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RESPONSIBLE NUTRIENTS RECOVERY FROM URBAN WASTEWATER

A CASE STUDY ON THE POTENTIAL RECOVERY OF PHOSPHORUS AND NITROGEN FROM THE CONVENTIONAL WASTEWATER TREATMENT PLANT LAS ESCLUSAS, GUAYAQUIL -ECUADOR

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Date	June/2025
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Course year	2024-2025
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ABSTRACT

The world is facing a water quality crisis in the form of water pollution and scarcity like it has never seen before. Discharges of untreated sewage wastewater flows into the natural watercourses constitute a menace to the environment. Academia and the scientific community have explored and proposed circular economy (CE) concepts aimed at mitigating the human footprint on natural resources and focusing on ensuring sustainable water management initiatives. Under this notion conventional wastewater treatment plants (CWWTP) are turning into water resource recovery facilities, which not only clean its wastewater but also recover the useful organic resources like energy and nutrients (phosphorus and nitrogen) that otherwise are destroyed or disposed back to the environment. However, research has also indicated that the implementation of these circular economy practices lacks a system's thinking approach when it comes to understanding the importance of social issues, where the needs and rights of all social actors and local communities are adequately considered. Consequently, this study provides a methodological approach which through qualitative and quantitative methods that integrates the opinions and preferences of stakeholders at various stages of the project, enhances the robustness of its findings. From the empirical input of key stakeholders, relevant criteria were identified to assess the sustainability impact of nutrient recovery technical alternatives from urban wastewater treatment plants.

The evaluation conducted at the Las Esclusas CWWTP in Ecuador (used as a case study) highlights the significance of social considerations, particularly in the context of implementing nutrient recovery technologies in countries from the Global South. A preliminary technical assessment showed that three commercially nutrient recovery technologies could be feasible to be implemented at this plant (precipitation/crystallization of struvite and mono-incineration & AshDEC to recover phosphorus and ammonia stripping to recover nitrogen). However, none of these technologies can be immediately implemented under current conditions. Many aspects will need to change before the plant is ready to recover nutrients like adding a secondary treatment. Yet the input from stakeholders in assessing relevant criteria for the purpose of measuring the sustainability performance per nutrient recovery technology, was instrumental to underline the importance of social aspects and emphasize the essential role of the institutional landscape. Challenges within the institutional domain, characterized by inefficiencies in the legislative and political systems, pose significant obstacles to the implementation of nutrient recovery technologies. In the specific case of Las Esclusas CWWTP, the absence of robust environmental legislation and institutional commitment towards circular economy projects, diminishes the feasibility and perceived value of implementing nutrient recovery systems. Furthermore, cross-cutting issues such as bureaucratic inefficiencies and lack of institutional transparency further complicates the attempt to progress at a faster rate within the context of the application of circular economy initiatives to the sustainable management of wastewater. Without proactive government engagement and inter-institutional collaboration, the transition to circular practices in the wastewater sector remains unlikely in countries from the Global South. This inclusive approach emphasizes the importance of considering social perspectives in wastewater management practices which ultimately contributes to more responsible and socially relevant decision-making processes.

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CHAPTER 1

1.1 INTRODUCTION

The rapid growth of the global human population, coupled with rapid urbanization and economic development, is placing unprecedented demands on water resources, putting freshwater ecosystems under immense pressure. Inadequate urban water management practices contribute to the pollution of these ecosystems, disrupting natural water cycles and posing harmful consequences to natural habitats' well-being. Untreated wastewater discharges, containing chemical and microbiological pollutants, have detrimental effects on the environment (Akpor et al., 2011). According to the latest UN Water Report, approximately 44% of domestic household wastewater globally is discharged into natural water courses without proper treatment (Alabaster et al., 2021). Moreover, it is estimated that 80-90% of sewage water produced by countries in the global south is discharged untreated into natural water bodies (UN Water, 2017).

In the global north (GN), conventional wastewater treatment plants (CWWTPs) are the predominant solution in urban settings. These large, high-tech centralized facilities are designed to clean and treat significant volumes of wastewater from metropolitan areas. However, these conventional infrastructures typically view wastewater as "waste" within a linear system approach, often overlooking environmental considerations such as material usage, land utilization, and the potential for resource recovery from wastewater (Chirisa et al., 2017; Libralato et al., 2012). Initially, these plants were primarily focused on sanitation for public health purposes. However, with increasing environmental awareness, there has been a shift towards considering the quality of discharged water, leading to regulatory measures in some regions of the world.

In response to growing concerns about the environmental impact of CWWTPs, there has been a push for the development of more sustainable approaches. This is particularly relevant in the context of addressing climate change and reducing greenhouse gas emissions associated with energy and material inputs. Academia and international institutions, including the United Nations, have advocated for innovative wastewater treatment approaches as part of Sustainable Development Goal 6 (SDG6) - water and sanitation for everyone. SDG6 emphasizes the three pillars of sustainability - People, Planet, and Profit - highlighting the need for holistic solutions that address social, economic, and environmental aspects (UN-DESA, 2022). To achieve these sustainability goals, wastewater treatment plants must integrate more sustainable practices such as water conservation, wastewater reuse, nutrient recovery, and harnessing the energy potential of wastewater (Chirisa et al., 2017; Guven et al., 2022). In order to change this linear thinking and implement innovative sustainable practices, a new approach named Circular Economy (CE) has emerged as a promising framework for achieving these objectives. Circular economy promotes the concept of reusing, recycling, and recovering resources to minimize waste and maximize sustainability benefits. Therefore, transforming linear and semi-circular material and energy flows into circular flows, which is becoming a viable option for countries, governments, academia and society to transform our unsustainable way of living (Saavedra et al., 2018).

With respect to wastewater management, CE concepts may lead to a “paradigm shift” from pollutant removals towards water and resource recovery facilitites (WRRFs) where wastewater is considered a resource rather than waste. In other words, a CWWTP will act as a factory providing many resources like clean water, energy, nutrients, etc. (Sgroi et al, 2018, Kehrein et al., 2020). In relation to energy consumption, for example, there is a need to substantially decrease the energy use by designing treatment processes with a focus on energy efficiency and recovery (Kehrein et al., 2020). Moreover, a WRRF can help to reduce environmental impacts by, for example, reusing digestate sludge to produce energy and reducing it from being landfilled (Guven et al., 2022), and recovering nutrients like nitrogen and phosphorus to be reused as raw materials to produce fertilizers (Ye et al., 2020). Especially, these two nutrients need to be removed from wastewater effluents because they are responsible for the rapid degradation of the natural water ecosystem, since their higher concentrations cause eutrophication (accelerated growth of algal blossoms) and a depletion of the water's dissolved oxygen affecting in this way all aquatic fauna and flora (Akpor, 2011; Schindler et al., 2016).

The recovery of nutrients such as phosphorus and nitrogen from wastewater has gained significance within the application of CE principles to wastewater management. Recognizing the importance of these principles has broaden opportunities for resource recovery, environmental sustainability, cost savings, climate change mitigation, regulatory compliance, innovation, resilience, and improvements in sanitary public health. In this context, for example, the development of criteria and indicators that are aligned with circular economy principles within the environmental, social, economic and technical dimensions, serve as decision-supporting tools to assess various aspects of wastewater treatment plant operations, including resource efficiency, material recovery, and waste reduction overall. By measuring and analyzing this information, wastewater treatment plants can identify areas for improvement and implement targeted strategies to optimize their circular economy performance, thereby enhancing sustainability and resource utilization (Preisner et al., 2022). Nevertheless, it is documented that current CE strategies have been mostly focused on the technical, economic, and environmental aspects behind sustainable innovative technologies. And, consequently, not much attention has been given to the social aspects underestimating the opinions and preferences from relevant stakeholders. As a result, some scholars like Korkonen et al., (2018) and Purvis et al., (2023), recognize that the notion of CE is failing to incorporate the social dimension into its agenda like social objectives and values that are inherent in societal structures and cultures. There is a lack of documented data surrounding the type of societal values and actors (researchers, policymakers, end-users) needed to assist on the responsible implementation of these CE efforts (Kehrein et al., 2020; Palmeros et al., 2022; Chrispim et al., (2020).

Thus, this study attempts to demonstrate the importance of giving priority to the social dimension in the assessment of nutrient recovery technologies at a CWWTP situated in a country from the Global South. By prioritizing the opinions and preferences of all relevant stakeholders, criteria that reflect environmental, economic, technical and especially social considerations are identified and analyzed to assess the potential capabilities of this wastewater treatment plant to responsibly recover nutrients.

1.2 POTENTIAL RECOVERABLE RESOURCES FROM WASTEWATER

As previously noted, the wastewater treatment processes generate a significant volume of organic and inorganic materials, requiring responsible management to minimize environmental impact. Municipal wastewater treatment plants offer a wealth of recoverable resources, including energy sources like biogas and electricity, as well as nutrients such as phosphorus and nitrogen, alongside cellulose, clean water, biochemicals, metals, and more. Given the focus of this study on phosphorus and nitrogen recovery, it is pertinent to provide a brief overview of these two nutrients as well as their importance over other resources that can be recovered from wastewater.

1.2.1 PHOSPHORUS (P)

GENERAL CHARACTERISTICS

Phosphorus (P) is an essential element for the survival of all living organisms. It is a key component in the molecular structure of nucleotides in DNA and RNA which carry energy to cells. Vegetables and meats are rich in phosphorus which comes from agricultural fertilizers making it an important raw material in the production of fertilizers. Beyond agriculture, phosphorus is crucial in diverse industries serving as a vital component in pharmaceuticals, chemicals, food processing, and advanced high-tech electronics.

Phosphorus is extracted from phosphate rock, which is a resource that is found only in a few countries worldwide. The limited availability of phosphate rock, combined with global reliance on these reserves has intensified phosphorus scarcity driving significant price increases in recent years. Countries without domestic phosphorus deposits depend heavily on imports, making them vulnerable to fluctuations in fertilizer and mineral markets. Geopolitical conflicts have amplified these challenges prompting the European Union to designate this mineral as a critical raw material due to its essential role in agriculture and limited supply stability (Altamira-Algarra, et al., 2022; Robles et al., 2020).

Most of the phosphorus consumed globally is used in fertilizers for agricultural production. Intensive farming practices have led to high levels of phosphorus run-off into aquatic environments from agricultural discharge into natural waterways and from untreated urban wastewater (Ye et al., 2020). This runoff is a primary driver of eutrophication in aquatic ecosystems, and contamination of ground water. About 70% of phosphorus losses occur through agricultural runoff, with the remaining 30% resulting from industrial and municipal waste discharges into waterways (Figure 1.1) (Vu et al., 2023).

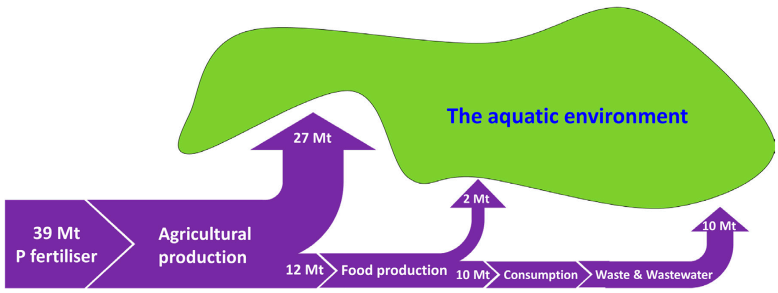


Figure 1. 1 Mass flow of Phosphorus (Vu et al., 2023)

Although the percentage of phosphorus run-off from waste & wastewater is lower than from agricultural sources, wastewater presents a more feasible opportunity for phosphorus recovery. Phosphorus concentrations in agricultural run-off are sufficient to cause eutrophication but are generally too low for effective removal and recovery with conventional wastewater treatment technologies (Altamira-Algarra, et al., 2022). In addition, studies show that more than half of the phosphorus consumed within a nation’s economy is ultimately lost through wastewater discharge, highlighting wastewater as an important source for phosphorus recovery (Salkunic et al., 2022). Given the limited availability of phosphorus and its environmental impacts, recent research has focused on developing phosphorus removal and recovery technologies (see Appendix 1 for more details) within wastewater treatment, aiming to support circular economy practices. Under a circular economy model, the recovery, reuse, and commercialization of phosphorus from wastewater could become a standard in wastewater management offering diverse applications for this valuable element (Table 1.1) (Egle et al., 2016).

Table 1. 1 Possible uses for recovered phosphorus (Egle et al., 2016)

Product (PO4-P)	Uses
Phosphate (Struvite, Calcium Phosphate)	Fertilizers
P-Trichoride	Food Processing Semi-conductor manufacture Additives for plastics and lubricant oils Insecticides Flame retardants
P-sulphide	Insecticides Lubricant oils
Sodium Hypophosphite	Nickel plating
Specialized forms of PO4-P	Vivianite (industrial application)

1.2.2 NITROGEN

GENERAL CHARACTERISTICS

Nitrogen (N) is also an important element for the subsistence of life. Almost 80% of nitrogen is found in the atmosphere in a non-reactive gas form. And the other 20% is found in soils in the reactive form as ammonium, nitrite, and nitrate which are essential elements for plant growth and agricultural practices. Since the discovery of extracting ammonia from nitrogen and hydrogen gases (the Haber-Bosch process 1909) to produce fertilizers, the production capacity of agricultural crops has more than quadrupled. Along with an exponential global increase in population that demands an increase in agricultural activities, these events have affected the nitrogen cycle (De Vries, 2021). The increasing use of fertilizers in the food production industry has "doubled the global cycling of reactive nitrogen over the last century" where only "17% is consumed by humans through crops or livestock while the remaining nitrogen is lost to freshwaters (run-off) (Figure 1.2) and the atmosphere" (Beckinghausen et al., 2020 Pg. 1). This problem has caused detrimental effects on terrestrial and aquatic ecosystems impacting air, soil, and water quality. Effects like the decline in plant diversity within terrestrial ecosystems and the proliferation of algal blooms in aquatic ecosystems, have caused oxygen-depleted "dead zones," which are attributed to nitrogen-induced eutrophication and acidification. Especially the nitrous oxide (N_2O) is considered a greenhouse gas to be responsible for the depletion of the ozone layer. Furthermore, other nitrogen oxides are causing high risks to the environment and human health like blue-baby syndrome in infants and the formation of carcinogenic nitrosamines in the human body (De Vries, 2021), (Jose J., 2023).

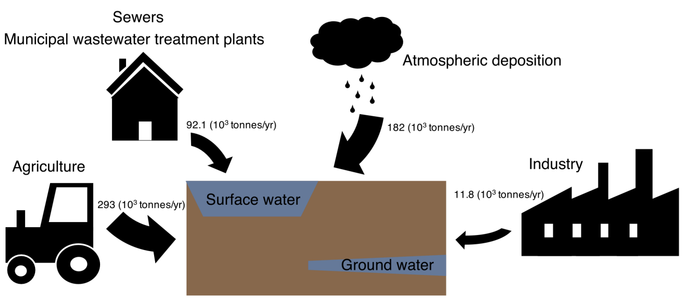


Figure 1. 2 Schema N loading to surface water & groundwater in a country (e.g.Canada)(Rahimi et al., 2020)

In the same token as with phosphorus, the environmental costs paired with a substantial high fertilizer price trend (Baffes and Koh, 2023), has incited investigation into alternative methods to recover nutrients like nitrogen to produce fertilizers. Nitrogen is recovered mainly as compounds for chemically based ammonia in the production of fertilizers. Figure 1.3 shows all the fertilizer products that can be produced from nitrogen recovery techniques (chemical, physical, biological) and feed source combinations like wastewater, sludge, digestate, reject water and urine.

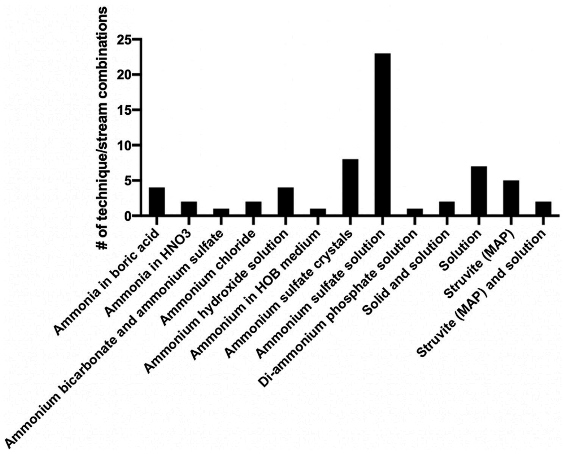


Figure 1. 3 Fertilizer products from N recovery techniques (Beckinghausen et al., 2020)

It is documented that the process to remove N from wastewater is complex and challenging and many recovery techniques and methods might not be feasible because they represent high costs (energy, maintenance, additive chemicals, etc) (Rahimi et al., 2020, Beckinghausen et al., 2020, Shaddel et al., 2019) (See Appendix 1 for further details). However, considering that municipal wastewater contains approximately 20 million tons of ammonium annually, making up nearly 19% of the total annual ammonium synthesized through the Haber-Bosch process, has instigated for the development of technologies that can recover reactive nitrogen in the form of ammonia (Jose J., 2023).

1.3 CONVENTIONAL WATER TREATMENT PLANTS

A conventional wastewater treatment plant's (CWWTP) main objective is to clean wastewater by using any or a combination of physical, chemical, and biological processes to remove pollutants from waste streams before their discharge to natural waterways. The treatment involves three stages. Figure 1.4 shows a diagram of the different treatments within a conventional wastewater treatment plant.

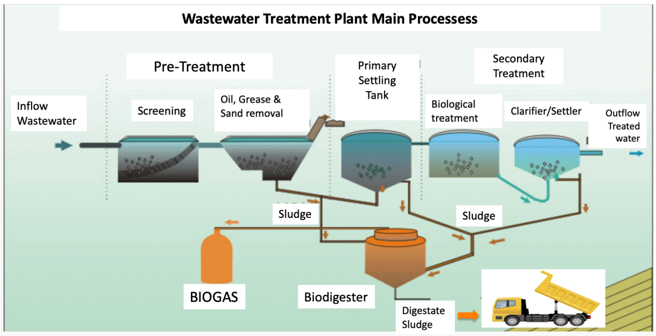


Figure 1. 4 Conventional wastewater treatment plant's main processes. Adapted from Ingenieria Aquaducto https://www.aquaductoingenieria.es

In Figure 1.5, a more detailed overview of the different treatment and their processes are described (Yadav et al., 2023). The first stages (Preliminary and Primary treatment) consist of removing all contaminant materials from the wastewater by physical and chemical treatment. Some of the techniques used are screening, comminution, grit removal, coagulation and flocculation, sedimentation and flotation. The second stage (Secondary treatment) involves the removal of the suspended solids and residual organics that are still present in the water via aerobic or anaerobic biological methods. The destruction or conversion of contaminants takes place by using microorganisms, and some of the techniques are membrane bioreactor, activated sludge process, trickling filter. The main aim of this method is to remove nutrients (nitrogen and phosphorus) and the degradable organic matter (sludge) from wastewater. The third stage (Tertiary treatment) is the final or sometimes called the advanced stage. It involves removing the organic matters and suspended solids left after secondary treatment. During this final treatment the quality of the effluent improves significantly making it appropriate for reuse. Some of the techniques used includes ion exchange, chemical oxidation, membrane processes, AC adsorption, etc (Rezai, Allahkarami, 2021).

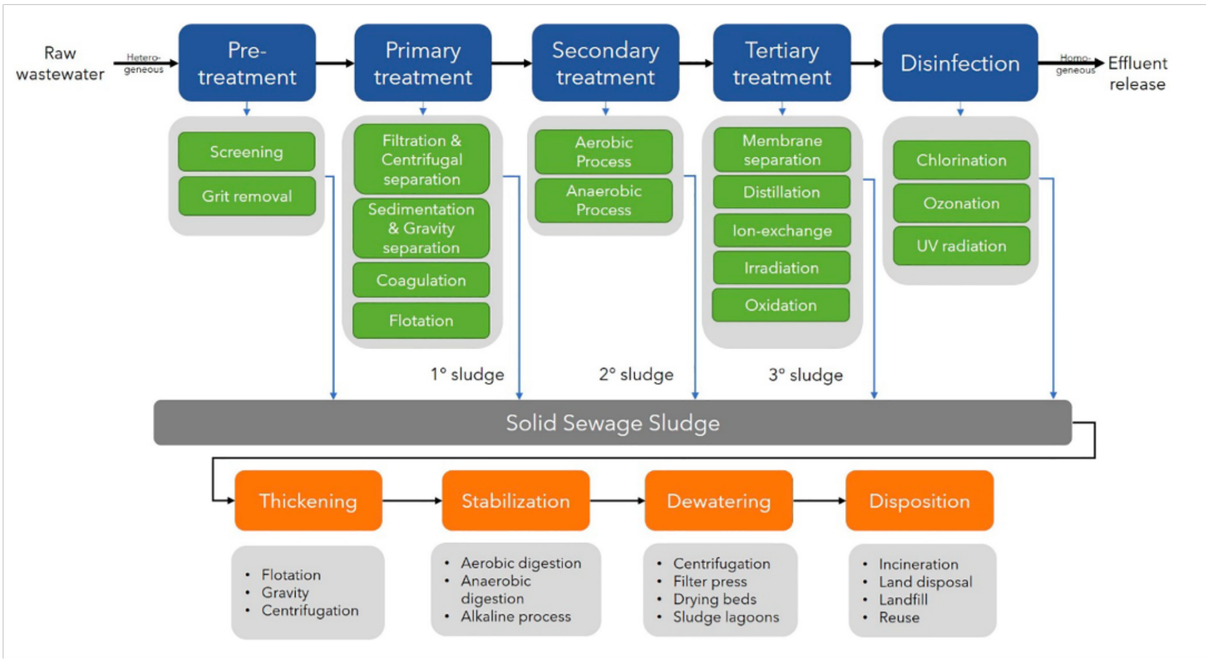


Figure 1. 5 Classical wastewater treatment processes (Yadav et al., 2021)

The selection of wastewater treatment techniques depends on various factors such as the plant's infrastructure, treatment objectives, seasonal variations, specific wastewater characteristics (such as composition and flow rates), and the country's economic conditions, especially where budget constraints exist. In response to these conditions, some treatment plants have adopted modified processes tailored to their unique requirements. One example is Chemically Enhanced Primary Treatment (CEPT), which involves the absence of secondary or biological treatment processes. This type of treatment involves both physical and chemical processes to treat wastewater by removing suspended solids, organic carbon and nutrients before releasing the water back to natural waterways. This physical-chemical treatment of wastewater is a modification of the simple primary treatment since it allows increasing the efficiency in the removal of gravitational sedimentation, by adding small doses of coagulants. The usage of coagulants helps to improve decontamination efficiency. The coagulants that are generally used are metal salts such as ferric chloride, alumina sulfate or poly-aluminum chloride. Several types of anionic, cationic, and uncharged polymers are also used as flocculants, where poly aluminum chloride (PACL) and polyacrylamide (PAM) are the widely used ones. Flocculants assist in the formation and maturation of flocs promoting their settling or flotation, thereby facilitating their removal from the wastewater. Coagulants and flocculants help improve the efficiency of solid-liquid separation processes (Figure 1.6). CEPT systems can reduce between 43.1–95.6% of COD (Chemical Oxygen Demand), 70.0–99.5% of suspended solids, and 40.0–99.3% of phosphorus depending on the characteristics of wastewater treated and type of coagulants and/or flocculants used (Shewa, 2020). CEPT is considered a cost-effective method for wastewater treatment that can achieve efficient effluent disinfection (Chagnon, Harleman., 2004) and is currently implemented at Las Esclusas CWWTP.

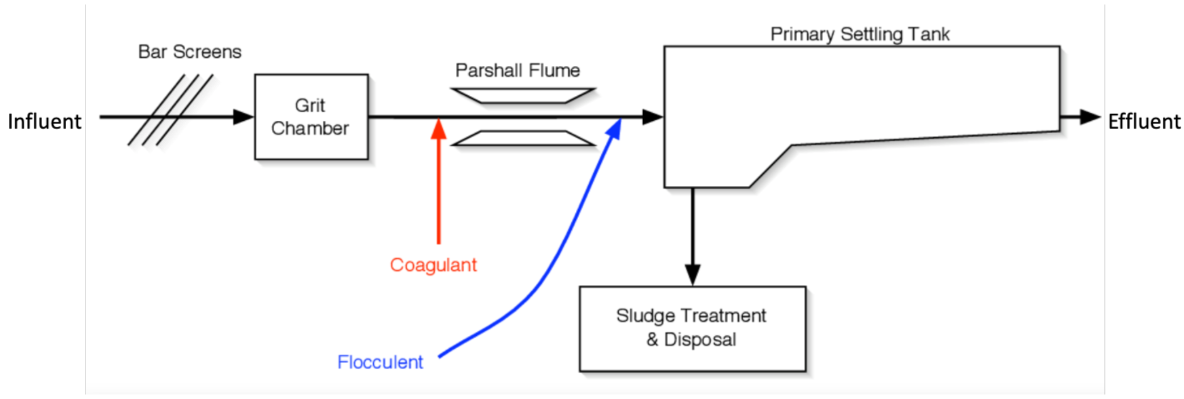


Figure 1. 6 Diagram of Conventional Primary Treatment and CEPT (Chagnon, Harleman., 2004)

1.4 CASE STUDY DESCRIPTION

As an important component in this project, a conventional wastewater treatment plant (CWWTP) situated in Ecuador, a country in the Global South was selected as a case study. This plant is particularly relevant for analysis due to its documented capacity to implement circular economy strategies such as the internal recovery and reuse of biogas from its anaerobic digesters. Additionally, since the waste sludge is currently landfilled, there is potential for nutrient recovery like phosphorus and nitrogen for use in the production of fertilizers. However, despite these promising possibilities, the plant does not currently implement such resource recovery initiatives. Several bottlenecks hinder the adoption of these CE practices including the production of renewable energy and the recovery of nutrients present in the waste sludge. Therefore, it is essential to assess opportunities that could enable this plant to optimize resource utilization from its effluent wastewater streams. This analysis is done on the plant’s current technical state without providing insights into possible future retrofiting.

1.4.1 LAS ESCLUSAS CWWTP

The Las Esclusas CWWTP is situated in the southern region of Santiago de Guayaquil, the capital of the Guayas province in Ecuador (Figure 1.7). Guayaquil is a coastal city that enjoys convenient access to the Pacific Ocean through the Gulf of Guayaquil. It is positioned at approximately latitude 2°19' south and longitude 79°53' west and maintains an average elevation of 4 meters above sea level with an approximate area of 34,500 hectares of flat terrain. The city lies within the Guayas, Daule, and Babahoyo River basin, which ultimately discharges into the Pacific Ocean to the east. As an essential center for social and economic advancement, Guayaquil hosts a population of approximately 3 million inhabitants, constituting nearly a quarter of the country's total population. Its climate is characterized as tropical, delineated by distinct dry and rainy seasons, with temperatures fluctuating between 15 and 35 degrees Celsius throughout the year.

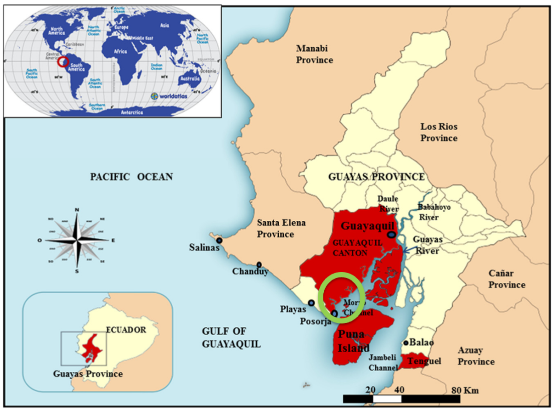


Figure 1. 7 Geographical location of the CWWTP Las Esclusas, Guayaquil-Ecuador
https://commons.wikimedia.org/wiki/File:Mapa_Sageo_de_Guayas_-_Guayaquil_C3.svg

Due to the city's location near the Daule-Guayas Rivers and the condition of existing pipes, groundwater infiltration into the sanitary sewer is high. Additionally, river tides, with fluctuations up to 4 meters, affect sewage system operation, requiring discharge limitations through control valves and pump stations to prevent overflow during high tide. Consequently, wastewater storage occurs in the pipes causing some raw sewage discharges directly into the Daule and Guayas rivers increasing pollution levels of both water ecosystems.

In order to address the aforementioned situation, the Municipality of Guayaquil, through its Municipal Drinking Water and Sewage Company EMAPAG EP, have taken concrete measures to improve sanitary conditions in the city. They decided to carry out projects to provide the city with 100% of coverage and connection to the sanitary sewer, as well as plans to complement the treatment of 100% of the wastewater produced by Guayaquil, according to the Guayaquil Drinking Water and Sewerage Master Plan updated in 2011. As part of a public-private partnership project funded by the World Bank and the European Investment Bank, the Ecuadorian municipal entity EMAPAG and the French company Veolia agreed in 2015 to construct two conventional wastewater treatment plants: Las Esclusas & Los Merinos. Las Esclusas, designed to cover the southern part of the city, was completed in 2022, and will benefit about 1,077,948 inhabitants in the areas of Isla Trinitaria, Guamo, and Suburbio Oeste. Los Merinos project has recently started construction and will cover the northern area of Guayaquil. The total project encompasses approximately 5,913 hectares in total area (Figure 1.8) (EMAPAG-EP, 2020) and will facilitate sewer network rehabilitation and intra-domiciliary connections.

Figure 1. 8 Aerial picture of CWWTP Las Esclusas. Presentation Representative from H&H constructores

The current infrastructure of the Las Esclusas plant is based on a Chemically Enhanced Primary Treatment (CEPT) system (as explained above), which is often selected over secondary treatment to clean wastewater in situations where specific circumstances warrant its application. The decision between CEPT and secondary treatment depends on various factors such as treatment objectives, budgetary constraints, space availability, seasonal variations, the need for rapid implementation, and specific characteristics of the wastewater being treated like composition and flow rates. This system was chosen to be implemented in Las Esclusas because of its most cost-effective treatment process capable of achieving efficient effluent disinfection.

1.5 RESEARCH GAP & MAIN RESEARCH QUESTIONS

As previously noted, the incorporation of societal dimensions essential for the successful implementation of nutrient recovery from wastewater have not been incorporated in the CE agenda appropriately. Many authors agree on the importance of prioritizing a social dimension by considering the opinions and preferences of all relevant actors during the implementation of nutrient recovery technologies, like Beckinghausen et al., 2020 posit, it is of great importance to consider stakeholder and consumer perspectives when effectively implementing nitrogen recovery from a wastewater treatment plant within a circular economy framework. This non-technical feedback is important as it can highlight insights that need to be addressed to better meet society and community needs. The information provided by stakeholders could help to avoid potential conflicts, protests, legal challenges, ensuring in this way the long-term success of projects like nutrient recovery from wastewater.

Thus, this study aims to identify potential technical alternatives for the recovery of phosphorus and nitrogen at the Las Esclusas CWWTP. Throughout an exploratory analysis of the different nutrient recovery technologies, their sustainability performance is assessed (ex-ante) prioritizing their social dimension impact. This analysis emphasizes on utilizing stakeholders' opinions and perspectives to assess criteria that in turn will help to measure the social performance of these different nutrient recovery technologies. Two rounds of semi-structure interviews with relevant stakeholders are conducted to extrapolate their opinions and perspectives towards the technical potential capabilities of Las Esclusas CWWTP to responsibly recover nutrients from its wastewater.

Consequently, the main research question and sub-questions translate into:

Main Research question:

What are sustainable technical alternatives to recover Phosphorus and Nitrogen at Las Esclusas CWWTP considering stakeholder's perspectives?

Sub-questions:

1. What commercially available technologies are feasible for recovery of Phosphorus and Nitrogen from the Las Esclusas CWWTP's effluent streams?
2. What are the criteria needed to assess sustainability performance for Phosphorus and Nitrogen recovery at the Las Esclusas CWWTP emphasizing stakeholders' perspectives?
3. In an ex-ante assessment, what is the potential performance of the commercial technologies identified in sub-question 1 considering the criteria from sub-question 2?

The research study is structured into 6 chapters:

Chapter 1 introduces the study, providing and overview of the technical processes employed at a CWWTP, and the potential nutrients that can be recovered to potentially produce agricultural fertilizers. Additionally, this chapter outlines the research gap with the corresponding main research question and sub-questions. Chapter 2 addresses the research methodology and methods needed to answer the main research question and sub-questions. Chapter 3 answers sub-question 1 by conducting a technical analysis to identify existing nutrient recovery technologies commercially available. Specifically, this analysis assesses how these technologies align with the technical system of the Las Esclusas CWWTP, aiming to identify potential phosphorus and nitrogen recovery methods applicable to the case study plant. Chapter 4 addresses sub-question 2 & 3 by collecting empirical data through interviews with pertinent stakeholders. It provides an exploratory analysis aimed at identifying criteria that are aligned with the opinions and preferences of the relevant stakeholders, as well as, with the attributes associated with the nutrient recovery alternative technologies identified in Chapter 3 to provide a hypothetical assessment of the sustainability performance of the identified nutrient recovery technologies for Las Esclusas CWWTP. Chapter 5 serves as the discussion and concluding section of the study. The main research question is addressed by presenting the relevant criteria chosen through the incorporation of stakeholder's opinions and preferences necessary to identify sustainable nutrient recovery technologies responsibly. Within the discussion section, any noteworthy and unforeseen insights emerging from the analysis and interpretation of results is explored in greater detail.

CHAPTER 2

2.1 RESEARCH METHODOLOGY

The research methodology and methods that would help to answer the main research question and sub-questions are summarized in Figure 2.1 below:

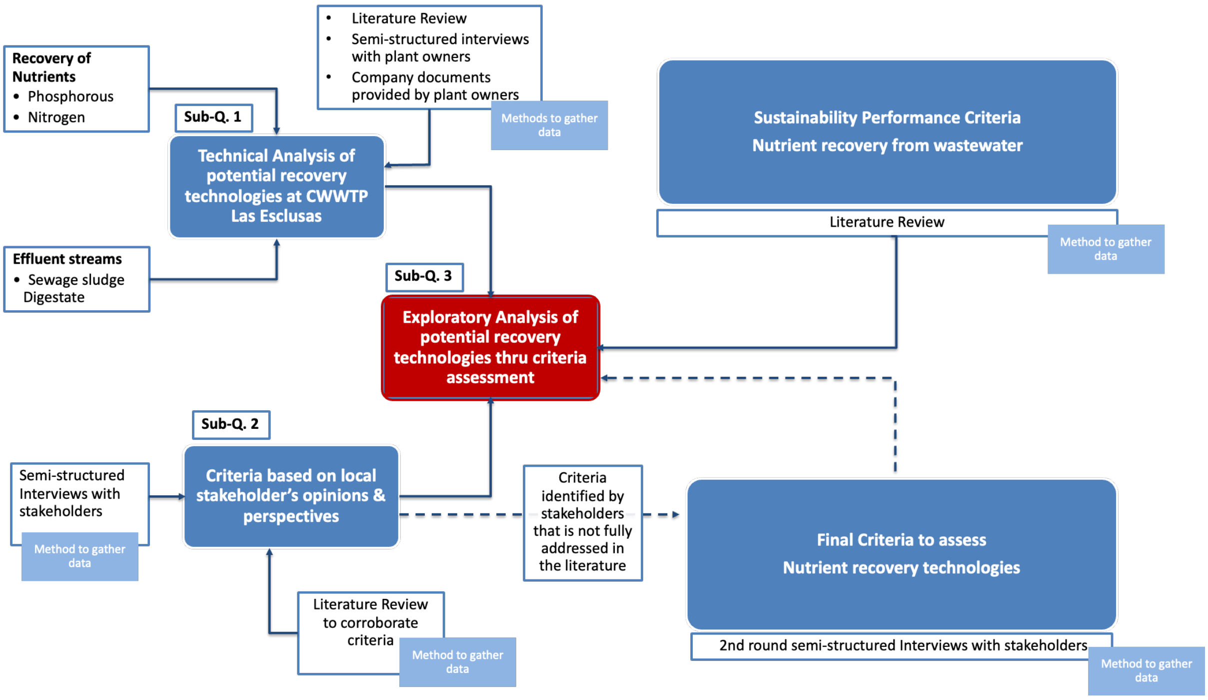


Figure 2. 1 Diagram of the methodology flow for this study

This research methodology starts with a technical analysis of potential nutrient recovery technologies which was done through an evaluation of the current technical state of Las Esclusas CWWTP. For this part, a literature review to retrieve information about nutrient recovery technologies that are commercially available was made. Also, information from documentation provided by the plant owners collected through semi-structured interviews about the current system at Las Esclusas CWWTP was used. Then, an assessment was made to identify which potential nutrient recovery alternatives from literature review are aligned with the Las Esclusas CWWTP's current infrastructure to foresee viable recovery alternatives at this plant. This part answers sub-question 1 (*What commercially available technologies are feasible for recovery Phosphorus and Nitrogen from Las Esclusas CWWTP's' effluent streams?*)

This study adopts an unconventional methodology by directly deriving evaluation criteria from stakeholder opinions and perspectives, gathered mainly through empirical data obtained from two rounds of semi-structure interviews. Rather than relying solely on established criteria in the literature, which was only used to corroborate the evaluated criteria, this approach tailors the assessment of nutrient recovery technology feasibility at Las Esclusas CWWTP to reflect the unique views and priorities of relevant stakeholders. The procedure is explained below:

1. Throughout a series of open-ended semi-structured interviews with stakeholders relevant to this project, and corroborating with existing criteria from literature review, a preliminary set of criteria is identified to assess the sustainable performance of nutrient recovery technologies at the environmental, economic, technical and social aspects. These criteria are deducted from a comparative evaluation method of the data collected from relevant existing literature, stakeholders' personal opinions and general characteristics of the technical processes currently available (Figure 2.2 part 1).

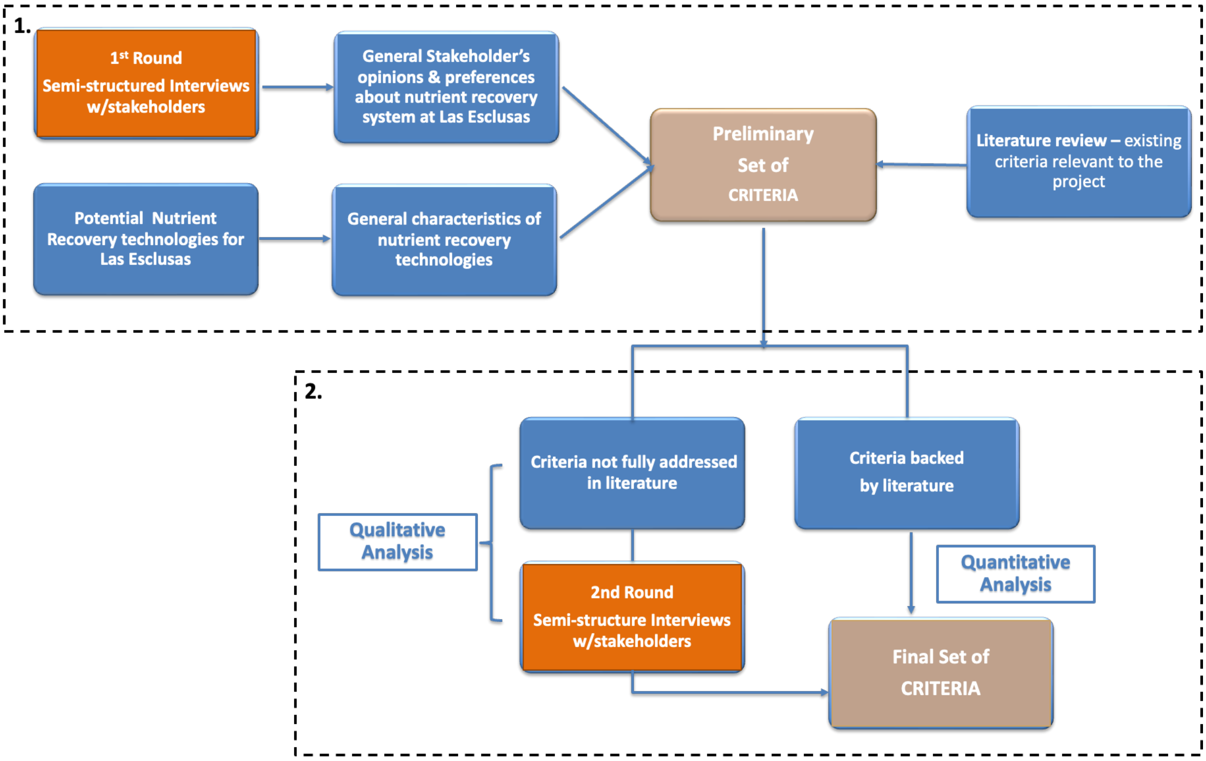


Figure 2. 2 Diagram of a responsible assessment framework used to identify relevant criteria for nutrient recovery systems (Part 1 & 2).

2. A second round of interviews is conducted to gather more targeted insights from stakeholders regarding criteria that are more superficially addressed in the existing literature. The first-round consisted only of general open-ended questions while the second round aimed to identify potentially overlooked but contextually significant factors from the stakeholders' point of view (Figure 2.2 part 2).

This part answers sub-question 2 *(What are the criteria needed to assess sustainability performance for Phosphorus and Nitrogen recovery at Las Esclusas CWWTP considering stakeholders perspectives?)*

Sub-question 3 *(In an ex-ante assessment, what is the potential performance of the commercial technologies identified in sub-question 1 considering the criteria from sub-question 2?)* is answered as an exploratory analysis without concrete results as to the assessment of sustainability performance of nutrient recovery technologies at the Las Esclusas CWWTP. This analysis provides a first step towards evaluating nutrient recovery technologies by considering environmental, technical, economic and social factors.

2.2 RESEARCH METHODS

The research methods for this research study primarily involved semi-structured interviews and a literature review. Firstly, a stakeholder analysis was conducted to identify key stakeholders who are aligned with the project's objectives. Later these stakeholders are interviewed throughout a series of open-ended semi-structure interviews.

2.2.1 STAKEHOLDER IDENTIFICATION

Key stakeholders involved in the fertilizer production value chain were identified using a strategic framework developed by Shaddel et al. (2019). This framework aligns with the objectives of this study as it provides a comprehensive strategy to choose stakeholders for the sustainable development of nutrient recovery processes from sewage sludge to produce fertilizers. According to this framework, the overall strategy for nutrient recovery in the wastewater management sector involves identifying stakeholders from four main areas: technology, policies and legislation, market, and economy. The corresponding stakeholders fall under the following groups: investors, politicians, legislators, NGOs, users, vendors, as well as research and development entities and academia.

For this research, fourteen stakeholders were identified and interviewed (Figure 2.3) on various topics related to nutrient recovery processes and technologies. These topics included their expertise in nutrient recovery processes at technical, institutional, social, environmental, and economic levels. Additionally, stakeholders were asked to provide their personal opinions on the acceptance and feasibility of commercializing fertilizers derived from sewage wastewater. Lastly, stakeholders were invited to share their perspectives on the barriers and opportunities that would impact the successful implementation of a nutrient recovery system at Las Esclusas CWWTP. In Appendix 4, the raw data collected from these interviews is presented.

Figure 2. 3 The proposed high-level strategy for sustainable development of nutrient recovery from sewage sludge. Adapted from Shaddel et al., 2019.

2.2.2 SEMI-STRUCTURED INTERVIEWS

Interviews represent the predominant method for data collection, with the semi-structured format emerging as the most prevalent technique in qualitative research. This format is favored due to its versatility and flexibility, facilitating reciprocity between the interviewer and participant. It allows for improvisation of follow-up questions based on the participant's responses and accommodates individual verbal expressions from participants (Kallio, et al., 2016)

The first round of interviews was based on open-ended questions designed to steer discussions toward the research topic. These questions were formulated to elicit spontaneous responses from participants, enabling the emergence of their personal feelings and experiences. Some questions began by exploring participants' prior knowledge of concepts such as circular economy, wastewater nutrient recovery, and the opportunities and constraints associated with commercializing these products.

These interviews were carried out in December 2023 in the city of Guayaquil, Ecuador with relevant stakeholders within the following groups (Table 2.1). It is pertinent to mention that during these interviews, plant owners also provided with documents about the plant's technical specifications.

Table 2. 1 Relevant stakeholders for first-round of interviews

Type	Source	No of Participants
Academia	ESPOL university	5 engineers
Plant owners	Veolia and H&H constructora	2 engineers
Gov and non-gov institutions	Water institution, Ministry of Environment, NGO	4 delegates
Vendor & User	Producer of organic fertilizer, farmer	2

Subsequently, during the second round of interviews, discussions with stakeholders were directed towards the acceptability of recovered products for fertilizer production and the institutional suitability of the country where Las Esclusas CWWTP is located. They were mainly asked to provide feedback on the criteria regarding the "acceptability of the recovered products" obtained through three different processes: precipitation/crystallization, incineration, and ammonia stripping. And, about the criteria "institutional suitability" comprised of institutional collaboration, support, and capacity. For this section, a representative stakeholder from the general public was interviewed to assess public perception and willingness to consume food products cultivated using fertilizers derived from nutrients recovered from wastewater.

The different stakeholders were approached for online interviews at the end of April 2024. Nevertheless, this time only half of the actors agreed to be part of this second round of interviews (Table 2.2):

Table 2. 2 Relevant stakeholders for second-round of interviews

Type	Source	No of Participants
Academia	ESPOL university	1 engineer
Plant owners	Veolia	1 engineer
Gov & non-gov. institutions	Water institution, Ministry of Environment, NGO	2 delegates

Vendor & User	Producer of organic fertilizer, farmer, general public	3

2.2.3 LITERATURE REVIEW

This research study entailed two literature reviews: one for collecting data for background information about the commercial nutrient recovery technologies available in the marketplace along with their detailed technical specifications. And a second one to find information about criteria used to measure the sustainability performance of nutrient recovery processes that will later serve to corroborate the data obtained empirically. The literature involved all kinds of studies mainly in the reign of life cycle assessments (LCA), techno-economic assessment (TEA), documented information from Las Esclusas CWWTP, a PhD, and media newscasts.

1. First literature review was conducted to obtain background information about wastewater treatment plants, types of resources that can be recovered from wastewater, and types of technologies currently available to recover nutrients like phosphorus and nitrogen. The search followed the keywords presented below:

- wastewater AND treatment AND plants AND nutrients AND recovery AND phosphorus AND nitrogen. Results: 50 documents

- AND technologies. Results: 23 documents

2. A thorough literature review was conducted mainly to identify criteria utilized to measure the sustainability performance of nutrient recovery processes. Some steps from Preisner et al., 2022 were considered as a guideline to do the literature review. Their steps consist of searching by the environmental, technical, economic, and social dimensions pertaining to nutrient recovery technologies specifically targeting phosphorus and nitrogen. Following the steps by Preisner et al., 2022, the keywords were more specifically targeted towards nutrient recovery technologies and their environmental, technical, economic, and social performance impacts.

Environmental dimension:

- wastewater AND environmental AND impacts AND of AND precipitation AND of AND struvite. Results: 55 documents

- wastewater AND environmental AND impacts AND of AND mono-incineration AND of AND sludge. Results: 6 documents

- wastewater AND environmental AND impacts AND of AND ammonia stripping. Results: 35 documents

Economic dimension:

- wastewater AND economic AND impacts AND of AND precipitation AND of AND struvite. Results: 27

- wastewater AND economic AND impacts AND of AND mono-incineration AND of AND sludge. Results: 2 documents

- wastewater AND economic AND impacts AND of AND ammonia stripping. Results: 13 documents

Social dimension:

- wastewater AND social AND impacts AND of AND precipitation AND of AND struvite. Results: 3 documents

- wastewater AND social AND impacts AND of AND mono-incineration AND of AND sludge. Results: 1 document

- wastewater AND social AND impacts AND of AND ammonia stripping. Results: 2 documents

Technical dimension:

- wastewater AND technical AND impacts AND of AND precipitation AND of AND struvite. Results: 7 documents

- wastewater AND technical AND impacts AND of AND mono-incineration AND of AND sludge. Results: 2 documents

- wastewater AND technical AND impacts AND of AND ammonia stripping. Results: 2 documents

The main database used was Scopus, with no limitation in terms of year, and region of study. Non-English articles were excluded as well as duplicates. From the entire list, all irrelevant articles were also not taken into consideration. The relevant scientific articles were searched at Google Scholar, ScienceDirect, SpringerLink, Multidisciplinary Digital Publishing Institute - MDPI publications database. ResearchGate was used to search for publications with restrictive access, and some of them were requested to the original author when not available for download.

In the next chapter, a technical analysis to assess which nutrient recovery technologies are feasible to be implemented in Las Esclusas CWTTP is done.

CHAPTER 3

3.1 TECHNICAL ANALYSIS OF POTENTIAL NUTRIENT RECOVERY TECHNOLOGIES

The objective of this section is to undertake a technical analysis to identify nutrient recovery technologies already in commercial use that could align with the existing technical system of Las Esclusas CWWTP. Initially, a brief overview of the current nutrient recovery technologies that are in used commercially is presented. Then, a feasibility analysis of the treatment system at Las Esclusas CWWTP with the nutrient recovery technical alternatives that are in the market is done to identify potential phosphorus (P) and nitrogen (N) recovery technologies feasible for this plant.

3.1.1 COMMERCIAL TECHNOLOGIES TO RECOVER PHOSPHORUS

To achieve commercialization of byproducts derived from recoverable nutrients such as phosphorus (P), several factors are integral in the evaluation of the commercial viability of such technologies. An essential factor is the access points within the wastewater treatment plants which significantly influence recovery efficiency owing to varying P concentrations. According to Vu et al. (2023), a phosphorus content threshold of 50 mg/L signifies that recovery becomes economically viable considering its associated costs (Figure 3.1)

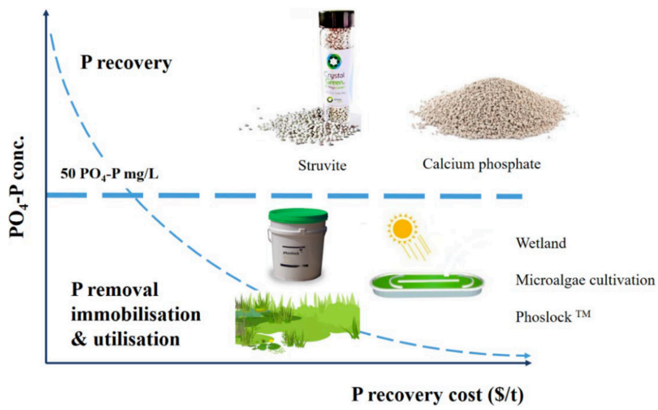


Figure 3. 1 Relationship between concentration and costs for P recovery (Vu et al., 2023)

The phosphorus concentration in a particular stream is just one of numerous factors influencing the profitability of a recovery process. Currently, struvite crystallization is considered the sole mature process for phosphorus recovery from aqueous streams. Still, it is in the developmental stages and may lack proven reliability and efficiency, which could deter commercial investment. It is documented that this method operates with marginal profitability and is influenced significantly by market factors (e.g. market demand, competition between recovered P fertilizer and conventional synthetic phosphorus fertilizers, consumer acceptance). To address the current gap, government subsidies for phosphorus recovery units or the implementation of taxes on extracted phosphorus are recommended (Li et al., 2019).

One of the objectives of this study is to evaluate the feasibility of technical alternatives for implementation at Las Esclusas CWWTP. Figure 3.2. provides an overview of the most recent available technologies for phosphorus recovery, which will be analyzed for feasibility at this plant in the subsequent analysis section (Vu et al., 2023). Further details on each method are available in Appendix 2.

Input materials	Name	Developer/Country of origin	Recovery mechanism	Min influent PO_4-P (mg/L)	Production capacity (t/yr)	Product
Liquid fraction	Ostara Pearl	Ostara, Canada	Precipitation/ crystallisation	100	> 1,000	Struvite
Liquid fraction	MagPrex ™	Centrisys/CNP, USA	Precipitation/ crystallisation	NA	NA	Struvite
Liquid fraction	Crystalactor ™	Royal Haskoning DHV, Netherland	Precipitation/ crystallisation	25	NA	CaP
Liquid fraction	Phosnix	Unitikia Ltd., Japan	Precipitation/ crystallisation	NA	NA	Struvite
Liquid fraction	Seaborne Gifhorn	Seaborne Laboratory, Germany	Precipitation/ crystallisation	600	NA	Struvite
Liquid fraction	Struvia	Veolia Water	Precipitation/ crystallisation	50	40	Struvite
Liquid fraction/ digestate	ANPHOS®	Colsen, Netherland	Precipitation/ crystallisation	50	650	Struvite
Liquid fraction/ digestate	PHOSPAQ™	Paques, Netherland	Precipitation/ crystallisation	50	>1,000	Struvite
Liquid fraction/ digestate	NuReSys®	Nutrient Recovery Systems, Belgium	Precipitation/ crystallisation	NA	NA	Struvite
Sludge ash	Ash Dec®	Ash Dec (Outotec), Austria	Thermal P recovery	NA	NA	Calcinated P fertiliser Phoskraft®

Figure 3. 2 Current commercial technologies for P-recovery (Vu et al., 2023)

3.1.2. COMMERCIAL TECHNOLOGIES TO RECOVER NITROGEN

To bring byproducts derived from recoverable nutrients like nitrogen (N) to commercial fruition, various factors play a crucial role in assessing the commercial viability of such technologies. In the same way as with phosphorus, access points within wastewater treatment plants are particularly important, as they greatly affect recovery efficiency due to differing nitrogen concentrations. That is the case of reject water streams in a wastewater treatment plant which is considered a good target to recover nitrogen because of its high concentration (Beckinghousen et al., 2020). The nitrogen concentration in a specific stream above 500 mg/L of nitrogen is generally considered optimal for economic feasibility (Kar et al., 2023). Currently, ammonia stripping stands as the most prevalent method. However, despite its lower operational costs compared to NH4+ removal through biological activated sludge systems, the technology has yet to fully develop to achieve profitability (Robles et al., 2020). Further details on each method are available in Appendix 2.

Some of the nitrogen recovery technologies that have been studied and are now commercialized include: (Kar et al., 2023).

- Air-stripping technology for ammonia recovery
- Membrane bioreactor integration for wastewater treatment
- Chemical process for simultaneous recovery of ammonia and phosphate to form struvite precipitate.
- Ammonia enrichment through membrane concentration

Table 3.1 shows the lab, pilot, and commercial projects that as of 2023, are active in the research, investigation and commercialization of nitrogen recovery techniques from different wastes (wastewater, manure, food, etc…) (Phosphorus Platform, 2023)

Table 3. 1 Current lab, pilot and commercial techniques to recover Nitrogen

Process to recover Nitrogen	Companies & Institutions Lab, pilot and commercial projects
Ammonia Stripping & scrubbing	Circular Values Bv Colsen (AMFER) Detricon Nijhuis Industries (Byosis)
From Stripping to fertiliser products	PureGreen Nijhuis Industries (Byosis)
Membrane Ammonia Stripping	Membratec VVT Finland (TYPKI) Mezt, Lenntech
Ion Exchange	Agua DB Cranfield University, UK KAMK University of Applied Sciences, Finland Krajete Cetaqua
Chemical N recovery from liquid phase	EasyMining (Aqua2N) – ESPP member

3.1.3 TECHNICAL SCREENING FOR SUITABLE RESOURCE RECOVERY ALTERNATIVES AT LAS ESCLUSAS CWWTP

Las Esclusas CWWTP treats an average wastewater flow of 2.56 m^3/s (EMAPAG-EP, 2023). This plant features a pre-treatment phase with a chemically assisted primary treatment (CEPT) only. The liquid phase treatment aims to eliminate suspended and floating solids, remove organic matter, and reduce pathogens. The sludge phase treatment aims to concentrate the solids settled in the clarifiers, stabilize the organic matter in the sludge and reduce the volume of sludge digested by dehydration. It is complemented by disinfection, sludge treatment, and odor management measures. The units with their respective characteristics of each of the treatment processes are detailed in Table 3.2 below:

Table 3. 2 Summary of the technical characteristics of the CEPT system at Las Esclusas CWWTP (EMAPAG - EP, 2023).

Type of treatment and equipment	Description
Pre-treatment	1.- Aerated Chamber: A mixing chamber with aeration through thick bubble diffusers. 2.- Screening Chamber: Four grating channels, coarse (8 mm) and fine gratings (6mm and 3mm). 3.- Vortex type grit trap: Three units designed for a peak flow rate of 3.07 m3/sec.
Primary treatment	1.- Rapid mixing, two units, retention time 40 seconds, between 300 and 500 sec-1. 2.- Pre-aeration and flocculation tanks, two units, retention time of 17 minutes. The mixers will be mechanical. 3.- Primary Clarifiers. - Three units 52.5 m in diameter, 5m deep.
Sludge digesters	1.- Gravity Thickeners. - Two units 13m in diameter. 2.- Fine Sludge Filtration Grids. - Two units with 2mm slots. 3.- Digesters. - Two tanks in service with a retention time of 15 days. Volume of each unit 5000m3. 4.- Solids Dehydration. - Two 3m wide belt presses in service. The solids will be dehydrated 35 hours a week, for 5 days. 5.- Bio-filters for Odor Control. - A 4,400m2 unit.
Desinfection unit	Sodium hypochlorite in situ, with a retention time of 43 minutes at 3.7m3/s
Discharge chambers	Diameter 2000mm, 30 "Tide-flex" type diffusers of 600mm.

In the schema below, the CEPT treatment processes of this wastewater plant are shown schematically (Figure 3.3)

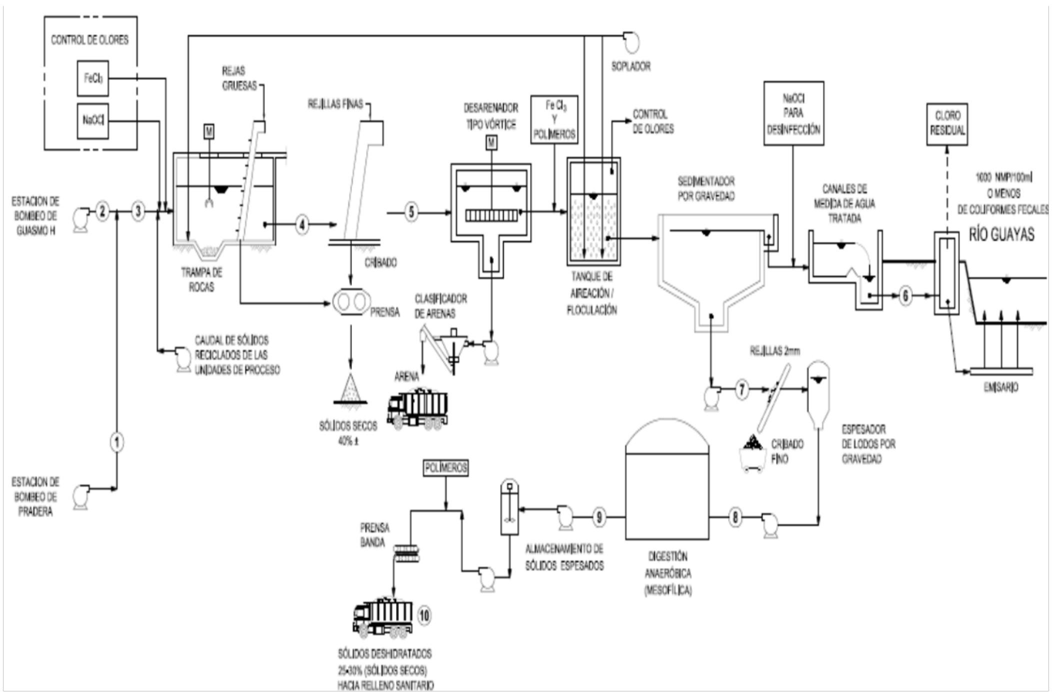
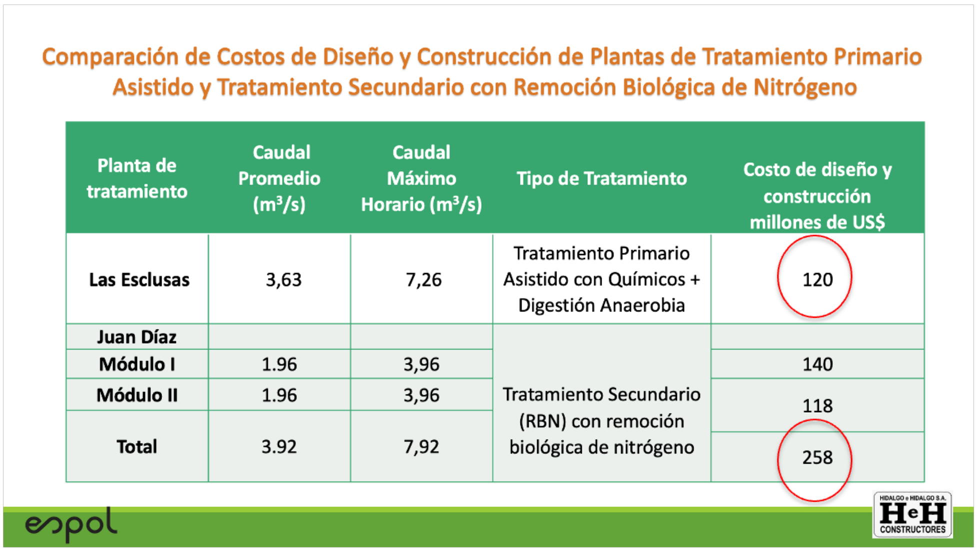


Figure 3. 3 Diagram CEPT system at CWWTP Las Esclusas (EMAPAG_EP, 2023)

According to EMAPAG-EP (2023) and interviews with plant owners, the selection for the CEPT treatment scheme done by project managers was based on the specific characteristics of the wastewater from the contributing inflow. Additionally, the flexibility that this type of treatment provides along with the cost effectiveness, makes this system more appealing (Plant owner, personal communication, December 4, 2023). Figure 3.4 below shows a comparison with another CWWTP (Juan Diaz, Peru) where the investment costs more than doubled if considered the addition of secondary treatment.



Comparación de Costos de Diseño y Construcción de Plantas de Tratamiento Primario Asistido y Tratamiento Secundario con Remoción Biológica de Nitrógeno

Planta de tratamiento	Caudal Promedio (m^3/s)	Caudal Máximo Horario (m^3/s)	Tipo de Tratamiento	Costo de diseño y construcción millones de US$
Las Esclusas	3,63	7,26	Tratamiento Primario Asistido con Químicos + Digestión Anaerobia	120
Juan Díaz			Tratamiento Secundario (RBN) con remoción biológica de nitrógeno	
Módulo I	1.96	3,96		140
Módulo II	1.96	3,96		118
Total	3.92	7,92		258

Figure 3. 4 Printscreen of slide from presentation "Estatus de los Procesos de Tratamiento de Aguas Residuales Municipales – Ecuador" shared by (Plant owner, personal communication, December 4, 2023)

Taking into consideration that the current technical system to meet discharge limits at Las Esclusas CWWTP is CEPT, so to scrutinize this plant and assess viable potential nutrient recovery technologies, there are relevant factors that are used for this purpose like concentration of nutrients in the wastewater influent, recovery efficiency, potential access points for phosphorus and nitrogen recovery, and existing infrastructure.

Inflow concentration

In the case of phosphorus, the inflow concentrations in the wastewater received by Las Esclusas CWWTP is considered low (approximately 7.3mg/L during dry season and 5.3 mg/L during wet season). For instance, processes such as struvite precipitation/crystallization remain particularly noteworthy. These technologies are well-suited for handling low-concentration wastewater, making them optimal choices for nutrient recovery in this context. However, the nitrogen concentration in the inflow is only between 45-50 mg/L which would make ammonia stripping being a costly process. (Plant owner, personal communication, December 4, 2023).

Recovery Efficiency

While many of the technologies claim high recovery efficiencies, it is crucial to acknowledge that this parameter can be influenced by numerous internal and external factors, for example, the weather temperature at the plant's location. A warmer climate typically fosters improved activated sludge function, which can positively impact recovery efficiencies (Von Sterling, Chernicharo., 2006). Consequently, a secondary/biological treatment will be beneficial to increase recovery efficiency. However, as previously noted, Las Esclusas plant currently operates with a Chemical Enhanced Primary Treatment (CEPT) system, lacking secondary/biological treatment capabilities. This configuration poses inherent challenges, especially regarding nutrient removal and recovery, given that numerous commercial technologies depend on secondary treatment to optimize efficiency, enhance byproduct production capacity, and comply with stringent discharge limits (Wang et al., 2009). In terms of nitrogen recovery, it is widely acknowledged that extracting ammonia with a CEPT system poses greater difficulty. Nitrogen could only be extracted from inlet wastewater, albeit with relatively low recovery efficiency (Beckinghousen et al., 2020). Taking this into consideration, it is noteworthy that sewage sludge thermochemical process offers a potential solution by enabling the recovery of phosphorus from sludge ash. The recovery efficiency does reach the 90%'s (Vu et al., 2023).

Given the current infrastructure of Las Esclusas CWWTP and treatment system, the potential scenarios for nutrient recovery at Las Esclusas plant are depicted in Figure 3.5 and 3.6.

Figure 3.5 illustrates the potential sources for nutrient recovery within the current Chemically Enhanced Primary Treatment (CEPT) system at the Las Esclusas plant. In this scenario, the primary digestate, combined with the small portion of the activated sludge treatment effluent, could serve as nutrient recovery sources following one recovery process alternative:

1. Nutrient recovery from the incineration of ashes recovered from dewatered sludge (digestate) which are rich in phosphates. Since this ash is not completely free of pathogens or heavy metals, it typically requires additional processes such as pyrolysis, gasification, or hydrothermal treatment. An example of this alternative is the Ash Dec® technology developed by Outotec, based on mono-incineration and thermochemical treatment. An incineration facility is needed for the mono-incineration step.
2. Ammonia Stripping could be used to recover nitrogen from either influent wastewater or digestate produced by the anaerobic digestion of sludge generated at the plant. However, the recovery efficiency is very low.

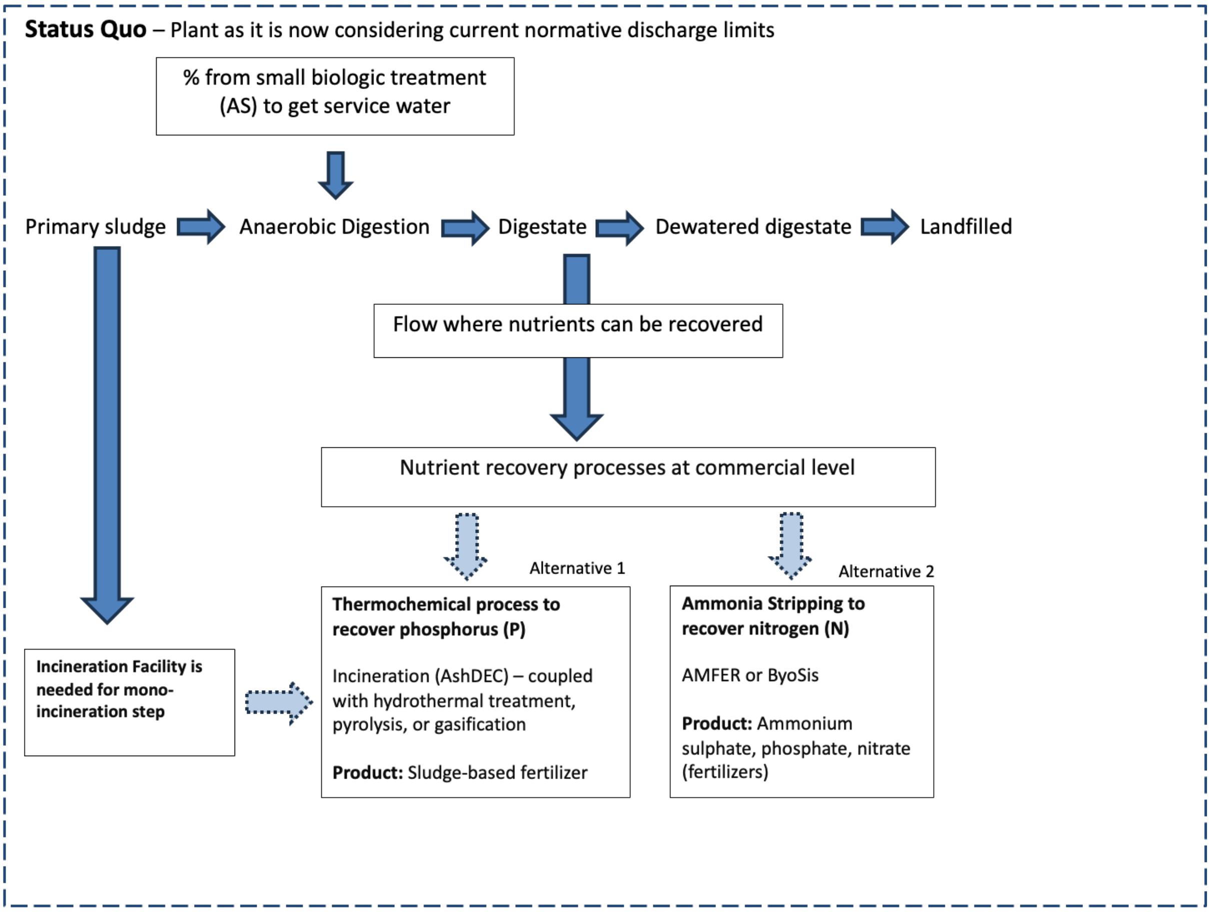


Figure 3. 5 Status quo under CEPT system of Las Esclusas wastewater treatment plant

Figure 3.6 depicts the potential sources for nutrient recovery in an upgraded configuration of Las Esclusas CWWTP which incorporates additional activated sludge treatment (secondary treatment). Under this scenario, nutrients can be extracted from the liquid fraction of the activated sludge (AS) as well as from the sludge digestate generated after anaerobic digestion. These streams exhibit higher concentrations of nutrients, leading to improved recovery efficiencies. In this scenario, there are additional commercial processes and technologies available beyond those mentioned above. Precipitation and crystallization of struvite processes are among the most widely used because they offer higher recovery efficiencies. Furthermore, due to their longer presence in the market, there are more companies that have developed innovative technologies in this field. Considering the characteristics of this plant in terms of influent concentration and technical feasibility, two systems that could be suitable are Struvia, developed by Veolia Water Technologies, and Crystalactor, developed by Royal Haskoning DHV.

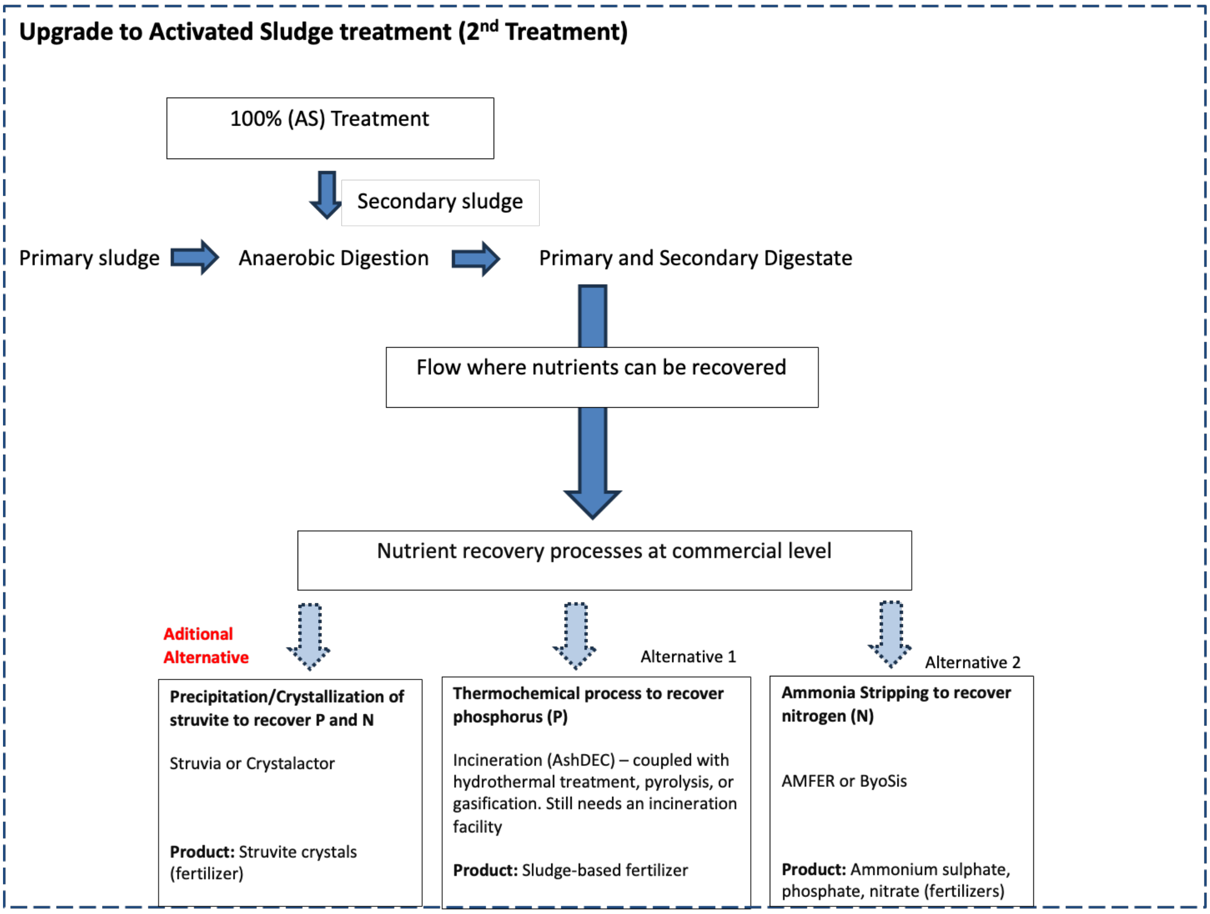


Figure 3. 6 Upgrade with secondary treatment for Las Esclusas wastewater treatment plant

By pre-screening commercial technologies (Appendix 3) to recover phosphorus and nitrogen and considering the technical system at las Esclusas CWWTP, the following processes are of interest. Some could be implemented to the plant as is now, and some require an upgrade to include secondary treatment to increase the nutrient recovery efficiency. These processes include:

- Thermochemical processes to recover Phosphorus

    - Incineration (AshDEC technology) could be implemented without secondary treatment,
- Precipitation/crystallization processes to recover Phosphorus
    - Struvia and Crystalactor technology need secondary treatment to be implemented
- Ammonia Stripping processes to recover Nitrogen
    - The two commercially available technologies, AMFER and ByoSis, need secondary treatment to achieve notable recovery efficiency. However, substantial investment is required to cover the operational costs associated with implementing these technologies.

This chapter analyzed the technical potential for nutrient recovery at the Las Esclusas CWWTP by identifying commercially available technologies that could be compatible with its current treatment configuration. Under the existing CEPT system, opportunities for nutrient recovery particularly nitrogen are limited. Phosphorus recovery could be achieved through the AshDEC process; however, this technology requires the availability of sludge ash, needing the installation of a mono-incineration facility, which entails significant capital investment. If the plant were to be retrofitted to incorporate secondary (biological) treatment, nutrient recovery options would expand significantly. The inclusion of biological treatment would improve nutrient availability, especially for nitrogen, enhancing the overall recovery efficiency of nutrient recovery technologies. Under such a configuration, Crystalactor and AMFER could be considered technically feasible technologies also. These selections are based on their compatibility with the plant's influent characteristics, which include relatively low phosphorus and nitrogen concentrations.

To assess the sustainability performance per technology, in the next chapter, criteria will be identified through the participation of relevant stakeholders whose opinions and preferences will contribute to determining the most sustainable technology. This process will be conducted through an exploratory analysis where empirical data from stakeholders will be compared and evaluated against insights from existing literature to ensure a comprehensive assessment.

CHAPTER 4

This chapter presents an exploratory analysis aimed at identifying criteria that are aligned with the opinions and preferences of the relevant stakeholders, as well as, with the attributes associated with the resource recovery alternative technologies identified in Chapter 3 to assess recovering phosphorus and nitrogen from waste digestate for fertilizer production at Las Esclusas CWWTP. First, key aspects related to nutrient recovery initiatives from wastewater are identified based on the opinions and preferences expressed by relevant stakeholders during the initial round of interviews. These insights are then integrated with the technical specification of the nutrient recovery technologies to form a preliminary set of evaluation criteria. This set is subsequently corroborated with criteria found in the existing literature. For aspects that were raised by the stakeholders but insufficiently addressed in literature, a second round of interviews is conducted to gather deeper stakeholder perspectives on underexplores topics. Finally, a hypothetical quantitative and qualitative evaluation of each nutrient recovery technology deemed feasible for implementation at the Las Esclusas CWWTP is carried out to assess their sustainability performance.

4.1 ANALYSIS OF STAKEHOLDER'S INTERVIEWS & NUTRIENT RECOVERY TECHNICAL ALTERNATIVES

4.1.1 STAKEHOLDER'S INTERVIEWS

To identify relevant criteria based on stakeholder's opinions and preferences, participants shared their perspectives through open-ended questions focused on nutrient recovery from wastewater at a wastewater treatment plant. The detailed empirical data from stakeholder's first round of interviews can be found in Appendix 4. The information gathered from stakeholder interviews provided general insights into the feasibility of implementing a nutrient recovery system at Las Esclusas CWWTP. Below some of the relevant issues raised by stakeholders from the different categories:

- It was observed that stakeholders from **Academia** with backgrounds in water issues, sanitation management, and biorefinery demonstrated significant expertise in environmental matters related to circularity. They were highly receptive to circular economy initiatives. This openness is driven in part by Ecuador's current energy security challenges, as the country struggles to produce sufficient electricity for national consumption. Additionally, stakeholders highlighted that Ecuador faces fertilizer shortages, resulting in elevated fertilizer prices. However, they noted that the implementation of nutrient recovery systems in wastewater treatment plants is currently unrealistic due to the lack of technical expertise, knowledge, and information within national institutions responsible for promoting and supporting such projects. Some stakeholders also emphasized the need to study the market acceptance of these products. They stressed the importance of research and development (R&D) incentives and the need for increased financial support. Furthermore, they identified institutional reform as crucial, citing the need for a more reliable and less corrupt governance framework to facilitate progress in this area.
- **Plant owners** expressed some skepticism and pessimism regarding the implementation of circular economy initiatives within Las Esclusas CWWTP. Their primary concerns stem from the current

priorities of the treatment plant, which focus on expanding sanitation coverage to more residents and meeting discharge limits for water release into the river. The current infrastructure is not adequately equipped at the moment to support second treatment processes, and with the current CEPT system (chosen due to costs constrains), nutrient recovery efficiency is expected to be low. The plant is not allowed to produce renewable energy internally because of legal constraints so the biogas from biodigesters is flared.

- **Vendors and Users** of fertilizer expressed openness to the idea of accepting a product recovered from wastewater. The acceptability of the product will depend on its safety and affordability. In addition, producers of fertilizer emphasized the importance of institutional capacity, support and collaboration in promoting these projects. Especially about new technology ownership, they warned that if it falls into the wrong hands it could lead to the creation of a monopoly that controls pricing.
- **Gov. & non-Gov. institutions** acknowledge that the country is still in the early stages of adopting circular economy (CE) initiatives and related technologies. There is currently little promotion or legislative support for such initiatives at the institutional level, since efforts remain focused on higher priority issues, such as expanding sanitation coverage to more populated areas.

The issues described above are presented in Table 4.1. The insights provided by stakeholders reflect essential conditions that are necessary to assess the sustainability performance of nutrient recovery technologies and, subsequently for their feasibility to be implemented at the case study plant. For instance, reliable electricity supply is critical for the effective operation of any technology. Also, the integration of complementary circular economy strategies such as the generation of renewable energy from anaerobic digesters can play a key role in reducing operational expenditures within the wastewater management system. Moreover, product acceptance is closely linked to affordability emphasizing the importance of costs considerations. Finally, the presence of a robust institutional framework supported by effective legislation and governmental support are imperative.

Table 4. 1 Stakeholder's empirical data – key topics raised by stakeholders as basis for criteria identification

Type of Interviewee	Key topics	Description
○ Plant owners ○ Academia ○ Gov & non-gov institutions	Energy security	○ Concern with country's energy availability
○ Plant owners ○ Academia ○ Gov & non-gov institutions	Circular economy initiatives	○ Potential # to recover nutrients at a lower cost
○ Plant owners ○ Academia	Biogas flared - GHGEs	○ Unavailable management for GHGEs
○ Plant owners ○ Academia ○ Gov & non-gov institutions ○ Vendor & User	Constraints with Investment & operational costs	○ Insufficient funds for CAPEX/OPEX
○ Plant owners ○ Academia	Lack of expertise & not enough technical workers	○ Inflexibility to retrofit ○ Low technical expertise

○ Plant owners ○ Academia ○ Gov & non-gov institutions ○ Vendor & User	Weak Institutional capacity to promote environmental laws	○ Non-compatibility with available legislation
○ Plant owners ○ Academia ○ Gov & non-gov institutions ○ Vendor & User	Non-existent inter-institutional support & collaboration	○ Lack of support from public & private entities
○ Plant owners ○ Academia ○ Vendor & User	Acceptability of end-products as long as they are cheaper than conventional ones	○ Willingness to use end-product so to create demand at the right price

4.1.2 TECHNICAL SPECIFICATIONS OF NUTRIENT RECOVERY TECHNOLOGIES

Table 4.2 highlights the key aspects of the various technical alternatives for the Las Esclusas plant identified in chapter 3. They are analyzed based on their key attributes and integrated to the insights raised by relevant stakeholders to assess compatibility with sustainability performance criteria.

Table 4. 2 Key characteristics per nutrient recovery technology & corroborated with existing literature

Type of nutrient recovery technology	Important characteristics/tech (Lit.Review)	Key topics from stakeholders
AshDEC (Incineration	○ High energy consumption ○ High investment costs ○ Dual process (Incineration & thermochemical) ○ Removes all heavy metals ○ Air pollution control needed ○ 90% efficiency P- recover	○ Energy security ○ Circular economy initiatives ○ GHGEs ○ Level of Expertise and labor requirements ○ Investment costs (CAPEX/OPEX)
Precipitation/Crystallization of Struvite	○ Energy consumption varies among different commercial precipitation/crystallization techs ○ Some techs recycle chemicals ○ Initial investment varies among different commercial techs	○ Circular economy initiatives ○ Energy security ○ GHGEs ○ Level of Expertise & labor requirements ○ Investment costs (CAPEX/OPEX)

	○ 70-80% efficiency P-recover	
Ammonia Stripping	○ Very high energy consumption ○ High investment costs ○ 70-75% efficiency N-recover	○ Energy security ○ Circular Economy initiatives ○ GHGEs ○ Level of Expertise & labor requirements ○ Investment costs (CAPEX/OPEX)

The perspectives gathered from stakeholders first round of interviews along with the technical specification of each nutrient recovery technology, are integrated to develop an initial set of relevant aspects to identify the evaluating criteria (Table 4.2). This preliminary set is then corroborated with criteria identified in the existing literature (Table 4.3). A brief overview of the literature-based criteria is first provided serving as a reference for validating both stakeholder derived insights and the technological characteristics of the nutrient recovery options under consideration.

4.1.3 EXISTING CRITERIA DEFINED (LITERATURE REVIEW)

Based on the aspects collected from stakeholders' perspectives and nutrient recovery technologies, the most relevant criteria addressed in the literature correspond to the following:

1. ***Energy security***
    a. **Definition:** energy security encompasses many definitions, and they oscillate among the following themes or dimensions: energy availability, infrastructure, energy prices, societal effects, environment, governance and energy efficiency (Ang et al., 2015). Nevertheless, it all falls under the notion of a country or region ensuring reliable and uninterrupted availability of energy in the short term and long term at an affordable price. In this way, energy availability is a crucial criterion due to the high energy demanded by most of the nutrient recovery alternative technologies.
    b. **Indicator:** energy availability is measured by the amount of energy required per technology. In this way, each nutrient recovery technology is assessed based on how much energy it consumes to recover nutrients. The unit is kwh/kg P or N produced.
2. ***Circularity***
    a. **Definition:** circularity involves the design and management of production and consumption systems in a way that minimizes waste, extends the life cycle of materials, and promotes the continuous reuse, recycling, and regeneration of resources (Stahel, W.R., 2020). Consequently, circularity is a crucial criterion and plays an important role within wastewater management when usable resources like nutrients (phosphorus and nitrogen) found in wastewater are recovered and reuse to produce fertilizer.
    b. **Indicator:** circularity is measured by the potential amount of nutrients (phosphorus and nitrogen) recovered to produce fertilizer. The unit is Kg struvite, Rhenanite phosphate, ammonia sulfate/kg P or N produced
3. ***Global Warming Potential***
    a. **Definition:** global warming potential (GWP) is related to fossil energy demand and the measurement of greenhouse gas emissions (GHGEs- CO2, N2O, CH4) resulting from the combustion of these fossil fuels (Zhou et al., 2019). All nutrient recovery processes emit gases

during their operations, for example, precipitation/crystallization of struvite emit GHGEs (CO_2 & CH_4) during their reactors' operations (e.g. leakages of biogas) (Pradel et al., 2019), and transportation of any recovered fertilizer.

b. **Indicator:** global warming potential is measured by the amount of greenhouse gas emissions produced. The unit is Kg CO_2 or CH_4/kg P or N produced. Although some studies present GWP in terms of CO_2 equivalent to encompass all harmful gases.

4. ***Investment & operational costs***
   a. **Definition:** investment and operational costs are fundamental criteria for all projects, as they directly impact long-term success. These costs are key indicators of a project's feasibility, efficiency, profitability and competitiveness. As a result, implementing state of the art technologies like nutrient recovery techs requires prioritizing a comprehensive cost assessment to ensure financial viability. Literature posits that although the current cost of phosphorus recovered from wastewater is significantly higher than the market price of mined phosphorus, it is still a promising alternative to phosphate rock mining since this resource is considered finite (Rodriguez -Freire et al., 2020).
   b. **Indicator:** CAPEX & OPEX expenditures in monetary terms (€)

5. ***Level of Expertise & labor requirements***
   a. **Definition:** level of expertise and labor requirements is very important when dealing with innovative technologies in a context with limited technical knowledge. Many nutrient recovery technologies currently on the market demand advance technological expertise, which in turn requires additional investments. Some might require more expertise and labor power than others like AshDEC in comparison to Crystalactor (see Appendix 2 for more technical details among technologies). According to Chrispim et al., 2020, a high level of operator skill is essential to optimize nutrient recovery efficiency. Furthermore, some of these technologies require increased workforce and maintenance efforts further contributing to operational complexity and cost. Adequate expertise ensures the effective use and maintenance of innovative technological systems.
   b. **Indicator:** can be qualitative for level of expertise (high vs. low) and quantitative for labor requirements (# extra-workers needed)
6. ***Institutional suitability***
   a. **Definition:** institutional suitability is examined from the perspective of the capacity, support, and collaboration provided by institutions towards circular economy initiatives within the context of nutrient recovery systems at a wastewater treatment plant.
   b. **Indicator:** this criterion is qualitatively assessed based on the presence and effectiveness of institutional capacity, support and inter-organizational collaboration. The evaluation considers whether these elements exist and the extent to which they function efficiently in facilitating the implementation of nutrient recovery technologies.

7. ***Acceptability of end-products***
   a. **Definition:** the acceptability of end-products is studied through the lens of public perception regarding the use of fertilizer derived from wastewater recovered nutrients. In addition to societal acceptance, factors such as regulatory compliance, market demand and price, product safety standards, and cultural attitudes toward the reuse of waste derived materials play a significant role in determining the viability of such products in the agricultural sector.
   b. **Indicator:** this criterion is qualitatively assessed based on stakeholders' expressed willingness to use the end-product and it is evaluated through a binary response of affirmative or non-affirmative.

By comparing Table 4.1 with Table 4.2, a first set of relevant criteria for every nutrient recovery technology is formulated below in Table 4.3. This table summarizes a first set of criteria that is relevant when both stakeholder 'opinions and the attributes of the nutrient recovery alternatives are aligned.

Table 4. 3 First set of relevant criteria

Type of interviewee	Description (indicators)	Criteria addressed in literature
○ Plant owners ○ Academia ○ Gov & non-gov institutions	○ Energy requirement	○ Energy security
○ Plant owners ○ Academia ○ Gov & non-gov institutions	○ Potential # to recover P or N	○ Circularity
○ Plant owners ○ Academia	○ GHGEs	○ Global warming potential
○ Plant owners ○ Academia ○ Gov & non-gov institutions ○ Vendor & User	○ CAPEX/OPEX	○ Investment & operational costs
○ Plant owners ○ Academia	○ High/low ○ Know-how availability	○ Level of Expertise & labor requirements
○ Plant owners ○ Academia ○ Gov & non-gov institutions ○ Vendor & User	○ Compatibility with available legislation	○ Institutional capacity
○ Plant owners ○ Academia ○ Gov & non-gov institutions ○ Vendor & User	○ Support from all Gov & non-gov institutions	○ Institutional support & collaboration
○ Plant owners ○ Academia ○ Vendor & User	○ Willingness to use end-product	○ Acceptability of end-products

4.1.4 EXTRA ASPECTS ELUCIDATED BY STAKEHOLDERS

The criteria identified above are criteria that is aligned with both stakeholder 'opinions and the attributes of the nutrient recovery alternatives. However, stakeholders also expressed other aspects during the first round of interviews that seemed quite important but not explicitly addressed in the literature. To further investigate these issues, a second round of interviews was conducted to explore these stakeholders' views in greater depth with regards to the nutrient recovery technologies identified to be feasible for Las Esclusas CWWTP. The additional insights gathered from stakeholders corresponded to institutional suitability (capacity, support and collaboration) and acceptability of end products. The detailed empirical findings from the second round of interviews are presented in Appendix 4.

The information obtained from the second round of interviews with relevant stakeholders raised the following important points:

- All stakeholders agreed on the inefficiencies within the Ecuadorian institutional system. They noted there are more fundamental priorities (e.g. extending road infrastructure to marginalized areas) that require government attention over circular economy initiatives. They mentioned a common issue among all Latin American countries: corruption in the public sector, where institutions often give priority to their own interests over collaboration which leads to inefficiency. Stakeholders agreed on the fact that Ecuador lacks significant investment in R&D related to circular economy projects. Additionally, they highlighted that the current legislation is not conducive to CE initiatives. For example, discharge limits are relatively lenient, offering no incentive to remove phosphorus and nitrogen from the effluent. They also identified significant legal barriers hindering the promotion of CE initiatives. One notable example is that biogas produced by digesters is burned rather than used for cogeneration to produce electricity, as the energy authority does not allow private energy production, preferring to retain control over electricity charges. Some acknowledge that small progress is being made around solid waste management such as biogas recovery from landfills, but no significant actions have been taken in the area of resource recovery from wastewater.
- Stakeholders expressed strong support to the idea of producing fertilizers from recovered nutrients in wastewater. They emphasized that this extra supply of fertilizers could help alleviate the current fertilizer shortages in the country. Nevertheless, they did mention that the cost of the end-product is a critical factor due to the financial constraints faced by all actors within the fertilizer value chain. Furthermore, stakeholders found that the level of altruism among farmers and final users of the cultivated products, along with the extend of agricultural knowledge within the farming community, are important aspects for acceptability. Stakeholders from Academica as well as fertilizer vendor and users, agreed on the need for sanitary permits and potentially certifications like ISO certification 59004 or BS8001 within the realm of sustainability and circular economy to enhance the commercial value of these products.

In the case of Las Esclusas CWWTP, it is evident that stakeholders emphasize the importance of social dimension criteria in assessing the feasibility of implementing a nutrient recovery system. Many aspects surrounding the institutional framework of a country plays a fundamental role in shaping the success of such projects. Likewise, the acceptability of recovered products is crucial for their future market commercialization of fertilizers produced from wastewater recovered nutrients.

4.2 FINAL PRIORITIZED SET OF CRITERIA

A final set of prioritized criteria was stablished to guide the assessment of nutrient recovery technologies (Table 4.4). It is important to note that the social aspects such as institutional capacity, support and collaboration, and the acceptability of end-products impact all the nutrient recovery alternatives equally so the technologies cannot be rank qualitatively. These criteria are considered the most relevant when assessing the feasibility of nutrient recovery technologies' implementation in CWWTPs like Las Esclusas.

Table 4. 4 Most relevant criteria for Las Esclusas CWWTP

Quantitative	Qualitative
• Energy security (energy consumption) • Circularity (# recovered nutrients) • Global warming potential (CO2 eq) • Investment & Operational costs (CAPEX, OPEX) • Level of Expertise & labor requirements (# skilled workforce)	• Institutional suitability (capacity, support, collaboration) • Acceptance of end-products

Although, the qualitative criteria are the most important for the case study, a comprehensive evaluation encompassing both qualitative and quantitative criteria is essential to adequately assess the sustainability performance of nutrient recovery technologies. The energy security criterion is considered in terms of energy availability with energy consumption serving as the most appropriate quantitative indicator expresses in electricity and/or heat usage per nutrient recovery technology. The circularity criterion is quantified based on the amount of nutrients recovered for fertilizer production by each technology. The global warming potential criterion is measured by the amount of greenhouse gas emissions produced by the different nutrient recovery processes. The level of expertise and labor requirements also quantitatively measure by determining the additional skilled workforce required to operate and manage nutrient recovery technologies. Investment and operational costs criteria provide an economic measure of the feasibility of each technology. On the qualitative side, the most important criterion corresponds to the institutional suitability of a country to have the capacity, support mechanisms, and inter-institutional collaboration necessary for the successful implementation of nutrient recovery systems. And product acceptability criterion which plays a crucial role in establishing a strong foundation for the market commercialization of recovered nutrients.

In the next section, each nutrient recovery alternative will be evaluated quantitatively and qualitatively using information from literature reviews and stakeholder interviews.

4.3 QUANTITATIVE EVALUATION PER NUTRIENT RECOVERY ALTERNATIVE (LITERATURE REVIEW & EMPIRICAL DATA)

The quantitative data for the first five criteria are presented as ranges and slightly evaluated for Las Esclusas CWWTP using information from empirical data collected via stakeholder's interviews and quantitative figures from reference plants documented in the literature. However, due to the variability of approaches, scopes and lack of detailed information in these studies, certain assumptions needed to be made. These assumptions, which influence all calculations are as follows:

- Assume Las Esclusas CWWTP has a secondary treatment as most of CWWTPs in the literature
- Studies from reference plants with comprehensive and accessible data serve as the basis for hypothetical calculations. Data is used case by case. Some include figures from the entire life cycle

processes within the wastewater treatment plant and others only from the specific process being evaluated.

- LCA studies that use 1 kg Phosphorus or nitrogen produced as Functional Units were chosen.

PRECIPITATION/CRYSTALLIZATION OF STRUVITE (PHOSPHORUS RECOVERY)

ENERGY SECURITY

As previously mentioned, energy security will be evaluated based on energy availability, specifically the capacity of a country to provide uninterrupted electricity supply. The most appropriate indicator to provide a quantitative measurement is energy consumption, expressed in terms of electricity and/or heat usage.

For more detail description of the precipitation/crystallization of struvite process refer to Appendix 1. It is documented that this process, which only requires electricity, consumes between 4.9-9.56 kwh/kg of P recovered (see Table 4.5). However, these ranges are not entirely comparable as some studies do not clearly specify which processes are included in their calculations. Nonetheless, based on these ranges, it can be reasonably assumed that they pertain exclusively to the process under evaluation.

Attributed to these measurements, several factors need to be considered including the size of the wastewater influent, the different wastewater treatments and processes (primary, secondary, tertiary), and the plant's capacity to generate and utilize renewable energy internally.

Table 4. 5 Ranges of electricity consumption for precipitation/crystallization of struvite

Energy Security	Units	Ranges	Assumptions/observations
Electricity consumption	kwh/kg of P produced	9.56 Pradel, Aissani* 4.9–6.6 Chrispim** 5.1 Amann **	*Only **precipitation** process. Total life cycle electricity consumption is 773.56 kwh/kg P produced **Does not specify exactly which processes are included in the calculation

References: Pradel, Aissani, 2019; Chrispim et al., 2020; Amann et al., 2018

In the following section, a hypothetical calculation of energy consumption at las Esclusas plant is done, using data from Pradel and Aissani (2019) as the basis for the reference plant in this analysis. Their work offers comprehensive and clearly documented information on all life cycle processes within their reference wastewater plant. These figures include efficiencies from all the processes in the plant.

Calculation:

Reference Plant (Pradel, Aisanni, 2019)	Las Esclusas CWWTP (info. Collected from Interview w/plant owners)
CWWTP inflow of wastewater: 38,975 m3/day **Concentration P:** 5.85 mg/L **P produced:** 26.4 kg/day **Electricity use:** 9.56 Kwh/kg P produced	**CWWTP Inflow of wastewater:** 2.56 m3/second=221,184 m3/day **Concentration P:** 5.1 mg/L (wet season), 7.3 mg/L (dry season)

P inlet: 38,975 m3/day x 5.85 mg/L

↓

x 5.85 g/m3 = 228.003,75 g/day

↓

= 228 kg/day

Reference Plant Ratio P produced to P inlet: 26.4 kg/day / 228 kg/day = 11.57%

Hypothetical P produced for Esclusas:

(Wet season) P inlet: 221,184 m3/day x 5.1 mg/L

↓

x 5.1 g/m3 = 1,128,038 g/day

↓

= 1,128 kg/day

(Dry season) P inlet: 221,184 m3/day x 7.3 mg/L

↓

x 7.3 g/m3 = 1,614,643 g/day

↓

= 1,614 kg/day

(Wet season) Las Esclusas P produced: 1,128 kg/day x 11.57% = 130.5 kg P/day

(Dry season) Las Esclusas P produced: 1,614 kg/day x 11.54% = 186 kg P/day

Electricity usage:

(Wet season) Las Esclusas CWWTP: 130.5 kg P produced/day x 9.56 kwh/kg P produced= 1,247 kwh/day

(Dry season) Las Esclusas CWWTP: 186 kg P produced/day x 9.56 kwh/kg P produced = 1,778 kwh/day

If Las Esclusas CWWTP were to implement a system based on precipitation/crystallization of struvite, the amount of electricity estimated that this plant will need is approximately 1,247 kwh/day during the wet season or 1,778 kwh/day during dry season.

Currently, Las Esclusas CWWTP consumes on average between 417 – 735 kwh/day for its normal operations so an estimation of the amount of electricity that this plant will need is two and half times more to operate an extra system to recover nutrients if it consumes 735 kwh/day.

Circularity is measured by the amount of nutrients recovered to produce fertilizer. Literature presents some ranges between 3.57 – 12 kg/kg of P produced that are part of nutrient recovery LCA studies. They show that the potential amount of fertilizer (struvite) that could be produced from recovering phosphorus from a municipal wastewater treatment plant varies depending on factors like amount of inflow, the percentage of phosphorus present in the wastewater, and if the plant has biological/secondary treatment (Table 4.6).

Table 4. 6 Ranges of potential production of Struvite via precipitation/crystallization of struvite

Circularity	Units	Ranges	Assumptions/observations
Potential of Struvite production	Kg Struvite/kg of P produced	3.57 Pradel, Aissani 10-12 Amman	Kg P recovered in the same struvite product

References: Pradel, Aissani, 2019; Amann et al., 2018

In the following section, a hypothetical calculation of the amount of struvite produced at las Esclusas plant is done, using data from Pradel and Aissani (2019) as the basis for the reference plant in this analysis. Their work offers comprehensive and clearly documented information on all life cycle processes within their reference wastewater plant. These figures include efficiencies from all the processes in the plant.

Calculation:

Reference Plant (Pradel, Aisanni, 2019)	Las Esclusas CWWTP (info. Collected from Interview w/plant owners)
Struvite production: 3.57 kg struvite/kg P produced	**Hypothetical P produced:** 130.5 kg P/day (as calculated above)

Hypothetical Struvite produced at Las Esclusas: 130.5 kg P/day x 3.57 kg struvite/kg P produced = 465 kg struvite/day.

If Las Esclusas CWWTP were to implement a system based on precipitation/crystallization of struvite, an estimated amount of struvite that could be produced is 465.8 kg struvite/day = 170,017 kg struvite/year.

Putting it in perspective, if a producer of TECA wood (interviewed December 2023) needs 3-4 times yearly 150 kg fertilizer/ hectare of cultivated land, this farmer will need an average of 600 kg/hectare per year. On average each farmer works at low scale with an average of 5 hectares. So, each farmer will need 600 kg/hectare per year x 5 hectares = 3, 000 kg/yr.

The hypothetical amount of struvite that could be produced at Las Esclusas CWWTP could satisfy the yearly demand of around 57 farmers.

GLOBAL WARMING POTENTIAL (GHGES)

In this study, the global warming potential is evaluated based on the greenhouse gas emissions (GHGEs) generated by various nutrient recovery processes. The emissions levels differ between processes and vary depending on the specific technologies employed for nutrient recovery. Literature shows that emissions of CO_2 ranges between 200-300 kg/kg of P recovered, and emissions from CH_4 about 14.73 kg/kg of P recovered (Table 4.7). These emissions correspond to the entire life cycle system (anaerobic digestion, cogeneration) not only the precipitation/crystallization of struvite process alone.

Table 4. 7 Ranges for GHGEs in the production of fertilizer via precipitation/crystallization of struvite

GHGEs	Units	Ranges	Assumptions/observations
CO_2	Kg/kg P produced Kg/kg P produced	213.26 Pradel, Aissani* 298 Sena**	**Emissions from whole system + Ostara Tech (struvite recovery) To convert to GWP using scientific multiplier (28) from IPCC fifth assessment report AR5 (www.ipcc.ch)
CH_4	Kg/Kg P produced	14.73 Pradel, Aissani*	

References: Pradel, Aissani, 2019; Sena et al., 2021

In the following section, a hypothetical calculation of the amount of CO_2 and CH_4 emitted at las Esclusas plant is done, using data from Pradel and Aissani (2019) as the basis for the reference plant in this analysis. Their work offers comprehensive and clearly documented information on all life cycle processes within their reference wastewater plant. To calculate the total global warming potential, CH_4 is converted to CO_2 equivalent using the scientific multiplier of 28 established by the IPCC in their 2014 Climate Change synthesis report.

Calculation:

Reference Plant (Pradel, Aisanni, 2019)	Las Esclusas CWWTP (info. Collected from Interview w/plant owners)
CO_2 emissions: 213.26 kg CO_2/kg P produced **CH_4 emissions:** 14.73 kg CH_4/kg P produced	**Hypothetical P produced:** 130.5 kg P/day (as calculated above)

Hypothethical CO_2 emissions at Las Esclusas Plant: 130.5 kg P /day * 213.26 kg CO_2/kg P = 27,830.43 kg CO_2/day

Hypothetical CH_4 emissions at Las Esclusas Plant: 130.5 kg P /day * 14.73 kg CH_4/kg P= 1,922.26 kg CH_4/day x 28 = 53,823.42 kg CO_2 eq./day

Total GWP: 81,653.85 kg CO_2 eq./day

If Las Esclusas CWWTP were to implement a system based on precipitation/crystallization of struvite, an estimated amount of CO_2 and CH_4 that could be produced are 27,830 kg CO_2/day and 1,922 kg CH_4/day with a total GWP potential of 81,654 kgCO_2eq./day.

At Las Esclusas CWWTP, due to legal constrains that prevent the cogeneration of electricity and the utilization of biogas produced in the anaerobic digesters, the biogas is currently flared and released directly into the atmosphere. The emissions from flaring the biogas at this plant are approximately 773 kg/day of CH_4 and 1,456 kg/day of CO_2 with a total GWP potential of 23,100 kg CO_2 eq. See below for calculation.

<table>
<tr><th>Las Esclusas given data (provided by plant owners)</th><th>Data (literature review)</th></tr>
<tr><td>
<table>
<tr><th>Parameter</th><th>Value</th><th>Unit</th></tr>
<tr><td>pH</td><td>7.18</td><td>-</td></tr>
<tr><td>Total Solids (TS)</td><td>32.71</td><td>g/L</td></tr>
<tr><td>Volatile Solids (VS)</td><td>14.26</td><td>g/L</td></tr>
<tr><td>Acidic Gas Volatile (AGV)</td><td>312.68</td><td>mg/L</td></tr>
<tr><td>Alkalinity</td><td>45.49</td><td>mg/L</td></tr>
<tr><td>Temperature</td><td>36.6</td><td>°C</td></tr>
<tr><td>Retention Time (HRT)</td><td>20</td><td>days</td></tr>
<tr><td>2 Digesters Volume</td><td>10,000</td><td>m^3</td></tr>
</table>
</td><td>
Daily Feed Volume: Digester Volume/HRT (hydraulic retention time)

Daily Volatile Solids input: VS concentration x daily feed volume

Assumptions : biodegradability factor of 55% (Mottet et al., 2010) and biogas yield of 0.5 m^3/kg VS degraded (Ngabala and J.K. Emmanuel, 2024)

Daily VS degraded: Daily VS input x biodegradability factor.

Daily biogas production: Daily VS degraded x biogas yield.

Raw biogas typically contains about 40-80% CH_4 and 15-60% CO_2 (Ngabala and J.K. Emmanuel, 2024)

Density CO_2: 1.97 kg/m3 (wikipedia, 2025)

Density CH_4: 0.657 kg/m3 (wikipedia, 2025)
</td></tr>
</table>

Daily feed volume: 10,000 m3/ 20 days = 500 m3/day (sludge processed per day)

Volatile solids input per day = 14.26 kg/m3 x 500 m3/day = 7,130 kg VS/day

VS degraded per day= 7,130 kg VS/day x 0.55 = 3,922 kg/day

Estimated Biogas per day = 3,922 kg/day x 0.5 m3/kg = 1,961 m3/day

Raw biogas typically contains CH_4 on average (40-80%) = 60%

Raw biogas typically contains CO_2 on average (15-60%) = 37.5%

Estimated CH_4 per day = 1,961 m3/day x 60% = 1,177 m3/day -----CH_4 density (0.657) = 773 kg CH_4/day x 28 = 21,644 kg CO_2 eq./day

Estimated C02 per day = 1,961 m3/day x 37.5% = 735 m3/day --------CO_2 density (1.98) = 1,456 kg CO_2/day

Total GWP of flaring biogas: 23,100 kg CO_2 eq./day

Adding the flaring emissions:

Total CH4: 1,922 kg CH4/day + **773 kg CH4/day** = 2,695 kg CH4/day x 28 = 75,460 kg CO2 eq./day

Total CO2: 27,830 kg CO2/day + **1,456 kg CO2/day** = 29,286 kg CO2/day

Total GWP: 104,746 kg CO2 eq./day

: 38,232,290 kg CO2 eq/year

: 38,232 tons CO2 eq/year

Consequently, to evaluate the significance of the total GWP generated by implementing nutrient recovery via precipitation/crystallization of struvite at Las Esclusas CWWTP, it could be contextualized within the national emissions data. According to the Emission Index Platform (2024), Ecuador's total GWP is approximately 72,300,000 tons CO2 eq./year. In comparison, the estimated 38,232 tons CO2 eq./year associated with this nutrient recovery process could constituted only a minor fraction of the national total and therefore could not represent a substantial contribution to the country's overall GWP.

INVESTMENT AND OPERATIONAL COSTS

Within nutrient recovery systems, high costs are documented to arise from the use of chemicals such as magnesium hydroxide, magnesium chloride, and sodium hydroxide which are required to facilitate struvite precipitation and crystallization (Desmidt et al., 2015). Still energy consumption also accounts for a substantial portion of the overall cost with requirements varying depending on the technology employed. In addition, the high initial capital investment for state-of-the art nutrient recovery technologies present a considerable financial burden. Reported costs in the literature depend on the amount of equivalent population (PE) as population increases then the initial investment costs will also increase (Table 4.8).

Table 4. 8 Ranges for investment and operational costs to produce fertilizer via precipitation/ crystallization of struvite

Initial investment & operational costs	Units	Ranges	Assumptions/observations
Investment costs	€ Million (100,000 PE) € Million (500,000 PE)	3 Egle* 5.8 Egle*	* OPEX (raw materials, personal, energy, maintenance, disposal). **No specified amount of Kg P recovered
OPEX	€ Thousand (100,000 PE) € Thousand (500,000 PE)	93,896 Egle* 385,981 Egle*	
Investment costs	€/kg P recovered	4.4-10 Chrispim**	

OPEX	€/kg P recovered	1.6 Chrispim**	

References: Chrispim et al., 2020; Egle et al., 2016

In the following section, a hypothetical calculation of the amount of investment and OPEX costs at las Esclusas plant is done, using data Egle et al., (2019) as the basis for the reference plant in this analysis. For this calculation, economies of scale principle is applied due to the comparison of CAPEXs and OPEXs of different investment projects.

Calculation:

Reference plant initial investment cost (Egle et al., 2016): €5.8 million (500,000 PE)

Las Esclusas CWWTP: 1,077,948 PE

Hypothetical Initial investment cost for Las Esclusas = €5.8 million/(500,000 PE/1,077,948 PE)^0.6

↓

= 5.8 million/0.6307 = €9,196 million

Hypothethical OPEX cost for Las Esclusas = €385,981/(500,000 PE/1,077,948)^1

↓

= 385,981/0.4638 = €832,214/year

If Las Esclusas CWWTP were to implement a system based on precipitation/crystallization of struvite, an estimated amount of initial investment and OPEX costs will be approximately €9,196 million and €832,214/year. If Las Esclusas' total investment was around 120 million dollars then the € 9,196 million corresponds to a CAPEX increase of 10% to implement this technology.

LEVEL OF EXPERTISE & LABOR REQUIREMENTS

From a qualitative point of view, technical expertise is an important criterion for countries in the Global South, where limited knowledge and financial resources that promote R&D, hinder infrastructure innovation. In the case of Las Esclusas CWWTP, plant owners highlighted the insufficient technical expertise across all workforce levels. Ecuador has struggle to develop sufficient expertise domestically leading to a heavy reliance on international support to address these gaps. This plant's management and operations are handled by the French company Veolia who has the technical expertise, yet the business practices and management strategies employed sometimes are not aligned effectively with local practices and conditions, creating operational and contextual mismatches. One interviewee mentioned that this misalignment is sometimes causing inefficiencies in operations, and local staff employed under such conditions are experiencing some stress which potentially may result in mental burn out due to the heightened pressure. From a quantitative perspective, job creation provides a measurable indicator of technical expertise. For instance, if the literature estimates that implementing and operating a nutrient recovery system would require approximately 2-4 technical workers, these positions would need to be created to ensure the system's functionality being a benefit for possible job hires.

MONO-INCINERATION & ASHDEC (PHOSPHORUS RECOVERY)

ENERGY SECURITY

Energy security is a vital criterion for this technology because these processes require a reliable and significant energy supply for their operation in the form of electricity and heat. As detailed in Appendix 1, the process involves sludge incineration followed by a thermochemical treatment (AshDEC) that effectively removes pollutants. The resulting end-product is called Rhenanite Phosphate (RP=NaCaPO4) which is a phosphate compound that can be used as a direct phosphate fertilizer (Pradel, Aissani, 2019) (Hermann & Schaaf, 2018).

Table 4.9 presents the ranges of average electricity and heat requirements documented in the literature. Differences in scope contribute to the observed discrepancies in the figures presented in the table, because all reports have different inflows of wastewater, different P content in the inflow, different figures of recovered P from depolluted ash. For instance, studies such as Pradel and Aissani (2019) include detailed electricity and heat consumption data for all life cycle processes associated with the AshDEC system only and does not provide figures for the mono-incineration of sludge in an incineration plant. Nevertheless, since this publication is the one that offers the most comprehensive and clearly documented information on AshDEC process, it is used again for the extrapolated calculations.

Table 4. 9 Ranges for energy consumption to produce RP with AshDEC

Energy Security	**Units**	**Ranges**	**Assumptions/observations**
Electricity consumption	kwh/kg of P produced	0.29 Hermann, Schaaf** 46.22 Pradel, Aissani* 0.96-1.28 Amann*** 0.65 Egle	*Includes AshDec Tech only and some end-of-life incineration processes. **Incineration is not included only AshDec tech with an input of sludge hot ash of 1725 kg/h ***Input of sludge hot ash is not available. Ash Dec Rhenanite process.
Heat consumption	kwh/kg of P produced	2.7 Hermann, Schaaf** 3.71 – 6.93 Amman*** 118.27 Pradel, Aissani* 0.36 Egle	

References: Hermann, Schaaf, 2018; Pradel, Aissani., 2019; Amann et al., 2018; Egle et al., 2016

In the following section, a hypothetical calculation of energy consumption at las Esclusas plant is done, using data from Pradel and Aissani (2019) as the basis for the reference plant in this analysis. Their work offers comprehensive and clearly documented information on all life cycle processes within their reference wastewater plant. These figures include efficiencies from all the processes in the plant.

Calculation:

Reference Plant (Pradel, Aisanni, 2019)	Las Esclusas CWWTP (info. Collected from Interview w/plant owners)
CWWTP inflow of wastewater: 38,975 m3/day **P produced:** 83.73 kg P/day **Concentration P:** 5.85 mg/L **Electricity use:** 46.22 Kwh/kg P produced **Heat use:** 118.27 kwh/kg P produced	**CWWTP inflow of wastewater:** 2.56 m3/second=221,184 m3/day **Concentration P:** 5.1 mg/L (wet season), 7.3 mg/L (dry season)

P inlet: 38,975 m3/day x 5.85 mg/L

↓

x 5.85 g/m3 = 228.003,75 g/day

↓

= 228 kg/day

Reference Plant Ratio P produced to P inlet: 83.73 kg/day / 228 kg/day = 36.7%

Hypothetical P produced for Esclusas:

(Wet season) P inlet: 221,184 m3/day x 5.1 mg/L

↓

x 5.1 g/m3 = 1,128,038 g/day

↓

= 1,128 kg/day

(Dry season) P inlet: 221,184 m3/day x 7.3 mg/L

↓

x 7.3 g/m3 = 1,614,643 g/day

↓

= 1,615 kg/day

(Wet season) Las Esclusas P produced: 1,128 kg/day x 36.7% = 414 kg P/day

(Dry season) Las Esclusas P produced: 1,615 kg/day x 36.7% = 593 kg P/day

Electricity usage:

(Wet season) Las Esclusas CWWTP: 414 kg P/day x 46.22 kwh/kg P produced= 19,135 kwh/day

(Dry season) Las Esclusas CWWTP: 593 kg P/day x 46.22 kwh/kg P produced = 27,408 kwh/day

Heat Usage:

(Wet season) Las Esclusas CWWTP: 414 kg P/day x 118.27 kwh/kg P produced = 48,963 kwh/day

(Dry season) Las Esclusas CWWTP: 593 kg P/day x 118.27 kwh/kg P produced = 70,134 kwh/day

If Las Esclusas CWWTP were to implement a nutrient recovery system based on AshDEC to produce fertilizer in the form of Rhenanite Phosphate, estimated amounts of electricity and heat that it will approximately need are: 19,135 kwh/day (wet season), 27,408 kwh/day (dry season) of electricity and 48,963 kwh/day (wet season), 70,134 kwh/day (dry season) for heat respectively.

Currently, Las Esclusas CWWTP consumes on average between 417 – 735 kwh/day electricity for its normal operations, so to operate an extra system to recover nutrients with AshDEC, the amount of electricity that this plant will need is estimated to be around 26 times more if it consumes 735 kwh/day during wet season, and 37 times more during dry season.

However, these values pertain exclusively to the AshDec process and do not account for the additional electricity required to operate an incineration facility. To have a brief estimate of what the total energy demand could be, a preliminary calculation is done using available data from Las Esclusas CWWTP based on its current CEPT system:

Total Solids at Las Esclusas

TS inflow= 263 mg/L (provided by plant owners) ⟶ 0,263 kg/m3

Las Esclusas inflow = 221,184 m3/day

TS = 221,184 m3/day x 0.263 kg/m3 = 58,171 kg/day ⟶ 58 Tons/day

Electricity consumption for standard incineration plant (Chang et al., 2025) = **~50–260 kWh/ Ton of TS**

Extra electricity needed if incineration plant is implemented:

50 kwh/Ton x 58 Tons/day = 2,900 kwh/day

260 kwh/Ton x 58 Tons/day = 15,080 kwh/day

This additional electricity will approximately increase the estimated total amount needed even more from 19,135 kwh/day to 22,035 kwh/day or 34,215 kwh/day (wet season), and in the dry season from 27,408 kwh/day to 30,308 kwh/day or 42,488 kwh/day.

The AshDEC system requires heat for its operation, typically in the form of natural gas. Many wastewater treatment plants are adopting circular economy practices by reusing biogas generated from their anaerobic digesters. Nevertheless, at Las Esclusas CWTTP, plant owners indicated that existing legislation prevents the reuse of biogas for electricity cogeneration forcing the facility to flare the excess gas instead. The lack of a heat figure from this plant prevents the corresponding calculation from being conducted. Therefore, it is impossible to make a sensible comparison and arrive to some conclusion.

CIRCULARITY

Circularity is measured by the potential amount of rhenanite phosphate (RP) recovered from sludge ash. As previously discussed, this end-product can be directly used as a fertilizer. Table 4.10 presents ranges documented in two LCA studies which provide comprehensive data. However, the third study lacks sufficient detail to allow for unit conversion so it can be compared to the other ones.

Table 4. 10 Ranges of potential production of RP with AshDec

Circularity	Units	Ranges	Assumptions/observations
Rhenanite Phosphate compound	Kg RP/kg P produced Kg/h	12.43 Amman 27.7 Pradel, Assani 2,311 Hermann, Schaaf	N/A

References: Amann et al., 2018; Pradel, Assani, 2019; Hermann, Schaaf 2018

In the following section, a hypothetical calculation of the amount of struvite produced at las Esclusas plant is done, using data from Pradel and Aissani (2019) as the basis for the reference plant in this analysis. Their work offers comprehensive and clearly documented information on all life cycle processes within their reference wastewater plant. These figures include efficiencies from all the processes in the plant.

Calculation:

Reference Plant (Pradel, Aisanni, 2019)	Las Esclusas CWWTP (info. Collected from Interview w/plant owners)
Rhenanite Phosphate (RP) production: 27.7 kg RP/kg P produce	**Hypothetical P produced:** 414 kg P/day (as calculated above)

Hypothetical Rhenanite Phosphate produced at Las Esclusas: 414 kg P/day x 27.7 kg RP/kg P produced = 11,467 kg RP/day.

If Las Esclusas CWWTP were to implement a system based on AshDEC amount of RP compound that could be produced is 11,467 kg RP/day=4,185,747 kg RP/year

Putting it in perspective, if a producer of TECA wood (interviewed December 2023) needs 3-4 times yearly 150 kg fertilizer/ hectare of cultivated land, this farmer will need an average of 600 kg/hectare per year. On average each farmer works at low scale with an average of 5 hectares. Each farmer needs 600 kg/hectare per year x 5 hectares = 3, 000 kg/yr.

The hypothetical amount of Rhenanite Phosphate that could be produced at Las Esclusas CWWTP could satisfy the demand of around 1,395 farmers.

GLOBAL WARMING POTENTITAL

Global warming potential of incineration and thermochemical processes to produce fertilizer from sludge ash does produce greenhouse gas emissions (GHGEs). Table 4.11 provides some data on output emissions of CO2 and CH4 that correspond to the entire life cycle system (anaerobic digestion, cogeneration) and AshDEC processes alone.

Table 4. 11 Ranges for GHGEs in the production of RP with AshDec

GHGEs	Units	Ranges	Assumptions/observations:
CO_2	Kg/kg P produced Kg/h	43.17 Pradel, Aissani* 396.4 Hermann, Schaaf**	*All processes within the WWTP included except emissions from incineration plant. **Only **Ash Dec** process included
CH_4	Kg/Kg P produced	1.06 Pradel, Aissanni*	

References: Pradel, Aissani., 2019; Hermann, Schaaf, 2018

In the following section, a hypothetical calculation of the amount of CO_2 and CH_4 emitted at las Esclusas plant is done, using data from Pradel and Aissani (2019) as the basis for the reference plant in this analysis. Their work offers comprehensive and clearly documented information on all life cycle processes within their reference wastewater plant. To calculate the total global warming potential, CH_4 is converted to CO_2 equivalent using the scientific multiplier of 28 established by the IPCC in their 2014 Climate Change synthesis report (IPCC, 2014).

Calculation:

Reference Plant (Pradel, Aisanni, 2019)	Las Esclusas CWWTP (info. Collected from Interview w/plant owners)
CO_2 emissions: 43.17 kg CO_2/kg P produced **CH_4 emissions:** 1.06 kg CH_4/kg P produced	**Hypothetical RP produced:** 414 kg RP/day (as calculated above)

Hypothethical CO_2 emissions at Las Esclusas Plant: 414 kg RP /day * 43.17 kg CO_2/kg P = 17,872 kg CO_2/day

Hypothetical CH_4 emissions at Las Esclusas Plant: 414 kg RP /day * 1.06 kg CH_4/kg P= 439 kg CH_4/day x 28 =12,292 kg CO_2 eq./day

Total GWP: 30,164 kg CO_2 eq./day

If Las Esclusas CWWTP were to implement a system based on AshDEC, estimated amounts of of CO_2 and CH_4 that could be produced are 17,872 kg CO_2/day and 439 kg CH_4/day, with a GWP of 30,164 kg CO_2 eq./day

At Las Esclusas CWWTP, due to legal constrains that prevent the cogeneration of electricity and the utilization of biogas produced in the anaerobic digesters, the biogas is currently flared and released directly into the atmosphere. The emissions from flaring the biogas at this plant are approximately 773 kg/day of CH_4 and 1,455 kg/day of CO_2. See above for calculation.

Adding the flaring emissions:

Total CH_4: 12,292 kg CO_2 eq/day + (**773 kg CH_4/day x 28)** = 33,936 kg CO_2 eq./day

Total CO_2: 17,872 kg CO_2/day + **1,456 kg CO_2/day** = 19,328 kg CO_2/day

Total GWP: 53,264 kg CO_2 eq./day

While this figure may not appear substantial or environmentally detrimental at first glance, it does not account for emissions associated with the incineration process, which could significantly increase the overall environmental impact. Chang et al., 2025, evaluated various sludge treatment technologies and found that the climate change impact of incineration ranged from approximately ~700 to 1,500 kg CO_2 eq/ton of total solids.

To estimate the GWP associated with the addition of an incineration facility at Las Esclusas, the same calculation method was applied using the total solids load of 58.17 ton per day. Based on emission factors for sludge incineration ranging from approximately ~700 to 1,500 kg CO_2 eq/ton of total solids, the resulting additional emissions are estimated to range between 40,719 kg CO_2 eq/day – 87,256 kg CO_2 eq/day.

The integration of AshDec technology in combination with an incineration facility results in a significant increase in total GWP with estimated emissions rising to between 93,983 kg CO_2 eq./day and 140,520 kg CO_2 eq./day, representing nearly a twofold or greater increase compared to the baseline.

INVESTMENT & OPERATIONAL COSTS

Investment & operational costs for these nutrient recovery processes are not well documented as the available data primarily pertains to the AshDec system alone excluding incineration. Literatrure does indicate that the initital investment for the AshDEc process may be approximately double than of the precipitaiton/crystallization of struvite process (Table 4.12). This lack of comprehensive financial information makes it challenging to acurately assess and compare mono-incineration & AshDec process with the precipitaiton/crystallization of struvite.

Table 4. 12 Ranges for investment and operational costs to produce RP with AshDec

Initial investment & operational costs	**Units**	**Ranges**	**Assumptions/observations:**
Initial investment	€ millions	10 Egle*	*Only for AshDec process
OPEX	€ millions/kg of P recovered	1.3 Egle*	Plant capacity for 15,000 tons Rhenanite hot ash/year

References: Egle et al., 2016

In the following section, a hypothetical calculation of the amount of CAPEX and OPEX costs at las Esclusas plant is done, using data Egle et al., (2019) as the basis for the reference plant in this analysis.

Calculation:

Reference plant initial investment (Egle et al., 2016): €10 million

Las Esclusas CWWTP RP production: 4,185,747 kg RP/year = 4,185 tons/year

Hypothethical initital investment cost:

(4,185 tons RP/year/15,000 tons RP/year)^0.6 x (10 million)= € 4.6 million

Hypothethical OPEX cost:

(4,185 tons RP/year/15,000 tons RP/year) ^1 x (1.3 million) = €362,700/year

If Las Esclusas CWWTP were to implement a nutrient recovery system based on AshDEC, the estimated capital investment (CAPEX) would be approximately € 4.6 million/year, with annual operational expenditures (OPEX) around € 362,700/year. However, these figures pertain exclusively to the Ash DEC recovery system, which assumes the availability of pre-incinerated sludge. In the current context, the implementation of AshDEC would necessitate the construction of a sludge incineration facility, which entails a significant additional capital investment. According to Nkuna et al. (2024), the investment costs for a small-scale sludge incineration plant (< 50,000 PE) ranges between €16 million and €35 million potentially undersized for the scale of Las Esclusas CWWTP which serves more than a million PE.

LEVEL OF EXPERTISE & LABOR REQUIREMENTS

Expertise is a technical and social criterion that uniformly impacts all nutrient recovery technologies. The same considerations identified for the precipitation/crystallization of struvite could be applicable here because the nutrient recovered is phosphorus. Nevertheless, for the mono-incineration processes, which involve the operation of an incineration facility, the demand for skilled labor is considerably greater due to the increased complexity of operations and maintenance (sludge conveyors, ash handling equipment, control center, enclosing structures), stringent environmental regulations and the need for specialized equipment and safety protocols (EPA, 2025).

AMMONIA STRIPPING PROCESS (NITROGEN RECOVERY)

ENERGY SECURITY

The end-product from this process is mainly in the form of ammonium sulphate $(NH_4)_2SO_4$ (AS) which comes in solid form fertilizer or liquid form if dissolved in water. This process relies on both electricity and heat as energy sources, making it less favorable than struvite precipitation to recover nitrogen in terms of energy efficiency (For details Table A-5 in Appendix 1). Specially, when the temperature of the inflow wastewater is low pre-heating is necessary. Nevertheless, ammonia stripping has the advantage of requiring fewer chemicals than precipitation/crystallization methods. For more information on this process, see Appendix 1. In the same way as with phosphorus, factors like type of flow of wastewater (inlet vs side streams), and the concentration of nitrogen influence the average electricity and heat consumption ranges presented in Table 4.13.

Table 4. 13 Ranges for energy consumption to produce AS via ammonia stripping process

Energy Security	Units	Ranges	Assumptions/observations:
Electricity consumption	kwh/kg of AS produced kwh/kg of AS produced	0.256 Kar* 0.7 Orner**	*Use median average of side streams for calculations **Use gas as a source for heat ~1200 cfm converted to kwh (~600 BTU) = ~4000 kwh/13,000 kg/AS produced Assumption the two plants are the same Only differ on N concentrations
Heat	kwh/kg of AS produced	0.336 Kar* 0.3 Orner**	

References: Orner et al., 2022; Kar et al., 2023

In the following section, a hypothetical calculation of energy consumption at las Esclusas plant is done, using data from Kar et al., (2023) as the basis for the reference plant in this analysis. Their work offers comprehensive and clearly documented information on all life cycle processes within their reference wastewater plant. These figures include efficiencies from all the processes in the plant.

Calculation:

Reference Plant (Kar et al., 2023)	Las Esclusas CWWTP (info. Collected from Interview w/plant owners)
Philadelphia WWTP sidestreams flow rate: 7,008 m3/day this is the sidestream not the inflow wastewater . To calculate a hypothethical amount for Las Esclusas side streams, it was necessary to search for this figure in the literature since in the present study this figure was not provided: Philaelphia WWTP's wastewater inflow rate (17,034 m3/day equivalent to 4.5 millions gallons/day) (City of Philadelphia, 2024)	**CWWTP inflow of wastewater:** 2.56 m3/second=221,184 m3/day Assume Las Esclusas CWWTP sidestreams ~ **90,997** m3/day = (221,184/17,034)* 7,008 **Concentration of N:** 45 mg/L = 0.05 kg/m3 (assume same concentration for sidestreams) **Las Esclusas N inlet:** 90,997 m3/day x 0.05 kg/m3 = 4,549 kg N/day

AS produced: 16,537 kg AS/day **Electricity use:** 0.256 Kwh/kg AS produced **Concentration of N:** 0.630 Kg/m3 **Reference plant N inlet:** 0.630 kg/m3 x 7,008 m3/day = 4,415 kg N/day	

Hypothetical Las Esclusas AS produced:

AS produced / Reference plant N inlet

Reference Plant Ratio AS produced to N inlet= (16,537 kg AS/day / 4,415 kg N/day) = 3.745 kg AS/kg N

Las Esclusas N inlet

Las Esclusas AS produced= 3.745 kg AS/kg N x 4,549 kg N/day =17,039 kg AS/day

Electricity usage:

Las Esclusas CWWTP: 17,039 kg AS/day x 0.256 kwh/kg AS= 4,362 kwh/day

If Las Esclusas CWWTP were to implement a system based on ammonia stripping to produce AS fertilizer, an estimated amount of electricity that this plant will need is approximately 4,362 kwh/day. In the case of this plant, since its location is in a tropical area with temperatures above 30 degrees Celsius year-round, the wastewater arrives preheated. This eliminates the need for significant external heating, unlike wastewater treatment plants in European countries, where additional energy is often required to achieve the necessary process temperatures.

Currently, Las Esclusas CWWTP consumes on average between 417 – 735 kwh/day for its normal operations so the amount of electricity that this plant will need is about six times more to operate an ammonia stripping system to recover nitrogen.

CIRCULARITY

The end-product from this process is mainly in the form of ammonium sulphate $(NH_4)_2SO_4$ (AS) which comes in solid form fertilizer or liquid form if dissolved in water. Similar to other phosphorus and nitrogen removal and recovery process, factors such as concentration of NH4-N in the digestate, wastewater inflow rate amount (m3/day), and operating conditions (e.g. temperature of the inflow water) impact the quantity of nitrogen-based fertilizer recovered (Kar et al., 2023). Table 4.14 presents ranges of AS produced, however, both studies take into consideration different functional units for their LCAs, so it is difficult to compare them.

Table 4. 14 Ranges of potential production of AS via ammonia stripping process

Circularity	Units	Ranges	Assumptions/observations:
Potential of AS production	kg of AS produced/day kg of AS produced /day	16,537 (Kar) 13,000 (Orner)	**Size digestate:** 7,008 m3/day (Kar) 37,800 kg/day (waste activated sludge) (Orner) **Concentrations:** NH4-N: 0.630 kg/m3 (Kar) NH4-N: 2860 kg/day (Orner)

References: Kar et al., 2023; Orner et al., 2022

In the following section, a hypothetical calculation of AS production at las Esclusas plant is done, using data from Kar et al., (2023) as the basis for the reference plant in this analysis. Their work offers comprehensive and clearly documented information on all life cycle processes within their reference wastewater plant. These figures include efficiencies from all the processes in the plant.

Calculation:

Reference Plant (Kar et al., 2023)	Las Esclusas CWWTP (info. Collected from Interview w/plant owners)
Philadelphia WWTP sidestreams flow rate: 7,008 m3/day **AS produced:** 16,537 kg AS/day **Concentration of N:** 0.63 kg/m3	**CWWTP inflow of wastewater:** 2.56 m3/second=221,184 m3/day Las Esclusas CWWTP sidestreams ~ **90,997** m3/day **Concentration of N:** 45 mg/L = 0.05 kg/m3 **Hypothetical AS produced at Las Esclusas:** 17,039 kg AS/day

Yearly AS produced at Las Esclusas = 17,039 kg AS/day * 365= 6,219,235 kg AS/year

If Las Esclusas CWWTP were to implement a system based on ammonia stripping to produce AS fertilizer, an estimated amount of AS that could be produced is 6,219,235 kg AS/year

Putting it in perspective, if a producer of TECA wood (interviewed December 2023) needs 3-4 times yearly 150 kg fertilizer/ hectare of cultivated land, this farmer will need an average of 600 kg/hectare per year. On average each farmer works at low scale with an average of 5 hectares. Each farmer needs 600 kg/hectare per year x 5 hectares = 3, 000 kg/yr.

The hypothetical amount of AS fertilizer that could be produced at Las Esclusas CWWTP could satisfy the demand of around 2,073 farmers.

In the case of las Esclusas CWWTP, the concentration of nitrogen in the wastewater is about 0.05 kg/m3, which is lower than the concentration in Kar's study. This is due to a higher inflow of wastewater at Las Esclusas. In principle this will mean that the amount of end-product would not be sufficient to justify the high process costs; however, as Kar et al., 2023 posits, this technology demonstrates significant potential for reducing the environmental footprint of AS compared to the conventional means of producing AS through the Haber Bosh approach (see Appendix 1 for more details).

GLOBAL WARMING POTENTIAL

For this study, greenhouse gas emissions (GHGEs) are evaluated based on energy usage and some chemicals inputs like H_2SO_4. Table 4.15 shows some figures from LCA studies that typically quantify GHGEs as CO_2 equivalents (GWP). Findings indicate that GHGE emissions are influenced by ammonia concentration and wastewater flow rate. Specifically, when a plant has low ammonia concentration but high flow rates, a larger volume of side stream water must be treated to yield the same amount of ammonium sulfate (AS) (Kar et al., 2023). This increased side stream treatment demands more resources which in turn increases GHGEs.

Table 4. 15 Ranges for GHGEs and GWP in the production of AS via ammonia stripping process

GHGEs	Unit	Ranges	Assumptions/observations:
CO_2,CH_4,N_2O,NO_x,NH_3	Kg CO_2 eq/day Kg CO_2 eq/Kg AS	6875 Orner* (chemicals) 793 Orner* (energy) 0.52 Orner* (chemicals) 0.06 Orner* (energy)	*No inventory of GHGEs separately. Only GWP in kg/CO_2 eq/day from chemicals and electricity. AS production in kg (13000) ** Emissions from air stripping process -chemicals & electricity. CO_2 emissions as CO_3/HCO_3,$CaCO_3$, in effluent, exhaust and removal.
CO_2 emissions	Kg /kg AS	3 Kar**	

Emissions from processes	Kg CO2 eq/kg AS	0.18-0.5 Kar**	Average emissions from processes **0.34 kg CO2 eq/kg AS**

References: Orner et al., 2022; Kar et al., 2023

In the following section, a hypothetical calculation of the amount of GHGEs emitted at las Esclusas plant is done, using data from Kar et al., (2023) as the basis for the reference plant in this analysis. Their work offers comprehensive and clearly documented information on all life cycle processes within their reference wastewater plant. In contrast to data presented by Pradel, Assani (2019), which were used for calculations above, Kar et al., 2023's paper provides emissions data in terms of global warming potential (GWP).

Calculation:

Reference Plant (Kar et al., 2023)	**Las Esclusas CWWTP (info. Collected from Interview w/plant owners)**
GWP (kg CO2 eq/kg AS emissions): 0.34 kg CO2 eq /kg AS produced	**Hypothetical AS produced at Las Esclusas:** 17,039 kg AS/day

Hypothetical GWP at Las Esclusas: (17,039 kg AS /day * 0.34 kg CO2 eq/kg AS)= 5,793 kg CO2 eq/day

If Las Esclusas CWWTP were to implement a system based on ammonia stripping to produce AS fertilizer, the GWP of this technology is around 5,793 kg CO2 eq/day. By adding total GWP from flaring emissions (calculated above) of 23,100 kg CO2 eq./day, then the estimated total GWP of adding an ammonia stripping technology to this plant will be 28,893 kg CO2 eq/day.

The absence of emissions data from Las Esclusas CWWTP poses a difficulty in making a comparative assessment. Nevertheless, insights from Kar et al., 2023 suggest that in the case of Las Esclusas CWWTP, where nitrogen concentrations are low due to high-water flow rates, there is a potential of having higher emissions due to the need to process larger water volumes to achieve equivalent AS recovery. However, these emissions could be offset by reduced heat requirements for preheating inlet wastewater, given the plant's location in a warm, tropical climate.

INVESTMENT & OPERATIONAL COSTS

The implementation of nutrient recovery technologies presents financial challenges due to high initial capital expenditures (CAPEX) estimated in the millions, as well as elevated operational and maintenance expenditures (OPEX) which come mainly from sulfuric acid and citric acid needed in the process (Table 4.16). Sulfuric acid accounts for approximately 71% of these expenses while citric acid takes about 24% (Kar et al., 2023). Up to date, nutrient recovery technologies result in net costs that significantly exceed potential revenue. Specially, ammonia stripping which is a technology that is not yet commercialized is impacted by substantial uncertainties in cost projections and lack of full-scale operation data (Orner et al., 2022).

Table 4. 16 Ranges for investment and operational costs to produce AS via ammonia stripping process

Initial investment & operational costs	Units	Ranges	Assumptions/observations:
CAPEX OPEX	€ millon € million/year	23.15 Kar* 27.5 Kar*	*Figures in USD converted to € using 2020 average exchange rate from www.irs.gov (rate 0.877 €/USD) CAPEX includes new infrastructure for air-stripping system only
CAPEX OPEX	N/A €/kg AS produced/day	0.84 Orner** (chemicals) 0.06 Orner** (energy)	

References: Kar et al., 2023; Orner et al., 2022

In the following section, a hypothetical calculation of the amount of initial investment and OPEX costs at las Esclusas plant is done, using data from Kar et al., 2023, as the basis for the reference plant in this analysis. The costs for Las Esclusas CWWTP are based on the AS produced.

Calculation:

Reference Plant (Kar et al., 2023)	Las Esclusas CWWTP (info. Collected from Interview w/plant owners)
Initial investment: € 23.15 million **CWWTP sidestreams flow rate:** 7,008 m3/day **Concentration N:** 0.63 kg/m3 **AS produced:** 16,537 kg AS/day	**Las Esclusas CWWTP sidestreams flow rate**: 90,997 m3/day **Concentration N:** 0.05 kg/m3 **Hypothetical AS produced at Las Esclusas:** 17,039 kg AS/day

Hypothethical initital investment cost: (17,039 kg AS/day / 16,537 kg AS/day)^0.6 x 23.15million = €23.57 million

Hypothethical OPEX cost: (17,039 kg AS/day / 16,537 kg AS/day)^1 x 27.5 million = € 28.3 million

If Las Esclusas CWWTP were to implement a system based on ammonia stripping process, the amount of initial investment and OPEX costs will be approximately € 23.57 million/year and € 28.3 million/year.

LEVEL OF EXPERTISE & LABOR REQUIREMENTS

Expertise is a technical and social criterion that affects all nutrient recovery technologies uniformly. However, in the case of ammonia stripping technology, it is documented that due to the complexity and amount of equipment required, the addition of two to four full-time staff will be necessary for effective operation and maintenance. (Orner et al., 2022) (Kar et al., 2023). This may pose a challenge for Las Esclusas if the required expertise is lacking within the workforce and if budget constraints limit the funds available for increasing staffing.

4.4 QUALITATIVE EVALUATION PER NUTRIENT RECOVERY ALTERNATIVE (EMPIRICAL DATA)

This part evaluates the social criteria identified by stakeholders as crucial for assessing nutrient recovery technologies. These criteria apply uniformly across all the identified nutrient recovery alternatives, meaning there are no significant variations between the technologies in terms of the influence of institutional suitability and the acceptability of end-products.

Institutional suitability as it was explained above is examined from the perspective of the **capacity**, **collaboration** and **support** provided by institutions towards circular economy initiatives within the context of nutrient recovery systems at a wastewater treatment plant. The empirical data from relevant stakeholders indicates that Ecuador's institutional suitability, particularly institutional **capacity** to enforce and manage effective legal standards, is underdeveloped. Specifically, in wastewater management, discharge limits to natural waterways for phosphorus and nitrogen have not been updated since 2003. Tabla 12 from Texto Unificado de Legislación Secundaria del Ministerio del Ambiente, Registro Oficial Suplemento N° 2 (March 31, 2003, Book VI, Annex 1) (Figure 4.1) reveal high allowable limits for nitrogen (15mg/L) and phosphorus (10mg/L) compared to international benchmarks, such as those in the EU. Currently, in the European Union, wastewater discharge limits mandate a total nitrogen concentration of 6 mg/L necessitating a minimum reduction of 85%, along with a phosphorus limit of 0.5 mg/L with a minimum reduction target of 90% (EU Parliament, 2023). This gap illustrates a clear regulatory disparity. For instance, the phosphorus concentration in the inflow wastewater at Las Esclusas CWWTP is approximately 6 mg/L, well below Ecuador's discharge limit of 10 mg/L. As a result, there is minimal regulatory incentive to further reduce or recover phosphorus as the incoming levels already meet local discharge standards without additional treatment. Plant owners posit that during the CEPT treatment, the application of ferric chloride $FeCl_3$ is enough to remove the phosphorus and decrease its concentration in the effluent. In addition, at Las Esclusas plant, which is a public-private partnership entity, stakeholders highlighted that, as the energy sector is publicly owned, current regulations prohibit the plant from recovering biogas for cogeneration to produce electricity for its own use. Until October 2024, no legal framework existed allowing private sector facilities to generate electricity independently, even in cases where government energy supply fall short. However, on October 28, 2024, new legislation was enacted permitting private sector entities to generate their own energy. Despite this advancement, restrictions remain as the legislative body caps the allowable megawatt capacity for private generation, prohibiting in this way full privatization of this basic need (Ecuavisa.com 29 October 2024).

PARÁMETROS	EXPRESADO COMO	UNIDAD	LÍMITE MÁXIMO PERMISIBLE
Mercurio total	Hg	mg/l	0,005
Níquel	Ni	mg/l	2,0
Nitratos - Nitritos	Expresado como Nitrógeno (N)	mg/l	10,0
Nitrógeno Total Kjedahl	N	mg/l	15
Fósforo total	P	mg/l	10

Figure 4. 1Texto Unificado de Legislación Secundaria del Ministerio del Ambiente, Registro Oficial Suplemento N° 2, del 31 de marzo de 2003. Libro VI. Anexo 1. Tabla 12 (EIA-Interagua, 2015, Tapia, 2008)

Stakeholders reported insufficient **support** from governmental institutions. Bureaucracy is cited as the primary barrier to the efficient accomplishment of newly develop projects. There is always a sense of mistrust between institutions leading to procedural obstacles instead of facilitation. A current example to this inefficiency within Ecuador's institutional framework is the implementation of renewable energy projects. Due to prolonged dry conditions impacting hydroelectric power production, Ecuador is facing energy shortages, underscoring the need for diversification in its energy matrix. Since 2017, eight renewable energy projects focused on photovoltaics and wind power have been proposed. However, bureaucratic delays persisted and only in 2023 were these projects signed by the current administration. Yet, this signing does not ensure implementation. The projects must still undergo a lengthy permitting process, requiring approvals and licenses from multiple entities, including the ministries of environment, energy/mines, as well as local municipalities. This bureaucratic sequence could take an additional six years: 2 years for planning and four for environmental, economic and technical evaluations. Notably two ready-to-launch projects, The Aromo Photovoltaic and Vionaco windmill projects, which together could produce approximately 400 MW, remain stalled due to the government's inability to guarantee payment for the generated energy. This example highlights the prolonged, decade-long trajectory needed to launch private investment-based electricity generation initiatives (Ecuavisa, 2024). In terms of inter-agency **collaboration**, Ecuador has limited international presence; however, it has demonstrated growing interest in fostering collaboration among domestic institutions with the support of international cooperation. A key example of this is the development of Ecuador's Circular Economy White Paper, which reflects coordinated efforts from El Ministerio de Produccion, Comercio Exterior, Inversions y Pesca, with German collaboration from GIZ (Deutsche Geselischaft fur Internationale Zusammenarbell GmbH), The university of San Francisco de Quito, and the CIEC (Centro de Innovacion y Economia circular). This paper compiles the concepts of circular economy proposing its integration as part of the country's regenerative and restorative development model. It defines the strategic lines and proposed actions to achieve this goal to continue advancing the roadmap to Ecuador's national circular economy strategy. It is structure around four main pillars: policy and financing, sustainable production, responsible consumption and integrated solid waste management.

Similar to institutional suitability, the **acceptability of end-products** uniformly impacts all nutrient recovery technologies. Stakeholder feedback on the use of agricultural fertilizer derived from phosphorus and nitrogen recovered at wastewater treatment plants reveals additional considerations beyond those found in the literature. Particularly, stakeholders stressed factors such as the cost of end-products, the level of altruism among farmers, and the extend of agricultural knowledge within the farming community. In a country like Ecuador, cost is a critical factor influencing acceptability at all levels, particularly given its developing economy. Most farmers operate in rural, marginalized, and economically disadvantage areas, where fertilizer price plays a decisive role. If the price of nutrient-recovered fertilizer exceeds that of conventional alternatives, farmers are likely to favor the cheaper option. However, a small subset of farmers – those with a stronger environmental commitment and higher levels of education and technical knowledge – may be more inclined to choose environmentally friendlier products despite the higher cost. This group exhibiting greater altruism and awareness of sustainable practices, recognizes the long-term benefits of reducing chemical inputs to prevent soil degradation, which may justify a willingness to pay a premium for eco-friendly fertilizers.

This chapter's main goal was to identify relevant criteria that are aligned with the opinions and preferences of the relevant stakeholders, as well as, with the attributes associated with nutrient recovery technologies identified in Chapter 3. Through an exploratory analysis of these criteria and their application to each nutrient recovery technology, a hypothetical quantitative and qualitative assessment was conducted with the aim to find the most sustainable performed technology.

Table 4.17 presents a comparative overview of the nutrient recovery technologies based on the selected evaluation criteria. The quantitative figures are illustrative and were derived by extrapolating data from a reference plant to the context of Las Esclusas. For the qualitative criteria, identical assessments were applied across all technologies, as these aspects – such as acceptance of end-product and institutional suitability - are considered uniformly relevant to each option within the local context.

Table 4. 17 Hypothetical sustainability performance figures per nutrient recovery technology for Las Esclusas CWWTP

HYPOTHETIC QUANTITATIVE FIGURES FOR LAS ESCLUSAS CWWTP	Energy Security Electricity & heat required	Circularity # recovered product	GWP CO2 eq.	Invest. & Oper. costs CAPEX & OPEX	Level Expertise & Labor requirements # skilled workforce
	Avg. wet & dry season		w/ flaring emissions		
Precipitation/ crystallization	1,513 kwh/day	465 Kg struvite/day	104,746 kg CO2 eq./day	€9,196 million (CAPEX) €832,214 /year (OPEX)	+ 2 workers (as is in literature)
AshDec w/o incineration plant	23,272 kwh/day (electricity) & 59,549 kwh/day (heat)	11,467 kg RP/day	53,264 kg CO2 eq/day	€4.6 million (CAPEX) €362,700/ year (OPEX)	+2 workers (Ash Dec only w/o manforce to run incineration plant
w/incineration plant	Extra 2,900 kwh/day – 15,080 kwh/day (electricity)		Extra 40,719 kg CO2 eq./day – 87,256 kg CO2 eq./day	> €35 million (CAPEX)	
Ammonia Stripping w/o thermal energy	4,362 kwh/day	17,039 kg AS/day	29,893 kg CO2 eq/day	€23 million (CAPEX) €28 million/year (OPEX)	+2 workers (as is in literature)

QUALITATIVE ASPECTS FOR LAS ESCLUSAS CWWTP	Institutional suitability	Aceptance end-products
		Affordable prices - main motivator for acceptance
Precipitation/ crystallization	Low efficient capacity Low collaboration Low support	Positive
AshDec only	Low efficient capacity Low collaboration Low support	Positive
Ammonia Stripping	Low efficient capacity Low collaboration Low support	Positive

This table highlights the inherent limitations of each nutrient technology considered for implementation at Las Esclusas CWWTP. For precipitation/crystallization of struvite, a key limitation is the relatively low yield of the recovered product, which becomes even less favorable when the influent wastewater contains low nutrient concentrations. Under those conditions, the recovery process may not be economically or operationally justifiable due to limited resource output. In the case of AshDEC, the requirement for a sludge incineration facility significantly increases energy consumption, resulting in higher greenhouse emissions and global warming potential thereby diminishing its attractiveness. The economic evaluation highlights the substantial capital and operational expenditures required for these technologies. In the case of Las Esclusas, such financial demands are particularly challenging given the existing budget constraints. Furthermore, the necessity for a highly skilled workforce to ensure proper operation and maintenance further limits their feasibility, particularly in developing countries where infrastructure and institutional suitability (capacity, support, collaboration) are often inadequate. In countries with limited economic resources, affordability becomes a primary concern for the population. As a result, consumers tend to opt for the most cost-effective products available, regardless of their origin or sustainability. This economic reality poses a significant challenge for the adoption of recovered fertilizer which is often more expensive due to high production and operational costs.

CHAPTER 5

DISCUSSION

Wastewater treatment serves as a crucial mechanism in preventing water pollution by effectively removing various contaminants before discharge into rivers, lakes, and oceans. Additionally, the treatment process plays a vital role in mitigating public health risks by eliminating harmful pathogens such as bacteria, viruses, and parasites, thereby reducing the likelihood of illnesses among individuals exposed to contaminated water. Among those contaminants, phosphorus and nitrogen play an important role in the sustainable management of wastewater. They are responsible for detrimental effects on terrestrial and aquatic ecosystems impacting air, soil, and water quality. Aquatic effects like the proliferation of algal blooms in aquatic ecosystems, which have caused oxygen-depleted dead zones, and are attributed to nitrogen-induced eutrophication and acidification. Furthermore, elevated concentrations in the air of nitrogen oxides where N2O is considered a greenhouse gas emitter has proven to be responsible for the depletion of the ozone layer while the other N oxides are causing high risks to the environment and human health like blue-baby syndrome in infants and the formation of carcinogenic nitrosamines in the human body. Nonetheless, since phosphorus is leveled as a finite element, it has instigated research to investigate the possibility to recover this important resource.

Research on wastewater treatment has facilitated the exploration of diverse resource opportunities within the waste stream. In the process of cleaning wastewater, a wastewater treatment plant ends it up with a lot of organic and inorganic materials and substances that need to be managed responsibly and considerate to the environment. There are a prominent number of resources that can be recovered from a municipal wastewater treatment plant in the form of energy (biogas, electricity), nutrients, cellulose, clean water, biochemicals, metals, etc. Among the nutrients that are the subject of this study, phosphorus and nitrogen are of most importance because they are the raw materials in the production of many agricultural fertilizers. This has instigated for the redesign of large-scale conventional wastewater treatment plants which infrastructure is not only destined to clean wastewater but to being a resource recovery factory of resources for reuse contributing in this way to a more circular economy system by maximizing resource efficiency and minimizing waste (Kehrein et al., 2020).

Nutrient recovery technologies that allow to recover nutrients like phosphorus and nitrogen from wastewater are still in its early stages. They present significant design complexities that require evaluation across multiple dimensions and criteria. These assessments primarily focus on technical, economic, and environmental aspects, addressing challenges such as technical uncertainties and operational issues, like high costs related to chemical usage and energy consumption. Selecting the most suitable technology will always be a trade-off between achieving high efficiency and recovery rates while minimizing environmental risks. However, the decision-making process for full scale implementation of nutrient recovery technologies has often neglected the social aspect. Societal and ethical considerations are frequently overlooked in evaluating the feasibility of emerging technologies despite their critical role in ensuring successful adoption and long-term sustainability (Yadav et al., 2021).

Hence, acknowledging the significance and often overlooked role that social factors have in the implementation of nutrient recovery systems, this research focuses on providing an ex-ante evaluation of sustainable nutrient recovery technologies for phosphorus and nitrogen at a wastewater treatment plant, with the focus on integrating stakeholders' perspectives on sustainability criteria at the environmental, technical, economic, and social dimensions. By evaluating the role of stakeholder's opinions and preferences in identifying and implementing sustainably performing nutrient recovery technologies at a conventional wastewater treatment plant in Ecuador, their perceptions are intrinsically integrated into the study's methodological framework.

Through empirical data collected via semi-structured interviews with key stakeholders, relevant criteria were identified that reflected stakeholder's opinions and preferences concerning the plant's current operational status and its capacity to implement nutrient recovery systems. These criteria were corroborated with literature particularly within the environmental, economic and technical dimensions. However, for the social dimension, certain criteria were not explicitly addressed in the literature. For these criteria a second round of interviews was conducted with selected stakeholders to explore a deeper understanding of these aspects.

Literature highlights many case studies that show the successful implantation of nutrient recovery technologies in countries from the Global North who are already commercializing these technologies at large-scale. Many of these studies are within the environmental, technical and economic domains emphasizing fully on the technological and economic development behind nutrient recovery processes and technologies.

Some of the LCA (Life-cycle Assessment) studies emphasize on the environmental part by measuring environmental impact of material, energy, GHGEs, aquatic and terrestrial toxicity of recovering nutrients from wastewater. Some TEA (Technical Economic Analysis) studies assess the economic feasibility of marketing recovered end-products examining factors such as return on investment and market competitiveness. Findings indicate that revenues generated from the commercialization of recovered fertilizers do not sufficiently offset the additional costs associated with their implementation. This is largely attributed to the high consumption of chemicals, which accounts for approximately 30 % of the gross costs (Mayor et al., 2023). Furthermore, the market price of fertilizers recovered from wastewater remains too high to compete effectively with conventional products, due to the high initial capital investments and expensive operational and maintenance requirements. And other studies, which concentrate on the technical engineering of the different nutrient recovery processes and technologies, investigate into technical advancements that could reduce their impact.

Many of these studies are based on wastewater treatment plants that practice primary, secondary and tertiary treatments that provides them with processes that favor the removal and recovery of nutrients like phosphorus and nitrogen. For example, secondary treatment aligned with activated sludge process (ASP) play a foundational role in preparing wastewater and sludge for recovery methods. In other studies, circular economy principles are seamlessly integrated into conventional processes. A common practice is the recovery of biogas which is utilized for onsite electricity cogeneration.

Nevertheless, literature on the social aspects related to the implementation of nutrient recovery systems remains limited. Most of the studies in the literature originate from countries in the Global North, where institutional and political systems are stable, and many utility companies are privatized giving the private sector full control over onsite operations. Regarding the acceptance of end-products, the literature briefly addresses factors such as acceptance depending on how similar the recovered products are to conventional ones, sanitary concerns related to the potential presence of pathogens in fertilizers made from recovered nutrients, and the role of fertilizer shortages in influencing public acceptance, with some suggesting that shortages may drive greater acceptance of these alternative products.

By comparing the data collected in this study with findings from previous research, several interesting and feasible aspects, as well as cross-cutting challenges were identified.

In the Global North, most wastewater treatment plants are equipped with primary, secondary and tertiary treatments which make the recovery of nutrients more feasible, whereas for a developing country from the Global South, the context is different. In the case of Las Esclusas CWWTP, this plant only operates with primary treatment named chemically enhanced primary treatment (CEPT) system, due to the lower costs this infrastructure represents. As one stakeholder aptly noted, "These innovative technological systems are good for "gringolandia" (Disneyland) but are seldom compatible with the systemic realities of countries in the Global South" like Ecuador. In the Global North, wastewater treatment plants are already practicing circular economy practices, such as on-site electricity generation via anaerobic digestion, enabled in part by the autonomy of privatized utility operators to pursue technological innovation. Additionally waste sludge is often reused for beneficial purposes, including composting for fertilizer or soil amendment. In contrast, Las Esclusas CWWTP landfills its partly dehydrated sludge, contributing to soil pollution. The technical expertise and R&D capacity necessary to operate and maintain nutrient recovery systems are widely available in the Global North but remain limited in the Global South. Meanwhile in the Global North are already increasingly progressing toward the commercialization of recovered products such as struvite-based fertilizers.

Nevertheless, a discussion on how the different alternatives compare in the context of Ecuador is necessary to reflect on. One key constraint is the legal prohibition against reusing biogas from anaerobic digesters for electricity generation, resulting in gas flaring and increase greenhouse gas emissions. This, combined with the national energy shortage hinders the economic and environmental viability of nutrient recovery technologies, which are typically more sustainable when integrated within circular economy frameworks. For example, the AshDEC, which requires a sludge incineration facility, entails both high capital investment and significant energy demand, rendering it unfeasible for implementation at Las Esclusas CWWTP. Although, ammonia stripping could benefit from the plant's warm tropical climate, potentially reducing thermal energy requirements, it remains the most expensive technology option currently available. In contrast, precipitation/crystallization of struvite appears to offer the lowest environmental and economic burden, particularly in terms of energy consumption and global warming potential. However, the main drawback lies in the relatively low yield of recovered nutrient end-product, which may be further exacerbated by the low phosphorus concentration in the influent at Las Esclusas. Regarding the technical expertise and social dimensions affecting the implementation of nutrient recovery technologies in Ecuador, there is a clear deficiency in both skilled labor and technical capacity across all assessed technologies. High capital and operational expenditures translate into elevated end-product prices, which poses a major barrier to public acceptance in a cost-sensitive context like Ecuador, where affordability is a primary concern. Furthermore, the implementation of nutrient recovery systems is not currently an institutional priority as national efforts remain focused on expanding access to basic sanitation services. This misalignment of priorities contributes to a lack of institutional capacity, limited institutional support, and insufficient inter-agency collaboration which are factors that collectively hinder the advancement of circular economy initiatives in the wastewater sector.

Institutional and societal challenges

This study took an extra step by prioritizing the societal dimension. As detailed in the methodology, the additional interviews were conducted to gather more specific insights. All stakeholders agreed that Ecuador's institutional suitability to support innovative projects like nutrient recovery systems is weak. There is no capacity, collaboration or institutional support to promote such initiatives. According to academia, Ecuador suffers from energy and fertilizer shortages. One palpable example is the current situation that the country is suffering at this moment. Severe energy shortages caused by prolonged droughts have affected hydroelectric power generation – Ecuador's primary energy source. The lack of diversification in the country's energy matrix has worsened the crisis causing blackouts for up to 12 hours a day.

Stakeholders frequently cited high levels of corruption within institutions, which prioritized personal gains over efficient fund administration. This creates an environment unsuitable for the development of efficient innovative initiatives like the implementation of nutrient recovery technologies. At this moment, the country is experiencing a process of deinstitutionalization, marked by political instability and power struggles characterized by authoritarian and undemocratic mechanisms cited by the Ecuadorean National Anticorruption Commission (CAN) (Ecuavisa, 2024).

Thus, the overall institutional suitability in the country tends to create barriers rather than facilitating project implementation. Bureaucratic inefficiencies limited institutional support, and weak inter-institutional collaboration, coupled with outdated legislation render Ecuador's institutional framework insufficiently prepared to initiate and sustain circular economy projects.

Acceptance of end-products

As a Global South country, Ecuador faces significant barriers to public acceptance of nutrient recovery products being the most important one the economic constraints. High cost recovered products are unlikely to be accepted among consumers who are forced to choose cheaper alternatives due to a lack in their purchasing power. While some environmentally conscious farmers may prefer chemically free fertilizers, such as struvite recovered from wastewater, their financial limitations might often preclude them from affording these options.

In general, by prioritizing stakeholder opinions and preferences, nutrient recovery systems can achieve greater sustainability, efficiency and cost effectiveness. For instance, in the case of Las Esclusas CWWTP, if academia and other local experts would have been consulted during the planning phase, more efficient and sustainable treatment processes would have been implemented. Given that the plant primarily treats domestic, rather than industrial wastewater, a biological treatment system would have been a more appropriate and sustainable choice that the Chemically Enhanced Primary Treatment (CEPT) system that was ultimately built. The plant owners justified the decision to implement the CEPT system, on the basis, of lower initial construction costs compared to a biological treatment system. However, the long-term operational expenses associated with the CEPT system, particularly the high cost of the chemicals required for its operation, may ultimately render it more expensive over time and for instance more detrimental for the water ecosystem.

These findings underscore the complex interplay of economic, technical, institutional, and societal factors that influence the feasibility of implementing nutrient recovery technologies in countries like Ecuador.

Limitations

The Literature highlights several technical and economical limitations that must be considered when evaluating the implementation of full-scale sustainable nutrient recovery technologies. Key limitations include high costs, operational challenges, a lack of technical expertise, workforce availability, skill development, production capacity and the need for training programs. Moreover, selecting an appropriate technology typically requires careful evaluation of factors such as the variability in wastewater quality and nutrient content (e.g. high nutrient concentrations mean more efficient recovery and cost effective), as well as treatment plant's ability to recover resources efficiently to offset operational costs and for instance market price for the recovered product (e.g. through onsite renewable energy production).

If these challenges are significant for countries in the Global North, they are likely to be even more pronounced for Las Esclusas CWWTP located in the Global South. Stakeholders consistently emphasized that this plant is currently not ready to implement a nutrient recovery system. Issues include low nutrient concentrations in the influent, insufficient capacity for renewable energy generation onsite, and the absence of suitable technologies and processes for cost-effective nutrient recovery. Operational challenges, a lack of technical expertise and skilled personnel, limited workforce availability, inadequate R&D capabilities, and insufficient institutional support and collaboration further exacerbate these difficulties.

A key limitation for the quantitative analysis, was the absence of site-specific data for Las Esclusas CWWTP, which constrained the accuracy of the estimations across evaluation criteria for comparing nutrient recovery technology alternatives. Consequently, data from a reference plant reported in the literature were extrapolated and adapted to approximate the conditions of Las Esclusas.

A logistical limitation of this study was the limited availability of stakeholders for the first round of interviews and an even smaller group for the second round. However, the similarity of their opinions and preferences suggests that the number of interviewees may have been sufficient to capture a representative perspective.

Future research directions

Potential future research of this study could involve identifying the most sustainable nutrient recovery technology by evaluating environmental, technical, economic, and social criteria supported by specific indicators. Methodologies such as Multi-Criteria Decision Analysis (MCDA) offer a systemic approach to determining the most feasible and sustainable solution while incorporating the preferences of various stakeholders. One key advantage of MCDA is its ability to engage multiple stakeholders, facilitating the integration of diverse perspectives. This collaborative approach enables a comprehensive understanding of the viewpoints held by different groups, leading to more informed and balanced decision-making (Reyes, 2017)

In addition, there is a need for more research focusing on the Global South, emphasizing technical guidance and technology transfer tailored to the unique characteristics of these regions. Solutions that are effective in the Global North may not necessarily be viable in the Global South due to differences in economic, environmental, and social contexts. For instance, at Las Esclusas CWWTP, a French company (Veolia) oversees plant management and operations. However, the business practices and management approaches employed by this foreign entity often do not align with local practices and conditions impacting the personnel sometimes negatively. Therefore, the active involvement of stakeholders could secure the successful implementation of sustainable and responsible nutrient recovery systems in countries of the Global South. Research initiatives should prioritize inclusivity by engaging stakeholders, who possess critical hands-on experience and knowledge of local procedures. Their input can guide the design and adoption of technologies better tailored to the unique characteristics and needs of the country.

CONCLUSION

The primary objective of this study was to identify sustainable nutrient recovery technologies for recovering phosphorus and nitrogen from wastewater, with a strong emphasis on incorporating stakeholder opinions and preferences. Through an exploratory analysis, the identifiable nutrient recovery technologies were evaluated through criteria across environmental, economic, technical and social dimensions to assess their sustainability performance. These criteria were corroborated with existing literature and supplemented with stakeholders' insights through two rounds of interviews aiming to highlight social aspects not explicitly covered in the literature. A CWWTP situated in Ecuador was used as a case study.

This study conducted an initial, exploratory assessment of potential nutrient recovery technologies that could be implemented at Las Esclusas: (i) precipitation/crystallization of struvite, (ii) mono-incineration and AshDEC processes for phosphorus recovery from digestate sludge, and (iii) ammonia stripping for nitrogen recovery. These options were evaluated using a set of criteria derived from stakeholder opinions and preferences and corroborated with insights from academic literature. The evaluation employed both qualitative and indicative quantitative analyses, relying on literature- based performance data and estimations to the local plant context. Due to the lack of site-specific data, results should be interpreted as approximate and illustrative rather than definitive.

Preliminary estimates suggest that precipitation/crystallization of struvite may be associated with the lowest energy demand, followed by ammonia stripping, whereas AshDEC exhibits comparatively higher energy requirements due to combined heat and electricity needs from an incineration facility. In terms of potential nutrient recovery, ammonia stripping appears to offer the highest estimated recovery of nitrogen, while phosphorous recovery through AshDEC and struvite precipitation/crystallization may yield lower outputs, particularly when based on CEPT system with limited nutrient concentrations. The lowest global warming potential is attributed to ammonia stripping followed by precipitation/crystallization and Ash DEC due to the emissions from an incineration facility. Economic estimates, based on literature-derived CAPEX and OPEX figures, indicates that ammonia stripping may be considerably more expensive than the other alternatives. However, these figures carry uncertainty due to the extrapolation involved. Regarding technical expertise and labor, all technologies are assumed to require a relatively high level of technical skill and additional personnel for maintenance and monitoring, although exact staffing needs were not available.

Insights from the second round of stakeholder interviews further highlighted weak institutional suitability- in terms of capacity, support and collaboration- as a major implementation barrier. Particularly due to the lack of a stable institutional framework capable of enacting sound legislation, supporting R&D, promoting academic and training programs, and allocating sufficient budget to subsidize pilot projects where necessary. Successful implementation of nutrient recovery systems depends heavily on the presence of a stable institutional framework as well as an efficient cross-institutional coordination that could enable the commercialization of recovered fertilizers. Another social criterion evaluated was public acceptance of fertilizers recovered from wastewater. Responses were tentatively positive conditioned by product affordability. The precarious economic situation of the country with many potential users living in poverty could further complicate market adoption pushing users towards cheaper, conventional alternatives.

Given the overall assessment, no single nutrient recovery technology can currently be recommended for immediate implementation at Las Esclusas CWWTP. The absence of secondary biological treatment significantly limits recovery potential, and retrofitting the plant would be a pre-requisite to increase recover efficiency but economically unfeasible. Moreover, leveraging on-site biogas for energy generation could offset operational energy demands, but legal restrictions currently prevent such circular economy initiatives. While the exploratory findings indicate areas of promise, more detailed site-specific evaluations will be essential to inform future decision-making.

Incorporating stakeholder opinions and preferences is essential to the selection and successful implementation of nutrient recovery technologies. The initial planning of Las Esclusas excluded meaningful stakeholder participation. Despite academic recommendations favoring a biological treatment system, which is more appropriate for the domestic nature of the wastewater, the decision makers opted for the lower-cost CEPT system commonly used for industrial effluents. As a result, plant operators now face significant operational challenges due to a mismatch between the treatment design and actual wastewater characteristics. While the biological option would have required a higher initial investment, it would have offered long-term environmental benefits and greater potential for nutrient recovery. This case illustrates the critical importance of integrating stakeholder input in infrastructure planning and technology selection. Stakeholder perspectives not only highlight systemic inefficiencies but also offer insights into local realities enabling more tailored and resilient project outcomes. Testing this methodology in a Global South country like Ecuador, it highlights how systemic barriers such as, weak governance, bureaucratic inefficiencies, political instability, and corruption, significantly hinder the implementation of circular economy initiatives like nutrient recovery from wastewater. This participatory approach ensures that sustainability assessments reflect both the technical feasibility and socio-political realities, thereby improving the chances of long-term success in circular economy initiatives.

APPENDIX 1

CONVENTIONAL METHODS TO REMOVE AND RECOVER PHOSPHORUS

The main difference between removing phosphorus from wastewater and recovering phosphorus is that removing's final objective is to make wastewater phosphorus-free, while recovering phosphorus focuses on re-using that reclaimed phosphorus to make other products like fertilizers for agricultural use.

Several methods have been developed to remove phosphorus from wastewater during treatment. These methods involved physical, chemical, and biological processes that can be part of the primary, secondary, or tertiary treatment, depending on how the wastewater treatment plant is established. The bulk of phosphorus removal from wastewater is achieved through two main methods: chemical and biological treatment. Both methods involve forming particles that can be separated from the water. These solid phosphorus particles become part of the total suspended solids (TSS) and are eventually removed in the sludge. Chemical treatment is the most widely used and involves adding specific chemicals and metal salts (e.g. iron, aluminum, magnesium, or calcium) to convert dissolved phosphorus into solids, which are then separated from the water along with sludge. This technique can be applied at different stages of the treatment. During primary treatment, chemicals are added before sedimentation and the resulting precipitate goes into primary sludge. During secondary treatment, metal salts are added directly to the aeration tank (activated sludge process) leading to phosphorus ending up in the secondary sludge. After sludge treatment, flocculants (synthetic water-soluble polymers) can be added to conglomerate more suspended solids into large loose flocs thus achieving solid-liquid separation. When combined with filtration, this process can achieve a very low phosphorus concentrations in the effluent. On the other hand, the conventional Enhanced Biological Phosphorus Removal (EBNR), which is carry out mainly during secondary treatment involves adding microorganisms called phosphate-accumulating organisms (PAOs) into the activated sludge. These microorganisms can store more phosphorus than other bacteria when they are under an alternating environment between anaerobic and aerobic zones. This method is considered more beneficial and eco-friendlier than chemical methods because it produces less sludge production, reduced chemical costs and less metal content in the sludge. This process has been used successfully in wastewater treatment plants for several decades and has greatly contributed to the development of phosphorus recovery (Salkunic et al., 2022) (Figure A1).

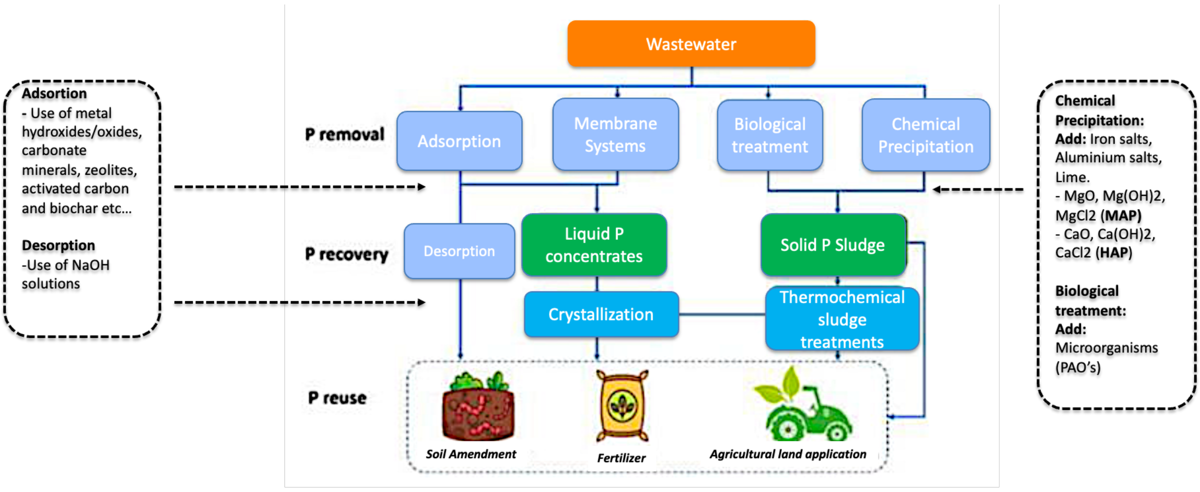


Figure A1. Current phosphorus removal technologies. Adapted from "Recovery of phosphorus from wastewater: A review based on current phosphorus removal technologies" by Zheng et al., 2023. Adding information from Bacelo et al., 2020).

The chemical processes that are the most widely used to remove P from wastewater are chemical precipitation and adsorption due to their stability, efficiency, and easiness to operate when compared to other processes (Ye et al., 2017). In Table A1, all the available removal methods are described with their advantages and disadvantages.

Table A1. Advantages and disadvantages of available P removal methods (Bacelo et al, 2020)

Method	Advantages	Disadvantages
Coagulation-Flocculation/Chemical Precipitation • Iron salts • Aluminium salts • Lime • MgO, $Mg(OH)_2$, $MgCl_2$ (**MAP precipitation**) • CaO, $Ca(OH)_2$, $CaCl_2$ (**HAP precipitation**)	• Reliable and well-established. • Able to remove ≥90–95% of P • MAP could be directly used as a soil fertilizer • HAP could be recycled by the phosphate industry • Existing levels of Ca^{2+}, Mg^{2+} and NH_4^+ in wastewater can be used to generate spontaneous precipitation or to reduce supplementation.	• Effectiveness and lower costs require high phosphate concentrations • Slight alkaline pH required • Control systems required (pH, variable doses of chemicals) • Need of significant amounts of chemicals • Sludge disposal and effluent neutralization required • Difficult recycling and valorisation of Fe/Al precipitates • Affected by suspended solids, organic matter, carbonates
Adsorption	• Easy operation and low costs • Possible use of low-cost adsorbents • Selectivity and effectiveness for low concentrations • Fast adsorption rate • Possible phosphate recovery	• Pre-treatment of the wastewater may be required • Influence of competing ionsD • Downstream processes needed to recover phosphate.
Biological method • EBNR	• Nearly 100% of phosphate removal could be achieved • Low operating costs • No/low chemicals usage	• Low effectiveness at trace level • Strict control required (strict anaerobic and aerobic conditions) • Sensitivity to inhibiting substances.
Membrane Processes • Electrodialysis (ED) • Reverse osmosis (RO) • Nanofiltration (NF)	• Excellent removal • Membrane concentrates can be used for phosphate recovery	• High capital cost • No ion selectivity • High energy costs for reverse osmosis and nanofiltration.

In wastewater management, phosphorus recovery can happen at different stages, from the liquid phase to the sludge phase and dry sludge phase. Figure A2, shows the different locations where P can be recovered throughout the different steps of the treatment process. From the liquid-phase, P can be retrieved from the anaerobic digestion supernatant, reject water, and the sludge dewatering filtrate with a biological phosphorus removal process. As polyphosphates stored within bacterial cells are partially released in anaerobic conditions, there is a notable increase in phosphate content within the sludge system. The process of recovering phosphate from the sludge phase, where phosphorus is present in chemically and/or biologically bound forms, involves two stages: recovery from the digester sludge before and after the dewatering unit (Desmidt et al., 2015). Instead, from the dry-phase, P can be subtracted from the dry surplus sludge and sewage sludge ash after incineration, being one of the most established access points after anaerobic digestate (Egle et al., 2016, Ye et al., 2020). For instance, the percentage recovery from the liquid phase ranges between 40%-50%, while from the dry phase, the percentage can reach 90% due to the fact that approximately 90% of the incoming phosphorus load is included in the sewage sludge. Ash from sewage sludge incineration is particularly promising as a phosphorus source for recovery technologies (Desmidt et al., 2015), (Lizarralde et al., 2019), (Salkunic et al., 2022). Another method for phosphorus recovery outside of the system boundary of a wastewater plant involves the aerobic composting of dewatered sludge, wherein organic matter undergoes decomposition through microbial activity (Chen et al., 2019).

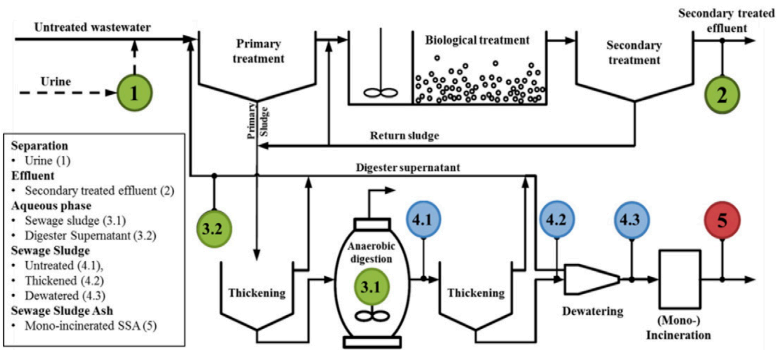


Figure A2. Possible access points for P recovery in a CWWTP (Egle et al., 2016)

Various methods and technologies involving physical, chemical and biological processes have been developed for recovering phosphorus from wastewater. Recovering P from anaerobic digestate, sludge centrate (liquor or process water) and sludge ash are the most widely used and involves four main steps: pre-treatment, enrichment, recovery (or extraction), and post-treatment. Pre-treatment includes actions like CO2 stripping, acidification, and filtration to prepare the material for recovery. For instance, CO2 stripping is used to adjust the pH of anaerobic digestate in some processes, while acidification is employed to transfer phosphorus from solid ash to a liquid phase. Filtration methods like sand filtration or microfiltration remove solid particles from the liquid to avoid interference in later steps. Enrichment, which is optional, boosts the phosphorus concentration in the liquid, reducing the need for costly chemicals in the recovery process. High-rejection membrane processes like reverse osmosis are used for this purpose. Recovery involves precipitation of P to recover struvite or calcium phosphate. Finally, post-treatment removes any remaining phosphorus from the solution before discharge Figure A3 (Vu et al., 2023).

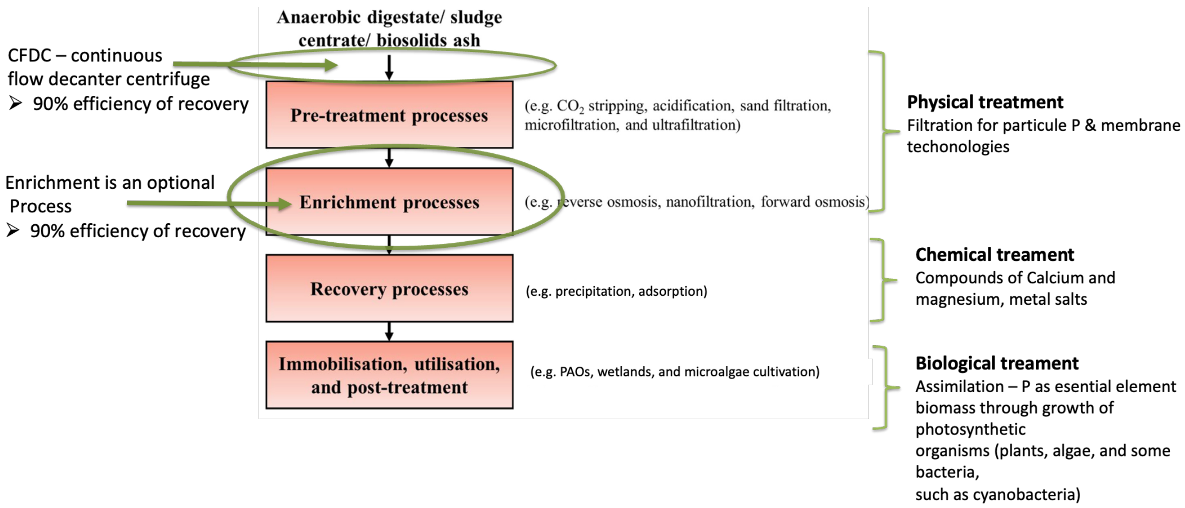


Figure A3. Schematic diagram showing major steps and processes in phosphorus recovery Adapted from "Recent technological developments and challenges for phosphorus removal and recovery toward a circular economy" by (Vu et al., 2023).

There are numerous techniques accessible to recover P, ranging from laboratory-scale experiments to pilot projects, but those demonstrating success at a plant scale are the most noteworthy like chemical precipitation and adsorption.

P - CHEMICAL PRECIPITATION

Chemical precipitation to recover P involves adding appropriate chemicals (Mg, Ca) that are used as precipitators. Since aluminum or iron in phosphates have limited value for industrial and agricultural uses, only magnesium or calcium tend to be added. These chemicals can be added before, during or after the conventional secondary treatment of municipal wastewater. They react with P to form Ca5(OH)(PO4)3 (hydroxyapatite = HAP) and MgNH4PO4·6H2O (struvite = MAP), where MAP after dewatering and crystallization can potentially be re-use as a fertilizer. There are several factors affecting the P recovery through chemical precipitation (Ye et al., 2020) (Table A2), still this process is the one with the highest efficiency recovery (over 80%) and it has been implemented at plant-scale (Ye et al, 2017).

Table A2. Main Factors that affect P recovery via chemical precipitation of struvite (Ye et al., 2017)

Recovery Factors	Effects on P recovery
Solution pH	• Range from 8-10.5 is recommended because higher pH values may result in forming unexpected metal-based precipitates while the precipitation rate is small at low pH level. • The pH values affect the speciation profiles of P ions in the aquatic environment.
Temperature	• Higher temperatures make the precipitates formation possible at lower pH. • Low temperatures (below 15 C) are beneficial for struvite precipitation.
Dose	• Struvite can form at low pH level around 5.3 if high concentrations of phosphorus are present. • Mg:P ratio should be more than one to obtain struvite. Ca:P should be over than 1.67
Foreign substances	• The presence of calcium ions can negatively affect the struvite precipitation.

	• The impacts of organic matter on chemical precipitation vary according to their properties, while some organics such as pharmaceuticals and hormones when detected in the recovered precipitates, can seriously harm human health and the environment if used as a fertilizer

As it was mentioned before, chemical precipitation methods are the most widely used to recover struvite.

P - ADSORPTION

Adsorption is another method to recover P from municipal wastewater. This process involves two steps where P is taken up by adsorbents, and then it is released (Desorption) from the loaded adsorbent resulting in a solution rich in nutrients. After desorption, the recovered phosphate is enriched in the ash or desorption solution, which can be utilized for direct land application. Metal- and biochar-based materials are popular adsorbents. There are three main mechanisms involved in phosphate adsorption: electrostatic attraction, ion exchange, and surface precipitation where if magnesium- and calcium-based adsorbents are used, then chemical precipitation can occur (Ye et al., 2017).

Adsorption has clear benefits due to its simple design and operation, low cost and high stability where most of the adsorbents are efficient and easy to find (Bacelo et al., 2020), nonetheless, up scaling the process is still in pilot experimentation. One important aspect is that this process allows P recovery from wastewater that has low concentration levels (<50 mg/L) (Vu et al., 2023). In the same way as with chemical precipitation, there are various factors influence P-adsorption (Ye et al., 2020) (Table A3).

Table A3. Main Factors that affect P recovery via adsorption (Ye et al., 2020)

Recovery Factors	Effects on P recovery
pH Value	• The surface charge on a given adsorbent is positive at the solution pH < adsorbent, so the P adsorption is enhanced due to electronic attraction; by contrast, negatively charged surface of the adsorbent would repulse P at pH > adsorbent. • The P forms are highly dependent on pH levels. • Competition is evident between OH^- ions and P, at high pH, which does not favor P adsorption.
Temperature	• Generally, P adsorption is an endothermic process which means higher temperature can facilitate the adsorption.
Coexistent Ions	• There are a lot of anions exiting in domestic and industrial wastewaters, such as CO_3, NO_3, F and SO_4. They would compete with P-ions for adsorption so their effects on P adsorption greatly depend on the given adsorbent's property and adsorption mechanisms. • The presence of CO_3^{2-} results in increasing pH value, which weakens P adsorption.
Desorption	• Solvent washing and calcination are the main desorption methods, which are determined by the adsorbent property and adsorption mechanism.

Following chemical precipitation, adsorption, Enhanced Biological Nutrient Removal (EBNR) processes, etc., the phosphorus-rich streams, whether in liquid or dry form, require additional treatment to produce a usable product. Several methods have been devised for phosphorus recovery, with the most utilized ones including crystallization, wet chemical processes, or thermochemical processes. Additionally, another noteworthy process is the composting of dewatered digestate, which has been considered as a method to treat waste sludge and converted into a usable product.

Crystallization is the standard method for recovering phosphorus from the **liquid phase** or the **liquid fraction after sludge digestion**. In this process, phosphorus is precipitated with calcium/magnesium or iron/aluminum salts in a crystallization tank which is either mixed or in a fluidized state to recover struvite or calcium phosphate. It primarily involves employing Enhanced Biological Phosphorus Removal (EBPR) to elevate the concentration of phosphorus and enhance recovery efficiency, which typically ranges from 10% to 40% from aqueous phase Presently, struvite crystallization technologies are predominantly employed at an industrial scale. These processes confer additional advantages such as mitigating challenges associated with sludge handling and enhancing its dewatering efficiency. Nevertheless, struvite, scientifically termed magnesium ammonium phosphate hexahydrate (MgNH4PO4 · 6H2O), manifests as a white mineral that naturally precipitates within sewage systems and wastewater treatment facilities. However, in such environments, struvite deposition can precipitate issues by adhering to undesirable locations like pumps, aerators, and pipelines due to diminished pressure conditions and the liberation of dissolved CO2. The removal of these deposits often entails considerable expenses. Nevertheless, when struvite is cultivated under controlled conditions within crystallization reactors, it yields small, homogeneous granules that are simpler to manage (Salkunic et al., 2022).

Wet chemical processes are used to recover P from **sewage sludge** or **sewage sludge ash** via leaching of P from previously precipitated P, by using acids and bases (sulfuric, hydrochloric, phosphoric, and carbonic). Acid leaching, commonly employed for sewage sludge ash treatment, dissolves heavy metals alongside iron and aluminum from the phosphorus precipitate. Attention must be paid to removing these metals from the solution due to their solubility. The re-dissolved phosphorus is then isolated, typically through methods like crystallization or precipitation as struvite or apatite. To maintain struvite quality, citric acid is added before struvite precipitation to form metal citrate salts that remain in the solution. (Salkunic et al., 2022).

Thermochemical processes involve applying heat to sewage sludge or ash from sludge incineration, encompassing various treatments at different temperatures and oxygen levels. These treatments, including hydrothermal treatment, pyrolysis, and gasification, do not typically require chemical additives. However, in thermochemical treatment of sludge ash, chemicals may be employed. In this method, significant phosphorus recovery is achievable. The ash from sewage sludge incineration contains about 90% phosphorus (Atienza-Martinez et al., 2014). The thermochemical treatment of **sewage sludge ash** involves subjecting the ash to high temperatures and chemical reactions to eliminate heavy metals and enhance the availability of phosphorus for fertilizer production. When used for **sewage sludge** treatment, lower temperatures are employed compared to sludge ash treatment, although, elevated temperatures and oxygen levels facilitate pathogen and organic matter removal from sewage sludge. Still metals and metalloids are typically left behind after these processes, rendering sewage sludge unsuitable for agricultural purposes, necessitating additional treatment for the obtained materials (Salkunic et al., 2022)

Composting is a biological aerobic process wherein microorganisms (bacteria, fungi, and actinomycetes) metabolize organic matter, leading to the reduction of the biodegradable fraction of the wastes into stable components suitable for application on land as organic fertilizer and soil amendment (Nafez et al., 2015). Traditionally, this fertilizer was used directly on land as it was considered a preferred method for nutrient recycling due to its recoverable nutrient content. However, this method has been restricted or banned in several European countries due to environmental risks associated with heavy metals, persistent organic pollutants, sludge pathogens and, mainly pharmaceuticals like hormones and antibiotics. As a result, nutrient recovery technologies that ensure the safety of the obtained product are now necessary (Robles et al., 2020).

CONVENTIONAL METHODS TO REMOVE AND RECOVER NITROGEN

Traditionally, nitrogen removal from wastewater has been the norm. However, recent emphasis on energy conservation, sustainability, and the circular economy has led to increased interest in nitrogen recovery from wastewater rather than simple nitrogen removal (Jose J., 2023). Nitrogen can be removed via physical, chemical, and biological processes to adhere to effluent concentration limits in municipal wastewater before its discharge back into natural watercourses. Table A4 provides a summary of various techniques for NH3/NH4+ ion removal, encompassing chemical precipitation, adsorption, and biological processes (Zhou et al., 2023).

Table A4. Advantages and disadvantages of available N removal methods (Zhou et al., 2023)

Method	Advantages	Disadvantages
Chemical Precipitation	• Produces valuable fertilizers at a moderate cost	• Requires additional Mg source • Incurs phosphate cost • Introduces new contaminants
Adsorption	• Simple and effective removal of NH_4 • Able to work at low NH_4 concentrations	• Adsorbents have different removal efficiencies
Biological method	• No need for chemical reagents and complicated configurations • High denitrification efficiency	• High costs • Requires external carbon source • Only operates at low input/output concentrations • Long start-up time

Biological processes are considered the status quo of removing N from wastewater due to their high efficiency in degrading pollutants and producing no secondary pollution. However, they are considered weary processes that consumes a lot of energy and requires additional carbon sources. In a conventional wastewater treatment plant, mainly equipped with secondary/biological treatment (after the activated sludge process), the removal of N involves biological processes driven by specific microbes. Here the reactive nitrogen (nitrate, nitrite, ammonium, and ammonia) is biologically converted to its non-reactive N_2 gaseous form which is then released back to the atmosphere. This occurs through the processes of nitrification, denitrification, anaerobic ammonium oxidation (Anammox) or nitrogen assimilation (Rahimi et al., 2020). Chemical methods function alike to those utilized for phosphorus, employing chlorination and magnesium ammonium phosphate hexahydrate (MAP) precipitation to effectively eliminate ammoniacal nitrogen. These methods typically boast straightforward operational procedures, swift reaction kinetics, and proficient denitrification. However, they are associated with high costs, labor intensiveness, and necessitate additional processing steps Furthermore, the physical techniques employed for nitrogen removal include ammonia stripping, ion exchange, and adsorption are still not cost-effective and demand high retention rates for organic pollutants. Additionally, they may lead to secondary pollution, necessitating further treatment measures (Zhou et al., 2023).

While various processes effectively remove nitrogen from wastewater, the loss of valuable ammonium often occurs. Traditional biological nitrogen removal methods do not facilitate ammonium recovery, leading to the release of gaseous N2O, a potent greenhouse gas, into the atmosphere. Consequently, there is growing interest in investigating methods to recover nitrogen from wastewater and transform it into a valuable product. Recovered nitrogen from municipal wastewater can be utilized as fertilizer, thereby reducing energy consumption and pollution associated with synthetic nitrogen fertilizer production (Jose J., 2023). As a result, many companies are prioritizing the development of technologies to directly recover nitrogen, bypassing the initial removal step.

Nevertheless, there are numerous nitrogen recovery strategies and technologies currently available for wastewater treatment in the same way as with P. Every type of wastewater stream present in a CWWTP, including inlet wastewater, sludge, digestate, and reject water, has unique properties that must be taken into account when designing the recovery technology. Usually, inlet wastewater is the stream with the least opportunity for recovering nitrogen because the concentration is very low. So, the recovery is more attainable during secondary/biological treatment. If the plant has anaerobic digestion of the sludge, N can also be recovered from the reject water from digestate (liquid phase left after the dewatering of anaerobically digested sludge) and digestate liquid left over from the anaerobic digestion. Alternatively, in non-digestion processes the reject water (the liquid portion post-solid-liquid separation) can contribute up to 30% of nitrogen load if recycled in the secondary treatment process. Since reject water presents high nitrogen concentrations (as ammonia), it is considered a significant stream if targeted for nitrogen recovery (Beckinghausen et al., 2020) (Figure A4)

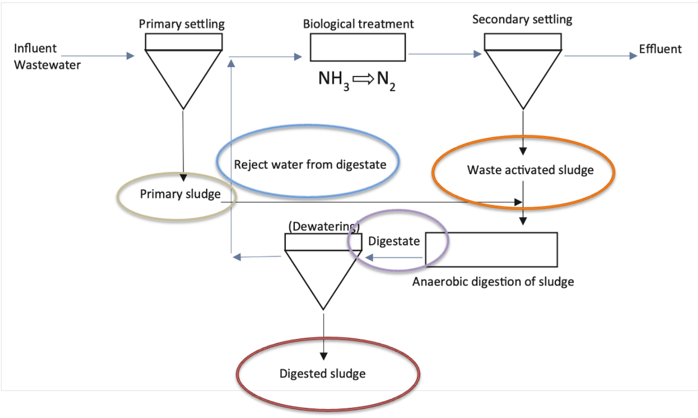


Figure A4. 8 Possible access points for N recovery in a CWWTP (Beckinghausen et al., 2020)

These technologies can generally be categorized into four strategies: direct recovery from wastewater or digester reject water, nitrogen concentration enhancement, urine or sludge treatment, and nitrogen incorporation into biomass. Figure A5 shows all available strategies possible to recover N along with the respective technologies (Van der Hoek et al., 2019)

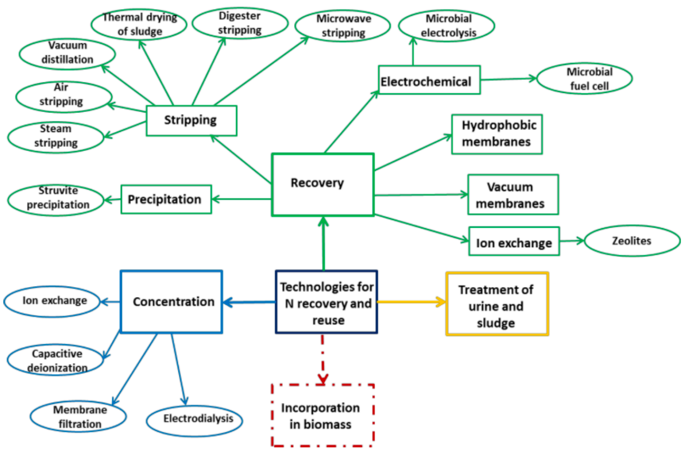


Figure A5. Overview of All various N-recovery technologies at lab, pilot, and plant scales (Van der Hoek et al., 2019)

However, the methodologies outlined in Figure A6 are currently undergoing pilot testing and implementation at plant scale. Ammonia stripping, MAP precipitation, and membrane technology are among the most widely adopted approaches (Jose J., 2023; Zhou et al., 2023).

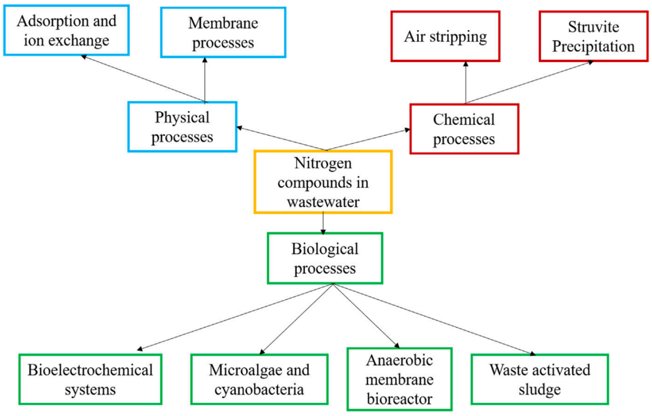


Figure A6. Overview of All various N-recovery technologies at pilot, and plant scales (Van der Hoek et al., 2019)

In Table A5 below, the most important characteristics of these three technologies are summarized: (Zhou et al., 2023)

Table A5. Nitrogen recovery technologies main characteristics (Zhou et al., 2023)

Method	Procedure	N-removal efficiency	Shortcoming	Recovery/effect factors needed	By-product
Ammonia Stripping	Through the difference in gas partial pressure, free ammoniacal nitrogen escapes from wastewater in a gaseous state	50-98%	• Large air consumption • High energy consumption • Secondary pollution. • Easy scaling	• Elevated pH levels • High temperatures • Ammonia concentrations exceeding 2000 mg/L	Ammonium sulfate
Struvite Precipitation (MAP)	By adding chemical reagents to form precipitation to achieve solid-liquid separation, to separate ammoniacal nitrogen	65-98%	• Requires additional phosphorus magnesium sources • Causes secondary pollution	• Requires high ammonia concentrations • Pre-treatment preparation needed	Struvite
Membrane Tech	Separation of nitrogen gas by selective ion permeation through membranes	64-99.8%	Membrane fouling and wastewater contaminants settle on the membrane surface, reducing the efficiency	• It can be operated at ambient temperature without a phase change. • Concentration and separation are performed concurrently • Addition of other substances is not needed	Ammonium salt fertilizer

AMMONIA STRIPPING

The stripping technology is a chemical process aimed at removing ammonium ions (NH4+) by converting them to ammonia gas (NH3) through air or gas injection into wastewater. This process involves four main steps:

- NH4+ conversion to NH3 gas,
- NH3 diffusion to the air-water interface,
- NH3 release to the air at the interface,
- NH3 diffusion from water interface into the air above.

Factors such as pH, temperature, and mass transfer area influence the process. NH4+ in wastewater can be released using air, steam, or biogas. Strippers can operate in continuous or batch mode. To prevent NH3 emissions and mitigate the greenhouse effect, NH3 is typically absorbed using phosphoric acid or sulphuric acid to form ammonium sulfate (AS). The recovered nitrogen is often used to produce fertilizer, typically as a 40%-60% ammonium sulfate solution with low organic contamination, directly from the effluent of the ammonia stripping process after pH neutralization. This technology can be beneficial for supporting agriculture, particularly in areas where nitrogen is required. However, the process only removes NH4+ and does not affect phosphorus and COD removal from wastewater (Rahimi et al., 2020), but it is a process that does not need the addition of too many chemicals.

STRUVITE PRECIPITATION

Struvite precipitation is a chemical method for removing NH4+ and phosphorus from wastewater. It is a straightforward, and eco-friendly process, but it has a lower ammonia recovery efficiency because it is more designed to capture phosphorus, so a lot of the ammonia is often left on the effluent. This process needs a continuous supply of chemicals to raise the pH of the solution (Jose J., 2023). Struvite crystals form through a reaction influenced mainly by the Mg: NH_4:P molar ratio and pH (optimal pH 9.0–10.0). However, it is commercially less widely used because it requires further processing (Rahimi et al., 2020).

MEMBRANES

Membrane technology plays a significant role in recovering nitrogen from wastewater treatment processes. It provides a range of benefits including improved water quality, energy savings, resource recovery, and environmental sustainability. Thus, the different membrane-based treatment schemes have the potential to overcome the challenges of nutrient recovery from wastewater and contribute to more efficient and sustainable wastewater management practices (Robles et al., 2020; Al-Juboori et al., 2022).

Some common membrane technologies used for nitrogen recovery from wastewater treatment include: (Al-Juboori et al., 2022)

Reverse Osmosis (RO): RO is a pressure-driven membrane process that can effectively remove nitrogen compounds, including ammonium ions, from wastewater by forcing the water through a semi-permeable membrane.

Membrane Distillation (MD): MD is a thermal-driven membrane process that can be utilized for nitrogen recovery by evaporating water through a hydrophobic membrane, leaving behind concentrated nitrogen compounds.

Gas Permeable Membranes (GPM): GPM technology allows for the transfer of gases, such as ammonia, across the membrane, enabling the recovery of nitrogen in the form of high-purity ammonium solutions.

Electrochemical Membranes (ECMs): ECMs utilize electrochemical processes to facilitate the separation and recovery of nitrogen compounds from wastewater streams, offering a sustainable approach to nitrogen removal.

Biologically Enhanced Membranes: Membrane technologies integrated with biological processes, such as anaerobic membrane bioreactors (AnMBR), can enhance nitrogen recovery by combining biological treatment with membrane separation.

Hybrid Membrane Systems: Combining different membrane technologies in hybrid systems can improve nitrogen recovery efficiency and address the limitations of individual processes, leading to enhanced nutrient recovery from wastewater streams.

APPENDIX 2

CURRENT COMMERCIAL TECHNOLOGIES TO RECOVER PHOSPHORUS

Pearl ® Ostara

This US patented technology was developed by the University of British Columbia, Canada, and it was first piloted at the Gold Bar Wastewater Treatment Plant in 2007 in Edmonton, Canada. Two years after, it was fully installed commercially for the first time at the Durham Advanced Wastewater Treatment Facility of Clean Water Services, Portland, Oregon (USA). The Pearl® technology provides cost effective nutrient recovery for reuse from pre-and post-digestion liquors, as well as industrial streams, through the controlled precipitation of crystalline struvite (Evoqua, 2024).

It has a production capacity of about 500 kg/day of struvite particles with sizes between 1.5mm and 4.5mm. Struvite crystals (Crystal Green®- high quality fertilizer) are recovered in a fluidized-bed reactor from a highly phosphorus concentrated influent (>100mg/L) (Kataki et al., 2016, Vu et al., 2023). The latest innovative process of the technology, the WASSTRIP™ system was designed to improve plant operations like implementing a turbo-charging nutrient removal and recovery in a controlled environment. The process helps to solve struvite operational issues like improving dewaterability and reducing biosolids production. The WASSTRIP (Waste Activated Sludge Stripping) process combines dewatered centrate with phosphorus and magnesium rich WAS filtrate (from a WAS P-Release Reactor) into the Pearl® process, increasing Crystal Green® production and reducing struvite in solids handling giving it a recoverable efficiency of up to 90% (Gysin et al., 2018, Latimer et al., 2022) (Figure A7)

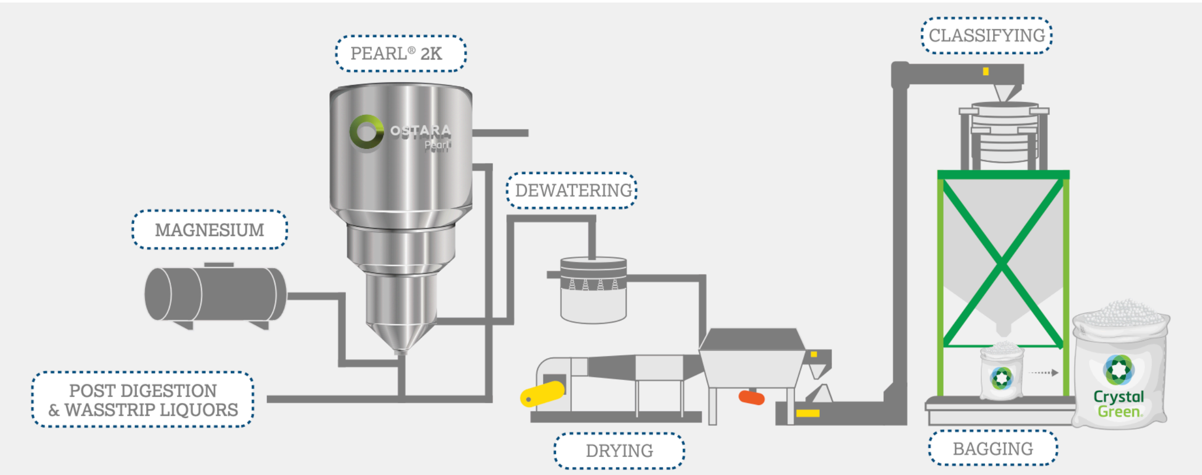


Figure A7. 1 Pearl Ostara Process. (Ostara, 2024)

MagPrex ™

MagPrex™is a nutrient recovery process from domestic and industrial wastewater owned by Centrisys/CNP (USA). The process forms struvite by using the soluble orthophosphate and ammonium present in the sludge. It adds magnesium chloride ($MgCl_2$) to increase the magnesium (Mg_2^+) which in the presence of oxygen (the system strips out the $CO^{2)}$) increases the pH forming struvite crystals that settles at the bottom of the reactor tanks. It has a couple of benefits (Wastewater Digest, 2022) (Figure A8):

- Improve sludge dewaterability.
- Reduce polymer consumption up to 30%
- Reduce maintenance up to 50%
- No sodium hydroxide required.
- Reduce struvite precipitation by harvesting, sequestration or centrate recovery.
- Up to 90% efficiency in recovering P.
- Reduce and stabilize nutrient loading in the return side stream to the wastewater treatment line

MagPrex is a cost-effective solution. It installs between the anaerobic digester and dewatering equipment. However, it does not specify if its compatible to work with different size wastewater inflows.

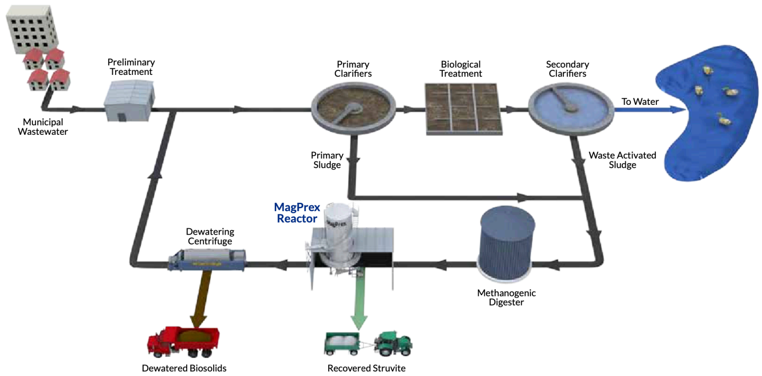


Figure A8. MAgPrex process (CentrysisCnp, 2022)

Crystalactor ™

This patented technology was developed by Royal Haskoning DHV in The Netherlands. This technology is different from the conventional precipitation, ion exchange or membrane filtration processes that removes P from wastewater. It is used along an enhanced biological nutrient removal (EBNR) treatment because it helps to reduce biosolids by 30% compared to EBNR only (Kataki, 2016). A Crystalactor fluidized bed reactor (Figure A9) is the main component which is partially filled with a suitable seed material such as sand or minerals and water that is pumped upward at an average speed of 40-100 m/h. Reagents (chemicals) are added to adjust pH and create saturation which will crystallize the target component(s) into high-purity crystals (pellets). These pellets need to dry in an open environment so there is no need for sludge dewatering, drying, or hauling of sludge which is considered as a sustainable advantage. Because of their high-quality composition, the pellets are typically recycled or repurposed in other facilities, leading to no residual waste requiring disposal. Should disposal of the pellets be necessary for any reason, their water-free nature results in low-volume secondary waste compared to bulky sludge. Hence, its zero-waste nature and cost-effectiveness render it a genuinely sustainable technology

(Giesen et al., 2009). Additionally, this technology boasts a small footprint as it consolidates multiple processes—including coagulation, flocculation, separation, and dewatering—within a single reactor (Ghosh et al., 2019).

Crystalactor water treatment technology can be used to treat water flows of all sizes, with an efficiency rate between 70% - 90%. It also removes many heavy metals and inorganic substances.

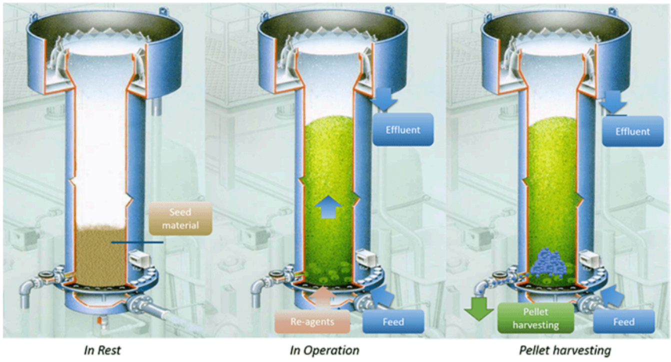


Figure A9. Crystalactor Process. (Royal HaskoningDHV, 2024)

Phosnix

The Phosnix process was developed by Unitika Ltd., and has been in operation in Japan since 1987. First full-scale implementation was done in 1998 in lake Shinji Eastern Clarification Center of Shimane Prefecture of Japan (Kataki et al., 2016). This technology can recover phosphorus from side streams of the wastewater treatment process (e.g. reject stream from membranes, supernatant liquid from sludge digesters, and the centrate/filtrate return stream from sewage sludge dewatering processes) (EPA, 2007) (Figure A10). The wastewater from sewage sludge is inserted into an aerated fluidized bed reactor from the bottom, along with magnesium hydroxide and NaOH to adjust pH to 8.2-8.8. Aeration allows the struvite crystals to act as seed material to encourage adherence of new particles and more crystal formation This technology requires less chemical supplementation due to its ability to transfer the effluent back to the initial wastewater treatment. It can treat influents of up to 1000 m^3 day $^{-1}$ with a PO_4-P recovery rate of 80–90%. Also, it is capable to produce between 500-550 kg/day of struvite; nonetheless, the recovered struvite is considered a raw material in the production of fertilizer so does need further processing before being commercialized (Ghosh et al., 2019).

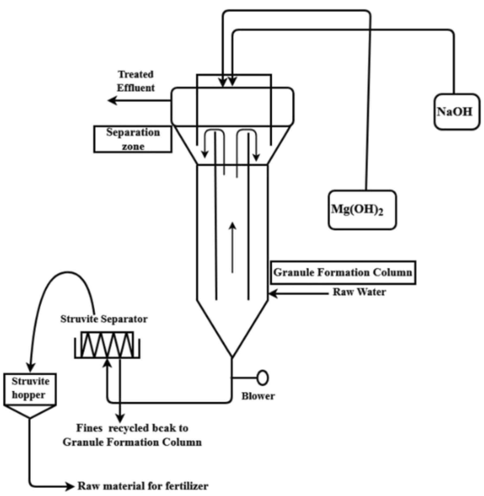


Figure A10. PHOSNIX process based on Ghosh et al., 2019.

Seaborn/Gifhorn

The Seaborne® process was developed in Germany by the Seaborne Environmental Research Laboratory back in 2000 to recover nutrients from digested sludge. This technology was first installed at large-scale in the wastewater treatment plant located in Gifhorn in 2007 with a treating capacity of about 1000 tons of dry sewage sludge (SS) per year, and it can treat ample water inflows of up to 600 mg/L (Vu et al., 2023). The Gifhorn site produces 270 kg struvite per day with a recovery rate of >90%. Due to the usage of diverse chemicals (H2SO4, Na2S, NaOH, MgO, flocculent), this process is not so cost efficient (Kataki et al., 2016).

This process treats and recovers phosphorus and nitrogen in the form of struvite (by chemical precipitation from supernatant) simultaneously removing heavy metals and cleaning digester gas. However, an additional process is needed to dispose of unwanted products (heavy metals) which increases operational costs (uses ion exchange to separate heavy metals from phosphate in the supernatant). In the diagram (Figure A11) below, this process is explained in more detail (Ye et al., 2017).

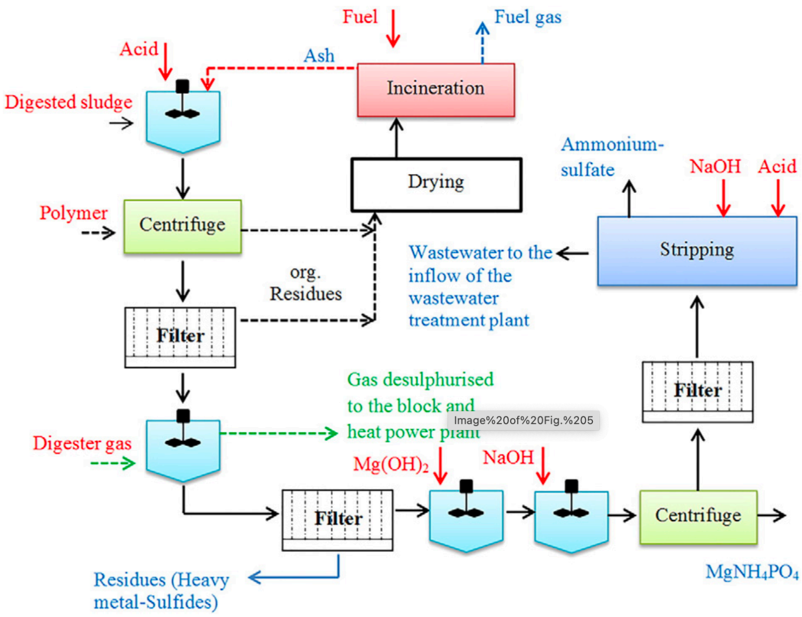


Figure A11. Diagram of Seaborn Process (Ye et al., 2017)

Struvia ™

The Sruvita Solution was developed by Veolia Water Technologies to recover phosphorus directly from medium to highly concentrated (50 mg/L) wastewater stream. An Struvia prototype unit was first implemented at the Brussels-North wastewater treatment plant in 2013 and 2014 where it has confirmed removal efficiency levels higher than 85 % (Salkunic et al., 2022)

In the presence of magnesium salt and with an increment to its pH, this technology induces precipitation of struvite from dehydrated anaerobic sludge, that is fed to a continuous stirred tank reactor (Turbomix™). This reactor encourages crystallization and growth of struvite pellets through a rapid mixing operation where an integrated lamella settler ensures the separation of the struvite, and the treated effluent is either returned for further treatment or discharged. The struvite pellets are recovered and store for packaging (Figure A12).

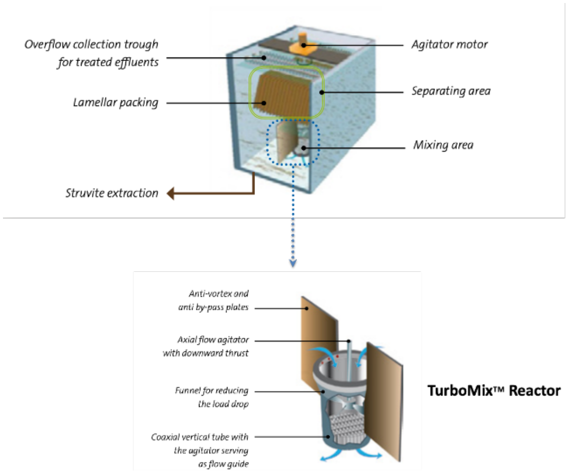


Figure A12. Struvia Process (Veolia Water Technologies (2024).

According to Veolia, this technology presents a lot of benefits. Among the most important ones are:

- Leads to a reduction in the production of sludge.
- Reduces operating costs by preventing dysfunctions like unplanned operation downtime costs caused by uncontrolled struvite precipitation that clogs pipes.
- Reduces the need to inject precipitation triggering reactive products like iron and aluminum salts.
- Requires a limited space and low maintenance.
- Struvita™ requires low operating costs and investment.

ANPHOS®

ANPHOS technology was developed by COLSEN, a family-owned company, in The Netherlands. It is documented that this process treats water with a minimum influent of about 50 mg/L and has so far accomplished about 93% of P-removal efficiency from anaerobic digester supernatant at a wastewater treatment plant in The Land van Cuijk. This technology is a batch process, use aeration to increase pH and precipitate struvite. It is composed of two separate reactors (Fig.…), a stripping tank and a reaction tank. The stripping tank is used for the aeration of wastewater to raise pH by stripping CO2 after which the water is pumped to the reaction tank where magnesium is added to promote the crystallization of struvite. Once settled in the reactor, struvite is transported to a dewatering device from where the final product is recovered. These pellets are a sand-like crystals with an average size of around 0.7 mm, however, they need additional processing to be applied as fertilizer (Ghosh 2019).

The overflow/treated effluent of the struvite system from the reaction tank can be either treated further or discharged (Colsen, 2024) (Figure A13).

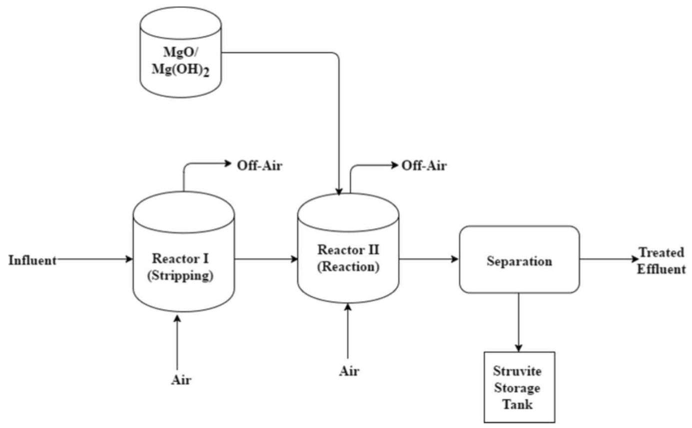


Figure A13. Anphos Process

Phospaq™

Phospaq technology has been developed also by a Dutch company named Paques, and currently operates in the city of Lomm (processes potato factory effluent) and at Oldburgen (processes dewatered sewage sludge effluent combined with the effluent from a potato factory) in The Netherlands. However, the technology has also been used in the UK at the Severn Trent's Stoke Bardolph wastewater treatment works for treatment of sludge dewatering liquor (Ghosh et al., 2019). Currently, the process presents a recovery efficiency that oscillates between 75% and 81% (Kataki et al., 2016).

The Phospaq is an aerated reactor system that precipitates struvite through the addition of MgO (magnesium oxide) and the stripping of CO^2 which maintains high pH levels between 8.2 and 8.3, simultaneously reducing COD. The crystallized struvite is harvested from the bottom of the aerated reactor producing struvite particles averaging 0.7mm in diameter. While decreasing the concentrations of heavy metals in the struvite pellets around 20 times lower than EU standards for fertilizers. Although the reactor is equipped with a patented internal separator to avoid flushing of fine particles, still this technology's main shortcoming is producing a lot of fine crystals that can be easily lost with the effluent (Figure A14) (Ghosh et al., 2019).

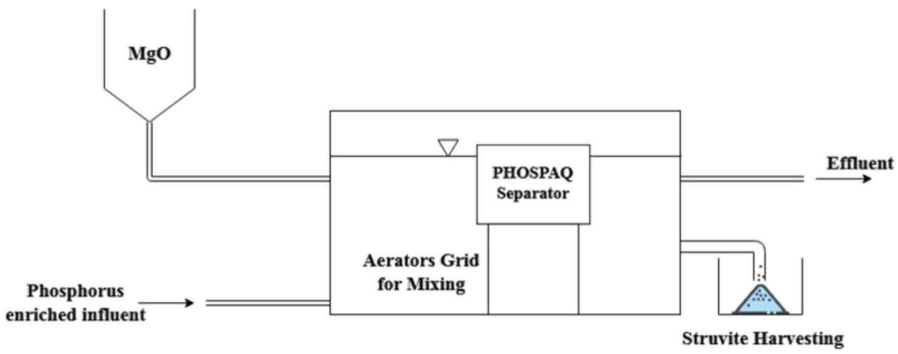


Figure A14. Phospaq process (Ghosh et al., 2019)

NuReSys®

Nutrient Recycle Systems (NuReSys) technology was developed by a Belgium company named Akwadok. This process recovers granular struvite that is precipitated between pH 8.5 and 8.7 which is controlled by the addition of NaOH and MgCl2 (magnesium chloride used as a crystallization agent). It recovers P from wastewater, digestate sludge, dehydrated digestion sludge or residual liquid after sludge dewatering (Ghosh et al., 2019) (Salkunic et al., 2022). This technology is equipped with a simple blade impeller, and it is operated in two reactors (one for air stripping and another for crystallization) (Ghosh et al., 2019) (Figure A15). Struvite pellets with an average diameter of 2-6 mm are collected by intermittent purging (Desmidt et al., 2015).

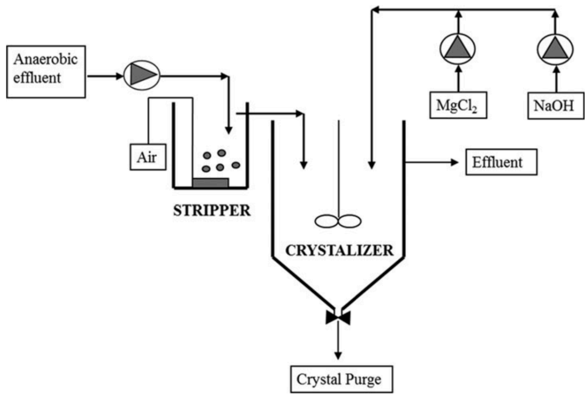


Figure A15. Schematic overview of the Nuresys process (anaerobic effluent of a WWTP is treated) (Desmidt et al., 2015)

In terms of recovery performance, it is reported that this technology could achieve 76% P-removal efficiency on a full-scale installation (potato processing), reaching up to 96% in the case of municipal wastewater (Ghosh et al., 2019). The struvite recovered from this process has been analyzed by an XRD test to verify its crystallographic structure, chemical composition, and physical properties and it has proven to be 100% struvite thus adapted for reuse as a fertilizer or as a soil conditioner.

Ash Dec®

ASH DEC Umwelt AG (Austrian company) was developed in 2009 but acquired by the German company Outotec in 2011, which has promoted the technology to industrial scale. It is a patented thermochemical process that eliminates heavy metals from sludge ash while it also allows for the recovery of nutrients from this ash (Figure A16). The first step involves the incineration of the sludge where all the organic pollutants are destroyed. The residual ashes have a high phosphorus content but still contain some heavy metals that were not completely removed. A second step comprises a thermochemical process where the ash is mixed with chemicals (MgCl2 and CaCl2) and exposed to high temperatures of around 1000 degrees Celsius to destroy left over heavy metals (mercury, cadmium, lead, copper, and zinc). This process incites a reaction that convert them to a gaseous state to be remove by an air pollution control system. After this thermochemical treatment, the phosphate output (treated ashes) is mixed with other nutrients to form fertilizer pellets containing (20–5–8 as N-P2O5- K2O) (Desmidt et al., 2015). The current recovery rate stands at around 90% since an average of 97% of all P present in the original dry sewage sludge ended up in the ash (Atienza-Martinez et al., 2014).

Under the licensed brand “PhosKraft”, these pellets are currently sold and used on pasture and cropland in Austria and Germany (Desmidt et al., 2015).

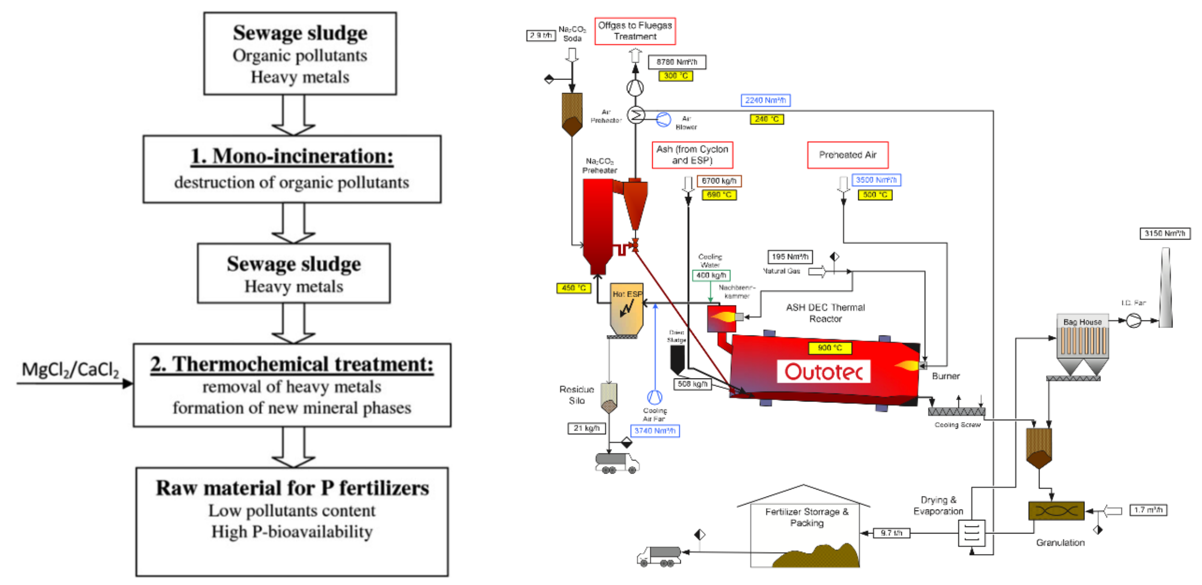


Figure A16. Ash Dec process (Hermann, L., 2024., Desmidt et al., 2015)

The main drawback of this technology is its high energy consumption, although this can be somewhat alleviated through careful process control. Nevertheless, a significant advantage is that the thermochemical process can also be applied to other phosphorus-rich ash sources. Thermal treatments are particularly suitable for less contaminated materials like manure, bones, and food waste. Despite their potential, none of these hydrothermal processes have not been fully adopted yet (Salkunic et al., 2022).

CURRENT COMMERCIAL TECHNOLOGIES TO RECOVER NITROGEN

The companies that are currently more established in the business of nitrogen recovery from wastewater treatment plants and fertilizer production from the recovered nitrogen are:

Colsen (AMFER®)

Nitrogen recovery using the AMFER® technology is optimal to treat wastewater streams with elevated ammonium levels. The unique stripper design, AMFER® can effectively treat highly contaminated flows, including thin manure or digestate, without the need for dewatering or pre-treatment. This heavy polluted wastewater is handled more efficiently by a proprietary aeration field and distribution system included in the stripping tank. The AMFER® process is conducted in a single batch step, where CO2 and ammonia (NH3) are sequentially stripped from the substrate in a dedicated column. The stripping air is then directed through a gas scrubber, resulting in the production of either ammonium sulphate or ammonium nitrate. Among some of the advertised advantages of AMFER® Technology (Colsen, 2024) (Figure A17) are:

- Energy-efficient processing of large nitrogen quantities.
- Lower energy consumption compared to nitrogen oxidation methods.
- Production of valuable artificial fertilizer.
- Enhanced capacity for feeding high-nitrogen co-substrates to digesters.

- Simplified discharge of residual flows in manure processing and biogas systems.
- Pasteurization capabilities within the same system.

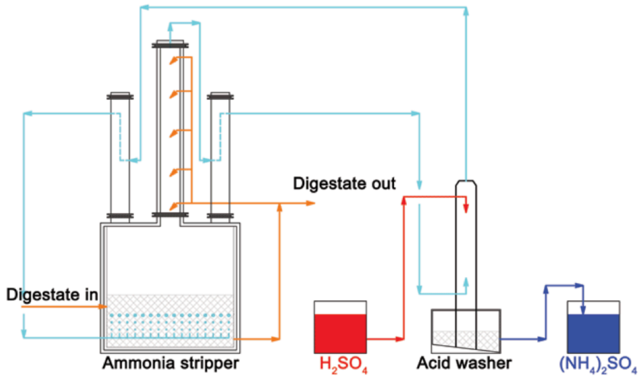


Figure A17. Amfer Process (Nutriman, 2021)

Nijhuis Industries (ByoFlex®)

The ByoFlex® system developed by Nijhuis Industries in The Netherlands is an ammonia stripping unit. It has been developed for highly concentrated and difficult substrates such as digestate or heavily polluted wastewater up to 15% dry matter (suspended and dissolved solids) without separation or filtration. The system can serve as a method for removing ammonia from wastewater to meet targeted nitrogen (ammonia) thresholds and broader effluent criteria. The efficiency of ammonia stripping relies significantly on digestate temperature, pH level, and electrical energy usage. Typically, achieving a N-NH4 recovery rate of 70-75% shows an optimal balance between operational and capital costs, although higher removal rates are achievable with certain adjustments. These adjustments may involve the use of extra chemicals (typically not needed), elevated temperatures, or increased electrical energy consumption, tailored to specific circumstances for optimal design. In many instances, the payback period can be less than 2-3 years.

This device is easy to clean and ensures hardly any clogging of the internal parts. The process (Figure A18) starts by pumping the substrate into the top and exposed to air in counterflow mode. Before entering the stripper, the substrate may undergo heating in a tube-in-tube heat exchanger or pH adjustment using an alkaline agent or optional CO2 stripping, or a combination of both methods.

Ammonia (NH3) is absorbed by the air, which is then directed through two ammonia scrubbers where the ammonia is removed using sulfuric acid and water, resulting in the formation of ammonium sulfate. This process yields a transparent, liquid, pH-neutral ammonium sulfate solution containing 8% nitrogen and 40% dry matter, suitable for use as fertilizer. The cleaned air is recycled back into the stripper and all operating columns maintain nearly identical temperatures. In a moist environment, gaseous ammonia (NH3) is in equilibrium with ammonium (NH4+). At higher temperatures or pH values, the formation of ammonia is favor and can be captured by the air. These parameters are crucial for designing the ammonia stripper (Byosis, 2022)

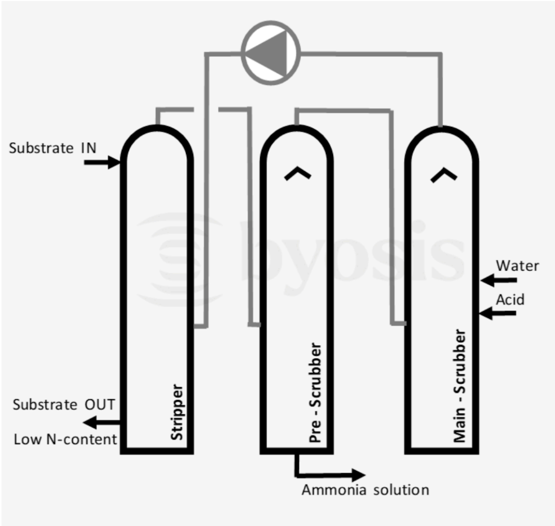


Figure A18. ByoFlex Process (Byosis, 2022)

For instance, an advantage of the ByoFlex® system is that it can be used as a pre-treatment system (Figure A19) for further processing of substrates, particularly when combined with biological treatment systems like conventional Nitrification/Denitrification or Membrane Bio Reactor with Reversed Osmosis. Nitrogen removal often dictates the sizing of these methods, influencing plant size, sludge production, and the requirement for a carbon source for bacteria. By decreasing the ammonium content of effluent using a ByoFlex® system, these systems can be constructed more compactly, leading to reduced operational expenditures.

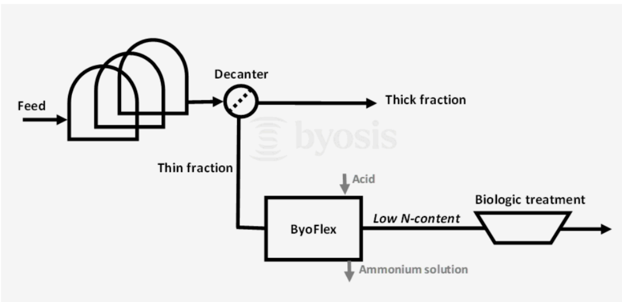


Figure A19. ByoFlex process as a pre-treatment system (Byosis, 2022)

APPENDIX 3

ASSESSMENT OF COMMERCIAL NUTRIENT RECOVERY TECHNOLOGIES

Commercial Techs to recover P & N	Recovery Mechanism	Energy consumption	Removal & Recovery Efficiency	Influent P/N concentration (mg/L)	Biological Treatment Required	Cost Effectiveness	Operational costs incurred by:	References
Pearl Ostara	Precipitation/ Crystalization	1.6 Kwh/kg P recovered	> 80%	100 -900	yes	yes	Chemicals - Mg. salts - sodium hydroxide	Desmidt et al., 2015, Gysin et al., 2018
MagPrex	Precipitation/ Crystalization	N/A	90%	N/A	yes	no	Chemicals - $MgCl_2$ - No Sodium Hydroxide	CentrysisCnp (2022), Wateronline (2022)
Crystalactor	Precipitation/ Crystalization	Only needs 1 reactor	70%-90%	60-80	yes	yes	Chemicals - Lime - Calcium - Chloride - Caustic soda	Desmidt et al., 2015, International water mine conference (2009)
Phosnix	Precipitation/ Crystalization	Aeration needed – high energy consumption	80%-90%	100-110	yes	yes	Less chemicals (Mg hydroxide, NaOH) – recycling of chemicals	Desmidt et al., 2015
Seaborne Gifhorn	Precipitation/ Crystalization	A lot of processes involved - high energy consumption	> 90%	600	yes	no	Chemicals - H2SO4 - Na2S - NaOH - MgO - Flocculents	Ye et al., 2017
Struvia	Precipitation/ Crystalization	Only needs 1 reactor	> 85%	50	yes	yes	Chemicals - Mg. salt - No reactive chemicals added like iron and aluminium salts	Salkunic et al., 2022 Veolia water Technologies (2024)
ANPHOS	Precipitation/ Crystalization	Aeration + 2 Reactors – high energy consumption	80%-90%	50	yes	no	Chemicals - Mg.	Ghosh et al., 2019
PHOSPAQ	Precipitation/ Crystalization	Aeration needed	75%-81%	60-65	yes	no	Chemicals - MgO	Kataki et al., 2016
NuReSys	Precipitation/ Crystalization	2 Reactors	85%	60-150	yes	no	Chemicals - NaOH - MgCI2	Desmidt et al., 2015
Ash Dec	Thermal incineration	High energy consumption. Electrical and heat Temp required (850 °C - 1.000 °C)	90%	N/A	no	no	Additives - Na2SO4 - NaHCO3 - Na2CO3 Lower chemical consumption	Salkunic et al., 2022 Uldrich et al., 2020
BYOFLEX & AMFER	Ammonia Stripping	Aeration needed Lower energy consumtion compared to other N oxidation methods	50-98%	> 40	No – but less opportunity to recover	no	Chemicals - Alkaline agent - Sulphuric acid	Rahimi et al., 2020 Byosis (2022)

APPENDIX 4

INTERVIEW DOCUMENTS USED FOR LOCAL STAKEHOLDERS

Preguntas abiertas para entrevistas con actores: Primera ronda

Proyecto: Recuperación de Productos (Nitrógeno y Fosforo) de las aguas servidas tratadas en la PTAR Las Esclusas, Guayaquil

Plant Owners:

- ¿Me puede proporcionar con algunos datos técnicos?
    - Cantidad de agua en el afluente
    - ¿Qué clase de tratamientos tiene la planta?
    - ¿Tiene alguna idea de cuanto P y N entra en el afluente?
- ¿Cuál es su conocimiento en cuanto a fertilizantes producidos con nutrientes recuperados de aguas servidas tratadas en una planta de tratamientos de agua?

- ¿Dentro de la PTAR que tan difícil seria implementar técnicamente un sistema de recuperación de nutrientes (Fosforo y Nitrógeno) que servirían como materia prima para la producción de fertilizantes?

- ¿Cuáles serían los impactos positivos y negativos en la implementación de un sistema para la recuperación de nutrientes del agua servida en la PTAR Las Esclusas?

- ¿Habría ganadores y perdedores si se implementase un sistema de recuperación?

- ¿Cuáles serían barreras y oportunidades en un proyecto de recuperación de nutrientes en la PTAR Las Esclusas? A qué nivel: social, económico, técnico, medio ambiente, legislación.

- ¿Usted piensa que si valdría la pena implementar un sistema de recuperación de nutrientes en la PTAR Las Esclusas?

Academia:

- ¿Conoce de casos de recuperación de recursos (energía, nutrientes etc) de aguas servidas en el Ecuador? ¿SI hay casos, en que áreas se están implementando estos procesos circulares?

- ¿Qué tan difícil seria de implementar estos procesos circulares dentro de la recuperación de nutrientes de las aguas servidas en el Ecuador?

- ¿Cuáles serían las barreras que impedirían su aplicación? ¿Cuáles serían las oportunidades que promulgarían el desarrollo de estos procesos circulares?

- ¿Tiene usted conocimiento sobre la industria de los fertilizantes en Ecuador? ¿Como es la demanda y la oferta?

- ¿Cuál es su conocimiento en cuanto a fertilizantes producidos con nutrientes recuperados de aguas servidas tratadas en una planta de tratamientos de agua?

- ¿Qué riesgos piensa usted que pueden existir? ¿A qué nivel? Social, económico, medio ambiente, legislación.

- ¿Cuáles creería usted que sean las barreras que impedirían la comercialización de estos productos? ¿De igual manera cuales serían las oportunidades que ayudarían a la comercialización de estos productos?

- ¿Cree usted que estos proyectos valen la pena ser investigados?

User:

- ¿Cuántos kilos de fertilizante utiliza usted al año?

- ¿Cree que los agricultores usarían fertilizante producido con materia prima recuperada de la planta de tratamientos de agua? ¿En qué condiciones lo aceptarían?

- ¿Cuáles creería usted que sean las barreras que impedirían la comercialización de estos productos? ¿De igual manera cuales serían las oportunidades que ayudarían a la comercialización de estos productos?

Gente del público y asociaciones de agricultura urbana:

- ¿Si usted supiera que un cierto producto fue crecido con fertilizante elaborado a base de nutrientes (Nitrógeno y Fosforo) recuperados de la planta de tratamientos de aguas servidas, usted lo compraría? ¿En qué condiciones lo aceptaría?

Institutions:

- ¿Hay iniciativas que incentiven la implementación de proyectos circulares en el Ecuador?

- ¿Conoce usted sobre la existencia de legislación relacionada a estas iniciativas circulares?

- ¿Cree usted que habría interés en promover e incentivar estos proyectos sostenibles en un futuro?

- ¿Cuáles creería usted que sean las barreras que impedirían el desarrollo de estos proyectos circulares? ¿De igual manera cuales serían las oportunidades que ayudarían a promover la recuperación de nutrientes de las aguas servidas?

Preguntas para entrevistas con todos los actores: Segunda ronda

Aceptabilidad de productos finales:

- ¿Está dispuesto usted a apoyar la producción, el uso y/o utilización de fertilizantes que contengan nutrientes recuperados del agua residual?

- ¿Está dispuesto usted a apoyar la producción, el uso y/o utilización de fertilizantes que contengan nutrientes recuperados del agua residual en forma de estruvita? Este producto se deriva del proceso de Precipitación/cristalización.

- ¿Está dispuesto usted a apoyar la producción, el uso y/o utilización de fertilizantes que contengan nutrientes recuperados del agua residual en forma de nutrientes procedentes de las cenizas de lodo? Este producto se deriva del proceso de incineración del digestato.

- ¿Está dispuesto usted a apoyar la producción, el uso y/o utilización de fertilizantes que contengan nutrientes recuperados del agua residual en forma de sulfato de amonio? Este producto se deriva del proceso de desnitrificación por stripping de amoníaco.

- ¿Tiene requisitos de calidad específicos para utilizar estos fertilizantes?

- ¿Estaría usted dispuesto a pagar más por fertilizante recuperado de aguas residuales que por el fertilizante químico convencional disponible en el mercado?

- ¿Qué más cree usted que se necesitaría para que se acepte usar estos fertilizantes?

- ¿Cuáles serían puntos positivos y negativos que afectarían su aceptación de estos productos?

Respaldo institucional:

- ¿Considera usted que hay respaldo institucional que promueva la recuperación de nutrientes de aguas servidas? ¿sabe usted si hay un presupuesto dedicado en esta área para la implementación?

- ¿Que sería necesario para que haya más respaldo institucional dentro del ámbito de recuperación de recursos de desechos sólidos y líquidos? ¿Qué otra forma de respaldo se necesitaría?

Colaboración institucional:

- ¿Conoce usted si hay eventos, una red nacional en donde se comparta o se haya compartido conocimiento dentro de la recuperación de recursos de desechos sólidos y líquidos?

- ¿Quiénes son participes de estos eventos?

- ¿Que sería necesario para que haya más colaboración institucional dentro del ámbito de recuperación de recursos de desechos sólidos y líquidos? ¿Qué otra forma de respaldo se necesitaría?

Capacidad Institucional:

- ¿Cree usted que las leyes existentes son compatibles con las leyes que serían necesarias para la implementación de sistemas de recuperación de recursos de desechos sólidos y líquidos?

- ¿Que sería necesario para que haya mejor capacidad institucional dentro del ámbito de recuperación de recursos de desechos sólidos y líquidos?

- ¿Cree usted que los funcionarios que están a cargo de emitir reglamentos, normativas que promuevan la implementación de sistemas de recuperación de recursos de desechos sólidos y líquidos tienen el suficiente conocimiento?

EMPIRICAL DATA OBTAINED FROM INTERVIEWS WITH LOCAL STAKEHOLDERS

1ST ROUND INTERVIEWS

Type of stakeholder	Topics raised
Plant owners	○ Environment- renewable energy, energy & chemical consumption, energy scarcity. Discharge of phosphorus and nitrogen to the river
	○ Technical – recovery efficiency/nutrient recovery potential. Lack of technical expertise
	○ Economic – costs constraints. High cost for energy
	○ Social/Governance – institutional capacity and compatibility (legislation). Be aware of culture. Low-income country
Academia	○ Environment- GHGEs, linear thinking, renewable energy, energy & chemical consumption, energy scarcity
	○ Technical – current infrastructure not justified. Plant is not conditioned to recover nutrients.
	○ Economic - needs to create an artificial demand. Current products that are in the market are cheaper. High costs for chemicals. EMAPAG is not authorized to sell energy. Scarcity of fertilizers and energy in the country.
	○ Social/Governance- compatibility with current legislation is LOW. Lack of interest from institutions. Acceptability from users important. Corruption.
Vendor & User	○ Environmental – chemical pollution of soils
	○ Technical - Ownership of the technology – who controls it?
	○ Economic - Fertilizer Industry has a monopoly. High prices for fertilizers. Affordability is low.
	○ Compatibility with current legislation is LOW. The "system" does not care, lack of farmer's influence on the market for fertilizers. Lack of support from the government towards farmers. Concerns about Health & Safety of by-products. Culture – protect "crops" at the expense of soil depletion. Lack of knowledge behind the use of fertilizers
	○ Environmental - depressed soils – indiscriminate use of chemical fertilizers. Decrease in efficiency of soils

	○ Technical - lack of technical knowledge regarding the science of fertilization among farmers
	○ Economic – prices are high since chemical fertilizers are imported
	○ Social/Governance - no coordination/cooperation among institutions to support and share its expertise. Empowerment of farmers – Job security and creation. Health & safety important aspect
Institutions	○ Environment – linear thinking (sewage water treated as waste). Circular economy only practiced for solid waste management. Energy scarcity – recovering biogas from landfills
	○ Economic – costs are very important. Energy scarcity
	○ Social/Governance - compatibility with current legislation is LOW. Non-existent. ○ There is NO support to promote circular economy projects. Its more about how to get rid-off the waste (sludge)

2ND ROUND INTERVIEWS

Type of stakeholder	Topics raised	Related aspects to Institutional suitability	Related aspects to acceptability of end products
Academia	Discharge limits in the effluent of nutrients like P & N are too high. There is no motivation to do anything Allowable discharge limits are wrongly measured. Authorities (Tulsma) do not consider the different flow rates of the river and only provide the concentration in mg/L without considering that the pollutant load would change based on the different flow rates that	○ Quality of legislation is mediocre ○ Institutions do not work together	○ Incentives like certification for end-products are needed ○ Costs are very important

	differ during dry and wet seasons. Implement certification (ISO 59004, BS8001) for commercialization. Give added value. Too much corruption		
Plant Owners	Implementing co-generation to produce electricity still on revision – Biogas is being burned These experiments are done only internally by Veolia (InterAgua) Legislation does not exist yet Legislation and regulations are needed EMAPAG verifies discharge limits of water to rivers. These limits need to get more stringent to create incentives Too much corruption	○ Non-compatibility with current legislation ○ Institutions do not share information ○ Quality of legislation is mediocre ○ Circular economy initiatives are not supported now	○ Lack of knowledge among the public about residual water. People are more afraid due to the connotation of being from sewage water. Awareness is crucial ○ Sanitary certification will be needed ○ Costs are very important
Institutions	Ecuador is behind compared to other countries in the same continent Disconnection among public entities Farmers do not have access to financial support Lack of interest among enterprises. Do not want to pay extra for extra processes Government is not paying attention. There is no cooperation among ministries that	○ Lack of institutional capacity to promote new initiatives ○ No government support ○ No cooperation or collaboration among ministries ○ Lack of legal framework	

	should collaborate to promote these initiatives Public Institutions are more concerned/occupied with everyday administrative problems. There is no time or capacity to promote new initiatives Central government does not provide a playing field Private and NGO sectors are little by little promoting CE projects Main priority of water institutions to increase coverage of potable water and sewage connections No legislation regarding circular economy initiatives in the context of water preservation. More concern to learn about flood prevention Political context: trend towards spending on quick, visible public works that gives politicians votes for reelection. Corruption Ministry of Finance when assigning budget there is no control of where the money is spent There is no water rectory, no clear rules. There is terrible setback. Weak institutional capacity, support, collaboration.		
Vendor & User	More prompt towards using organic products from fertilizantes to	○ Institutional support at all levels (monetary,	○ Past experiences w/similar products (organic based)

	pesticides due to positive experienes. Better for soil quality, performance and sustainabilty of it. Concern about composition of the recovered product – must have certification (free of pathogens and heavy metals). Supports a transparent offer of these products Benefits vs. costs needs to be assessed. There should be support from institutions like subsidies from government to influence the price. Perhaps redirect some money from the utilities bill towards these initiatives Lack of legislation, support, control. Inflated fertilizer prices – nobody controls Dissemination of information is necessary so the end-user is well informed Use depends on Important aspect: Ownership of the technology. Who will control it? There is no culture of protecting the enviroment over satisfying a neccesity Lack of farmer’s influence on the market for fertilizers Overuse of chemical fertilizers affects the soil	know-how) is almost non-existent	○ Agricultural expertise/ Level of knowledge ○ Subsidies might be needed ○ End-user needs to be well informed ○ Level of subsidies allocation ○ Country’s income level ○ Type of culture (monetary welfare over environmental welfare) ○ Costs are very important

	condition. Lack of knowledge There is a monopoly (chemical fertilizer producers). Control the price. Tend to increase exponentially without reason Complete negligence from governmental institutions. No control, no support		

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