Transport before the up-grade of Salvatronda sludge center

WWTps	Ton sludge/y	TS%	Ton TS/y	km/y (for disposal)
SALVATRONDA	6110	19	1161	41265
Giavera	951	14	133	7790
Carbonera	1733	22	381	12775
Montebelluna	3068	19	583	22477
Mussolente	665	18	120	7252
Paese	4232	25	1058	28684
Sernaglia	426	20	85	3655
Treviso	3419	23	786	29666
Valdobbiadene	655	16	105	4250
Borgopadova	2919	26	759	19479
			TOTAL	**177293**

The wastewater (not treated) coming from the Imhoff tanks is discharged into the soil without being collected in the plant. Only the greenhouse gasses from the process is considered and amounts to 65.7 kg CO_2/y as can be seen in the table 88.

Table 88 GHG emissions from Salvatronda wwtp

GHG EMISSIONS FROM SALVATRONDA WWTP		**ton CO2 eq tot/y**
Biologic reactor	biogenic	212,5
dissolved GHG in the effluent	not biogenic	617
sludge line	biogenic	0,89
composting plant	biogenic	129,51
Carbon sequestration	biogenic	-77,86
GHG EMISSIONS FROM IMHOFF TANKS		**ton CO2 eq tot/y**
emession to air	biogenic	10941
dissolved GHG in the sewage sludge treated in Imhoff	biogenic	65,7
GHG EMISSIONS FROM COMPOSTING PLANT OF THE EXTERNAL SLUDGE		**ton CO2 eq tot/y**
composting plant	biogenic	451,9
Carbon sequestration	biogenic	-272,2

3.5.1.3 Economic evaluation in the As it is configuration

The economic evaluation is done considering both the capex and opex of the plant, in a time life of 1 year. Since the costs are unknown, an analysis of the literature has been done.

The operative costs and the capital costs have been chosen from the literature. The time boundary considered for the economic evaluation is one year.

All the costs have been implemented in Umberto as fixed cost, so considering the entire annual price (€/y). The only data in which the unfixed value is implemented is the energy, for which the value is 0.1957 €/kWh. It is the cost of the energy supplied to companies in Italy.

3.5.1.4 Castelfranco design configuration

The water line of the design PHA recovery configuration of the plant is composed by pretreatments, which produce screen and grit, the primary filtration, the biological reactors, the secondary settlers and finally by the filtration and UV disinfection process. The sludge line consisting is very complex, because the project involves the production and recovery of phosphorus in the form of struvite and of biopolymers.

Also in this case the territorial scenario is analyzed, since all the sludge from the other plants in the territory is collected in Salvatronda. Basically, the sludge line will be upgraded in order to become a territorial centre for sludge valorisation and for resource and energy recovery. The maximum treatment capacity will be extended up to 406000 PE.

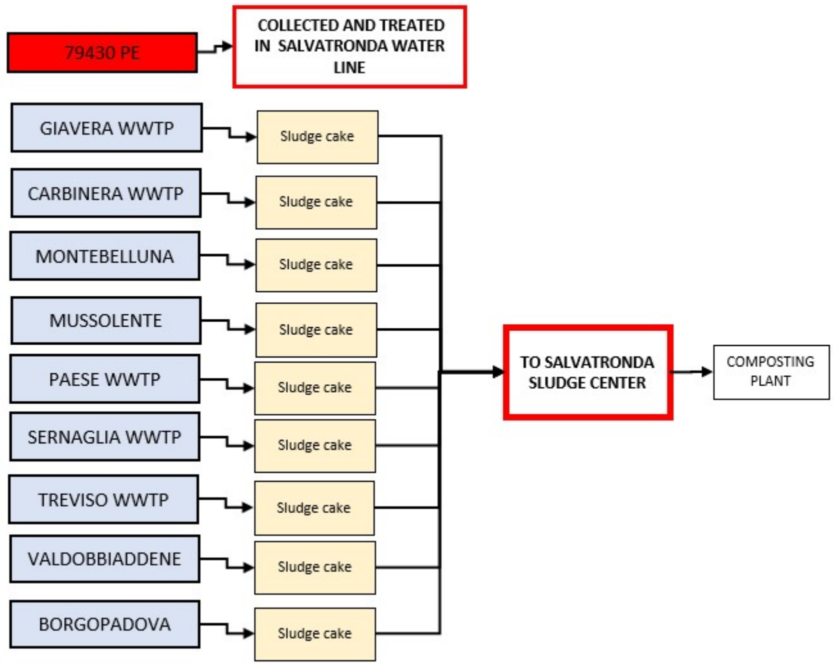


Figure: 35 Territorial scenario after the up-grade of Salvatronda sludge center

Table 89 Sludge quantity and Transport after the up-grade of Salvatronda sludge center

EXTERANAL SLUDGE	Ton sludge/y	TS%	Ton TS/y	km/y
Sludge of 9 WWTPs to Salvatronda	18288	22	4023	17483
Disposal from Salvatronda to composting plants	4560	90	4104	31893
			TOTAL	**49376**

The life cycle assessment is done in the same way of the real configuration, in order to compare the two scenarios. The sludge line is considered in the same stage, while the external coming in the first phase as in the previous plant. It means that the chemical production is not considered together with the energy production, while the transportation and all the emissions from the processes are implemented.

The water line is quite similar to the one of the As it is configuration plant. The main differences are related to the presence of the primary filtration instead of the primary sedimentation and the biological nutrient removal instead of the denitrification-nitrification process. Indeed, in this second case, instead of iron chloride for the phosphorus precipitation, the external carbon source is doses. Since it is a design configuration, the kind of external carbon dosed in the plant is unknown. At first the acetic acid has been implemented in Umberto, but the impacts related to its production are too

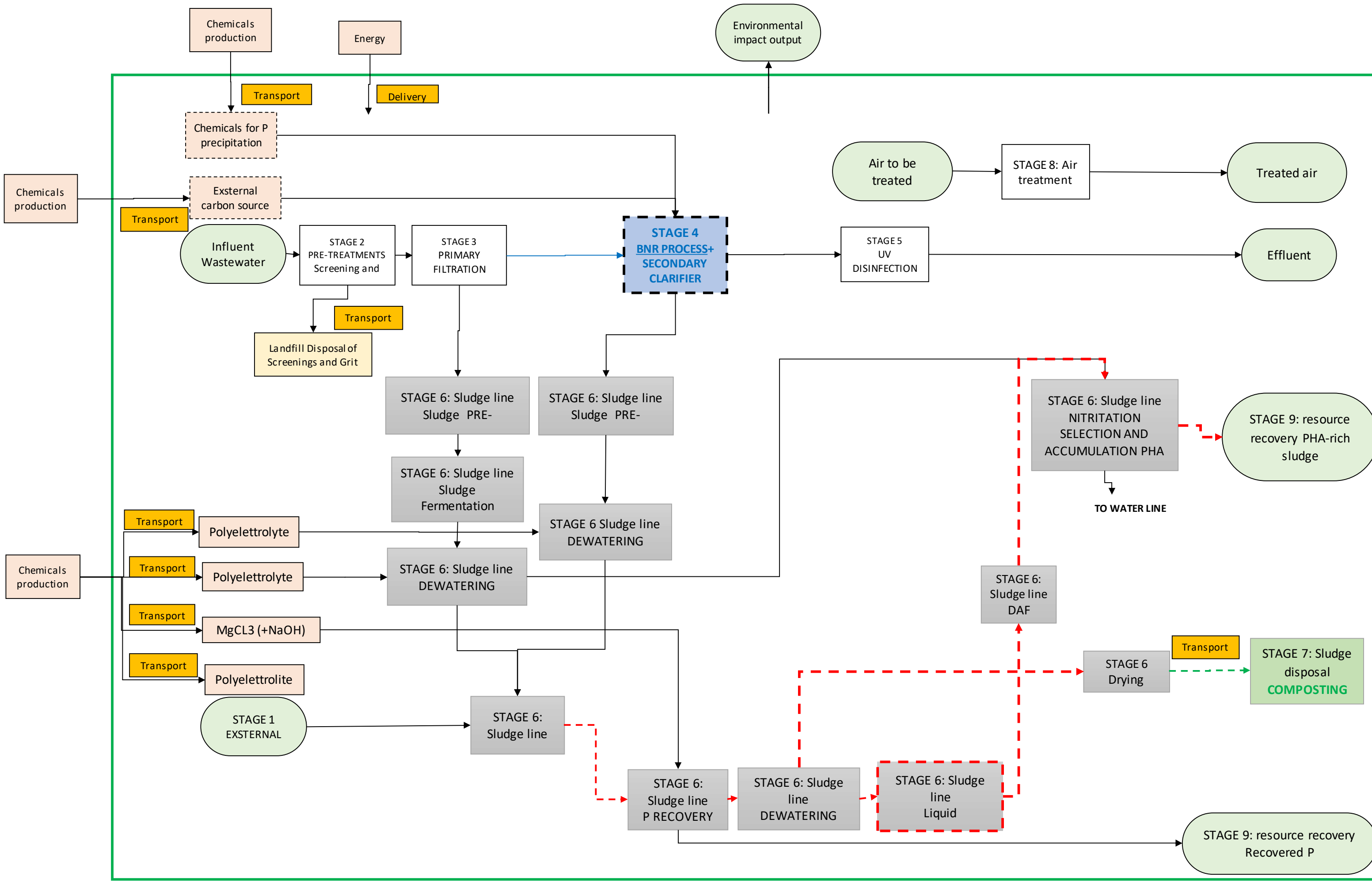


Figure: 36 System boundary of Castelfranco design scenario high. So, the choice fell on another readily external carbon source called methanol, since this element production has a lower environmental impact it would be better to choose this element.

Actually, as said in the previous case the chemicals and the energy are studied and considered as "market for" in Umberto. A market activity is an activity that does not transform inputs, but simply transfers the intermediate exchange from one transforming activity to another transforming activities that consumes this intermediate exchange as an input. Anyway, the acetic acid impacts were high and consequently not convenient.

Since the amount of external carbon to dose is given in kgCOD/d, an assumption for the implementation as methanol is required. Metcalf and Eddy, proposes to consider the theoretic ratio 1.5 gCOD/1g methanol. It means that if the amount of external carbon is 4800 kgCOD/d, the methanol needed to dose is 2133 kg methanol/d.

Given the complexity of the sludge line, it appears more convenient to deeply explain the assumptions and choices made for this part of the plant.

As in the previous case, here too the polyelectrolyte is implemented as polyacrylamide.

For the P recovery as struvite, the MgCl3 is required to be dosed. Since the ecoinvent database does not have this chemical implemented, another simplification is needed.

In the "Sustainable sewage sludge management fostering phosphorus recovery and energy efficiency" report deliverable D9.2 within the Seventh Framework Programme Grant agreement European project, the MgCl3 is implemented as magnesium oxide. The value is weighed with the number of moles of the dosed chemical, so the final value of MgCl3 is 1.46 kg/d.

Since the struvite can be used as fertilizer, the values of the avoided fertilizer production have to be implemented in the life cycle assessment. They have been inserted as "fertilizer as N" and "fertilizer as P2O5", with negative values as used in the composting facility stage.

For the implementation of struvite product, the fertilizers are used again.

The PHA is applying as polyester complexed starch biopolymer, since it is the only element similar to the biopolymer un the database. The avoided plastic production due to the production of biopolymer has to be considered. Roibás-Rozas 2020 proposes to use the polyethylene terephthalate (PET), considering that 0.72 kg PET is equal to 1 kg of PHA.

The greenhouse gasses emissions are taken from the carbon footprint analysis done for the P and biogas recovery design configuration.

Table 90 GHG emissions from the Salvatronda design scenario plant

		tonCO2e/y	kgCO2eq/y
biological process emission (excluded reagents)	Secondary treatment	600	600000
dissolved GHG	Disinfection	1800	1800000
anaerobic supernatant emission	Nitritation and biomass selection	5549	5548867
dryer emission	Dryer	26	26047
air treatment emission	Air treatment emission	103,2	103200,00
storage emission	Storage tank	3,2	3202
composting emission	composting plant	525	525000
Carbon sequestration		-316	-316000

Some of the processes in the sludge line require the thermal energy. Both the fermenter require the heat, in order to reach a temperature of 35-40°C so that fermentation can take place to produce soluble organic carbon. The first fermenter needs 8636,4 Mj/d, considering that 1KWh/ is equal to 3.6 Mj. The second one requires 1761,84 Mj/d, with the same assumption. The thermohydrolizer require more energy than the fermenter, since it must reach higher temperatures (150°C), but the highest energy consuming is the dryer. It requires 79912,8 Mj/d. The thermal energy is in general produced by the boiler, using the methane, so that the applying process is the “heat production, natural gas, at boiler atmospheric low-NOx non modulating, <100 kW, Europe without Switzerland”, taken from the database.

Table 91 Thermal energy required

	kWh/d	**Mj/d**
Total thermic energy	**37899**	**136437,84**
Fermenter (I sludge)	2399	8636,4
THP	12813	46126,8
Fermenter (supernatant)	489,4	1761,84
Dryer	22198	79912,8

The composting facility, as in the previous case, is implemented in the phase “sludge disposal” and is composed by the transport process, the composting process and the spreading. The assumptions made in the real case, are also valid for this configuration, bearing in mind the different quantities of sludge involved.

In this configuration, another phase considered in the system is the one in which the air treatment process is assessed.

Table 92 Air treatment

	Nm3/h	Nm3/y
Primry filtration	420	3679200
prethickening	180	1576800
dewatering	240	2102400
thickening	900	7884000
pretreatments	300	2628000
Scena	3000	26280000
ESSICCATORE	18000	157680000
	TOT	**201830400**

The process listed in the table 92 are the ones in which the air is sucked in, to be treated. The air treatment process has been implemented by building a separate line, which does not come into contact with the main treatment line. This is due to the fact that mass balance is considered in Umberto. By inserting an outgoing flow into the various processes that is not calculated in the inlet, the software can give an error, since it does not understand the nature of this additional flow.

Further, the odorimetric unit is not considered, since it is not implemented in the database. It means that the only greenhouse gasses are assessed in the analyses in this phase.

3.5.1.5 Economic evaluation in the design configuration

The capex and opex costs of the plant are again found out analyzing the literature. The reason is related to the fact that for this configuration no priced bill of quantities has been made. In fact, only the feasibility study for this scenario was evaluated.

The reasoning made for the previous case will also be applied in this scenario, so the time boundary considered for the economic evaluation is one year and all the costs have been implemented in Umberto as fixed cost, considering the entire annual price (€/y). The only data in which the unfixed value is implemented is the energy, for which the value is 0.1957 €/kWh. It is the cost of the energy supplied to companies in Italy. Umberto can find the costs due to the energy dividing the cost for each process.

In the operative costs, the revenue is considered, since the material recovery takes place. In particular, 2,3 €/PE/y are considered for recovered PHA and 0,43 €/kg is assessed for P recovery.

The capex cost is calculated using the results of the analyses conducted in the smart plant project, (Deliverable D4.5) (Table 85 chapter 3.5.3).

3.7 Experimental activity and laboratory batch tests

In order to have detailed information about the characterization of the supernatant and of the sludge, laboratory tests have been done on samples of two different wastewater treatment plants and managed by the Hera company, nominated as WWTP1 and WWTP2.

The standard methods for the examination of water and wastewater is used to conduct the laboratory test.

In particular, samples are taken

1) from the recirculation of the biological processes (secondary sludge from line 1 and 2)
2) from the inflow of the digester (pre-thickened sludge)
3) from the supernatant of the dewatering process

Further, to characterize the sludge, the concentration tests (to find the TS% and TVS%) was conducted before the fermentation test.

The supernatant samples are used to test the amount of COD, soluble COD, NH4, TKN, TSS, P-PO4 and total P. The tests were done to find the COD, TKN and total P and, on filtered samples, soluble COD, N-NH4 and P-PO4 were investigated.

Since the WWTP1 is subjected to the feasibility study for the PHA recovery (Modena), the samples of the sludge (both secondary sludge and predigested sludge) are used to do fermentation test.

The fermentation is a process composed by two steps: the hydrolysis and the acidogenesis phase where the fermentation of monomers takes place and the production of VFAs.

As already said, the Volatile Fatty acids are product usable for a lot of activities, one of which is the production of the PHA. So, the fermentation tests are required in order to test if the sludge taken from the plant is suitable for this kind of work.

It is important to say that, for simplicity, the samples are called with a letter that correspond to a different type of sludge:

- A: activated sludge from the line 2 of the water line (WWTP1)
- B: activated sludge from the line 1 of the water line (WWTP1)
- C: sludge entering the digester (WWTP1)
- D: activated sludge from the line 1b of the water line (WWTP2)
- E: activated sludge from the line 2 of the water line (WWTP2)
- F: sludge entering the digester (WWTP2)

Six bottles of 1 volume liter, with samples are taken in the thermostatic box in order to maintain them to a temperature of 35°C. The bottles are closed to favor the anaerobic environment. In order to keep the sludge mixed, a magnetic stirrer is inserted into the bottles. These magnets rotate because of the presence of a magnetic plate that active the movement of the stirrer inside the bottle.

Table 93 Operating conditions of fermentation lab tests

		WWTP1			WWTP2		
		A (WAS sludge line 2)	B (WAS sludge line 1)	C (fango pre-thickening)	D (WAS sludge line 2)	E (WAS sludge line 1)	F (fango pre-thickening)
Mixing	-	YES	YES	YES	YES	YES	YES
T°C	**°C**	35	35	35	35	35	35
Reactor volume	**L**	1	1	1	1	1	1
HRT	**d**	5-9	5-9	5-9	5-9	5-9	5-9
MLSS	**mg/L**	8600	14280	46820	9180	14800	39620
MLVSS	**mg/L**	4090	5680	23240	5049	10200	27100
gVSS in tank	**gVSS**	4.1	5.7	23.2	5.0	10.2	27.1
LOAD VSS Fed	**gVS/L reactor**	**4.1**	**5.7**	**23.2**	**5.0**	**10.2**	**27.1**
TS%	**%**	1.4	1.1	5.1	1.6	1.05	4.65
TVS/TS	**-**	**0.48**	**0.54**	**0.51**	**0.55**	**0.69**	**0.68**

The fermented sludge has been analyzed in order to find the concentration of VFA, soluble COD, NH4 and PO4 during the time (5 days, 7 days and 9 days of retention time).

Figure: 37 Picture of the 6 bottles with the fermenting sludge

4. Results and discussion

4.1 Castelfranco Veneto

4.1.1 PHA recovery scenario

The aim of this work is to conduct a feasibility study for the PHA recovery in the plants analyzed. Using the method exposed in the chapter 3 (material and methods), the scenario was studied and will be explain in this chapter. In appendix 1l, the entire PHA recovery plant is shown.
Starting from the design configuration, in which biogas was recovered, the configuration changes only after the phosphorus recovery stage. It means that the plant will have the possibility to recover not only the biopolymers, but also the struvite.
In particular, to have a better idea about the plant structure, a brief summary of the type of sludge and the structure of the plant will be shown.

The primary sludge coming from the water line is treated in the thickener, fermented and dewatered before to be mixed with the biological and external sludge.

The secondary sludge is treated in a dynamic thickener and dewatered in a centrifuge. The secondary sludge together with the primary sludge and the sludge coming from external plants, are thermohydrolyzed in THP, to increase the amount of soluble carbon before entering in the P recovery process.

The centrifuge located after the P recovery tank is used to increase the solids in the sludge, so the process will create supernatant rich in nitrogen and soluble COD and poor in TSS. The hypothesis that the water is poor in phosphorus can be done considering that these processes works after the P recovery process.
Since the water is full in CODs, is an optimal substrate for the fermentation. The fermentation product is the VFA, that as said in the previous chapters is the material required to produce biopolymers.
The HRT was supposed equal to 10 days as the literature suggests and so the volume of the fermenter can be calculated (V=102m^3), while the VFA was supposed to be 40% of the total COD.

Table 94 Fermented liquor characteristics

FERMENTED LIQUOR

Flow	245,3	m3/d
VFA	2896	kgVFA/d
CODs non VFA	4343,9	kgCOD/d
N	108,4	KgN/d
P	~ 0	KgP/d
TSS	914,0	kgTS/d

The fermented water (characteristics in table 94) coming from the fermenter enters in the DAF (Dissolved air floatation) process, where a further solid-liquid separation occurs. The sludge comes back to the centrifuge, while the water, together with the supernatants from the dryer and from the primary sludge dewatering is pumped in the nitritation and biomass selection. The selection of PHA storing bacteria was integrated with the side stream treatment of nitrogen removal via nitrite from sewage sludge reject water (Frison, 2018)
This step is the most important one because allow the abatement of the nitrogen and phosphorus and the acclimatation of the biomass needed for the PHA accumulation.

The water from this tank, characterized by low concentration in nitrogen and phosphorus, is sent to the water line as rejected water, together with the water coming from the pre-ticketers and from the biological sludge dewatering.
On the contrary, the microorganisms from the nitritation and biomass selection tank are sent to the polyhydroxyalkanoates accumulation tank, where the PHA storage is improved.
Starting from the yields found analyzing the literature, the calculation gives a daily amount of VSS equal to 837 kg VSS and an amount of PHA equal to 293 kg/d.

Table 95 Recovered PHA

VSS	837	kgVS/d
PHA	293	kgPHA/d
PHA	0,89	kgPHA/PE/y

In the table 95 there is also the value specified with respect to the population equivalent.
In the context of the feasibility study of PHA production in full-scale plants, a detailed study was carried out as scope of the Horizon 2020 research and innovation program. In particular, the SMART-Plant (Scale-up of low-carbon footprint material recovery techniques in existing wastewater treatment plants) analyzes a new technology for the production of PHA and the recovery of phosphorus as struvite (SCEPPHAR, short cut enhanced phosphorus and PHA recovery). These studies have shown that it is possible to produce an amount equal to 1-1.2 kgPHA/PE every year.
The specified value, in this case, is in line with the value proposes by the SMART PLANT assessment.
A comparison between the design PHA recovery scenario and the biogas production configuration is required in order to define the better case.
As the table 96 shown, the As it is configuration produces only the biogas, while the other one, produces only biopolymers. The amount of sludge produced in the second configuration is higher than the other.
The reason could be related to the fact that, in the first configuration, the sludge is treated in the diester, where the organic matter is stabilized, and the biogas is produced. When the sludge is processed in this way, an amount of VSS is consumed to produce the gas. In particular in this case 6569 kgVS/d are destroyed, so the solids outgoing from the digestors, that enters in the dewatering are 11832 kgTSS/d. On the other hand, in the second configuration there is no VSS destruction process in the sludge, since the fermenter works with the supernatant. It means that the solids entering in the centrifuge are 18258 kgTSS/d, higher amount with respect to the previous scenario. Since the sludge, in both cases, is treated in the dryer, it comes out with a concentration of 90%TS, that leads to a variation in the dry tq sludge quantity.
The problem is that, the sludge disposal price wanders around 100 €/ton, so if the amount of dry sludge to be disposed increases, the cost increases, as can be seen in the table 96.
She revenue due to the PHA production is cancelled, by the cost of the sludge disposal.
On the other hand, the loads of the nitrogen and phosphorus, in the second configuration decreases, since the pollutants are consumed in the nitritation and biomass selection reactor to develop the microorganism selection.

Table 96 Summary of results

CASTELFRANCO		AS IT IS CONFIGURATION	PHA RECOVERY CONFIGURATION	
Chosen flux	-		SLUDGE	SUPERNATANT
fermented/digested Q	m3/d	300	73	245
VFA yield	gCODVFA/gVS	-	0,25	5,3
SELECTION yield	gVSS/gCODVFA	-	0,25	
ACCUMULATION yield	gCODPHA/gVS	-	0,58	
PRODUCED PHA	kgPHA/d	0	293	
specific PHA	kg/AE/y	-	0,9	
PRODUCED BIOGAS	Nm3/d	5.000	0	
PRODUCED METHANE	Nm3/d	2.519	0	
DISPOSED	ton/y	4.560	7.034	
PHA REVENUE	Euro/y	0	374.351	
METHANE REVENUE	Euro/y	110.332	0	
SLUDGE DISPOSAL COST	Euro/y	456.000	703.396	
REVENUE	Euro/y	110.332	16.623	
N in supernatant	kg/d	106	24	
P in supernatant	kg/d	3	2	

4.1.2 Life Cycle Assessment and Life Cycle Costs results

The results of the life cycle assessment and of the life cycle costs are explained in this chapter.

The first figure (Figure 38) represents an overview of all the impact categories analyzed for Catslefranco WWTP, both for as it is and design scenarios.

In the figures below, each impact is seen in percentage, individually.

At first, let's consider the current scenario. Starting from the climate change it can be said that in this category the impact reaches the 85%, because there isa rate that is instead recovered. The only category which reaches almost 100% is the freshwater eutrophication. It means that in this case there are no credits due to the avoided production of materials. The other three categories have a very high negative contributions, so their impacts are 40%, 22% and 18% for the fossil depletion, the human toxicity and the terrestrial acidification, respectively.

The different colors represent the phases that impacts in the category.

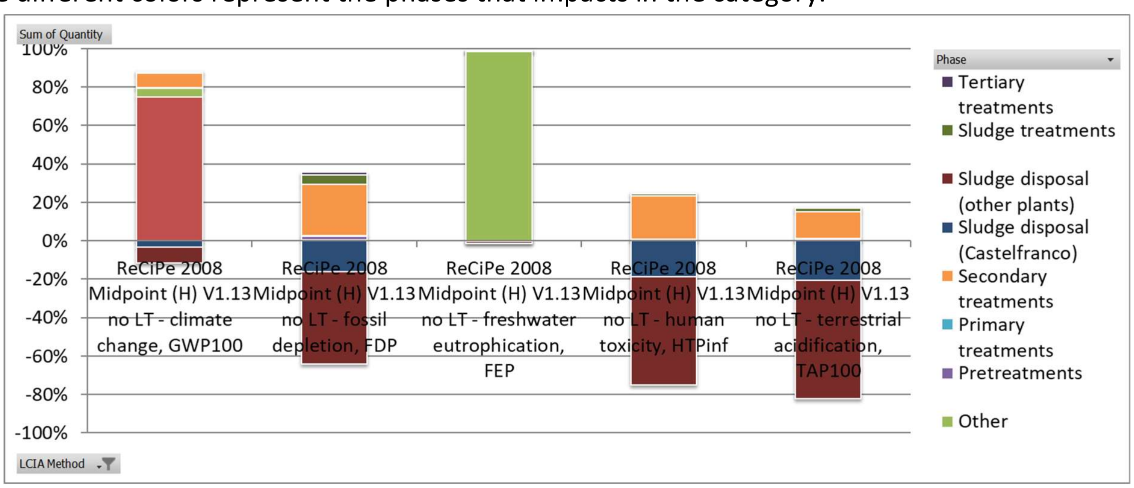


Figure: 38 impact categories (as it is scenario)

For the design scenario, the climate change reaches almost the 100%, because the avoided production of the materials has little impacts in this category. Both the fossil depletion and the freshwater eutrophication have about 5 % of negative impacts. The reason is attributable to the fact that the production for example of the chemical reagents impacts on the fossil depletion, which is the category that includes depletion of non-renewable resources, i.e. fossil fuels, metals and minerals. If the production of the chemicals is avoided, the impacts decrease.

The human toxicity and the terrestrial acidification are still more affected by negative emissions.

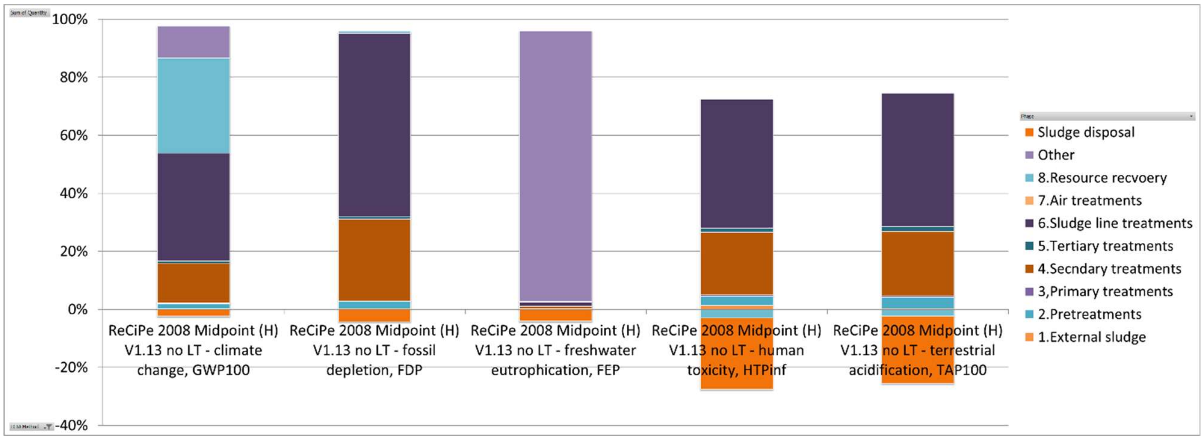


Figure: 39 Impact categories (design scenario)

The following paragraphs report the single categories, comparing the results of the As it is configuration with the results of the design scenario.

As it is – Castelfranco WWTP and territorial scenario

The ‘’X’’ axis represents the phases in which the system was divided: “external liquid wastes treatments”, “pretreatments”, “primary treatments”, “secondary treatments”, “tertiary treatments”, “sludge treatments”, “sludge disposal (Castelfranco)”, “Imhoff tank” and “sludge disposal (other plants)”.For each phase, the impact due to the single process is considered.

The first impact category to be assessed is the climate change. As said before, the system analyzed is composed by the Castelfranco Veneto WWTP, the sludge from other 9 WWTPs and the sewage sludge treated by the Imhoff tank (capacity of about 79430 PE).

Starting from the emissions of the plant, the following graph can be studied.

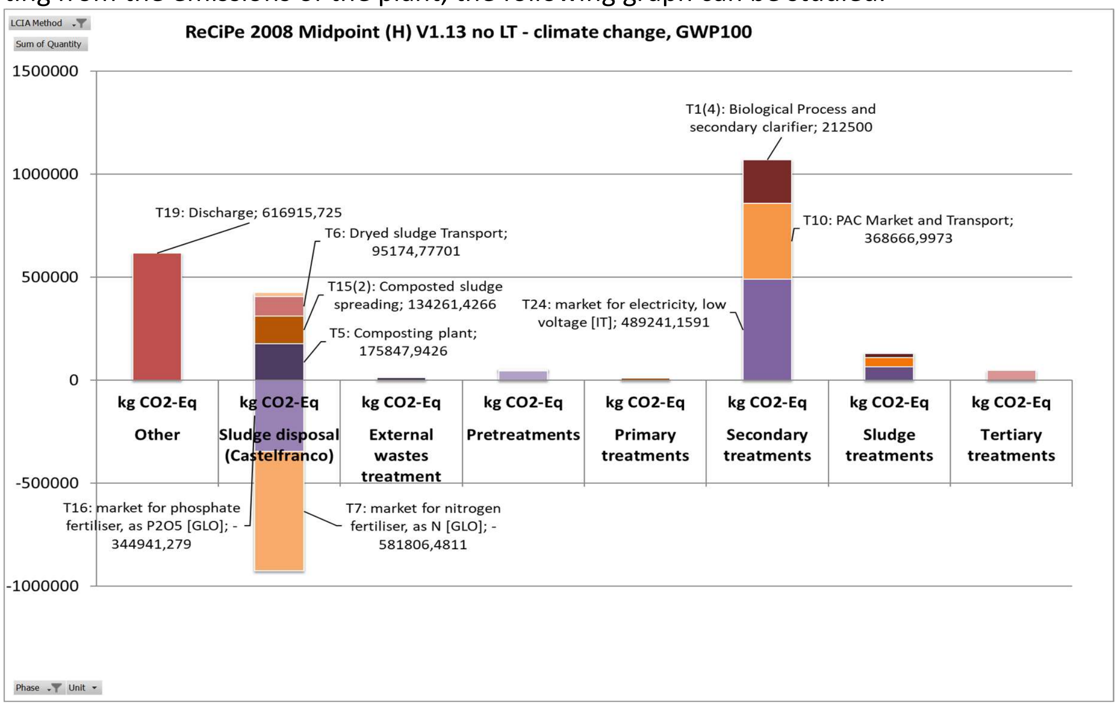


Figure: 40 Climate change impact category (Salvatronda as it is no territorial scenario)

it is possible to observe that the sludge disposal phase is characterized by both positive and negative emissions (avoided effects). These credits are due to the avoided fertilizer production since the compost has been produced.

Indeed, the negative contributions are given by the production process: “market for phosphate fertilizer” and “market for nitrogen fertilizer”. The impact values are -344.941 CO2eq/y and -581.806 CO2eq/y, respectively.

The pretreatments phase emits 53.420 kg CO2eq/y and the main contribution is due to the market for electricity. Other smaller contributions come from the treatment of inert waste, so the sand disposal process, the sand and grit transport and the disposal of the screen.

The primary treatments phase emits a very low amount of greenhouse gasses (9.271 kg CO2eq/y), due to the energy consumption as well as the tertiary treatment (46.107 kg CO2eq/y).

The “secondary treatment” is the most impacting phase since, the biological reactor emits greenhouse gasses due to the process itself and in addition it consumes energy and chemicals. The other process impacting in this phase is the transport of the chemical dosed in this process (polyaluminium chloride).

The emissions due to the secondary treatments are 48% of the total plant positive emissions. In particular, the contribution due to the electricity in this phase, amounts to 489.241 kg CO2eq/y (21,95%) and the one of the chemical reagent is 368.667 kg CO2eq/y (16,54%) in terms both of its

production and transport. The lower value is given by the biological process itself (212.500 kg CO2eq/y, 9,54%).
The phase “others” represents the 27,68% (616915 kgCO2eq/y) of the total emissions (only positive emissions) of the plant. The higher contribution is due to the discharge of the water in the surface water body, since the greenhouse gasses dissolved in the water is considered.
The sludge disposal phase contributes for the 13% of the total positive emissions. It is composed by the contributions of different processes, such as the composting facility (175.848 kg CO2eq/y), the composted sludge spreading (134.261 kg CO2eq/y) and the dewatered sludge transport (95.174 kg CO2eq/y) from the Salvatronda plant to the composting plant. The following figure (Figure41) shows the emissions considering the percentage impact with respect to the total positive impacts of the plant.
The sludge treatment phase is characterized by emission values given by the electricity consumption of both the processes that compose the phase, the emission from the sludge line and the poly transport and the transfer of the intermediate exchange from the transforming activity to the dewatering activity. The total emissions of this phase are 129.671 kg CO2eq/y, which corresponds to 5% of the positive impacts of the plant.
The “market for phosphate” impacts for the -26,5%, while the “market for nitrogen” impacts for -44,7%. It means that the impact of the secondary treatments and of the category “others” increase in percentage: 45% and 81%, respectively.
If the territorial scenario is considered, all the impacts of the plant become smaller with respect to the emissions of the Imhoff tanks. Indeed, the impact of this stage is 73,8% (10.941.000 kg CO2eq/y) of the positive emissions of the plant.
The Sludge disposal of other plants is the other stage that mostly impacts in the territorial scenario. Its emissions are given by the contribution of different processes, such as the composting sludge spreading (697.047 kg CO2eq/y), the composting plant process (526.357 kg CO2eq/y) and the sludge transport (268603 kg CO2eq/y).
The negative values can be attributed to the avoided production of fertilizers: 1.741.496 kg CO2eq/y due to the avoided fertilizer production as N and 1.032.498 kg CO2eq/y due to the avoided fertilizer production as P2O5.

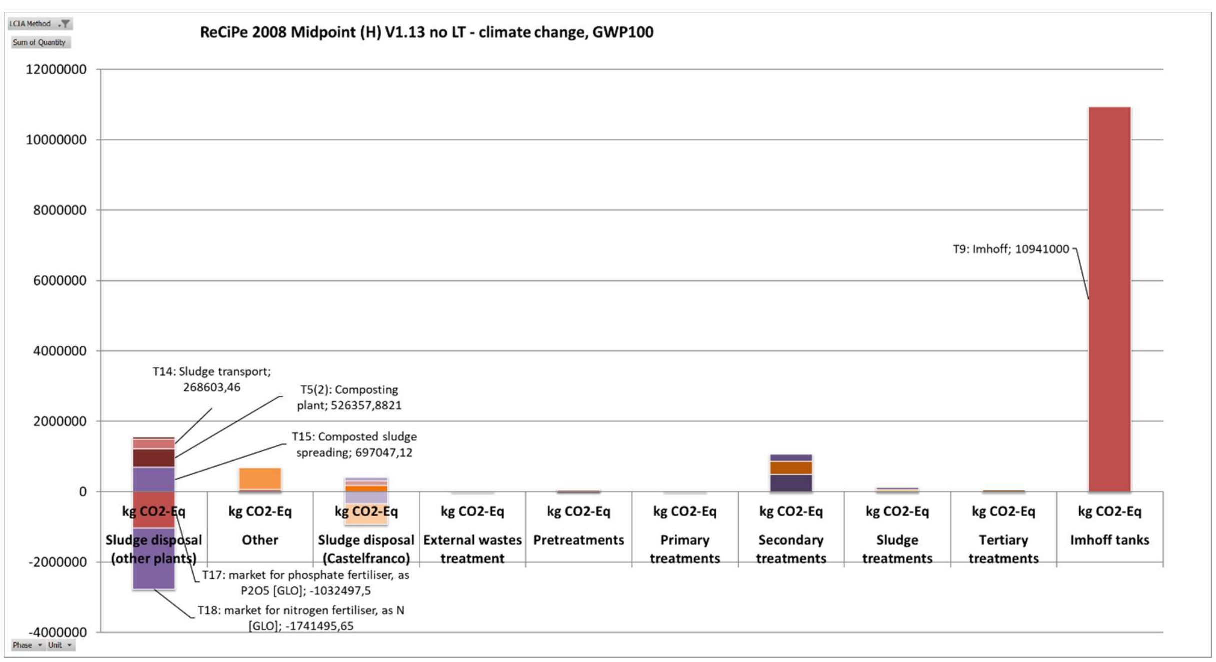


Figure: 41 Climate change impact category (Salvatronda as it is territorial scenario)

Finally, consider the consumption of energy. As expected, contribution of the secondary treatments is the major one, since the aeration is needed for the biological processes (489.241 kgCO2eq/y). The sludge treatment phase is the only one composed by two contributions: dewatering emits 63.366 kgCO2eq/y and thickening that emits 46.190 kgCO2eq/y.

The second impact category considered is the fossil depletion. This includes depletion of non-renewable resources, i.e. fossil fuels, metals and minerals. It is calculated as kg oil eq consumed in one year.

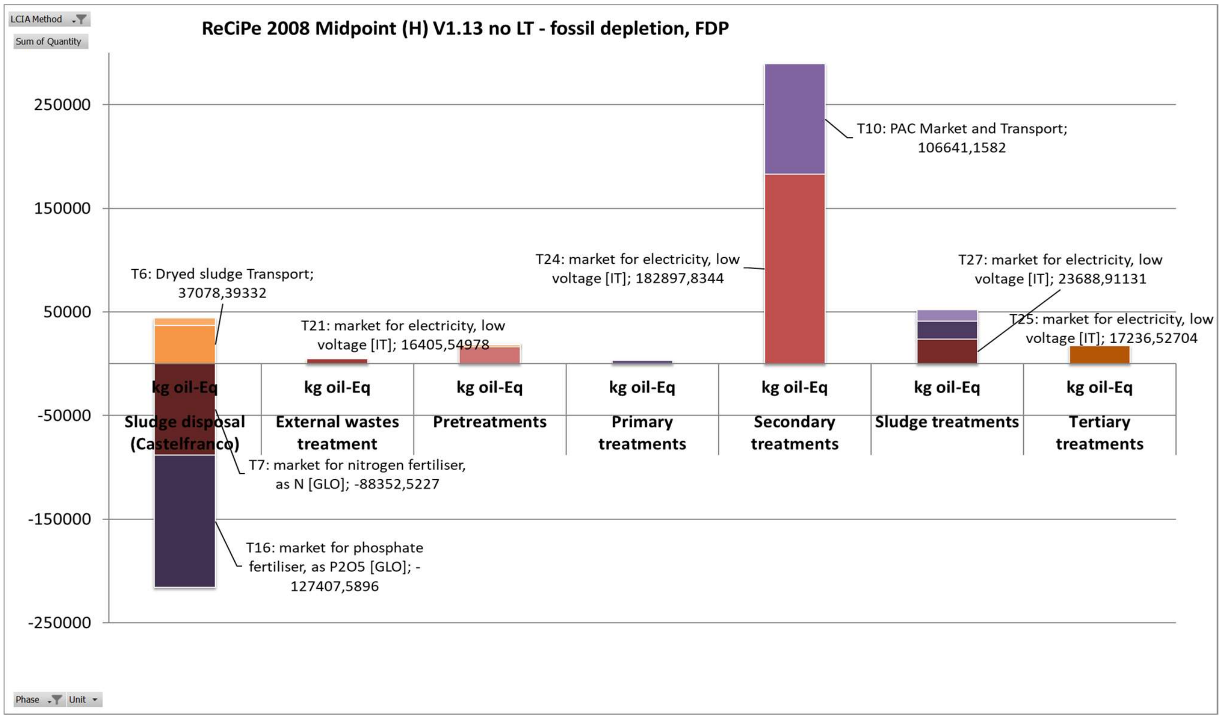


Figure: 42 Fossil depletion impact category (Salvatronda as it is no territorial scenario)

As done before, the emissions of the plant alone are analyzed before studying the territorial scenario. The higher emission value is given by the secondary treatment phase (67%). Part of this emissions are given by the electricity (182898 kg oil eq/y) and the chemical market activity and transport (106641 kg oil eq/y). 11% of the fossil depletion emissions are given by the sludge treatments, in particular by the electricity for the dewatering (23689 kg oil eq/y), the electricity for the dynamic thickening (17368 kg oil eq/y) and the market for polyaluminium chloride (11.268 kg oil eq/y). The sludge disposal impacts for 10% of the positive total impacts, because of the contribution of the dried sludge transport (37.078 kg oil eq/y) and electricity for the composting facility (7263 kg oil eq/y).

The negative values are related to the credits due to the fertilizers production avoided. 127.408 kg oil eq/y given by the phosphate fertilizer avoided and 88352 due to the avoided production of fertilizer as nitrogen.

Pretreatments and tertiary treatments impact for 3,81% and 4%, respectively, while the external treatments and the primary treatments emits very low values, almost negligible.

If the territorial scenario is considered, the "sludge disposal (other)" phase is assessed in the calculation. It is the phase in which the external sludge from the others nine plants transport their sludge in the compost facility. So, the transport (104.643 kg oil eq/y), the composting process and the spreading are taken into account in this phase. The energy consumption has an impact of 21739 kg oil eq/y. The negative emissions are related to the fertilizer not produced, thanks to the production of compost. The credits due to the nitrogen fertilizer is 264461 kg oil eq/y, while the credits given by the phosphate fertilizer is 381364 kg oil eq/y. As it can be seen in the figure below (Figure 43), the Imhoff tanks don't contribute in this impact category. The reason is related to the fact that this process does not require the energy, so it does not present impacts.

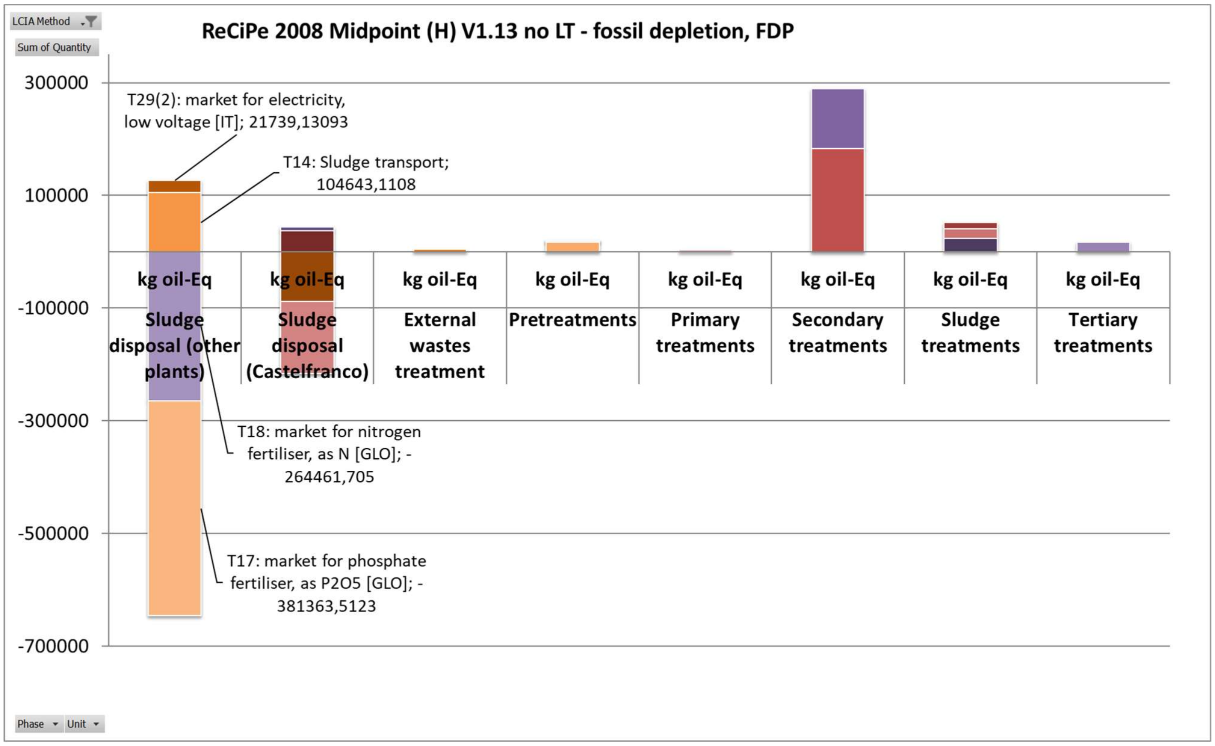


Figure: 43 Fossil depletion impact category (Salvatronda as it is territorial scenario)

The following category is the freshwater eutrophication. Eutrophication potential (EP) is defined as the potential to cause over-fertilisation of water and soil. It can cause the increase growth of biomass. The category is expressed in kg P released in one year.

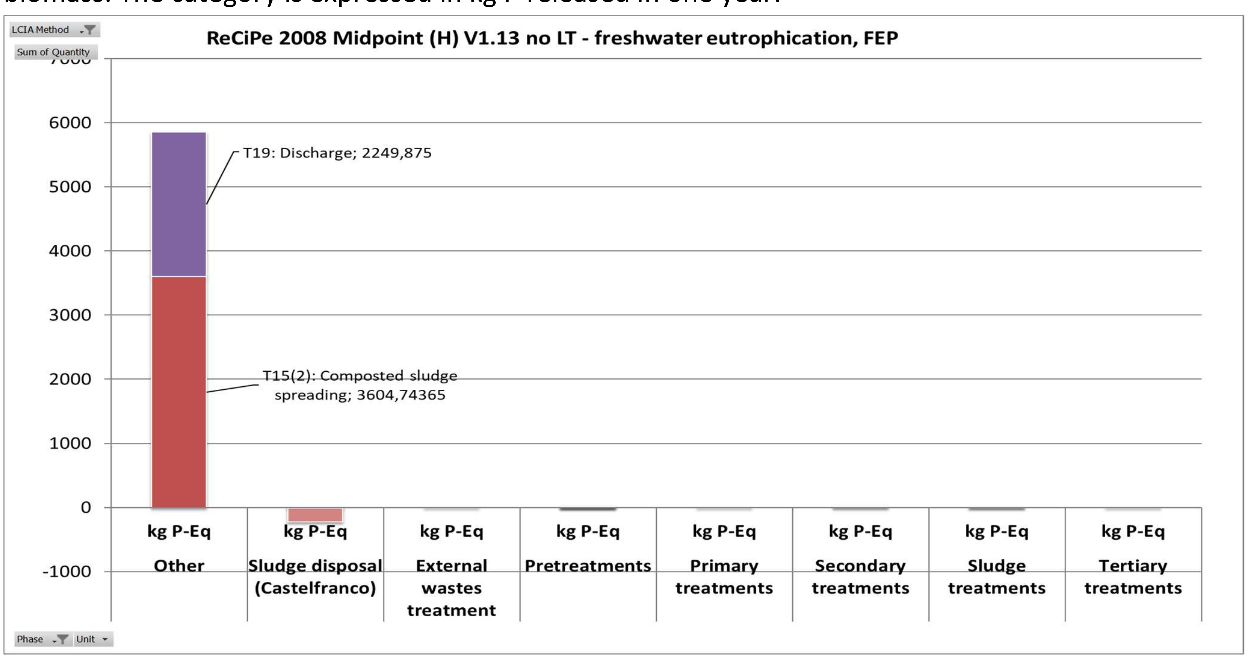


Figure: 44 Freshwater eutrophication impact category (Salvatronda as it is no territorial scenario)

In the plant scenario, so without considering the contributions of the Imhoff tanks and of the sludge disposal from other plants, the only phase that impacts on this category is the one called “other”.

The compost sludge spreading in this category impacts for 61,13% (3.605 kg P-eq/y), while the discharge impacts for 38,15% (2.250 kg P-eq/y) of the positive impacts of the plant.

The territorial scenario has the graphic profile quite similar to the one of the plant configuration. The only difference is that the higher contributions are attributable to the Imhoff tanks discharge (43.490 kg P-eq/y) and the composted sludge spreading of the other plants (18.617 kg P-eq/y).

In this case, the impacts percentages change: Composted sludge spreading (Castelfranco) impacts for 5,3%, the discharge for the 3,3%, the Imhoff tanks for the 64% and the composted sludge spreading of the other plants for 27,4%.

This is justified by the fact that the composted sludge volumes of the other plants are much greater than the quantity of sludge of the single plant in Castelfranco. Further, although the quantities of water discharged and of the sludge from the Imhoff tank are similar (Qsludge from imhoff=17680m3/d and Qwater discharged=12328m3/d), the emissions from the Imhoff tank spreading are higher because the pollutants concentrations in the sludge are much greater than the concentrations in the discharged water.

Terrestrial acidification is characterized by changes in soil chemical properties following the deposition of nutrients (namely, nitrogen and sulfur) in acidifying forms. Indeed, the unit of measure is kgSO2eq/y. It is given by the transport and the chemicals activities. As seen in the figure 45, there are negative values in the sludge disposal stages, due to the avoided production of chemicals, that are much larger than the positive value.

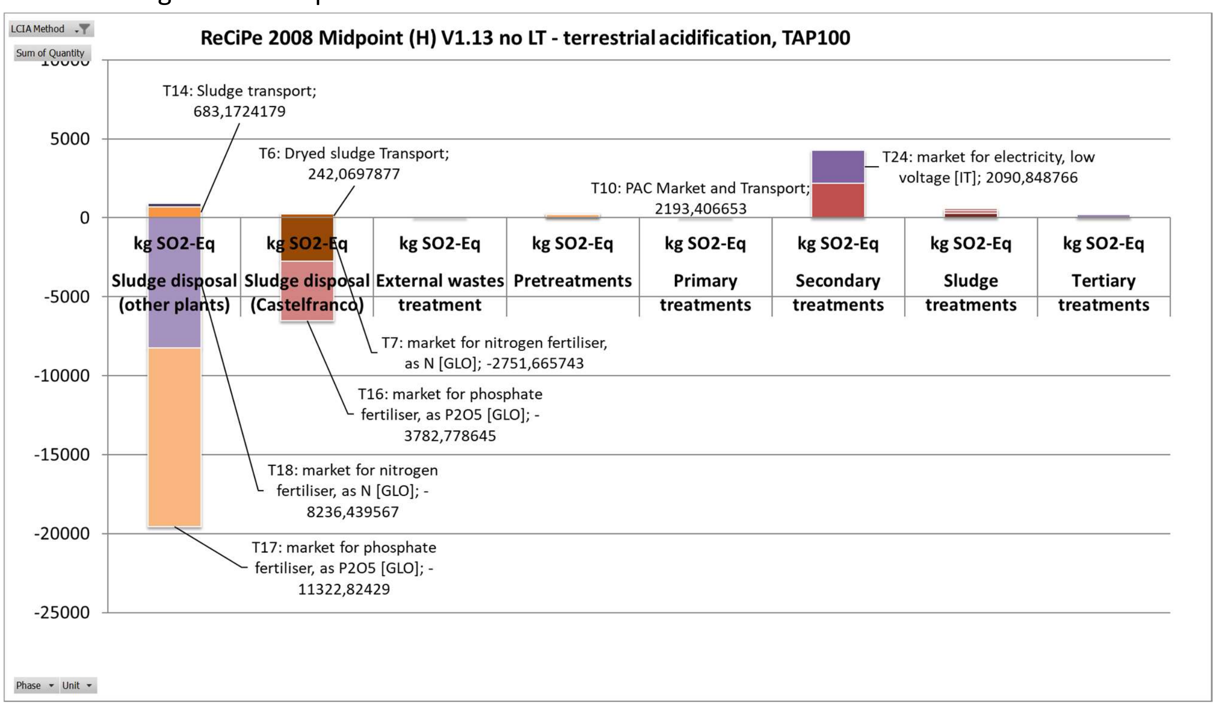


Figure: 45 Terrestrial acidification impact category (Salvatronda as it is territorial scenario)

In the figure, the plant scenario emissions are tabled. As expected, the secondary treatment impacts more than the other categories, with 2193 kg SO2 eq/y (38,57%) and 2091 kg SO2 eq/y (36,77%) for PAC market and transport and market for electricity, respectively.

The stage of the sludge disposal impacts especially with negative impacts: the market for nitrogen fertilizer emits -2752 kg SO2 eq/y, while the market for phosphate fertilizer emits -3783 kg SO2 eq/y.

Finally, the territorial scenario is considered, in order to understand the difference with the plant configuration.

The sludge disposal (other plants) phase, impacts mostly negatively: - 8.236 kg SO2 eq/y thanks to the avoided production of fertilizer as N and -11.323 kg SO2 eq/y thanks to the other avoided fertilizer.

As it is scenario- Economic evaluation results

The tables below (Tables 97 and 98) summarize the results of the economic evaluation done for the plant. The calculations are done on the bases of the data found in the literature.

Table 97 Economic evaluation results (opex)

COST ITEM	Sub-category	euro/kg	kg chemicals/y	euro/y	References
OPEX	POLY	2,4	6677	16024,8	(Nooru M. Cata Saadt, 2012)
	PAC	0,16	21000	3360	File report "confronto-offerte UNIVPM"
	Sub-category	**€/PE/y**		**euro/y**	**References**
	PERSONNEL	9,5		42747625	(Yago Lorenzo-Toja, 2016)
	MANTAINANCE	3,5		15749125	(Yago Lorenzo-Toja, 2016)
	Sub-category	**(€/tons)**	**ton screen to be disposed/y**	**euro/y**	**References**
	screen DISPOSAL	118,5	84,68	10034,6	(Elenco Prezzi: Per gli automezzi e le attrezzature si fa riferimento al punto 8.3.3 del Disciplinare di gara 01/2017)
	sand DISPOSAL	208,5	274,48	57229,1	(Elenco Prezzi: Per gli automezzi e le attrezzature si fa riferimento al punto 8.3.3 del Disciplinare di gara 01/2017)
	Sub-category	**(€/kWh)**		**euro/y**	**References**
	ELECTRICITY	0,1957			https://luce-gas.it/business/offerte/costo-kwh-aziende

Table 98 Economic evaluation results (capex)

COST ITEM	WWTP	PE	(€/PE)	€/y	References
CAPEX	activated sludge WWTP	73300	219	16.052.700	Bid/tenders in Italy, Monterotondo, Roma, ACEA SPA; ref ASTEA Spa

The total costs amount to 1758080 €/y for the total operative costs.

The following figure (Figure 46) represents the results provided by Umberto software. As it can be seen by the figure, the phase that requires the most economic expenditure is the secondary treatments phase, which contributes for the 80%. The reason is given by the fact that it requires more electric energy, since it must provide electricity for the aeration for the biological compartment. Furthermore, it must be said that the cost of personnel and maintenance has been entered only in this stage and is not distributed in the other phases.

The cost of the sludge line treatment contributes for the 7%. This value is related to the energy consumption for both the dynamic thickening and the dewatering and for the chemical reagent dosed in the centrifuge to optimize the solid-liquid separation.

The other processes require less energy consumption, so their economic expenditure is lower.

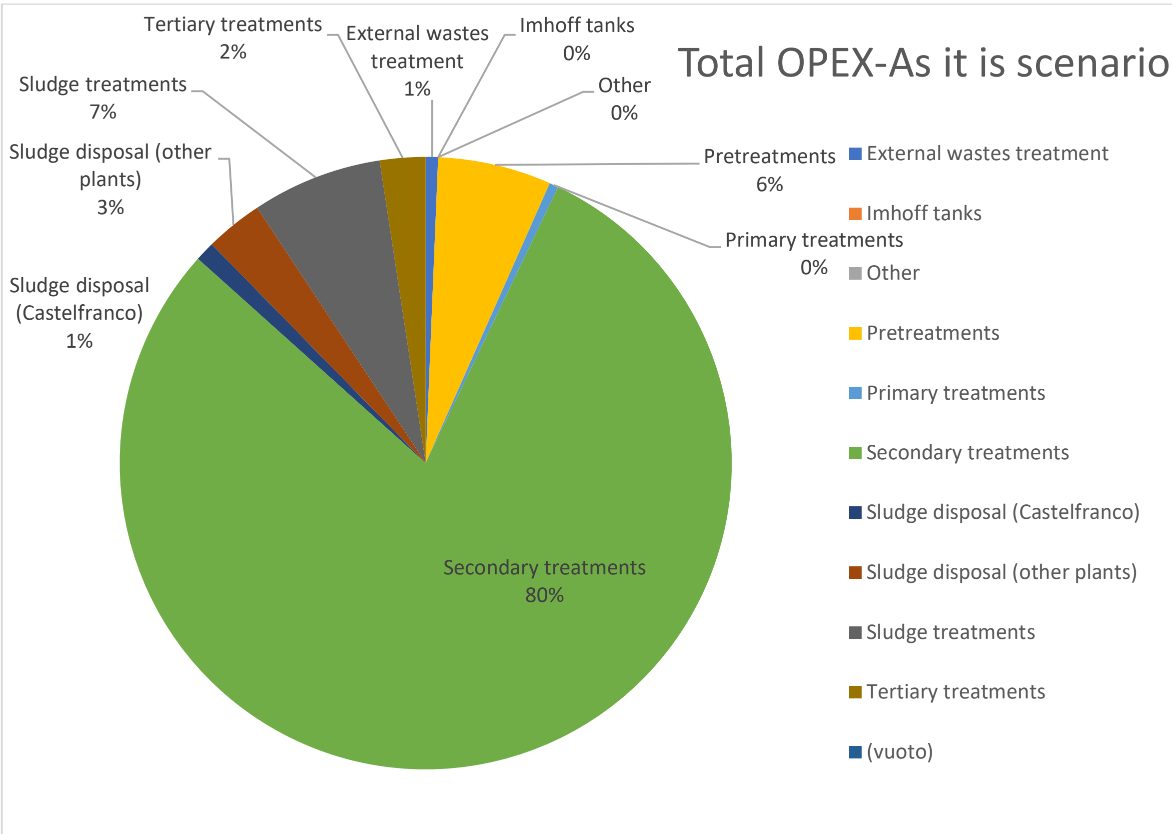


Figure: 46 Total OPEX (As it is scenario)

Design scenario- PHA recovery- Castelfranco WWTP

The phases in this case are 9: “external sludge”, “pretreatments”, “primary treatments”, “secondary treatments”, “tertiary treatments”, “sludge line treatments”, “sludge disposal”, “air treatments” and “resource recovery”.

Detailed impact assessment results, highlighting contributions of sub processes for each treatment, are reported in the following figures.

The climate change shows the greenhouse gasses emissions of the entire system. The imagine below shows that the resource recovery phase has the major impacts in this category (36% of the positive impacts). The most impacting process is the nitritation and biomass selection, that impacts for 31,37% (5.548.400 kg CO2 eq/y) of the positive impacts.

It is the step in which the acclimatation of the microorganisms occurs and the nitritation of the ammonia takes place. It is a very useful process from the water treatment and PHA production point of view, but it is characterized by very high emissions. However, it has also the negative contribution due to the avoided elements production. In particular, the recovery of the struvite means create a product useful for the agriculture, that allow to avoid the production of chemical fertilizers (-

727.188 kgCO2 eq/y). On the other hand, the production of biopolymers substitutes the use of fossil plastic and also its production (-173.546 kg CO2 eq/y).

The other phase that impacts a lot in the climate change is the "sludge line treatment" stage (34% of the positive impacts). This is due to the fact that the sludge line is composed by a lot of processes which gives their contribution. Anyway, the most impacting process is the heat production activity (3.877.574 kg CO2 eq/y), which is needed for the processes that requires high temperature, such as the fermenters and the thermohydrolizer.

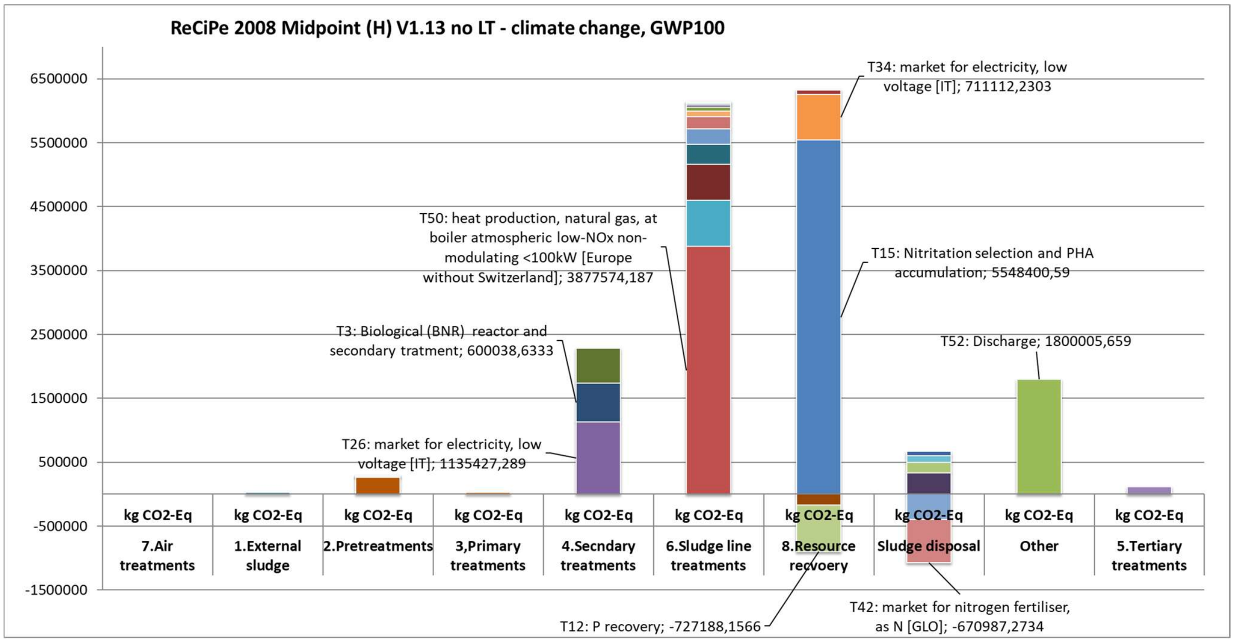


Figure: 47 Climate change impact category (Design scenario)

The "secondary treatment" stage emissions (13% of the positive impacts) are given first of all by the electric energy (1.135.427 kg CO2 eq/y) and then, by the emissions of the biological nutrient removal reactor (600.038 kg CO2 eq/y). The third contribution is due to the external carbon activities and transport (546.551 kg CO2 eq/y). As already said, the external carbon chosen is the methanol. At first, it was decided to include acetic acid as external carbon source. Following the first iteration with Umberto, it was found that the production of acetic acid has very high impacts in terms of climate change and more. So, the choice fell on this second product: methanol.

Another interesting stage is the sludge disposal phase (4% of the positive impacts). As it can be seen in the figure 47, there are negative contribution in this stage. Indeed, in this phase, the avoided fertilizers production in considered (-397.148 kg CO2eq/y for the phosphate fertilizer and -670.987 kg CO2eq/y for the nitrogen fertilizer), since the compost is produced in the composting facility with the sludge produced by the plant.

Now, let's consider the electric energy for each phase.

The most consuming process is the biological reactor, that emits 1.135.427 kg CO2eq/y (26% of the total emissions of the electric energy).

Anyway, the most consuming phase is the sludge line treatments stage with 1.989.658 kgCO2eq/y of emissions (43% of the total emissions of the electric energy).

The resource recovery phase impacts for the 17% emitting 711.112 kg CO2 eq/y from the nitritation reactor and 67854 kg CO2 eq/y from the P-recovery tank.

Transport for the external carbon source impacts 546.551 kg CO2 eq/y (53,2% of the total emissions of the transport), while, the POLY for the sludge line emits 306.735 kg CO2 eq/y and 60082 kg CO2 eq/y for both the dewatering process inside this phase, for a total impact value of 35% of the total emissions caused by the transport. The transport to composting plant has lower impacts, in fact contributes for 7,5% of the total emissions caused by the transport.

Going on with the others impact categories, the fossil depletion category is the next one.

In the sludge line treatment, the main contribution is given by heat production activity, that emits 1.810.221 kg oil eq/y (40,5% of the positive impacts). Further the polyelectrolyte consuming activities and the transport produced impacts in this category for 4,03% of the positive impacts.

Further, as already said, the secondary treatment is the higher consuming activity. As expected, indeed, it has the higher emission values in this category after the sludge line treatment phase (28% of the positive impacts). It emits 790.629 kg oil eq/y, caused by the external carbon transport and 424.468 kg oil eq/y because of the electricity in this stage.

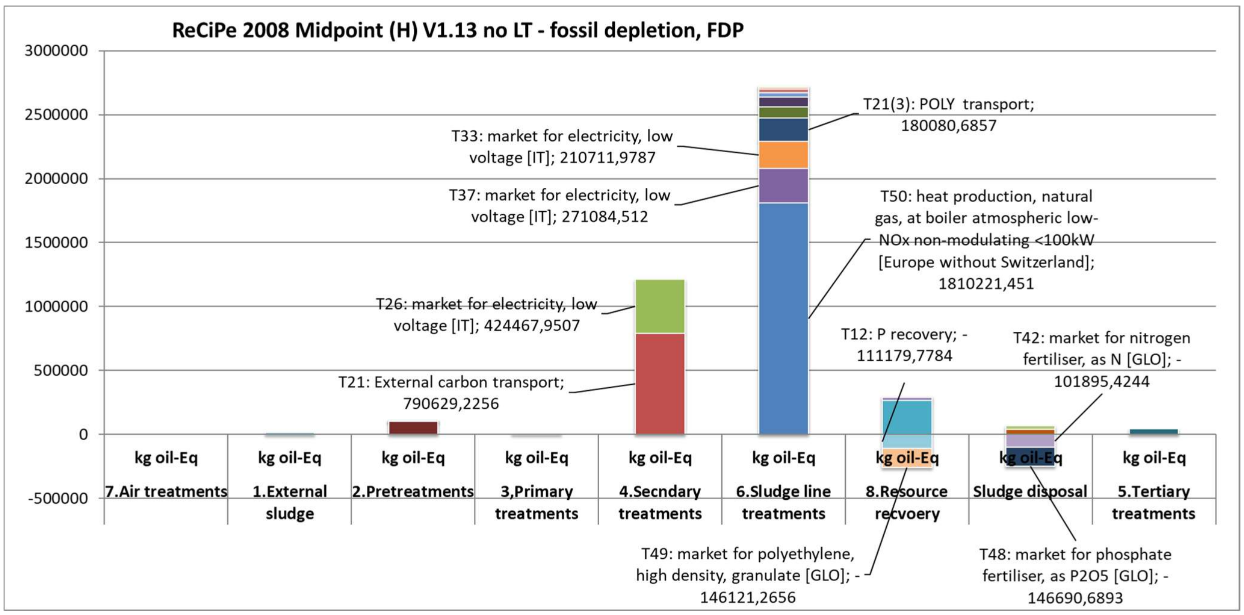


Figure: 48 Fossil depletion impact category (Design scenario)

The resource recovery treatment emits 265.842 kg oil eq/y because of the electric energy consumption. At the same time, in this category there are also credits due to the avoided production of fertilizers and plastics, since the struvite and the PHA are produced.

The avoided fertilizer production due to the phosphorus recovery as struvite saves 111.180 kg oil eq/y, while the saving due to the not produced fossil-based plastics is 146.121 kg oil eq/y.

The same happens in the sludge disposal phase, where the production of compost allow to avoid the production of chemical fertilizers. The market for phosphate fertilizer emits -146.691 kg oil eq/y and the market for nitrogen fertilizer emits -101.895 kg oil eq/y.

The energy consumption is evaluated in the fossil depletion category to investigate which is the higher energy consuming.

The sludge line treatment is the higher electricity consuming phase, since it is composed by different processes. It emits about 700.000 kg oil-eq/y (43% of the total emissions due to the electricity)

As expected, the other phase that impact a lot in this category is the secondary treatments stage (26% of the total emissions due to the electricity), which consume a lot of energy for the aeration inside the biological reactor.

The resource recovery phase impacts for the 17,5% of the total emissions due to the electricity, since the nitritation and biomass selection phase consumes a lot of energy (265842 kg oil eq/y).

The next category to be analyzed is the freshwater eutrophication. The emissions in this field are very small for all the stages, except that the phase “other” (96,89% of the positive emissions). The contribution of kg P eq is given mainly by the water discharged in the surface water body (4.409 kg Peq/y). It emits for 72,15%. The other part of the impacts is given by the spreading of the compost (1512 kg Peq/y).

There is also a small credit due to the avoided production of fertilizers (sludge disposal phase). The higher one is linked to avoided production of the phosphate fertilizer (-253 kg Peq/y).

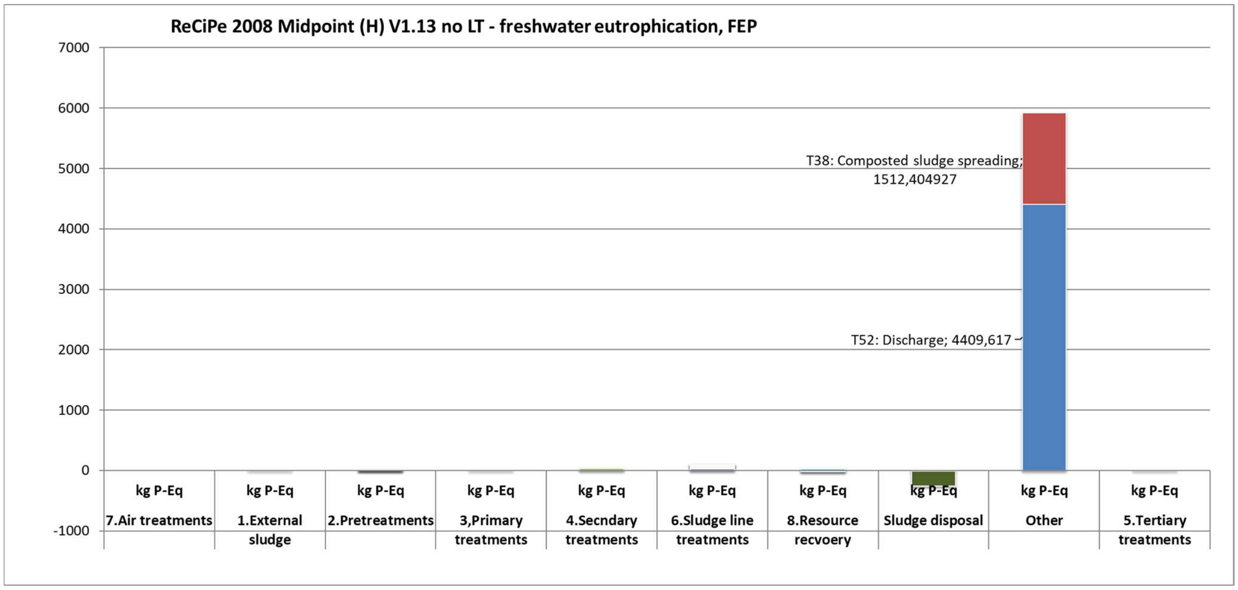


Figure: 49 Freshwater eutrophication impact category (Design scenario)

As already said, terrestrial acidification changes the chemical properties of the soil, because of the deposition of nutrients (nitrogen and sulfur) in acidifying forms. Indeed, the unit of measure is kgSO2eq/y.

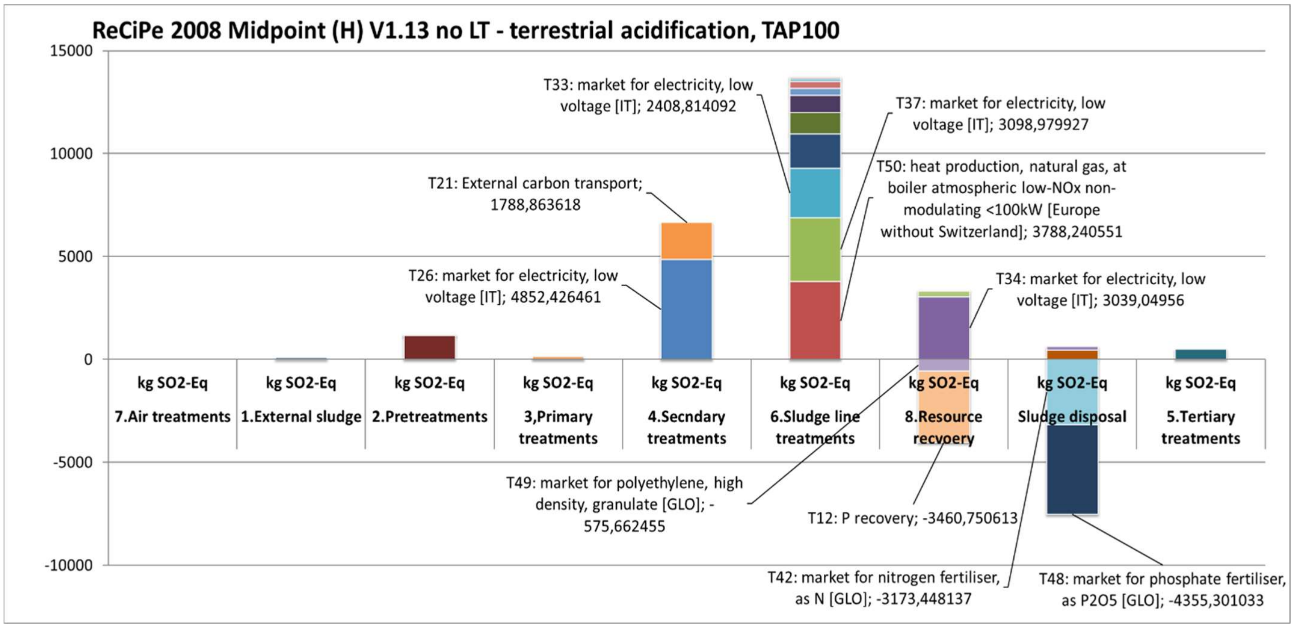


Figure: 50 Terrestrial acidification impact category (Design scenario)

Also in this case, higher emissions are caused by the sludge line treatments phase (52% of the positive emissions). In particular, the heat production emits 3.788 kg SO2/y (15%), while the electricity completes the other part of the column.

The secondary treatments emissions reach the 25% of the total positive emissions in this category. 4852 kg SO2/y are emitted by the electricity consumption, while 1789 kg SO2/y by the market for external carbon source and its transport.

The positive emission of the resource recovery phase is caused mainly by the electric energy use (11%, 3039 kg SO2/y). Further, the negative emissions in this phase are very important with respect to the emissions of this stage. Indeed 3461 kg SO2/y are the credits due to the P recovery as struvite, while 576 kg SO2/y are the saving thanks to the PHA recovery.

Finally, the negative values of the sludge disposal phase are higher with respect to its positive emissions. Indeed, the avoided phosphate fertilizer saves 4355 kg SO2/y, and the avoided nitrogen fertilizer saves 3173 kg SO2/y.

Design scenario- PHA recovery -Economic evaluation results

The capital and operative costs are reported in the tables 99 and 100 as results of the calculations based on the data found in the literature.

Table 99 Economic evaluation (opex)

COST ITEM	Sub-category	€/PE/y (average values)			€/y	References
OPEX	PERSONNEL	16,5			1.980.000	(Yago Lorenzo-Toja, 2016) (Hernandez-Sancho, 2014)
	MANTAINANCE	4,28			513.000	- (Yago Lorenzo-Toja, 2016); (Hernandez-Sancho, 2014)
	Sub-category	**Dollaro/ton**	**€/kg**	**kg/y**	**€/y**	**References**
	POLYELECTROLYTE	2400	2	129174	310.016	Nooru M. Cata Saadt, 2012
	MgO	28000	28	532	14.884	http://www.inframat.com/products/12R-0801.htm
	Sub-category	**€/ton**	**€/kg**	**kg/y**	**€/y**	**References**
	EXTERNAL CARBON	350	0,35	1168000	408.800	Vivaservizi
	Sub-category	**€/ton**	**ton/y**		**€/y**	**References**
	SCREEN DISPOSAL	208,5	247		51.521	(Elenco Prezzi: Per gli automezzi e le attrezzature si fa riferimento al punto 8.3.3 del Disciplinare di gara 01/2017)
	GRIT DISPOSAL	118,5	808		95.718	(Elenco Prezzi: Per gli automezzi e le attrezzature si fa riferimento al punto 8.3.3 del Disciplinare di gara 01/2017)
	Sub-category	**€/KWh**				**References**
	ELECTRICITY	0,1957				luce - gas costo-kwh-aziende (euro/kWh)
Benefits	**Sub-category**	**Average (€/PE/y)**			**€/y**	**References**
	recovery-benefit (PHA)	-2,3			-276.000	smart plant
	Sub-category	**(€/kg)**	**kg/y**		**€/y**	**References**
	recovery-benefit (struvite)	-0,43	1727		-742,6	smart plant

Table 100 Economic evaluation (capex)

COST ITEM	WWTP	PE	(€/PE)	€	References
CAPEX	advanced N and P removals	120000	250	30.000.000	(- EVALUATION of the Council Directive 91/271/EEC of 21 May 1991, concerning urban waste-water treatment, EC, Dec 2019)

The following figure (Figure 51) represents the results from Umberto software that is able to divide the cost for each phase analyzed.

The most important economic value is certainly the cost of the secondary treatment stage, that contributes for the 54%. The reason is attributable to the fact that it consumes a lot of energy for the maintenance of the aerobic environment in the biological reactor. Further it consumes external carbon, that have been bought from other plants. Finally, it is important to say that in the secondary treatment stage, the personnel and the maintenance are considered.

The sludge line treatments contribute for the 28%, since it consumes energy for all the processes of the sludge line and further it requires polyelectrolyte to optimize the solid liquid separation in some activities.

Another energy consuming activity is the ntritation and biomass selection which is the process used to produce PHA. Indeed, the phase resource recovery in which the nitritation process is considered contributes for the 10%.

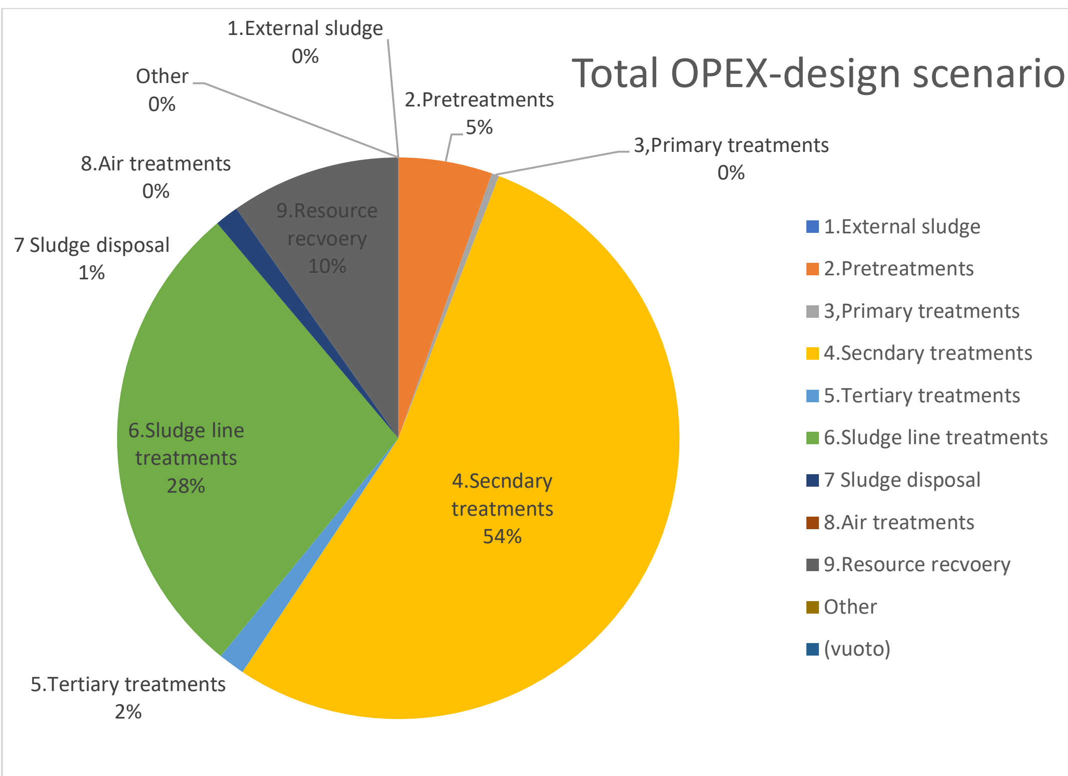


Figure: 51 Total OPEX (design scenario)

Comparison between the configurations

The comparison is done considering two impact categories: the climate change and the freshwater eutrophication.

Starting from the climate change category, as can be seen from the graphs below, in the current scenario the most impact phase is the Imhoff tank activity (10.941.000 kg CO2 eq/y), that impacts for 81 % on the total emissions.

The stages of the sludge disposal (both the one of Castelfranco and the one of the other plants) are characterized by the presence of the negative impacts. As said before, it is the credits due to the avoided production of the fertilizers. Indeed, since the compost is produced, the production of an amount of fossil-based fertilizer can be avoided.

Considering the design scenario, the resource recovery phase has the major impacts in this category (36% of the positive impacts). The most impacting process is the nitritation and biomass selection, that impacts for 31,37% (5.548.400 kg CO2 eq/y) of the positive impacts.

The negative contributions are present thanks to the avoided elements production. In particular, the recovery of the struvite means create a product useful for the agriculture, that allow to avoid the production of chemical fertilizers (-727.188 kgCO2 eq/y). On the other hand, the production of biopolymers substitutes the use of fossil plastic and also its production (-173.546 kg CO2 eq/y).

The other phase that impacts a lot in the climate change is the "sludge line treatment" stage, that impacts for 34% of the positive impacts. This is due to the fact that the sludge line is composed by a lot of processes which gives their contribution. Anyway, the most impacting process is the heat production activity (3.877.574 kg CO2 eq/y).

Comparing the scenarios, it can be said that treating the wastewater in the imhoff tanks separately is less sustainable than treating it in the plant chain. In fact, the emissions due to the imhoff tanks and the water line of the as it is scenario is 86% of the total impact. On the other hand, the emissions of water in the design scenario contribute for 26% of the total impact of the plant.

This means that the emissions of the most impacting process are 4 times lower in the design case where the sludge of that sludge is collected in the main line of the Salvatronda plant.

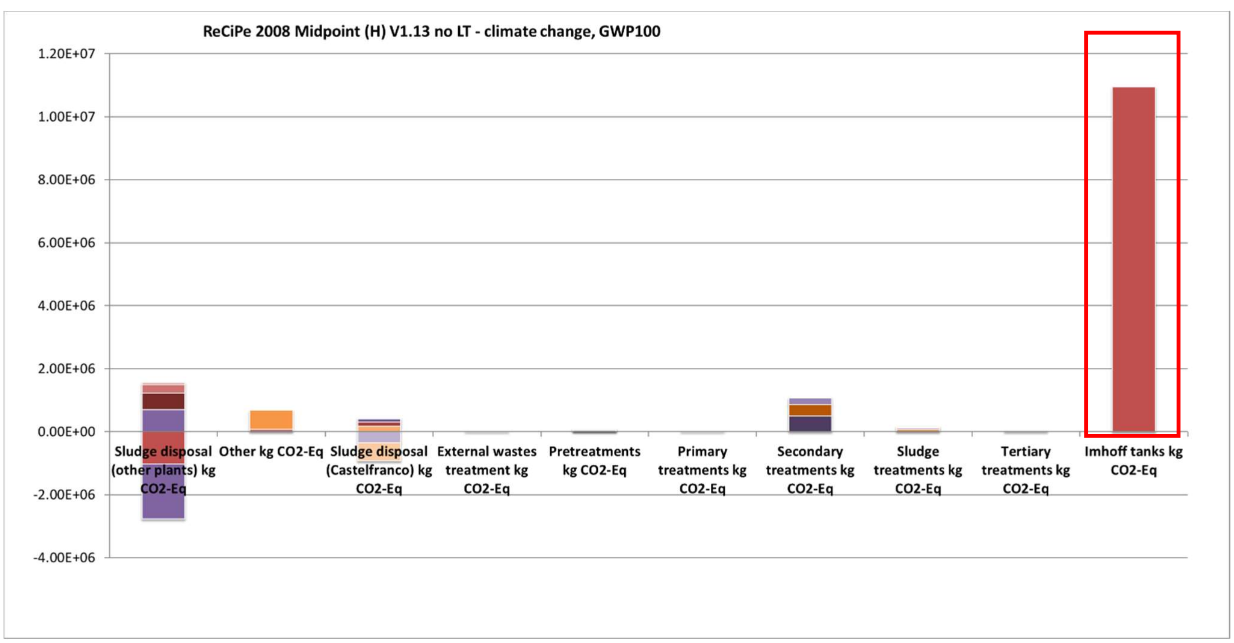


Figure: 52 As It Is scenario - climate change

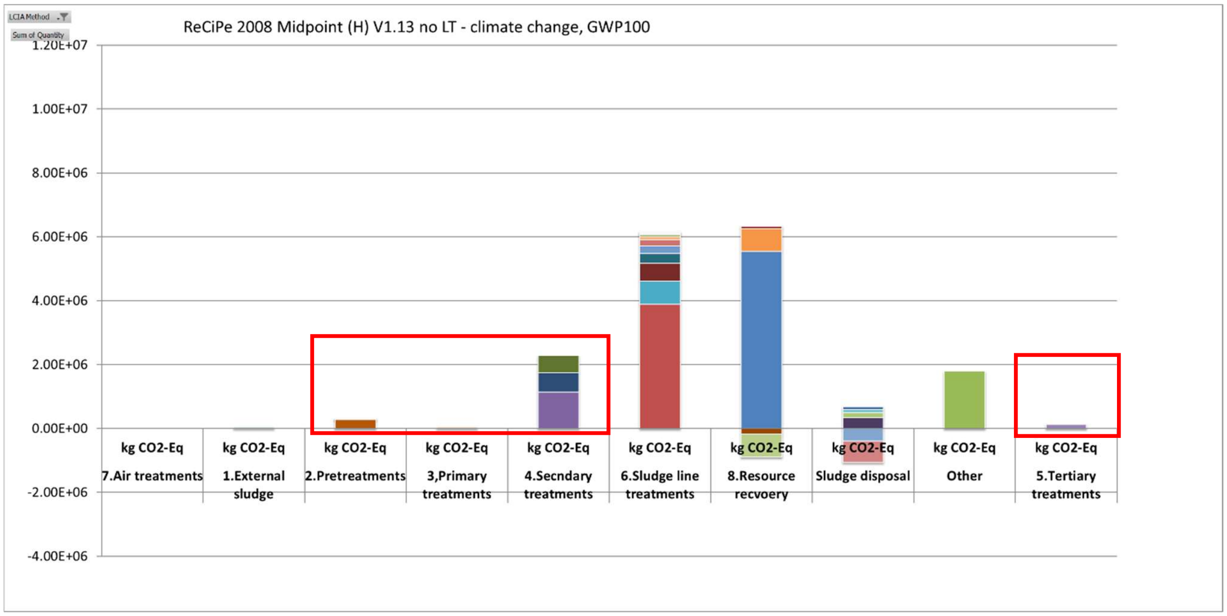


Figure: 53 Design SCENARIO-- climate change

The freshwater eutrophication category is the category in which the major impactant stage is the so called "other" phase. The reason is due to the fact that this category is related to the possibility to cause over-fertilisation of water, that can cause the increase growth of biomass.

The higher contributions are attributable to the Imhoff tanks discharge (43.490 kg P-eq/y) and the composted sludge spreading of the other plants (18.617 kg P-eq/y). But there are also the contribution of the composted sludge spreading and the treated water discharge.

The value of the composted sludge from external plants is higher than the value of the composted sludge from Castelfranco, because the composted sludge volumes of the other plants are much greater than the quantity of sludge of the single plant in Castelfranco.

Further, the emissions from the Imhoff tank spreading are higher than the treated water discharged, because the pollutants concentrations in the water from Imhoff tanks are much greater than the concentrations in the discharged treated water.

The Eutrophication caused by the design configuration of Castelfranco is much less than that of the as it is scenario, as can be seen from the figures.

This is related to the fact that in the design case, although the nutrients in the water discharge have quite similar concentrations, there is no discharge of water from Imhoff tank. In fact, that water has concentration of pollutants similar to that of wastewater, since the treatment of Imhoff tanks is not efficient in reducing pollutant loads.

So, in this category, the impacts of the As it is scenario are 67961 kg P eq/y, while in the design configurations the impacts caused by the same stage ("other") are lower and equal to 5922 kg P eq/y.

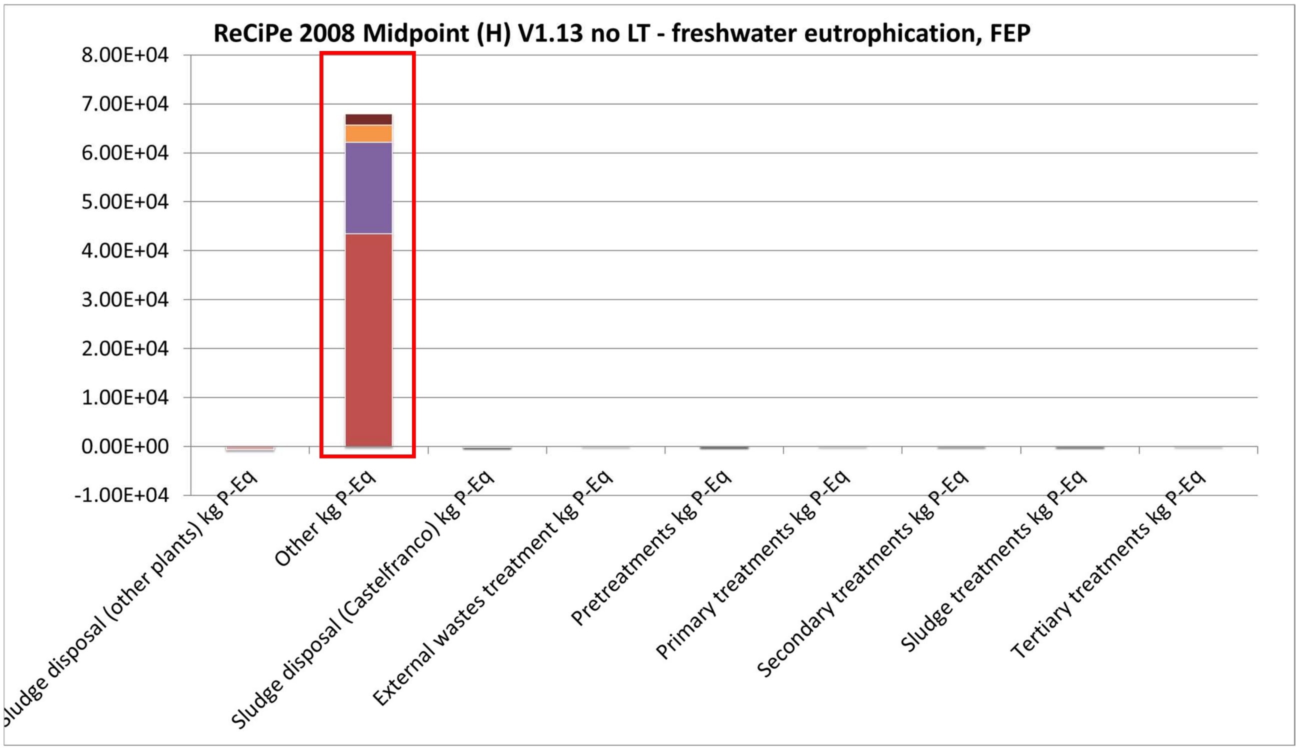


Figure: 54 As It Is scenario - freshwater eutrophication

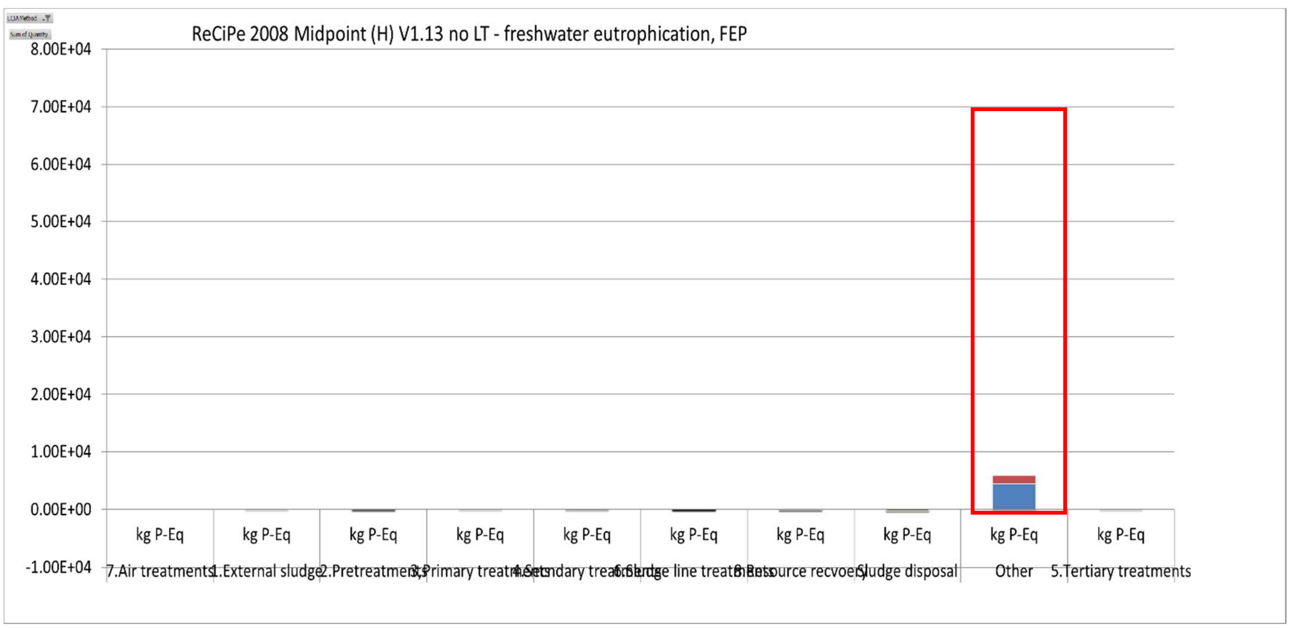


Figure: 55 Design SCENARIO- freshwater eutrophication

4.2 Modena

4.2.1 PHA recovery scenario

The PHA recovery scenario of Modena Canale Navigli wastewater treatment plant is done considering the results came out from the literature analysis conducted to study the PHA recovery scenarios and operating parameters.

In particular, the yield and the process parameters are chosen on the bases of the analysis exposed in the chapter 2.2, while the scenarios have been identified considering the studies conducted by Vincenzo Conca et al. (2020) and Nicola Frison et al. (2018).

Since the sludge line treats the external sludge as well as the WAS sludge coming from the water line, two configurations have been found to produce both PHA and biogas.

CONFIGURATION 1 (Appendix 2c):

The first case is the one in which only the sludge coming from the water line goes in the fermenter while the external sludges are used to produce biogas in the digestor.

The sludge coming from the biological rectors goes at first in the thickener, where, thanks to a percentage of abatement of 97%, the sludge is thickened to a concentration of 3.5%. The flowrate that enters in the fermenter is 236.6 m3/d with 8281 kgTSS/d of suspended solids. The table 101 shows the characteristics of the sludge entering the fermenter.

Table 101: thickened sludge influent in the fermenter

Flow	236,6	m3/d
TS%	3,5	%
TSS	8281	kgTS/d
TVS/TS	0,62	
TVS	5134,0	kgVS/d

The fermenter used the volatile solids in order to produce volatile fatty acids, so the value of TVS in the outlet is lower with respect to the inlet value, as can be notice in the table 102. The fermenter HRT values are between 5 and 10 days, so the volume have been calculated considering the retention time of 5, 8 and 10 days.

The daily production of VFA, which will be used to produce PHA, amounts to 1313 kg VFA, considering a yield of 0.26 gCOD (VFA)/gVSS. This value of VFA yield is taken from the real case study explained in the chapter 2.2.2 of this work (Liu, 2018).

Table 102: fermented sludge characteristics

FLOW	237	m3/d
TSS	8280,6	kgTSS/d
TVS	4209,9	kgTVS/d
VFA	1312,3	kgCODVFA/d
N	399	kgP/d
P	224	kgTN/d
TVS/TSS	0,5084	

A solid liquid separation is required in order to obtain a fermented liquid, rich in readily organic matter. This water is sent to the nitritation and biomass selection together with the supernatant of the centrifuge, last process of the plant.

The process has the aim to oxidize the ammonium to nitrate, denitrify the nitrate to nitrogen gas and select the biomass suitable for the recovery of biopolymer.

Phosphorus is essential for energy metabolism (ATP) as well as being an ingredient to RNA, DNA and phospholipids. It means that a restriction of P given available COD is required to promote a channelling of COD to PHA storage instead of for active growth (Valentino, 2016). So, it is important also to stabilize the optimal amount of nutrient. In any case, the phosphorus is consumed by the microorganism up to about 70-75% of the inlet value.

The table 103 shows the characteristics of the nitritation and acclimatation tank. It can be notice that the OLR is a little bit lower than the typical one. This could mean that a little amount of external carbon is required. The HRT is calculated on the bases of the volume, that depends also on the flowrate entering in the tank (439 m3/d), in order to allow that the process takes place.

Table 103: characteristics of the nitritation and biomass selection process

OLR	0,66	kgVFA/m3/d
HRT	4,6	d
volume	2.000	m3
VSS	3,3	kg/m3
SRT	5,6	d
VSS/CODVFA	0,16	-
E% N	80	%
E% P	75	%

The growth yield of the microorganisms is taken from the literature analyses, as already exposed, considering a theoretical ratio of 1.42 gCODVSS/gVSS.

The cycles of the SBR consisted of feeding, reaction phase (aerobic and anoxic), settling and finally discharge, with an SRT assumed to be 5.6 d, as suggested by literature.

It means that two flows come out from the reactor: a solid and a liquid one. The liquid flow, sent to the main line where is it treated together with the other water flow, is characterized by small amount of pollutants, since they are removed in the nitritation and biomass selection reactor.

Table 104: nitritation and biomass selection reactor effluent

Flow	438,9	m3/d
N	79,7	kg/d
P	55,9	kg/d

The solid effluent is instead rich in selected biomass and is sent to the PHA accumulator.

The yield of PHA is assumed to be 0.66 gPHA/gVSS, considering a conversion ratio of 1.67 gPHA/gPHACOD and the amount of PHA obtained in this scenario is 141 kgPHA/d as can be seen in the table 105.

The table shows that in this scenario, only 0.4 kgPHA/AE/y can be recovered, demonstrating that the production of PHA from secondary sludge alone is not optimal. This value is calculated considering the people equivalent of the entire plant for the first case since only the plant sludge is sent in fermentation and used for the biopolymer recovery.

Table 105: PHA obtained from scenario 1

PHA	141	kgPHA/d
PHA	0,59	kgPHA/AE/y

In this configuration, the sludge from the post thickener (after fermentation), together with the external sludge, is sent in the digestor in order to recover biogas, exploiting all the capabilities of the sludge, already fermented.

Considering a specific gas production (SGP) of 0.15 Nm3/kg VS, an amount of 966.4 Nm3/d of biogas is produced. The same percentage of 67% of methane of Modena wwtp actual scenario is considered inside the biogas flow, so that 647,5 kg CH4/d of methane is produced.

The sludge, after digestion, shows a lower amount of VSS, since they are destroyed during the process. The last phase of the sludge line is represented by the centrifuge, with an abatement percentage of 99%. The sludge produced amounts to 36.5 m3/d with 9224 kg/d of solids.

Table 106: characteristics of biogas

Flow CH4	647,5	Nm3/d
Flow biogas	966,4	Nm3/d
CH4	67	%
CH4	2,25	m3CH4/PE/y

The literature suggests that annually the CH4 produced per people equivalent is about to 4.6-4.9. In this case the plant shows a lower value: 2.25 m3CH4/PE/y. It can be due to that the chosen SGP is too low.

Actually, the reason why a very low SGP was chosen is due to the fact that the biogas production of the real plant is low, as already mentioned in the previous explanations of the plant

CONFIGURATION 2 (Appendix 2d):

The second scenario is designed in order to exploit all the sludge treated in the plant to produce fatty acids useful not only for the PHA, but also for the biological removal of nitrogen and phosphorus.

So, the secondary sludge, together with the external sludge goes in the dynamic thickener, (% of abatement of 97%) in order to achieve a TS% of about 3.5%. The external sludge composed by different code (CER code) liquid waste coming from food industries, so characterized by high amount of organic matter. It means that could be a reasonable choice to use it as feedstock for the fermentation step.

The thickened sludge is sent into the fermenter, where the VSS are transformed in VFA with a assumed yield of 0.28 gCOD (VFA)/gVSS. As done in the previous scenario, the volume of the fermenter has been calculated considering different HRT.

The amount of VFA recovered in this scenario is higher than the amount produced in the previous configuration (1312 m3/d in case 1 and 2135.5 m3/d in case 2). The reason could be associated with the fact that the sludge quantity and the VFA yield is higher, since the municipal sludge combined with the OFMSW show a better VFA potential. The fermented sludge is, then, treated in the thickener in order to separate the solids from the rich VFA liquid supernatant.

The liquid flow, together with the centrifuge rejected water, is treated in the nitritation and biomass selection, where the nitrogen and phosphorus are biologically removed using the recovered organic matter.

At the same time, the selection of microorganisms capable of storing biopolymers takes place in the same reactors, with a yield considered of 0.35 gVSS/gCOD (VFA). The percentage of abatement for nitrogen and phosphorus are assumed by the literature (Table 107).

Table 107: characteristics of nitritation and biomass selection reactor

OLR	1,07	kgVFA/m3/d
HRT	6,3	d
volume	2.000	m3
VSS	3,3	kg/m3
SRT	5,6	d
VSS/CODVFA	0,35	-
E% N	80	%
E% P	75	%

As already said, the sludge and the liquid part are separated in this process, thanks to a final settling phase. The water from this process, characterized by lower amount of P and N with respect to the inlet water, is sent in the water line.

Table 108: Rejected water from nitritatio and biomass selection characteristics

Flow	318,1	m3/d
N	79,7	kg/d
P	55,9	kg/d

The sludge, rich in selected biomass goes in the PHA recovery tank, where the accumulation process takes place, with a yield assumed equal to 0,7 gPHA/gVSS.

The final calculated value of recovered PHA is 524 kg PHA/d as can be seen in the table 109. In this second case, the PHA that can be recovered annually are 1,8 kgPHA/AE.

Table 109: PHA obtained from scenario 2

VSS	737	kgVS/d
PHA	524	kgPHA/d
PHA	1,82	kgPHA/AE/y

Coming back to the static thickener, the sludge obtained in this step, is sent to the digestor. The same SGP of the previous case is considered (SGP=0.15 Nm3/d) and the biogas recovered is 866.4 Nm3/d with 580.5 Nm3 CH4/d.

Table 110: biogas characteristics

Flow CH4	580,5	Nm3/d
Flow biogas	866,4	Nm3/d
CH4	67	%
CH4	2,02	m3CH4/AE/y

The annual suggested value is 3.6-4, much greater than that calculated in this case.

4.2.2 Comparison and economic evaluation

A comparison between the scenarios is required in order to define the better configuration for the resource recovery.

Since the second case allow to produce a higher amount of biopolymer, it must be chosen in the case in which the most important goal is the PHA recovery. Anyway, in terms of revenue, other products and bioproducts must be considered.

In the As it is scenario, an amount of sludge equal to 13196 ton/y is produced and a daily volume of biogas of 1023 Nm3. Considering that the cost of the sludge disposal amounts to 100 € /ton and that the gain due to the production of biogas (market price) is equal to 0.12 € /m3 (Conca, 2020), the value of the revenue can be calculated in the case of the actual scenario and the value is shown in the table 111 (30.015 €/y).

In the other cases, as said previously, the biopolymer production scenario is designed, so that the biogas recovery has a lower efficiency. Anyway, the saving is higher, because the price of PHA is about 5 € /kg PHA (Conca, 2020).

In particular, in the first case, only the secondary sludge is fermented and exploited for the PHA recovery, so the amount of biopolymer recovered is lower with respect to the last case.

The revenue due to the polymer production is 180293 €/y, since the produced PHA amounts to 96 kg PHA/d, while the revenue due to the biogas production is 28360 €/y. It means that the total revenue is 198395 €/y as exposed in the table 111.

Table 111: Summary of results

MODENA		**AS IT IS SCENARIO**	**CONFIGURATION 1**	**CONFIGURATION 2**
Chosen flows	-	**FANGHI SEC+EXT**	**FANGHI SECONDARI**	**FANGHI SEC+EXT**
Fermented flowrate	m3/d	299	237	350
VFA yield	gCODVFA/gVS	-	0,26	0,28
Selection Yield	gVSS/gCODVFA	-	0,16	0,35
Accumulation growth yield	gCODPHA/gVS	-	0,66	0,71
Produced PHA	kgPHA/d	0	141	524
Specific PHA	kg/AE/y	-	0,59	1,82
Producted BIOGAS	Nm3/d	1.023	966	866
Produced CH4	Nm3/d	685	647	580
Sludge to be disposed	ton/y	13.196	12.999	11.653
PHA REVENUE	Euro/y	0	180.293	669.727
METHANE REVENUE	Euro/y	30.015	28.360	25.425
Disposal cost	Euro/y	1.319.616	1.299.860	1.165.320
REVENUE	Euro/y	30.015	198.395	819.432
N in the supernatant	kg/d	109	37	26
P in the supernatant	kg/d	6	5	5

If the sludge disposal is considered, it can be notice that the amount of sludge produced in the scenario 1 is lower with respect to the As it is one, since the volatile solids are destroyed in the digestor and in the fermenter.

The last scenario is the better one in terms of economic evaluations and resource recovery. Indeed, since all the available sludge is fermented, a higher amount of TVS is available for the production of biopolymers.

This means that a smaller volume of biogas will be produced daily. Since the market price of PHAs is higher than the gain from gas recovery, it is in any case an advantageous scenario.

The produced sludge is 11653 ton/y, which is lower with respect to the other configurations.

Therefore, the revenue that income from the production of resources amounts to 819432 €/y, while the price of the sludge to be disposed of will be around 1165320 €/y.

The specific PHA value is calculated considering the people equivalent of the entire plant for the first case since only the plant sludge is sent in fermentation and used for the biopolymer recovery.

Although the PE value by which it was divided is lower with respect to the second case, the specific value is low, meaning that the use of secondary sludge alone is not convenient.

Indeed, the second case is calculated with respect to the people equivalent of the plant plus the people equivalent of the external sludge.

4.2.3 Advanced simulation platform results

The Modena wastewater treatment plant has an inlet flowrate of 83.383 m3/d, with a COD (Chemical Oxygen Demand) concentration equal to 126,3 mg/l, BOD (Biological Oxygen Demand) 57 mg/l, N (Nitrogen) 22,3 mg/l, P (Phosphorus) 2,1 mg/l and TSS (Total Suspended Solids) 58 mg/l. To insert the TSS value, the software requires the Inert Suspended Solid, which is the inert part of the total suspended solids and coincides with ~1/3 of the TSS concentration.

The results of the simulation are listed in the following table (Table 112), in comparison with the real values.

Table 112 results of the simulation (water line)

	REAL	SIMULATED	unit of measure	error %
INGRESSO LINEA ACQUE				
FLOW	83.263	83383,00	m3/d	0,14
COD conc	126,3	126,3	mgCOD/L	0,03
BOD conc	57,00	64,8	mgBOD/L	13,68
TN conc	22,3	22,3	mgTN/L	0,15
TP conc	2,1	2,1	mgP/L	0,00
TSS conc	58,00	61,66	mgTSS/L	6,31
SURNATANTI TOT				
FLOW	1241,38	1121,75	m3/d	9,64
COD conc	3280,39	1300	mgCOD/L	60,37
TSS	1909,18	1080,21	mgTSS/L	43,42
N	147,13	160	mgTN/L	8,74
P	52,02	57	mgP/L	9,57
BIOLOGICO LINEA 1				
FLOW	50702,8	50702,8	m3/d	0,00
MLSS in vasca	4100,0	3601	mg/L	12,17
MLSS ricircolo	8800,0	6943	mg/L	21,10
SRT		20,55	D	
Qw		523,0	m3/d	
Qr+Qw	72523,6	54000,0	m3/d	25,54
BIOLOGICO LINEA 2				
FLOW	33801,8	33801,8	m3/d	0,00
MLSS in vasca	3766,7	2607	mg/L	30,79
MLSS ricircolo	7600,0	5017	mg/L	33,99
SRT		18,60	D	
Qw		516,0	m3/d	
Qr+Qw	48516,0	3600,0	m3/d	25,80
CHEMICAL				
FeCl3	933,7	965	kgFeCl3/d	3,35
EFFLUENTE LINEA 1				

TSS conc	3,5	2,99	mgTSS/L	14,57
EFFLUENTE LINEA 2 PRE MBR				
TSS conc	6,3	0,36	mgTSS/L	94,24
EFFLUENTE TOT				
COD conc	21,0	11,8	mgCOD/L	44,02
BOD conc	4,0	2	mgBOD/L	40,17
TN conc	8,8	8,7	mgTN/L	1,68
TP conc	0,6	0,52	mgP/L	18,53
TSS conc	5,7	1,8	mgTSS/L	68,34
N-NH4 conc	0,8	0,4	mgN-NH4/L	52,97
N-NO3 conc	7,0	7,0	mgN-NO3/L	0,25

The higher difference between the real and the simulated data is given by the supernatant characterization: in particular the most important difference is represented by the concentration of organic carbon. Indeed, in the real case the concentration value related to the COD is 3613,6 mg/l, while the simulated value is 7132,8 mg/l. The problem in this case is related to the excessive production of VFA by digesters, which work more as fermenters than as digesters.
There are no other substantial errors/differences in the table (Table113) shown, so you can proceed, commenting on the sludge line.

Table 113 results of the simulation (sludg line)

	REAL	SIMULATED	unit of measure	error %
INGRESSO LINEA FANGHI				
FLOW	1039,6	920,0	m3/d	11,50
TS%	0,82	0,83	%	0,63
TSS	8529,14	7619,30	kgSS/d	10,67
FANGHI ESTERNI				
Flow	237,95	237,95	m3/d	0,00
TSS	4092,75	4091,76	kgSS/d	0,02
TVS/TS	0,60	0,63		4,33
TS%	1,72	1,72	%	0,00
SURNATANTE DA ISPESSITORE II				
FLOW	122,1	139,8	m3/d	14,49
TSS	318,07	281,07	kgTS/d	11,63
USCITA ISPESSITORE				
FLOW	408,01	410,20	m3/d	0,54
TSS	10284,32	10961,56	kgTS/d	6,59
TVS/TS		0,65		
TS%	2,52	2,67	%	5,93
% DISTRUZIONE TVS				
R%TVS	14,84	14,98	%	0,98
DIGESTORI				
Flow biogas	1022,81	82,80	Nm3/d	91,90
CH4	67,00	34,27	%	48,85
FlowCH4	685,28	28,38	Nm3/d	95,86
INGRESSO CENTRIFUGA				

Flow	408,01	410,20	m3/d	0,54
TS%	2,30	2,17		5,65
TSS	9384,25	8917,27	kg/d	4,98
FANGO PRODOTTO				
TS%	25,87	24,60	%	4,90
TSS	9351,80	8912,81	kgSS/d	4,69
TVS/TS	0,56	0,57		2,15
P%TS	2,62	1,00	P%TS	61,83
N%TS	4,67	1,40	N%TS	70,02
SURNATANTE DA CENTRIFUGA				
FLOW	371,86	374	m3/d	0,58
TSS	32,45	4,46	kgTS/d	86,26

As shown from the table 113, the compared values are similar, so there are no big differences between the reality and the simulation.

However, it should be noted the presence of an anomalous value which represents the biogas produced by the anaerobic digestion process.

The real data calculated in the plant is 1022,8 Nm3/d, which correspond to a calculated value of destroyed TVS value of 20%. The simulated value, on the contrary, is equal to 82,8 Nm3/d. It means that the digesters are not able to produce biogas. Probably the methanogenic phase is shorter than expected. It is clear that, if they work mostly in acidogenic phase, it produces a lot of Volatile Fatty Acids (VFA), that contribute to increment the COD in the supernatant directed to the water line.

It is possible to compare the production of VFA with the production of biogas: under normal process conditions, organic matter is used to produce biogas, so probably that quantity of VFA would have been enough to produce 1022,8 Nm3 biogas per day.

From the calculation it is possible to understand that part of those VFAs are used to produce biogas, while the remaining part will remain as VFA in the sludge.

4.2.4 Nutrients impact on the water line

The use of the advanced simulation platform is required in order to compare the impact on the water line in the case of PHA recovery scenarios.

Since the biopolymer production plants are characterized by the nitritation tank, the supernatants that come back to the main line of the plant, are characterized by lower amount of nutrients (Nitrogen and Phosphorus). It means that the pollutants load that flows in the plant is lower with compared with the real case.

As easily imaginable, the effluent of from the plant that goes into the water body will have a lower concentration of both nitrogen and phosphorus.

Table 114 water line impacts

	REAL	SIMULATED	CASE 1 (PHA recovery scenario)	CASE 2 (PHA recovery scenario)	unit of measure
TOTAL SUPERNATANT					
FLOW	1241,38	1121,75	1242,90	1246,60	m3/d
COD conc	3280,39	1300	1300	1300	mgCOD/L
TSS	1909,18	1080,21	786,8	522,74	mgTSS/L
N	147,13	160	46,4	25,1	mgTN/L

P	52,02	57	22,9	10,9	mgP/L
TOTAL EFFLUENT					
COD conc	21,0	10,0	10,1	10,1	mgCOD/L
BOD conc	4,0	2,3	2,3	1,4	mgBOD/L
TN conc	8,8	11,7	10,1	9,8	mgTN/L
TP conc	0,6	0,7	0,2	0,1	mgP/L
TSS conc	5,7	1,7	1,6	1,6	mgTSS/L
N-NH4 conc	0,8	0,4	0,4	0,4	mgN-NH4/L
N-NO3 conc	7,0	9,9	8,5	8,1	mgN-NO3/L

In particular, the phosphorus shows low concentrations from 11,7 mg N/l in the simulated case up to 9.8 mg N/l in the second case with treatment process designed for the removal of nutrients.

Considering the phosphorus, it can be notice that the concentration values in the case of PHA recovery is far below the threshold required by law. Indeed, the decree 152/2006 requires a concentration of phosphorus in the effluent lower than 1-2 mg/l, while in Modena the values reach 0,1 mg/l. It means that the chemical dosed ($FeCl_3$) is too high for the precipitation of that nutrient.

The result of the analysis is, therefore, positive, because dosing lower amount of iron for the chemical precipitation means to have lower impact both in terms of economic and environmental analysis.

4.3 Castiglione

4.3.1 PHA recovery scenario

The feasibility study on the Castiglione plant was conducted using three different substrates. The first is the primary sludge of Castiglione, the second is the activated sludge, while the last is the mix between two previous sludges.

The configurations of Castiglione wastewater treatment plant have been designed considering the operating parameters found out assessing the literature.

In particular, the yield and the process parameters are chosen on the bases of the analysis exposed in the chapter 2.2, while the scenarios have been identified considering the studies conducted by Vincenzo Conca et al. (2020) and Nicola Frison et al. (2018).

CONFIGURATION 1 (Appendix 3c):

The sludge coming from the primary clarifiers is sent to the thickening process, together with the external waste coming from a pharmaceutical industry. Once the sludge is thickened, reaches a concentration of 3,3 %TS (table 115). The flowrate that enters in the fermenter is 1974,6 m3/d with 65556 kgTSS/d of suspended solids. The table 115 shows the characteristics of the sludge entering the fermenter.

Table 115 characteristics of the sludge entering the fermenter

Flow	1974,6	m3/d
TS%	3,32	%
TSS	65556	kgTS/d
VSS/TSS	0,73	
VSS	47856	kgVS/d
N	2136	kgN/d
P	236	kgP/d

To produce VFA, the volatile solids are destroyed, so that, calculating the TVS in the outgoing flow, these should result in less quantity than the entrance (see table 116). The amount of VFA is calculated considering the VFA yield found in literature.

Table 116 sludge coming from the fermenter

Flow	1974,6	m3/d
TS%	2,9	%
TSS	56932	kgTS/d
VSS	33021	kgVS/d
VSS/TSS	0,58	
VFA	21066	kgVFA/d
N	2136	kgVFA/d
P	236	kgVFA/d
N%TS	3,8	%
P%TS	0,4	%

In particular for this sludge, the growth yield of the laboratory-scale primary sludge is considered: 0,31 gCOD(VFA)/gCOD(VS), which is equal to 0,44 in terms of gCOD(VFA)/g(VS) (considering the theoretic ratio of 1.42 gCOD(VS)/gVS. The daily production of VFA amounts to 21066 kg VFA.

The design of the fermenter was also done in terms of sizing. The HRT values are, by literature, between 5 and 10 days, so the volume have been calculated considering the retention time of 5, 8 and 10 days.

Table 117 Fermenter volume calculation

Volume (HRT=5d)	9873	m3
Volume (HRT=8d)	15797	m3
Volume (HRT=10d)	19746	m3

After the fermentation, the sludge is subjected to a solid-liquid separation process. In this case, this happens thanks to a thickener with a percentage of abatement of 99%. The sludge is sent to the digestion reactor together with the secondary sludge of the plant, while the water, rich in VFA is used as substrate to recover the biopolymer.

The digestor has a percentage of VSS destruction of about 17%, with a Specific Gas Production equal to 0,13 Nm3CH4/kgVS. Considering a load of destroyed TVS equal to 9730,0 kgTVS destroyed/d, the digestor produces 11562 Nm3/d in terms of biogas and 7284 Nm3/d in terms of methane. The table 118 shows the characteristics of the sludge that enters in the digestor.

Table 118 characteristics of the sludge that enters in the digestor

Flow	2552,3	m3/d
TS%	3,6	%
TSS	89428,1	kgTS/d
VSS	55836,1	kgVS/d
VSS/TSS	0,6	
N	3602	kgN/d
P	729	kgP/d
N%TS	4,0	%
P%TS	0,8	%

The sludge after digestion is sent to a post thickener. Part of the solids in the thickener are sent in the pre thickening process of the primary sludge. On the contrary, the sludge is sent to the dewatering, where the separation from liquid supernatant takes place. The rejected water from the supernatant is sent to the nitritation and biomass selection, together with the primary sludge supernatant from the post thickening.

The sludge that come out from the centrifuge is 195,9 m3/d with a concentration of 25,6%. Part of the sludge is sent to the dryer, while the other the remaining part bypasses it. The produced sludge has the following characteristics and is sent to the composting plant.

Table 119 characteristics of the produced sludge

Quantity	132248,4	kg/d
Flow	132,25	m3/d
TSS	50623,9	kgTSS/d
TS%	38,3	%
VSS/TSS	0,62	

The table 120 shows the characteristics of the water that enter in the nitritation and biomass acclimatation process.

Table 120 Characteristics of the water that enter in the nitritation and biomass acclimatation process

FLOW	1643,5	m3/d
TN	36,3	kgTN/d
TP	5,4	kgP/d
TSS	875	kgTSS/d
VFA	21066	kgVFA/d
N	36	kgN/d
P	5	kgP/d

The primary sludge has a VS growth yield of about 0,25 gVSS/gCODVFA, producing an amount of 5192 kg VSS/d. Actually, this value is the one related to the cellulosic sludge. The reason is given by the fact that the data for the primary sludge was not available and this one was the more similar to the primary sludge.

The % of abatement of nitrogen and phosphorus is considered equal to 80% and 75%, respectively, so that the supernatant has a concentration of nutrients equal to 0,5 mgN/l and 0,1 mgP/l.

The PHA growth yield is 1,09 gPHA/gVSS, since it is the typical value of the primary sludge. It allows the production of 5664 kgPHA/d with a specific value of 1,05 kgPHA/AE/y which is completely in the range proposed by SMART PLANT analysis.

CONFIGURATION 2 (Appendix 3d):

In the second configuration, the activated sludge is used for the fermentation and production of the readily organic carbon source (VFA).

The characteristics of the secondary sludge, after the thickening process, are listed in the table 121.

Table 121 Characteristics of the secondary sludge, after the thickening process

Flow	1143,2	m3/d
TSS	33065	kgTS/d
TS%	2,9	%
VSS/TSS	0,7	
VSS	23146	kgVS/d
N	1488	kgN/d
P	496	kgP/d

This is the sludge that is sent in the fermenter. The sizing of the reactors are done considering the HRT equal to 5, 8 and 10 days as in the previous case.

Table 122 Fermenter volume calculation

Volume (HRT=5d)	5716	m3
Volume (HRT=8d)	9145	m3
Volume (HRT=10d)	11432	m3

The growth yield for the VFA is considered to calculate how many fatty acids are present in the outgoing sludge. The value assumed is the one of the real case plants described in the chapter 2.2.2, equal to 0,26 gCODVFA/gVS.

This ratio produces an amount of VFA equal to 5916 kg/d. The sludge after the fermentation is subjected to the thickening process in order to divide the solids from the VFA rich supernatant. The rejected water is sent to the nitritation and biomass selection reactor, while the sludge comes to the digestor together with the primary sludge.

The digestor, considering an SGP of 0,13 Nm3/kgVS, produces 13752 kg biogas/d with a CH4/biogas ratio of 0,63.

The destroyed TVS are 11573,4 kg /d, so the outgoing sludge presents this data (table 123):

Table 123 Characteristics of the sludge from the digester

Flow	2784,5	m3/d
TS%	2,9	%
TSS	80237	kgTS/d
VSS	55072	kgVS/d
VSS/TSS	0,69	
N	3571	kgN/d
P	688	kgP/d

The sludge goes to the post-thickener, where the sludge reaches an assumed concentration of 4% TS and then to the dewatering. The supernatant from this last process is sent to nitritation and biomass selection activity, while the sludge goes in part to the dryer. The produced sludge amounts to 130746 kg TQ/d with a concentration of 38,3%TS.

Coming back to the acclimatation process, this is the characteristic of the water entering to the nitritation reactor.

Table 124 characteristic of the water entering to the nitritation reactor

Flow	1403,5	m3/d
TSS	832,7	kgTS/d
N	37,4	kgN/d
P	9,3	kgP/d
VFA	5916,0	kgVFA/d

The VS yield considered is 0.23 gCOD(VSS)/gCOD(VFA), which is the one related to the secondary sludge in laboratory case studies. The % of abatement of nitrogen and phosphorus is considered equal to 80% and 75%, respectively, so that the supernatant has a concentration of nutrients equal to 0,6 mgN/l and 0,2 mgP/l.

The PHA produced amounts to 636 kg/d with a specific value of 0,12 kgPHA/PE/y.

It is a very low value, that allow to understand that the secondary sludge is not so good for the PHA recovery processes, since the growth yield of the VFA, the VS and PHA are too low.

Table 125 Produced PHA

VSS	958	kgVS/d
PHA	636	kgPHA/d
PHA	0,12	kgPHA/AE/y

CONFIGURATION 3 (Appendix 3e):

The third scenario is the one in which both the primary ad secondary sludge are exploited for the VFA production.

After the thickening the primary and biological sludge are mixed together. The characteristics of the mixed sludge are reported in the table below (Table 126).

Table 126 characteristics of the mixed sludge

Flow	3117,8	m3/d
TSS	98621	kgTS/d
TS%	3,2	%
VSS/TSS	0,7	
VSS	71002	kgVS/d
N	3717	kgN/d
P	758	kgP/d
N%TS	3,8	%
P%TS	0,8	%

The fermenter has a yield of 0,45 gCODVFA/gVS, since it is the typical value for the mixed sludge, considering the ratio 1,42g COD(VSS)/gVSS. The produced VFA are 21746 kgVFA/d and the used VS are 38.459 kg VS destroyed/d.

The volume of the reactors have been calculated considering the HRT equal to 5, 8 and 10 days as in the previous cases.

Table 127 Fermenter volume calculation

Volume (HRT=5d)	5716	m3
Volume (HRT=8d)	9145	m3
Volume (HRT=10d)	11432	m3

The sludge after the fermentation is subjected to the thickening process in order to divide the solids from the VFA rich rejected water. The supernatant is sent to the nitritation and biomass selection reactor, while the sludge goes to the digestor, in order to exploit the sludge also to produce the biogas. The quantity of biogas produced is about 6647,9 Nm3/d, with 63 % of methane.

The used TVS in the digestor are 5594,6 kgTVS distrutti/d, so the outgoing sludge has 26622,2 kgVS/d. The other characteristics are listed in the table 128.

Table 128 characteristics of the digested sludge

Flow	1388,7	m3/d
TS%	3,3	%
TSS	45900,3	kgTS/d
VSS	26622,2	kgVS/d
VSS/TSS	0,58	
N	3680	kgN/d
P	751	kgP/d

This sludge is sent to the thickening, dewatering and drying processes, to reach a concentration of 38,3%TS and an amount of sludge produced of 82193,2 kg TQ/d.

The water sent to the nitritation and biomass selection process is rich in fatty acids and presents loads of nitrogen and phosphorus of 52,4 kgTN/d and 10,7 kgP/d, respectively. The VSS growth yield of the process is equal to 0,11 gVSS/gVFACOD, so that the selected microorganisms produced are 2450 kgVS/d.

The yield for the PHA production is 0,45 gCODPHA/gCODVSS, that can be seen also as 1,07 gPHA/gVSS, considering both the ratio of 1,67 gPHA/gCODPHA and 1,42 gCODVSS/gVSS.

Table 129 Produced PHA

VSS	2450	kgVS/d
PHA	2615	kgPHA/d
PHA	0,48	kgPHA/PE/y

As shown in the table 129, the quantity of produced PHA is equal to 2615 kgPHA/d and the specific value, considering the people equivalent is about 0,48 kgPHA/PE/y. It is a little bit lower with respect to the value proposed by SMART PLANT. Anyway, it must be said that the yield values we have taken are those found from the laboratory scale and pilot scale case studies. If full-scale case study values had been available, the calculation would certainly have been less error prone.

4.3.2 Comparison and economic evaluation

A comparison between the configurations is required in order to define the better configuration for the resource recovery, both in terms of recovery and economic evaluation.

In the As it is scenario, an amount of sludge equal to 51.317ton/y is produced and a daily volume of biogas of 27.202 Nm3.

The gain due to the production of biogas (market price) is equal to 0.12 € /m3 (Conca, 2020), so the value of the revenue due to the biogas production is 750.608 €/y for the actual scenario.

The cost of the sludge disposal is considered equal to 100 € /ton so that the cost for all the sludge is, in the real case, 5.131.694 €/y.

In the other cases, as said previously, the biopolymer production scenario is designed, so that the biogas recovery has a lower efficiency. Anyway, the saving is higher, because the price of PHA is about 5 € /kg PHA (Conca, 2020).

In the first case, only the primary sludge is fermented and exploited for the PHA recovery, producing 5664 kg PHA/d.

The revenue due to the polymer production is 7.235.889€/y, while the revenue due to the methane production is 319.037€/y, since the methane produced in this configuration is 7284 m3/d. It means that the total revenue is 7.108.946 €/y as exposed in the table 130.

In the second case, the secondary sludge is used for the fermentation. The produced polymer gives a revenue of 812.813 €/y, while the produced methane allows to gain 379.481 €/y. The disposed sludge amounts to 47.722 ton/y, a little bit lower with respect to the other case. Its disposal requires 4.772.221 €/y. It means that the total revenue in this scenario is 801.159 €/y, considering the recovered resources (biogas and polymers) and the sludge to be disposed.

Finally, the third case, the one in which all the sludge is used to produced VFA, the produced PHA amounts to 2615 kgPHA/d, in order to revenue 3.340.310 €/y, while the revenue due to CH4 production is 183.443 €/y, since 4188 Nm3/d has been produced.

The amount of sludge to be disposed is much less than in the other two cases, almost half, since the volatile solids are destroyed both in the digestor and in the fermenter. So the annual cost is 3.000.052 €/y. The revenue is, therefore, 4.904.787 €/y. This value is lower with respect to the one in the other cases, because both the biogas and PHA produced are in lower amount.

Table 130 Summary of the results

CASTIGLIONE		AS IT IS	CONFIGURATION 1	CONFIGURATION 2	CONFIGURATION 3
Chosen flux	-	I SLUDGE+ II SLUDGE+ EXT	I SLUDGE+EXT	II SLUDGE	I SLUDGE+ II SLUDGE+ EXT
fermented/digested Q	m3/d	3.118	1.975	1.143	3.118
VFA yield	gCODVFA/gVS	-	0,44	0,26	0,45
VSS yield	gVSS/gCODVFA	-	0,25	0,16	0,11
accumulation yield	gCODPHA/gVS	-	1,09	0,66	1,07
Produced PHA	kgPHA/d	0	5664	636	2615
specific PHA	kg/AE/y	-	1,05	0,12	0,48
Produced Biogas	Nm3/d	27.202	11562	13752	6648
Produced Methane	Nm3/d	17.137	7284	8664	4188
Disposed sludge	ton/y	51.317	48.271	47.722	30.001
PHA REVENUE	Euro/y	0	7.235.889	812.813	3.340.310
METHANE REVENUE	Euro/y	750.608	319.037	379.481	183.443
Sludge disposal cost	Euro/y	5.131.694	4.827.066	4.772.221	3.000.052
REVENUE	Euro/y	750.608	7.108.946	801.159	4.904.787
N in supernatant	kg/d	534	7,3	7,5	10,5
P in supernatant	kg/d	53	1,3	2,3	2,7

Considering the nutrient in the supernatant, it can be seen that the loads in the case 1, 2 and 3 are much smaller than in the real case. This is due to the fact that the rejected waters, before returning to the main line of the implant, are treated in the nitritation and biomass selection reactor.

Considering the data exposed in the table, the better scenario in terms of biopolymer production is the one that uses the primary sludge for to produce VFA in the fermenter. Indeed, it produces the higher PHA quantity. Anyway, in terms of economic revenue, the best case is the second one, since its revenue is 801.159 €/y. The reason is given to the facts that in this scenario higher amount of methane in recovered and also that the quantity of the sludge to be disposed is lower.

4.4 Experimental activity results

At first, the experimental results on the samples taken from the supernatant of the dewatering process are exposed.

The pH measured with the probe is more or less equal to the neutrality.

It must be said that, being a post digestion supernatant, in both cases, the organic carbon value can be high, but the amount of readily biodegradable carbon could be very low.Ammonia values are in both case around 300-400 mgN/L, and TKN slightly higher than NH4 values.

Most of the P, which is present in low concentrations, is soluble, in fact, for WWTP1 there are 14 mg P-PO4/ l with the total concentration of P of 21 mg P/ l, while inWWTP2 there are 35,2 mg P-PO4/ l and a total P concentration of 40,5 mgP/l. This evidence is justified by the fact that, as the solids concentrations are low, most of the P is not bound to the solids but is soluble.

Table 131 results from the tests on the supernatant from dewatering

	Unit of measure	**WWTP1– supernatant from dewatering**	**WWTP2 – supernatant from dewatering**
pH		7,7	7,55
TKN	mg N/l	414,6	351,6
N-NH4	mg N-NH4/l	402,3	330
TSS	TSS mg/l	40	260
CODtq	mg O2/l	183,3	529,2
CODs	mg O2/l	62,5	95,8
Ptot	mgP/L	21,0	40,5
P-PO4	mgP-PO4/L	14,0	35,2

Tests on solids are carried out on the sludges (both those of biological recirculation and pre-digestion). The results showed that the sludge has the following concentrations.

Table 132 TS% and TVS/TS tests results

	TS%	**TVS/TS**
A (biological recirculation-line 2) – WWTP1	1,1	0,51
B (biological recirculation-line 1) - WWTP1	1,4	0,48
C (pre-digestion sludge) - WWTP1	5,1	0,54
D (biological recirculation-line 1b) – WWTP2	1,6	0,55
E (biological recirculation-line 2) - WWTP2	1,05	0,69
F (pre-digestion sludge) - WWTP2	4,65	0,68

From the table 132, it is possible to observe that the ratio TVS/TS of WWTP1 are lower than the ratio of WWTP2.

These low values of TVS/TS ratio in WWTP1 may depend on the fact that the solid retention time of biologic reactor is too low.

The other tests carried out for the sludges are MLSS and MLVSS.

Table 133 MLSS and MLVSS tests results

	MLSS (mg/l)	MLVSS (mg/l)
A (biological recirculation-line 2) – WWTP1	8600	4090
B (biological recirculation-line 1) - WWTP1	14280	5680
C (pre-digestion sludge) - WWTP1	46820	23240
D (biological recirculation-line 1b) - WWTP2	9180	5049
E (biological recirculation-line 2) - WWTP2	14800	10200
F (pre-digestion sludge) – WWTP2	39620	27100

The calculated concentration of the sludge in mg/l are similar to the results taken from the TS% and TVS% tests. In particular, the sample B has a concentration of 14280 mg MLSS/l which is equal to 1,4% TS.

Now, let's consider the tests done on the fermented sludges. As already said, the samples on which the laboratory tests were carried out were taken from the recirculation of the biological sludge and from the sludge entering to anerobic digestion.

Table 134 Results of the test performed on the fermented sludges (WWTP 1)

	HRT	5d			7d			9d		
WWTP1	Samples	A (line 1b)	B (line 2)	C (pre dig)	A (line 1b)	B (line 2)	C (pre dig)	A (line 1b)	B (line 2)	C (pre dig)
pH	-	8,2	8	8,5	7,83	7,31	7,99	7,21	7,06	7,17
N-NH4	**mg/L**	42	61	242	59	61	375	64	76	417
P-PO4	**mg/L**	1,42	3,49	9,47	3,55	9,04	20,33	1,61	12,26	10,43
COD s	**mg/L**	167	0	0	1542	1375	1125	1167	1083	1417
Glycolate	**mg/L**	0,00	0	0	0	0,1	0	0	0	0
Acetate	**mg/L**	78,92	3,4	3,1	7,2	16,89	0,85	17,47	0,519	2,6
Propionate	**mg/L**	20,9	9,5	0	8,45	6,74	0	21,28	0	0
Formate	**mg/L**	0	0,1	0,6	0,45	0,37	0,37	0,15	0,22	0
Butyrate	**mg/L**	0	0	0	0	0	0	0	0	0
VFA	**mg/L**	**99,82**	**13,00**	**3,70**	**16,10**	**24,12**	**1,22**	**38,90**	**0,74**	**2,56**
VFA/CODs	**%**	60	-	-	1	2	0,1	3,3	0,1	0,2
MLVSS	**mg/L**	4090	5680	23240	4090	5680	23240	4090	5680	23240
TS%	**%**	1,4	1,1	5,1	1,4	1,1	5,1	1,4	1,1	5,1
TVS/TS	-	0,48	0,54	0,51	0,48	0,54	0,51	0,48	0,54	0,51
YIELD mgVFA/gVSS	-	24,41	2,29	0,16	3,94	4,25	0,05	9,51	0,13	0,11

Since the fermentation occurs in acidic environment, the pH is measured and shows a decrease of value during time, from 8 in the fifth day to 7 in the ninth day of fermentation.

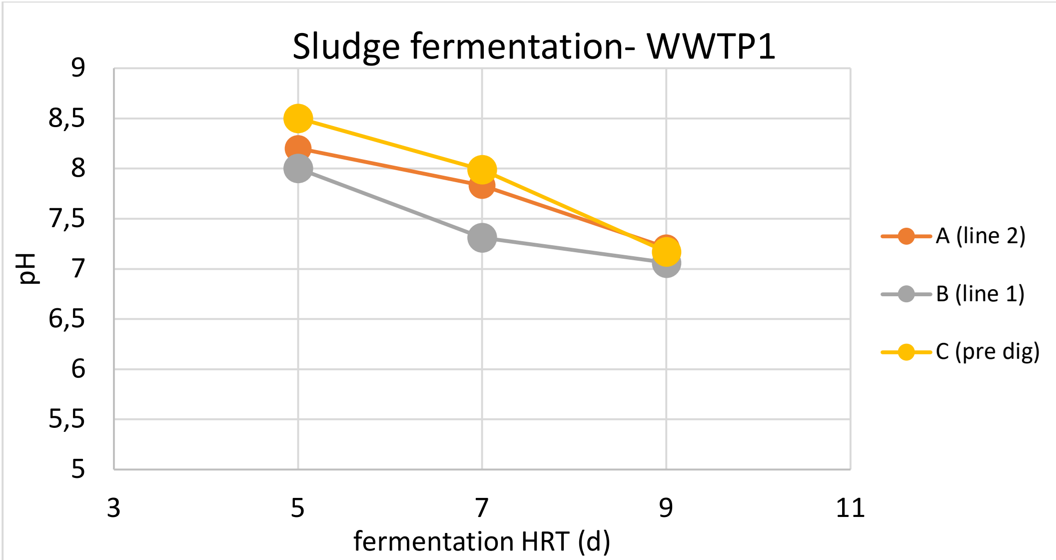


Figure: 56 Variation of pH during the fermentation time (WWTP1)

Assessing the results, it can be notice that there is a progressive increase of NH4 and P-PO4 from the fifth to the ninth day of fermentation. This is the effect of the hydrolysis, which is the first phase of the fermentation, before the VFA production.

This can be seen on all samples, especially on sample C. In particular, it shows an increase in N-NH4 from 242 mg N-NH4/l (fifth day), to 375 mg N-NH4/l (seventh day) to 417 mg N-NH4/l (ninth day). The concentrations of NH4-N, PO4-P, VFA, CODs of the different fermented samples depending on the variation of the fermentation HRT are graphed below.

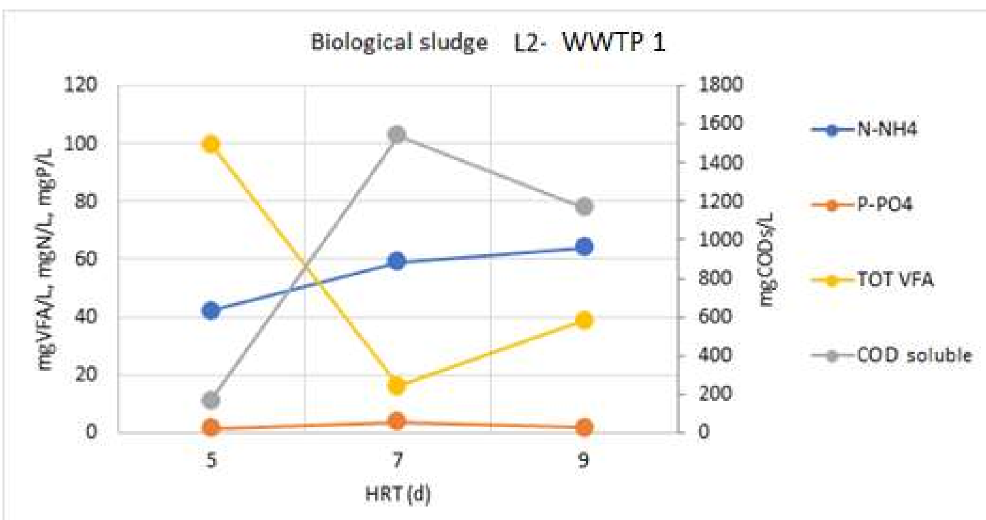


Figure: 57 Variation of pollutants during the fermentation time- biological sludge L2 (WWTP1)

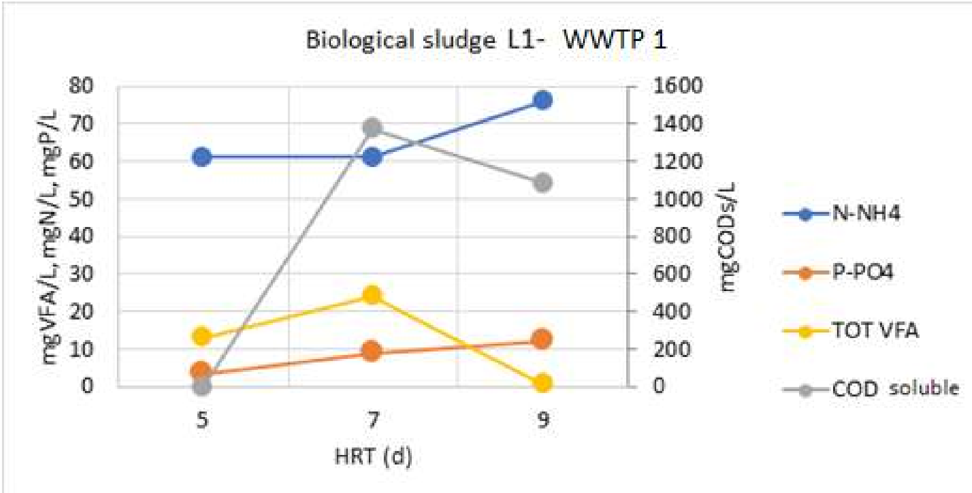


Figure: 58 Variation of pollutants during the fermentation time- biological sludge L1 (WWTP1)

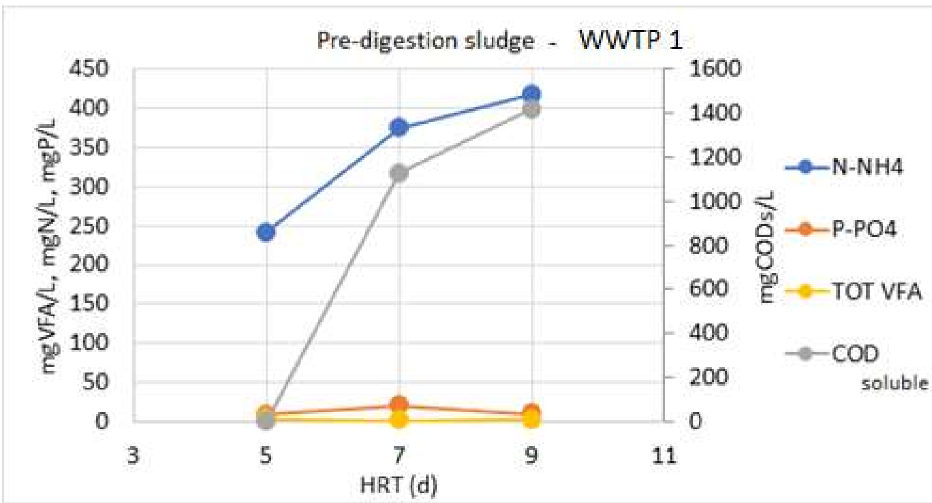


Figure: 59 Variation of pollutants during the fermentation time- pre-digestion sludge L1 (WWTP1)

There is a slight effect in VFA production, especially on sample A, which shows a yield of 24,41 mgVFA/gVSS, 3,94 mgVFA/gVSS and 9,51 mgVFA/gVSS in the fifth, seventh and ninth day of fermentation, respectively.

The sample B, on the contrary, shows a maximum yield at the seventh day of fermentation, equal to 4,25 mgVFA/gVSS.

The pre-digestion sludge seems to be the least inclined to produce VFA, since its yield are significantly lower than those of the other samples: 0,16 mgVFA/gVSS at the fifth day, 0,05 mgVFA/gVSS at the seventh day, 0,11 mgVFA/gVSS at the ninth day.

Now, the considerations about the WWTP2 sludge are done.

Table 135 Results of the test performed on the fermented sludges (WWTP 2)

	HRT	5d			7d			9d		
WWTP2	Samples	**D (line b)**	**E (line 2)**	**F (pre dig)**	**D (line b)**	**E (line 2)**	**F (pre dig)**	**D (line b)**	**E (line 2)**	**F (pre dig)**
pH	**-**	8,3	8,0	8,2	7,9	7,4	7,5	7,0	6,7	6,5
N-NH4	**mg/L**	28,1	59,9	294,2	38,8	54,2	478,1	61,3	412,9	574,5
P-PO4	**mg/L**	8	20	28	10	37	29	10,5	53,7	49,2
COD solubile	**mg/L**	-	417	2625	1417	1917	4250	1250	2333	4667
Glicolato	**mg/L**	0	0	0	0	0	0	0	0	0
Acetato	**mg/L**	156,9	332,3	1225,8	183,3	425,5	1010,7	198,2	480,0	1339,7
Propionato	**mg/L**	6,0	112,4	714,7	10,3	167,1	612,5	31,0	207,0	1086,2
Formato	**mg/L**	0,1	0,0	4,4	0,1	0,3	0,4	0,2	0,0	0,4
Butirrato	**mg/L**	0,0	0,0	348,9	0,0	0,0	295,2	0	12,8	388,6
VFA	**mg/L**	**163**	**445**	**2294**	**194**	**593**	**1919**	**229,5**	**699,8**	**2814,9**
VFA/CODs	**%**	-	107	87	14	31	45	18	30	60
MLVSS	**mg/L**	5049	10200	27100	5049	10200	27100	5049	10200	27100
TS%	**%**	1,6	1,1	4,7	1,6	1,1	4,7	1,6	1,1	4,7
TVS/TS	**-**	0,55	0,69	0,68	0,55	0,69	0,68	0,55	0,69	0,68
YIELD mgVFA/gVSS	**-**	32,3	43,6	84,6	38,4	58,1	70,8	45,5	68,6	103,9

The pH is measured and shows a decrease of value during time, from 8 in the fifth day to 6,5 in the ninth day of fermentation as listed in the table 135.

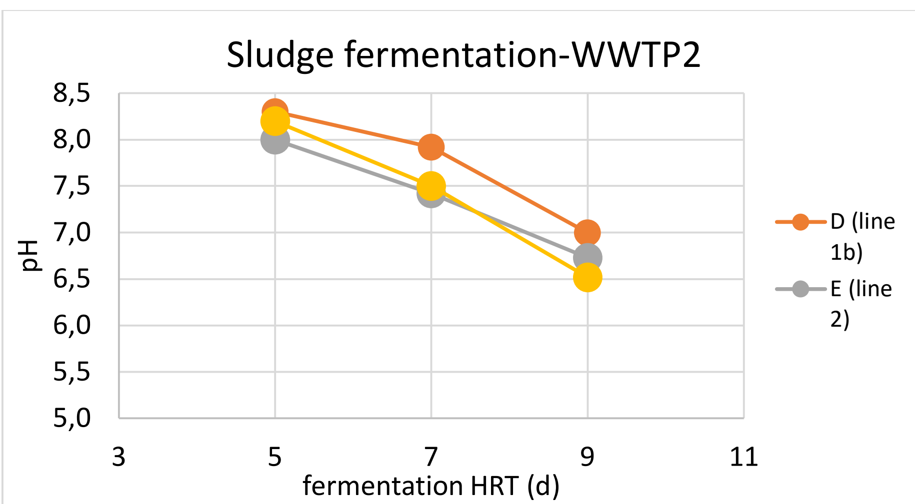


Figure: 60 Variation of pH during the fermentation time (WWTP2)

Analyzing the results, it can be notice that there is a progressive increase of NH4 and P-PO4 and CODs from the fifth to the ninth day of fermentation. It is in line with what as expected, because the first phase of the fermentation is the hydrolysis. This can be seen on all samples, especially on sample F. In particular, it shows an increase in N-NH4 from 294,2 mg N-NH4/l (fifth day), to 478,1 mg N-NH4/l (seventh day) to 574,5 mg N-NH4/l (ninth day).

The growth effect in the VFA produced can be notice in all the samples. The sample F is the one in which this effect is more evident, indeed it has yields of 84,6 mgVFA/gVSS, 70,8 mgVFA/gVSS and 103,9 mgVFA/gVSS in the fifth, seventh and ninth day of fermentation, respectively.

The samples D and E show their maximum yields at ninth day: 45,5 mgVFA/gVSS and 68,6 mgVFA/gVSS for the D and E samples, respectively.

Obviously, the amount of soluble COD in each test is higher than the amount of the VFA. Indeed the volatile fatty acids are part of the total soluble carbon present in the fermented liquid.

In the following graphs, it is possible to see the variation of nutrients and of the yield in the different days of fermented samples.

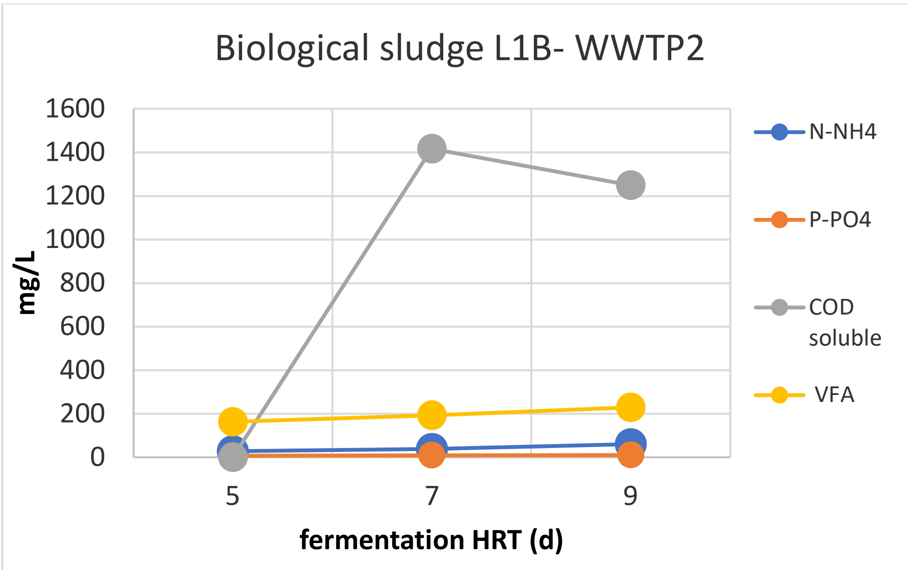


Figure: 61 Variation of pollutants during the fermentation time- biological sludge L1B (WWTP2)

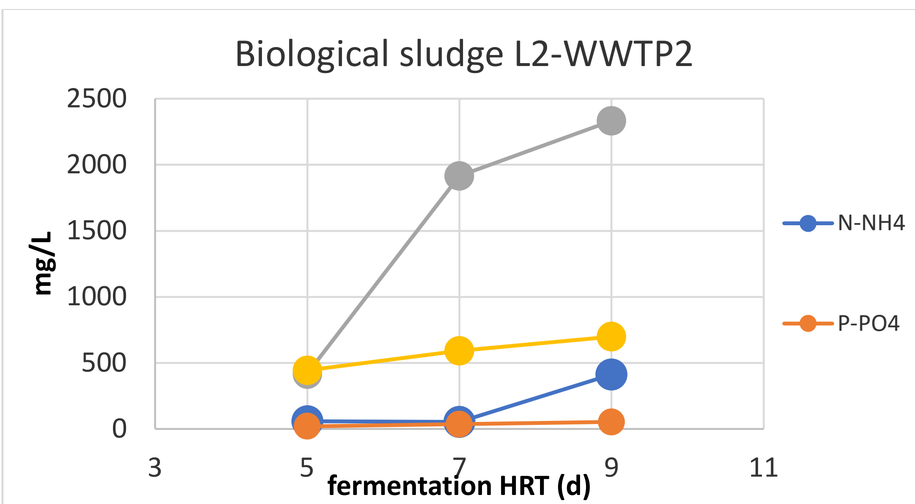


Figure: 62 Variation of pollutants during the fermentation time- biological sludge L2 (WWTP2)

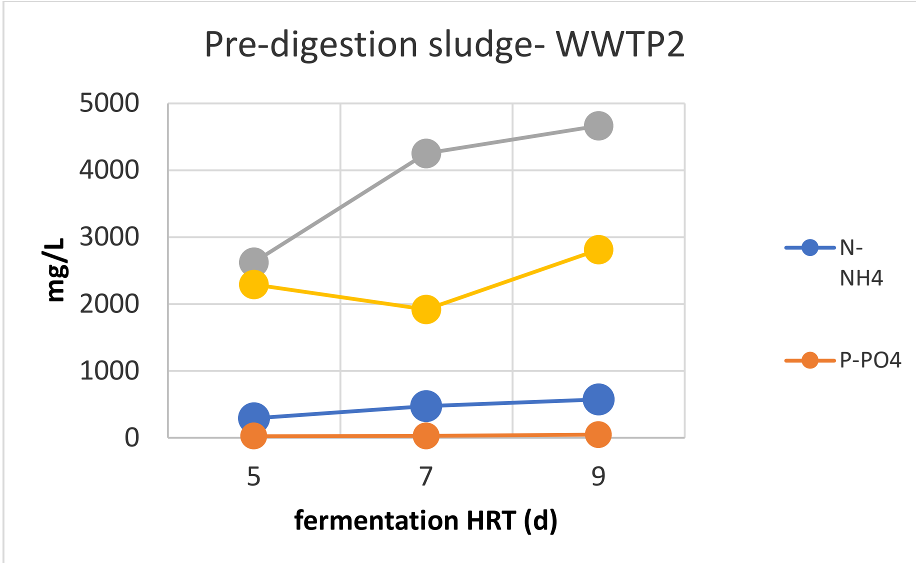


Figure: 63 Variation of pollutants during the fermentation time- pre-digestion sludge L1 (WWTP2)

The graph shows the increase in the specific production of VFA (mgVFA/gVSS) as the concentration of VSS in the reactor increases.

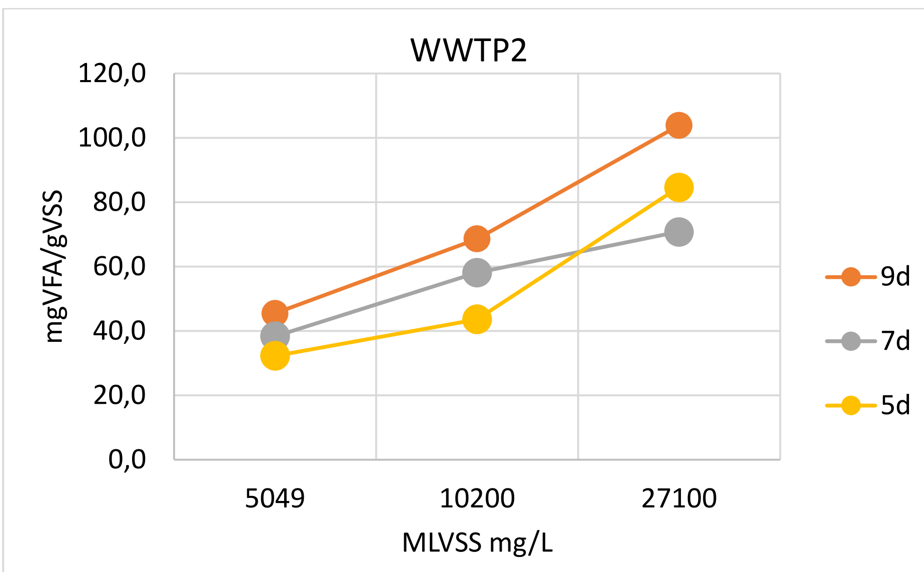


Figure: 64 variation of the MLVSS concentration during fermentation time (WWTP2)

From these results, other considerations can be done. Looking the following graph in fact it is possible to understand that the ratio TVS/TS% is a fundamental parameter for the fermentation. In fact, increasing the TVS/TS ratio, the VFA yield increase more or less linearly.

Further, the figure 67 relates the TVS/TS ratio, the yield and the HRT. It is possible to notice that the yield increases if both the other parameters increase.

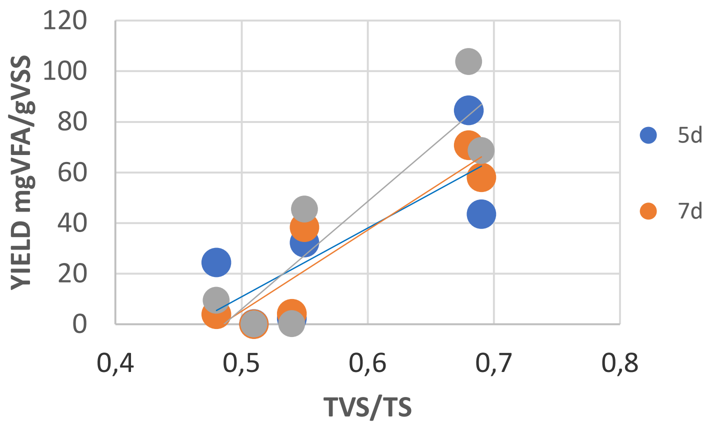


Figure: 65 Yield increase with TVS/TS ratio

Indeed, since the TVS/TS ratio is low in WWTP1 (from 0,48 to 0,54 TVS/TS), it has low capability to convert VS in VFA.

On the contrary, WWTP2 has higher amount of volatile fraction with respect to the total volatile solids (0,55 to 0,69 TVS/TS). This guarantee a higher efficiency of this sludge to covert the TVS into volatile fatty acids. This is the reason why the VFA yields in WWTP2 are higher than in Modena.

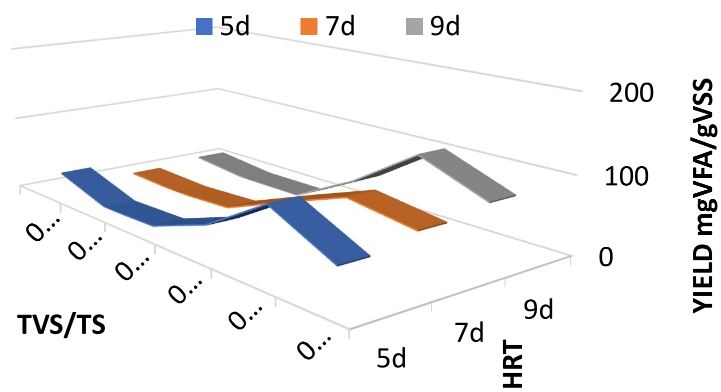


Figure: 66 relation between the TVS/TS ratio, the yield and the HRT

The last evidence is the one shown in the following graph. As expected, the specific yield (mgVFA/gVSS) increases if the pH decreases due to acidogenic conditions.

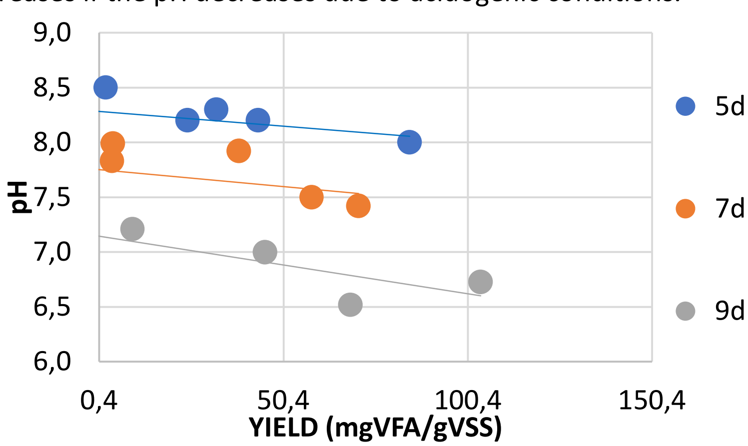


Figure: 67 Variation of pH with the Yield (mgVFA/gVSS)

5. Conclusions

The scope of this work was to evaluate the feasibility of PHA recovery in real urban wastewater treatment plants.

The study carried out on the Castelfranco plant led to minor changes to the flow scheme. In fact, in order to modify the design scenario (biogas recovery) to plan a PHA recovery unit, a new fermenter with a volume of 100 m3 was inserted for VFA production. The nitritation reactor, already present in the scheme, is also used for the selection of the microorganisms used for the production of PHA. For the latter, another fed batch reactor, necessary for the accumulation of biopolymers in microorganisms, was designed. Using a VFA Yield of 0,25 COD(VFA)/VS and a PHA accumulation of 0,33 PHA/VSS, the PHA recovered reaches a value of 293 kg PHA/d.

The life cycle assessment conducted on the Castelfranco current configuration and design PHA recovery scenario led to interesting results. Indeed, it can be summarized that treating the wastewater with imhoff tanks separately is less sustainable than treating it entirely in the plant chain. In the design scenario in fact the wastewater that in the previous case were treated in the Imhoff tanks, are sent to the main line of the plant, since the upgrading of Castelfranco is both for water line and sludge line (centralized platform for the treatment of sludge of the entire territory managed by ATS). Further, the emissions due to the imhoff tanks and the water line of the as it is scenario impacts for 86% of the total impact. On the other hand, the emissions of water line in the design scenario contribute 26% of the total impact of the plant. This means that the emissions of the most impacting process are 4 times lower in the design case.

For the Modena plant two configurations have been planned. The first one allows to recover 141 kgPHA/d with secondary sludge fermentation, while with the second scenario 524 kgPHA/d can be recovered with both secondaty and external sludge fermentation.

Actually, in these scenarios, the recovery of biogas is also proposed. Moreover, an economical evaluation has been done, proving that this last configuration is the best one to gain higher percentage of materials that leads to better situation from economic point of view.

Finally, the impacts on the water line were evaluated, since the sludge line has been modified and expanded. The assessment highlights that the supernatant from the sludge line are poorer in nutrients contents since the sludge line is treated with a nitritation reactor (about 85% of N and 75%of P removals).

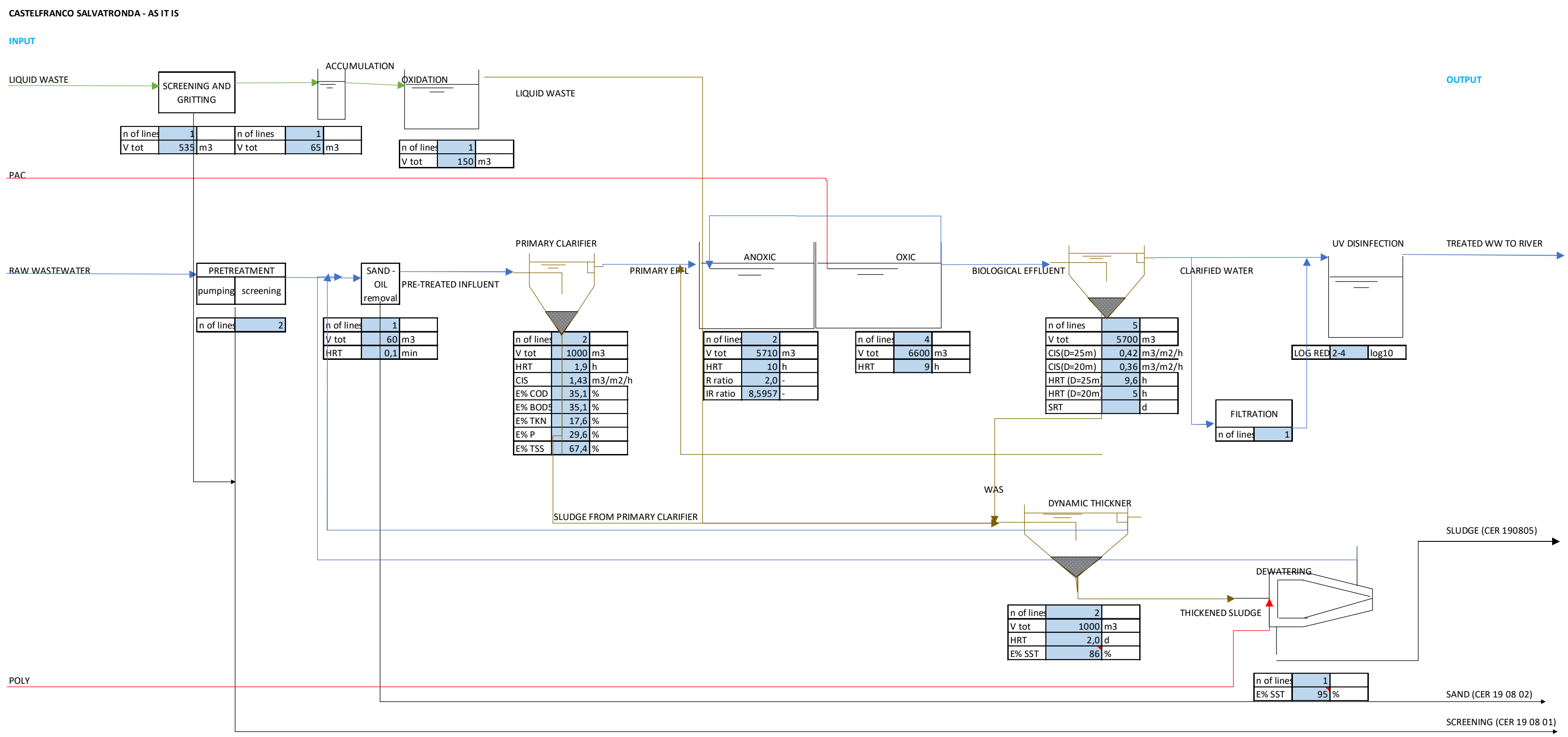
The last plant assessed was the Castiglione WWTP, for which three feasibility study configurations have been planned. The first, including primary sludge fermentation, produces 5664 kgPHA/d (1,05 kgPHA/AE/y), the second, including the secondary sludge fermentation recovers 636 kgPHA/d (0,12 kgPHA/AE/y), while the third, that uses both the primary and the secondary sludge produces 2615 kgPHA/d (0,48 kgPHA/AE/y).

The experimental results obtained from the laboratory tests demonstrate that more the sludge has VS (volatile solids) content more it is capable to convert VS matter in VFA, with maximum yield of about 90 mgVFA/gVS at 7 days of HRT.

To conclude, it can be stated that, from the results obtained in the feasibility studies, at a theoretical level, the recovery of biopolymers is feasible in each treated plant. Future studies will allow to prove these results by implementing the schemes on real plants.

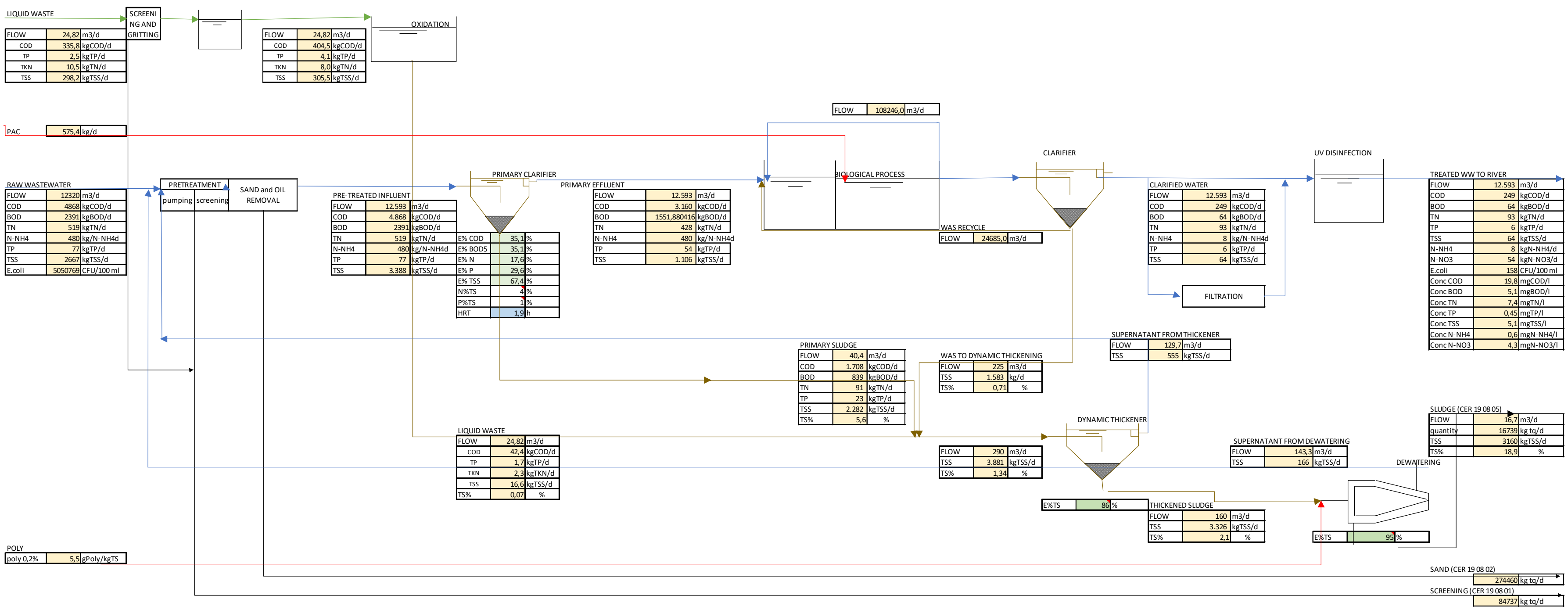
6. Appendix

1a Volumetric characteristics of Castelfranco WWTP as it is

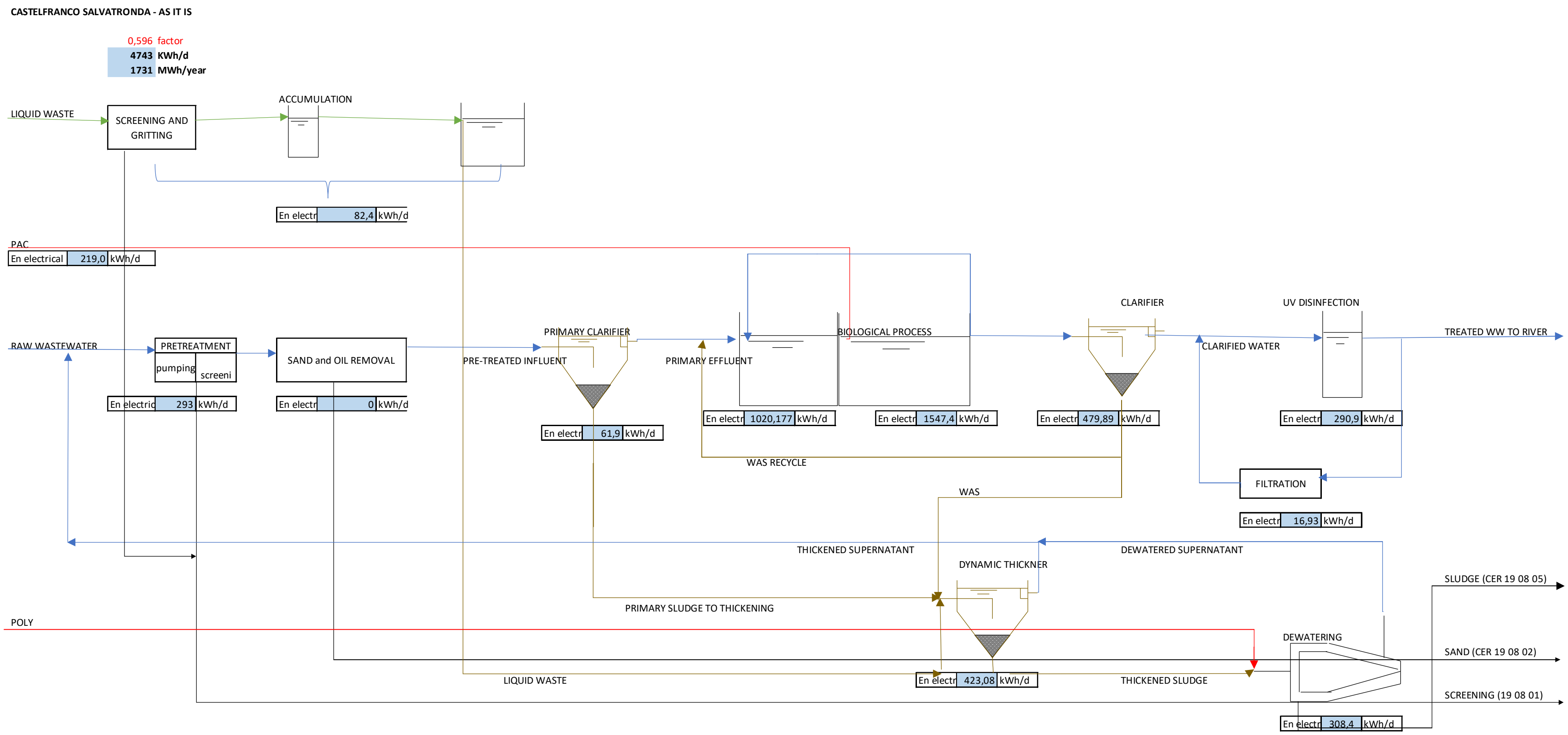


1b Mass balance of Castelfranco WWTP as it is

CASTELFRANCO SALVATRONDA - AS IT IS

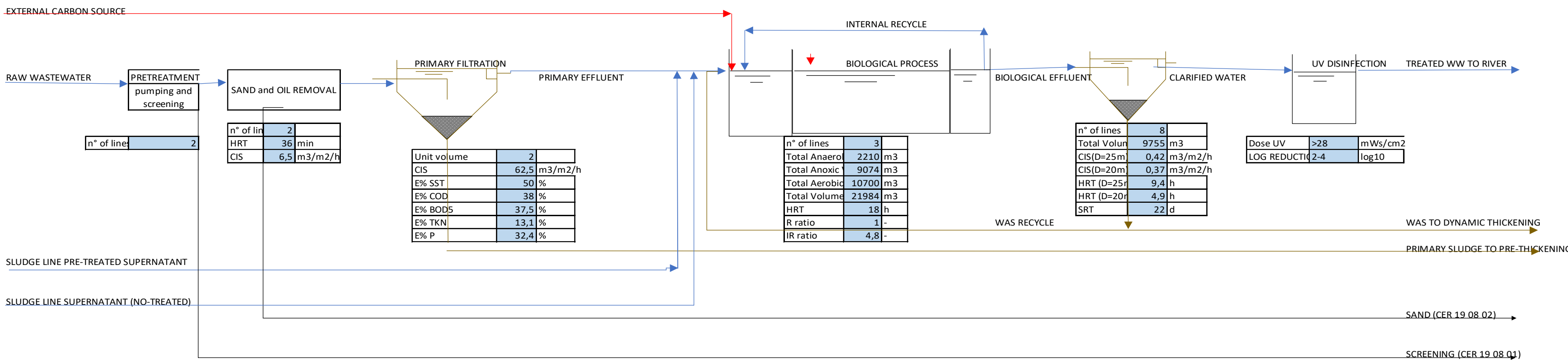


1c Energy of Castelfranco WWTP as it is



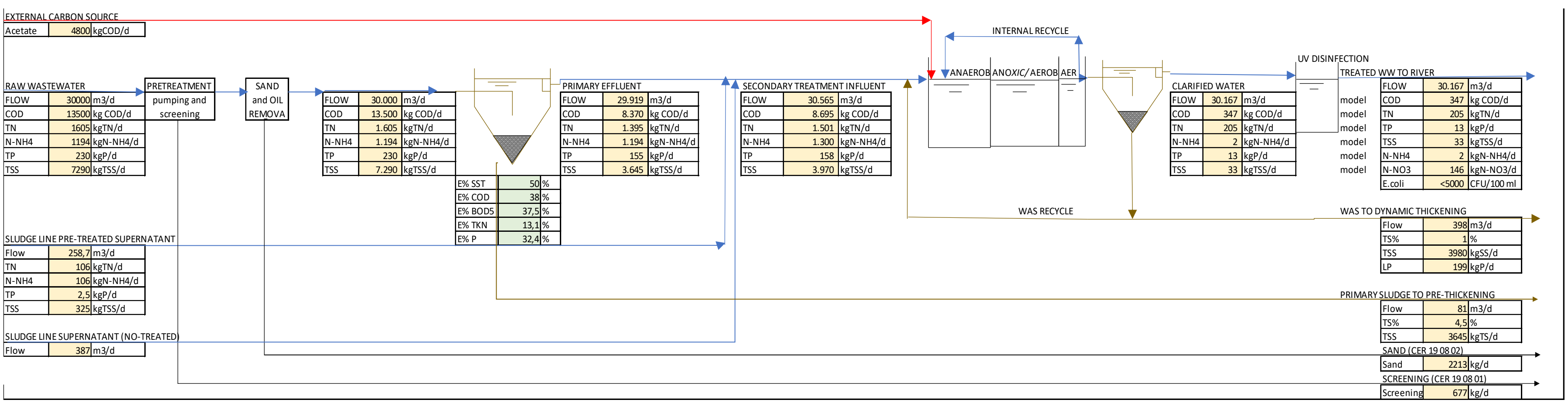
1d Volumetric characteristics of Castelfranco WWTP design-water line

CASTELFRANCO SALVATRONDA - WATER LINE

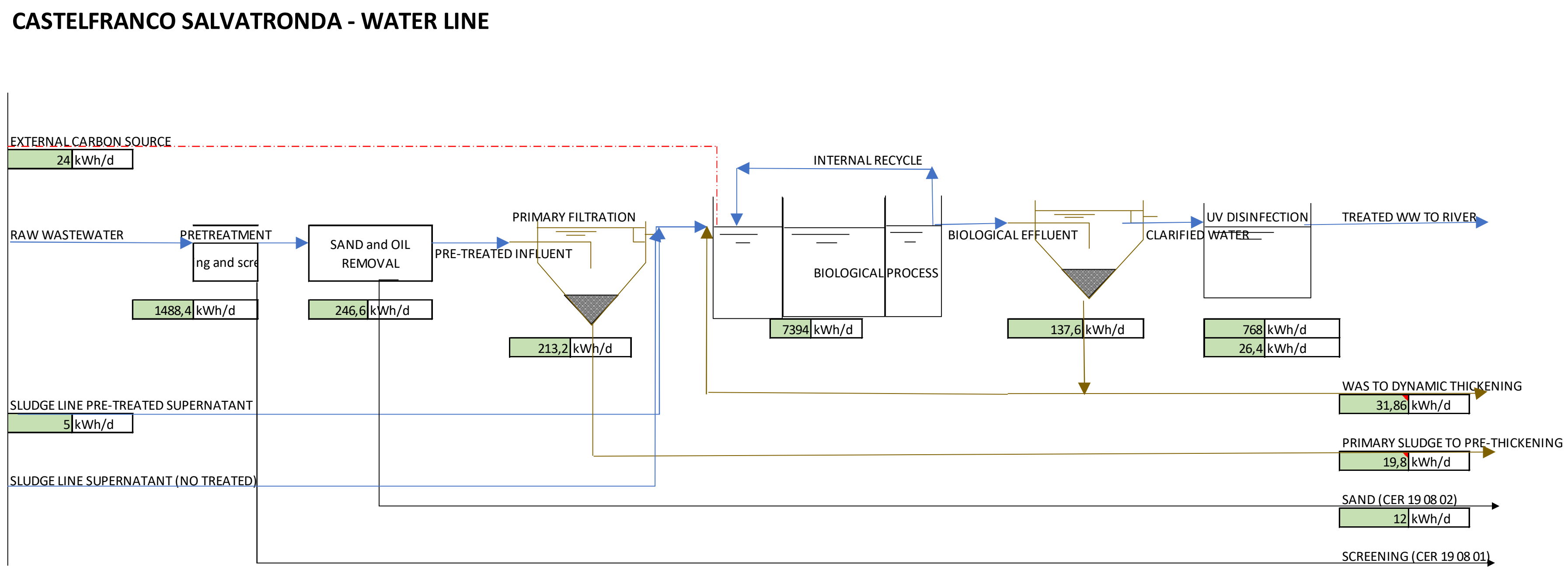


1e Mass balance of Castelfranco WWTP design – Biogas recovery- water line

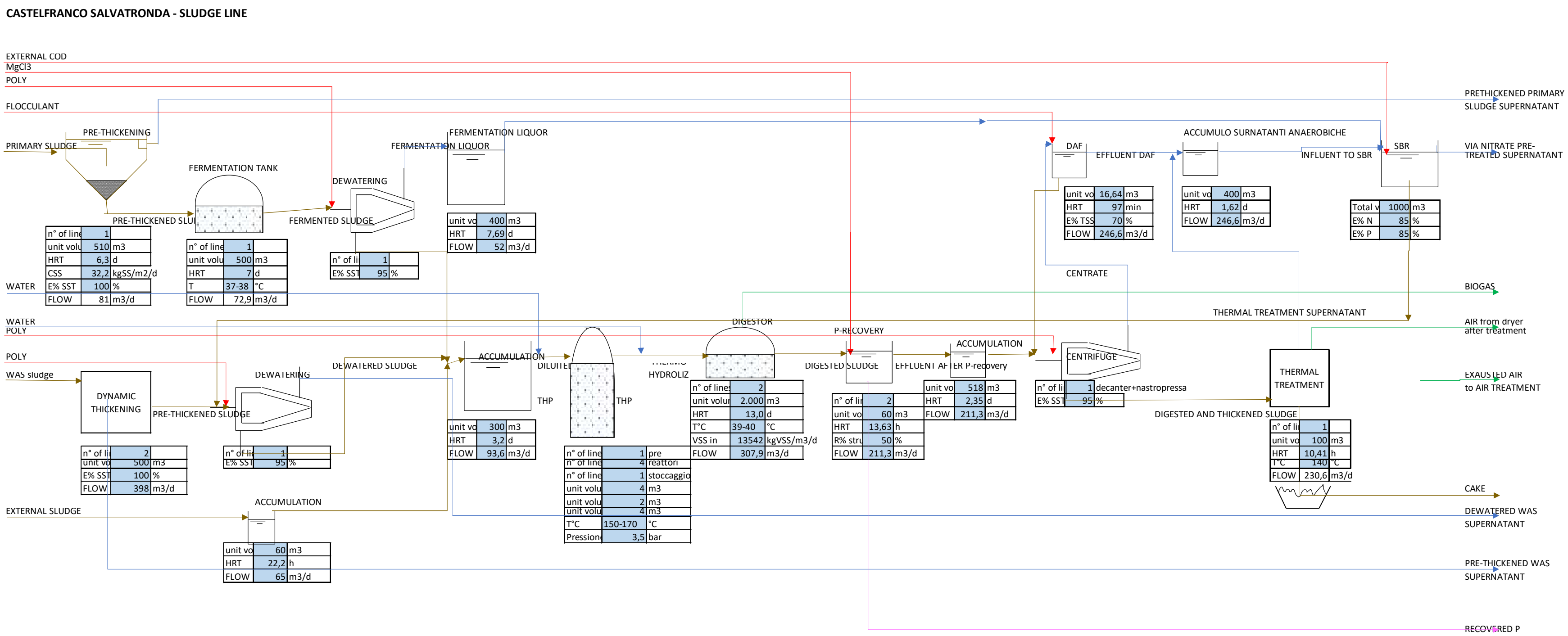
CASTELFRANCO SALVATRONDA - WATER LINE -BNR



1f Energy balance of Castelfranco WWTP design-water line

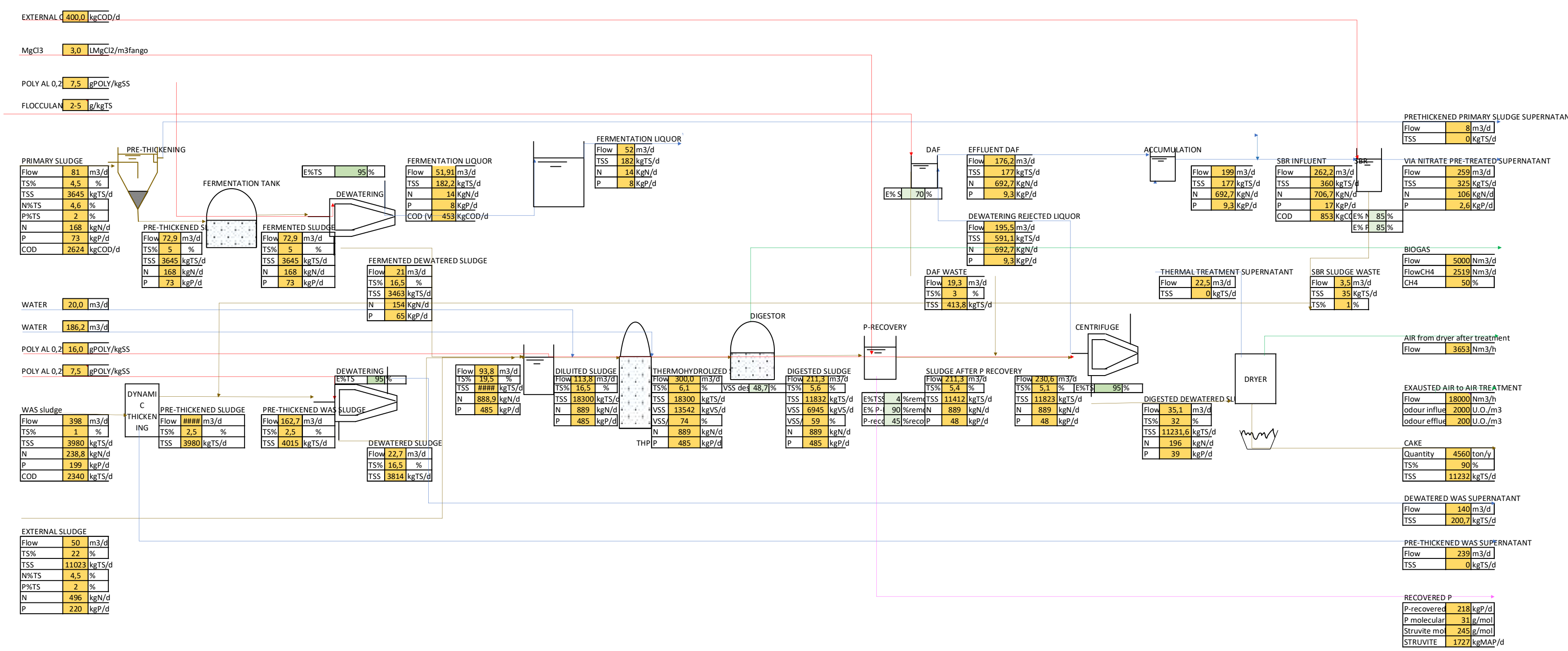


1g Volumetric characteristics of Castelfranco WWTP design – biogas recovery-sludge line

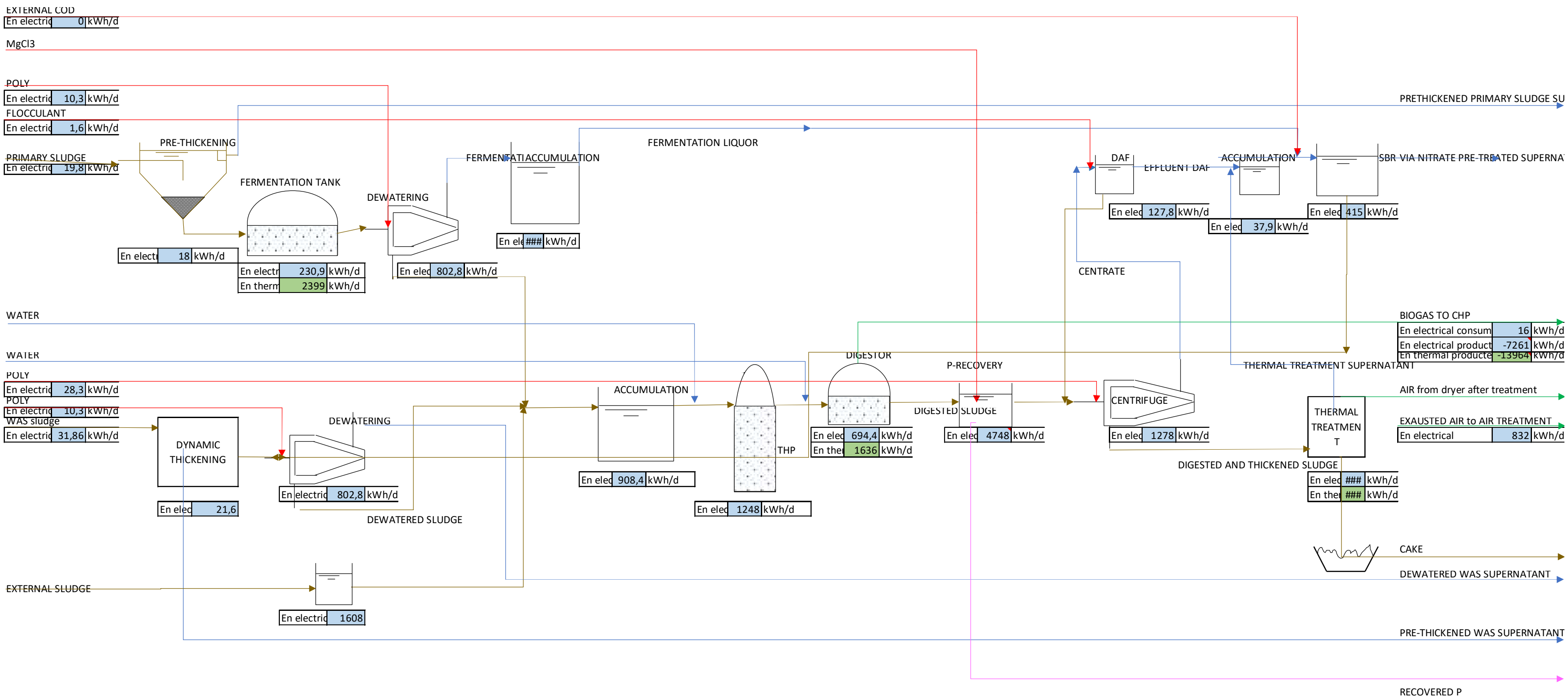


1 h Mass balance of Castelfranco WWTP design- biogas recovery-sludge line

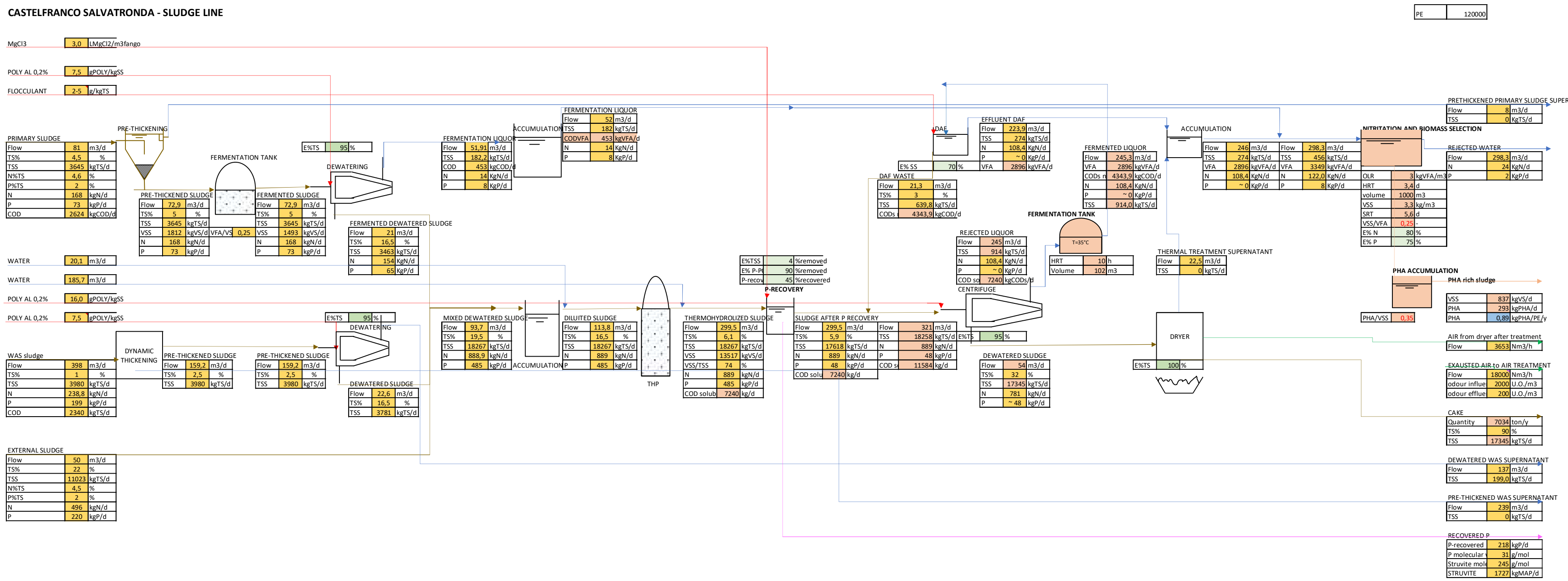
CASTELFRANCO SALVATRONDA - SLUDGE LINE



1i Energy balance of Castelfranco WWTP design- biogas recovery-sludge line

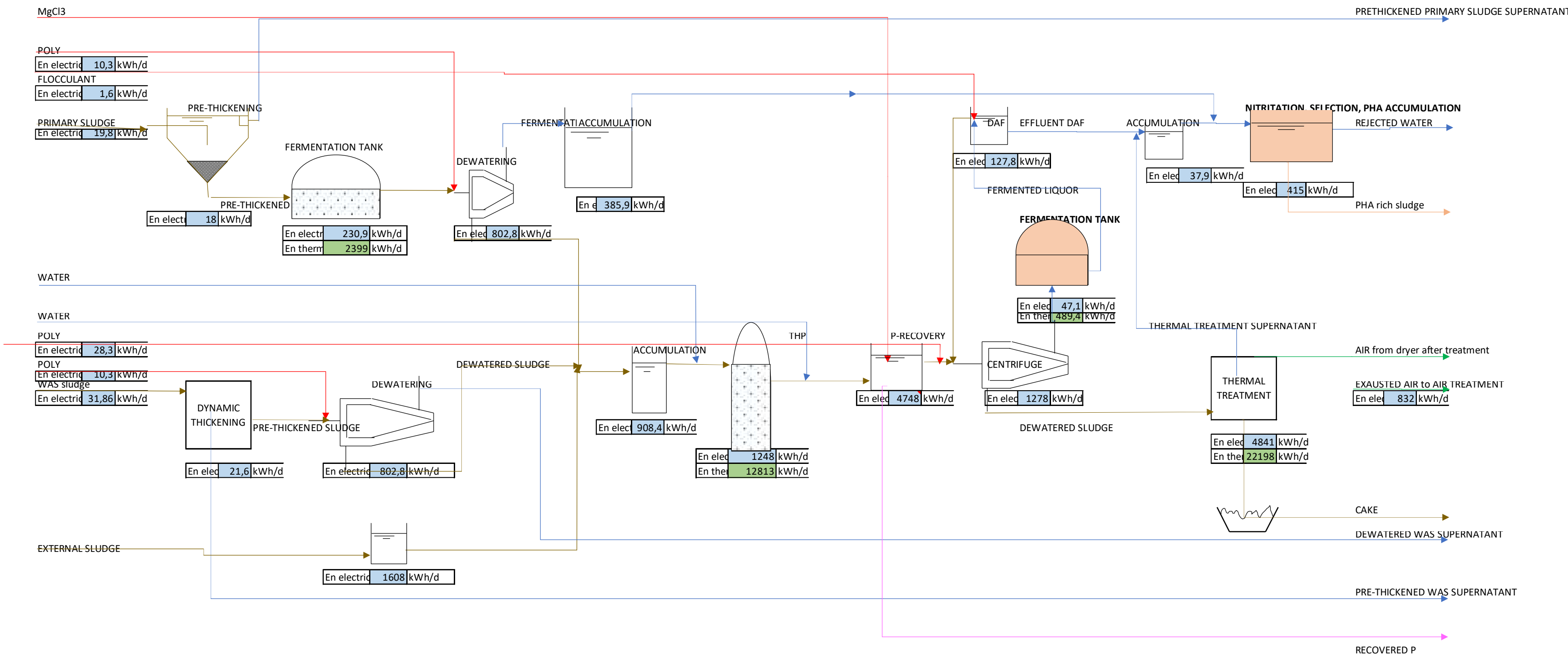


1l Mass balance of Castelfranco WWTP design- PHA recovery-sludge line



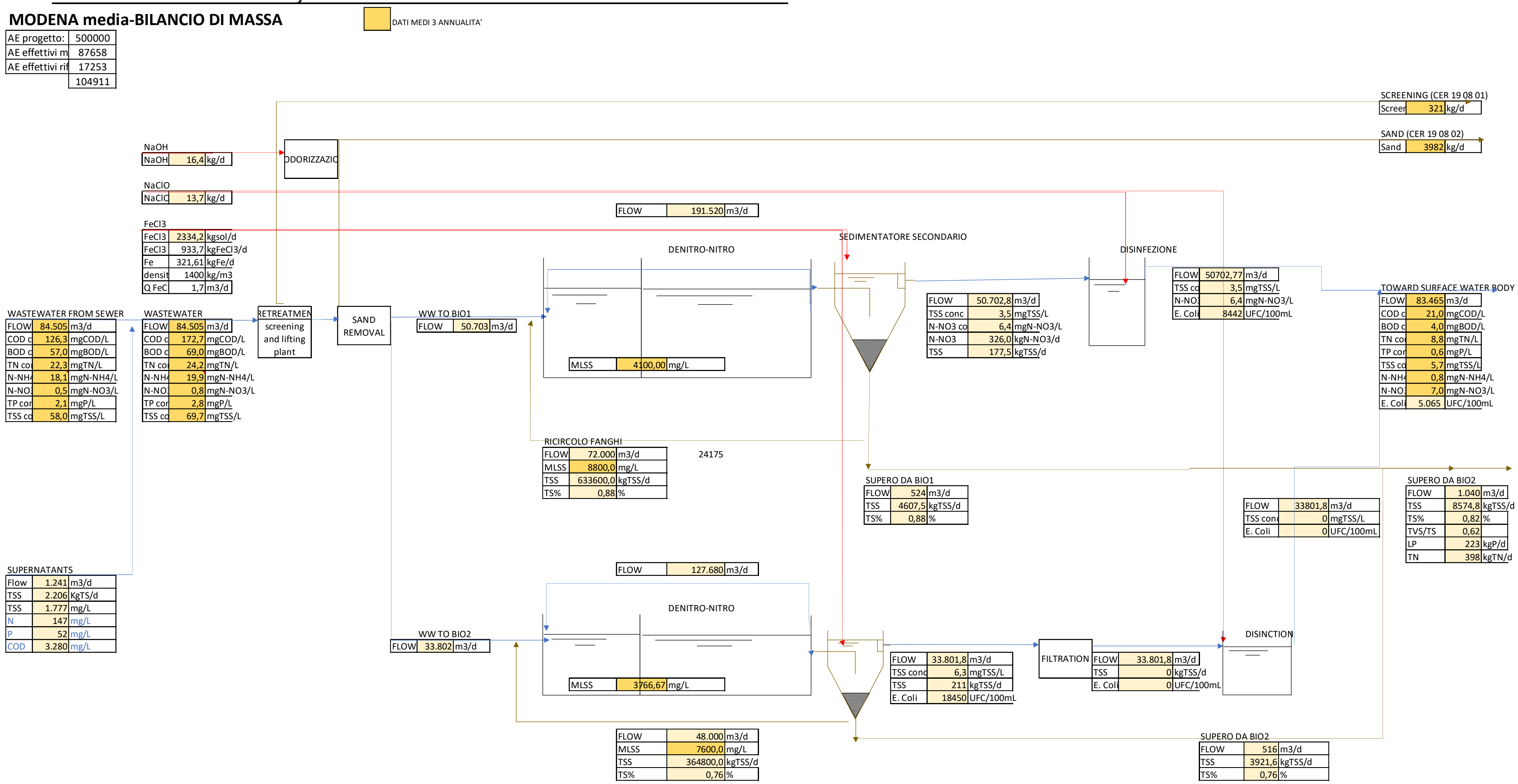
1m Energy balance of Castelfranco WWTP design- PHA recovery-sludge line

CASTELFRANCO SALVATRONDA - SLUDGE LINE

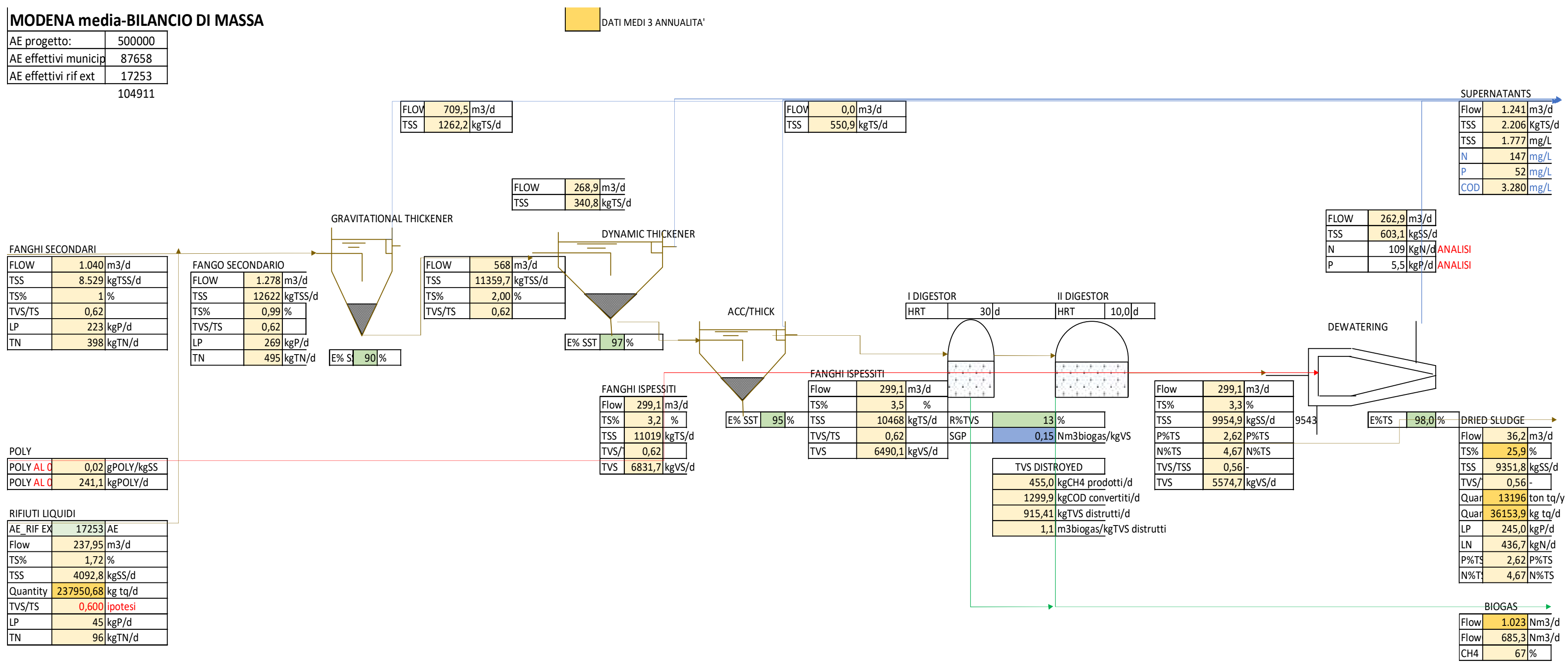


2a Mass balance of Modena WWTP as it is-WATER LINE

MODENA media-BILANCIO DI MASSA



2b Mass balance of Modena WWTP as it is-SLUDGE LINE



2c Mass balance of Modena WWTP- PHA recovery 1

MODENA-MASS BALANCE PHA_case1:fermentation biological sludge

SECONDARY SLUDGE

FLOW	1.041	m3/d
TSS	8536,7	kgTSS/d
TS%	0,82	%
TVS/TS	0,62	
TN	399	kgTN/d
LP	224	kgP/d
N%TS	4,7	%
P%TS	2,6	%

DYNAMIC THICKENER

E% SST	97	%

SUPERNATANT

FLOW	804	m3/d
TSS	256	kgTSS/d

THICKENED SLUDGE

Flow	236,6	m3/d
TS%	3,5	%
TSS	8281	kgTS/d
TVS/TS	0,62	
TVS	5134,0	kgVS/d
TN	387	kgTN/d
LP	217	kgP/d
N%TS	4,7	%
P%TS	2,6	%

FERMENTER

T=35°C

HRTmi	5	d
Vmin	1183	m3
HRTme	8	d
Vmedi	1893	m3
HRTma	10	d
Vmax	2366	m3
resa fe	0,26	gCODVFA/gVS

FANGHI FERMENTATI

FLOW	237	m3/d
TSS	8280,64	kgTSS/d
TVS	4209,88	kgTVS/d
VFA	1312,25	kgCODVFA/d
N	387	kgTN/d
P	217	kgP/d
TVS/TS	0,5084	
N%TS	4,7	%
P%TS	2,6	%

GRAVITATION THICKENER

E% SST	95,0	%

Flow	196,7	m3/d
TS%	4,0	%
TSS	7866,6	kgTS/d
TVS	3999,4	kgVS/d
TVS/TS	0,5084	
N	367	kgTN/d
P	206	kgP/d
N%TS	4,7	%
P%TS	2,6	%

SUPERNATANT

Q	39,92	m3/d
Conc T	10.370	mg/L
TSS	414	kgTSS/d
VFA	1312	kgCODVFA/d
N	19	kgTN/d
P	11	kgP/d

LIQUID WASTES

Flow	237,95	m3/d
TS%	1,72	%
TSS	4092,8	kgSS/d
Quantity	237950,7	kg tq/d
TVS/TS	0,600	ipotesi
VSS	2456	kgVSS/d
TN	96	kgTN/d
LP	45	kgP/d

DIGESTORE

Flow	434,6	m3/d
TS%	2,8	%
TSS	11959,4	kgTS/d
TVS/TS	0,54	
TVS	6455,0	kgVS/d
N	464	kgTN/d
P	251	kgP/d
N%TS	3,9	%
P%TS	2,1	%

SGP	0,15	Nm3/kgV

TVS DISTRUTTI IN	
429,9	kgCH4 prodotti/d
1228,2	kgCOD convertiti/d
864,9	kgTVS distrutti/d
1,1	m3biogas/kgTVS distrutti

Flow	434,6	m3/d
TS%	2,1	%
TSS	9316,8	kgTS/d
TVS/TS	0,60	
TVS	5590,1	kgVS/d
N	464	kgTN/d
P	251	kgP/d
N%TS	5,0	%
P%TS	2,7	%

Q	438,93	m3/d
TSS	507	kgTSS/d
VFA	1312	kgCODVFA/d
N	185	kgTN/d
P	19	kgP/d

BIOMASS SELECTION AND NITRITATION

OLR	0,66	kgVFA/m3/d
HRT	4,6	d
volume	2.000	m3
VSS	3,3	kg/m3
SRT	5,6	d
VSS/CO	0,16	-
E% N	80	%
E% P	75	%

PHA ACCUMULATION

PHA/VSS	0,66	gPHA/gVSS

BIOGAS

Flow CH4	647,5	Nm3/d
Flow biog	966,4	Nm3/d
CH4	67	%
CH4	2,25	m3CH4/AE/

REJECTED WATER

Flow	1242,9	m3/d
N	36,9	kg/d
P	4,8	kg/d
N conc	29,7	mg/l
P conc	3,9	mg/l

PHA rich sludge

VSS	213	kgVS/d
PHA	141	kgPHA/d
PHA	0,59	kgPHA/AE/y

ANAEROBIC SUPERNATANT

Flow	399,0	m3/d		
TSS	93,2	kgTS/d		
N	165,2	kgN/d	ANALIS	5
P	8,4	kgP/d	ANALIS	3

DEWATERING

E% SST	99,0	%

SLUDGE PRODUCED

Flow	35,6	m3/d
TS%	25,9	%
TSS	9223,7	kgTS/d
TVS/TS	0,60	
TVS	5534,2	kgVS/d
N	459	kgTN/d
P	249	kgP/d
N%TS	5,0	%
P%TS	2,7	%

2d Mass balance of Modena WWTP- PHA recovery 2

MODENA -MASS BALANCE PHA_case 2:fermentation on biologic + external sludge

WAS SLUDGE

FLOW	1.041	m3/d
TSS	8536,7	kgTSS/d
TS%	0,82	%
TVS/TS	0,62	
TN	399	kgTN/d
LP	224	kgP/d
N%TS	4,7	%
P%TS	2,6	%

LIQUID WASTES

Flow	237,95	m3/d
TS%	1,72	%
TSS	4092,8	kgSS/d
Quanti	237950,68	kg tq/d
TVS/TS	0,600	ipotesi
VSS	2456	kgVSS/d
TN	96	kgTN/d
LP	45	kgP/d
N	405	mg/L
P	190	mg/L
TSS	17200	mg/L

FLOW	1.279	m3/d
TSS	12629,5	kgTSS/d
TS%	0,99	%
TVS/TS	0,62	
TN	495	kgTN/d
LP	269	kgP/d
N%TS	3,9	%
P%TS	2,1	%

DYNAMIC THICKENER

E% SST	97	%

SURNATANTE

FLOW	929	m3/d
TSS	379	kgTSS/d

FANGHI ISPESSITI

Flow	350,0	m3/d
TS%	3,5	%
TSS	12251	kgTS/d
TVS/TS	0,62	
TVS	7595,4	kgVS/d
TN	480	kgTN/d
LP	261	kgP/d
N%TS	3,9	%
P%TS	2,1	%

FERMENTER

T=35°C

HRTmi	5	d
Vmin	1750	m3
HRTme	8	d
Vmedi	2800	m3
HRTma	10	d
Vmax	3500	m3
resa fe	0,28	gCODVFA/gVS

FERMENTED SLUDGE

FLOW	350	m3/d
TSS	12250,6	kgTSS/d
TVS	6091,5	kgTVS/d
VFA	2135,5	kgCOD
N	480	kgTN/d
P	261	kgP/d
TVS/TSS	0,50	
N%TS	3,9	%
P%TS	2,1	%

STATIC THICKENER

E% SST	95,0	%

Flow	291,0	m3/d
TS%	4,0	%
TSS	11638,1	kgTS/d
TVS	5786,9	kgVS/d
TVS/TS	0,49724	
N	456	kgTN/d
P	248	kgP/d
N%TS	3,9	%
P%TS	2,1	%

SUPERNATANT FROM ACCUMULATION + THICKENER

Q	59,07	m3/d
Conc T	10.370	mg/L
TSS	613	kgTSS/d
VFA	2136	kgCODVFA/d
N	24	kgTN/d
P	13	kgP/d

DIGESTOR

Flow	291,0	m3/d
TS%	4,0	%
TSS	11638,1	kgTS/d
TVS/TS	0,50	
TVS	5786,9	kgVS/d
N	456	kgTN/d
P	248	kgP/d
N%TS	3,9	%
P%TS	2,1	%

SGP	0,15	Nm3/kg

TVS DISTRUTTI IN	
385,4	kgCH4 prodotti/d
1101,1	kgCOD convertiti/d
775,4	kgTVS distrutti/d
1,1	m3biogas/kgTVS distrutti

Flow	291,0	m3/d
TS%	2,9	%
TSS	8352,5	kgTS/d
TVS/TS	0,60	
TVS	5011,5	kgVS/d
N	456	kgTN/d
P	248	kgP/d
N%TS	5,5	%
P%TS	3,0	%

BIOGAS

Flow CH4	580,5	Nm3/d
Flow biog	866,4	Nm3/d
CH4	67	%
CH4	2,02	m3CH4/AE/y

Q	318,09	m3/d
TSS	696	kgTSS/d
VFA	2136	kgCODVFA/d
N	131	kgTN/d
P	18	kgP/d

BIOMASS SELECTION AND NITRITATION

OLR	1,07	kgVFA/m3/d
HRT	6,3	d
volume	2.000	m3
VSS	3,3	kg/m3
SRT	5,6	d
VSS/CO	0,35	-
E% N	80	%
E% P	75	%

PHA ACCUMULATION

PHA/VSS	0,71	gPHA/gVSS

REJECTED WATER

Flow	1246,6	m3/d
N	26,2	kg/d
P	4,6	kg/d
N conc	21,1	mg/l
P conc	3,7	mg/l

PHA rich sludge

VSS	737	kgVS/d
PHA	524	kgPHA/d
PHA	1,82	kgPHA/AE/y

DEWATERING

E% SST	99,0	%

ANAEROBIC SUPERNATANT

Flow	259,0	m3/d		
TSS	83,5	kgTS/d		
N	107,2	kgN/d	ANALISI	5
P	5,4	kgP/d	ANALISI	2

SLUDGE PRODUCED

Flow	31,9	m3/d
TS%	25,9	%
TSS	8269,0	kgTS/d
TVS/TS	0,60	
TVS	4961,4	kgVS/d
N	452	kgTN/d
P	245	kgP/d
N%TS	5,5	%
P%TS	3,0	%

3a Mass balance of Castiglione WWTP as it is-WATER LINE

WATER LINE CASTIGLIONE - MASS BALANCE

AE progetto: 3.840.000

AE serviti: 2.000.000

PRETREATMENT: screening

SAND and OIL REMOVAL

WASTEWATER + LIQUID WASTES (IMHOFF)

FLOW	564239	m3/d
COD conc	420	mgCOD/L
BOD conc	217	mgBOD/L
TN conc	34	mgTN/L
N-NH4 conc	21	mgN-NH4/L
TP conc	4	mgP/L
TSS conc	216	mgTSS/L
COD	237008	kg COD/d
BOD	122547	kg BOD/d
TN	18902	kgTN/d
N-NH4	12041	kgN-NH4/d
TP	2347	kgP/d
TSS	122079	kgTSS/d
AE COD	1975070	
AE N	1575166	

FLOW	596301,0	m3/d
COD	288820,4	kg COD/d
BOD5	122547,0	kg COD/d
TN	19914,5	kgTN/d
N-NH4	12040,9	kgTN/d
TP	2529,3	kgP/d
TSS	183394,7	kgTSS/d

WATER TO MODULES 1, 2, 3

76 % of flowrate

FLOW	451399,9	m3/d
COD	218637,0	kg COD/d
BOD	92768,1	kg COD/d
TN	15075,3	kgTN/d
N-N	9114,9	kgTN/d
TP	1914,7	kgP/d
TSS	138829,8	kgTSS/d

I SETTING

HRT cad	2,4	h
n° sed I	6	
E%TS	58	%
E%BOD	36	%
E%COD	46	%
E%N	16	%
E%P	10	%

FANGO PRIMARIO

FLOW	5392,1	m3/d
COD	100336,5	kg COD/d
BOD	33617,8	kg BOD/d
TN	2426,4	kgTN/d
TP	191,5	kgP/d
TSS	80881,6	kgTSS/d
TS%	1,5	%
N%TS	3,0	%
P%TS	0,2	%

EFFLUENT FROM I CLARIFIERS MOD1,2,3

FLOW	446007,7	m3/d
COD	118.301	kg COD/d
BOD	59.150	kg BOD/d
TN	12.649	kgTN/d
TP	1.723	kgP/d
TSS	57.948	kgTSS/d

ANOX — AE

MLSS	4957	mg/L
Vbiologi	238248	m3

Qma	792000,0	m3/d

E%COD	86,1	%
E%TN	60,1	%
E%P	70,1	%
E%TSS	84,0	%

FLOW	576000,0	m3/d
MLSS	7460	mg/L
TS%	0,746	%

II SETTLING

FEFFLUENT FROM SECONDARY SED. MOD1, 2, 3

FLOW	598904,6	m3/d	FLOW	741172,7	m3/d
COD	16.416	kg COD/d	COD	20.378	kg COD/d
TN	5.049	kgTN/d	TN	6.773	kgTN/d
N-NH4	491	kgN-NH4/	N-NH4	848	kgN-NH4/d
N-NO2	42	kgN-NH4/	N-NO2	63	kgN-No2/d
N-NO3	2.569	kgN-NH4/	N-NO3	3.784	kgN-No3/d
TP	515	kgP/d	TP	734	kgP/d
TSS	9.295	kgTSS/d	TSS	11.503	kgTSS/d

BIOLOGICAL SLUDGE MODULES 1,2,3

FLOW	4.197	m3/d	3671
MLSS	7460,0	mg/L	
TSS	31309,6	kgTSS/d	31403
TS%	0,746	%	
SRT	38	d	30

BYPASS FILTRATION

FLOW	377332,7	m3/d
COD	10.375	kg COD/d
TN	3.448	kgTN/d
N-NH4	432	kgN-NH4/d
N-NO2	32	kgN-NH4/d
N-NO3	1.927	kgN-NH4/d
TP	374	kgP/d
TSS	5.856	kgTSS/d

TO FILTRATION

FLOW	363840,0	m3/d
COD	10.004	kg COD/d
TN	3.325	kgTN/d
N-NH4	416	kgN-NH4/d
N-NO2	31	kgN-NH4/d
N-NO3	1.858	kgN-NH4/d
TP	360	kgP/d
TSS	5.647	kgTSS/d

FINAL FILTRATION

CHLORINATION TO REUSE IN DRINKING WATER LINE

I SLUDGE TOWARD SLUDGE LINE

FLOW	7141	m3/d
TSS	107111	kgTSS/d
TS%	1,50	%
TVS	77119,9	kgTVS/d
TVS/TS	0,7	
N%TS	3,0	%
P%TS	0,2	%
TN	3213,3	kgTN/d
TP	253,6	kgTP/d

TOWARD WATER BODY

FLOW	726425,3	m3/d
COD conc	18,9	mgCOD/L
BOD conc	5,0	mgBOD/L
TN conc	7,9	mgTN/L
N-NH4 conc	1,2	mgN-NH4/L
TP conc	0,8	mgP/L
TSS conc	5,4	mgTSS/L
COD	13722,2	kg COD/d
BOD	3610,3	kg BOD/d
TN	5760,6	kgTN/d
N-NH4	871,7	kgN-NH4/d
TP	552,1	kgP/d
TSS	3886,4	kgTSS/d

RETURN FLUSH WATER

FLOW	14747,5	m3/d
COD	6656,0	kg COD/d
TN	1012,5	kgTN/d
TP	182,1	kgP/d
TSS	7616,6	kgTSS/d

SUPERNTANT FROM THICKENING

FLOW surn	17315	m3/d
COD	45156	kg COD/d
TSS surn	53000	kgTSS/d
COD	2608	mg COD/l
TSS surn	3061	mg TSS/l

RETURN FLUSH FROM SAND FILTRATION

FLOW ritorno filt	14747	m3/d
TSS ritorno filtro	8316	kgTSS/d
COD	6656	kgCOD/d
N	1013	kgN/d
P	182	kgP/d
TSS ritorno filtro	564	mgSS/L
COD	451	mgCOD/l

SUPERNATANT FROM DEWATERING

FLOW	1146	m3/d
COD	674	kg COD/d
BOD5	182	kg BOD5/d
TN	535	kgTN/d
TP	53	kgP/d
TSS	353	kgTSS/d

FeCl3 al 40%

FeCl3 40%	14.175	kgsol/d
FeCl3	5.670	kgFeCL3/d
Fe	1953,0	kgFe/d
density FeCl3 40%	1400	kg/m3
Q FeCl3 40%	10,1	m3/d

WATER TO MODULES 4

24,30 % of flowrate

FLOW	146047	m3/d
COD	70857	kg COD/d
BOD5	29961	kg COD/d
TN	5374	kgTN/d
N-NH4	2926	kgTN/d
TP	667	kgP/d
TSS	44918	kgTSS/d

I SETTING

HRT cad	2,4	h
n° sed I	2	
E%TS	58	%
E%BOD	36	%
E%COD	46	%
E%N	15	%
E%P	10	%

EFFLUENT FROM I CLARIFIERS MOD4

FLOW	144298,1	m3/d
COD	38132	kg COD/d
BOD	19066	kg COD/d
TN	4587	kgTN/d
TP	601	kgP/d
TSS	18688	kgTSS/d

PRIMARY SUDGE

FLOW	1748,6	m3/d
BOD	10.895	kg BOD/d
COD	21789,7	kg COD/d
TN	787	kgTN/d
TP	67	kgP/d
TSS	26229	kgSS/d
TS%	1,5	%

E%COD	89,6	%
E%TN	62,4	%
E%P	63,5	%
E%TSS	88,2	%

ANOX — OX — ANOX — OX — ANOX — OX

MLSS	6050,00	mg/L
Vbiologico	88560	m3

FLOW	192000	m3/d
MLSS	8540	mg/L
TS%	0,85	%

II SETTLING

FEFFLUENT FROM SECONDARY SED. MOD4

FLOW	142268,1	m3/d
COD	3.962	kg COD/d
TN	1.724	kgTN/d
N-NH4	357	kgN-NH4/d
N-NO2	21	kgN-No2/d
N-NO3	1.215	kgN-No3/d
TP	219	kgP/d
TSS	2.208	kgTSS/d

BIOLOGICAL SLUDGE MOD 4

FLOW	2.030	m3/d
MLSS	8540,0	mg/L
TSS	17336	kgTSS/d
TS%	0,85	%
SRT	31	d

ACTIVATED SLUDGE TOWARD SLUDGE LNE

FLOW	6227,0	m3/d
TSS	48645,8	kgTSS/d
TS%	0,78	%
TV/TS	0,72	
N%TS	4,50	ipotesi
P%TS	1,50	ipotesi
TN	2189,1	kgTN/d
TP	729,7	kgTP/d

SAND (CER 19 08 02)

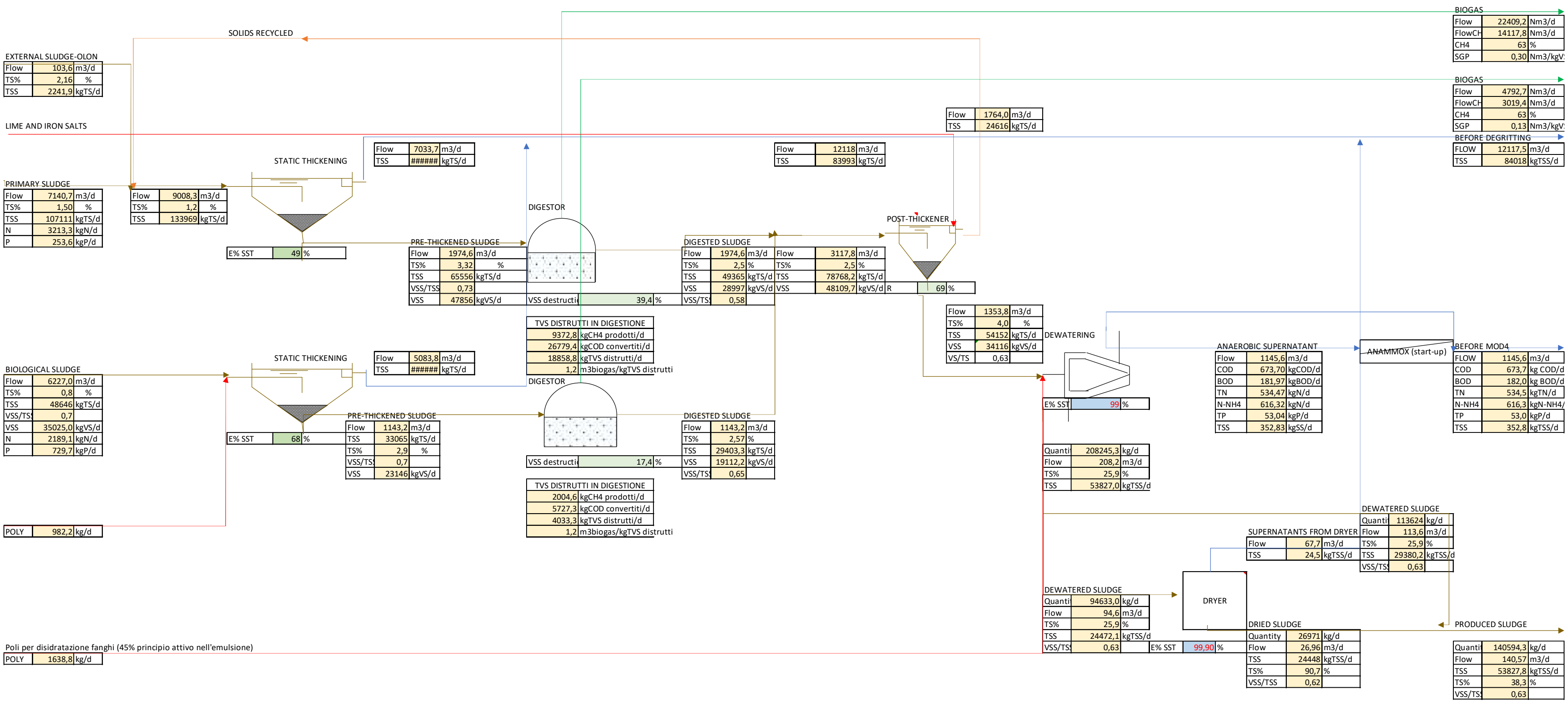
SCREENING (CER 19 08 01)

3b Mass balance of Castiglione WWTP as it is-SLUDGE LINE

SLUDGE LINE CASTIGLIONE-SLUDGE LINE

AE progetto: 3.840.000

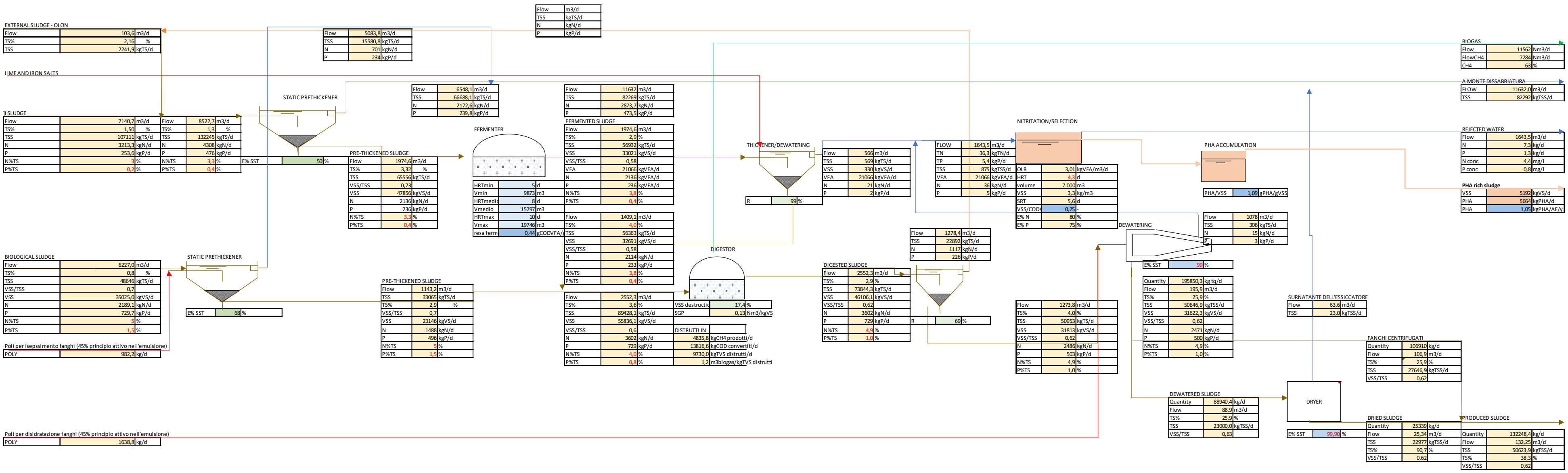
AE serviti: 2.000.000



3c Mass balance of Castiglione WWTP- PHA recovery 1

SLUDGE LINE CASTIGLIONE-CASE1 PHA RECOVERY

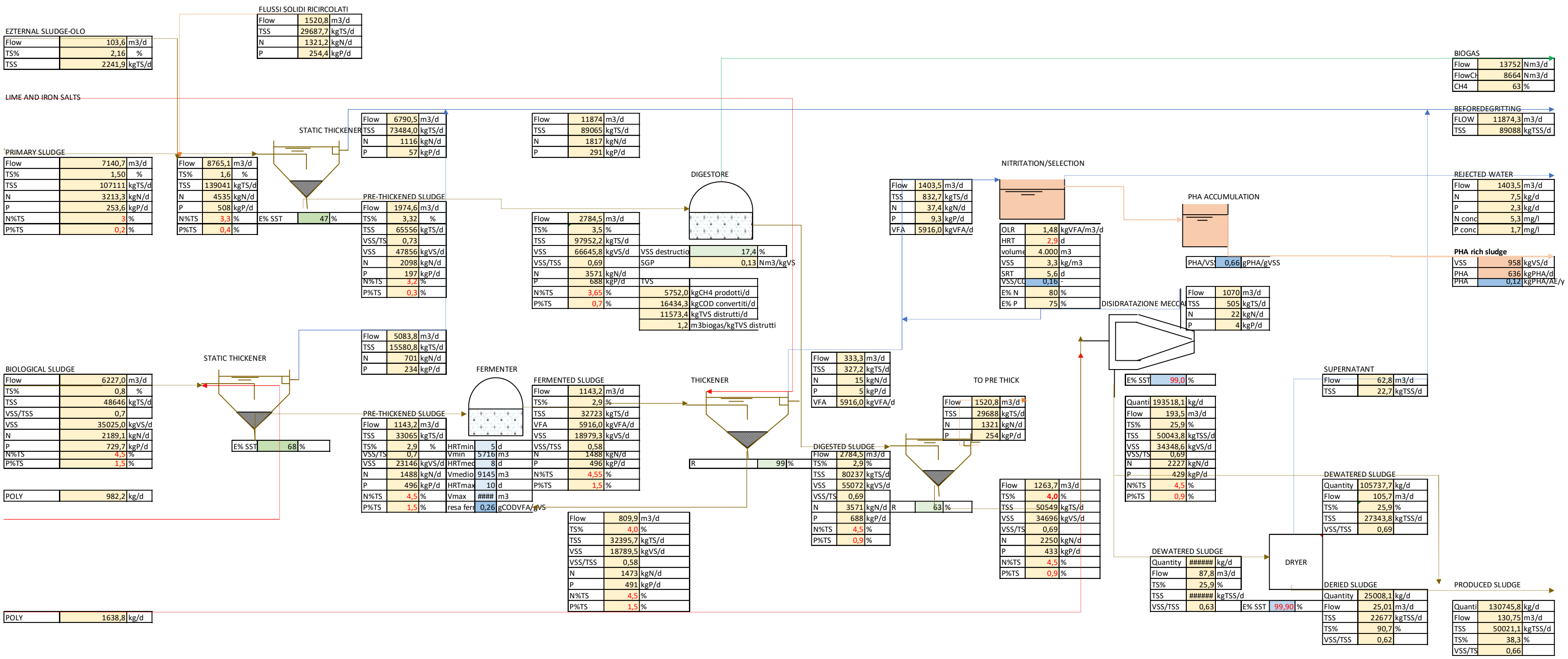
AE progett	3.840.000
AE serviti:	2.000.000



3d Mass balance of Castiglione WWTP- PHA recovery 2

SLUDGE LINE CASTIGLIONE-CASE 2 PHA RECOVERY

AE progetto	3.840.000
AE serviti:	2.000.000



3e Mass balance of Castiglione WWTP- PHA recovery 3

SLUDGE LIINE CASTIGLIONE-CASE3- PHA RECOVERY

AE pr	3.840.000	
AE se	1.975.070	base COD

FLUSSI SOLIDI RICIRCOLATI

Flow	596,9	m3/d
TSS	14229,1	kgTS/d
N	1140,7	kgN/d
P	232,7	kgP/d

EXTERNAL SLUDGE-OLON

Flow	103,6	m3/d
TS%	2,16	%
TSS	2241,9	kgTS/d

LIME+IRON SALTS

PRIAMTY SLUDGE

Flow	7140,7	m3/d
TS%	1,50	%
TSS	107111	kgTS/d
N	3213,3	kgN/d
P	253,6	kgP/d
N%TS	3	%
P%TS	0,2	%

Flow	7841,2	m3/d
TS%	1,6	%
TSS	123582	kgTS/d
N	4354,0	kgN/d
P	486,3	kgP/d
N%TS	3,5	%
P%TS	0,4	%

STATIC PRETHICKENING

E% SST	53	%

Flow	5866,6	m3/d
TSS	######	kgTS/d
N	2125,1	kgN/d
P	224,0	kgP/d

PRE-THICKENED SLUDGE

Flow	1974,6	m3/d
TS%	3,32	%
TSS	65556	kgTS/d
VSS/TSS	0,73	
VSS	47856	kgVS/d
N	2229	kgN/d
P	262	kgP/d
N%TS	3,4	%
P%TS	0,4	%

PRE-THICKENED SLUDGE

Flow	3117,8	m3/d
TSS	98621	kgTS/d
TS%	3,2	%
VSS/TSS	0,7	
VSS	71002	kgVS/d
N	3717	kgN/d
P	758	kgP/d
N%TS	3,8	%
P%TS	0,8	%

FERMENTER

HRTmi	5	d
Vmin	15589	m3
HRTme	8	d
Vmedi	24942	m3
HRTma	10	d
Vmax	31178	m3
resa fe	0,45	gCODVFA/gVS

Flow	10950	m3/d
TSS	73606	kgTS/d
N	2826,2	kgN/d
P	457,7	kgP/d

FERMENTED SLUDGE

Flow	3117,8	m3/d
TS%	1,8	%
TSS	56107	kgTS/d
VSS	32542	kgVS/d
VSS/TSS	0,58	
VFA	21746	kgVFA/d
N	3717	kgN/d
P	758	kgP/d
N%TS	6,6	%
P%TS	1,4	%

THICKENER

R	99	

Flow	1729	m3/d
TSS	561	kgTS/d
VSS	325	kgVS/d
VFA	21746	kgVFA/d
N	37	kgN/d
P	8	kgP/d

FLOW	2399,2	m3/d
TN	52,4	kgTN/d
TP	10,7	kgP/d
TSS	751	kgTSS/d
VFA	21746	kgVFA/d
N	52	kgN/d
P	11	kgP/d

NITRITATION/SELECTION

OLR	3,11	kgVFA/m3/d
HRT	2,9	d
volume	7.000	m3
VSS	3,3	kg/m3
SRT	5,6	d
VSS/COD	0,11	-
E% N	80	%
E% P	75	%

PHA ACCUMULATION

PHA/VSS	1,07	gPHA/gVSS

BIOGAS

Flow	6647,9	Nm3/d
FlowCH	4188,2	Nm3/d
CH4	63	%

A MONTE DISSABBIATURA

FLOW	10950,4	m3/d
TSS	73621	kgTSS/d

REJECTED WATER

Flow	2399,2	m3/d
N	10,5	kg/d
P	2,7	kg/d
N conc	4,4	mg/l
P conc	1,1	mg/l

PHA rich sludge

VSS	2450	kgVS/d
PHA	2615	kgPHA/d
PHA	0,48	kgPHA/AE/y

Flow	5083,8	m3/d
TSS	15580,8	kgTS/d
N	701	kgN/d
P	234	kgP/d

BIOLOGICAL SLUDGE

Flow	6227,0	m3/d
TS%	0,8	%
TSS	48646	kgTS/d
VSS/TS	0,7	
VSS	35025,0	kgVS/d
N	2189,1	kgN/d
P	729,7	kgP/d
N%TS	5	%
P%TS	1,5	%

POLY	982,2	kg/d

STATIC PRETHICKEN

E% SST	68	%

PRE-THICKENED SLUDGE

Flow	1143,2	m3/d
TSS	33065	kgTS/d
TS%	2,9	%
VSS/TSS	0,7	
VSS	23146	kgVS/d
N	1488	kgN/d
P	496	kgP/d
N%TS	5	%
P%TS	1,5	%

POLY	1638,8	kg/d

Flow	1388,7	m3/d
TS%	4,0	%
TSS	55546	kgTS/d
VSS	32217	kgVS/d
VSS/TSS	0,6	
N	3680	kgN/d
P	751	kgP/d
N%TS	6,6	%
P%TS	1,4	%

DIGESTOR

VSS destru	17,4	%
SGP	0,13	Nm3/k

TVS	
2780,5	kgCH4 prodotti/d
7944,4	kgCOD convertiti/d
5594,6	kgTVS distrutti/d
1,2	m3biogas/kgTVS distrutti

DIGESTED SLUDGE

Flow	1388,7	m3/d
TS%	3,3	%
TSS	45900,3	kgTS/d
VSS	26622,2	kgVS/d
VSS/TS	0,58	
N	3680	kgN/d
P	751	kgP/d
N%TS	8,0	%
P%TS	1,6	%

R	69	%

TO PRE-THICK

Flow	596,9	m3/d
TSS	14229	kgTS/d
N	1141	kgN/d
P	233	kgP/d

Flow	791,8	m3/d
TS%	4,0	%
TSS	31671	kgTS/d
VSS	18369	kgVS/d
VSS/TS	0,58	
N	2539	kgN/d
P	518	kgP/d
N%TS	8,0	%
P%TS	1,6	%

DEWATERING

Flow	670	m3/d
TSS	190	kgTS/d
N	15	kgN/d
P	3	kgP/d

E% SST	99	%

Quanti	121737,0	kg/d
Flow	121,7	m3/d
TS%	25,9	%
TSS	31481,2	kgTSS/d
VSS	18259,1	kgVS/d
VSS/TS	0,58	
N	2524	kgN/d
P	515	kgP/d
N%TS	8,0	%
P%TS	1,6	%

DEWATERED SLUDGE

Quanti	66439,2	kg/d
Flow	66,4	m3/d
TS%	25,9	%
TSS	17181,2	kgTSS/d
VSS/TS	0,58	

DRIER SUPERNATANT

Flow	39,5	m3/d
TSS	14,3	kgTSS/d

DEWATERED SLUDGE

Quantity	55297,8	kg/d
Flow	55,3	m3/d
TS%	25,9	%
TSS	14300,0	kgTSS/d
VSS/TSS	0,63	

DRYER

E% SST	99,90	%

DRIED SUPERNATANT

Quantity	15754,0	kg/d
Flow	15,75	m3/d
TSS	14286	kgTSS/d
TS%	90,7	%
VSS/TSS	0,62	

PRODUCED SLUDGE

Quanti	82193,2	kg/d
Flow	82,19	m3/d
TSS	31466,9	kgTSS/d
TS%	38,3	%
VSS/TS	0,60	

4a Life cycle Inventory- Castelfranco WWTP as it is

	Castelfranco WWTP		LIFE CYCLE INVENTORY											
	AS IT IS													
			Quantity by	Water line				Liquid Waste Line	Sludge line		79430 PE not collected	External sludge	Composting system	
Functional unit	m3/y effluent wastewate	4499750,0		stage 1	stage 2	stage 3	stage 4	Stage 1	stage 1	stage 2	Stage 1	Stage 2	Stage 1	
			Unit	Pumping at WWTP, screening, sand and oil removal	primary sedimentation	Activated Sludge Process (AN-OX)+ Secondary clarifier	(FILTRATION)+UV Disinfection and discharge in river	Screening, grit removal (Accumulation tank) Oxidation tank	Dynamic thickening	Sludge Dewatering	Wastes not collected (Imhoff)	External sludge from other plants	Composting plant	Notes
Input														
INFLUENT	Wastewater		m3/y	0,999	1,00	1,018	1	0,002			6453200,000			
	Supernatant from thickener		m3/y	0,011										
	Supernatant from dewatering		m3/y	0,012										
	Sludge TQ		kgTQ/m3					2,013	23,50	12,98		18288000,0000	5,4	
	COD		kgCOD/m3	0,395	0,395	0,256	0,020	0,027			3479034,0000			
	BOD		kgBOD/m3	0,194	0,194	0,126	0,005							
	TSS		kgTSS/m3	0,216	0,275	0,090	0,005	0,024	0,315	0,2698	20294365,0000	3291840,0000		
	TN		kgN/m3	0,042	0,042	0,035	0,007	0,00085			347903,4000		0,0115	
	TP		kgP/m3	0,006	0,006	0,004	0,000	0,00020			4289,22000		0,0038	
	E.Coli (water emission)		UFC/100ml	5050769	5050769									
CONSUMED ENERGY	Consumed electricity		kWh/m3	0,0238	0,0050	0,265	0,025	0,007	0,034	0,0250			X	
	Consumed thermal Energy		kWh/m3											
	Consumed Biogas		Sm3/m3											
CHEMICALS	PAC for P removal		kg/m3			0,0467								
	POLY for sludge line		kg/m3							0,001				
CHEMICALS TRANSPORT	PAC for P removal		km (mean			0,035								
	POLY for sludge line		km (mean							0,035				
WASTE TRANSPORT	Sludge 19 08 05 to composting facility		km (mean distance)											
Output														
EFFLUENT	Reclaimed water (water)		m3/y	0,999	1,018	1,000	1,000	0,0020			6453200,0000			
	Sludge TQ		kgTQ/m3						12,97849881	1,35779			X	
	Supernatant to water line		m3/y						0,010520696	0,01162				
	COD		kgCOD/m3	0,395	0,256	0,020	0,0198	0,0034			260904555,0000			
	BOD		kgBOD/m3	0,194	0,126	0,005	0,0051							
	TSS		kgTSS/m3	0,216	0,090	0,005	0,0051	0,001347	0,27	0,256	15220773,7500			
	TN		kgN/m3	0,042	0,035	0,007	0,0074	0,000187		0,0115	347903,4000		0,0077	
	TP		kgP/m3	0,006	0,004	0,0005	0,0005	0,000138		0,0038	43487,92500		0,0036	
	E.Coli (water emission)		UFC/100ml	5050769,2			158,0							
PRODUCTED ENERGY	Biogas produced		Sm3/m3d											
	Thermal energy produced		kWh/m3											
	Produced electricity		kWh/m3											
WASTE	Screenings 19 08 01 (landfill waste disposal)		kg/m3	0,0188										
	Grit 19 08 02(landfill waste disposal)		kg/m3	0,0610										
	Sludge 19 08 05 to composting facility		kg/m3							1,4		18288000,0		
	Waste from Compost facility		kg/m3											
	Sludge to sludge line		kg/m3		3,3	18,2		2,0						
WASTE TRANSPORT	Screenings, (landfill waste disposal)		km (mean distance)	0,054										
	Grit 19 08 02(landfill waste disposal)		km (mean distance)	0,021										
	Sludge 19 08 05 to composting facility		km (mean							0,175		0,165		
	External liquid waste to wwtp		km (mean											
EMISSIONS	GHG Emission to air	CO2eq	kg/m3			0,047	0,1371			0,0	10941000,0		0,029	dissolved GHG in effluent (red value)
	Emission to soil	PO4 (soil emission)	kg/m3										X	
		NO3 (soil emission)	kg/m3										X	
		Suspended solids	kg/m3										X	
		E.Coli (soil	UFC/100ml										X	

4b Life cycle Inventory- Castelfranco WWTP design scenario- PHA recovery

	Castelfranco WWTP		LIFE CYCLE INVENTORY																			
	DESIGN CONFIGURATION																					
			Quantity by	Water line W1				Sludge line (R1)										Disposal Scenario (to be implemented according to				
Functional unit	m3 influent wastewater	11024042,51		stage 1	stage 2	stage 3	stage 4	stage 1	stage 2	stage 3	stage 4	stage 5	stage 6	stage 7	stage 8	stage 9	Stage 10	Stage 1				
			Unit	Pumping at WWTP, screening, sand and oil removal	Dynamic Filtration	Intermittent Aeration (BNR)+ Secondary clarifier	(FILTRATION)+UV Disinfection and discharge in river	Pre-thickening (I+II sludge)	Fermentation (I sludge)	Sludge Dewatering (I+II sludge)	THP (I+II+QExt)	P recovery	Dewatering	Liquid fermentation+ DAF	Nitritation selection and PHA accumulation	Dryer	Air treatement	D1: Composting	D2: Cement	D3: Landfill	D4: Direct Spreading	Notes
Input																						
INFLUENT	Wastewater		m3/m3	0,9933	0,9933	1,0132	1,000							0,0081	0,0099							
	Supernatant from sludge line		m3/m3			0,0226																
	Sludge TQ		kgTQ/m3					15,86	2,4137	7,73	3,77	9,9148	10,62			1,7945		0,6381	0,6381	0,6381	0,6381	
	Air		m3/m3														201830400					
	Oudor Unit		U.O./m3														0,0002					
	COD		kgCOD/m3	0,447	0,447	0,2771	0,0115						0,3835									
	VFA		kgCOD/m3												0,11088							
	BOD		kgBOD/m3	0,271	0,271	0,1695	0,005761															
	TSS		kgTSS/m3	0,241	0,241	0,1207	0,001093	0,252	0,1207	0,2525	0,6081	0,6048	0,6045	0,0303	0,01510	0,5743		0,5743	0,5743	0,5743	0,5743	
	TN		kgN/m3	0,053	0,053	0,0462	0,006787	0,0135	0,0056		0,0294	0,0294	0,0294	0,0036	0,00404	0,0258		0,0258				
	TP		kgP/m3	0,008	0,008	0,0051	0,000430	0,0090	0,0024		0,0161	0,0161	0,0016	0,0000	0,00026	0,0016		0,0016				
	E.Coli (water emission)		UFC/100ml																			
CONSUMED ENERGY	Consumed electricity		kWh/m3	0,0578	0,007	0,251	0,026302	0,0030	0,0076	0,0538	0,1246	0,1572	0,0432	0,0186	0,01500	0,1603	0,0275	0,0369	X			
	Consumed thermal Energy		Mj/m3						0,2859		1,5272			0,05833		2,6459						
	Consumed Biogas		Sm3/m3																			
CHEMICALS	FeCl3 for P removal		kg/m3																			
	External Carbon Source		kg/m3			0,105950245																
	Chemical for pH adjustment		kg/m3												X							
	MgCl3		kg/m3									0,0002										
	POLY for sludge line		kg/m3							0,0019			0,00967	0,00015								
CHEMICAL TRANSPORT	FeCl3 for P removal		ton*km																			
	External Carbon Source		ton*km			0,0350																
	Chemical for pH adjustment		ton*km												X							
	MgCl3		ton*km									0,035										
	POLY for sludge line		ton*km							0,035			0,035	0,035								
WASTE TRANSPORT	Transport of External sludge		ton*km								0,0208							0,1134	X	X	X	
OTHER	Fresh Water		kg/m3								0,6655	6,148										
Output																						
EFFLUENT	Reclaimed water (water)		m3/m3	0,9933	0,9906	1,0000	1,0000							0,0074	0,0099	0,0007						
	Sludge TQ		kgTQ/m3		2,6819			7,6847	2,4137	1,4431	9,9148	9,9148	1,7945	0,7061		0,6381						
	Air		m3/m3	2628000	3679200			9460800					2102400		26280000	157680000	201830400					
	Oudor Unit		U.O./m3														0,00002					
	COD		kgCOD/m3	0,447	0,3	0,011489	0,011489				0,2397	0,240										
	VFA		kgCOD/m3											0,0959								
	BOD		kgBOD/m3	0,271	0,2	0,005761	0,005728															
	TSS		kgTSS/m3	0,241	0,1	0,001093	0,001093	0,2525	0,1207	0,240	0,608	0,583	0,5743	0,009072		0,5743						
	TN		kgN/m3	0,053	0,05	0,006787	0,006787	0,0115	0,0056		0,0294	0,0294	0,0258	0,003589	0,000795	0,0258		0,0173				
	TP		kgP/m3	0,008	0,01	0,000430	0,000430	0,0051	0,0024		0,0161	0,0016	0,0016	0,000000	0,000066	0,0016		0,0015				
	E.Coli (water emission)		UFC/100ml				5000,00000															
PRODUCT RECOVERY	PHA		kg/m3												0,009701							
	P		kg/m3									0,0072										
PRODUCTED ENERGY	Biogas produced		Sm3/m3																			
	Thermal energy produced		kWh/m3																			
	Produced electricity		kWh/m3																			
WASTE	Screenings 19 08 01 (landfill waste disposal)		kg/m3	0,0224																		
	Grit 19 08 02(landfill waste disposal)		kg/m3	0,0733																		
	Sludge 19 08 05 to (D1 or D2 or D3 or D4)		kg/m3													0,6381		X	X	X		
	Sludge to sludge line		kg/m3		2,68187	13,17756																
WASTE TRANSPORT	Screenings, (landfill waste disposal)		ton*km	0,0537																		
	Grit 19 08 02(landfill waste disposal)		ton*km	0,0219																		
	Sludge 19 08 05 to (D1 or D2 or D3 or D4)		ton*km													0,1134						
EMISSIONS	GHG Emission to air	CO2eq	kg/m3			0,05443	0,16328						0,0003		0,5033	0,0024	0,0094	0,047623	X	X	X	dissolved GHG in effluent (red value)
	Emission to soil	PO4 (soil emission)	kg/m3																			
		NO3 (soil emission)	kg/m3																			
		Suspended solids (soil	kg/m3																			
		E.Coli (soil emission)	UFC/100ml																			

7. References

- EVALUATION of the Council Directive 91/271/EEC of 21 May 1991, concerning urban waste-water treatment, EC, Dec 2019. (n.d.).

A. Banerjee, P. E. (1999). The effect of addition of potato-processing wastewater on the acidogenesis of primary sludge under varied hydraulic retention time and temperature.

Alba Roibás-Rozas, A. M.-C. (2020). Environmental assessment of complex wastewater valorisation by polyhydroxyalkanoates production.

Almudena Hospido, M. T. (2005). Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes.

B. Rinco´n, E. S. (2008). Effect of the organic loading rate on the performance of anaerobic acidogenic fermentation of two-phase olive mill solid residue.

(2020). *BIT, Bioeconomia in Italia.*

Buonocore, E., Mellino, S., De Angelis, G., Liu, G., & Ulgiati, S. (2018). Life cycle assessment indicators of urban wastewater and sewagesludge treatment. *Ecological Indicators, 94*, 13-13. doi:10.1016/j.ecolind.2016.04.047

Byrne, D. M., Lohman, H. A., Cook, S. M., Peters, G. M., & Guest, J. S. (2017). Life cycle assessment (LCA)of urban water infrastructure: emerging approaches to balance objectives and inform comprehensive decision-making. *Environ. Sci.: Water Res. Technol., 3*, 1002-1014. doi:10.1039/C7EW00175D

Conca, V. (2020). Long-term validation of polyhydroxyalkanoates production potential from the sidestream of municipal wastewater treatment plant at pilot scale. *Chemical Engineering Journal*.

Corominas, L., Byrne, D. M., Guest, J. S., Hospido, A., Roux, P., Shaw, A., & Short, M. D. (2020, October 1). The application of life cycle assessment (LCA) to wastewater treatment: a best practice guide and critical review. *Water Research, 184*, 116058. doi:10.1016/j.watres.2020.116058

Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S., & Shaw, A. (2013). Life cycle assessment applied to wastewater treatment: state of the art. *Water Research, 47*(15), 5480-5492. doi:10.1016/j.watres.2013.06.049

Crutchik, D. (2018). Biore!nery of cellulosic primary sludge towards targeted Short Chain Fatty Acids, phosphorus and methane recovery. *ScienceDirect*.

DaRos, C. (2020). Sieving of municipal wastewater and recovery of bio-based volatile fatty acids at pilot scale. *ScienceDirect*.

Deal, E. G. (2019). Communication from the Commission to the European Parliament.

Diaz-Elsayed, N., Rezaei, N., Ndiaye, A., & Zhang, Q. (2020). Trends in the environmental and economic sustainability of wastewater-based resource recovery: A review. *Journal of Cleaner Production, 265*, 121598. doi:10.1016/j.jclepro.2020.121598

Elenco Prezzi: Per gli automezzi e le attrezzature si fa riferimento al punto 8.3.3 del Disciplinare di gara 01/2017. (n.d.).

Elsayed Elbeshbishy, H. H. (2011). Single and combined effect of various pretreatment methods for biohydrogen production from food waste.

EuropeanCommission. (2019). Insights into the European market for bio-based chemicals.

Frison, N. (2018). Development of a Novel Process Integrating the Treatment of Sludge Reject Water and the Production of Polyhydroxyalkanoates. *Environmental science technology*.

HaiyanWu, D. Y. (2009). The effect of pH on anaerobic fermentation of primary sludge at room temperature.

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (Eds.). (2018). *Life Cycle Assessment.* Springer International Publishing. doi:10.1007/978-3-319-56475-3

He Liu, P. H. (2018). Full-scale production of VFAs from sewage sludge by anaerobic alkaline fermentation to improve biological nutrients removal in domestic wastewater.

Herbert H. P. Fang, M. A. (2000). EFFECT OF HRT ON MESOPHILIC ACIDOGENESIS OF DAIRY WASTEWATER.

Hernandez-Sancho, M. M.-S. (2014). Benchmarking in wastewater treatment plants: a tool to save operational costs.

I. Maharaj, P. E. (2001). The role of HRT and low temperature on the acid-phase anaerobic digestion of municipal and industrial wastewaters.

ISO. (2006). Environmental Management—Life Cycle Assessment—Requirements and Guidelines (ISO 14044). Geneva: ISO, The International Organization for Standardization.

JRC, EU. (2010). ILCD handbook: general guide for Life Cycle Assessment: detailed guidance. *Publications Office of the European Union: Luxembourg*.

Kourmentza, C. (2017). Recent Advances and Challenges towards Sustainable.

Lee, W. S. (2013). A review of the production and applications of waste-derived volatile.

Lise Appels, S. H. (2013). Influence of microwave pre-treatment on sludge solubilization and pilot scale semi-continuous anaerobic digestion.

Madkour, M. H. (2020). PHA Recovery from Biomass.

Menna, F. D. (2018). Life cycle costing of food waste: A review of methodological approaches.

MinisteroDell'Ambiente. (26/03/2020). Decreto ministeriale. Ministero dell'ambiente e della tutela del territorio e del mare.

Nebot, E. (1995). Effect of the feed frequency on the performance of the Anaerobic Filters.

Peng Zhanga, Y. C. (2009). Waste activated sludge hydrolysis and short-chain fatty acids accumulation under mesophilic and thermophilic conditions: effect of pH.

Rincón-Molina, A. Z.-R.-R. (2019). Removal of High Concentrations Decachlorobiphenyl of Earthworm Eisenia fetida and its Symbiotic Bacteria in a Vermicomposting System.

Rodriguez-Perez, S. (2017). Challenges of scaling-up PHA production from waste streams. A.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., & Shiina, T. (2009). A review of life cycle assessment (LCA) on some food products. *Journal of Food Engineering, 90*(1), 1-10. doi:doi.org/10.1016/j.jfoodeng.2008.06.016

Seong-Jin Lim, B. J.-M.-d.-r. (2008). Anaerobic organic acid production of food waste in once-a-day feeding and drawing-off bioreactor.

Simon Bengtsson, A. W. (2008). Production of polyhydroxyalkanoates by glycogen accumulating organisms treating a paper mill wastewater.

Simon Bengtssona, J. H. (2008). Acidogenic fermentation of industrial wastewaters: Effects of chemostat retention time and pH on volatile fatty acids production.

Su Jiang, Y. C. (2007). Effect of sodium dodecyl sulfate on waste activated sludge hydrolysis and acidification.

Valentino, F. (2016). Carbon recovery from wastewater through bioconversion into biodegradable.

Wee Shen Lee, A. S. (2014). A review of the production and applications of waste-derived volatile fatty acids.

Yago Lorenzo-Toja, I. V.-R.-R. (2016). Benchmarking wastewater treatment plants under an eco-efficiency perspective.

Yizhen Zhang, C. Z. (2020). Wastewater treatment technology selection under various influent conditions and effluent standards based on life cycle assessment.