OPTIMIZATION OF SLUDGE MANAGEMENT AND DEHYDRATION PROCESSES AT BASF TARRAGONA WWTP

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TABLE OF CONTENTS

NOMENCLATURE

CAPEX. Capital expenses
COD. Chemical oxygen demand
DS. Dry solids
FQ. Physic-chemical
GHG. Greenhouse gas
ICP. Inductively coupled plasma
LOI. Loss of ignition
NPV. Net present value
OPEX. Operation expenses.
PFD. Process flow diagram
RD. Royal Decree
ROI. Return on investment
SOP. Sum of products
SPHE. Spiral plate heat exchanger
TDS. Total Dissolved Solids
TOC. Total organic carbon
TS. Total solids
VOC. Volatile organic compounds
VS. Volatile solids
WWTP. Waste Water Treatment Plant

ABSTRACT

This thesis documents the successful optimization of sludge dewatering processes at BASF Tarragona's wastewater treatment plant (WWTP). The project addressed challenges caused by outdated centrifuges from the 1990s, which implied high maintenance costs and delivered suboptimal dewatering performance. Furthermore, reliance on drying beds—exposed to adverse climatic conditions—resulted in sludge rewetting, reversing the benefits of centrifuge dewatering. The need for external transport services to remote drying beds compounded inefficiencies, resulting in sludge with high moisture content, significant waste volume, and elevated disposal costs.

Alternative sludge disposal methods, including composting and biogas production, were evaluated but demonstrated to be unsuitable due to heavy metal concentrations exceeding regulatory limits (RD 1310/1990). Consequently, landfill disposal remained the most viable option. To optimize the process, various mechanical dewatering and drying technologies were assessed based on economic, operational, and sustainability criteria, identifying the filter press as the optimal solution.

The filter press enhanced the dewatering process by achieving 39% dry solids content in a single mechanical stage, surpassing the 35% requirement. This eliminated the need for transport to drying beds, reducing operational complexity and internal logistics. The solution demonstrated significant cost-effectiveness, with the lowest operational costs ([redacted] €/year), a competitive initial investment ([redacted]€), and annual savings ranging from [redacted]€ in 2025 to [redacted]€ in 2026 due to landfill tariff increases. Additionally, the project achieved a net present value (NPV) of [redacted]€, a payback period of 8 months, and reduced sludge volumes from [redacted]t/year to [redacted]t/year.

Energy efficiency was notably improved, with specific energy consumption reduced to 1 kWh/t sludge compared to the current 5 kWh/t sludge, leading to a greenhouse gas emissions reduction of 8 t CO_2eq/week. These outcomes deliver substantial operational, environmental, and economic benefits.

Basic engineering for the selected solution incorporated a thermal conditioning stage utilizing residual heat, further enhancing dewatering performance. The design was evaluated for safety using a HAZOP analysis, confirming it as inherently safe.

1. INTRODUCTION

1.1. Background

1.1.1. Overview of the WWTP at BASF Tarragona and Current Status

The Wastewater Treatment Plant (WWTP) at BASF Tarragona is responsible for treating the wastewater from most of the plants and facilities on-site, including BASF Sonatrach PropanChem (BSP), Agricultural Products Cluster (AP), Dispersions Cluster (DP), and external companies like [redacted], [redacted], and [redacted]. In addition to wastewater treatment, the plant supplies essential utilities such as steam, industrial air, process water, nitrogen, and oxygen to the facilities. Over time, the WWTP has adapted to handle the increasing and variable nature of incoming wastewater streams effectively.

The treatment process includes physical-chemical treatment (coagulation and flocculation of dissolved matter) and a biological stage (activated sludge). However, only wastewater from [redacted] and the Dispersions Cluster undergoes physical-chemical treatment due to its higher dissolved matter content. One unique challenge is presented by [redacted]'s titanium oxychloride solution, which is highly acidic (pH close to zero) and contains traces of 1,3-dichloropropanol, a carcinogenic compound. The titanium oxychloride solution serves as a coagulant in the physical-chemical treatment process, eliminating the need for additional commercial coagulants. Any excess is neutralized with caustic soda, resulting in byproducts such as titanium hydroxide, glycerin, and common salt, which precipitate as a white slurry. After neutralization, this stream re-enters the treatment cycle and combines with other sludge types.

The treated water (effluent) is sent to a third-party facility for further processing before being discharged into the sea. The mixed sludge, produced from both the physical-chemical and biological treatments, generates an output of approximately 9,000 tons annually. Sludge is dewatered and dried using centrifuges and drying beds, though operational challenges led to the shutdown of a partial drying facility. Consequently, sludge is now simply piled in drying beds, with weather conditions often reversing drying progress and increasing moisture levels instead of reducing them.

Currently classified as non-hazardous waste, the sludge is sent to a landfill for disposal. Regular analyses are conducted according to RD 69/2009 to ensure compliance with parameters such as moisture, chlorides, TDS, COD, and LOI. If any of these parameters falls outside acceptable limits, additional stabilization treatment is required, significantly increasing disposal costs. Transporting this sludge, which is approximately 75% water, adds to high logistics costs, as landfill fees are based on the total sludge weight, regardless of water content.

1.1.2. Sludge Management and Treatment Options

Effective sludge management depends on factors like sludge composition, available resources (capital, available area, energy), and the evolving regulatory environment. In alignment with the waste hierarchy outlined in Law 7/2022, sludge treatment preferences include reduction (process improvements to minimize waste generation), reuse (composting), recycling (agricultural use, construction), energy recovery (incineration, pyrolysis, biogas production), and finally, controlled disposal (landfilling). With increasing environmental regulations and a push towards reducing landfill use for sludge disposal, alternative disposal methods, such as energy valorization, are prioritized, provided the sludge meets minimum dryness standards.

To meet these standards and optimize sludge treatment, dewatering and drying are typically necessary. Sludge volume reduction begins with thickening to remove free water (not bound to solids), followed by mechanical dewatering or natural drying to release capillary-bound water. Drying processes further remove bound water, achieving the dryness levels needed for more sustainable disposal options like energy valorization of the sludge.

Designing an efficient dewatering and drying process is critical, as these stages are energy-intensive. Identifying an energy-efficient solution tailored to the specific characteristics and requirements of each scenario is essential for minimizing operational costs and ensuring effective sludge management.

1.2. Objectives

Based on the presented background, this project aims to optimize the management and dewatering/drying processes of sludge at the BASF Tarragona WWTP. The optimization must take into account an anticipated 50% reduction in sludge input from the [redacted] stream, which will impact the overall sludge management scenario at the plant. The main objectives:

1. **Evaluate Alternative Sludge Management Options**
   Identify feasible alternatives for sludge management, considering current regulations and detailed sludge characterization. The evaluation will focus on determining whether there are sustainable management options that comply with legislative requirements and meet environmental and operational standards.
2. **Propose Moisture Reduction Solutions**
   In scenarios where alternative management options are not viable, propose effective solutions to reduce sludge moisture content to below 35% dry solids. Achieving this target will be essential for improving sludge handling, enabling potential disposal options like incineration, and meeting disposal regulations.
3. **Ensure Integration with Existing Plant Infrastructure**
   Design the chosen solution for integration into the existing plant infrastructure. This includes compatibility with current systems, space constraints, utility availability, and minimal disruption to ongoing operations.

1.3. Methodology and Scope of Work

Step 1: Initial Data Collection and Plant Familiarization

The project begins with gathering detailed information about the WWTP and its processes, focusing specifically on sludge production and drying. This involves identifying primary sources of sludge production and analyzing sludge characteristics such as flow rates, composition, and any additives used. Evaluating the current dewatering performance is essential, with particular attention to the achieved dryness levels and transportation costs. Data collection will rely on available BASF documentation, direct communication with plant operators, and insights from relevant personnel to understand daily operational practices.

Step 2: Sludge Characterization

The next phase requires an in-depth study of the physical-chemical and biological sludge types independently to obtain a reliable and detailed characterization. This characterization will inform the available options for treatment, management, and final disposal. Laboratory analyses (either at the WWTP lab or external labs with suitable equipment and availability) are necessary to verify compliance with legal limits for critical parameters.

Step 3: Literature Review on Existing Technologies and Best Practices

After defining the problem framework, a literature review will be conducted using credible sources such as scientific journals, publications, and technical books. This review aims to explore existing technologies and industry best practices that could meet project objectives. The focus will also include operational requirements for these technologies and potential auxiliary treatments that might be necessary if new solutions are implemented.

Step 4: Resource Assessment at the Plant

A crucial part of this project is understanding the resources available at the BASF plant across multiple aspects. Communication with operators and other stakeholders will provide insights into available utilities, physical space, labor capacity, and potential sources of residual energy that could be utilized in sludge treatment processes. This resource assessment will be key to selecting feasible technologies that align with the plant's current capabilities.

Step 5: Technology Selection and Supplier Contact

Once potential technologies are identified, suppliers will be contacted via websites and phone calls to gather preliminary budget estimations. Presenting a well-defined problem description will be critical to obtaining accurate budgetary quotes. This step will ensure that each proposed solution’s capital expenditure (CAPEX) requirements are clearly understood before proceeding to the economic analysis.

Step 6: Economic and Sustainability Analysis (Business Case)

Based on the CAPEX data and operating costs (OPEX) associated with each technology, a business case will be developed to compare the project alternatives. Economic indicators, such as the net present value (NPV), return on investment (ROI), and payback period, will be calculated to facilitate a comparative evaluation. Additionally, sustainability metrics, such as environmental footprint and labor utilization, will be analyzed to provide a holistic view of each technology’s impacts across multiple dimensions.

Step 7: Technology Selection and Final Decision

Following the comparative analysis, the most suitable technology will be selected based on a weighted consideration of key indicators aligned with the plant’s strategic goals. The decision process will prioritize metrics that align with both cost-effectiveness and sustainability objectives, ensuring an optimal solution tailored to the plant's needs.

Step 8: Basic Engineering and Integration into Plant Infrastructure

With the selected process defined, basic engineering will be carried out to detail how the new technology will integrate with the existing plant. This will include specifying any necessary ancillary equipment to manage sludge from production through to final disposal. Equipment sizing and process flow diagrams (PFDs) will be developed to provide a clear overview, along with a proposed control strategy. Additionally, operational procedures and safety considerations will be documented, including mitigation strategies to address potential risks associated with the new process.

2. THE WASTE WATER TREATMENT PLANT AT BASF TARRAGONA

In order to better understand the context and application of this project, a brief description of the WWTP is presented. The plant could be divided into three main processes: physical-chemical treatment, biological treatment and sludge management.

Figure 2.1 WWTP’s block diagram. Red for physical-chemical treatment, green for biological treatment, and purple for sludge dewatering. (L. Campos, 2023)

2.1. Physical-Chemical Treatment

[redacted]

2.1.1. R-1101

[redacted]

[redacted]

2.2. Biological Treatment

[redacted]

2.3. Sludge Management at WWTP

Sludge management is a common practice in large-scale wastewater treatment plants, and its disposal methods vary based on the water source and treatment type. Sludge can be repurposed as biofuel through fermentation, incinerated, used as fertilizer, or incorporated into concrete production. However, some sludge is unsuitable for reuse and may require additional treatment before landfill disposal.

At WWTP-UT, three types of sludge are produced, mixed, and thickened to 24-25% dry matter in centrifuges. Previously, sludge was dried to 95% in a process using steam-heated air and a fluidized dryer, but operational challenges led to its discontinuation. The steam, previously supplied by [redacted] turbines from [redacted], became costly due to a significant price increase in 2024 after a contract expired.

Table 2.1 Type of sludge produced at WWTP BASF Tarragona.

Sludge	Source	Description
[redacted]	[redacted]	[redacted]

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Currently, sludge is packed into 50-ton batches and stored in two designated drying areas on-site. However, the additional drying achieved in these areas is minimal, typically improving the centrifuge results by only 1-2% in terms of dry solids under optimal conditions. This process is also highly dependent on weather. On rainy days, the sludge reabsorbs moisture, negating the drying efforts and reversing the progress achieved by the centrifuges. This weather sensitivity makes the drying process inconsistent and less reliable for maintaining or improving sludge dryness levels.

Weekly, samples from each batch on the drying areas are analyzed alternately by external companies [redacted] and [redacted] to measure parameters such as TDS, COD, LOI, chlorine concentration, and conductivity.

Table 2.2 Parameter limits established by RD 69/2009 for sludge in Catalonia.

Parameter	**Landfill limitation (RD 69/2009)**
TDS (mg/kg)	60000
Chlorides (mg/kg)	15000
COD (mg/kg)	800
Loss at 105ºC (%)	65
LOI (% over dry matter)	15

While most parameters are subject to exceptions under Royal Decree 69/2009, exceeding TDS limits requires stabilization by an external company at an additional cost of [redacted] per ton.

2.4. Role and Tasks Carried Out at BASF

My role as an intern in the Process Department at WWTP BASF Tarragona has been entirely dedicated to optimizing sludge dewatering and drying processes. Under the supervision of Nuria Huguet Subiela, with whom I maintained daily communication, I provided updates on new findings, progress, and any challenges relevant to the project.

My responsibilities included a broad range of activities. I conducted extensive literature research to explore optimization opportunities and investigate potential new technologies to replace the current dewatering processes. Additionally, I gathered relevant project information by consulting company documents and engaging with personnel from various departments, including the control room, process and operations, and maintenance teams.

To address gaps in information, particularly regarding sludge properties, I collaborated with plant operators to collect sludge samples that represented the actual proportions sent to the centrifuges. I conducted laboratory analyses on these samples, leveraging the available equipment to provide critical data for the project.

Furthermore, I interacted with multiple suppliers of dewatering and drying technologies to obtain real-world quotations and assess the project's economic feasibility. This involved organizing meetings to discuss project goals, operational details, and objectives. I also facilitated the shipment of sludge samples to suppliers for pilot plant testing, allowing us to evaluate the performance and suitability of proposed technologies.

To expand my understanding and gain insights into alternative approaches, I visited the facilities of AITASA, where I was given a detailed tour of their treatment plant, with a particular focus on their mechanical dewatering process using filter presses.

Throughout the internship, I presented my findings to stakeholders, including plant and department managers from process, operations, and maintenance. These presentations served as a platform to gather feedback, align the project with their needs, and incorporate their insights into my work. This collaborative approach ensured that my contributions were both practical and aligned with the goals of the project and the organization.

3. LITERATURE REVIEW

In this section, a brief and concise literature review is presented, covering the fundamental aspects related to this project. It includes disposal options, characterization and structure of sludge, as well as the available drying and dewatering techniques based on the type of water to be removed. Operational issues and important factors to consider are also addressed, with an emphasis on the cost-effectiveness of these processes.

3.1. Final Disposal Options for Sludge

Industrial sludge management involves a range of treatment and disposal methods according to the specific sludge properties, regulatory requirements, and environmental considerations. The choice of technique depends on the sludge's characteristics, objectives, and available infrastructure.

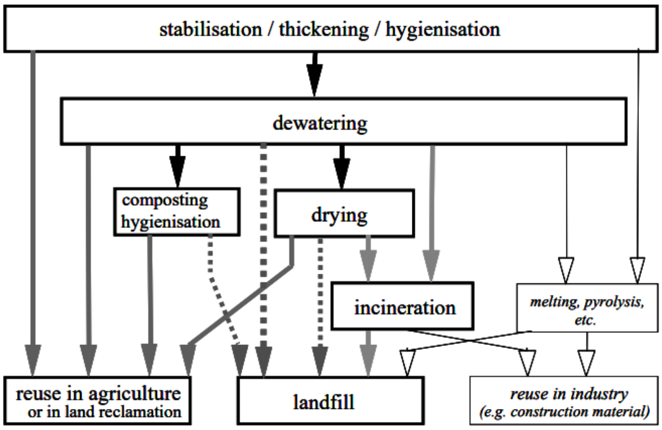


Figure 3.1 Alternatives for sludge handling to reuse or disposal.

The standard approaches include: (Kumar et al., 2024)

- **Dewatering**. Techniques like centrifugation and solar drying reduce moisture content, improving sludge handling and reducing volume.
- **Stabilization.** Processes such as aerobic digestion, lime treatment, and thermal methods reduce organic content, control microorganisms, and mitigate odors, enhancing sludge stability.
- **Incineration.** High-temperature combustion converts sludge into ash and heat, eliminating pathogens and reducing waste volume, though pollution control measures are essential.
- **Land Application**. Treated sludge can enhance soil fertility as a fertilizer, provided environmental and safety standards are met.
- **Landfilling**. For sludge unsuitable for treatment or reuse, secure landfill disposal ensures controlled decomposition while minimizing environmental risks.
- **Recycling and Resource Recovery**. Extracting metals, producing biofuels, or generating biogas from sludge supports sustainability by reducing waste and recovering valuable resources.

Emerging technologies like pyrolysis and hydrothermal carbonization are promising advancements, offering innovative ways to manage and repurpose industrial sludge while minimizing environmental impact.

3.2. Sludge Composition & Structure

The water present in sewage sludge can be categorized based on how it is physically bonded to sludge particles, as represented in Figure 3.2. These categories include: (Thomé-Kozmiensky & Pelloni, 2011)

- **Free water**. This is not bound to sludge particles and represents the largest portion of water. It can typically be separated through simple processes like gravitational thickening.
- **Interstitial water**. Held by capillary forces between the particles in sludge flocs, this type of water requires mechanical dewatering techniques to be effectively removed.
- **Surface water**. Attached to particle surfaces by adhesive forces, this water is more tightly bound and cannot be separated mechanically.
- **Intracellular water**. Contained within the cells of microorganisms, it is the most strongly bound type of water.

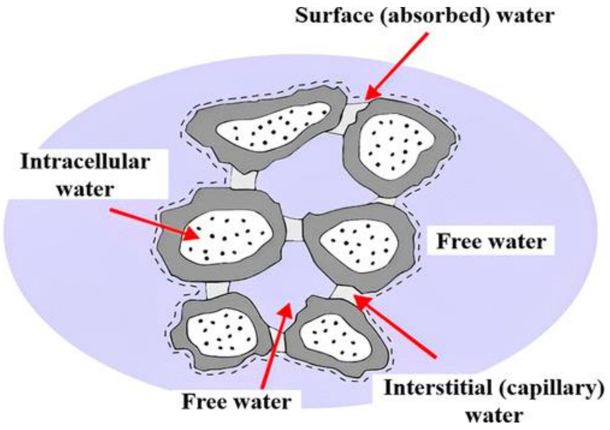


Figure 3.2 Illustration of a sludge floc structure and the types of bond water. (Golbabaei Kootenaei et al., 2022)

The process of dewatering involves overcoming the bonding forces holding water in the sludge, with these forces increasing progressively from free water to intracellular water.

While free water is relatively easy to remove mechanically by thickening, interstitial water requires mechanical methods like centrifugation or filtration.

Surface and intracellular water, due to their stronger bonding forces, can only be separated through thermal methods, such as drying. (Thomé-Kozmiensky & Pelloni, 2011)

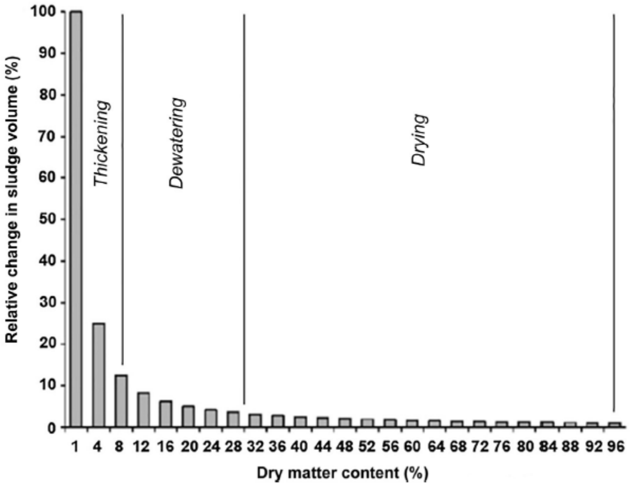


Figure 3.3 Volume reduction and change of sludge and suitable processing techniques with respect to dry matter content. (an Ecolab Company NALCO Water, 2018)

3.3. Stages in a Sludge Treatment Plant

In sludge treatment, three primary pre-processing stages are commonly employed: thickening, dewatering, and thermal drying. Each stage serves a distinct purpose in reducing sludge volume, improving handling efficiency, and preparing the material for final disposal or further processing.

Thickening is usually the first step and focuses on reducing the volume of sludge by removing free water. This process increases the solids concentration from a highly diluted state, typically ranging from 0,5% to 2% dry solids (DS) to a thicker slurry with a concentration of approximately 2%–15% DS. Thickening reduces the volume of sludge to be handled in subsequent stages, minimizing the overall cost and size of the treatment system.

Dewatering follows thickening and targets the removal of water held between sludge particles (interstitial water). It achieves a much higher solids concentration, generally between 20% and 35%, compared to thickening. Dewatering reduces the weight and volume of sludge even further, making it easier and more cost-effective to transport, store, and dispose of.

Thermal drying takes the process a step further by removing both free and bound water from the sludge. By applying heat, this method can achieve solids concentrations as high as 92% DS or more. Thermal drying transforms the sludge into a dry, granular material, significantly reducing its weight and volume. In some cases, this dried sludge can be repurposed, for example, as a fertilizer or a fuel source, adding potential value to the treatment process.

Table 3.1 Summary of the main differences between dewatering and drying processes. (an Ecolab Company NALCO Water, 2018; Davis, 2020)

Aspect	**Dewatering**	**Drying**
Purpose	Reduce water content to concentrate sludge	Further reduce water to make sludge dry or granular
End product solids content	15 – 35 %	60 – 95 %
Type of water removed	Mostly free water	Free and bound water
Methods	Mechanical (centrifuges,	Thermal (belt dryers, solar

	presses, etc)	drying, etc)
Energy requirement	Low to medium	High (thermal or natural solar)
Processing time	Usually short (minutes to hours)	Longer (hours to weeks)

3.3.1. Factors that Influence Dewaterability

The following figure illustrates the factors that influence the dewaterability of sludge. It is widely observed that wastewater treatment plants in different locations often achieve varying dewatering results, even when employing the same type of equipment. This variation arises due to several factors: (*Water Treatment Handbook*, 1991)

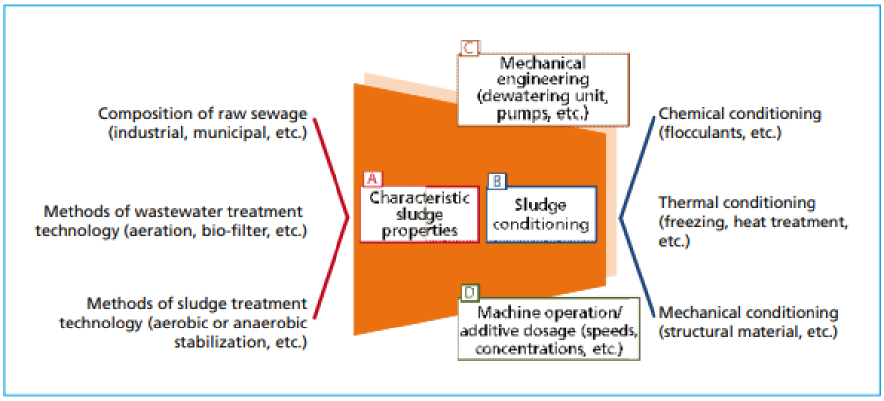


Figure 3.4 Factors influencing dewaterability of sludge. (Thomé-Kozmiensky & Pelloni, 2011)

- **Properties of the Sewage Sludge**. The characteristics of sludge are influenced by the quality of the raw water and the specific technologies used in wastewater and sludge treatment. These properties are often difficult to alter significantly. Industrial discharges, in particular, can adversely affect sludge characteristics, such as its dewatering performance. However, implementing tailored technologies can mitigate these negative impacts and improve sludge behavior during treatment.
- **Sewage Sludge Conditioning**. The type of conditioning applied to the sludge before dewatering plays a crucial role. Proper conditioning methods can enhance the dewatering efficiency and overall performance of the equipment.
- **Type of Dewatering Equipment**. The mechanical design and type of dewatering technology (e.g., centrifuges, filter presses, screw presses) significantly affect the process. Each type of equipment interact with the sludge properties differently, influencing the results.
- **Operational Parameters**. Factors such as equipment speed, specific machine settings, and the dosage and concentration of additives can greatly impact dewatering performance. Optimizing these parameters based on the unique characteristics of the sludge is essential for achieving the best results.

These factors show the complexity of achieving consistent dewatering performance and the need for a tailored approach at each treatment plant to address site-specific conditions.

3.3.2. Sludge Pre-Treatment & Conditioning Processes

Sewage sludge particles naturally carry negative surface charges, creating electrostatic repulsive forces that hinder their sedimentation and dewatering. To overcome these forces and improve dewatering efficiency, sludge can be conditioned using one of three main approaches: (Thomé-Kozmiensky & Pelloni, 2011; *Water Treatment Handbook*, 1991)

- **Chemical Conditioning**
  This involves adding cationic charge carriers, such as inorganic compounds (iron, aluminum, or calcium salts) or organic chemicals like polymers. These additives destabilize the sludge particles, leading to the formation of flocs through flocculation and co-precipitation. Organic flocculants, often combined with iron salts, are widely used in wastewater treatment facilities.
- **Thermal Conditioning**
  Thermal methods rely on heat treatment to improve sludge dewatering properties. Heating sludge to moderate temperatures (around 40–60°C) is particularly effective for raw sludge and can utilize waste heat for energy efficiency. Thermal disintegration processes can further enhance dewatering by breaking down sludge structure. (Topal & Arslan, 2009)
- **Mechanical Conditioning**
  Mechanical methods involve adding structural materials, such as ash or coal, to improve sludge properties for dewatering.

These conditioning techniques can be critical to achieving efficient sludge dewatering and optimizing downstream treatment processes.

3.3.3. Mechanical Dewatering Methods

Mechanical dewatering of sewage sludge involves two primary approaches: separating the liquid and solid phases using a mechanically generated centrifugal field or applying filtration pressure. Below is an overview of the key dewatering technologies: (Davis, 2020)

- **Centrifuge**. Centrifuges utilize centrifugal force to accelerate water separation from sludge. A rotating drum with an internal screw conveyor moves the sludge towards the discharge as it accumulates on the drum walls. This method is widely used due to its efficiency, with approximately half of the sewage sludge in certain regions being dewatered this way.
- **Belt Filter Press**. In this method, sludge is compressed between two filter belts that pass through a series of rollers, progressively increasing pressure to remove water. The performance depends on factors like flocculant dosage, belt type, speed, and applied pressure. Belt filter presses are often employed in smaller facilities due to their simplicity and lower capacity compared to other technologies.
- **Filter Press**. Filter presses consist of filter plates covered with cloth, forming chambers that are filled with sludge under high pressure. Water drains through the cloth, leaving behind a solid filter cake. The pressing power, filtration time, and chemical conditioning significantly influence dewatering efficiency. This method is favored for achieving high dryness levels.

- **Screw Press**. Screw presses use a slow-rotating conical screw inside a cylindrical sieve to dewater sludge. The last section of the screw operates as a high-pressure zone, while filtrate water drains through sieve plates. These systems are increasingly popular due to their simplicity and effectiveness in various applications.

Each technology achieves specific dryness levels based on its design and operational parameters.

The choice of dewatering technology significantly impacts annual costs, which include investment, operation, and personnel expenses. While optimizing dewatering reduces sludge disposal costs, it may incur higher upfront or operational expenses. Conducting a detailed cost-benefit analysis tailored to local conditions is crucial for selecting the most cost-effective solution.

3.3.4. Thermal Drying Techniques

After dewatering sludge, further reduction of water content can be achieved through partial or full drying, resulting in maximum volume reduction. This process significantly increases the sludge's calorific value, reaching up to 17,000 kJ/kg, making it a valuable fuel source for mono-incineration plants, power stations, or cement facilities. (Thomé-Kozmiensky & Pelloni, 2011)

Efficient sludge drying requires well-integrated sludge management systems. Energy for drying can come from renewable sources like solar power or from waste heat, emphasizing the importance of innovative energy integration approaches, such as combined drying and incineration systems.

Drying involves removing water from sludge through evaporation, categorized based on heat transfer methods: convection, contact, and radiation drying. Each technique has specific applications and operational features: (Davis, 2020)

- **Convection Dryers**
  This method involves direct contact between sludge and a drying gas, which circulates around or flows through the material.
    - **Drum Dryers**. Sludge is continuously mixed and transported in a rotating drum by hot gas flow, guide plates, or inclined positioning.
    - **Belt Dryers**. Sludge is evenly distributed onto a conveyor belt with perforated plates, where it is dried by hot air.
- **Contact Dryers**
  Here, the sludge is heated indirectly by a thermal carrier through a solid surface, avoiding direct contact between the heat source and the material.
    - **Thin-Film Dryers**. The sludge forms a thin film on the heated surface of a double-walled cylinder, with a rotor ensuring even distribution.
    - **Disk Dryers**. Comprising a rotor with hollow disks circulated by a heat medium, these dryers are generally efficient and low maintenance.
- **Radiation Dryers**
  Heat transfer occurs via electromagnetic radiation, typically infrared.
    - **Solar Dryers**. Utilizing sunlight, these systems minimize primary energy consumption. The sludge is dried in a greenhouse-like structure with a sealed floor, where insolation drives the drying process. Additional waste heat can enhance performance.

Solar drying is increasingly popular in small-scale facilities, but its impact on total drying capacity is minimal. Effective sludge drying not only reduces waste volume but also transforms sludge into a valuable energy resource, supporting sustainable waste management practices.

3.3.5. Challenges in Sludge Management

This section addresses the challenges associated with sludge processing and management, focusing on critical aspects such as operational issues, emission control, and the risks inherent to the properties of sludge and its transformation during treatment processes.

3.3.5.1. Risk of Spontaneous Self-Ignition

Sludge can exhibit self-ignition behavior due to the gradual oxidation of organic particles, a process that produces heat and can lead to spontaneous combustion under certain conditions. The following factors are causes and triggers for the sludge to exhibit this behavior. (Díaz et al., 2019)

- **Chemical Composition**. Sludge contains flammable organic materials that are prone to oxidation. These materials react with oxygen in the air, releasing energy in the form of heat.
- **Particle Size and Distribution**. Fine particles, with a high surface area relative to volume, facilitate faster reactions with oxygen, reducing the self-ignition temperature.
- **Ambient Conditions**. The surrounding temperature, humidity, and airflow influence the rate of oxidation and the likelihood of self-heating.
- **Storage Volume and Geometry**. Larger or densely packed volumes of sludge trap heat, creating favorable conditions for self-heating and ignition.
- **Moisture Content**. High moisture levels can initially delay ignition by requiring heat for evaporation, but as water evaporates, oxidation accelerates, increasing ignition risk.

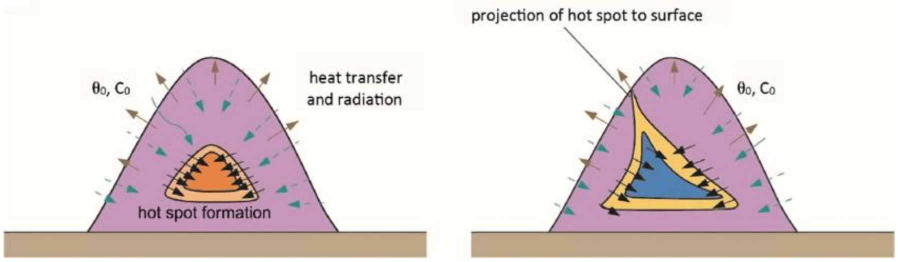


Figure 3.5 Development of sludge self-ignition behavior mechanisms; hot spot formation and propagation to surface. (Díaz et al., 2019)

The mechanism of self-ignition can be explained as follows:

- **Self-Heating**. At normal temperatures, oxygen interacts with the surface molecules of organic particles in the sludge. This exothermic reaction produces heat, which raises the temperature of the sludge-air system.

- **Humidity Evaporation**. As the temperature increases, water in the sludge evaporates, consuming heat. However, once the water is removed, the oxidation process accelerates due to reduced cooling effects.
- **Self-Ignition**. If the heat generated exceeds the rate at which it dissipates, the temperature reaches a critical point where the reaction becomes self-sustaining, leading to combustion.

Self-ignition poses a serious hazard in sludge drying and storage, necessitating close monitoring of factors like temperature, particle size, and storage configuration. Proper storage design, moisture management, and adequate ventilation are essential preventive measures. By addressing these factors, operators can implement strategies that significantly reduce the likelihood of self-ignition and enhance safety in sludge management facilities.

3.3.5.2. VOCs Emissions

In accordance with Directive 2010/75/EU, emission limits for volatile organic compounds (VOCs) have been established, highlighting the importance of addressing this aspect in sludge drying operations. Drying technologies operating at high temperatures lead to the volatilization of these compounds, releasing them into the air and posing potential risks to both the environment and human health. To comply with current regulations, it is essential to implement effective air treatment systems that capture and eliminate VOCs before their release into the atmosphere. (Davis, 2020)

Furthermore, the composition of the sludge and the specific conditions of the process influence the quantity and type of VOCs emitted, making detailed analysis necessary to design appropriate control solutions. Commonly used air treatment technologies include thermal oxidation systems, biofilters, and adsorption technologies, which significantly reduce emissions.

3.4. Cost Effectiveness in Sludge Management

Energy costs represent a significant portion of operational expenses in sludge management facilities, often accounting for up to 75% of total costs. This shows the importance of adopting cost-effective strategies to optimize energy use. One approach involves the integration of renewable energy technologies, which harness natural resources to minimize reliance on external energy inputs. Another effective strategy is energy integration within the facility. For instance, the production of biogas from anaerobic digestion processes can provide a sustainable fuel source to power operations, reducing dependency on external energy supplies. Similarly, mono-incineration plants can utilize the energy released from sludge combustion to support drying processes and other energy-intensive tasks.

Regardless of the chosen approach, careful evaluation and monitoring of energy consumption are critical to identifying inefficiencies and implementing targeted improvements.

4. METHODOLOGY

In this section, the methodology and reasoning applied in the development of the project are presented to ensure the achievement of the initially set objectives.

4.1. Strategy

To achieve the initially set objectives, a plan has been developed to define the actions and various tasks to be carried out, as well as the steps to address the information gaps necessary to meet these objectives.

First, understanding the physical-chemical characteristics of the sludge is essential to determine which technologies are most suitable and which final disposal options are realistic, in accordance with legislation, regulations, and the physical properties of the sludge. Therefore, all available information has been collected. Due to the lack of analytical data on the sludge, several laboratory analyses have been conducted using the resources available at the BASF Tarragona site.

Once the physical-chemical characteristics of the sludge have been defined, viable options for its disposal or subsequent use can be identified, in compliance with the limits set by legislation. This will determine whether the separation of physical-chemical and biological sludges is feasible and makes sense, or if it is preferable to continue treating them together, as has been done so far.

The results of this analysis will also determine whether it is viable in the long term to explore alternative methods for sludge disposal, aside from landfilling.

However, one of the main objectives is the optimization and reduction of the current sludge dewatering processes. Therefore, the development of the search for alternatives to implement new technologies will be presented, along with the evaluation of different indicators across various aspects (economics, energy, operations, environment, etc.). This approach will allow for a well-informed decision and provide the best solution for the project at hand.

4.1.1. Sludge Characterization & Disposal Options

According to Law 7/2022, of April 8th (Spain), which extensively develops the concept of waste and contaminated soil hierarchy within the framework of a circular economy, its first point establishes a clear preference for waste prevention and management.

The following figure illustrates, in order of preference, the treatments and/or disposal options in waste management, in this case, for sludge.

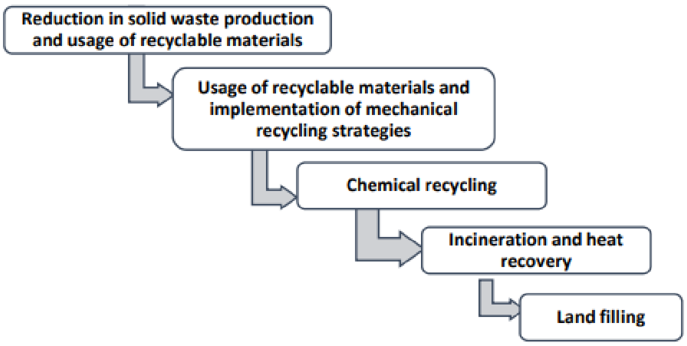


Figure 4.1 Recommended recycling strategies hierarchy for solid waste management.

4.1.1.1. Minimization

The concept of minimization is based on the idea that the best waste is the one that is never generated. While it is impossible to eliminate waste production entirely, what can be achieved is a significant reduction in the quantity of waste generated and its associated environmental impacts. Minimization not only aims to reduce the volume of waste but also its toxicity and harmfulness, which helps mitigate its negative effects on the environment and public health.

In this case, the optimization of the current dewatering processes would serve as a way to minimize the waste production.

4.1.1.2. Reuse

Reuse refers to the possibility of reusing a product or material based on its nature and the proximity of opportunities to the point of waste generation. In the case of sludge, there are several viable alternatives for sludge of biological origin. One of the most common options is its application to soil as fertilizers or for composting, provided that it has a high organic content and does not contain contaminants in toxic concentrations. This practice helps to close the nutrient cycle in nature, promoting sustainability.

Spanish legislation, specifically RD 1310/1990, establishes the limits applicable to biological sludges from industrial activities, ensuring that their reuse does not pose a risk to human health or the environment. With proper control, the reuse of these sludges can be an effective strategy for reducing environmental impact and maximizing resource utilization.

4.1.1.3. Energy Recovery

Energy recovery from sludge can be performed in various ways, depending on its composition. In the case of the biological sludge available, the two main alternatives to be studied are biogas production and incineration.

Biogas is obtained through the anaerobic digestion of sludge, a process in which microorganisms break down organic matter in an oxygen-free environment, releasing methane that can be used as an energy source. However, both from a legislative and operational standpoint, not all sludges are suitable for this process. The legislation governing this treatment is RD 1620/2007, which sets the requirements and parameters to ensure that the anaerobic digestion process is safe and efficient.

On the other hand, sludge incineration is a feasible option, but it involves a very high investment. Additionally, the plant does not produce enough sludge to justify the implementation of this process on a large scale, so, for now, it is not considered a viable option.

4.1.1.4. Landfilling

In the event that none of the alternative disposal and final destination options for sludge have shown potential, the waste must be disposed of in a regulated landfill, in compliance with all applicable regulations to ensure that it does not pose a risk to public health or the environment.

However, even in this scenario, the principle of minimization should be applied. This means that, whenever possible, methods should be explored and implemented to reduce both the amount of waste generated and its harmfulness before final disposal. Minimizing waste sent to landfills not only contributes to sustainability but also helps extend the lifespan of landfills and minimizes their long-term environmental impact.

4.1.1.5. Strategy & Methodology Tree

The strategy to be followed to assess whether it is worthwhile and feasible to separate the biological sludge in order to minimize waste sent to landfills and obtain economic benefits is illustrated in the following strategy tree.

This approach allows for a structured analysis of the different available options, considering key factors such as technical feasibility, potential economic benefits, environmental impact, and regulatory compliance. By using this decision tree, an informed decision can be made on whether separating biological sludges is an effective solution from both an economic and environmental standpoint.

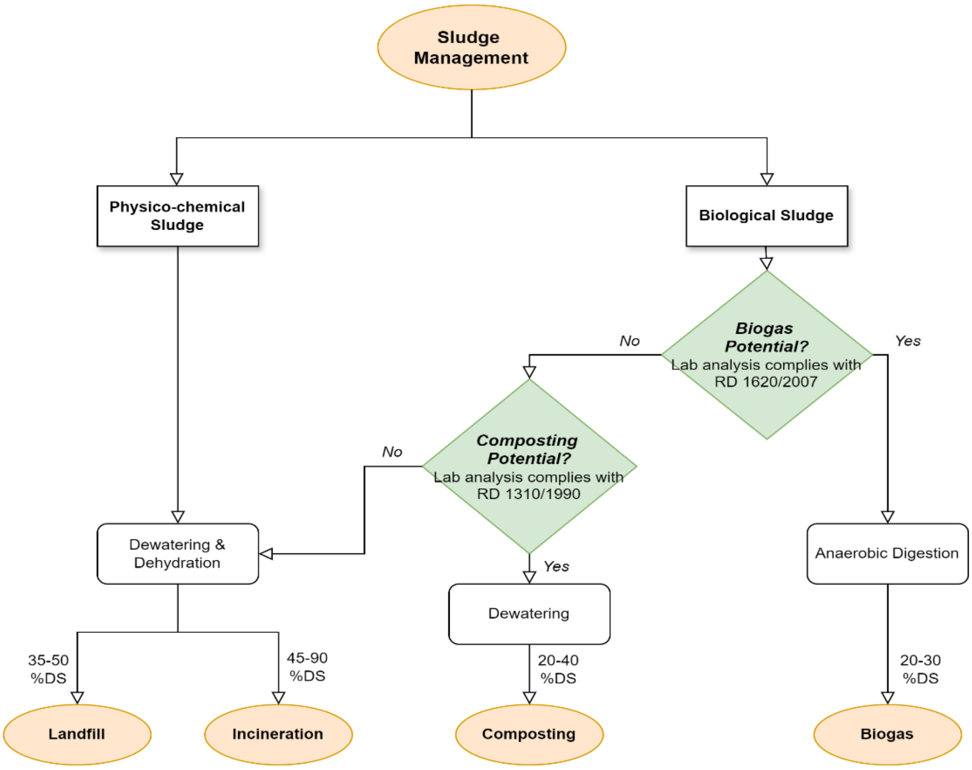


Figure 4.2 Strategy & Methodology Tree.

A characterization of the sludge will be carried out in accordance with RD 1620/2007 and RD 1310/1990, which primarily set limits on the content of heavy metals. This characterization will verify whether the sludge meets legal requirements regarding toxicity and safety levels for disposal and possible reuse. If the sludge complies with the mentioned regulations, a future study could be considered to assess the economic feasibility of its treatment and potential valorization.

If the sludge does not meet the established regulations, the only viable option would be to continue operating as done to date, mixing the physical-chemical and biological sludges. In this case, the implementation of a new mechanical dewatering and/or drying process will be carried out to reduce the volume of the generated waste and ensure compliance with requirements for final disposal.

4.1.2. Optimization of Current Dewatering & Drying Process

The following objectives are to be met with the implementation of a new technology and will be factors affecting the technology selection.

- **Compliance with Upcoming Regulations for Landfill Disposal**
  With the expiration of the current admission form in 2026, the sludge must meet a minimum 35% dryness level in order to be accepted at a regulated landfill. Failure to meet this requirement will necessitate additional stabilization of the sludge, which would drastically increase handling costs (from the current [redacted] to €250/ton). Ensuring compliance with these future regulations is a key objective in selecting the appropriate technology and will be a constraint for the outlet dryness.
- **Reduction of Sludge Handling Costs (Transport and Disposal)**
  Currently, the sludge has a very high water content (~25% dryness), resulting in significant landfill costs for sludge that consists mostly of water. To minimize transport and disposal costs, it is essential to reduce the water content in the sludge, which will lead to more cost-effective management and disposal.
- **Reduction of Residue Production**
  Beyond economic reasons, reducing the volume of residue produced is an environmental priority. Reducing the amount of waste generated will help improve sustainability and minimize environmental impact of the whole BASF Tarragona site.
- **Optimization of Current Operations and Reduction of Operational Costs**
  The existing equipment is outdated and requires high maintenance costs. The current dewatering system performs poorly, and the drying beds do not significantly improve dryness results. Additionally, during rainy periods, the sludge becomes wetter, making the issue worse. Therefore, optimizing or replacing the existing dewatering and drying systems is crucial to improving both performance and operational costs.
- **Elimination of Dependence on Drying Bed Areas**
  If feasible, the objective is to reduce or eliminate reliance on the drying beds by implementing a technology that does not require these areas or by incorporating a storage system capable of handling the sludge production efficiently, without relying on external drying space.

4.1.2.1. Potential Stages in the Dewatering and Drying Process

A dewatering and drying process typically involves several stages, with each step depending on factors such as the technologies employed, the regulatory requirements to be fulfilled, and the desired level of dryness to be achieved. The process is designed to ensure compliance with legislation, optimize performance, and meet specific operational goals. The following illustration presents a schematic overview of the main operations involved, providing a clear understanding of the sequence and interaction of the different stages.

- **Pre-conditioning**
  The slurry may undergo an optional pre-conditioning stage, as outlined in previous sections. This stage offers various alternatives, and the selection of a specific method depends on factors such as available resources, economic considerations, and operational goals. While pre-conditioning is not mandatory, it can significantly enhance dryness levels before mechanical dewatering, also improving the

efficiency and effectiveness of subsequent operations. The decision to include this step is often driven by the desired dryness outcome and the overall optimization of the process.

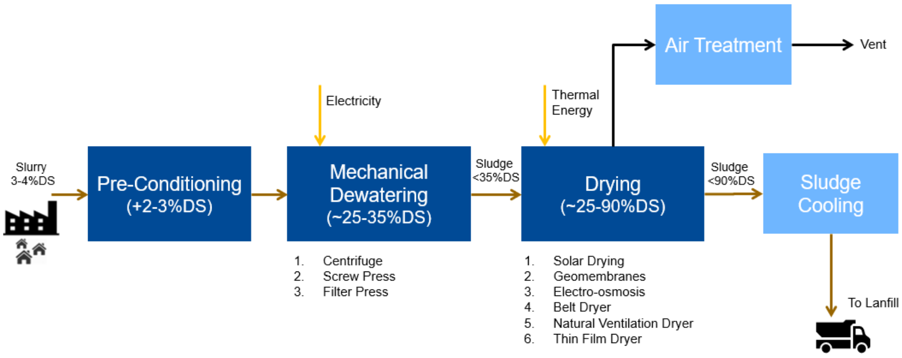


Figure 4.3 Schematic Overview of the Dewatering and Drying Process Stages.

- **Mechanical Dewatering**
  This is the core stage of the process, as it is a prerequisite for any further drying operations. Mechanical dewatering is highly cost-effective because it relies solely on the physical removal of water without the need for intensive energy input. Depending on the characteristics of the sludge, this stage can achieve dryness levels of up to 35% or even higher, making it an essential step in preparing the sludge for subsequent treatments.
- **Drying**
  Drying is typically employed when very high dryness levels are required, beyond what mechanical dewatering can achieve. This stage often involves the use of thermal energy, such as steam, to evaporate the remaining water. However, alternative technologies, such as solar drying, offer a more energy-efficient option by eliminating the need for steam. Solar drying can achieve dryness levels ranging from 90% to 99%. The choice of drying technology depends on an economic analysis to determine its feasibility and cost-effectiveness, particularly in light of sludge disposal costs. Since drying technologies operate at high temperatures, certain risks must be addressed: (Davis, 2020)
    - Self-Ignition: High dryness levels can increase the risk of sludge self-ignition.
    - VOC Generation: Exposing sludge to high temperatures can lead to the volatilization of volatile organic compounds (VOCs).

  To mitigate these risks, additional measures may be necessary:
    - Cooling the sludge after drying to reduce self-ignition hazards.
    - Implementing air treatment systems to capture and eliminate VOCs before releasing air into the environment.

These considerations are crucial when evaluating the viability and designing the drying technologies for sludge management.

4.2. Sludge Characterization

The analyses conducted and the corresponding results are detailed in this section. The determination of various indicative parameters relevant to wastewater treatment was performed on the leachate extracted from the sludge, following the experimental method presented in section A.1.

Table 4.1 Leachate and Sludge Analysis performed on the 30th of August (2024) of the uncentrifuged physical-chemical and biological sludges obtained from the process purges at the BASF WWTP Tarragona.

	Method	**Physical-Chemical Sludge**	**Biological Sludge**
Leachate Analysis			
Suspended Solids (ppm)	Filtration & Gravimetric method (A.1.)	[redacted]	[redacted]
Dissolved Solids (ppm)	Gravimetric method (A.1.)	[redacted]	[redacted]
Total Solids (ppm)	Calculated	[redacted]	[redacted]
pH	Potentiometric Method (A.1.)	[redacted]	[redacted]
Conductivity (mS/cm)	Conductometric Method (A.1.)	[redacted]	[redacted]
Ammonia Concentration (NH^{4+}, ppm)	Commercial Kit	[redacted]	[redacted]
Chemical Oxygen Demand, COD (ppm)	Commercial Kit	[redacted]	[redacted]
Total Organic Carbon, TOC (ppm)	Commercial Kit	[redacted]	[redacted]
Total Nitrogen (ppm)	Commercial Kit	[redacted]	[redacted]
Sludge Analysis			
Dryness (% Dry Solids, DS)	Gravimetric method (A.1)	[redacted]	[redacted]
Humidity (% Water)	Calculation	[redacted]	[redacted]

The dryness of the sludge is a key parameter to assess for the development of the project. Several samples were taken under different conditions, including non-centrifuged sludge, physicochemical sludge, and biological sludge separately, as well as centrifuged sludge from the drying beds at various points. The results are presented in the following table.

Table 4.2 Dryness Analysis of Sludge Samples at Different Conditions using the Gravimetric Method.

Sample Nº	**Sampling Date**	**Sample Description**	**Sampling Location**	**Processing**	**Dryness Result (% Dry Solids)**	**Analysis Date**
1	30/08/24	Physico-chemical Sludge	Process Purge	Un-centrifuged	3,21±0,59	09/09/24

2	30/08/24	Biological Sludge		Sludge	2,64±0,98	09/09/24
3	19/09/24	Sludge mix: 75% FQ 25% Bio			3,50±0,66	30/09/24
4	09/10/24	Sludge from Drying Beds Residence Time 2h	Drying Beds: superficial layer	Centrifuged Sludge	23,37±0,88	09/10/24
5	09/10/24		Drying Beds: buried layer		23,13±0,15	09/10/24
6	09/10/24	Sludge from Drying Beds Residence Time 72h	Drying Beds: superficial layer		24,39±0,43	09/10/24
7	09/10/24		Drying Beds: buried layer		23,77±0,22	09/10/24
8	01/12/24	Sludge mix: 75% FQ (neutralization out of service, [redacted] [redacted]) 25% Bio	Process Purge	Un-centrifuged Sludge	3,27±0,79	12/12/24

Following the previously defined strategy, analyses were conducted to assess and quantify the presence of heavy metals in the biological sludge to evaluate its potential for composting or biogas production. The analytical method used for this purpose was ICP (Section A.1).

Table 4.3 Results of Heavy Metal Analysis by Mass Spectrometry (ICP).

Metal Quantified by ICP	**Physico-chemical Sludge Results** (mg/kg on dry matter basis)	**Biological Sludge Results** (mg/kg on dry matter basis)	**RD 1310/1990 Limits** (mg/kg on dry matter basis)
Cadmium (Cd)	N.D.	N.D.	20
Copper (Cu)	102	112	1000
Nickel (Ni)	357	1057	300
Lead (Pb)	1277	584	750
Zinc (Zn)	253	2512	2500
Mercury (Hg)	5	20	16
Chromium (Cr)	112	97	1000

The results indicate that the biological sludge exceeds the permissible concentrations for nickel, zinc, and lead. Additionally, titanium was also detected, likely due to its presence in the effluent from the physicochemical treatment that is also processed in the biological treatment. The titanium originates from the residual stream of [redacted], demonstrating that this metal does not fully precipitate during the neutralization stage and ultimately reaches the biological treatment.

Based on these results, the possibility of composting and/or biogas production using only this biological sludge is disregarded.

4.3. Dewatering & Drying Technologies and Suppliers

This section presents the technology alternatives and suppliers found in the market that could provide the necessary equipment for the BASF Tarragona site.

4.3.1. Mechanical Dewatering

4.3.1.1. Centrifuge (Flottweg)

The first option considered is the replacement of the aging centrifuges with new ones that provide better operation and performance.

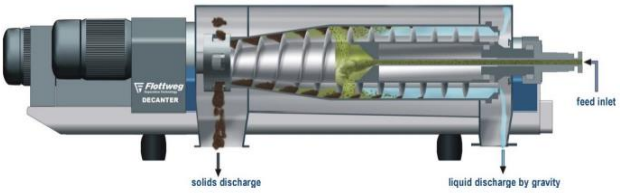


Figure 4.4 Decanter centrifuge from Flottweg.

- **Operating Principle**: A machine that uses high-speed rotation to separate the components of a mixture based on their density gradient. (Davis, 2020)
- **Supplier**: Flottweg (Germany).
- **Dryness:** 27% DS (confirmed by laboratory analysis).

4.3.1.2. Screw Press (Huber)

Another option for mechanical dewatering is the screw press. This technology is commonly used in wastewater treatment plants and sludge management processes

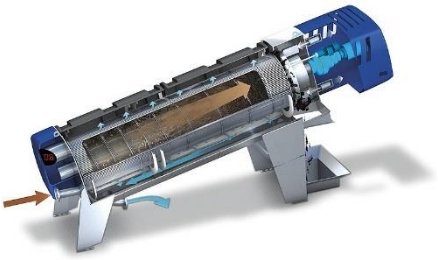


Figure 4.5 Screw Press from Huber.

- **Supplier**: Huber (Germany).
- **Dryness**: 24% DS. Source: Huber.
- **Operating Principle**: A machine that applies mechanical pressure through a rotating screw to compress and separate the liquid from the solids in the sludge. This process is highly efficient, allowing for effective dewatering with minimal energy consumption. The screw press technology is particularly suitable for various types of sludge, offering reliable performance and a compact design that is easy to integrate into existing systems. (Davis, 2020)

4.3.1.3. Filter Press (Autemi)

The last mechanical dewatering option considered has been the filter press.

Figure 4.6 Filter Press from Autemi.

- **Supplier**: Autemi (Italy).
- **Dryness**: 39% DS (confirmed by lab analysis performed by Autemi).
- **Operating Principle**: A machine that applies pressure to the sludge to separate the solids through a filtering medium, retaining the solids on the filter plates. The filter press uses this mechanical pressure to achieve efficient solid-liquid separation, resulting in a dewatered sludge cake. This process is highly effective for achieving high levels of dryness, especially in sludges with high solid content, and is widely used for industrial applications. (Davis, 2020)

4.3.2. Drying

4.3.2.1. Solar Drying (Thermo-System)

The solar drying using greenhouses is an option widely used in Spain due to the suitable weather. This technology can be supplied with additional energy for improved drying results.

THERMO-SYSTEM
INDUSTRIE- & TROCKNUNGSTECHNIK GMBH

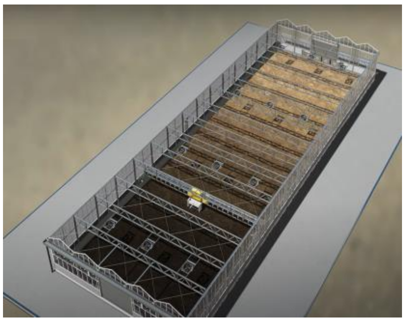


Figure 4.7 Solar Drying Greenhouse by Thermo-System.

This technology has surface needs depending on the outlet dryness to be achieved, production, additional supply of energy, etc. The pre-design conducted by Thermo-System proved to be capable of achieving 55% DS by using the surface already available in the drying beds with a small increase. The following illustration shows the distribution outlining in red the area that would be covered by the greenhouses.

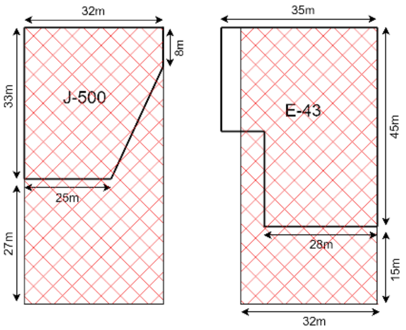


Figure 4.8 Surface Corresponding to Drying beds J-500 and E-43 and future greenhouse implementation outlined in dashed red.

- **Supplier**: Thermo-System (Germany).
- **Dryness**: <60% DS. Source: Thermo-System.
- **Operating Principle**: Solar energy is used to evaporate the moisture from the sludge through controlled ventilation, accelerating the drying process under natural conditions. This technology leverages the power of the sun to achieve efficient drying, reducing the need for external energy sources and making it a more sustainable option. The controlled airflow ensures that the drying process is uniform and effective. (Davis, 2020)
- **Additional Equipment Needed**:
  - Surface Area: 1920 m² (32m*60m)
  - Storage Capacity: 800 tons. Due to low efficiency during winter season.

4.3.2.2. Geomembranes (Geosin)

The geomembranes are a batch technology that operates with disposable synthetic bags, called geomembranes.

Figure 4.9 Geomembranes by Geosin.

The ideal location for the geomembranes requires a drainage system for the filtered water to be sent back to the wastewater treatment. Therefore, the following structure would be placed under the geomembranes in order to provide with a steep and inclined surface and allow water to flow down to the wastewater collection System.

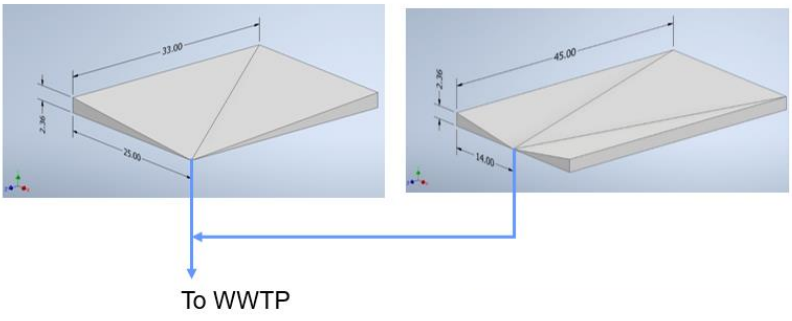


Figure 4.10 Proposal for a drainage system build at the drying beds.

- **Supplier**: G&G (Portugal).
- **Dryness**: <65% DS. Source: Geosin.
- **Operating Principle**: The sludge is contained in permeable geomembranes that allow water evaporation and drainage while retaining the solids. The system harnesses solar heat and airflow to accelerate the dehydration process. This approach is designed to enhance the natural drying process by using renewable energy sources, making it an environmentally friendly and efficient solution. (Davis, 2020)
- **Additional Equipment**:
  - Drainage system.

4.3.2.3. Electro-Osmosis (Bluewin)

The electro-osmosis dryer is an innovative technology for sludge drying.

Electro-Osmosis Dehydrator

Figure 4.11 Electro-osmosis dryer by Bluewin.

The following figures exemplify the electro-osmotic phenomena that causes the sludge drying.

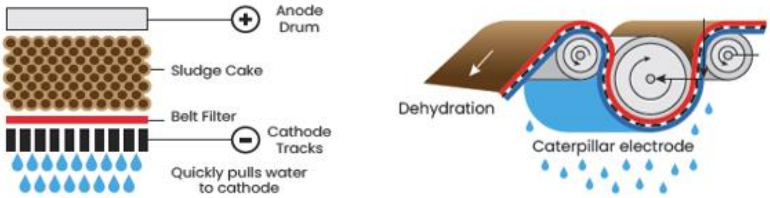


Figure 4.12 Operational principle of the electro-osmosis dryer. (Iwata et al., 2013)

- **Supplier**: Bluewin (South Korea)
- **Dryness**: <50% DS. Source: Bluewin.
- **Operating Principle**: An electric field is applied to dehydrate the sludge through electroosmosis. This process uses electrical energy to generate movement of water molecules, facilitating the removal of moisture from the sludge. Electroosmosis offers an energy-efficient method of dewatering, particularly useful for sludge with high water content, and can significantly improve the speed of the drying process.

4.3.2.4. Belt Dryer (Huber)

The belt dryer Technology uses hot air to heat the sludge and evaporate the water. The hot air can be generated by supplying a source of waste heat if available but also steam. However, the amount of energy needed is really high, and in the case of this project, the belt dryer would be supplied with steam to operate.

HUBER
TECHNOLOGY
WASTE WATER Solutions

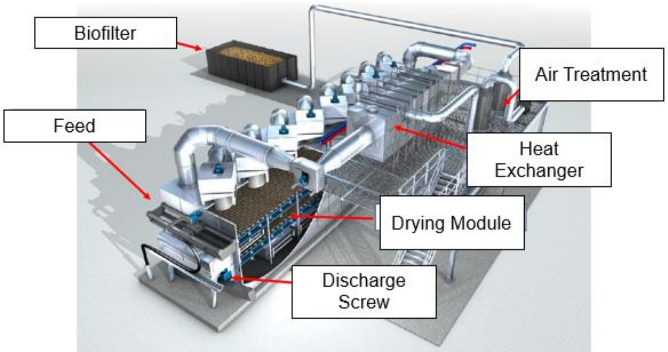


Figure 4.13 Belt Dryer by Huber.

- **Supplier**: Huber (Germany)
- **Dryness**: <90% DS. Source: Huber.
- **Operating Principle**: The sludge is transported on a belt through a chamber where hot air flows counter currently, evaporating the moisture from the sludge. This process enhances the drying efficiency by utilizing a controlled airflow and temperature to rapidly reduce the water content. The countercurrent airflow ensures that the hot air directly contacts the sludge, promoting effective evaporation. (Davis, 2020)
- **Additional Equipment**:
  - Air Treatment (scrubber)
  - Sludge Cooling

4.3.2.5. Natural Ventilation Dryer (Huber)

This technology is similar to the belt dryer. The air used is at a much lower temperature (60 to 120ºC) and together with a ventilation system, it is able to dry the sludge. This avoids the emission of VOCs in therefore, no air treatment is needed.

This technology consists of modular containers, that can be gradually installed to achieve a higher dryness if needed.

Figure 4.14 Natural Ventilation Dryer by Huber.

- **Supplier**: Huber (Germany)
- **Dryness**: <50% DS. Source: Huber.
- **Operating Principle**: The sludge is transported on a belt through a chamber where hot air flows counter currently, evaporating the moisture from the sludge. This method utilizes the heat and airflow to efficiently remove water from the sludge, reducing its moisture content. The countercurrent airflow maximizes contact between the hot air and the sludge, accelerating the evaporation process and improving drying efficiency. (Davis, 2020)
- **Additional Equipment**:
  - Sludge Cooling

4.3.2.6. Thin Film Dryer (GIG Karasek)

The last drying technology considered is the thin film dryer, which uses steam as a thermal fluid to heat up the sludge in the equipment and evaporate the moisture.

This technology needs a condensation stage for the evaporated water in order to be recovered and sent back to the treatment.

GIG KARASEK
A Member of Dr. Aichhorn Group

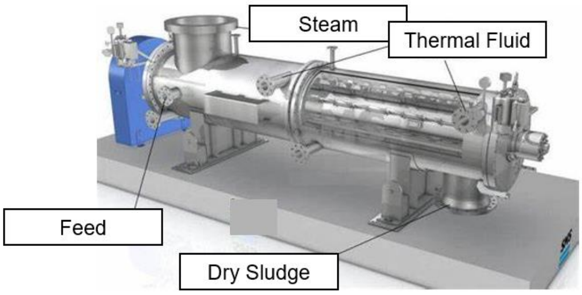


Figure 4.15 Thin Film Dryer by GIG Karasek.

- **Supplier**: GIG Karasek (Germany).

- **Dryness**: 45% DS. Source: GIG Karasek.
- **Operating Principle**: The sludge slides over a continuously heated, thin surface, where the heat causes the evaporation of the water contained in the sludge. This method uses a heating surface that ensures efficient heat transfer to the sludge, promoting rapid moisture removal. The continuous nature of the process ensures consistent drying results and helps to achieve the desired dryness efficiently. (Davis, 2020)
- **Additional Equipment**:
  - Air Treatment (scrubber)
  - Sludge Cooling
  - Distillate Condensation

4.3.3. Summary, Risks & Benefits

The following tables present the key characteristics of each technology, as well as the risks and benefits identified in their use.

Table 4.4 Main Characteristics, Risks And Benefits Of Mechanical Dewatering Technologies Presented.

	Centrifuge	Screw Press	Filter Press
Outlet Dryness (% Dry Solids)	27 (lab-certified by supplier)	24	39 (lab-certified by supplier)
Maintenance	Medium (rotative parts)	Low	High (periodic cloths replacement)
Manpower	Fully automated	Fully automated	Automated (needs periodic observation to ensure proper cake discharge)
Capital Investment	261 k€	312 k€	653 k€
Electricity Consumption	42 kW	7 kW	Average 7 kW
Risks	Higher energy consumption	Lower dryness outlet Higher additive consumption	Higher maintenance (cloths replacement)
Benefits	Already known operation (current technology) High dryness outlet	Low energy consumption	Maximum dryness achieved by only mechanical dewatering

Table 4.5 Main Characteristics, Risks And Benefits Of Drying Technologies Presented.

	Solar Drying	**Geo-membranes**	**Electro-Osmosis**	**Belt Dryer**	**Natural Ventilation Dryer**	**Thin Film Dryer**
Outlet Dryness (% DS)	50-55	60-65	50	90	50	45
Capital Investment	1,05 M€	0,30 M€ + 100k€/y	0,39 M€	3,65 M€	2,24 M€	1,5 M€
Electricity Consumption	44 kW	-	400 kW	70 kW	282 kW	150 kW
Thermal Energy Consumption	-	-	-	720 kW	-	130 kW
Risks	Need to expand drying bed areas	Annual purchase of geo-membranes & subject price to fluctuations	Supplier in South Korea: can be challenging for maintenance & spare parts supply Intensive usage of electricity & subject to fluctuations	Steam usage & subject to fluctuations Air treatment needed due to VOC emissions	Intensive usage of electricity & subject to rate fluctuations	Steam usage & subject to rate fluctuations High capital investment Condensation of evaporated water Air treatment needed due to VOC emissions

Benefits	Minimal operational costs	Minimal capital investment	Low capital investment and operational costs	Maximum outlet dryness (90% DS)	Modular installation (flexibility and possibility of drying more by installing more units in the future)	Compact equipment

4.3.4. Technology Combinations

According to Figure 4.3, which presents the structure of a sludge dewatering and drying plant, combinations of mechanical dewatering technologies and thermal drying will be explored to identify possible alternatives that could be implemented to meet the established objectives.

4.4. Business Case: CAPEX & OPEX Estimation

The CAPEX and OPEX of a technology are key economic information to be considered in the comparison of different sludge dewatering and dehydration proposals. From these calculations, crucial economic metrics -such as Net Present Value (NPV) and payback period- are derived. These metrics are essential for assessing the economic feasibility of a given option and its long-term sustainability.

This section presents the methodology used to calculate each component of the CAPEX and OPEX for each alternative. It also details the assumptions, tools, and factors taken into account during the calculation process.

4.4.1. Assumptions, Challenges & Limitations

The estimation of CAPEX and OPEX relies on certain assumptions to fill certain gaps in data or standardize the analysis among alternatives.

- Equipment Performance. It is assumed that equipment operates at optimal efficiency under standard operating conditions.
- Resource Costs. Energy, water, and chemical costs are based on current market rates (current bills at the WWTP) and assumed to remain stable throughout the project’s operational life.
- Lifespan of Equipment. The equipment's operational life is assumed based on supplier indications.
- Labor Requirements. Labor costs are estimated using standard operational schedules provided by supplier.
- Maintenance Frequency. Maintenance intervals and costs are assumed based on supplier information when available.

Several challenges have arised during the estimation process, including:

- Data Variability. Variability in sludge characteristics may affect equipment sizing and cost estimates.
- Environmental Regulations. Adhering to strict discharge and emissions standards can significantly increase costs, particularly for auxiliary equipment. Therefore, technologies that operate in a way that makes this additional treatment necessary, will present higher costs.
- Future Utility Price Changes. Uncertainty in future energy prices, labor costs, and chemical availability adds uncertainty to long-term OPEX projections.
- Supplier Dependence. Accurate cost estimates rely heavily on supplier input, which may vary in detail, accuracy, or timeliness.

While every effort is made to ensure comprehensive and accurate estimations, the following limitations should be noted.

- Scalability Assumptions. Assumes that scaling equipment capacity will follow linear cost relationships, which may not be true for all technologies.
- Unforeseen Costs. Unexpected expenses, such as additional regulatory compliance requirements or integration with existing infrastructure, may arise.
- Limited Historical Data. For novel or less common technologies, the lack of historical cost data may lead to higher estimation uncertainty.

4.4.2. Methodology for CAPEX Calculations

El Capital Expenditure (CAPEX) of a project represents the capital investment required for the purchase of tangible assets necessary for the implementation of a specific process or one of the proposed alternatives. This concept includes the costs associated with the purchase, installation, and commissioning of equipment and infrastructure essential to the project.

In the context of this project, CAPEX includes all initial costs related to the implementation of sludge dewatering and dehydration technologies. The following items are presented, along with the sources used, assumptions made, and other important factors considered in the calculation process.

4.4.2.1. Primary Equipment Costs

Equipment can be divided into primary and auxiliary systems.

- **Primary Equipment**. These are the core systems that perform the main function and purpose of the process, in this case, the dewatering or drying of sludge.
- **Auxiliary Equipment**. These include all other systems necessary to complement the primary equipment and ensure its proper operation. Examples include fluid transport and storage systems, heating or cooling units, and treatment systems required to comply with environmental regulations.

The cost of **primary equipment** (and some of the auxiliary equipment) has been obtained directly from supplier quotations. These are based on the variables required for proper equipment sizing, including:

- **Sludge characteristics**. Depending on the technology, and the energy source used, it is necessary to know some parameters. The characterization of the sludge is also important to determine the equipment’s construction materials.
    - Type: primary, secondary, mixed, digested or undigested.
    - Initial solids content (TS, %)

    - Volatile solids content (VS, %)
    - Sludge density
    - Estimated composition (presence of fats, heavy metals or other pollutants).
    - Chloride content or other components that determine the material to be used in the equipment.
- **Slurry Production.** Daily or hourly flow rate of slurry to be treated (which defines the design capacity of the equipment). It is important to know if there are production peaks (variability) or other variations due to seasonal factors.
- **Dewatering & Drying Targets**. Specify the end use or disposal method of the sludge, as well as the desired solids content after dewatering and/or drying.
- **Operational Conditions & Available Resources.** Operation mode of the plant (continuous/batch or other), as well as resources available at the site.
    - Operating hours (specify if the equipment will run daily or weekly).
    - Available space or physical dimensions of the area where the equipment will be installed.
    - Energy availability. Electric supply specifications (voltage, frequency, etc.)
    - Water availability. Specify the quality of the water available as well as variables, such as temperature, for cleaning or cooling stages.
    - Steam or thermal energy available. Energy sources that can be used in thermal energy dryers.
- **Environmental & Regulatory Factors.** Factors related to environmental and governmental regulations that may imply a restriction or requirement on the level of dryness to be obtained or in the effluent quality.
    - Effluent or treated water discharge limits in mechanical dehydration.
    - Emission limits, usually caused during thermal drying at moderate or high temperatures (dust, odors, gases, etc.)
    - Local climatic conditions (temperature and humidity that may affect drying performance).
- **Existing Infrastructure & Constraints**. The new equipment has to be integrated with the current system and facilities.
    - Integration with existing systems: Compatibility with current piping, conveyors...
    - Access to the site. Delivery and installation constraints (narrow spaces, limited load-bearing capacity...).
    - Level of automation. Automation requirements subject to manpower availability.

4.4.2.2. Auxiliary Equipment Costs

The cost of auxiliary equipment not included in the previous quotation has been estimated based on similar equipment previously supplied to the plant, for which the sizing parameter (e.g., area, capacity) and price are known. To estimate the price of the equipment, the required sizing parameter was determined, and the following relationships were applied: (Towler & Sinnott, 2013)

$$C_2 = C_1 \left(\frac{S_2}{S_1}\right)^n \tag{4.1}$$

$$Cost\ in\ year\ A = Cost\ in\ year\ B \times \frac{Cost\ Index\ in\ year\ A}{Cost\ Index\ in\ year\ B} \tag{4.2}$$

Where C_1 is the cost of the previously purchased equipment, C_2 is the cost estimation of the new equipment, S is the sizing parameter of each equipment and n is an index corresponding to the type of equipment to be estimated.

These equations have been used to estimate the costs of equipment such as the intermediate storage tank for sludge (located after mechanical dewatering and before thermal drying) and dry sludge silos. These sludge containers have been sized to handle a capacity equal to having a 2 day production storage capacity, in order to account for plant stops or any issues interfering with the continuous and normal operation of the plant.

4.4.3. Methodology for OPEX Calculations

The Operational Expenditure (OPEX) of a process includes the daily costs of operating equipment and systems, including additives, energy, labor, maintenance, and utilities.

$$OPEX = Energy\ Costs + Utility\ Costs\ (water, air\ \ldots) + Additives\ Costs + Maintenance\ Costs + Labor\ Costs \tag{4.3}$$

The details on the calculations performed to obtain the OPEX estimations can be found in appendix B.1.

4.4.4. Summary & Comparison

Based on the calculations, assumptions, and information provided by suppliers, a comparative analysis of the CAPEX and OPEX for each considered technology has been conducted.

4.4.4.1. CAPEX Comparison

The CAPEX for each combination of technologies has been calculated by considering both primary and auxiliary equipment. The cost of primary equipment was obtained directly from quotations provided by the technology suppliers. The following table summarizes the prices of these equipment items.

Table 4.6 Supplier quotations for the technology alternatives of mechanical dewatering and thermal drying.

Technology	**Mechanical Dewatering**	
	Provider, Country	
Centrifuge	Flottweg (Germany)	2 units: 261 220 €
Screw Press	Huber (Germany)	2 units: 312 814 €
Filter Press	Autemi (Italy)	2 units: 653 200 €
	Thermal Drying	
Electro Osmosis	Bluewin (Korea)	2 units: 390 000 €
Natural Ventilation Dryer	Huber (Germany)	2 240 000 €*
Thin Film	GIG Karasek (Germany)	970 000 €*
Belt Dryer	Huber (Germany)	3 650 000 €*
Solar Dryer	Thermo System (Germany)	997 360 €
Geo Membranes	Geosin (Portugal)	101 512 € (/yr)

*The price includes not only the primary equipment but also the auxiliary equipment needed such as coolers, wet scrubbers, condensers, etc.

To calculate the CAPEX for the complete proposal, the required equipment and operations were identified based on each technology. Due to the high number of alternatives analyzed, one example alternative is presented below. This example illustrates the method used to determine all necessary equipment and provides an estimation of the total equipment cost.

Example: Centrifuge and Thin Film Dryer

This alternative includes the centrifuge as a first mechanical dewatering stage and the thin film dryer as the thermal drying.

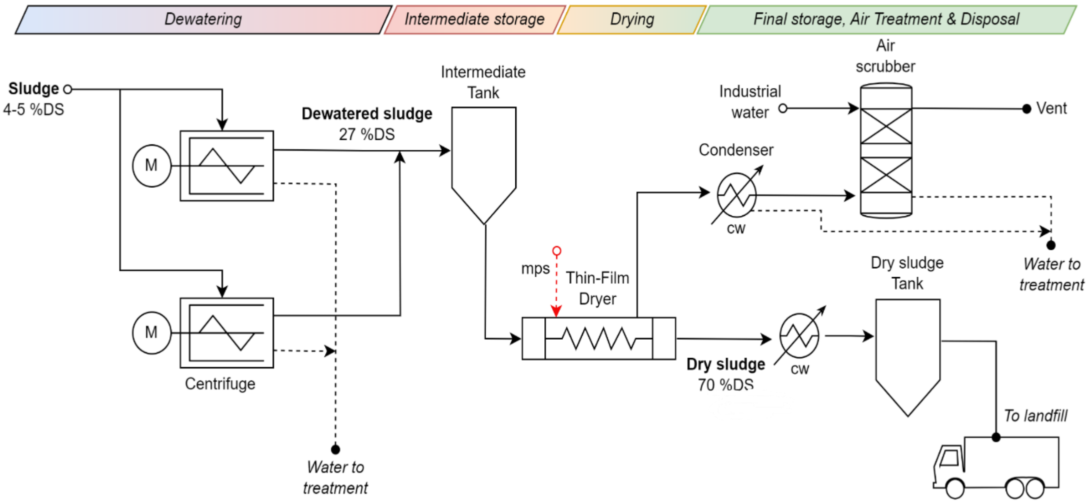


Figure 4.16 Diagram of the technology alternative including centrifuge as mechanical dewatering and thin film dryer as thermal drying.

The thin-film dryer technology operates by heating the sludge to high temperatures using steam and evaporating its water content. As a result, the generation of a vapor stream needs subsequent condensation. The non-condensable gas stream contains a high level of VOCs, which must be minimized to comply with regulations before being vented to the atmosphere. This requires the implementation of a scrubber, where the VOCs in the gas are absorbed using water.

For sludge storage and buffering, an intermediate tank has been implemented after mechanical dewatering to ensure operational continuity in case of maintenance or other interruptions affecting the thin-film dryer. Similarly, redundancy has been incorporated into the centrifuges to maintain uninterrupted operation in the event of maintenance or failure of one unit.

The CAPEX breakdown for all equipment included in the plant is provided below.

Table 4.7 CAPEX breakdown of the centrifuge and thin film dryer alternative.

Mechanical Dewatering			
	Capacity	**Units**	**Cost**
Centrifuge (Flottweg)		2	130 610 €/u
Intermediate Storage Tank	70 m^3	1	47 585 €/u
Thermal Drying			
	Capacity	**Units**	**Cost**
Thin-Film Dryer		1	970 000 €
Condenser		1	Included
Air Scrubber		1	Included
Sludge Cooler		1	Included
Dry Sludge Silo	20 m^3	1	52 500 €/u
TOTAL CAPEX			1 331 304 €

4.4.4.2. OPEX Comparison

The following table details the OPEX for each technology, the equations used, the information sources consulted, and any relevant comments describing the calculations performed.

Table 4.8 Summary of the operational expenses (OPEX) calculations and assumptions made for the current case and each of the considered mechanical dewatering and drying technologies.

	Mechanical Dewatering				**Thermal Drying**					
	Current (Centrifuge)	Centrifuge	Screw Press	Filter Press	Electro Osmosis	Natural Ventilation Dryer	Thin Film	Belt Dryer	Solar Dryer	Geo Membranes
Supplier	GEA Westfalia	Flottweg	Huber	Autemi	Bluewin	Huber	GIG Karasek	Huber	Thermo System	Geosin
Country	Germany	Germany	Germany	Italy	Korea	Germany	Germany	Germany	Germany	Portugal
Operation Mode	Continuous	Continuous	Continuous	Batch (6 cycles/day)	Continuous	Continuous	Continuous	Continuous	Batch (42 cycles/yr)	Batch
Inlet % DS	4	4	4	4	27*	27*	27*	27*	35	27*
Outlet % DS	24	27	24	39	50*	43*	45*	90*	60	67*
Energy Costs. Sources: supplier, calculations										
Installed Power (kW)	35,25	33,4	7,1	6,875	400	282	150	70	44	-
Thermal Energy (kW)	-	-	-	-	-	-	136	650	-	-
Utilities. Sources: supplier										
Water	3 washing cycles/day 12 min/cycle 20 L/min	Supplier: 3 washing cycles/day 10 min/cycle 20 L/min	Supplier: 2 washing cycles/day 10 min/cycle 102 L/min	Supplier: 2 washing cycles/day 10 min/cycle 85 L/min	Supplier: 16 L/min	Supplier: 8 m^3/h cooling water	Supplier: 10 m^3/h cooling water	Supplier: Ind. Water: 7 L/min Cooling water: 23 m^3/h	-	-
Ind. Air	-	-	-	Supplier: 5,085 Nm^3/cycle	Supplier: 0,005 Nm^3/min	-	-	-	-	-
Additives & Consumables. Sources: supplier, (*Water Treatment Handbook*, 1991)										
Flocculant (Polymer)	[redacted]	Bibliography assumption: 3 kg/ton DS	Bibliography assumption: 6 kg/ton DS	Bibliography assumption: 1 kg/ton DS	-	-	-	-	-	Bibliography assumption: 1 kg/ton DS

Defoamer	[redacted]	Concentration: 1 mL/L 400 L/h	Concentration: 1 mL/L 400 L/h		-	-	-	-	-	-
Lube (grease)	[redacted]	1 kg/300 h	1 kg/300 h	1 kg/month	-	-	-	-	-	-
Lime	[redacted]	-	-	3 tons/week (additional to the stabilization)	-	-	-	-	-	-
Maintenance & Spare Parts. Sources: supplier, (Towler & Sinnott, 2013)										
Spare Parts	Reported data from SAP (total costs):	Supplier: Mechanical wearing parts 2000 €/year	No supplier data Assumption based on bibliography: 3%	Supplier: Filter Cloth Replacement 350 €/6 month	Supplier: 1st and 2nd years: free of cost 3rd year on: 15000 €/yr	Supplier: 1,5% of initial investment	No supplier data Assumption based on bibliography: 3%	Supplier: 1,5% of initial investment	Supplier: 2500 €/yr	Purchase of membranes: 101512 €/yr
Maintenance	[redacted]	No supplier data Assumption based on bibliography: 3%		No supplier data Assumption based on bibliography: 3%						-
Labor. Sources: supplier										
Labor Usage	-	-	-	Supplier: Filter Cloth Replacement: needs 24 h and 2 operators Lubrication: needs 4 h once per month	-	-	-	-	Supplier: Daily examination 0,25h Sludge Discharge 8 h/day	-
TOTAL OPEX (€/week)	[redacted]	1483,8	1781,3	2219,7	4357,5	3823,3	8350,7	11962,3	4431,6	3898,7

*Inlet and outlet dryness depends on the mechanical dewatering technology used prior to the drying stage. The data on the table serves as estimation.

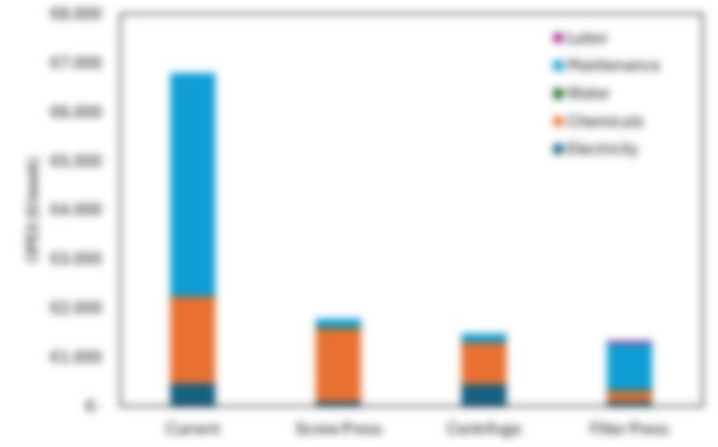


Figure 4.17 Comparison and breakdown of operational expenses of mechanical dewatering technologies.

Regarding the mechanical dewatering technologies, the comparison is presented in Figure 4.17. As shown, the OPEX for the currently used technology is significantly higher than for the proposed alternatives. This is primarily due to the high maintenance costs of the current equipment, which are driven by its age and the malfunctions caused by wear and tear.

The alternative technologies exhibit similar overall OPEX levels but with distinct cost distributions. For both the screw press and the centrifuge, the most prominent expense is for additives, followed by electricity and maintenance costs. However, for the filter press, the cost of additives is notably lower, with maintenance costs being the most significant.

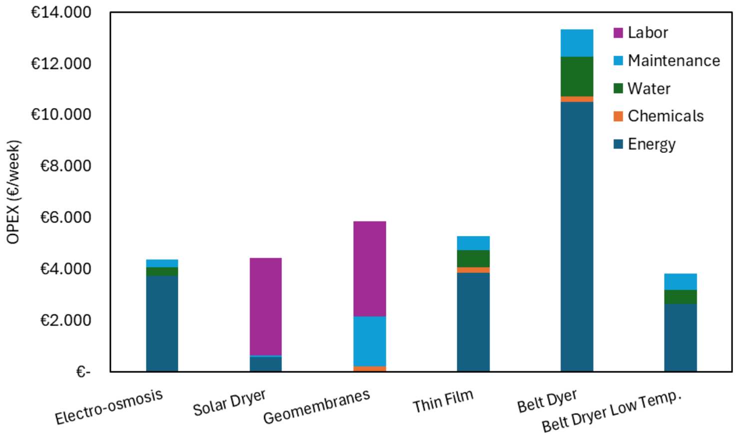


Figure 4.18 Comparison and breakdown of operational expenses of thermal drying technologies.

Regarding thermal drying technologies, the belt dryer stands out for its high energy consumption, primarily due to its reliance on an expensive energy source (steam). However, it delivers the highest sludge dryness by far, reaching 90%.

The thin-film dryer, natural ventilation dryer, and electro-osmosis also exhibit high energy consumption, with electricity being the main energy source for the latter two technologies.

On the other hand, solar dryers and geomembrane-based solutions have significantly lower or nearly negligible energy costs. However, these technologies need higher external labor expenses, as they require the deposition and transport of sludge to the areas where the technology would be implemented. This needs the continued use of Ecojet's external service for sludge handling and maintenance.

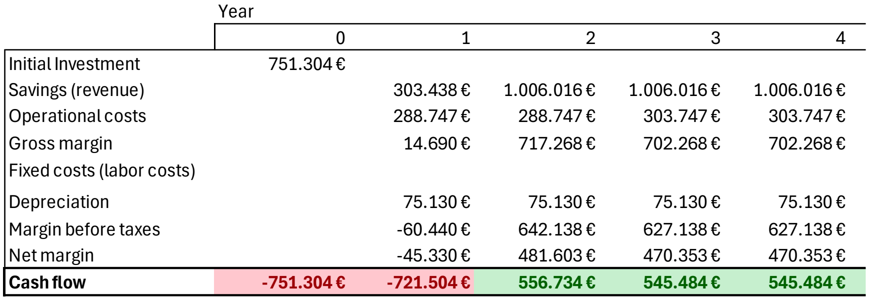
4.4.5. Economic Analysis: Indicators & Cashflows

After completing the investment and operational cost estimations, the cash flows were calculated, enabling the determination of various economic indicators that will support decision-making from a financial perspective.

4.4.5.1. Calculation of Economic Indicators & Cashflows

As previously stated, the objectives of the project are the minimization of transport and disposal costs of sludge (reduction of sludge production) and compliance with dryness regulations.

Therefore, the economic revenues in this project are defined as the savings in sludge handling and disposal generated with the implementation of a new technology.



	Year				
	0	1	2	3	4
Initial Investment	751.304 €				
Savings (revenue)		303.438 €	1.006.016 €	1.006.016 €	1.006.016 €
Operational costs		288.747 €	288.747 €	303.747 €	303.747 €
Gross margin		14.690 €	717.268 €	702.268 €	702.268 €
Fixed costs (labor costs)					
Depreciation		75.130 €	75.130 €	75.130 €	75.130 €
Margin before taxes		-60.440 €	642.138 €	627.138 €	627.138 €
Net margin		-45.330 €	481.603 €	470.353 €	470.353 €
Cash flow	**-751.304 €**	**-721.504 €**	**556.734 €**	**545.484 €**	**545.484 €**

Figure 4.19 Example of cashflow calculations.

4.4.5.2. Results & Comparison

In this section, the results obtained in the calculation of the different economic indicators are presented, as well as a comparison between the different alternatives considered. This aspect provides the economic aspect in the selection of the most suitable technology for the project.

Due to the numerous technology combinations, they have been presented using shortcut nomenclature, which is presented below.

Table 4.9 Shortcut nomenclature used to identify the different technology alternatives.

Acronym	Technology
C	Centrifuge
SP	Screw Press
FP	Filter Press
ELO	Electro Osmosis Dryer

NVD	Natural Ventilation Dryer
BD	Belt Dryer
GM	Geo Membranes
TF	Thin Film Dryer
SS	Solar Dryer

Figure 4.20 Comparison of total costs in the 1st year of implementation of the alternative (initial investment plus operational costs) and final dryness obtained with each alternative.

The figure above shows the total costs in the first year of implementation of each technology combination alternative. It is observed that in general, a higher final drying result also implies a higher capital investment, except in the case of NVD, in which the capital investment is very high despite providing a final drying comparable to other more economic technologies.

Operating costs are also higher in belt dryer (BD) technology because of the use of steam.

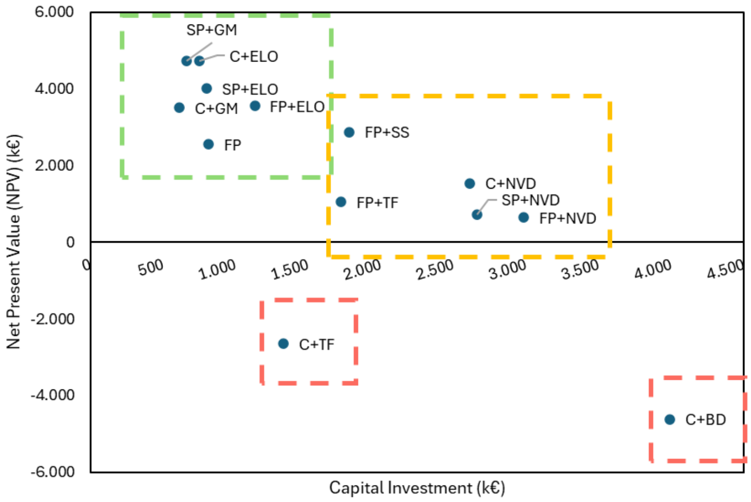


Figure 4.21 Comparison of NPV with respect to the initial capital investment for each alternative.

Figure X.6. shows the NPV with respect to the initial capital investment. The interpretation of the relationship of these two indicators allows us to decide whether an alternative is good or not according to the location of the point on the graph. All alternatives with NPV values are not economically interesting projects, as is the case of C combined with TF and BD.

When the NPV is positive, alternatives with a lower capital investment should be selected, as is the case of the alternatives within the rectangle outlined in green.

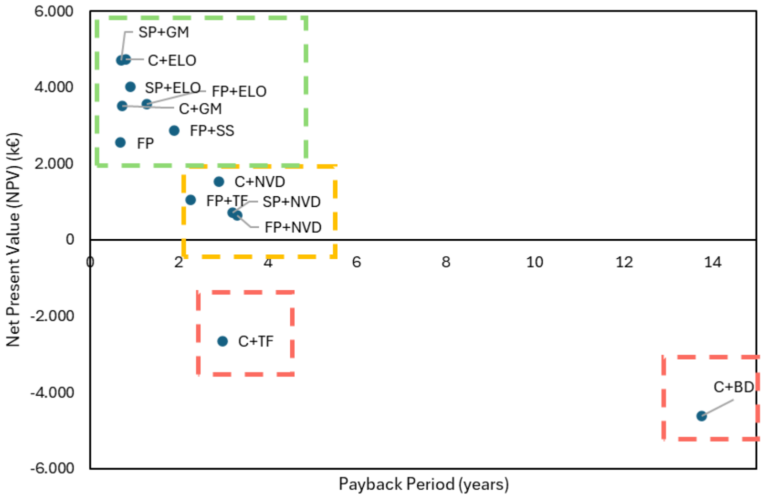


Figure 4.22 Comparison of the NPV with respect to the payback period of each alternative.

Another interesting relationship and economic indicator is NPV with respect to the payback period. As in the previous relationship, negative NPV values are not interesting from an economic point of view. In the same way, very high values of payback period indicate that the investment is recovered in a long time. In the same way, the most interesting alternatives are indicated by a green underlined rectangle.

Based on the figures and ratios shown, it is determined that the alternatives involving thermal drying are not economically interesting for this project, since they require a very high investment with respect to the NPV.

The options that have proven to be interesting are technologies that do not have a high operational cost (low use of electricity and/or no use of steam), such as centrifuge, filter press and/or screw press combined with geomembranes or electro osmosis.

The following figure shows the cash flows of the alternatives of economic interest for the project.

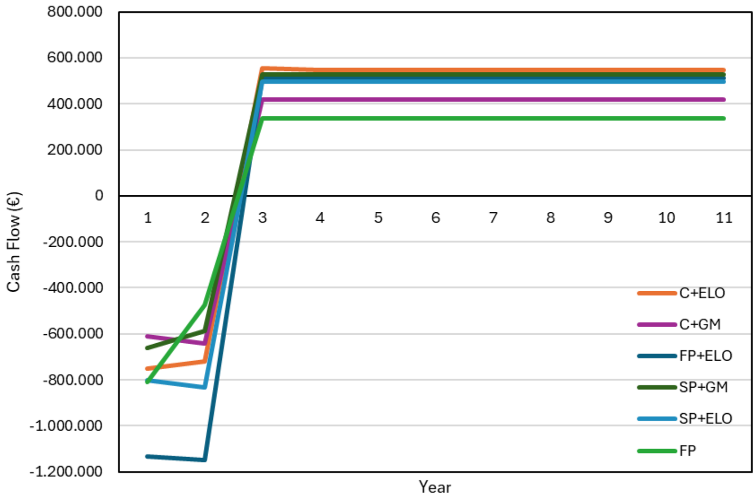


Figure 4.23 Comparison of cash flows of the most promising alternatives according to NPV and Payback Period.

4.5. Sustainability Indicators

Carbon dioxide emissions are one of the main sources of pollution associated with transportation and landfill disposal of sludge. Therefore, an estimation of emission reductions for the different alternatives has been made to provide an environmental indicator and evaluate the alternatives in a holistic manner.

The considered emissions come from the process (use of utilities), the road transport of sludge to the authorized landfill, and finally, the emissions occurring at the landfill.

Below are the emission factors used for the calculations.

Table 4.10 $CO_{2,eq}$ emission factors of the utilities used.

Utility	Emission Factors
Steam	[redacted] kg $CO_{2,eq}$/t steam (Source: BASF)
Electricity	[redacted] kg $CO_{2,eq}$/kWh (Source: BASF)
Diesel	[redacted] kg $CO_{2,eq}$/l diesel (Houghton, 1997)

The following figure presents the breakdown of total emissions for each alternative in the dewatering/drying process, transportation, and landfill.

Figure 4.24 Breakdown of $CO_{2,eq}$ emission sources for each technology combination alternative.

As can be seen, the emissions caused by the process are higher in alternatives that make intensive use of steam and/or electricity.

Emissions at the landfill and from transportation are greater in the options that achieve lower drying, as the mass of sludge to be transported and disposed of in the landfill is higher.

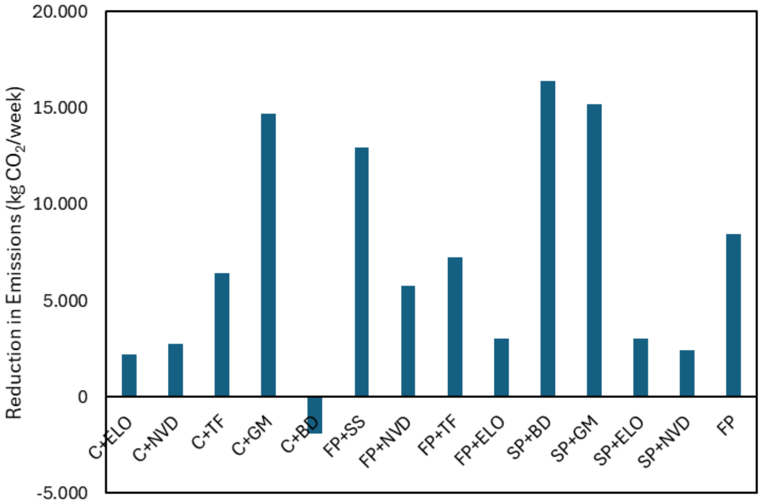


Figure 4.25 Reduction in $CO_{2,eq}$ emission achieved by using each technology combination alternative.

By observing the emission reductions compared to the current scenario, a similar trend is noted, where technologies that provide higher drying (resulting in a lower final sludge mass) achieve a greater reduction in emissions.

4.6. Selection Criteria for Optimal Solution

4.6.1. Indicators

The economic indicators are critical for assessing and comparing the alternatives based on their financial impact. These indicators help determine which solution provides the best value and cost-effectiveness. The indicators used for evaluating economic performance include:

- **Cost of sludge processing (€/ton of processed sludge):** This represents the total cost incurred for processing one ton of sludge, including equipment, labor, and other related expenses.
- **Cost of dried sludge (€/ton of dried sludge):** This measures the cost of processing the sludge into a dried form.
- **Cost of disposal (€/ton of sludge):** This represents the disposal fee applied to the sludge once it has been processed. It takes into account all the costs associated with transporting and disposing of the treated sludge. The tariff is specific to the type of sludge and the disposal method used.

The energy indicators are used to measure the efficiency of each alternative in terms of energy consumption.

- **Specific energy consumption (kWh/t evaporated water):** This measures the amount of energy required to evaporate one ton of water.
- **Specific energy consumption (kWh/t processed sludge):** This indicator quantifies the energy used to process one ton of sludge, giving a direct insight into how energy-intensive a specific technology is.

Operational indicators evaluate the performance of the sludge treatment process and its operational efficiency.

- **Sludge production (t/day):** This indicates the amount of sludge produced per day during the treatment process.
- **Solids content:** This measures the percentage of solid matter within the sludge.
- **Manpower usage:** This indicator tracks the labor required to operate and maintain the treatment system. Lower manpower usage often indicates a more automated.
- **Water recovery rate (%):** This measures the percentage of water that is recovered during the treatment process. Higher water recovery rates indicate that the technology is effective in reclaiming water.
- **Evaporation rate (t water/h):** This tracks the rate at which water is evaporated from the sludge. A higher evaporation rate suggests a faster dewatering process.
- **Sludge mass reduction (%):** This indicator measures the reduction in sludge volume or mass as a result of treatment.

The environmental indicators are focused on assessing the environmental impact of each technology.

- **GHG emissions (kg CO2eq/week):** This measures the total greenhouse gas emissions produced per week by the treatment process.

- **Specific GHG emissions (kg CO2eq/ton dried sludge):** This evaluates the amount of greenhouse gases emitted per ton of dried sludge produced. This indicator helps to compare the carbon intensity of different sludge treatment processes.
- **Specific water consumption (L/kg dried sludge):** This measures the amount of water consumed in the treatment process per unit of dried sludge produced.

Together, these indicators allow for a comprehensive assessment of each alternative based on economic, operational, energy, and environmental factors, providing a holistic approach.

4.6.1.1. Mechanical Dewatering Technologies

The following figure presents some of the most relevant indicators, such as the specific energy consumption per ton of processed sludge and the specific cost of sludge processing.

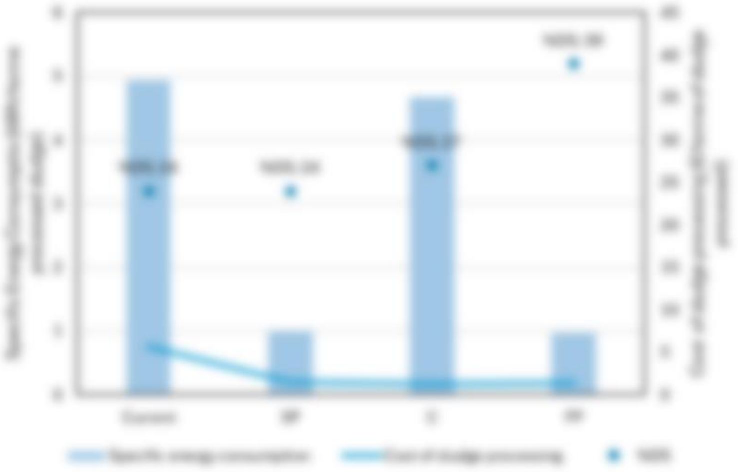


Figure 4.26 Specific energy consumption and specific cost of sludge processing for mechanical dewatering technologies.

As can be observed, the specific energy consumption is higher in centrifuges, as their electricity consumption exceeds that of the other options. The filter press and screw press present lower specific energy consumption, with the filter press offering a significantly higher drying capacity.

The specific cost of sludge processing is higher with the current technology, while there are no significant differences compared to the other alternatives.

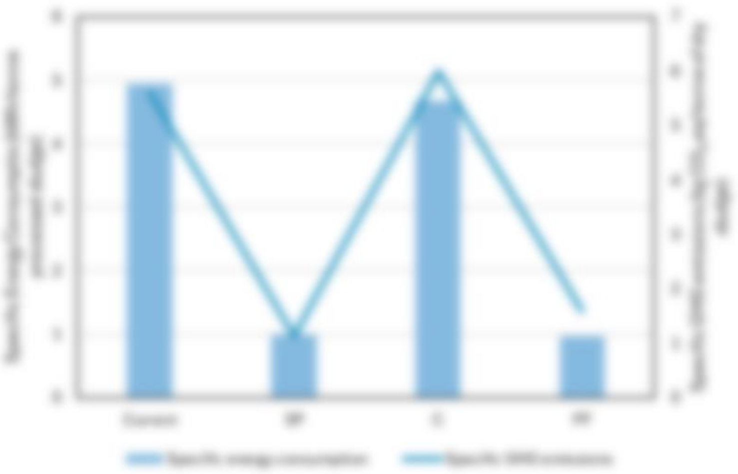


Figure 4.27 Specific energy consumption and specific GHG emissions for mechanical dewatering technologies.

In the previous figure, the relationship between specific energy consumption and GHG emissions is shown. It can be observed that higher specific energy consumption leads to higher GHG emissions, primarily due to the increased energy consumption.

4.6.1.2. Drying Technologies

The following figures present some of the most relevant indicators calculated for the drying technologies.

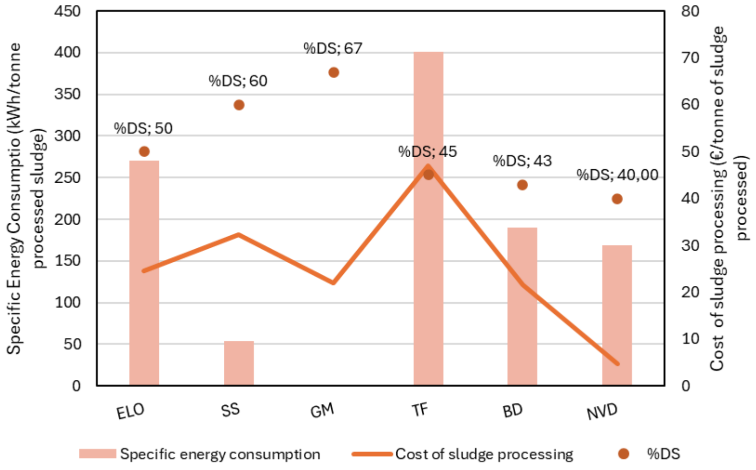


Figure 4.28 Specific energy consumption and specific cost of sludge processing for drying technologies.

The specific energy consumption is higher in technologies that use more steam or electricity, such as ELO, TF, BD, and NVD. Solar drying and geomembranes, on the other hand, present a drastically lower value compared to the aforementioned alternatives.

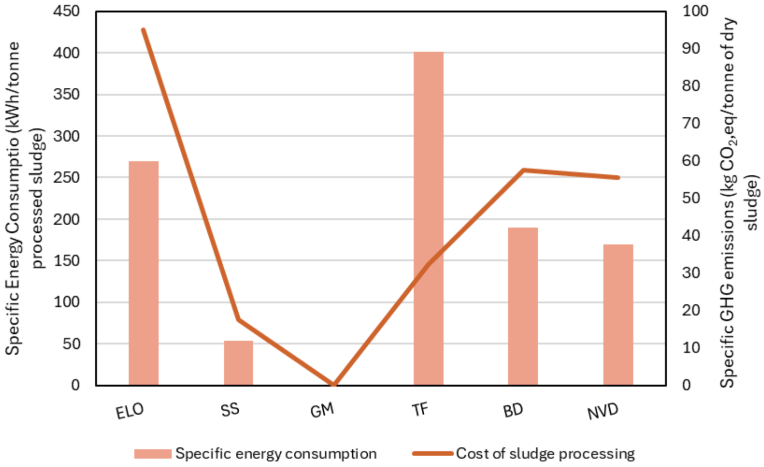


Figure 4.29 Specific energy consumption and specific GHG emissions for mechanical dewatering technologies.

The relationship between the specific energy consumption and GHG emissions show the same tendency as in the dewatering technologies. Higher energy consumption results in higher GHG emissions.

4.6.1.3. Technology Combinations

The indicators calculated for the Technology combinations are presented in this section.

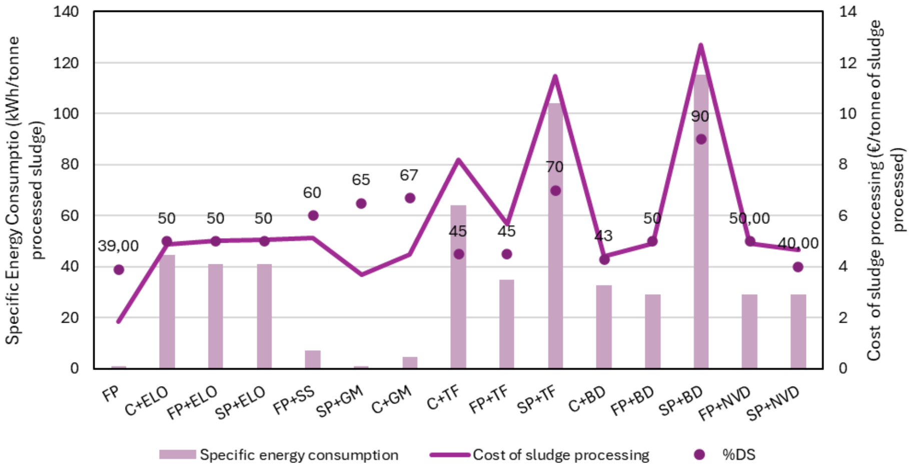


Figure 4.30 Specific energy consumption and specific cost of sludge processing for all technology combinations.

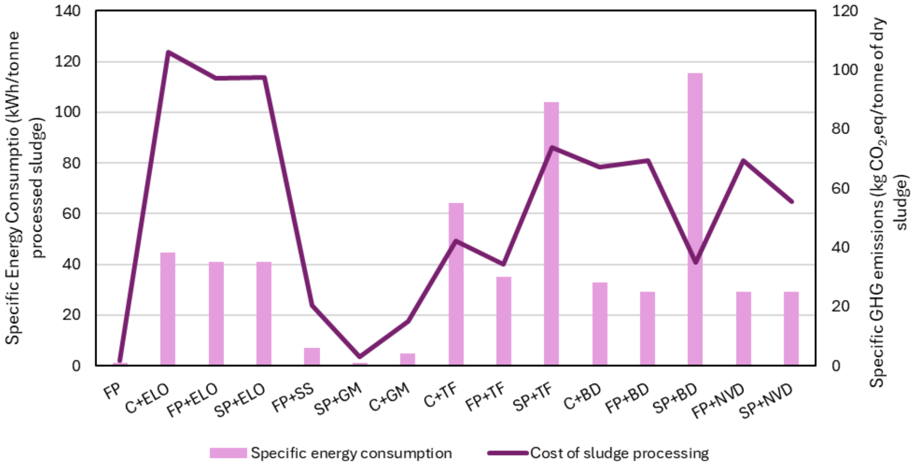


Figure 4.31 Specific energy consumption and specific GHG emissions for all technology combinations.

From the figures, it is evident that drying technologies significantly influence the specific energy consumption, as the highest energy expenditure occurs during this stage. Combinations that include solar drying or geomembranes demonstrate a lower specific energy consumption.

It can also be observed that the filter press achieves the best results in terms of both specific energy consumption and the specific cost of sludge processing, while also contributing to the lowest GHG emissions.

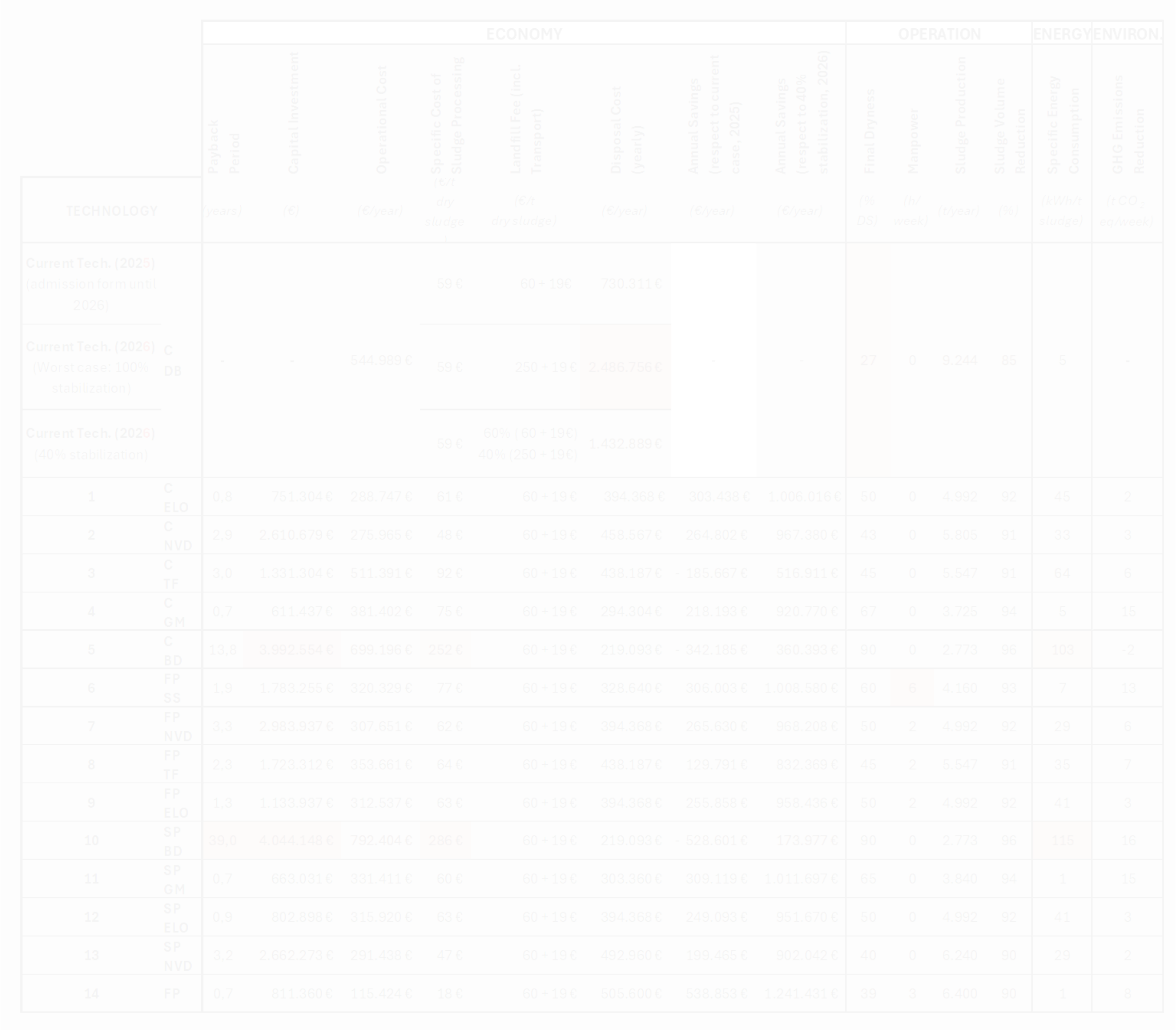
4.6.1.4. Summary

The results for all indicators and all technologies considered can be found in appendix B.3.

4.6.2. Decision Matrix

Based on the information presented, indicators have been calculated to evaluate each combination of technologies in various relevant aspects: economy, operation, energy, and environment. The combination of this information and results provides sufficient criteria to make a decision regarding the alternative that offers the most benefits at all levels. A summary of the most relevant indicators has been compiled into a decision matrix.

Each column of the matrix corresponds to an indicator, and a color scale has been implemented for each one. Red is assigned to the worst values in the set, orange/yellow to the intermediate values, and green for the best values for that indicator.



		ECONOMY								OPERATION				ENERGY	ENVIRON.
TECHNOLOGY		Payback Period (years)	Capital Investment (€)	Operational Cost (€/year)	Specific Cost of Sludge Processing (€/t dry sludge)	Landfill Fee (incl. Transport) (€/t dry sludge)	Disposal Cost (yearly) (€/year)	Annual Savings (respect to current case, 2025) (€/year)	Annual Savings (respect to 40% stabilization, 2026) (€/year)	Final Dryness (% DS)	Manpower (h/week)	Sludge Production (t/year)	Sludge Volume Reduction (%)	Specific Energy Consumption (kWh/t sludge)	GHG Emissions Reduction (t CO₂ eq/week)
Current Tech. (2025) (admission form until 2026)	C DB	-	-	544.989 €	59 €	60 + 19€	730.311 €	-	-	27	0	9.244	85	5	-
Current Tech. (2026) (Worst case: 100% stabilization)					59 €	250 + 19 €	2.486.756 €								
Current Tech. (2026) (40% stabilization)					59 €	60% (60 + 19€) 40% (250 + 19€)	1.432.889 €								
1	C ELO	0,8	751.304 €	288.747 €	61 €	60 + 19 €	394.368 €	303.438 €	1.006.016 €	50	0	4.992	92	45	2
2	C NVD	2,9	2.610.679 €	275.965 €	48 €	60 + 19 €	458.567 €	264.802 €	967.380 €	43	0	5.805	91	33	3
3	C TF	3,0	1.331.304 €	511.391 €	92 €	60 + 19 €	438.187 €	- 185.667 €	516.911 €	45	0	5.547	91	64	6
4	C GM	0,7	611.437 €	381.402 €	75 €	60 + 19 €	294.304 €	218.193 €	920.770 €	67	0	3.725	94	5	15
5	C BD	13,8	3.992.554 €	699.196 €	252 €	60 + 19 €	219.093 €	- 342.185 €	360.393 €	90	0	2.773	96	103	-2
6	FP SS	1,9	1.783.255 €	320.329 €	77 €	60 + 19 €	328.640 €	306.003 €	1.008.580 €	60	6	4.160	93	7	13
7	FP NVD	3,3	2.983.937 €	307.651 €	62 €	60 + 19 €	394.368 €	265.630 €	968.208 €	50	2	4.992	92	29	6
8	FP TF	2,3	1.723.312 €	353.661 €	64 €	60 + 19 €	438.187 €	129.791 €	832.369 €	45	2	5.547	91	35	7
9	FP ELO	1,3	1.133.937 €	312.537 €	63 €	60 + 19 €	394.368 €	255.858 €	958.436 €	50	2	4.992	92	41	3
10	SP BD	39,0	4.044.148 €	792.404 €	286 €	60 + 19 €	219.093 €	- 528.601 €	173.977 €	90	0	2.773	96	115	16
11	SP GM	0,7	663.031 €	331.411 €	60 €	60 + 19 €	303.360 €	309.119 €	1.011.697 €	65	0	3.840	94	1	15
12	SP ELO	0,9	802.898 €	315.920 €	63 €	60 + 19 €	394.368 €	249.093 €	951.670 €	50	0	4.992	92	41	3
13	SP NVD	3,2	2.662.273 €	291.438 €	47 €	60 + 19 €	492.960 €	199.465 €	902.042 €	40	0	6.240	90	29	2
14	FP	0,7	811.360 €	115.424 €	18 €	60 + 19 €	505.600 €	538.853 €	1.241.431 €	39	3	6.400	90	1	8

Figure 4.32 Decision matrix composed of indicators related to economic, operational, energy, and environmental aspects.

4.6.3. Proposed Solution

After thoroughly reviewing all the collected information, the business case analysis, and calculating several key indicators related to economic, operational, energy, and environmental aspects, the most optimal solution has been determined to be the filter press, for the following reasons:

- **Simplicity of the solution**: This option involves just one stage of mechanical dewatering, eliminating the need for a separate drying stage.
- **Elimination of drying beds and reduced need for external sludge transportation**: By removing the drying beds, the process becomes more efficient, and there is no need for the external company Ecojet to transport the sludge within the site. This results in reduced labor costs.
- **Compliance with dryness regulations**: Based on certified pilot lab analysis from the supplier (appendix A.3), the filter press can achieve 39% Dry Solids (DS)

without the use of additives. Furthermore, there is potential for improvement by incorporating pre-treatment stages or adding chemical aids.

- **Lowest operational costs**: The filter press option stands out due to its minimal use of additives and reduced electricity consumption, resulting in significantly lower operational costs compared to other alternatives.
- **Low capital investment**: The filter press requires a lower initial capital investment than many other technologies, making it a cost-effective solution.
- **Highest annual savings**: Due to lower operational costs and the reduction in sludge mass, the filter press offers the highest annual savings compared to the current technology disposal costs.
- **Lowest specific energy consumption**: This technology consumes minimal energy for dewatering the sludge, making it a highly energy-efficient solution.
- **Shortest payback period**: With a payback period of only 0,7 years, the investment will be fully recovered in less than a year.
- **Lowest specific cost of sludge processing**: The costs associated with processing the sludge are significantly lower, driven by the reduced operational and energy expenses.
- **GHG emissions reduction**: The reduction in sludge mass leads to a decrease in transport requirements and overall residue generation, contributing to a reduction in greenhouse gas emissions.

The filter press not only meets technical and regulatory requirements but also delivers superior cost savings, operational efficiency, and environmental benefits, proving to be the optimal choice for the sludge treatment process.

5. BASIC ENGINEERING OF THE PROPOSED SOLUTION: FILTER PRESS

5.1. Selection of the Filter Press

In this section, the design, sizing and control strategy of the filter press plant are discussed in depth, presenting it as the technology of choice for sludge dewatering. After the evaluation of various alternatives, as previously seen, the filter press has shown to be the optimal solution, balancing economic, energy and environmental aspects.

The decision to implement a dewatering process based on the filter press technology is due to its unique ability to achieve the required sludge dryness in a single mechanical dewatering stage, eliminating the need for any thermal drying. This distinction not only simplifies the process, but also significantly reduces both capital expenditure (CAPEX) and operating expenditure (OPEX) compared to other technologies, as it has been observed on previous sections.

5.2. Process Description

This section provides an in-depth explanation of the sludge dewatering process, detailing the reasoning behind key design decisions and the functions of each piece of equipment within the system. It also presents the most relevant operating variables selected to achieve optimal performance and efficiency.

More specific and technical details will be included in subsequent sections, where design calculations, supporting data, and other relevant information will be shown. These will offer a deeper understanding of the methodologies and engineering principles that have been applied in the system’s design.

5.2.1. Sludge Reception & Buffering

The mixture of biological and physicochemical sludge, originating from the decanters and purges of the treatment process, flows into the underground tank R-9B. This tank serves as a buffer to mitigate variations in flow rate and/or sludge composition, ensuring stability for the subsequent sludge dewatering process.

The sludge mixture contains a lime concentration of 15% relative to the dry solids content. This lime is added during the stabilization stage of the biological sludge, following the purge carried out in the biological treatment process.

Lime acts as an additive that, in addition to its essential role in stabilizing the sludge by eliminating biological activity, also enhances mechanical dewatering using filter presses. Lime is an inorganic chemical that, upon contact with the sludge slurry, acts as a precipitant. It promotes the formation of larger insoluble solid particles that precipitate, improving water filtration efficiency.

Simultaneously, lime also aids in cleaning the filter cloths, reducing scaling and facilitating the release of sludge cakes from the press. (W. Bell, 1989)

The R9-B pit has a capacity of [redacted] m³ and is coated with a specialized resin coating to prevent corrosion damage and infiltration caused by the sludge. As previously stated, the sludge has a high chloride content [redacted] ppm) and a water content of approximately 97%. A paddle agitator ensures continuous mixing of the sludge to prevent the settling of solids. (Green & Southard, 2019)

The sludge contained in pit R9-B is transported using the diaphragm pneumatic pumps P70A/B, which have a capacity of up to 20 m³/h. These pumps are installed in a redundant configuration to ensure reliable operation and maintain continuity in the process.

5.2.2. Thermal Conditioning of Sludge

The sludge mixture is directed to the thermal conditioning stage, carried out in the spiral plate heat exchanger W-1. At this stage, the sludge, initially at ambient temperature (25–30°C), is heated to reach 55°C. Thermal conditioning induces permanent changes in the structure of the flocs and cell clusters, partially breaking bonds and membranes. This process enhances the efficiency of subsequent mechanical dewatering. (Topal & Arslan, 2009)

Heating the sludge creates a density gradient between the solid fraction and the various liquid components (primarily water), which enhances subsequent filtration. Thermal conditioning has been shown to improve the final dryness achieved by 2–3%, according to data from BASF Ludwigshafen. It is important to note that the temperature reached in the sludge is sufficient to enhance dewatering efficiency without reaching levels that would volatilize organic compounds present in the sludge. As a result, issues related to odors or VOC emissions are avoided.

The heat medium used consists of condensates, which serve as a source of residual heat. These condensates are obtained from the steam distribution system located within the same WWTP facility, where steam pressure is reduced from 35 bar to 5 bar. The condensates generated during this pressure reduction are stored in the condensate tank B-5626 and are produced at a rate of 4 m^3/h, with a temperature of approximately 100–95°C.

Typically, these condensates are reused in the industrial water circuit; however, their energy content is wasted, and they can occasionally cause operational issues, such as promoting the growth of Legionella bacteria in the water. Utilizing this residual heat source represents a cost-free resource that enhances the mechanical dewatering of sludge while simultaneously mitigating operational challenges in the water circuit.

The heat exchanger W-1 has been designed as a spiral plate heat exchanger, a type highly suitable for handling dirty fluids. (Khorshidi & Heidari, 2016) Its elevated and continuous variation in flow direction promotes constant turbulence, minimizing low-velocity zones within the fluid. This effectively reduces solid deposition and, consequently, fouling.

The heat exchanger operates in a counter-current flow configuration, ensuring highly efficient energy transfer. It features a heat exchange area of 14 m^2.

After thermal conditioning, the lower-temperature condensates (60°C) are returned to the condensate storage tank.

5.2.3. Chemical Conditioning of Sludge

Under normal operating conditions, thermally conditioned sludge is directed to the chemical conditioning tank B-1, where polyelectrolyte is added at a concentration of 1 kg per ton of dry solids. (W. Bell, 1989)

In the event that W-1 is out of service for maintenance or any other reason, a bypass system has been implemented. This allows the thermal conditioning stage to be skipped, sending the sludge directly to chemical conditioning. However, the final dryness of the sludge would not benefit from the improvements typically provided by thermal conditioning.

In tank B-1, the polyelectrolyte or flocculant reacts with the sludge, facilitating the formation of large aggregates known as flocs. The formation of these flocs is essential for improving the filtrability of the solids, thereby enhancing the mechanical dewatering process through filtration.

The sludge and polyelectrolyte are mixed and brought into contact with each other through gentle agitation (within the range of 20-50 rpm) using a Rushton flat-blade turbine agitator. The required agitation power should be within the range of 0,04-0,1 kW/m^3, providing sufficient but gentle mixing to homogenize the mixture and form flocs without being too aggressive, which could difficult floc formation or even break up the formed flocs, reversing the process. (Sinnott, 2005) The necessary residence time for thermal conditioning is typically 20-25 minutes.(W. Bell, 1989)

Tank B-1 is an atmospheric tank with a capacity of 10 m³. The tank is equipped with thermal insulation to retain the heat of the sludge. However, in the event that the sludge remains in the tank longer than expected and the temperature drops below a certain level, a system has been implemented to recirculate the sludge back to W-1 using the pneumatic diaphragm pump P-71.

5.2.4. Sludge Filtration Process

Once the sludge is conditioned, it is ready for the filtration stage using the filter press. Both the filters and the respective feed pumps are installed in duplicate to ensure operational continuity in case of maintenance, breakdowns, or other unforeseen circumstances.

The filtration stage in the filter press is a batch process, although the filter press is fully automated (requiring no intervention from the operator(s)). In this particular case, six filtration cycles are performed per day to meet the demand, each consisting of several distinct stages: (Autemi, 2021)

- **Filling**. Duration: 18 minutes. The sludge is pumped into the filter press until it is fully filled.
- **Filtration**. Duration: 188 minutes. The water is separated from the sludge as it passes through the filter cloths, while the solids are retained in the chambers, forming a sludge cake.
- **Discharge and Cleaning**. Duration: 34 minutes. Once filtration is complete, the filter plates are opened to release the dehydrated sludge cakes.

The feed pumps are hydraulically driven piston pumps, as they are capable of performing the function without causing excessive shear stress, thus preventing the degradation of the flocs formed. (Green & Southard, 2019) The P-72A/B pumps serve two functions: initially, when the pressure is still low, they provide a high flow rate to fill the filter press with sludge for filtration. Once the filter is filled and the operating pressure is reached, the pumps continue feeding the filter press, but at a reduced flow rate, due to the progressive formation of the cake within the press and the resistance it creates to the water flow through the membrane. The filter presses, F-1A/B, are also equipped with a hydraulic screw system to apply pressure to the membranes and facilitate the formation of the cake. (Autemi, 2021)

The filter press is also equipped with an automatic high-pressure washing system, which includes a water tank (B-2) and a piston pump (P-73). This system can reach pressures up to 90 bar, ensuring thorough cleaning of the membranes, which extends their service life and maintains the performance of the filter presses over a longer period.

5.2.5. Sludge Cake Handling & Disposal

Once filtration is completed, the plates of the filter press automatically open, releasing the cakes, which fall by gravity into the trailers positioned directly under the filter presses. The filtered water is returned to the treatment process.

The trailers have a capacity of 30 m³, which is sufficient to accumulate dried sludge for a reasonable period before it is sent for disposal at an authorized landfill.

5.3. Equipment Sizing & Design

Once filtration is completed, the plates of the filter press automatically open, releasing the cakes, which fall by gravity into the trailers positioned directly under the filter presses. The filtered water is returned to the treatment process.

The trailers have a capacity of 30 m³, which is sufficient to accumulate dried sludge for a reasonable period before it is sent for disposal at an authorized landfill.

5.3.1. Sludge Pit & Pumping, R-9B & P-70A/B

Both the R-9B sludge pit and the P-70A/B pumps are existing equipment in the plant. Therefore, no additional design is required, as they fully meet the capacity requirements.

5.3.2. Spiral Plate Heat Exchanger, W-1

Thermal conditioning is an alternative pretreatment step that has shown to significantly enhance the performance of mechanical dewatering processes at WWTP BASF Ludwigshafen, as shown in the figure 5.1. It achieves this by modifying and breaking the bonds in cellular aggregates and flocs, improving the separation efficiency during dewatering. (Topal & Arslan, 2009)

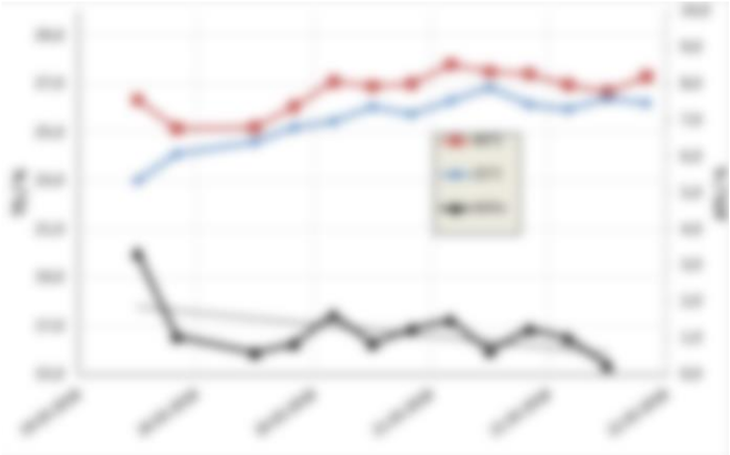


Figure 5.1 Outlet mechanical dewatering dryness results for undigested mixed industrial sludge without thermal conditioning (blue line, 25ºC) and with thermal conditioning (red line, 40ºC). Source: WWTP BASF Ludwigshafen.

Given the availability of a highly convenient residual heat source in terms of proximity and thermal capacity, the implementation of a thermal conditioning stage prior to mechanical dewatering with filter presses was chosen.

Thermal conditioning involves heating the sludge to moderate or high temperatures, depending on the availability of energy resources and the desired outcomes. In this case, the process is carried out using a spiral plate heat exchanger, a particularly suitable type of exchanger for handling dirty fluids due to its internal hydrodynamics.

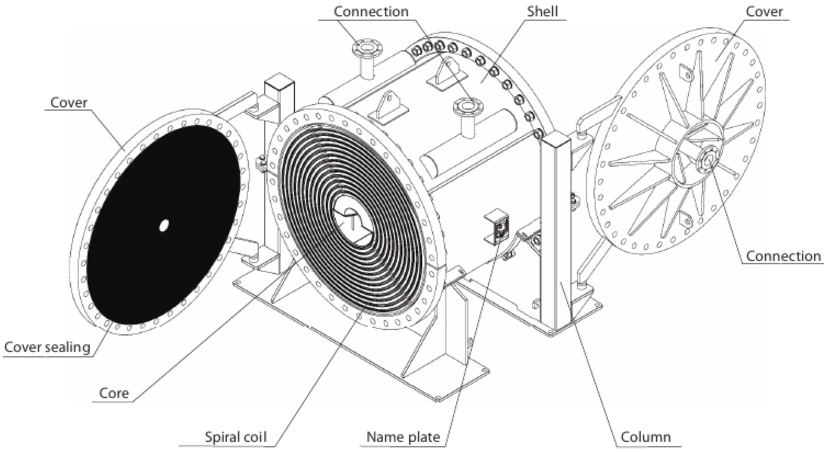


Figure 5.2 Illustration of a SPHE with key components highlighted. (Danfoss, 2020)

The spiral geometry of the exchanger creates a continuous change in flow direction, which minimizes low-velocity zones. This reduces the accumulation of solid particles and, consequently, fouling. The design ensures consistent performance and efficient heat transfer, making it an ideal choice for sludge thermal conditioning. (Khorshidi & Heidari, 2016)

5.3.2.1. Shortcut Rating Method

The design of the SPHE (spiral plate heat exchanger) has been carried out using a well-proven shortcut rating method. (Minton, 1970)

The shortcut rating method for spiral plate heat exchangers utilizes a similar approach to that used for shell-and-tube heat exchangers, as described by Minton, and Slusser. This method integrates classical empirical equations for film heat transfer coefficients with heat balance equations and geometric correlations specific to the heat exchanger's design.

The overall equation derived from this method includes factors from three groups:

- **Fluid Properties**. Factors related to the physical characteristics of the fluid, such as viscosity, density, and thermal conductivity.
- **Exchanger Performance**. Factors describing the duty or heat transfer requirements of the exchanger.
- **Mechanical Design**. Factors tied to the arrangement and geometry of the heat transfer surface, such as channel spacing and plate dimensions.

These groups are combined with a numerical factor to calculate the fraction of the total driving force, represented by the log mean temperature difference (LMTD), dissipated across each resistance element in the heat flow path.

A trial design is considered satisfactory when the sum of these resistance fractions equals 1. Physically, this means the total temperature drop across all resistances matches the available driving temperature difference.

Additionally, the pressure drops for both fluid flow paths must be evaluated to ensure they remain within acceptable limits. Achieving a balance between effective heat transfer and pressure drop often requires iterative adjustments to the design. Multiple trials are typically necessary to refine the parameters and meet performance objectives.

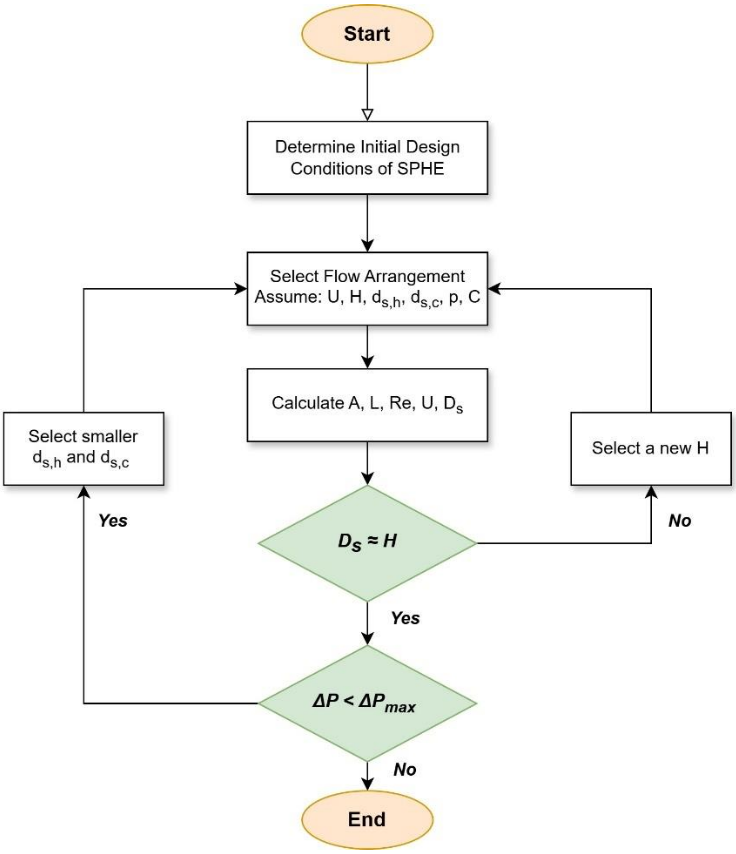


Figure 5.3 Flow chart to design the crossflow spiral plate heat exchanger using the Minton's shortcut method.

The method begins by defining the geometric parameters of the SPHE (which will define the geometry to be rated) in accordance with the ASME Section VIII standard. (Naphon & Wongwises, 2006)

- Channel spacing between plates for hot and cold fluids, d_s.
- Plate width, H.
- Plate thickness, p.
- Inner core diameter, C.

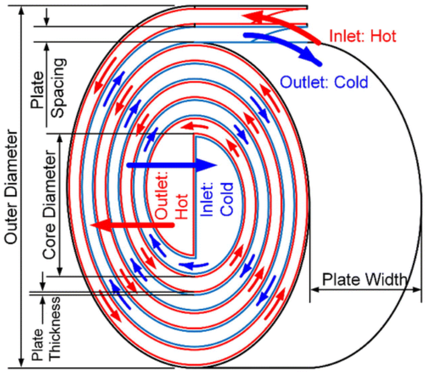


Figure 5.4 Geometrical features of a spiral plate heat exchanger. (Shirazi et al., 2022)

Once, these parameters have been defined, we can now calculate the geometry relationships, necessary for the subsequent calculation steps.

$$D_e = \frac{1{,}3 \cdot (d_s H)^{0{,}625}}{(d_s + H)^{0{,}25}} \tag{5.1}$$

$$D_H = \frac{2 d_s H}{d_s + H} \tag{5.2}$$

$$A_c = d_s H \tag{5.3}$$

$$D_s = \sqrt{15{,}36 L\left(d_{s,h} + d_{s,c} + 2p\right) + C^2} \tag{5.4}$$

Where D_e is the equivalent diameter, D_H is the hydraulic diameter, A_c is the channel area and D_s is the spiral outer diameter.

Once the geometry is defined appropriately, it is time to define the fluid regime for each fluid and determine if the flow is laminar, transition or turbulent in each of the channels. A critical value of the Reynold's number is also calculated, since it determines which correlations can be used to calculate the heat-transfer factors and pressure drop equation.

$$Re = 10000 \left(\frac{\dot{m}}{H\mu}\right) \tag{5.5}$$

$$Re_c = 20000 \left(\frac{D_e}{D_H}\right)^{0{,}32} \tag{5.6}$$

Table 5.1 Empirical heat-transfer factors for the different heat exchange mechanisms across the heat exchanger. Imperial units system. (Minton, 1970)

Mechanism	Numerical Factor	Physical Property Factor	Work Factor	Mechanical Design Factor
Spiral flow No phase-change Liquid Re > Re,c	20,6	$\frac{\mu^{0{,}467} MM^{0{,}222}}{SG^{0{,}889}}$	$\frac{W^{0{,}8}(T_{in} - T_{out})}{\Delta T_{LMTD}}$	$\frac{d_s}{LH^{0{,}2}}$

Spiral flow No phase-change Liquid Re < Re,c	32,6	$\frac{MM^{2/9}}{SG^{8/9}}\left(\frac{\mu_f}{\mu_{bulk}}\right)^{0,14}$	$\frac{W^{2/3}(T_{in}-T_{out})}{\Delta T_{LMTD}}$	$\frac{d_s}{LH^{2/3}}$
Plate Sensible heat transfer	500	$\frac{C_{p,f}}{k_{plate}}$	$\frac{W(T_{in}-T_{out})}{\Delta T_{LMTD}}$	$\frac{p}{LH}$
Fouling Sensible heat transfer	6000	$\frac{C_{p,f}}{h}$	$\frac{W(T_{in}-T_{out})}{\Delta T_{LMTD}}$	$\frac{1}{LH}$

For each element of resistance in the SPHE, the factors in the previous table have to be calculated in order to determine the fraction of corresponding heat driving force as follows:

$$\frac{\Delta T_i}{\Delta T_{LMTD}} = Numerical\ Factor \times Physical\ Property\ Factor \times Work\ Factor \times Mechanical\ Design\ Factor \tag{5.7}$$

$$Sum\ of\ Products\ (SOP) = \frac{\Delta T_h}{\Delta T_{LMTD}} + \frac{\Delta T_c}{\Delta T_{LMTD}} + \frac{\Delta T_{plate}}{\Delta T_{LMTD}} + \frac{\Delta T_{fouling}}{\Delta T_{LMTD}} \tag{5.8}$$

The end goal is to achieve an end SOP value of 1, meaning the total temperature drop across all resistances matches the available driving temperature difference, and therefore this is a satisfactory design.

However, the pressure drop must also be evaluated and made sure to be under acceptable limits. Therefore, a maximum allowed pressure drop should be defined for each channel.

When any of these restrictions is not met (SOP value or allowed pressure drop), the geometry of the SPHE has to be modified.

For a SPHE, the best design is often that in which the outside diameter (D_s) approximately equals the plate width (H).

Table 5.2 Empirical heat-transfer and pressure drop equations for the different mechanisms. Imperial units system. (Minton, 1970)

Mechanism	**Empirical equations**
Spiral flow No phase-change Liquid Re > Re,c	$h = \left(1 + 3,54\frac{D_e}{D_H}\right)0,023C_p\frac{\dot{m}}{A_c}Re^{-0,2}Pr^{-2/3}$ $\Delta P = 0,001\frac{L}{SG}\left(\frac{W}{d_sH}\right)^2\left[\frac{1,3\mu^{1/3}}{(d_s+0,125)}\left(\frac{H}{W}\right)^{1/3} + 1,5 + \frac{16}{L}\right]$
Spiral flow No phase-change Liquid Re < Re,c	$h = 1,86C_p\frac{\dot{m}}{A_c}Re^{-2/3}Pr^{-2/3}\left(\frac{L}{D_e}\right)^{-2/3}\left(\frac{\mu_f}{\mu_{bulk}}\right)^{-0,14}$ $\Delta P = 0,001\frac{L}{SG}\left(\frac{W}{d_sH}\right)^2\left[\frac{1,035\mu^{1/2}}{(d_s+0,125)}\left(\frac{\mu_f}{\mu_{bulk}}\right)^{0,17}\left(\frac{H}{W}\right)^{1/2} + 1,5 + \frac{16}{L}\right]$

Once a satisfactory design has been reached, the heat transfer coefficients can be calculated, enabling the overall heat transfer coefficient to be calculated and therefore, obtaining the resulting design heat transfer area.

$$U = \frac{1}{\frac{1}{h_h}+\frac{p}{k_{plate}}+\frac{1}{h_c}+r_{f,i}+r_{f,o}} \tag{5.9}$$

$$\dot{Q} = \dot{m}_h C_{p,h}\left(T_{h,in} - T_{h,out}\right) = \dot{m}_c C_{p,c}\left(T_{c,in} - T_{c,out}\right) \tag{5.10}$$

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{5.11}$$

$$A = \frac{\dot{Q}}{U \Delta T_{LMTD}} \tag{5.12}$$

5.3.2.2. Design Summary of W-1

After applying the shortcut design method, a successful design has been achieved that meets the established objectives. The following key considerations were incorporated:

- **Construction Material**. AISI 316L stainless steel was selected for all parts in contact with the sludge. This choice is critical given the high chloride content of the sludge, which poses a significant corrosion risk for non-resistant materials. (Sinnott, 2005)
- **Fluid Velocity**. The fluid velocity inside the channels ranges from 0,7 to 0,8 meters per second (m/s) in this type of heat exchanger, ensuring adequate flow for optimal heat exchange. (Minton, 1970)
- **Flow Configuration**. A cross-flow configuration was selected for this design. This arrangement allows for effective heat transfer.
- **Permissible Pressure Drop**. The allowable pressure drop was defined based on the viscosity of the fluids. For this design, a maximum pressure drop of 60 kPa was set for the sludge side and 35 kPa for the condensate side. (Sinnott, 2005)
- **Oversizing Factor**. Since the thermo-physical properties used in the design are based on estimates from sludge of similar origin and dryness, an oversizing factor has been applied to accommodate potential deviations in these properties. This ensures the design remains robust under varying conditions.

The following tables contain all relevant results achieved in the use of the presented method.

Table 5.3 Design objectives for the SPHE and thermal, hydraulic and fluid regime results.

Design Parameters	Hot Side	Cold Side
Fluid	Condensates (water)	Slurry (4% dry solids)
Total Flow Rate (kg/h)	[redacted]	[redacted]
Inlet Temperature (ºC)	95	25
Outlet Temperature (ºC)	70	55
Average Temperature (ºC)	82,5	40
Allowable Pressure Drop	35	60

(kPa)		
Material of Construction	Stainless Steel (AISI316L)	
Thermo-physical Properties		
Density (kg/m^3)	968,34	1019,68
Specific Heat Capacity (J/kg·K)	4198,93	2529,11
Thermal Conductivity (W/m·K)	0,6714	2,5608
Dynamic Viscosity (cP)	0,3439	4,4180
Source	See section A.2. (Layth et al., 2022) (Cao et al., 2016)	(Pátek et al., 2009)
Fluid Regime Parameters		
Re	17243	2459
Re$_c$	5386	5899
Pr	2,16	4,36
Fluid velocity (m/s)	0,64	0,83

As it can be seen in the previous table, the Reynolds number for water is above the critical Reynolds number, meaning that the fluid regime is turbulent. The opposite happens in the case of the sludge. These results are important to determine the heat transfer correlations to be used, as it has already been described.

Table 5.4 Geometrical parameters of the final SPHE design.

Geometry Parameters	**Hot Side** (water)	**Cold Side** (slurry)
Channel spacing, d$_s$ (m)	0,00476 (3/16 in)	0,00635 (1/4 in)
Hydraulic diameter, D$_H$ (m)	0,0094	0,0125
Channel area, A$_c$ (m^2)	0,0022	0,0029
Plate Width, H (m)	0,4572 (18 in)	
Plate Length, L (m)	12,61	
Spiral Outer Diameter, D$_s$ (m)	0,5685	
Plate Thickness, p (m)	0,0032 (0,125 in)	
Core Diameter, C (m)	0,2032 (8 in)	

In the previous table, it can be seen that a compact design has been achieved. It can be seen that the resulting spiral outer diameter and plate width have similar values, meaning that the design achieved is an acceptable and optimal design. (Minton, 1970)

Table 5.5 Thermal performance and heat exchange results of the SPHE design.

Heat Exchange Parameters	**Values**	
Heat Transferred, Q (kW)	186,97	
ΔT$_{LMTD}$ (ºC)	35,7	
Heat Transfer Coefficient, h (W/m^2·K)	Hot side (water)	2985,55
	Cold side (slurry)	1041,59

	Plate	2544,20
Overall Heat Transfer Coefficient, U (W/m^2·K)	592,39	
Calculated Heat Transfer Area, A (m^2)	11,53	
Design Heat Transfer Area, A_D (m^2)	14,42	
Design Plate Length, L (m)	15,77	

The overall heat transfer coefficient usually expected in applications similar to the one at hand ranges 250 to 950 W/m^2·K. (Green & Southard, 2019) Therefore, the result achieved is satisfactory.

Table 5.6 Operating and design conditions: temperatures and pressures.

	Hot Side (water)	**Cold Side** (slurry)
Operation Temperature (ºC)	95	55
Design Temperature (ºC)	100	100
Operation Pressure (bar)	10	7
Design Pressure (bar)	12	12
Pressure Drop (kPa)	4,11	39,23

The condensate water typically operates at 95°C and 10 bar, but the design values are defined to be at 100°C and 12 bar for safety. Similarly, while the sludge side usually operates at 55°C and 7 bar, the design values match those of the condensate side. This ensures that, in case of mechanical damage to the SPHE, where higher pressure and temperature from the condensate side might transfer to the sludge side, the equipment can safely handle the elevated conditions, preventing failure and ensuring reliability.

5.3.3. Conditioning Tank, B-1

The conditioning tank is a critical stage in the filtration process using filter presses. The primary objective of this stage is to achieve the optimal and efficient formation of sufficiently large flocs, with enough durability to get to the mechanical dewatering by filter presses.

A well-designed chemical conditioning stage has a significant impact on the effectiveness of mechanical dewatering. Several factors must be considered, including the use of additives, the selection of appropriate additives, agitation, and residence times. When properly designed, these elements work together to enhance sludge filterability.

This section will address these factors in detail, presenting the chosen design and the rationale behind its selection.

5.3.3.1. Additive Selection & Dosage

The sludge to be dewatered very often must be conditioned so that flocs can form by means of coagulation or flocculation in order to improve their filterability. The compounds used are usually minerals (iron salt, limestone and aluminum salt in a minor part) or organic (polyelectrolytes). (Deltreil, 2003)

The sludge can also be filtered without any additives, as the results obtained from Autemi have shown. However, at industrial scale, this process is not the most standard, and operational problems like cake sticking to the cloths is likely to happen. Additionally, Autemi's report indicated a potential for improvement in the dryness results up to plus 3% dry solids with the usage of additives.

Therefore, taking a conservative approach, it has been decided to carry out a chemical conditioning of sludge using additives.

Lime

One of the most commonly used additives when using a filter press is lime. This is a mineral reagent that improves filtration capacity by:

- Reducing the amount of bound water.
- Precipitating calcium salts (reduced suspended solids and more filtration capacity).
- Injecting a dense mineral loading (increasing cake's permeability)

For a mixed industrial sludge, the lime is usually added in a range of 15-30 % with respect to the sludge dry mass. The lime is prepared mixing it with water until obtaining a so called lime milk, with a concentration ranging 50-80 g/L. (*Water Treatment Handbook*, 1991)

Lime is an additive already used in the process of stabilization of biological sludge. However, the addition has not been monitored and the concentration and amount being added have been unknown. Therefore, laboratory analysis have been carried out to identify the current concentration and dosage added, in order to determine the addition needed.

To determine the current consumption, the following data was available: there is a delivery frequency of 1 truck with 20 tons every 6 weeks, which results in a consumption of 3,11 tons of lime per week.

Table 5.7 Lime milk concentration and dosage variables: current situation and target bibliographic values.

Additive	**Current**	**Bibliography**
Lime Concentration (g/L)	[redacted] (determined by gravimetric analysis, see appendix A.1)	50-80 (*Water Treatment Handbook*, 1991)
Lime Dose (% respect to dry solids)	[redacted] (consumption: 3,11 tons/week)	15-30 (*Water Treatment Handbook*, 1991)

According to the information presented, the lime concentration should not be modified, since it is within the target range.

However, in order to reach a 15% of lime with respect to dry solids, more solution has to be added. According to calculations, with a current dosage of [redacted] L/h of lime at a concentration of [redacted] g/L, in order to reach the mentioned target, [redacted] L/h have to be added.

Cationic Polyelectrolyte

Polyelectrolytes (or synthesis polymers) are currently being used in conditioning, directly injected into the centrifuges. They can be used alone, or they can be combined with lime in this case, producing a propagulation. They allow thick flocs to form with about some grams per kilograms of dry materials only, and a smaller concentration is required when a filter press will be used.

According to bibliography, the current polymer will be used in combination with lime, in a concentration of 1 kg/ton DS. (*Water Treatment Handbook*, 1991)

As the infrastructure for lime and polymer addition plant already exist and are in use, no further designs need to be made, since the small modifications needed can be handled by the current equipment.

5.3.3.2. Vessel Design

The geometry of the conditioning vessel has been designed to optimize the flocculation process, ensuring efficient mixing, proper contact time for additives, and uniform flow patterns. The following key design factors were considered:

- **Volume and Residence Time.** The vessel volume was selected to provide a residence time of 20–30 minutes, which is sufficient for the additives to interact with the sludge and form stable flocs. This ensures effective chemical conditioning while maintaining process efficiency. (*Water Treatment Handbook*, 1991)
- **Liquid Fill Level.** The vessel is designed to operate with 70% liquid fill to allow space for agitation and mixing dynamics, reducing the risk of overflow and ensuring sufficient headspace for process variability.
- **Height-to-Diameter Ratio (H/D).** An H/D ratio of 1,2 to 1,5 was chosen, balancing effective mixing and minimizing dead zones. This range supports uniform energy distribution throughout the tank, essential for floc formation. (Green & Southard, 2019)
- **Top Clearance.** A minimum top clearance of 20% of the vessel height was incorporated to prevent splashing and accommodate variations in liquid levels during operation. (Green & Southard, 2019)
- **Material Selection.** The vessel is constructed from stainless steel AISI 316L, chosen for its excellent corrosion resistance and durability. This material is particularly suitable for handling chemically aggressive environments, such as those involving lime milk and sludge. Furthermore, this material has already shown to be effective in the current plant. (Sinnott, 2005)

The combination of these factors ensures that the vessel geometry supports optimal process conditions for flocculation. Proper residence time and mixing dynamics allow for effective interaction between additives and sludge.

5.3.3.3. Mixer Design

The pitched-blade turbine was selected for its ability to generate a combined axial and radial flow, ensuring efficient top-to-bottom circulation, suspension of solids, and uniform mixing in low-viscosity sludge (<5 mPa·s). This design minimizes vortex formation and shear, protecting floc integrity while preventing sedimentation of denser solids.

Key design considerations: (Green & Southard, 2019)

- **Impeller Diameter (D_a/D).** According to literature, the diameter of this type of propeller should be designed in a range of 0,3 to 0,5 respect to the vessel diameter.
- **Bottom Clearance.** The clearance between the bottom of the vessel and the lowest impeller is set at 1/3 of the total height. This positioning minimizes stagnant zones and ensures that the impeller effectively circulates the contents, promoting thorough mixing and preventing sedimentation of sludge.

- **Baffles.** The vessel is equipped with four baffles, each with a width equivalent to 1/8 of the vessel diameter. These baffles prevent vortex formation, improving mixing efficiency by promoting turbulent flow and enhancing the distribution of additives.
- **Power Density and Speed**. For this application, considering flocculation and sludge density, suitable ranges for speed and power density according to literature are 30-50 rps and a maximum value of 300 W/m³.

In order to determine the heat transfer in an agitated vessel with a pitched-blade turbine, the following correlation can be used. (Green & Southard, 2019)

$$Re = \frac{D_a^2 N \rho}{\mu} \tag{5.13}$$

$$Nu = 0{,}85 Re^{0{,}66} Pr^{0{,}33} \left(\frac{h}{D_T}\right)^{-0{,}56} \left(\frac{D_a}{D_T}\right)^{0{,}13} \left(\frac{\mu_f}{\mu_w}\right)^{0{,}14} \tag{5.14}$$

In order to determine the power consumption of the agitator inside of the chemical conditioning tank, the following figure can be used to estimate it. The figure includes empirical-correlations for different pitched-blade turbine geometries.

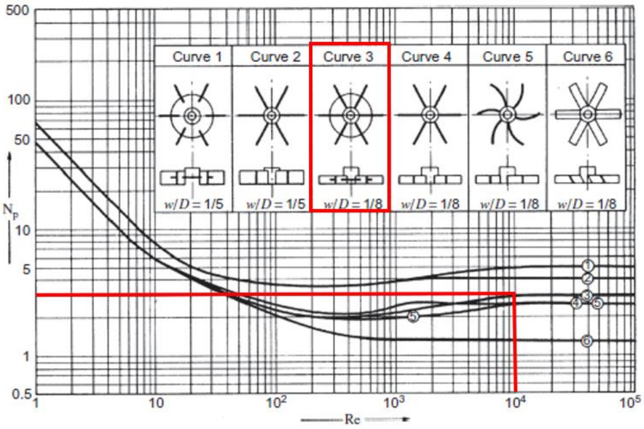


Figure 5.5 Power correlations for baffled turbine impellers, for tank with four baffles. (Towler & Sinnott, 2013)

The pitched-blade turbine selected has been marked in red in figure X.5. Once the flow regime and Reynolds number have been calculated, the power number (N_p) can be obtained to calculate the power consumption.

$$P_a = N_p D_a^5 N^3 \rho \tag{5.15}$$

5.3.3.4. Design Summary of B-1

The following tables contain all relevant results achieved in the design of the vessel B-1 and the agitator BR-1.

Table 5.8 Additives Concentrations and Dosing for Chemical Conditioning.

Additive	**Concentration (g/L)**	**Dose**
Lime Milk	80	15 % respect to dry solids
Cationic Polyelectrolyte	6	1 kg/ton dry solids

Table 5.9 Geometric Specifications of Vessel B-1.

Vessel Design Variable	**Value**
Material	Stainless Steel AISI 316L
Maximum Flowrate, v_{max} (m^3//h)	12,32
Residence Time, τ (min)	20
Calculated Volume, V_{calc} (m^3)	6
Liquid Fill Level (%)	70
Tank Volume, V_T (m^3)	10
Height-to-Diameter, H/D	1,37
Tank Height, H (m)	2,90
Tank Diameter, D_T (m)	2,10
Liquid Height, h (m)	2,02
Bottom Clearance (m)	0,96
Top Clearance (%)	52,38
Nº of Baffles	4
Baffle Width (m)	0,18

Table 5.10 Geometric, Flow and Power Parameters of Pitched-Blade Turbine BR-1.

Mixer Design Variable	**Value**
Propeller to Vessel Diameter, D_a/D_T	0,3
Propeller diameter, D_a (m)	0,63
Agitation Speed, N (rps)	35
Reynolds Number, Re	$7{,}29 \cdot 10^4$
Power Number, N_p (from Figure 5.5)	3
Power Consumption, P_a (W)	598,48

5.3.4. Filter Press, F-1A/B

The filter press is the core piece of equipment used for the mechanical dewatering of sludge. It is here where the results of the prior conditioning stages are evident.

This equipment operates in batch mode, meaning that the inflow and outflow rates are variable. In this section, we present the calculations associated with the dewatering cycle and analyze how the operational variables change throughout the process.

The supplier of this equipment is Autemi.

5.3.4.1. Features of the Filter Press

The filter press model selected is the Autemi's APF1200. The key features are the following, focusing on parts and technologies:

Figure 5.6 Illustration of Autemi’s APF1200 filter press. (Autemi, 2021)

- **Frame and Structure**.
    - Constructed from high-grade carbon steel, reinforced with stainless steel (AISI 316L) at contact points for durability and corrosion resistance.
    - Designed to handle working pressures of up to 12 bar and peak pressures of 16 bar, ensuring structural integrity during operations.
    - Includes dual lower reinforcing beams for added rigidity and resistance to deformation.
- **Hydraulic Unit**.
    - Equipped with a double-acting hydraulic cylinder featuring a thick chromium-coated rod for longevity.
    - Includes a pressure transmitter (4-20 mA output) for remote monitoring and compliance with Industry 4.0 protocols.
- **Filtering System**.
    - Utilizes recessed polypropylene filter plates with a high central feeding system.
    - Features high-detachment polypropylene filter cloths, optimized for sludge drainability, and under-cloths for additional support.
- **Sludge Feeding and Discharge**.
    - Double feeding system through stainless steel piping (AISI 316L) with integrated pressure relief to ensure safe operation during opening cycles.
    - Discharge system includes a four-point common manifold made of PVC for efficient filtrate removal.
- **Automation and Control**.
    - Controlled via a Siemens S7-1200 PLC and a user-friendly 10" HMI touchscreen panel.
    - Offers remote diagnostic capabilities and integration with Industry 4.0 systems (e.g., Modbus, ProfiNET).
- **Safety Features**.
    - Light curtain protections for operator safety, ensuring machine shutdown if the working area is breached.
    - Optional sliding doors for complete enclosure and added protection.

    - An extra safety package includes overpressure valves, safety cords, and thermostatic alarms.
- **Plate Management**.
    - Automatic one-by-one plate opening and shaking system for easy cake discharge.
    - Pneumatic systems allow for adjustable shaking cycles to facilitate cake removal.
- **Core Blow Function**.
    - Uses compressed air to clean residual liquid from feed holes post-filtration, preventing contamination and blockages in the next cycle.
- **Add-Ons**.
    - High-pressure automatic cloth washing system (80–100 bar) with a recirculation skid.
    - Drip trays (AISI 316L) to collect water during filtration, maintaining clean operations.
    - Lifting hoist for plate maintenance and installation.

- **Energy Efficiency**.
    - Intelligent hydraulic system with an energy-saving mode for optimal power consumption.
    - Estimated total energy consumption of 27,5 kWh per filtration cycle.
- **Maintenance and Reliability**.
    - Designed for ease of routine maintenance, including filter cloth replacement, lubrication, and system cleaning.
    - Supplied with a two-year warranty, excluding normal wear and third-party components.

5.3.4.2. Filter Press Cycle

The mechanical dewatering cycle using the presented filter press is described below. Each cycle has a total duration of 4 hours (240 minutes), allowing for six complete cycles to be performed within a single day.

Table 5.11 Stages of the Mechanical Dewatering Cycle: Descriptions and Key Process Variables.

Stage	Time Duration (min)	Description	Process Variables
Filter Press Filling	18	➢ During the initial filling phase, the feed pump delivers sludge at a relatively high flow rate to fill the filter press chambers quickly. This stage aims to evenly distribute the sludge without reaching high pressure. ➢ The target is to fill the filter press chambers within a short time frame (e.g., 15 minutes), ensuring even sludge distribution before applying	**Flowrate:** linear increase up to maximum flowrate (12,32 m^3/h) **Pressure:** linear increase up to 6 bar

Filtration	188	significant pressure. **Pressurization Phase** ➢ Once the chambers are filled, the feed flow rate decreases as the pressure increases. ➢ The pump may reduce its speed or increase the pressure incrementally, depending on the characteristics of the sludge and the desired final dryness of the filter cake. ➢ The flow rate gradually decreases because the volume of filtrate being removed slows down as the cake forms, creating more resistance to the flow. **High Pressure Phase** ➢ At this stage, the flow rate is minimal, focusing on applying high pressure to maximize the dryness of the filter cake. ➢ The feed pump may cycle on and off or maintain pressure without significantly increasing the flow rate.	**Flowrate:** decreasing **Pressure:** quick build up and maintenance of maximum pressure of 12 bar
Cake Discharge & Cloth Washing	34	➢ Before opening, a core blow function is activated to remove residual slurry in the feed channels. This process uses compressed air (2,924 Nm³/cycle) to clean the feed holes, ensuring no liquid slurry remains to contaminate the discharged cakes or subsequent cycles. ➢ Cake Release: The solid cakes, with a dry solids content of ~35%, are released. ➢ After cake discharge, high-pressure washing with water is performed to maintain the permeability and effectiveness of the filter cloths.	

The following figure shows the inlet slurry flowrate and pressure profiles during a filtration cycle.

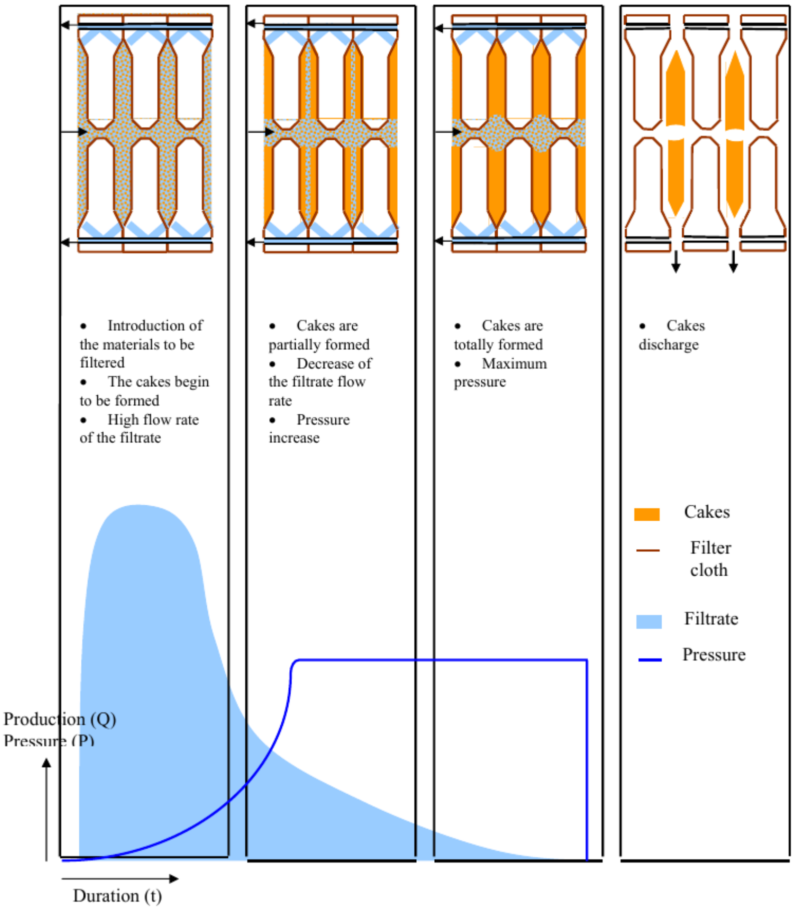


Figure 5.7 Description of cake formation, flowrate and pressure profiles in a filter press cycle.

Inlet Flowrate Estimation

The feed flow rate to the filter press is a crucial variable to consider for the proper design of both the conditioning tank B-1 and the effective feeding of the filter press.

In the absence of an exact feeding profile for the filtration stage, the following estimate has been made using information provided by the supplier.

- **Initial Filtration Flowrate**. The feed flow rate to the filter press varies depending on the part of the filtering cycle. In the filling stage, the flowrate is maximum. Therefore, in the initial time of the filtration stage, the flowrate is:
  - $Q(t_{in} = 0) = \frac{Filter\ Press\ Volume}{Filling\ time} = \frac{3{,}08\ m^3}{0{,}25\ h} = 12{,}32\ \frac{m^3}{h}$
- **Flowrate at 25% of filtration cycle**. The inlet flowrate when 25% of the filtration the time has passed is:
  - $Q(0{,}25t_{out}) = 11{,}41\ \frac{m^3}{h}$
- **Final Flowrate**. During the filtration stage, the flowrate varies starting at the maximum flowrate (filling flowrate) and decreasing overtime until reaching 0 m^3/h in the end of the stage.
  - $Q(t_{out}) = 0\frac{m^3}{h}$

- **Total Volume Processed**. The total volume processed in the filtration stage is the difference between the total volume processed in the cycle and the filter press volume (fed during the filling stage).
    - $V(t_{out}) = 25{,}61\, m^3$

Using the provided data and assuming a quadratic decrease in the flow rate, the flow rate profile can be determined by calculating the coefficients of the corresponding equation. Once the flow rate expression is established, the processed volume profile can also be derived by integrating the flow rate function.

$$Q(t) = at^3 + bt^2 + ct + d \tag{5.16}$$

$$V(t) = At^4 + Bt^3 + Ct^2 + dt \tag{5.17}$$

Table 5.12 Coefficients for flowrate and volume expressions in the filtration stage.

Profile	**a**	**b**	**c**	**d**
Q(t)	-0,067	-0,913	-0,408	12,32
	A	B	C	d
V(t)	-0,017	-0,304	-0,204	12,32

In the following figure, the volume inside B-1 is shown, together with the inlet flowrate and the outlet flowrate. The outlet flowrate corresponds to the inlet flowrate to the filter press. The figure shows how the volume inside B-1 returns to its initial value after a filter press cycle, accounting for the filter press feed variations.

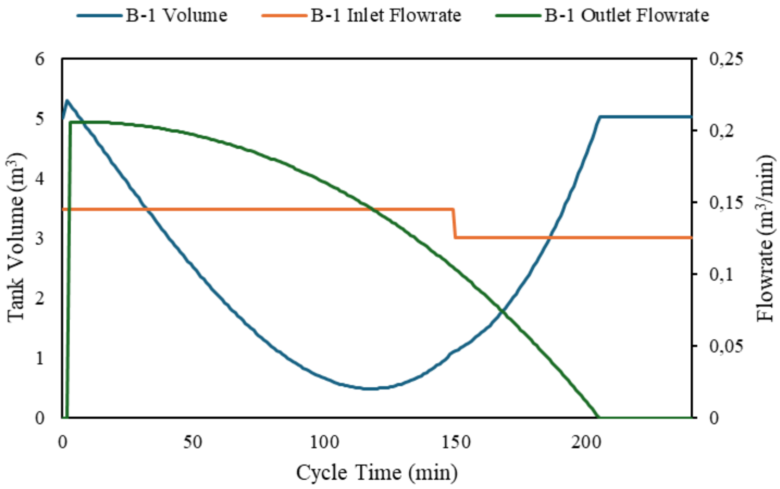


Figure 5.8 Volume, inlet and flowrate profiles of B-1 during a filter press cycle.

5.3.4.3. Power Consumption

Since the filter press operates together with the feeding pump and both work in cycles, energy consumption is also cyclical, meaning there is no constant consumption rate. However, an estimate can be made, as detailed below.

Table 5.13 Installed power of electricity consuming elements in the filter press system and estimation of total average consumption during a cycle.

Element	**Installed Power (kW)**	**Active Time per Cycle**	**Total Consumption (kWh/cycle)**
Filter Press Motor	5,5	3 min for forward stroke/cycle 4 min for return stroke/cycle 10 min/cycle for replenishment during cycle TOTAL: 17 min	1,56
Plate Opening System Motor	1,1	30 min/cycle	0,55
Feed Pumps, P-72A/B	7,5	15 min at 3,75 kW 188 min at 7,5 kW	25
TOTAL			27,5

Therefore, with a cycle duration of 4h, the average energy consumption would take a value of 6,875 kW.

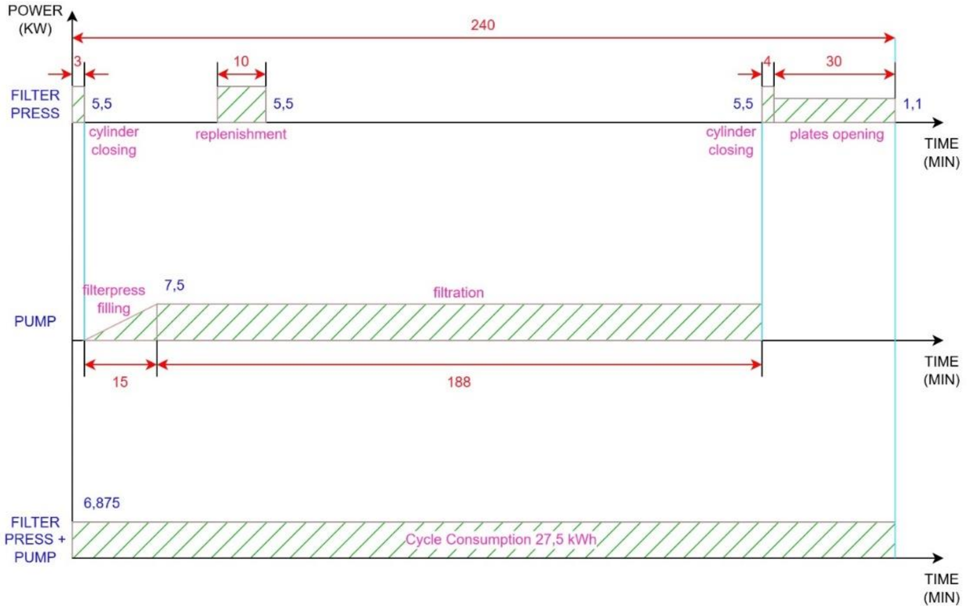


Figure 5.9 Power consumption of elements in the filter press system.

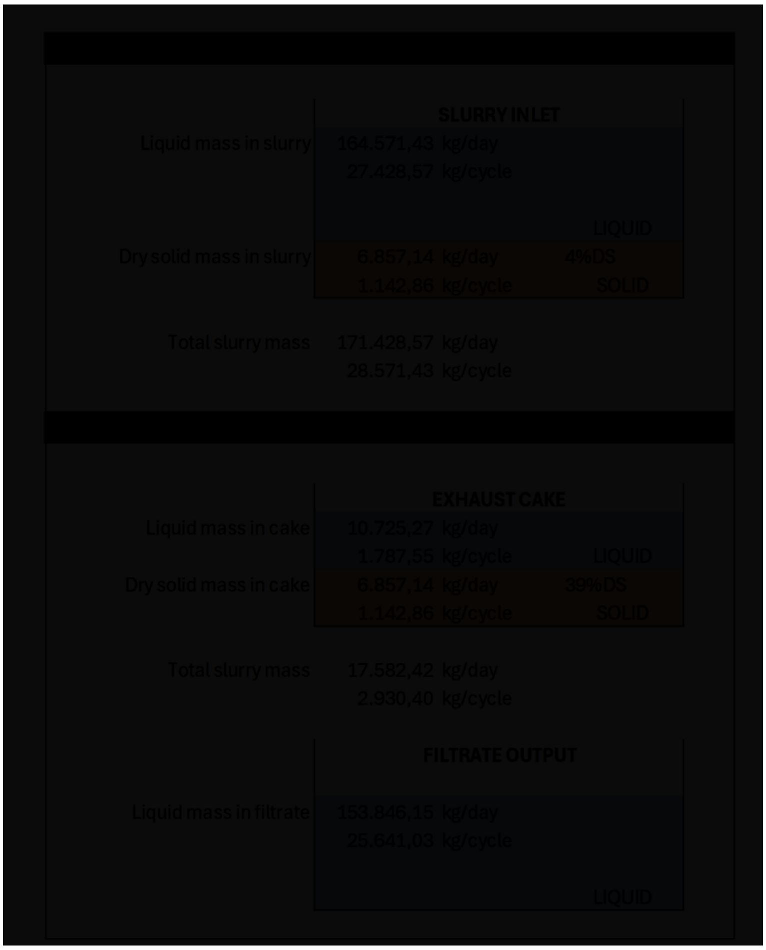
5.3.4.4. Mass Balance

The slurry enters the press, containing mostly liquid and a small percentage of solids (4%).

After dewatering, a solid cake is produced with a higher solid concentration (39%).

Most of the liquid exits as filtrate. The process effectively separates the liquid and solids, reducing the moisture content in the final solid cake.

The equations used to carry out the mass balance in the filter press can be found in appendix C.1.



	SLURRY INLET		
Liquid mass in slurry	164.571,43	kg/day	
	27.428,57	kg/cycle	
			LIQUID
Dry solid mass in slurry	6.857,14	kg/day	4%DS
	1.142,86	kg/cycle	SOLID
Total slurry mass	171.428,57	kg/day	
	28.571,43	kg/cycle	

	EXHAUST CAKE		
Liquid mass in cake	10.725,27	kg/day	
	1.787,55	kg/cycle	LIQUID
Dry solid mass in cake	6.857,14	kg/day	39%DS
	1.142,86	kg/cycle	SOLID
Total slurry mass	17.582,42	kg/day	
	2.930,40	kg/cycle	

	FILTRATE OUTPUT		
Liquid mass in filtrate	153.846,15	kg/day	
	25.641,03	kg/cycle	
			LIQUID

Figure 5.10 Summarized mass balance of the filter press cycle.

5.3.4.5. Design Summary & Technical Data, F-1A/B

The following tables contain all relevant technical data of the filter press F-1A/B.

Table 5.14 Technical Data Summary of Filter Press F-1A/B.

General Data	
Slurry Kind	25% biological, 75% chemical
Slurry Density (kg/m^3)	1023
Slurry Dry Solid Content (% DS)	4
Cake Density (kg/m^3)	1100
Plant Features	
Volume Slurry per Day (l/day)	192000
Avg Filtration Time per Cycle (h)	4
Expected Filtration Cycles per Day	6
Filter Press Working Time per Day (h)	24
Filter Press Sizing	
Type	Automated recessed plate filter press

Filter Press Volume (l)	3080
Plate Size (mm)	1200x1200
Chamber Thickness (mm)	25
Max Design Pressure of the Plates (bar)	16
Max Working Pressure of the Plates (bar)	12
Feeding Position	High Central
Kind of Filtered Discharge	Common Manifold (4 points)
Nº of Installable Plates	80
Single Recessed Plate Filtering Volume (l)	27
Single Recessed Plate Filtering Area (m^2)	2,18

5.3.5. Auxiliary Equipment

In this section, the calculations and design criteria for the auxiliary equipment used in the sludge dewatering process with filter press are presented and explained.

5.3.5.1. Feed Pump, P-72A/B

A piston pump is ideal for feeding a filter press in the sludge dewatering process due to its ability to meet the unique requirements of handling sludge with suspended solids and maintaining the operational efficiency of the filter press. Key factors include: (Green & Southard, 2019)

- **Protecting Sludge Integrity**. Piston pumps operate with low shear, minimizing damage to sludge particles and preserving chemically formed floc.
- **Variable Flow and Pressure**. The pump delivers high-volume, low-pressure flow at the start of the cycle, transitioning to low-volume, constant high-pressure flow as the filtration progresses. This matches the filter press's operational needs.
- **Handling Solids Effectively**. Piston pumps avoid internal pockets or dead spots where solids could accumulate, minimizing clogging risks.
- **Durability and Surge Management**. Hydraulic-driven piston pumps, combined with surge suppression tanks, dampen pressure fluctuations on the filter press, ensuring steady performance and protecting the equipment.

A piston pump provides the precise control, reliability, and gentle handling necessary for an efficient sludge dewatering process.

The piston pump is designed and provided by the filter press’s provider Autemi. According to the feeding needs of the filter press, the model selected is the Dragon DR-30, which has the following features:

- **Energy Efficiency**. Intelligent control through a hydraulic unit with a variable flow-rate pump reduces energy consumption.
- **Durability**. High-quality materials and coatings (AISI 304/316 stainless steel) ensure resistance to wear and corrosion.
- **Operational Control**. Advanced monitoring through PLC and HMI provides user-friendly operation and diagnostic capabilities.

Figure 5.11 Illustration of Autemi’s Dragon DR-30 piston pump. (Autemi, 2021)

The pump accounts for its own control system.

- **Hydraulic Unit**.
    - Variable flow-rate pump with constant power.
    - Proportional valve for energy-saving operation (E.S.S. - Energy Saving System).
    - Emergency level probe, pressure transducer, and safety thermostat included.
    - Air/oil heat exchanger for efficient cooling.
- **Electrical Panel**.
    - Painted carbon steel housing.
    - Includes Siemens S7-1200 PLC and a 4" Weintek HMI touchscreen.
- **Proximity Switches**. Installed for motion reversal and control of acceleration/deceleration ramps.
- **Air Replenishing Unit**. For regulating water hammer effects.

The following table contains a summary of the technical details of this pump.

Table 5.15 Design and construction technical details for the Autemi’s piston pump P-72A/B. (Autemi, 2021)

Parameter	**Design Value**
Type	Volumetric Single-Cylinder Piston Pump, double effect
Materials	AISI 304 and AISI 316L for wetted parts
Design Flow Rate (m^3/h)	0 to 30
Maximum Pressure (bar)	0 to 15
Installed Power (kW)	7,5
Power Supply	400V, 50Hz, 3-phase

5.3.5.2. High Pressure Water System, B-2 & P-73

After cake discharge, high-pressure washing is performed to maintain the permeability and effectiveness of the filter cloths. A mobile washing trolley cleans the cloths thoroughly along their entire surface.

Figure 5.12 Illustration of Autemi's high pressure water system. (Autemi, 2021)

The system accounts for the following components.

- **High-Pressure Piston Pump, P-73**. Delivers water at the required pressure for cleaning.
- **Automatic Valves**. Controls the washing water flow to and from the pump.
- **Storage Tank, B-2**. Holds washing water.
- **Maximum Pressure Valve**. Ensures safety during high-pressure operations.
- **Pressure Regulator**. Maintains consistent water pressure during washing.

Table 5.16 Design and construction technical details for the high pressure water system. (Autemi, 2021)

Parameter	**Design Value**
Washing Pressure (bar)	90
Pump Flow Rate (l/min)	85
Pump Power (kW)	22
Vertical Translation Motor Power (kW)	1,1
Horizontal Translation Motor Power (kW)	1,5
Tank Volume (l)	3000
Construction Material for Skid	Painted Carbon Steel

5.3.5.3. Dewatered Sludge Containers

As previously explained, the sludge cakes generated by the filter press fall by gravity into containers located directly under the equipment. These containers serve as the storage and transportation medium for the dewatered sludge to the authorized landfill. Therefore, it is essential to ensure that their capacity is sufficient to handle the volume of sludge produced between transportation intervals.

In this case, sludge transportation is managed by an external company (Griñó), which operates from Monday to Friday. Consequently, the containers must be capable of storing all the sludge produced over the weekend, as transportation services are unavailable during that time.

Table 5.17 Sludge cake density and production basis used in the sludge containers design.

Sludge Density at 39% DS	(kg/m^3)	1260
Sludge Production	(t/year)	6400
	(t/3 days)	52,75
	(m^3/3 days)	41,86

According to the production of sludge, a volume of sludge of 41,86 m^3 can be expected to accumulate throughout the weekend. Therefore, sludge containers have been designed with a capacity of 25 m^3 to be able to handle this need.

With this capacity, three containers would be needed to comply with the sludge production:

- **Weekend Storage**. During the weekend (Friday, Saturday and Sunday), two of the containers are used to store the sludge generated.
- **Monday Pickup and Replacement**. On Monday morning, the external company arrives to collect the two full containers that were used over the weekend. The third empty container is placed under the operating filter press.
- **Container Return**. Later on Monday, the transport company returns the two containers they emptied. These now empty containers are ready to be used again.
- **Weekday Operations**. During weekdays, sludge production is less demanding on storage capacity due to the regular availability of transportation services. The external company can be called 1-2 times during the weekdays.

Figure 5.13 Illustration of Tisvol's sludge containers.

The following table contains all technical details related to the sludge containers design.

Table 5.18 Design and construction technical details for the Tisvol sludge containers.

Design Parameter	**Value**
Provider and Model	Tisvol, AA6-X783140-ECC
Number of Containers	3
Capacity (m^3)	25
Tare (kg)	5280
Exterior Dimensions	
Total Length (mm)	8450

Width (mm)	2550
Height (mm)	2936
Interior Dimensions	
Ground Length (mm)	7530
Lateral Width (mm)	2370
Lateral Height (mm)	1400

5.4. Control Strategy

To develop the P&ID of the sludge dewatering plant, the objective of each stage or piece of equipment was first properly defined. Subsequently, the variables that need to be controlled at each stage were determined, based on the objectives, as well as the operating limits of these variables.

5.4.1. Sludge Pit, R-9B

The sludge pit R-9B functions as a critical reservoir where both biological and physicochemical sludge converge and are properly mixed. The primary purpose of the pit is to ensure process continuity and mitigate disturbances caused by the variable flowrate and composition typical of the treatment plant operations.

- **Level Control**. The sludge pit's level must be carefully controlled to avoid overfilling or excessively low levels, both of which could affect downstream processes. The level is regulated by adjusting the inlet flowrate. A level sensor continuously monitors the sludge pit's level. The inlet flowrate is manipulated to maintain the level within acceptable operational limits.
- **Agitation Speed Control**. To ensure proper hydrodynamics and prevent settling or stratification of sludge, the agitation speed within the pit is controlled. This is achieved by modulating the agitation speed based on the sludge pit level. A feedback system adjusts the agitator's speed to maintain optimal mixing conditions.

5.4.2. Sludge pumps, P-70A/B

The flowrate provided by pumps P70A/B is regulated to ensure stable operation. These pumps are pneumatic diaphragm pumps, and their flowrate is controlled by manipulating the industrial air supply delivered to them.

The industrial air flowrate to the pumps is adjusted based on the desired flowrate setpoint. By increasing or decreasing the industrial air delivered, the diaphragm's actuation speed is altered, regulating the pump's output flowrate.

5.4.3. Spiral plate heat exchanger, W-1

The sludge outlet temperature in the SPHE is regulated using a cascade control strategy.

The primary control loop monitors the sludge outlet temperature and adjusts the condensate inlet flowrate to maintain the desired setpoint. This ensures that the system responds effectively to variations in sludge temperature or process conditions.

To reduce disturbances, a secondary (cascade) control loop is implemented. This secondary loop monitors the condensate temperature and accounts for variations to stabilize the heat transfer process. This improves the responsiveness of the primary loop.

5.4.4. Conditioning Tank, B-1

The conditioning tank is a crucial stage as it ensures proper mixing with additives, facilitates floc formation, and maintains optimal conditions needed prior to filtration. The following control strategies are implemented to achieve these objectives:

- **Agitation Control**. Agitation in the conditioning tank is designed to homogenize the sludge and additives, ensuring sufficient mass transfer without damaging the flocs. The agitation speed is controlled based on the tank's level, which is monitored and regulated to maintain steady operational conditions. Adjusting the agitation speed in response to the level ensures that mixing remains gentle and effective even with varying liquid volumes inside the tank.
- **Polymer Concentration Control**. To maintain the desired ratio of polymer to solids in the sludge, the polymer solution inlet flowrate is manipulated. The setpoint for this ratio is predefined, and real-time measurements of the sludge inlet flowrate and its solids concentration are used to calculate the required polymer flowrate. This ensures the precise addition of polymers, optimizing floc formation while minimizing waste and chemical costs.
- **Temperature Control**. The sludge is preheated to a low-moderate temperature of 50ºC to enhance the reaction between the sludge and additives. However, during the final stages of the filtration cycle, when there is no outflow, the sludge may experience a slight temperature drop due to prolonged residence time. A cascade control loop monitors the sludge temperature and activates pump P-71 if the temperature drops below a specified value. The pump recirculates a portion of the sludge to the heat exchanger, restoring the temperature to the desired value.

5.4.5. Filter Press and Feed Pump, F-1A/B & P-72A/B

The filter press operates with a dynamic flowrate and pressure profile. The control strategy for the filter press and feed pumps is as follows:

- **Filling Stage**: Flowrate Control. At the start of the filtration cycle, the primary objective is to fill the filter press chambers efficiently. During this stage, the feed pumps are manipulated to achieve the desired flowrate. A flowrate control loop regulates the pump operation to maintain a high flowrate while the filter press chambers are still filling, as the pressure is still in the process of building up.
- **Filtration Stage**: Pressure Control. Once the filter press is filled, the process goes to the filtration stage, where the primary goal is to maintain constant pressure to allow the cake to form inside the chambers. At this point, the control strategy shifts from flowrate control to pressure control. A pressure control loop adjusts the feed pump operation to maintain the desired pressure, ensuring steady and consistent cake formation.
- **Filter Press Machine Controls**. The filter press itself is equipped with built-in control systems that monitor and regulate its internal operations. These systems ensure that the pressure remains within acceptable safety limits and manage the various operational phases of the machine, such as cake discharge and plate movements.

5.4.6. Piping & Instrumentation Diagram (P&ID)

The P&ID resulting from the control strategy can be found in appendix C.2.

5.5. Safety & Mitigation Strategies

Safety is a fundamental aspect of any industrial plant, especially in facilities that handle processes with potential mechanical, environmental, or worker-related risks. In the case of a mechanical dewatering plant using a filter press, several risks must be identified and effectively managed to ensure safe operation.

A commonly used tool to analyze risks in an industrial plant is the HazOp analysis (Hazard and Operability Study). This analysis focuses on identifying possible dangerous scenarios in the operation of a plant and evaluating the security and contingency measures that must be implemented to minimize risks.

5.5.1. Nodes & Scope of the Study

The HazOp study will be structured by dividing the process into three nodes:

- **Sludge Storage and Transfer at Sludge Pit R-9B.**
  This node focuses on the storage and transfer of sludge to downstream processes. Potential risks include:
    - Overflows or leaks from the sludge pit leading to environmental contamination.
    - Pump failures (P-70A/B), resulting in disruptions to sludge transfer.
    - Sediment accumulation in the pit affecting operational capacity.
    - Worker safety risks associated with confined space entry or handling.
- **Sludge Conditioning at SPHE W-1 and Vessel B-1.**
  This node involves preparing the sludge for dewatering through thermal and chemical conditioning. Potential risks include:
    - Thermal system malfunctions in W-1, such as overheating or inadequate temperature control.
    - Leaks or fouling in the heat exchanger, reducing efficiency or causing spills.
    - Incorrect chemical dosing in B-1, leading to environmental or worker hazards.
    - Reactions or material incompatibilities causing corrosion.
- **Mechanical Dewatering at the Filter Presses F-1A/B.**
  This node represents the final step, where dewatered sludge cakes are produced. Potential risks include:
    - Hydraulic system failures causing leaks or overpressures.
    - Mechanical malfunctions of the filter presses.
    - Sludge spills or improper handling, leading to environmental contamination or safety hazards.

Out of Scope Equipment and Processes

Certain equipment and processes already operating in the plant are excluded from this HazOp study, as they are considered out of scope. These include:

- The lime addition plant, responsible for dosing lime for chemical treatment.
- The polymer preparation plant, where polymers are prepared for use in the conditioning process.

Safety Measures and Objectives

For each node, the HazOp study will identify potential hazardous scenarios and define preventive and mitigation measures, such as:

- Installing detection and alarm systems for abnormal conditions.
- Emergency shutdown systems for critical equipment.
- Providing operators with appropriate personal protective equipment (PPE).
- Establishing clear operating, maintenance, and emergency procedures.

By systematically analyzing each node, the HazOp study aims to minimize risks, protect workers, ensure equipment reliability, and safeguard the environment, contributing to the overall safety and efficiency of the dewatering plant.

5.5.2. HazOp Methodology

More details regarding the HazOp methodology used can be found in appendix C.2.

5.5.3. HazOp of Node 1: Sludge Buffering at R-9B

As can be seen in the P&ID, the involved control loops are F1001, NR1001 and L1001.

Table 5.19 HazOp of Node 1: Sludge Buffering at R-9B.

Guide word	Deviation	Possible causes	Consequences	Safeguards	Actions
More	More level at R-9B	L1001 failure (reads lower than actual level)	Possibility of overflow (loss of product and contamination of the surrounding area) No safety consequences		Set a high-level alarm on L1001
Less	Less level at R-9B	L1001 failure (reads more than actual level)	Incomplete operation or process interruption Loss of priming in pumps P70-A/B with possible air ingress into the system No safety consequences		Set a low-level alarm on L1001
No	No flow to R-9B	F1001 failure (closes) Lack of feed	Incomplete operation or process interruption		Set a low-flow alarm on F1001

			No safety consequences	
Less	Less flux to R-9B	Same as ‘No flow a R-9B’		
More	More flow to R-9B	F1001 failure (opens)	Same as ‘More level at R-9B’	Set a high-flow alarm on F1001
Reverse	Reverse flow rate	Not applicable		
More	More pressure at R-9B	Not applicable (atmospheric pit)		
Less	Less pressure at R-9B	Not applicable (atmospheric pit)		
More	More temperature at R-9B	Not applicable		
Less	Less temperature at R-9B	Not applicable		
Other	Different composition to R-9B	Discontinuous operation of the physical-chemical treatment Variation in the wastewater arriving at the plant	Alteration in the dryness achieved in the filter press (subsequent stage) No safety consequences	
As well as	As well as corrosion/ erosion in R-9B	Variation in the wastewater arriving at the plant	Structural damage to the pit coatings and/or pipes No safety consequences	Design R-9B and pipes for this case (stainless steel and appropriate coating)
No	No utilities	Instrument air failure	F1001 opens F1002 closes	
	No containment	No relevant cases		

5.5.4. HazOp of Node 2: Conditioning at SPHE W-1 & B-1

As can be seen in the P&ID, the involved control loops are F1002, F1003, F1004, L1002, T1001, T1002, H1001, H1002 and NR1002.

Table 5.20 HazOp of Node 2: Sludge Buffering at R-9B.

Guide word	**Deviation**	**Possible causes**	**Consequences**	**Safeguards**	**Actions**
More	More level at B-1	L1002 failure (reads lower than actual level) Blockage at the outlet	Possibility of overflow (loss of product and contamination of the surrounding area) Increase in residence time (possible sludge sedimentation inside B-1) No safety consequences		Set a high-level alarm on L1002
Less	Less level at B-1	L1002 failure (reads more than actual level)	Incomplete operation or process interruption Decrease in residence time (poor conditioning and worsening of filtration) No safety consequences		Set a low-level alarm on L1002
No	No flow to W-1	F1002 failure (closes) Air supply failure Failure of pump P-70 Lack of feed	Heating of W-1 to 95ºC Incomplete operation or process interruption No safety consequences		Set a low-flow alarm on F1002 Design W-1 for this scenario (minimum Td = 100ºC) Pump

				redundancy (P-70 A/B)
		Same as 'No flow to W-1'		
	No flow to B-1	Blockage in W-1 (closure of outlet valves, etc.)	Sludge heating (95ºC). Possible pressure increase in W-1 with the potential for thermal expansion and mechanical damage Risk of contamination of the condensate network with sludge	Design safety valve Y.10001.10 for this case Conduct periodic turbidity measurements in the condensate storage tank B-5626 to rule out contamination
Less	Less flow to W-1	Same as 'No flow to W-1'		
	Less flow to B-1	Same as 'No flow to B-1'		
More	More flow to W-1	F1002 failure (opens) F1004 failure (opens)	Reduction in heat exchange capacity (poor thermal conditioning) The maximum pressure provided by pumps P-70A/B is 7 bar (industrial air pressure). No safety consequences	Set a high-flow alarm on F1002 and F1004
	More flow to B-1	Same as 'More level at B-1' F1003 failure (opens) (poly-electrolyte)	Same as 'More level at B-1' Potential excessive concentration of polyelectrolyte (poorer chemical conditioning) No safety	Set a high-flow alarm on F1003

			consequences		
Reverse	Reverse flow rate	Recirculation of sludge from B-1 to pumps P-70A/B instead of to W-1 due to the pressure difference	Undesired fluid mixture in the sludge supply system No safety consequences		Sectorize with automatic valves H1001 and H1002
More	More pressure at W-1	Same as 'No flux to B-1: Blockage in W-1 (closure of outlet valves)' Same as 'More flow to W-1'	The maximum pressure provided by pumps P-70A/B is 7 bar (industrial air pressure)		
	More pressure at B-1	Not applicable (atmospheric vessel)			
Less	Less pressure at W-1				
	Less pressure at B-1	Not applicable (atmospheric tank)			
More	More temperature at W-1	Failure of T1001 (opens) Same as 'No flux to B-1: Blockage in W-1 (closure of outlet valves, etc.)'			Set high-temperature alarm on T1001
	More temperature at B-1	Same as 'More temperature at W-1'			Design B-1 for this case (minimum Td = 100ºC)
Less	Less temperature at W-1	Failure of T1001 (closes)	Poor thermal conditioning No safety		Set low-temperature alarm on T1001

			consequences		
	Less temperature at B-1	Same as 'Less temperature at W-1'			
Other	Different composition to B-1	Discontinuous operation of the physical-chemical treatment (R11) Variation in the wastewater arriving at the plant	Alteration in the dryness achieved in the filter press (subsequent stage). No safety consequences		
As well as	As well as corrosion/ erosion in R-9B	Variation in the wastewater arriving at the plant	Structural damage to the pit coatings and/or pipes No safety consequences		Design W-1 and B-1 for this case (stainless steel)
No	No utilities	Instrument air failure	F1002 closes F1003 closes F1004 opens H1001 opens H1002 closes T1001 closes		
	No containment	There are no relevant cases			

5.5.5. HazOp of Node 3: Mechanical dewatering at Filter Press F-1A/B

This node comprises all the equipment supplied by Autemi, which includes its integrated control system, making it a self-contained unit. Consequently, safety aspects are considered to be covered by the supplier, as the design and integration of the equipment are externally provided by Autemi.

The node is equipped with several sensors to measure key process variables such as pressure and temperature, allowing for monitoring from the control room. However, the control loop is inherently managed within the equipment itself.

6. CONCLUSIONS

Following my internship at BASF and active involvement in the project to optimize and renovate the sludge dewatering processes at BASF Tarragona's WWTP, the objectives initially established have been successfully achieved.

The challenge addressed was an outdated and inefficient sludge dewatering system. The centrifuges, installed in the 1990s, imply high maintenance costs and do not provide optimal dewatering performance compared to modern centrifuges. Additionally, the subsequent sludge drying stage relies on drying beds where sludge is piled without protection from climatic conditions. As a result, rain or cold weather reverses the drying process, rewetting the sludge and reversing the benefits of centrifuge dewatering.

Additionally, the drying beds are located far from the sludge generation site, needing external transport services from the centrifuges to the drying beds. This results in sludge with a high moisture content, with nearly three-quarters of its composition being water. This situation presents significant room for improvement in reducing waste volume and the associated costs of transportation and disposal.

In alignment with the objectives outlined in Section 1.1.2, the following results were obtained.

Alternative disposal methods, such as composting or biogas production, were evaluated to manage sludge more sustainably. However, due to the heavy metal content exceeding the limits set by RD 1310/1990 (with notable concentrations of Hg, Zn, Ni, and Ti from the [redacted] stream managed at the WWTP), these alternatives were determined to be unsuitable. Consequently, landfill disposal remains the best option for this sludge under current conditions.

Efforts were directed towards modernizing the existing sludge dewatering facilities. Various mechanical dewatering and drying technologies were reviewed, and an evaluation of economic, operational, and sustainability indicators was conducted. This assessment identified the filter press as the most viable solution.

The filter press offers a simple solution by requiring only one mechanical dewatering stage to meet the 35% dry solids requirement. Autemi, the selected supplier, guaranteed a 39% dry solids outcome (appendix A.3), significantly surpassing the limit. This simplicity eliminates the need for sludge transport to drying beds and their subsequent use, as the filter press would operate directly at the sludge generation location, removing internal transport requirements.

Based on the business case, the filter press demonstrated the lowest operational costs ([redacted]€/year) and one of the lowest initial investment costs ([redacted]€). Sludge volume reductions from [redacted]t/year to [redacted]t/year would generate substantial annual savings: [redacted]€ with current 2025 landfill rates and up to [redacted]€ with 2026 rates, when non-compliance with the 35% ds requirement implies additional costs.

The project has a net present value (NPV) of [redacted]€ and a payback period of less than one year (8 months). The filter press also exhibited the lowest specific energy consumption (1 kWh/t sludge), significantly improving on the current rate of 5 kWh/t sludge. Lower energy consumption per ton of sludge, combined with reduced sludge volumes, translates into a greenhouse gas emissions reduction of 8 t CO2eq/week.

These results are highly satisfactory, offering substantial improvements over the current situation, including annual cost savings, enhanced operational efficiency, environmental benefits, and representing the optimal choice among the studied alternatives.

Following the selection of the best sludge dewatering alternative, basic engineering for the proposal was completed. This includes a thermal conditioning stage utilizing residual heat, as demonstrated in a similar plant, to further improve the dryness achieved by the filter press. The design is efficient and inherently safe, with no significant safety concerns identified during a HAZOP analysis, validating the proposal's inherent safety.

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APPENDICES

A. LAB METHODS AND SLUDGE PROPERTIES

A.1. LAB METHODS

A.1.1. Sludge Leachate Preparation

To extract the liquid phase (leachate) from sludge for analysis of soluble compounds like nutrients, metals, or organics.

Steps:

1) **Sample Collection**. Obtain sludge from a wastewater treatment plant or similar source. Ensure the sample is representative by mixing thoroughly.
2) **Separation Process**. Use vacuum filtration with Whatman filter paper or a membrane filter (0,45 µm pore size). This separates solid particles from the liquid leachate.
3) **Preservation**.
    a. For metals: Acidify the leachate with nitric acid ($pH < 2$) to stabilize the sample.
    b. For organics. Keep samples refrigerated (4°C) and avoid exposure to light to prevent degradation.
4) **Storage**. Use clean, inert containers like glass or HDPE to avoid contamination.

A.1.2. Thermogravimetric Analysis for Sludge Dryness

To measure the moisture content and determine the proportion of solids in sludge.

1) **Sample Preparation**. Weigh a small sludge sample (1-2 grams) using the moisture analyzer.
2) **Drying Settings**:
    a. Temperature: Typically set to 105°C to evaporate water without decomposing organic matter.
    b. Duration: Automatically determined by the equipment or set manually until the weight stabilizes.
3) **Drying Process**. The analyzer applies heat while continuously measuring the weight. As moisture evaporates, the weight decreases.
4) **Final Measurement**. The instrument records the final weight once it stabilizes. The dryness percentage is calculated as

$$Dryness\ (\%) = \frac{Dry\ weight}{Initial\ weight} \times 100 \qquad (A.1.1)$$

A.1.3. IPC Analysis to Determine Metals in a Sample

To identify and quantify trace metals (for instance Fe, Cu, Zn, Pb, Cd) in sludge or leachate samples.

1) **Sample Preparation**:
    a. Acid Digestion:
        i. For solid samples (sludge): Use a microwave digestion system or hot plate with concentrated acids like HNO_3 or HCl.

        ii. For liquid samples (leachate): Dilute directly with acid if necessary.
    b. Ensure complete dissolution of metals into a liquid phase.

2) **Instrument Calibration**:
    a. Prepare standards with known concentrations of target metals.
    b. Use these standards to create a calibration curve.
3) **ICP Analysis**:
    a. Inject the prepared sample into the instrument.
    b. The plasma ionizes the sample, and the instrument detects the characteristic signals of each metal.
4) **Quality Control and Data Interpretation**:
    a. Run blanks, duplicates, and certified reference materials to ensure accuracy.
    b. The instrument software matches signals to known standards, calculating concentrations in mg/L.

A.2. <u>Sludge Thermo-Physical Properties</u>

Sludge is a complex substance with highly variable properties due to the fluctuating composition of the substances processed during treatment. This variability makes it difficult to characterize all its properties. However, obtaining reliable estimates is essential for process and equipment design. These estimates can often be sourced from literature, provided the sludge in question has comparable origins (industrial, municipal, digested, or undigested) and has similar dryness levels.

In the case of the BASF Tarragona WWTP, as it has already been presented, laboratory analyses were conducted to estimate sludge properties using the resources and equipment available on-site. While this approach provided valuable insights, certain properties require more sophisticated methods and specialized equipment, which were not accessible during the analysis.

To address these gaps, this section includes bibliographic correlations and estimates of the thermophysical properties of the sludge. This data is crucial for the subsequent design and optimization of the selected sludge dewatering alternative.

However, it is important to note that these are only estimates and may not fully represent the actual behavior of our sludge. For greater accuracy, determining these properties through external laboratories with the capabilities should be considered. This approach would help ensure that the data used in the design and optimization of the selected sludge dewatering alternative are as precise and representative as possible.

A.2.1. Heat Capacity & Thermal Conductivity

A study on undigested industrial sludge (which can be assimilated to the sludge in this specific application) had been performed to determine several properties like shrinkage, density, and thermos-physical properties. (Layth et al., 2022)

Experimental results acquired between 35 and 70ºC, showed that the effective thermal conductivity, as well as the heat capacity, do not depend on the temperature.

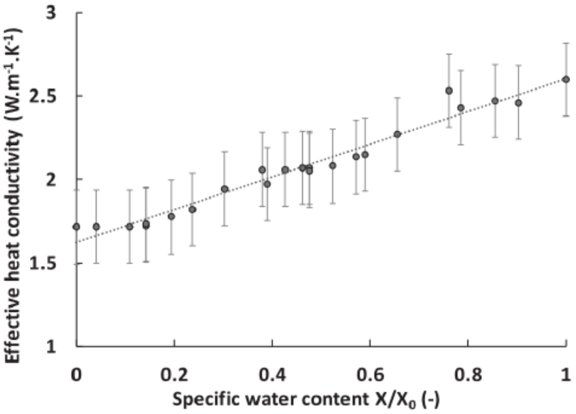


Figure 7.1 Evolution of the sludge thermal conductivity versus specific water content at 65ºC. (Layth et al., 2022)

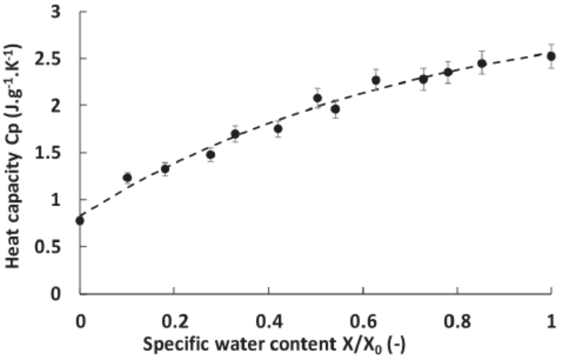


Figure 7.2 Evolution of the sludge heat capacity versus specific water content at 65ºC. (Layth et al., 2022)

According to the mentioned study, the heat capacity of the sludge suffers an exponential decrease with water reduction from water. The decrease is not linear, as it could have been expected. This nonlinear unideal behavior can be explained by the reduction of water and simultaneous increase of salt concentration in the solution. As salts have a lower heat capacity, that affects the sludge heat capacity considering physical and chemical phenomena.

The correlations between studied thermal properties and water content are the following:

$$k\ \left[\frac{W}{m\cdot K}\right] = 0{,}98\frac{X}{X_0} + 1{,}62 \qquad \text{(A.2.1)}$$

$$C_p\left[\frac{J}{kg\cdot K}\right] = -2{,}32e^{\left(-1{,}39\frac{X}{X_0}\right)} + 3{,}14 \qquad \text{(A.2.2)}$$

Where the specific water content X is calculated as follows:

$$X = \frac{dry\ mass - water\ mass}{dry\ mass} \qquad \text{(A.2.3)}$$

A.2.2. Density & Dynamic Viscosity

Sludge rheological data has been investigated in a study where undigested industrial sludge was used. (Cao et al., 2016)

The results revealed that the sludge samples showed shear-thinning and thixotropic characteristics. It was found that, irrespective of the existence of anaerobic digestion, sludge samples all showed a qualitatively same rheological behavior, while they quantitatively behaved differently. It was also proved that both solid concentration and temperature effected sludge rheology critically.

The properties for undigested industrial sludge at a dry solid content of 4 %DS can be assimilated to the properties of the sludge at BASF WWTP Tarragona.

Table 7.1 Dynamic viscosity and density values for undigested industrial sludge with 4 % dry solids. (Cao et al., 2016)

T (ºC)	μ (cP)	ρ (kg/m^3)
20	4,858067183	1026,68
35	4,418040758	1019,68
55	3,214613112	1012,68

Table 7.2 Developed model for límit viscosity. (Pevere et al., 2006)

T(ºC)	**A**	**B**	**R^2**
20	0,25364	0,73812	0,98908
35	0,27399	0,69509	0,98017
55	0,20727	0,68536	0,97877

$$\mu_\infty = A \cdot e^{B \cdot TS\%} \tag{A.2.4}$$

The best correlation between limit viscosity or the value of sludge thixotropy and solids concentration were determined by regression analysis. In this study, the Ostwald de Vaele model fits the experimental data best.

A.3. <u>Autemi's Filter Press Pilot Plant Test</u>

LABORATORIO CHIMICO

Referto di Analisi N.

B. CAPEX AND OPEX CALCULATIONS

B.1. OPEX Calculations

This section outlines the equations and methodologies used to estimate these costs, detailing assumptions, data sources, and any technology-specific considerations. By breaking down each cost component, the analysis supports informed decision-making when comparing process alternatives.

$$OPEX = Energy\ Costs + Utility\ Costs\ (water, air \ldots) + Additives\ Costs + Maintenance\ Costs + Labor\ Costs \tag{B.1.1}$$

B.1.1. Energy Consumption

The energy source depends on the technology. Mechanical dewatering relies on electricity, while thermal drying typically uses steam or another form of thermal energy in addition to electricity.

Electricity

The installed power includes all parts that consume energy in the equipment: motors, lubrication systems...

$$Electricity\ Consumption\ \left(\frac{kWh}{week}\right) = Installed\ Power\ (kW) \times Operation\ Time\ \left(\frac{h}{week}\right) \tag{B.1.2}$$

$$Electricity\ Cost\ \left(\frac{€}{week}\right) = Electricity\ Consumption\ \left(\frac{kWh}{week}\right) \times Electricity\ Rate\ \left(\frac{€}{kWh}\right) \tag{B.1.3}$$

Steam

The thin film and belt dryer technologies use this source of thermal energy. The steam consumption is determined through an energy balance based on the mass of water that has to be evaporated in order to reach the dryness output.

$$Required\ Thermal\ Energy\ (kW) = Mass\ of\ Evaporated\ Water\ \left(\frac{kg}{s}\right) \times Latent\ Heat\ of\ Vaporization\ \left(\frac{kJ}{kg}\right) \tag{B.1.4}$$

$$Thermal\ Energy\ Consumption\ \left(\frac{kWh}{week}\right) = Required\ Thermal\ Energy\ (kW) \times Operation\ Time\ \left(\frac{h}{week}\right) \tag{B.1.5}$$

$$Steam\ Consumption\ \left(\frac{kg}{s}\right) = Required\ Thermal\ Energy\ (kW) \div Latent\ Heat\ of\ Vaporization\ (sat. steam\ @6\ bar)\left(\frac{kJ}{kg}\right) \tag{B.1.6}$$

$$Steam\ Costs\ \left(\frac{€}{week}\right) = Steam\ Consumption\ \left(\frac{kg}{week}\right) \times Steam\ Rate\ \left(\frac{€}{kg}\right) \quad \text{(B.1.7)}$$

B.1.2. Water

Industrial water

The industrial water is usually used by technologies to wash and flush every given operating time as a cleaning measure.

$$Water\ Consumption\ \left(\frac{L}{day}\right) = Cleaning\ Cycles\ \left(\frac{cycles}{day}\right) \times Cycle\ Duration\ \left(\frac{min}{cycle}\right) \times Cycle\ Consumption\ \left(\frac{L}{min}\right) \quad \text{(B.1.8)}$$

$$Water\ Costs\ \left(\frac{€}{week}\right) = Water\ Consumption\ \left(\frac{L}{week}\right) \times Water\ Rate\ \left(\frac{€}{L}\right) \quad \text{(B.1.9)}$$

Cooling water

Technologies that apply high temperatures to dry the sludge, need a subsequent cooling stage.

$$\dot{Q}_c = \dot{m}_s C_{p,s} \Delta T_s \quad \text{(B.1.10)}$$

$$\dot{m}_{cw} = \frac{\dot{Q}_c}{C_{p,cw} \Delta T_{cw}} \quad \text{(B.1.11)}$$

$$Cooling\ Water\ Costs\ \left(\frac{€}{week}\right) = Water\ Consumption\ \left(\frac{L}{week}\right) \times Water\ Rate\ \left(\frac{€}{L}\right) \quad \text{(B.1.12)}$$

B.1.3. Compressed Air

Used in pneumatic devices such as valves and blowing systems (core blow filter press).

$$Air\ Consumption\ \left(\frac{Nm^3}{week}\right) = Air\ Consumption\ per\ Cycle\ \left(\frac{Nm^3}{cycle}\right) \times Cycle\ Frequency\ \left(\frac{cycles}{week}\right) \quad \text{(B.1.13)}$$

$$Air\ Costs\ \left(\frac{€}{week}\right) = Air\ Consumption\ \left(\frac{Nm^3}{week}\right) \times Air\ Rate\ \left(\frac{€}{Nm^3}\right) \quad \text{(B.1.14)}$$

B.1.4. Chemical Additives & Consumables

Additives usually used to enhance the mechanical dewatering stage and/or minimize operational problems such as foaming.

Additives

Polymer, defoamer and other chemicals.

$$Polymer\ Consumption\ \left(\frac{kg}{h}\right) = Polymer\ Dose\ \left(\frac{kg}{ton\ DS}\right) \times Dry\ Solids\ Concentration\ \left(\frac{ton\ DS}{ton\ sludge}\right) \times Sludge\ Flowrate\ \left(\frac{ton\ sludge}{h}\right) \quad \text{(B.1.15)}$$

$$Polymer\ Costs\ \left(\frac{€}{week}\right) = Polymer\ Consumption\ \left(\frac{kg}{week}\right) \times Polymer\ Price\ \left(\frac{€}{kg}\right) \quad \text{(B.1.16)}$$

Lubrication

Greasing of moving parts.

$$Grease\ Consumption\ \left(\frac{kg}{week}\right) = Grease\ Consumption\ per\ Cycle\ \left(\frac{kg}{cycle}\right) \times Greasing\ Frequency\ \left(\frac{cycles}{week}\right) \quad \text{(B.1.17)}$$

$$Grease\ Costs\ \left(\frac{€}{week}\right) = Grease\ Consumption\ \left(\frac{kg}{week}\right) \times Grease\ Price\ \left(\frac{€}{kg}\right) \quad \text{(B.1.18)}$$

B.1.5. Maintenance & Spare Parts Costs

Mostly provided by supplier. When not, a 3% with respect to the initial investment costs will be considered according to literature. (Towler & Sinnott, 2013)

$$Annual\ Maintenance\ Costs\ \left(\frac{€}{year}\right) = Initial\ Investment\ (€) \times Annual\ Maintenance\ Percentage\ \left(\frac{\%}{year}\right) \quad \text{(B.1.19)}$$

$$Spare\ Parts\ Cost\ \left(\frac{€}{year}\right) = Yearly\ Replacements\ \left(\frac{nº}{year}\right) \times Spare\ Parts\ Cost\ (€) \quad \text{(B.1.20)}$$

B.1.6. Labor Costs

Tasks of inspection, spare parts replacement, sludge transportation withing the plant (external labor services Ecojet to drying beds), cleaning, etc.

$$Task\ Labor\ Consumption\ \left(\frac{h}{week}\right) = Work\ Time\ (h) \times Nº\ of\ Necessary\ Operators \times Frequency\ \left(\frac{times}{week}\right) \quad \text{(B.1.21)}$$

$$Labor\ Costs\ \left(\frac{€}{week}\right) = Task\ Labor\ Consumption\ \left(\frac{h}{week}\right) \times Labor\ Rate\ \left(\frac{€}{h}\right) \quad \text{(B.1.22)}$$

B.2. Calculation of Economic Indicators & Cashflows

The different elements of the cashflow have been calculated as follows:

Initial Investment

Corresponds to the CAPEX of the project.

Revenue

As defined, the revenue in this particular project corresponds to the savings generated by the implementation of a new technology.

$$Disposal\ Costs = Sludge\ Production \times (Landfill\ fee + Transport\ fee) \tag{B.2.1}$$

$$Disposal\ Savings = Current\ Disposal\ Costs - New\ Disposal\ Costs \tag{B.2.2}$$

$$Annual\ Savings = Disposal\ Savings + (Current\ OPEX - New\ OPEX) \tag{B.2.3}$$

$$Revenues = Annual\ Savings - New\ OPEX \tag{B.2.4}$$

Gross Margin

Represents the difference between the project's revenue and its cost of operation.

$$Gross\ Margin = Revenues - OPEX \tag{B.2.5}$$

Depreciation

It is the accounting method used to allocate the cost of a tangible asset over its useful life. It reflects the reduction in value of an asset as it is used over time.

$$Depreciation = CAPEX \times Depreciation\ Rate\ (\%) \tag{B.2.6}$$

Margin before taxes

It reflects the financial performance after all operating expenses and interest expenses have been accounted for but before tax obligations.

$$Margin\ Before\ Taxes = Gross\ Margin - Fixed\ Costs - Depreciation \tag{B.2.7}$$

Net margin

Net margin represents the percentage of revenue that remains as profit after all expenses (including operating expenses, taxes, and interest) have been deducted.

$$Net\ Margin = Margin\ Before\ Taxes \times (100 - Tax\ Rate(\%)) \tag{B.2.8}$$

Cash flow

Cash flow refers to the movement of money into and out of a business. It is an essential measure of a project's liquidity, showing whether it can meet its short-term obligations and fund its operations. Cash flow is calculated by adding up all cash inflows (e.g., revenue from sales) and subtracting all cash outflows (e.g., operating expenses, capital expenditures)

Economic Indicators

The economic indicators use the information obtained through the calculation of the project's cashflows and transforms it into valuable data that allows for comparisons between projects.

- **Net Present Value (NPV).** Present value of the project. It represents how much value it generates (in current terms).

$$NPV = \sum \frac{Net\ Cashflows}{(1+r)^t} - Capital\ Investment \qquad \text{(B.2.9)}$$

- **Return on Investment (ROI).** Expresses the expected profit as a percentage of the investment cost.

$$ROI = \left(\frac{Net\ Revenue}{Capital\ Investment}\right) \times 100 \qquad \text{(B.2.10)}$$

- **Payback Period.** Expresses the time required for the project's accumulated income to equal the initial investment, recovering the invested capital.

$$Payback\ Period = \frac{Capital\ Investment}{Cashflow} \qquad \text{(B.2.11)}$$

B.3. Indicators Results

The following tables contain all indicators results for all technologies considered, both separately and in combination of dewatering and drying technologies.

Table 7.3 Indicators results for separate mechanical dewatering and drying technologies.

Technology	Mechanical Dewatering				Drying					
	Current	SP	C	FP	ELO	SS	GM	TF	BD	NVD
Energy										
Specific Energy Consumption (kWh/t evap. water)	[redacted]	1,2	5,5	1,1	587,0	129,4	0,0	1003,1	511,6	423,0
Specific Energy Consumption (kWh/t sludge)	[redacted]	1,0	4,7	1,0	270,0	53,9	0,0	401,3	190,4	169,2
Operation										
Sludge Production (t/day)	[redacted]	28,6	25,4	19,6	13,7	11,4	10,2	15,2	15,9	17,1
Outlet Dryness (%DS)	[redacted]	24,0	27,0	39,0	50,0	60,0	67,0	45,0	43,0	40,0
Manpower (h/week)	[redacted]	0,0	0,0	2,8	0,0	3,0	0,0	0,0	0,0	0,0
Water Recovery Rate (%)	[redacted]	86,8	88,7	92,3	63,0	64,1	81,8	54,8	51,0	93,8
Evap. Rate (t wàter/h)	[redacted]	6,0	6,1	6,3	0,7	0,3	0,6	0,6	0,6	9,0
Mass Reduction (%)	[redacted]	83,3	85,2	88,6	46,0	41,7	59,7	40,0	37,2	90,0
Economy										
Cost (€/t	[redacted]	1,5	1,2	1,4	24,5	32,3	21,9	47,0	21,5	4,7

unprocessed sludge)										
Cost (€/t processed sludge)	■	8,9	8,3	12,6	45,4	55,4	54,4	78,3	34,3	46,7
Environment										
GHG Emissions (t CO_2/week)	■	0,2	1,1	0,2	9,1	1,4	0,0	3,4	6,4	6,7
Specific GHG Emissions (kg CO_2/t sludge)	■	1,1	6,0	1,6	95,0	17,6	0,0	32,3	57,6	55,5
Specific Water Consumption (L/kg sludge)	■	0,7	0,8	0,1	0,9	0,0	0,9	0,0	0,0	1,2

Table 7.4 Indicators results for all technology combinations.

Technology	FP	C+ELO	FP+ELO	SP+ELO	FP+SS	SP+GM	C+GM	C+TF	FP+TF	SP+TF	C+BD	FP+BD	SP+BD	FP+NVD	SP+NVD
Energy															
Specific Energy Consumption (kWh/t evap. water)	1	49	45	45	8	1	5	70	38	110	36	32	121	32	32
Specific Energy Consumption (kWh/t sludge)	1	45	41	41	7	1	5	64	35	104	33	29	115	29	29
Operation															
Sludge Production (t/day)	18	14	14	14	11	11	10	15	15	10	16	14	8	14	17
Outlet Dryness (%DS)	39	50	50	50	60	65	67	45	45	70	43	50	90	50	40
Manpower (h/week)	3	0	2	0	6	0	0	0	2	0	0	2	0	2	0
Water Recovery Rate (%)	93	96	96	96	97	98	98	95	95	98	94	96	100	96	94
Evap. Rate (t wàter/h)	6	9	9	9	7	7	7	9	9	7	9	9	10	9	9
Mass Reduction (%)	90	92	92	92	93	94	94	91	91	94	91	92	96	92	90
Economy															
Cost (€/t unprocessed sludge)	2	5	5	5	5	4	4	8	6	11	4	5	13	5	5
Cost (€/t processed sludge)	18	61	63	63	77	60	75	92	64	201	48	62	286	62	47
Environment															
GHG Emissions (t CO_2/week)	0	10	9	9	2	0	1	5	4	5	7	7	2	7	7
Specific GHG Emissions (kg CO_2/t sludge)	2	106	97	97	20	3	15	42	34	74	67	69	35	69	55
Specific Water Consumption (L/kg sludge)	0	3	2	3	0	3	3	1	0	2	1	0	0	0	1

C. BASIC ENGINEERING ADDITIONAL INFORMATION

C.1. Mass Balance of the Filter Press

The following equations show the summarized mass balance of the filter press.

Solids Mass Balance

$$M_{solids,feed} = M_{solids,cake} \tag{C.1.1}$$

$$M_{solids,feed} = C_{feed} M_{feed} \tag{C.1.2}$$

$$C = \frac{M_{solids}}{M_{solids} + M_{liquid}} \tag{C.1.3}$$

Where $M_{solids,feed}$ is the mass of solids fed to the filter press, C_f is concentration of solids in the feed, $M_{solids,cake}$ is the total mass of solids in the filter cake.

Liquid Mass Balance

$$M_{liquid,feed} = M_{filtrate} + M_{liquid\ in\ cake} \tag{C.1.4}$$

$$M_{liquid,feed} = (1 - C_f) M_{feed} \tag{C.1.5}$$

Where $M_{filtrate}$ is the mass of the liquid collected as filtrate and $M_{liquid\ in\ the\ cake}$ is the mass of the liquid retained in the filter cake.

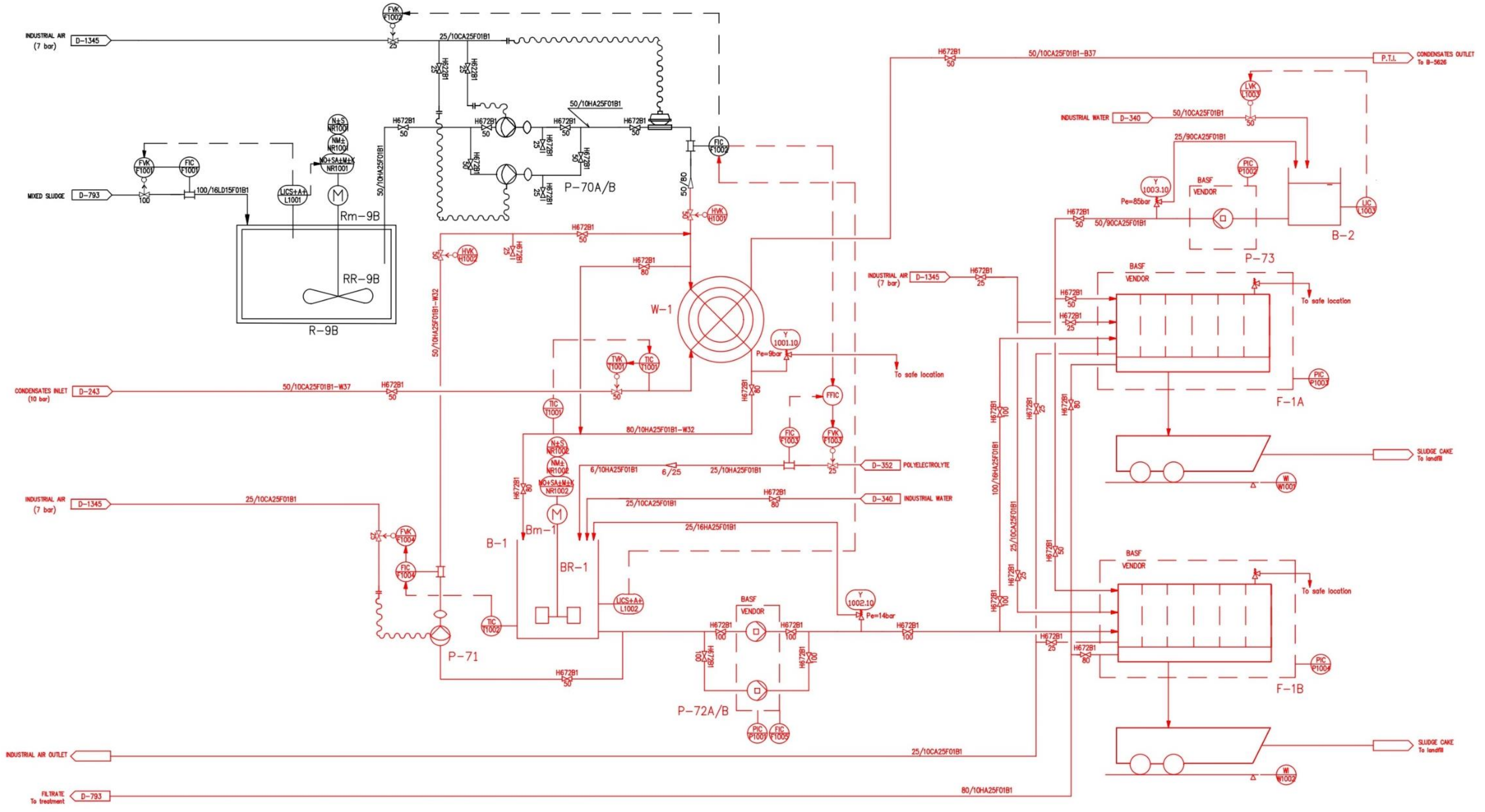
Overall Mass Balance

$$M_{feed} = M_{cake} + M_{filtrate} \tag{C.1.6}$$

$$M_{cake} = M_{solids,cake} + M_{liquid\ in\ cake} \tag{C.1.7}$$

C.2. P&ID

0 10 20 30 40 50 60 70 80 90 100 Escala del plano original en mm.



R-9B
SLUDGE PIT
50 m³

RR-9B
MIXER
PROPELLER D= 2000
49 rpm

RRm-9B
ELECTRIC MOTOR
2.2 Kw 1500 rpm

B-1
CONDITIONING TANK
10 m³

BR-1
MIXER
FLAT-BLADE TURBINE D= 600
35 rpm

BRm-1
ELECTRIC MOTOR
0,5 Kw 1000 rpm

B-2
HIGH-PRESS. WATER TANK
3.8 m³

P-70A/B
WILDEN NEUMATIC PUMP
XPS 830/SSAAA/TWS/TF/STF/0504
DN50 Pd= 8.6bar

P-71
WILDEN NEUMATIC PUMP
XPS 830/SSAAA/TWS/TF/STF/0504
DN50 Pd= 8.6bar

P-72A/B
FEED PISTON PUMP
DRAGON DR30-CR.3
DN100 Pd= 15bar

P-73
CAKE WASHING PISTON PUMP
85 lit./min Pd= 90bar

W-1
SPIRAL PLATE HEAT EXCHANGER
187 Kw 14 m²
Td=100°C Pd=12bar

F-1A/B
AUTEMI FILTER PRESS
70 PLATES 3160 lit.

BASF
We create chemistry

BASF Españ̃ola S.L.
Tlf. +34 977 256 200
43006 TARRAGONA

Proyecto N./Año

	Fecha	Nombre
Dibujado	12/2024	C. EL HMIDI
Comprobado		
Aprobado		

Objeto
SLUDGE DEWATERING
WITH FILTER PRESS

Escala
Edificio N.
A-12
Plano N.

Rev.	W	X	P	Q
R	S	T	U	V

Sustituido por
Sustituye a

C.3. HazOp Methodology

The HazOp method focuses on studying specific parts of the process (stages, equipment, etc.), also called nodes. Each node (including all incoming or outgoing pipelines as well as utilities) is independently examined for potential hazards caused by deviations from normal or desired operation. These deviations come from the guide word applied to the process parameters. (Crowl & Louvar, 2011)

Guide words apply to both general (react, mix) and specific (pressure, temperature) parameters. In the next table can be found the guide words originally proposed by the ICI.

Table 7.5 Original HazOp guide words and meaning. (Crowl & Louvar, 2011)

Guide word	**Meaning**
No	Negation of the design intent
Less	Quantitative decrease
More	Quantitative increase
Part of	Qualitative decrease
As well as	Qualitative increase
Reverse	Logical opposite of the intent
Other than	Complete substitution

The HazOp methodology is put into practice in the following steps: preparing for the review, performing the review, documenting results. Next figure illustrates the concept of the HazOp analysis technique.

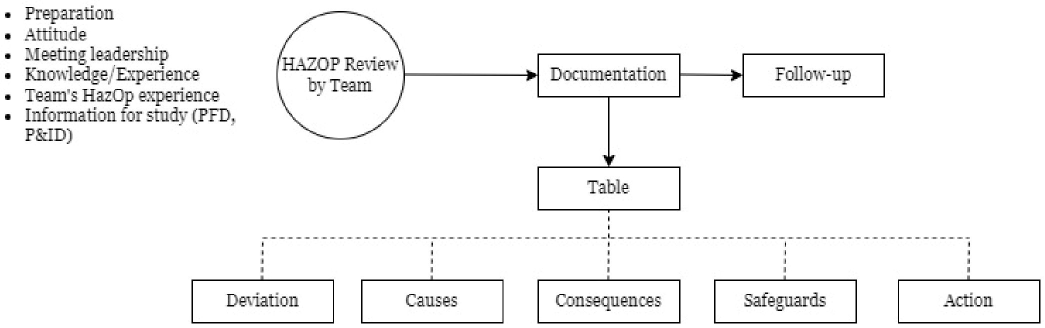


Figure 7.3 HazOp analysis technique.

The HazOp analysis methodology takes into account the following hypotheses: (Crowl & Louvar, 2011)

- The facility is well designed, in relation to the experience, the knowledge of the processes involved and the application of the relevant standards and codes.
- The construction materials have been adequate, and the building has been done correctly.
- The analyses are a "snapshot" where events of immediate effect are mixed with events of high temporal inertia.

D. SELF-EVALUATION QUESTONNAIRE

Evaluate the acquired competences according to the tasks you have carried out.

Degree Competences		**Task in which you have observed the competence**	**Self evaluation [Rank 1 to 10]**	**Aspects to be improved**
SPECIFIC COMPETENCES				
A1.1	Effectively apply knowledge of basic, scientific and technological materials pertaining to engineering.	Design and dimensioning of equipment	7	
A1.2	Design, execute and analyze experiments related to engineering	Sludge characterization	8	
A1.3	Be able to analyze and synthesize the continuous progress of products, processes, systems and services, whilst applying criteria of safety, economic viability, quality and environmental management. (G6)	Bussiness case	8	
A1.4	Know how to establish and develop mathematical models by using the appropriate software in order to provide the scientific and technological basis for the design of new products, processes, systems and services and for the optimization of existing ones. (G5)	Design of heat exchanger	8	
A2.1	Be able to apply the scientific method and the principles of engineering and economics to formulate and solve complex problems that arise in processes, equipment, installations and services, in which the material undergoes changes to its composition, state or energy content, these changes being characteristic of industrial chemistry and other related sectors such as pharmacology, biotechnology, materials sciences, energy, food and the environment. (G1)	Project in general	8	
A2.2	Conceive, project, calculate and design processes, equipment, industrial installations and services in the field of chemical engineering and related industrial sectors in terms of quality, safety, economics, the rational and efficient use of natural resources and the conservation of the environment. (G2)	Design and dimensioning of equipment	7	
A2.3	Lead and technically and economically manage projects, installations, plants, companies and technological centres in the ambit of chemical engineering and related industrial sectors. (G3)	Project in general	7	
A3.1	Apply knowledge of mathematics, physics, chemistry, biology and other	Sludge characterization	8	

	natural sciences by means of study, experience, practice and critical reasoning in order to establish economically viable solutions for technical problems (I1).			
A3.2	Design and optimize products, processes, systems and services for the chemical industry on the basis of various areas of chemical engineering, including processes, transport, separation operations, and chemical, nuclear, elctrochemical and biochemical reactions engineering (I2).	Project in general	8	
A3.3	Conceptualize engineering models and apply innovative problems solving methods and appropriate IT applications to the design, simulation, optimization and control of processes and systems (I3).	Project in general	8	
A3.4	Be able to solve unfamiliar and ill-defined problems by taking into account all possible solutions and selecting the most innovative. (I4)	Project in general	7	
A3.5	Lead and supervise all types of installation, process, system and service in the different industrial areas related to chemical engineering (I5).	Project in general	7	
A3.6	Design, construct and implement methods, processes and installations for the integrated management of waste, solids, liquids and gases, whilst also taking into account the impacts and risks of these products (I6).	Project in general	8	
A4.1	Lead and organize companies and production and service systems by applying knowledge and abilities regarding industrial organization, commercial strategy, planning and logistics, mercantile and labour legislation, and financial and costs accounting (P1).	Project in general	8	
A4.2	Lead and manage the organization of work and human resources by applying criteria regarding industrial safety, quality management, occupation risk prevention, sustainability and environmental management (P2).	Project in general	7	
A4.3	Manage research, development and technological innovation whilst ensuring the transfer of technology and taking into account property and patent rights (P3).	Project in general	9	
A4.4	Adapt to structural changes in society caused by economic, energy or natural factors so as to be able to solve any resulting problems and to contribute technological solutions with a high commitment to sustainability (P4).	Project in general	8	
A4.5	Lead and monitor the control of installations, processes, products, certification, auditing, verification, testing and reports (P5).	Project in general	7	

A5.1	Carry out, present and defend (once all the curriculum credits have been obtained) an original individually produced piece of work before a university panel. The work will consist of a professional integrated Chemical Engineering project that synthesizes (TFM1)			
TRANSVERSAL COMPETENCES				
B1.1	Communicate and discuss proposals and conclusions in a clear and unambiguous manner in specialized and non-specialized multilingual forums (G9).	Project in general	8	
B1.2	Adapt to changes and be able to apply new and advanced technologies and other important developments with initiative and entrepreneurial spirit. (G10)	Project in general	7	
B2.1	Lead and define multidisciplinary teams that are able to make technical changes and address management needs in national and international contexts. (G8)	Project in general	7	
B3.1	Work in a team with responsibilities shared among multidisciplinary, multilingual and multicultural teams	Project in general	8	
B4.1	Be able to learn autonomously in order to maintain and improve the competences pertaining to chemical engineering that enable continuous professional development. (G11)	Project in general	8	
B5.1	Carry out and lead the appropriate research, design and development of engineering solutions in new or little understood areas, whilst applying criteria of creativity, originality, innovation and technology transfer. (G4)	Project in general	8	
B5.2	Bring together knowledge, make judgements and take decisions on the basis of incomplete or limited knowledge whilst taking into account the social and ethical responsibilities of professional practice. (G7)	Project in general	7	
NUCLEAR COMPETENCES				
C1.1	Have an intermediate mastery of a foreign language, preferably English	Project in general	9	
C1.2	Be advanced users of the information and communication technologies	Project in general	8	
C1.3	Be able to manage information and knowledge	Project in general	8	
C1.4	Be able to express themselves correctly both orally and in writing in one of the two official languages of the URV	Project in general	8	
C2.1	Be committed to ethics and social responsibility as citizens and professionals	Project in general	9	
C2.2	Be able to define and develop their academic and professional project	Project in general	8	

b) Evaluate the final master project and suggest improvements.

Key steps	**Evaluation [Mark 1 to 10]**	**Improvement proposed**
Selection/assignment of the project (dissemination, communication, assignment requirements...)	10	
Stay (welcome, length, relationship, follow-up made by the company...)	10	
Follow-up made by URV tutor	10	
Other aspects to be considered (which ones...)		