# UNIVERSITAT POLITÈCNICA DE VALÈNCIA

## Escuela Técnica Superior de Ingeniería de Caminos, Canales y Puertos

# Cuantificación de diferentes escenarios del nexo agua-alimentos-energía para el tratamiento y reutilización de aguas residuales en un sistema de tratamiento basado en microalgas.

Trabajo Fin de Máster

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# Abstract


This thesis explores the quantification of different Water-Food-Energy (WEF) nexus scenarios within a microalgae-based wastewater treatment and reuse system. Analyzing a real existing Wastewater Treatment Plant (WWTP), we focused on energy consumption and production, biofertilizer production, microalgal and nutrient valorization, and sludge management within the WEF nexus framework.

Two scenarios were considered to estimate the potential WEF Nexus implementation: Scenario 0 depicts conventional treatment where nitrogen and phosphorus removal meet discharge standards, with no water reuse. Potable water is sourced from groundwater, and there is no in-house fertilizer production. Scenario 0 is analyzed to identify potential optimization solutions for existing installations, incorporating evaluations of the agricultural sector and energy consumption. Scenario 1 involves combining conventional activated sludge (CAS) treatment with microalgal cultivation, where a portion of settled wastewater is diverted to the HRAP. Reclaimed water and biofertilizer produced in HRAP are utilized to meet the needs of tomato crops. Scenario 1 introduces sustainable strategies based on microalgae cultivation to optimize water, food, and energy resources, minimize environmental impacts, and outline areas for further research.

Our study reveals that implementing the WEF nexus enhances integration among water, energy, and food systems. Specifically, Scenario 1 demonstrated a significant 34% reduction in net energy consumption compared to Scenario 0, with a modest 24% decrease in energy production. Reusing HRAP-reclaimed water for drip irrigation across various scales resulted in substantial energy savings of approximately 63%.

Scenario 1 shows a 34% reduction in net energy consumption compared to Scenario 0, with significant energy savings of approximately 63% through HRAP-reclaimed water for irrigation. This approach reduces reliance on groundwater and enhances resource efficiency.

While nutrient recovery increased modestly (2% for Nitrogen, 3% for Phosphorus) in agriculture, further research is needed to optimize productivity within the WEF nexus framework.

This study underscores the importance of sustainable practices in wastewater treatment and resource management amid environmental and agricultural challenges.

# List of abbreviations

AD. *Anaerobic Digestion*

$BOD_5$. *Biochemical oxygen demand over a 5-day period*

CAS. *Conventional activated sludge*

CE. *Circular Economy*

CHP. *Combined heat and power*

COD. *Chemical Oxygen Demand*

COVID-19. *Coronavirus disease 2019*

DS. *Decision support*

EU. *European Union*

HRAP. *High Rate Algal Pond*

HRT. *Hydraulic retention time*

KPI. *Key Perfomance Indicators*

MPBR. *Membrane photobioreactor*

$N\text{-}NH_4$. *Ammonium nitrogen*

$N\text{-}NO_2$. *Nitrous nitrogen*

$N\text{-}NO_3$. *Nitric nitrogen*

p.e.. *Population equivalent*

PNA. *Percent Nitrogen Absorption*

$P\text{-}PO_4$. *Orthophosphate phosphorus*

RA. *Rapid Audit*

$SO_4$. *Sulphates*

SRT. *Solids Retention Time*

SS. *Suspended Solids*

TN. *Total Nitrogen*

TP. *Total phosphorus*

TPE. *Total Pollution Equivalent*

TSS. *Total suspended solids*

UNICEF. *United Nations International Children's Emergency Fund*

WRRF. *Water resource recovery facility*

WTEI. *Wastewater treatment energy index*

WW. *Wastewater*

WWT. *Wastewater treatment*

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# 1. Introduction

## 1.1. Water, Food and Energy as indispensable resources

Water is a resource of paramount importance, essential in myriad ways for our lives and the world around us. It is intricately linked to the productivity of natural resources and ecosystems, serving as a cornerstone for their health and functionality (Miralles-Wilhelm et al., 2016). This indispensable substance is required for all living organisms to live, develop, and reproduce, with human beings being no exception. Beyond these fundamental biological needs, water plays a critical role in ensuring food security by supporting agricultural activities and livestock. It is a key driver of industrial production, facilitating various manufacturing processes, and it is crucial for conserving biodiversity and maintaining environmental balance.

Additionally, water is a foundational element for the energy sector. It is vital for the production and transmission of energy, including hydroelectric power generation, cooling in thermal power plants, and as a necessary input in various renewable energy technologies. The interdependence between water and energy systems underscores the importance of integrated resource management (Klein et al., 2016).

Despite its critical importance, water has increasingly become a scarce commodity due to several factors. The growing human population has led to higher demand and consumption of water, straining available resources (Chakkaravarthy Dhanasekaran et al., 2019). Neglect and over-exploitation of water resources, along with pollution and inefficient management practices, have further exacerbated this scarcity. Climate change also contributes to the variability and unpredictability of water availability, compounding the challenges of water management.

The cumulative effect of these pressures means that what was once an abundant and freely available resource is now under significant threat. This situation needs urgent and sustainable management practices to preserve water availability for future generations. Strategies such as improved water use efficiency, pollution control, and the development of sustainable water supply systems are essential to address these challenges. By adopting a holistic approach to water management, we can ensure that this vital resource continues to support life and human activities in the years to come.

Measures of water scarcity indicate that 4 billion people currently experience water shortages for at least one month each year (Mekonnen et al., 2016). This issue is projected to worsen due to increasing population pressure, changing water consumption behaviours, and the impacts of climate change, making it increasingly challenging to maintain water consumption at sustainable levels.

According to the United Nations, current and future drivers of water scarcity could result in a scenario where, by 2025, over 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the global population will be facing water-stressed conditions. UNICEF estimates that by 2030, approximately 700 million people could be displaced due to severe water scarcity. Furthermore, by 2040, roughly one in four children worldwide is expected to live in areas of extremely high water stress.

From this perspective, water scarcity is an increasingly widespread issue, affecting a growing portion of the world's population. It stands as a significant global threat alongside other critical risks such as climate change and potential pandemics, underscoring the urgent need for sustainable water management and conservation efforts. Effective strategies must include improving water use efficiency, implementing advanced water recycling and reuse technologies, enhancing the resilience of water supply systems to cope with the anticipated challenges, and develop innovative water governance that include efficiency as priority. Without these measures, the global community will face profound socioeconomic and environmental consequences (United Arab Emirates Ministry of Foreign Affairs report, 2023).

The alarming issue of water scarcity is deeply intertwined with the agricultural sector. The majority of water resource —70%—is consumed in agriculture (which includes livestock, aquaculture, and forestry) (FAO, 2020). In some less developed countries, this figure reaches a surprising 90% (FAO, 2018). Recent estimates indicate that between 702 and 828 million people worldwide, corresponding to 8.9 to 10.5 percent of the global population, faced hunger in 2021. Food insecurity was already a pressing issue, but the COVID-19 pandemic exacerbated the situation, leaving humanity struggling to recover. Projections suggest that nearly 670 million people will still be undernourished by 2030—78 million more than in a scenario where the pandemic had not occurred. Additionally, the war in Ukraine has significant implications for global agricultural markets through disrupted trade, production challenges, and fluctuating prices, further threatening food security and nutrition for many countries in the near future (FAO; IFAD; UNICEF; WFP; WHO, 2022).

Additionally, the ongoing war in Ukraine has significant implications for global agricultural markets, affecting trade, production, and prices. Ukraine and Russia are major exporters of key commodities such as wheat, maize, and sunflower oil. Disruptions in their production and export capacities have led to increased volatility in global food prices, further exacerbating food insecurity and nutrition challenges in many countries. This conflict casts a shadow over the state of food security and nutrition, particularly in regions heavily reliant on these imports, complicating efforts to address hunger and undernourishment (FAO; IFAD; UNICEF; WFP; WHO, 2022).

Although the overarching theme is humanity's ongoing dependence on fossil fuels, the current energy crisis is also driven by the aftershocks of the COVID-19 pandemic, recent geopolitical events, unfavorable weather conditions, and underinvestment in green energy sources. The aforementioned recent conflict in Ukraine has disrupted energy supplies from Russia, a major supplier of natural gas and oil to many countries. This disruption has resulted in skyrocketing energy prices and has not been offset by equivalent actions from governments to introduce clean alternatives or diversify energy sources (IEA, 2021). The failure to transition to renewable energy solutions exacerbates the vulnerability of global energy markets and highlights the critical need for sustainable energy policies and investments.

While many countries have made public pledges to achieve net zero emissions by 2030, these commitments often lack the necessary government spending and policy support to be effective. Despite the ambitious goals, the practical implementation has been insufficient, leaving a significant gap between policy and action (IEA, 2021).

The surge in fossil fuel prices has exacerbated this issue by sharply increasing the cost of energy production. Globally, these increased costs have been passed on to consumers in the form of higher energy bills, significantly contributing to the cost-of-living crisis felt around the world. This situation has underscored the urgent need for substantial investment in renewable energy infrastructure.

A transition towards more sustainable energy practices is essential to mitigate future energy crises and ensure long-term energy security. Investing in renewable energy sources, such as wind, solar, and hydropower, is critical for reducing dependency on fossil fuels and achieving climate goals. Additionally, enhancing energy efficiency measures and supporting technological innovation in the energy sector are vital steps toward a more resilient and sustainable energy future.

This complex scenario demonstrates the interdependence of water, food, and energy systems and the necessity for comprehensive strategies that address these challenges collectively. By prioritizing sustainable practices and fostering international cooperation, we can enhance resilience against future crises and work towards a more secure and sustainable future.

## 1.2. Nutrient Scarcity (P and N)

Nutrient scarcity, particularly of phosphorus (P), presents a significant challenge for global food security and environmental sustainability. Nitrogen (N), on the other hand, is obtained from the air, but its extraction process consumes a significant amount of energy. Both elements are crucial for plant growth and agricultural productivity, yet their availability and efficient use are under threat due to a combination of factors.

### 1.2.1. Nitrogen

Nitrogen nutrition is a critical factor influencing crop productivity, significantly impacting plant physiology, growth, metabolism, and root morphology (Muratore et al, 2021). The varying availability of nitrogen nutrients in soil—both inorganic forms like nitrate and ammonium, and organic compounds such as urea and free amino acids—can profoundly affect these processes. In agricultural soils, nitrogen availability frequently limits crop productivity. Consequently, there is widespread global use of nitrogen fertilizers, despite their negative impacts on ecosystems and significant socioeconomic costs (Muratore et al, 2021). This is largely due to the overuse of fertilizers, which leads to issues such as soil degradation, water contamination, and increased greenhouse gas emissions.

Nitrogen is abundant in the atmosphere but must be converted into reactive forms to be usable by plants. This conversion is achieved through industrial processes like the Haber-Bosch method, which is energy-intensive and has significant environmental impacts. The widespread use of nitrogen fertilizers has led to various environmental issues, including water pollution and greenhouse gas emissions (Galloway et al., 2008). Overuse of nitrogen fertilizers, particularly those containing ammonium ($NH_4^+$), can lower the soil pH, leading to soil acidification. This process can harm beneficial soil microorganisms, reduce nutrient availability, and hinder plant growth (Goulding et al., 2016). Moreover, excess nitrogen can cause an imbalance in soil nutrients. High levels of nitrogen can inhibit the uptake of other essential nutrients like potassium, magnesium, and calcium, leading to deficiencies that affect plant health and yield (Fageria et al., 2010). Also, intensive use of nitrogen fertilizers, often coupled with heavy machinery, can contribute to soil compaction. Compacted soils have reduced porosity, limiting root growth, water infiltration, and air exchange, which are critical for healthy plant development (Hamza et al., 2005).

The production and application of nitrogen fertilizers involve substantial energy consumption, and their overuse poses environmental risks (Xu et al., 2012). The reliance on nitrogen fertilizers to boost crop yields, while effective in the short term, results in long-term negative consequences for both ecosystems and human health. These include the eutrophication of water bodies, soil acidification, and the release of nitrous oxide, a potent greenhouse gas.

Addressing these challenges requires a multifaceted approach. Improving the efficiency of nitrogen use in agriculture, promoting sustainable farming practices, and developing alternative fertilizers with lower environmental impacts are crucial steps. Additionally, policies and regulations that limit excessive fertilizer application and encourage the adoption of environmentally friendly practices are essential for mitigating the adverse effects of nitrogen fertilizers on the environment.

### 1.2.2. Phosphorus

Phosphorus, often referred to as "the key to life," is crucial for vital biological processes such as energy transfer, metabolic reactions, and genetic coding (Troeh et al., 1993; Marschner et al., 1995). Unlike nitrogen, which is abundantly available in the atmosphere and can be biologically fixed, phosphorus is primarily derived from finite rock phosphate reserves. These reserves are essential for producing phosphate fertilizers, which are heavily relied upon in current agricultural practices.

If current consumption rates persist, we could face a phosphorus shortage crisis by the end of the century (Cordell et al., 2009). The 'phosphorus problem' has recently gained considerable attention for two primary reasons. Firstly, excessive phosphorus entering wastewater (WW) systems poses significant economic and ecological challenges. Phosphorus runoff leads to the eutrophication of water bodies, causing harmful algal blooms and subsequent declines in water quality and aquatic life. Secondly, while agricultural demand for phosphate fertilizer is increasing to maintain crop yields, global reserves of rock phosphate are rapidly dwindling (Baker et al., 2015).

Addressing these dual challenges requires urgent action to improve phosphorus use efficiency in agriculture. This includes developing and implementing sustainable farming practices that minimize nutrient runoff, such as precision agriculture and the use of slow-release fertilizers. Additionally, exploring alternative phosphorus sources and recycling methods, such as recovering phosphorus from wastewater, can help mitigate the impending shortage.

Furthermore, policy interventions are necessary to promote sustainable phosphorus management. Regulations that limit excessive fertilizer application and incentives for adopting environmentally friendly practices can play a crucial role. Research and innovation in phosphorus recovery and reuse technologies are also essential for long-term environmental and agricultural sustainability. By adopting these measures, we can ensure that phosphorus, a vital nutrient, remains available for future generations.

## 1.3. Water-Food-Energy Nexus

By 2050, it is projected that approximately 64% of the developing world and 86% of the developed world will be urbanized. This rapid urban expansion is expected to bring about significant social, economic, and environmental challenges, while also presenting opportunities for enhancing energy efficiency (Mazza et al., 2022). This growing urbanization underscores the critical importance of developing sustainable approaches that can meet the needs of current and future generations.

At the forefront of these challenges and opportunities lies the Water-Energy-Food (WEF) nexus, a concept that highlights the interconnected and interdependent relationships between water, food, and energy systems. The security and sustainability of these vital resources hinge on their effective management and availability in relation to each other. More recent approaches to the nexus consider additional factors like carbon emissions, climate change, and ecosystems. However, including these elements makes the assessment more complex. Therefore, this work concentrates specifically on the WEF nexus to keep the scope clear and manageable.

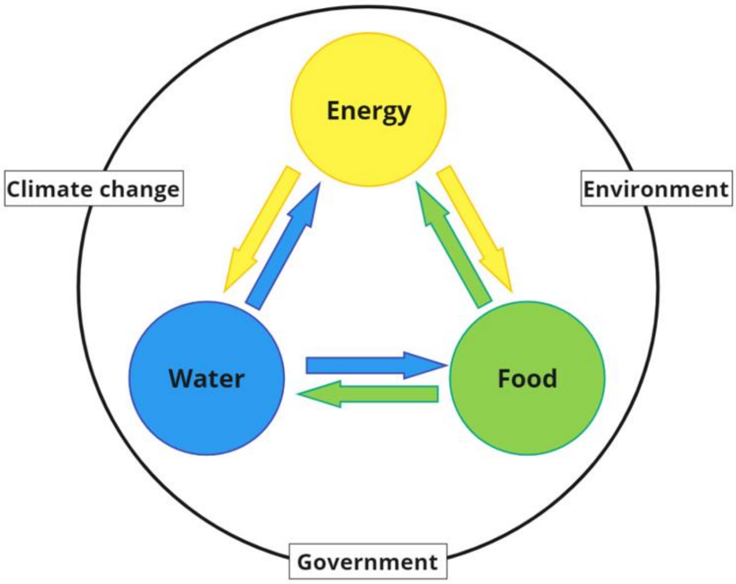


*Fig. 1. WEF Nexus schematic diagram*

The WEF nexus framework illustrates the intricate connections between water, food, and energy components. Each of these sectors relies heavily on the others for its functionality and sustainability, as depicted in the table 1 below:

*Table 1 WEF Nexus components*

| | **Water** | **Food** | **Energy** |
|---|---|---|---|
| **Water** | - | Crop irrigation, livestock watering, and food processing | Hydropower, thermal power (cooling) |
| **Food** | Consumption and pollution | - | Agricultural machinery, transportation, fertilizer production, and food processing |
| **Energy** | Extracting, treating, and distributing water (desalination, water treatment) | Irrigation systems, fertilizers, and machinery | - |

### 1.3.1. Water for Food

Irrigation within the agricultural sector stands as the most water-intensive industry, accounting for 70% of global water consumption (Hoff et al., 2011; Daher et al., 2012; FAO, 2020).

Irrigation is essential for ensuring adequate water supply to crops, especially in regions with insufficient rainfall. Water availability directly impacts agricultural yields, with water scarcity often leading to decreased crop productivity and exacerbating food insecurity (FAO, 2020). Agricultural practices contribute to water stress through both consumption and pollution, needing sustainable water management strategies (UN Water, 2020). Efficient irrigation techniques and technologies are critical for conserving water resources and maintaining agricultural productivity.

### 1.3.2. Water for Energy

Water plays a crucial role in various energy production processes. It is utilized in cooling systems within thermal power plants (including coal, oil, gas, and nuclear), acts as the driving force behind hydroelectric generation, and serves as a medium in geothermal energy extraction.

Hydropower plants exploit the kinetic energy of flowing water, whereas thermal power plants employ water as a heat transfer medium, predominantly in cooling systems. Water intensity quantifies the volume of water required per unit of energy produced, typically measured as $m^3$/MWh. For thermal plants, water intensity encompasses both water consumption and losses during cooling processes. In contrast, for hydropower, intensity primarily considers reservoir evaporation, given that water passes through turbines without being consumed (Lamberton et al., 2010).

Biofuels sourced from agriculture offer alternative energy solutions but often demand significant water inputs. For example, producing one liter of ethanol from irrigated corn can consume between 190 to 2,260 liters of water, while producing a liter of soybean-based biodiesel may require up to 9,040 liters. Lamberton et al., 2010 and Desai et al., 2013 have documented this wide range across different energy sources.

The quantity and quality of available water resources profoundly impact the operational efficiency of energy facilities, highlighting the critical interdependence between water and energy sectors (Hamawand, I, 2023).

### 1.3.3. Food for Water

Agricultural activities impact water resources through water consumption and pollution. The use of fertilizers and pesticides in farming can lead to water contamination, affecting water quality and ecosystem health. Sustainable agricultural practices, such as organic farming and integrated pest management, can help reduce water pollution and mitigate the environmental impact of food production on water resources.

The relationship between food production and water resources presents unique challenges distinct from other interconnections. While certain vegetation can naturally filter water during treatment processes, food production itself contributes to water-related issues. Untreated food waste and excessive fertilizer use are significant contributors to water pollution. In the United States, for example, a staggering 27% of edible food is wasted, with less than 3% being recycled, highlighting substantial inefficiencies (Cuéllar et al., 2010; Buzby et al., 2011). Mismanagement of food waste not only reduces clean water availability but also degrades fertile soil.

Rising global food demand has intensified agricultural practices, including land intensification. This process involves heightened groundwater extraction and increased use of fertilizers and pesticides. Residues from these inputs can infiltrate soil and waterways, leading to severe water quality degradation. Furthermore, expanding agricultural areas can deplete soil fertility, alter runoff dynamics, and impact groundwater recharge (Hoff, 2011). These complex interactions underscore the urgent need for sustainable agricultural strategies to mitigate water-related challenges and ensure enduring environmental health.

### 1.3.4. Food for Energy

The growing emphasis on environmentally friendly energy sources has spurred the advancement of bioenergy technologies. Bioenergy, derived from natural materials, offers significant environmental benefits as it is water-soluble, non-toxic, and biodegradable. This renewable energy source also contributes positively to the social economy by reducing pollution, enhancing farmland value, and mitigating oil price fluctuations (Shi et al., 2009).

Bioenergy encompasses various categories based on its energy products. Biofuels such as bioethanol and biodiesel are liquid forms of bioenergy used widely as alternatives to traditional petroleum-based transportation fuels. Biogas, another form of bioenergy, is produced through biomass gasification processes (Yuan et al., 2008). Biofuels and biodiesel are particularly prominent among these categories, extensively utilized in developed countries to diminish reliance on fossil fuels (Daher et al., 2012).

The primary sources for bioenergy production include agricultural crops like corn, sugar cane, wheat, and soybeans, as well as food waste. Agricultural crops are predominantly used to produce biofuels and biodiesel, while food waste serves as a vital resource for biogas production, used in cooking and heating applications. Currently, global bioenergy production predominantly focuses on biofuel ethanol and biodiesel, yielding approximately 35.8 million tonnes of oil equivalent ($M_{toe}$) annually, with biogas production contributing 16.4 $M_{toe}$ per year (Smyth et al., 2010).

### 1.3.5. Energy for Water

When it comes to wastewater treatment (WWT), the water and sewerage sector stands as the largest consumer of electricity in urban areas, accounting for approximately 40% of total urban energy consumption (Masłoń, A et al., 2020). This sector's high energy demand arises from the numerous energy-intensive processes required to operate water and wastewater treatment plants effectively. Key components such as pumps, air compressors, surface aerators, dewatering machines, analysis equipment, mixers, and other moving parts necessitate substantial energy input.

Improving the energy efficiency of these existing facilities is crucial for achieving sustainable energy goals. Enhancing energy efficiency not only reduces operational costs but also minimizes the environmental impact of wastewater treatment processes. By implementing advanced technologies and optimizing operational practices, treatment plants can significantly lower their energy consumption. This reduction in energy use directly contributes to global energy security and environmental sustainability by decreasing greenhouse gas emissions and conserving valuable resources (Hamawand, I, 2023).

Investing in energy-efficient infrastructure and practices is essential for cities aiming to create sustainable urban environments. Modernizing equipment, incorporating renewable energy sources, and adopting innovative treatment technologies can transform wastewater treatment plants into energy-efficient facilities. This transformation supports broader sustainability objectives and helps cities mitigate the adverse effects of climate change.

Furthermore, energy-efficient wastewater treatment contributes to the resilience of urban infrastructure, ensuring that cities can maintain essential services even in the face of increasing energy demands and environmental pressures. By prioritizing energy efficiency in the water and sewerage sector, we can make significant strides toward sustainable urban development and a more secure and sustainable energy future.

### 1.3.6. Energy for Food

Energy plays a critical role across the entire food production chain, encompassing agricultural operations, food processing, and distribution. From the cultivation of crops to the preservation and transportation of food products, energy-intensive processes like heating, cooling, refrigeration, and logistics are essential. Efficient energy management within the food sector is crucial not only for reducing greenhouse gas emissions but also for minimizing environmental impacts on energy resources. Investment in sustainable energy technologies and practices is pivotal in building resilient food systems and ensuring long-term energy security.

These interdependencies highlight the necessity of integrated approaches to managing water, food, and energy systems. By adopting sustainable practices and policies, we can enhance resource efficiency, strengthen resilience against climate change effects, and advance broader sustainability objectives.

Recognizing and managing these interconnections is essential for developing integrated strategies that ensure resource security, promote efficiency, and address the challenges posed by urbanization. By adopting a holistic approach to managing the WEF nexus, policymakers and stakeholders can mitigate risks, enhance resilience, and foster sustainable development pathways for urban and rural communities alike.

### 1.3.7. Environment and climate change

The over-exploitation of natural resources has profound environmental consequences, necessitating significant water and energy inputs for rehabilitation. Climate change exacerbates these challenges by altering temperature and rainfall patterns. Global warming, characterized by rising temperatures, accelerates aridification, diminishes glacier water storage, and contributes to sea-level rise (Wicaksono et al., 2017).

Among natural resources, water is particularly vulnerable to the impacts of climate change. Shifts in rainfall patterns and increased frequency and intensity of extreme events like floods and droughts are direct consequences (Hoff, 2011). Statistical data from the United Nations International Strategy for Disaster Reduction indicate a notable increase in extreme natural disasters over the past decade, with projections suggesting further escalation (UNISDR, 2012).

Moreover, changes in water availability and rainfall patterns disrupt water supplies critical for hydropower generation and irrigation (World Economic Forum, 2011).

## 1.4. Circular economy and wastewater treatment

The wastewater treatment sector in the European Union consumes approximately 1 percent of the total energy usage, resulting in significant energy costs borne by taxpayers (European Commission, 2022). In response, the EU has established a target to achieve energy neutrality in the wastewater sector by 2040. This ambitious goal encompasses the production of renewable energy, carbon neutrality, and the development of a resource-efficient bioeconomy (European Commission, 2021a).

To ensure a seamless transition towards the WEF Nexus objectives, Water Resource Recovery Facilities (WRRFs) should be considered central to this study. With both the global community and the EU striving for energy neutrality, there is an increasing emphasis on extending the life cycle of products, as well as maximizing reuse and recycling. This concept, known as the Circular Economy (CE), is gaining widespread popularity as a means to achieve these sustainability goals.

The primary materials used in the system that can be recovered from the WFFRs and reintegrated are as follows:

1. Nutrients
2. Energy
3. Organic matter (both Sludge and Microalgae biomass)
4. Water

### 1.4.1. Nutrient removal and recovery

Nutrients are mainly recovered in order to comply with two principal goals: environmental protection and resource conservation.

Pollution reduction is a crucial benefit of nutrient recovery from Water Resource Recovery Facilities (WRRFs). By capturing and reusing nutrients such as nitrogen and phosphorus, WRRFs significantly minimize the release of these potentially harmful substances into the environment. This process addresses several critical environmental issues.

Firstly, nitrogen and phosphorus are key contributors to water pollution. When discharged untreated into water bodies, they can cause eutrophication, which leads to harmful algal blooms. These blooms deplete oxygen levels in the water, resulting in "dead zones" where aquatic life cannot survive. The illustration of eutrophication as an environmental threat is provided below (retrieved from Logic Clean$^{TM}$):

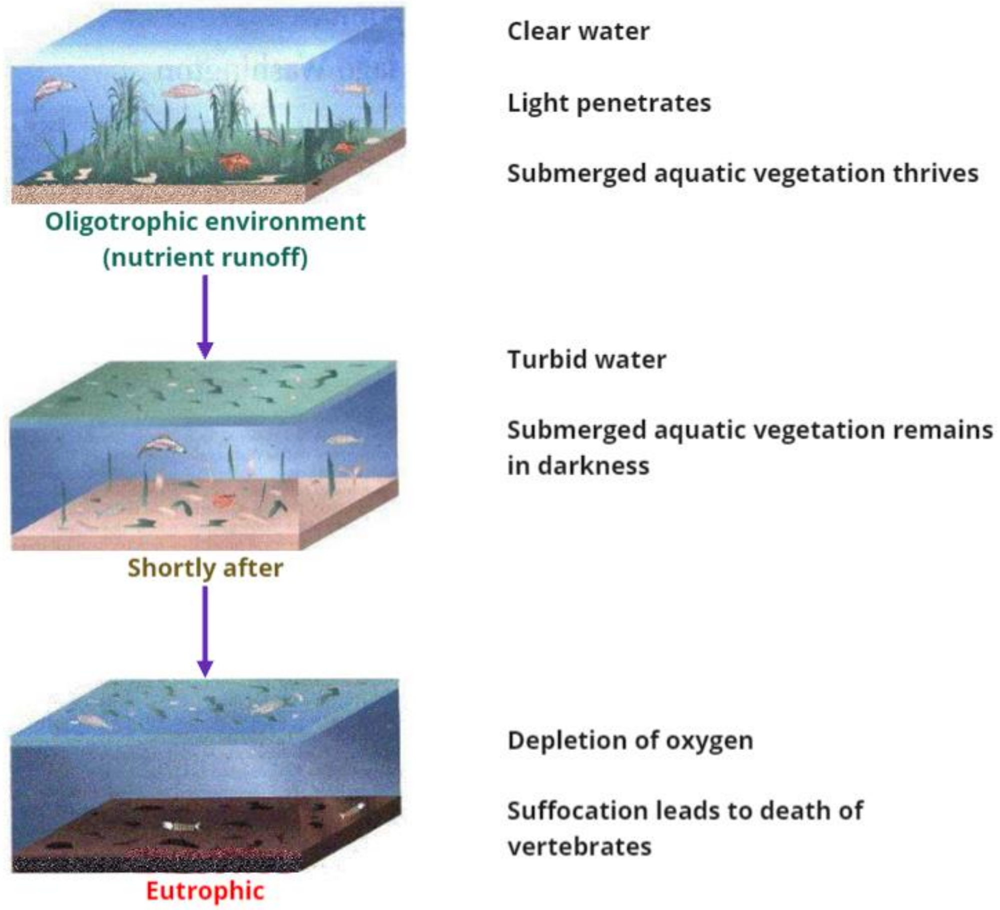


*Fig. 2. Process of eutrofication*

Secondly, nutrient recovery helps to protect drinking water sources. Excess nitrogen in water supplies can convert to nitrate, a compound harmful to human health, especially for infants and pregnant women. High nitrate levels in drinking water have been linked to conditions such as methemoglobinemia, also known as "blue baby syndrome" (Knobeloch et al., 2000).

Furthermore, nutrient recovery supports the principles of the circular economy by transforming waste into valuable resources. For example, phosphorus recovered from wastewater can be used to produce fertilizers, reducing the need for mining finite phosphate rock reserves (Cordell et al., 2009). This not only conserves natural resources but also reduces the environmental impact associated with fertilizer production.

In addition to environmental benefits, nutrient recovery from WRRFs can have significant economic advantages. By producing and selling recovered nutrients, WRRFs can create new revenue streams, potentially lowering operational costs and offering financial incentives for sustainable practices (Molinos-Senante et al., 2011).

### 1.4.2. Energy

Energy recovery from Water Resource Recovery Facilities (WRRFs) can be achieved through several innovative technologies and processes, including anaerobic digestion. Anaerobic digestion is a biological process that decomposes organic matter in the absence of oxygen, producing biogas as a by-product. This biogas is primarily composed of methane ($CH_4$) and carbon dioxide ($CO_2$), with methane being the valuable component that can be used as a renewable energy source.

The organic sludge generated during wastewater treatment is fed into anaerobic digesters, where microorganisms break down the organic material, producing biogas. This biogas can then be captured and utilized in combined heat and power (CHP) units to generate electricity and heat, significantly improving the energy efficiency of the WRRF. Alternatively, the biogas can be upgraded to biomethane for injection into the natural gas grid or used as vehicle fuel (Appels et al., 2008). By implementing anaerobic digestion and biogas utilization, WRRFs can transform from energy-intensive facilities into energy-neutral or even energy-positive operations.

### 1.4.3. Organic material

The organic material can be recovered from the effluent in two ways: as sludge and as microalgae biomass.

#### *1.4.3.1. Sludge*

As mentioned earlier, anaerobic digestion of sludge yields biogas, which can be utilized for electricity and heat generation or refined into biomethane, serving as a renewable energy source (Appels et al., 2008). Additionally, sludge has been widely used as soil amendment by directly applying it to soil or after composting. However, current EU-Regulation 2019/1009 on fertilizers forbids the commercialization of this by-product.

#### *1.4.3.2. Microalgae biomass*

In recent years, the search for sustainable and efficient wastewater treatment methods has intensified. Various alternative approaches have been explored to enhance resource recovery, reduce environmental impact, and improve overall treatment efficiency. Among these methods, the use of microalgae in wastewater treatment has emerged as a promising solution.

##### 1.4.3.2.1. Microalgal biomass valorisation

Microalgae are ubiquitous eukaryotic photosynthetic microorganisms that are found in almost every aquatic habitat such as freshwater, soda lakes, riverine, marine, saline, hyper-saline environments, etc. (Leliaert et al., 2012). Microalgae play a significant role when it comes to primary production in nature and form the basis of the food chain in aquatic environments (Malapascua et al., 2014). For example, it is a natural food source for many important aquaculture organisms such as molluscs, shrimps, and fish (Selvarajan, R et al., 2015).

The popularity of microalgal biotechnology industry has skyrocketed in recent years due to global hunger threat, since hydrocarbons, proteins and fertilizers can be obtained from microalgal biomass. Microalgal systems do not require huge volumes of freshwater and immense surfaces of arable land, as compared to many common crops like sunflower or corn (Mutanda et al., 2020). Microalgal cultivation has a promising future due to its high photon conversion efficiency, ability of being harvested all-year round in salt/wastewater systems and to produce non-toxic biodegradable biofuels (Cobos et al., 2017). The microalgal systems could also be implemented in municipal, domestic and agricultural wastewater treatment systems as long as the latter contain sufficient amounts of nitrates, phosphates and other necessary elements (Zhou et al., 2014).

Microalgae can thrive in various types of WW and possess significant potential for removing contaminants from industrial and urban effluents (Abdelfattah et al., 2023). Additionally, microalgae effectively remove various toxins through biosorption, bioaccumulation, and biodegradation processes. The microalgal species such as *Tetradesmus,* *Chlorella, Botryococcus, Phormidium, Limnospira* (formerly *Arthrospira, Spirulina*), and *Chlamydomonas* are reported to be highly effective when it comes to bioremediation of nutrients, heavy metals, emerging contaminants and pathogens originated from wastewater flow (Lopez-Sánchez et al., 2022; Ahmad et al., 2021).

#### 1.4.3.2.2. Microalgal treatment

In recent years, microalgae-based wastewater treatment is gaining attention due to its low energy requirements, adaptability to diverse environmental conditions, and ability to convert wastewater nutrients into valuable compounds. This approach has proven to be both economic and sustainable. Due to the growing interest in this technology, more and more research is carried out every year.

Nowadays, it is possible to use microalgae cultivated in high rate algal ponds (HRAPs) and serve as a byproduct of wastewater treatment (Mehrabadi et al., 2015). HRAPs are shallow, open raceway ponds, typically 15-30 cm deep, that use paddlewheels for mixing. In these bioreactors, microalgal cultures are stirred using a paddlewheel, ensuring the cells receive light, $CO_2$, and nutrients, while also preventing sedimentation (Park et al., 2011). The microalgae produce oxygen through photosynthesis, which can be utilized by bacteria without the need for aeration. Additionally, the carbon dioxide produced from organic matter degradation is utilized by the algae. Their performance relies on a symbiotic relationship between bacteria and microalgae, enabling low-energy wastewater treatment. These ponds effectively recover dissolved nutrients, which are assimilated into the algal biomass. This harvested algal biomass can subsequently be utilized as a biofuel feedstock. Compared to conventional mechanical wastewater treatment systems used in large cities, WWT HRAPs have lower capital and operating costs (Muga et al., 2008).

High Rate Algal Ponds (HRAPs) represent a sustainable and cost-effective alternative to traditional systems. They offer significant advantages, including up to a 50% reduction in footprint and capital costs compared to facultative lagoons, thanks to shorter HRT. HRAPs mitigate evaporation losses, improve ammonia removal efficiency (59-74%) (Buchanan et al, 2018a), and have lower energy requirements, which can be fulfilled using solar power.

The process of biomass valorisation obtained using a HRAP system is detailed in the following figure 3 (adapted from Ibrahim et al, 2023):

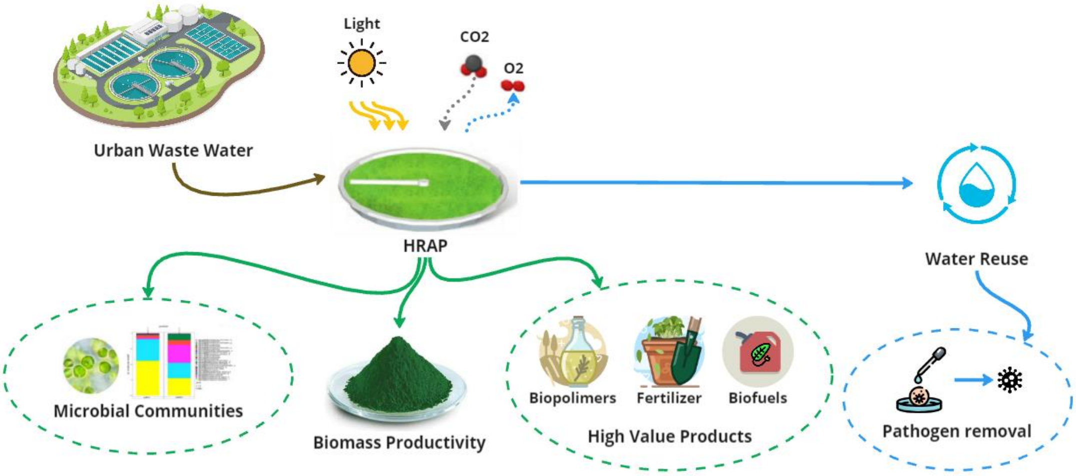


*Fig. 3. HRAP biomass valorisation*

Investigation was conducted in order to reach the maximum optimization for the HRAP installation, starting from regulating light availability (Clagnan et al., 2023) and continuing with Hydraulic Retention Time (HRT) adjustment using membrane photobioreactor technology (MPBR) (Luo et al., 2018).

In wastewater treatment process a MPBR is implemented to integrate membrane filtration with photobioreactors in HRAP systems. In these conditions, the MPBR functions as a combined treatment system where suspended solids are separated from the water flow. This process also filters and retains nutrients, allowing for their subsequent valorisation. The membrane in the MPBR serves to separate the biomass from the water post-treatment, effectively removing suspended solids (SS), chemical oxygen demand (COD), and nutrients simultaneously. It is generally accepted that there are five crucial components to the MPBR system efficiency, which are namely biomass concentration, composition, production, nutrient uptake and harvesting potential (Luo et al., 2018). While traditional HRAP systems already benefit from low energy consumption due to solar energy capture through photosynthesis, integrating MPBR can further optimize the process. The membranes allow for continuous operation and reduce the need for extensive post-treatment processes. The primary objective of incorporating the membrane is to recover water. However, membrane filtration can be costly and may not be economically viable unless water recovery is achieved effectively.

# 2. Objectives

The objectives of this study are outlined as follows:

1. Develop a methodology to evaluate and quantify the Water-Energy-Food (WEF) Nexus, including factors, parameters, and indicators for analysis.

2. Quantify the WEF Nexus in conventional wastewater treatment.

3. Compare conventional wastewater treatment plants (WWTPs) with microalgae-based water resource recovery facilities (WRRFs) in terms of the WEF Nexus.

4. Discuss the results obtained from the evaluation and comparison.

The primary aim of this research is to develop, analyze, and quantify sustainable scenarios within the Water-Food-Energy (WEF) Nexus framework. This study will encompass three main aspects of the WEF Nexus: Water (focusing on water treatment and reuse with and without microalgal cultivation); Food (centered around the agricultural sector with a focus on tomato cultivation); and Energy (which includes assessing energy consumption within WRRFs and irrigation systems, as well as evaluating biogas and biofertilizer production potential).

# 3. Methods

A methodology to quantify the WEF Nexus will be developed and applied to a theoretical microalgae-based WRRF that treats urban wastewater.

The research began by focusing on the Falconara Marittima WWTP, situated in Ancona, Italy. The WWTP operating parameters for the given WWTP were previously estimated by Ortega Pérez (2023) and adapted to the goals of this study.

Two scenarios were considered to estimate the potential WEF Nexus implementation:

1. Scenario 0 depicts conventional treatment where nitrogen and phosphorus removal meet discharge standards, with no water reuse. Potable water is sourced from groundwater, and there is no in-house fertilizer production.
2. Scenario 1 involves combining conventional activated sludge (CAS) treatment with microalgal cultivation, where a portion of settled wastewater is diverted to the HRAP. Reclaimed water and biofertilizer produced in HRAP are utilized to meet the needs of tomato crops.

Scenario 0 is analysed to identify potential optimization solutions for existing installations, incorporating evaluations of the agricultural sector and energy consumption. In contrast, Scenario 1 introduces sustainable strategies based on microalgae cultivation to optimize water, food, and energy resources, minimize environmental impacts, and outline areas for further research.

Summarizing, the WEF Nexus pillars analyzed in this study will focus on the following aspects:

1. Water: Evaluation of the water treatment processes within the wastewater treatment facility. This includes assessing parameters such as water quality improvements through nitrogen and phosphorus removal, water reuse potentials, and the overall efficiency of treatment technologies in Scenario 0 and Scenario 1.
2. Energy: Analysis of energy production and consumption associated with the wastewater treatment processes. This involves quantifying energy inputs required for conventional treatment methods in Scenario 0 and comparing them with the energy demands, possible energy production and potential savings associated with microalgal cultivation in Scenario 1.

3. Food: Assessment of food production aspects, specifically the cultivation of tomato crops using reclaimed water and biofertilizer produced from the microalgal-based WRRF in Scenario 1. This includes evaluating crop yield, nutrient uptake efficiency, and the environmental footprint associated with agricultural practices in both scenarios.

## 3.1. Description of the wastewater treatment plant

The baseline scenario was built considering an already existing WWTP Falconara Marittima, which has an organic capacity of 85,000 p.e. (population equivalent) and water treatment volume of 8,024,525 $m^3$ annually (21.895 $m^3$ daily)

According to the current legislation (Council Directive 91/271/EEC), the discharge limits are set as provided in the table 2 below:

*Table 2. Discharge limits for water effluent established by the current legislation*

| Basic discharge limits | | |
|---|---|---|
| **Parameter** | **Value** | **Units** |
| **Total Nitrogen** | 15 | mg/l N |
| **Total Phosphorus** | 2 | mg/l P |
| **Chemical Oxygen Demand** | 125 | $mg \cdot L^{-1}$ |
| **Biochemical Oxygen Demand** | 25 | $mg \cdot L^{-1}$ |
| **Total Suspended Solids** | 35 | $mg \cdot L^{-1}$ |

It should be noted that the total phosphorus and total nitrogen values were set in compliance with current legislation (Commission directive 98/15/EC), which specifies requirements for discharges from urban wastewater treatment plants into sensitive areas prone to eutrophication (2 mg/l and 15 mg/l respectively).

The overall process is described in the fig. 4.

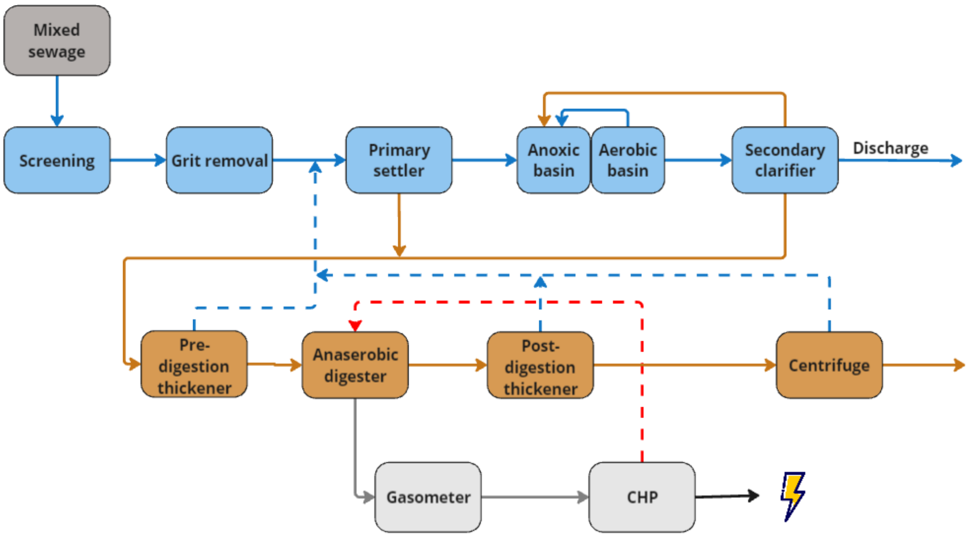


*Fig. 4. Outline of the Falconara Marittima WWTP*

The wastewater treatment process begins with mixed sewage undergoing screening and grit removal as a pre-treatment. After these initial steps, the water flows into the primary settler, where primary sludge is generated and directed to the sludge line for further processing.

Once the water exits the primary settler, it enters the anoxic-aerobic tank. In this phase, recirculation occurs, allowing both water and sludge to move through the system. This step is crucial for nitrification and denitrification processes to take place. Following biological treatment, the wastewater flows into the secondary clarifier, where secondary sludge is produced. This secondary sludge is also sent to the sludge line to be treated along with the primary sludge, preparing it for anaerobic digestion (AD).

The mixed sludge undergoes treatment, followed by thickening and anaerobic digestion, during which biogas is produced. The system is equipped with a gasometer, which provides temporary storage for the generated biogas and helps maintain consistent pressure in the biogas collection system. This pressure regulation is crucial for the efficient operation of biogas utilization systems, such as CHP units. After storage, the biogas is sent to the CHP system, which powers the WWTP and generates heat for the anaerobic digestion process.

The previously known dimensions of the WWTP in question are represented in the table 3. It should be highlighted that the convertible basin corresponds to either anoxic or aerobic basin and it was added into the simulation as additional aerobic volume in order to simplify the calculation process (Ortega Pérez, 2023).

*Table 3. Dimensions of different treatment units of Falconara Marittima WWTP obtained by Ortega Pérez, 2023*

| Dimensions of different treatment units Falconara Marittima WWTP | | | |
|---|---|---|---|
| **Treatment element** | **Dimension** | **Unit** | **Value** |
| **Primary settlers** | Nº of units | - | 2 |
| | Shape | - | Circular |
| | Diameter | m | 26 |
| | Average depth | m | 2.5 |
| | Unit area | $m^2$ | 530 |
| | Unit volume | $m^3$ | 1325 |
| **Secondary clarifiers** | Nº of units | - | 2 |
| | Shape | - | Circular |
| | Diameter | m | 32 |
| | Average depth | m | 2 |
| | Unit area | $m^2$ | 804 |
| | Unit volume | $m^3$ | 1608 |
| | Retention time (avg. flow) | h | 4.1 |
| | Retention time (peak flow) | h | 2.1 |
| **Anoxic basins** | Nº of units | - | 2 |
| | Shape | - | Rectangular |
| | Depth | m | 5.7 |
| | Length | m | 20.4 |
| | Width | m | 15.3 |
| **Aerobic basins** | Nº of units | - | 2 |
| | Shape | - | Rectangular |
| | Depth | m | 4.4 |
| | Length | m | 35 |
| | Width | m | 16 |
| **Convertible basin** | Nº of units | - | 1 |
| | Shape | - | Rectangular |
| | Depth | m | 4.4 |
| | Length | m | 13.25 |
| | Width | m | 16 |

## 3.2. Simulation assumptions and considerations

The simulation process conducted by Ortega Pérez (2023) laid a foundation for advancing our research. Consequently, a detailed view of the simulation process will not be provided here.

A table with the tested values for the different treatment stages in the sludge line is provided below. It is important to note that the values presented in table 4 remained consistent throughout the entire study and were applied to both scenarios, as the morphology and size of the installations were not subject to change.

*Table 4. Tested values for the different treatment stages in the sludge line obtained by Ortega Pérez, 2023*

| **Dimensions of different treatment units Falconara Marittima WWTP** | | | |
|---|---|---|---|
| **Treatment element** | **Dimension** | **Unit** | **Value** |
| **Pre-digestion thickener** | Nº of units | - | 1 |
| | Shape | - | Circular |
| | Diameter | m | Calculated by DESASS |
| | Average depth | m | 2.5 |
| | Retention time | h | 12 |
| | Overflow rate | $m^3 \cdot m^{-2} \cdot h^{-1}$ | 0.9 |
| | SS loading rate | $kgSS \cdot m^{-2} \cdot h^{-1}$ | 2.9 |
| | Extraction flow | $Q_{ext}/Q_{in}$ | 0.5 |
| **Anaerobic digester** | Nº of units | - | 1 |
| | Diameter | - | Calculated by DESASS |
| | Average depth | m | 1 |
| | Extra gas volume | % sludge volume | 10 |
| | Total volume | $m^3$ | Set by DESASS |
| | SRT | d | 20 |
| | Pressure | atm | 1.02 |
| | Temperature | ºC | 35 |
| **Post-digestion thickener** | Nº of units | - | 1 |
| | Shape | - | Circular |
| | Diameter | m | Calculated by DESASS |
| | Average depth | m | 2.5 |
| | Retention time | h | 12 |
| | Overflow rate | $m^3 \cdot m^{-2} \cdot h^{-1}$ | 0.9 |
| | SS loading rate | $kgSS \cdot m^{-2} \cdot h^{-1}$ | 2.9 |

| | | | |
|---|---|---|---|
| | Extraction flow | $Q_{ext}/Q_{in}$ | 0.5 |
| **Sludge dewatering** | Solids in sludge | % | 25 |
| | Solids in water | % | 100 |
| | P precipitation | | As struvite |
| | P removal | % | 70 |

In order to initiate the simulation, specific values were input into the system. These values, which are detailed in table 5 below, were carefully chosen to reflect the conditions necessary for the accurate modeling of the treatment processes. The parameters include various operational and environmental factors that influence the performance of the wastewater treatment stages. It is essential to note that these values remained consistent throughout the entire study and were applied uniformly across both scenarios. This consistency ensures that any observed differences in outcomes are attributable to the distinct processes being evaluated, rather than variations in input parameters.

The water sample was analysed in order to determine the values of biochemical oxygen demand over a 5-day period ($BOD_5$), total suspended solids (TSS), alkalinity, pH, total nitrogen (TN), ammonium nitrogen ($N\text{-}NH_4$), nitrous nitrogen ($N\text{-}NO_2$), nitric nitrogen ($N\text{-}NO_3$), total phosphorus (TP), orthophosphate phosphorus ($P\text{-}PO_4$) and sulphates ($SO_4^{2-}$).

*Table 5. Input parameters for simulation obtained by Ortega Pérez, 2023*

| Parameter | Value | Unit |
|---|---|---|
| **$BOD_5$** | 165 ± 21 | mg $O_2$/L |
| **TSS** | 292 ± 130 | mg SS/L |
| **Alkalinity** | 363 ± 29 | mg $CaCO_3$/L |
| **pH** | 8.11 ± 0.26 | - |
| **TN** | 39.88 ± 6.15 | mg N/L |
| **$N\text{-}NH_4$** | 28.36 ± 2.92 | mg N/L |
| **$N\text{-}NO_2$** | 0.33 ± 0.26 | mg N/L |
| **$N\text{-}NO_3$** | 3.13 ± 0.94 | mg N/L |
| **TP** | 5.74 ± 1.48 | mg P/L |
| **$P\text{-}PO_4$** | 5.74 ± 1.48 | mg P/L |
| **$SO_4^{2-}$** | 129 ± 15 | mg/L |

### 3.2.1. Scenario 0

Scenario 0 is defined as conventional WW treatment, without the inclusion of water reuse, fertigation, fertilizer production, microalgae cultivation, or resource reuse. For the calculation of this scenario, the system will be divided into subunits in such a way that simplifies the analysis and facilitates the understanding of the processes involved, as well as eases the comparison with scenario 1.

This scenario represents a non-reuse baseline scenario for our research. The input water consists of mixed sewage, while the output water must comply with basic legal discharge requirements. As this is a non-reuse scenario, the treatment process is designed solely to meet these legal discharge standards, and the resulting water is neither potable nor suitable for agricultural use. Consequently, risk-based concerns are minimized since there is no direct contact between this treated water and crops, as irrigation water, which is potable, is sourced separately. Given this context, wastewater disinfection with chlorine is not considered necessary due to the additional costs and the fact that the treated water will not be reclaimed.

The general outline of the WEF Nexus interconnections can be observed in a fig. X. As it can be clearly observed, the whole plant is divided into 4 subsections, for the sake of the study simplification. Here we analysed the flow of resources between different segments to obtain a generic yet representative picture. The general interconnections of the Water-Energy-Food (WEF) Nexus are depicted in figure 5. The entire plant is segmented into four sections for the purpose of simplifying the study. We analyzed resource flows between these segments to provide a broad yet representative overview. Given our research focus on all three Nexus pillars—water, energy, and food—it is unnecessary to delve into every operational detail of each specific installation. The aim is not to optimize the treatment plant for Nexus efficiency but to evaluate the approach, emphasizing decision-making rather than process operation.

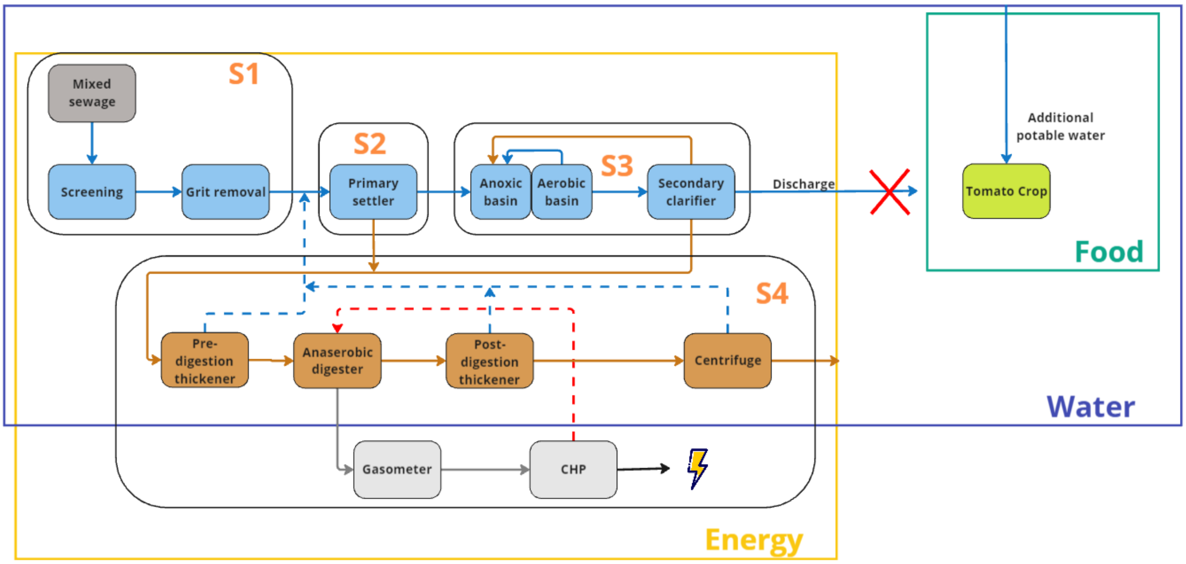


*Fig. 5. Outline of the scenario 0*

#### *3.2.1.1. Water*

Ideally, the Scenario 0 should reflect the current functionality of the Falconara Marittima WWTP. The input data used in this research were either previously known or estimated in the simulation conducted by Ortega Pérez (2023) in the aforementioned study.

Considering this information, the simulation parameters for WWT in this scenario are depicted in the table 6 below:

*Table 6. Selected values for the main simulation parameters in the scenario 0 obtained by Ortega Pérez, 2023*

| Simulation parameter | Value | Unit |
|---|---|---|
| **Influent wastewater flow** | 21895 | $m^3/d$ |
| **Sludge extraction in the primary settlers** | 0.02 | Qext/Qin |
| **Total anoxic volume** | 3558 | $m^3$ |
| **Total aerobic volume** | 4928 | $m^3$ |
| **SRT** | 14 | days |
| **Flow of precipitation reagent added to the WW** | 0.5 | $m^3/d$ |
| **Internal recirculation** | 2 | Qrec/Qin |
| **Sludge flow extracted from the secondary clarifiers** | 0.5 | Qext/Qin |

In Scenario 0, it can be observed that chlorine disinfection is not utilized. Chlorine, along with the necessary equipment for its application, represents a significant cost in wastewater treatment operations. By skipping chlorine disinfection, operational expenses could be significantly reduced, particularly in smaller or resource-limited wastewater treatment plants (WWTPs). Additionally, the elimination of chlorine disinfection can mitigate the formation of potentially harmful disinfection by-products and reduce the environmental impact associated with chlorine production and transportation.

Moreover, there is no water reuse. With this in mind, an alternative is proposed: in this research, the water comes from a groundwater source. In a country like Spain, where droughts are frequent, it is important to note that the amount of groundwater stored is often greater than the amount recharged by rainfall or other sources. This allows reliance on groundwater resources in case of insufficient surface water. Groundwater typically requires much less processing, mainly involving pumping water to the surface and chlorinating it for disinfection and removal of odors or taste. The treated water is then pumped to the distribution system or storage tanks before distribution) (Yang et al., 2013).

The drip irrigation system was implemented in the present study out of all other considered methods. Each irrigation method is characterized by a specific efficiency level, defined as the ratio of water that effectively reaches the crops compared to the total amount of water supplied. Surface irrigation has the lowest efficiency level at 0.5, whereas sprinkler irrigation is a bit more efficient, with an efficiency level of 0.7. Drip irrigation, the most efficient method, has an efficiency level of 0.9 (Marinelli et al., 2021), which is why it was chosen for the study and taken into account for the evaluation of our scenarios. With this in mind, the total amount of irrigation water should be recalculated in order to make up for the water loss.

#### *3.2.1.2. Energy*

After a comprehensive review of the literature, the specific energy consumption for drip irrigation systems using groundwater was determined to be 0.68 $kWh/m^3$, including the energy required for extraction, essential groundwater treatment, and distribution to the irrigation system(Soto García et al, 2014). This value is in the range of the average specific energy consumption in wastewater treatment plants (approximately 0.64 $kWh/m^3$)This parameter will be described in detail later on, in the agriculture part.

In order to estimate the WWTP energy consumption, the ENERWATER methodology was considered (Longo et al., 2019). The aim of this method is to provide guidance to water experts and auditors for evaluating the energy performance of WWTPs. It leads to a final energy diagnosis and calculation of the Wastewater Treatment Energy Index (WTEI). The ENERWATER methodology involves classifying WWTPs into different types, identifying stages of treatment, defining key performance indicators (KPIs), and reviewing existing energy monitoring standards. It includes a detailed description of the ENERWATER methodology, with step-by-step guidelines for its application and potential future standard implementation.

There are two approaches for the energy study: Rapid Audit (RA) and Decision Support (DS). The first one is a rapid tool to compare the performance of a given WWTP with other plants and determine the need for a detailed monitoring campaign. The Decision Support method involves extensive monitoring of energy consumption and water quality parameters to accurately calculate the water treatment energy index for each stage of the WWTP and the plant as a whole. This process aims to diagnose functional and equipment inefficiencies, thereby allowing the development of targeted energy-saving strategies. Both methodologies are similarly structured but require inputs of varying detail. Table X provides suggested KPIs for implementing the DS methodology (Longo et al., 2019).

*Table 7. Identification of KPIs*

| Plant function | Stage | Parameter | DS methodology |
|---|---|---|---|
| **Pumping** | S1 | Flow | $kWh/m^3$ |
| **Removal of suspended solids** | S2 | TSS | $kWh/kg\ TSS_{rem}$ |
| **Removal of organic matter** | S3 | COD | $kWh/kg\ TPE_{rem}$ |
| **Removal of nitrogen** | | TN | |
| **Removal of phophorus** | | TP | |
| **Removal of produced sludge** | S4 | Total Solids | kWh/kg TSE |
| **Sludge dewatering** | | | |

In both cases, data can be reported as daily, monthly, or yearly averages, with a recommended data gathering period of 3 years to account for seasonal variability due to human activities and rainfall patterns.

#### *3.2.1.3. Food*

In this scenario, it is imperative to conduct a comprehensive analysis of various crops, considering their specific soil requirements, to select an appropriate candidate for our study. The main crop characteristics for corn, carrot and tomato are represented in the table X.

*Table 8. Characteristics and requirements for crops cultivated in the peri-urban area of Peschiera Borromeo (adapted from Marinelli et al., 2021)*

| Parameter | Unit | Corn | Carrot | Tomato |
|---|---|---|---|---|
| **Crop productivity** | ton/ha | 10 | 50 | 100 |
| **N demand** | kgN/ha | 135-235 | 150 | 250 |
| **P demand** | kgP/ha | 58-80 | 70 | 65 |
| **Emissions/Carbon sequestration** | ton$CO_2$e/ha | 3.52 | 2.27 | 2.11 |
| **Crop water demand** | $m^3$/ha | 5000 | 5200 | 5400 |
| **Expected revenue** | €/kg | 0.26 | 0.48 | 0.78 |

In the Ancona region of Italy, growing tomatoes can be advantageous due to several key factors. The Mediterranean climate in this region is particularly favorable for year-round open field agriculture. This climate supports natural sunlight and adequate rainfall throughout the year, making open field cultivation economically viable with lower initial investment and operational costs compared to greenhouse farming.

Open field farming in Ancona reduces reliance on artificial heating, cooling, and irrigation systems, which not only lowers production expenses but also minimizes the carbon footprint associated with greenhouse gas emissions. This method ensures sufficient yields to meet market demands while offering flexibility for crop rotation and efficient land use. These factors collectively make open field tomato cultivation in the Ancona region a sustainable and cost-effective choice, particularly suitable for small to medium-scale farmers looking to optimize resource management and productivity.

Since tomatoes have the most beneficial characteristics for our research—such as the highest crop productivity and expected revenue, as well as the lowest phosphorus demand and greenhouse gas emissions—they were selected as the primary crop for the study.

For the sake of the calculation certain simplification were taken into account:

- The area considered for the study is 1 hectare;
- No water reuse, the water input is groundwater;

– Total nitrogen is 5 mgN/l and Total Phosphorus is 1 mgP/l in the groundwater extracted (USGS, 2004);

### 3.2.2. Scenario 1

The scenario 1 comprises the conventional activated sludge (CAS) with a bypass of a settled wastewater fraction to the HRAP Plant. For this scenario, the considerations are mostly the same as those for the baseline scenario (scenario 0), with a few adjustments:

1. The influent wastewater flow to the HRAP accounts for approximately 20% of the original flow, following the considerations of Ortega Pérez, 2023.
2. The treated and filtered water is directed straight to the tomato crop to ensure a stable interconnection between the components of the Water-Energy nexus. This consideration was done as the treated wastewater is assumed to accomplish with the requirements for reclaimed water (Hernandez-Cuenca, 2024).

The flow diagram of the Scenario 1 can be represented as follows:

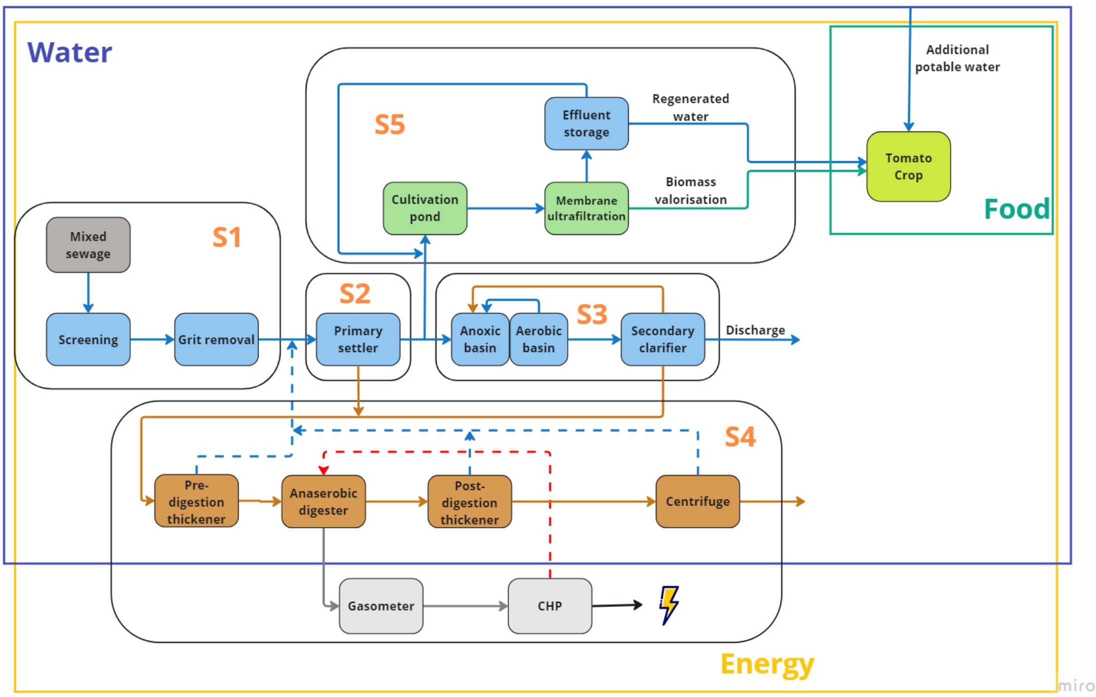


*Fig. 6. Outline of the scenario 1*

#### 3.2.2.1. Water

The simulation parameters were previously obtained from the work Ortega Pérez, 2023, and can be used as default design parameters as shown in the table 9:

*Table 9. Input data for Scenario 1 obtained by Ortega Pérez, 2023*

| | **Scenario 1 parameters** | | | |
|---|---|---|---|---|
| | **Simulation parameter** | **Value** | **Unit** | **From** |
| **Data for the recalculated plant** | Influent wastewater flow | 17463 | $m^3/d$ | Calc. |
| | Sludge flow extracted from the primary settlers | 0.02 | $Q_{ext}/Q_{in}$ | Tested |
| | Total anoxic volume | 3558 | $m^3$ | Actual |
| | Total aerobic volume | 3872 | $m^3$ | Tested |
| | SRT | 14 | days | Tested |
| | Flow of precipitation reagent added to the wastewater | 0.25 | $m^3 \cdot d^{-1}$ | Tested |
| | Internal recirculation | 2 | $Q_{rec}/Q_{in}$ | Tested |
| | Sludge flow extracted from the secondary clarifiers | 0.5 | $Q_{ext}/Q_{in}$ | Tested |
| | | | | |
| **Data for the parallel plant** | Influent flow to the HRAP | 4432 | $m^3/d$ | Calc. |
| | HRAP's surface area | 20000 | $m^2$ | Tested |
| | HRAP's depth | 0.3 | m | Tested |
| | Nitrogen removal rate | 20 | $g\ N \cdot m^{-3} \cdot d^{-1}$ | Seco, et al., 2018 |
| | Phosphorus removal rate | 0.3 | $g\ P \cdot m^{-3} \cdot d^{-1}$ | Seco, et al., 2018 |
| | Biomass productivity | 7 | $g\ VSS \cdot m^{-3} \cdot d^{-1}$ | García, et al., 2018 |
| | | | | |
| | Total influent wastewater flow | 21895 | $m^3/d$ | |
| | | | | |
| | Ratio Sludge Treatment/Total | 80 | % | |
| | Ratio HPAR/Total | 20 | % | |

In this scenario, HRAP was implemented and 20% of the flow was bypassed to this parallel plant. Additionally, they contribute to a reduced carbon footprint, require minimal operational intervention, and are adaptable to seasonal variations in population, ensuring reliable public health management without the need for additional treatment processes.

The resource distribution in the plant for Scenario 1 is depicted in the fig. X below. As it can be clearly seen, one more subunit is added to the process, which corresponds to the microalgal treatment.

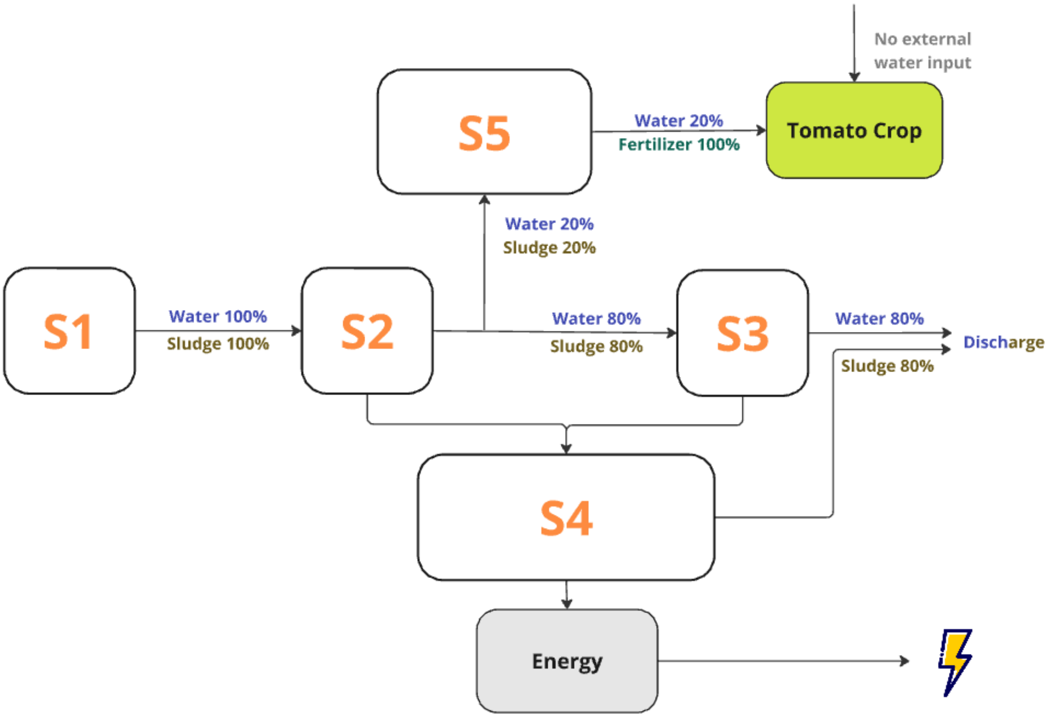


*Fig. 7. Resource distribution for Scenario 1*

#### 3.2.2.2. Energy

Since 20% of the initial flow is diverted to the parallel plant, the projected values for sludge and biogas production will decrease. The assumptions about biogas production remain the same as in Scenario 0, but the sludge production estimation differs, affecting all subsequent calculations.

HRAPs are recognized for their potential in wastewater treatment and bioenergy production, but their energy consumption remains a critical factor in evaluating their overall sustainability. Energy consumption in HRAPs primarily involves the operation of paddlewheels used to maintain water circulation and mixing, which is crucial for optimizing algal growth and nutrient removal efficiency. Studies have shown that the energy demand for operation in HRAPs reaches 0.25 kWh per cubic meter of treated wastewater (Garfí et al, 2017). Additionally, the energy costs associated with HRAPs are relatively lower compared to conventional wastewater treatment processes, such as activated sludge systems, primarily due to the reduced need for aeration. However, the overall energy balance of HRAPs can be influenced by factors such as pond depth, hydraulic retention time, and algal biomass harvesting methods, which require careful optimization to enhance energy efficiency (Posadas et al., 2015).

#### *3.2.2.3. Food*

In the agricultural sector, most parameters remain unchanged because factors such as, for example, nitrogen mineralization and drip irrigation efficiency remained constant independently the wastewater treatment technology used. However, a few additional points need to be considered:

- There is an additional input of nutrients coming from the effluent of the HRAP, i.e., the remaining nutrient content after treatment, which must be under legal limits. This amount will be added to our crops and substitute the mineral fertilizers (fertigation).
- The reclaimed water produced during the treatment in the HRAP will be used as prior water source for fertigation. If this water would not be enough to satisfy the plant requirements, groundwater will be used to complement it.

# 4. Results and discussion

## 4.1. Water

### 4.1.1. Scenario 0

The primary objective of our water research was to efficiently integrate the water treatment cycle and reuse reclaimed water within our sustainable framework. Optimization simulations, carried out in previous research (Ortega Pérez, 2023), played a crucial role in this process. In the WEF nexus, the water component serves as the foundation, underpinning our production of biogas, fertilizers, and water.

With this in mind, obtaining energy data, crucial for biogas production, was prioritized. This data is reflected in Table 10.

*Table 10. Sludge production data obtained for Scenario 0*

| Parameter | Value | Unit |
|---|---|---|
| **Primary sludge production** | | |
| **SST** | 6392.2 | kgTSS/d |
| **SST** | 125.3 | $m^3/d$ |
| **Secondary sludge production** | | |
| **SST** | 6739.7 | kgTSS/d |
| **SST** | 842.5 | $m^3/d$ |
| **Mixed sludge** | | |
| **Mix 1º y 2º** | 13132.0 | kgTSS/d |
| **Mix 1º y 2º** | 967.8 | $m^3/d$ |
| **Mix 1º y 2º** | 13569 | $gTSS/m^3$ |
| **AD Volume** | 19356 | $m^3$ |
| **SRT** | 20 | d |
| **Anaerobic digestion** | | |
| **bCOD load,1** | 0.0 | KgbBOD/d |
| **bCOD load,2** | 1472 | KgbBOD/d |
| **Mix** | 1471.8 | KgbBOD/d |
| **Volumetric loading factor** | 37.74 | $KgVSS/m^3d$ |
| **Sludge production (thickener)** | | |
| **TSS,eff** | 46000 | mgTSS/L |
| **Q,thick** | 285.5 | $m^3/d$ |
| **AD Volume** | 4282.2 | $m^3$ |
| **Volumetric loading factor** | 2.39 | KgVSS/m3d |

### 4.1.2. Scenario 1

In this integrated system, water recycling supports sustainable irrigation practices for tomato crops. Simultaneously, microalgal biomass undergoes cultivation and processing to yield nutrient-rich fertilizer. Before proceeding to calculate the quantity of fertilizer biomass derived from microalgae, it is essential to accurately determine the total biomass production. This step ensures precise assessment and utilization of the cultivated biomass for agricultural purposes.

*Table 11. HRAP Effluent properties*

| Parameter | Value | Unit |
|---|---|---|
| **Flow to HRAP** | 4432 | $m^3$/ha |
| **Biomass productivity** | 0.075 | kg/$m^3$/day |
| **Biomass** | 450 | kgVSS/d |
| **% water in biomass** | 90 | % |
| **Amount of water in biomass** | 405 | kg water |
| **Unit conversion** | 0.405 | $m^3$ water |
| **Output (reclaimed water)** | 4431.6 | $m^3$ water |
| **TN** | 8.58 | mg N·$L^{-1}$ |
| **TP** | 1.61 | mg P·$L^{-1}$ |

When algae are exposed to excess nutrients and light becomes the limiting factor for growth, most algal species typically maintain a consistent cellular phosphorus content of approximately 1% of their dry weight (Goldman, 1980). Nitrogen typically constitutes approximately 7–10% of the dry weight of a cell, in this study the value of 10% will be considered (Simon, 1971).

In field studies, the reported values for percent fertilizer nitrogen absorption (PNA) by crops typically range between 30% and 70% (Yamaguchi, 1991). This variability reflects how efficiently crops take up nitrogen from applied fertilizers under different agricultural conditions and management practices. Factors such as soil type, moisture levels, fertilizer application methods, and crop species can influence PNA. Researchers and agricultural experts often monitor and adjust fertilizer applications based on these absorption rates to optimize nutrient use efficiency and crop yield. For this study, the value of 50% is taken into account.

These assumptions and considerations are shown in the table 12.

*Table 12. Nutrient content of the microalgal biomass produced by the HRAP*

| Parameter | Value | Unit |
|---|---|---|
| **N content** | 10 | % |
| **P content** | 1 | % |
| **Dry biomass** | 45 | kg |
| **Total amount of N** | 4.5 | kg N |
| **Total amount of P** | 0.45 | kg P |
| **Portion absorbed** | 0.5 | |
| **N absorbed** | 2.25 | kg N |
| **P absorbed** | 0.225 | kg P |

In total, 45 kg of biomass was produced from the HRAP, which will be utilized as a fertilizer due to its nutrient richness. However, it is expected that only 50% of this biomass will be effectively absorbed by plants, as not all nutrients in biofertilizers are fully taken up by crops (Yamaguchi, 1991). This absorption efficiency highlights the importance of accurately estimating nutrient availability and optimizing application methods to maximize the benefits of organic fertilizers in agricultural practices.

With a daily wastewater flow of 21,895 $m^3$ and the configuration previously simulated by Ortega Perez, 2023, a certain amount of sludge is produced. The details of this sludge production are shown in table 13 below:

*Table 13. Sludge production data obtained for Scenario 1*

| Parameter | Value | Unit |
|---|---|---|
| **Primary sludge production** | | |
| **SST** | 5098.3 | kgTSS/d |
| **SST** | 99.97 | $m^3/d$ |
| **Secondary sludge production** | | |
| **SST** | 4363.0 | kgTSS/d |
| **SST** | 545.3 | $m^3/d$ |
| **Mixed sludge** | | |
| **Mix 1º y 2º** | 9461.3 | kgTSS/d |
| **Mix 1º y 2º** | 645.30 | $m^3/d$ |
| **Mix 1º y 2º** | 14661.9 | $gTSS/m^3$ |
| **AD Volume** | 12906 | $m^3$ |
| **SRT** | 20 | d |
| **Anaerobic digestion** | | |
| **bCOD load,1** | 2482.4 | KgbBOD/d |
| **bCOD load,2** | 1023.0 | KgbBOD/d |
| **Mix** | 3505.4 | KgbBOD/d |
| **Volumetric loading factor** | 0.57 | $KgVSS/m^3d$ |

| Sludge production (thickener) | | |
|---|---|---|
| **TSS,eff** | 46000 | mgTSS/L |
| **Q,thick** | 205.7 | $m^3/d$ |
| **AD Volume** | 3085.1 | $m^3$ |
| **Volumetric loading factor** | 2.39 | $KgVSS/m^3 \cdot d$ |

### 4.1.3. Comparison

The comparative data involving the output from both the water line and the sludge line. is shown in the table 14 below.

*Table 14. Comparative analysis of water production and nutrient elimination in both scenarios*

| Water | | | |
|---|---|---|---|
| **Parameter** | **Scenario 0** | **Scenario 1** | **Units** |
| **Wastewater flow** | 21895 | 17463 | $m^3/d$ |
| **Ratio CAS/HRAP** | 100/0 | 80/20 | - |
| **$DBO_5$** | 3 | 2.8 | mg $O_2$/L |
| **DQO** | 79 | 76 | mg $O_2$/L |
| **SST** | 16 | 14 | mg SS/L |
| **N total** | 9.33 | 10.2 | mg N/L |
| **P total** | 1.46 | 1.77 | mg P/L |
| **Reclaimed water** | - | 4432 | $m^3/d$ |
| **Produced mixed sludge** | 13132.0 | 9461.3 | kgTSS/d |
| **Biomass produced (biofertilizer)** | - | 450 | kgVSS/d |

Through the implementation of our system, we have demonstrated the feasibility of incorporating reused water into agricultural activities and compensating energy consumption with biogas production. This integration not only enhances resource efficiency but also supports sustainable agricultural practices.

## 4.2. Energy

### 4.2.1. Scenario 0

In the RA, KPIs correspond to the total energy consumption (e.g., gross energy consumption). Conversely, in the DS, KPIs are directly tied to the specific stage, and are calculated using the particular portion of energy consumption associated with that function, this methodology was selected for our research. The summary statistics for the database of KPIs used in the DS methodology are presented in table 15.

*Table 15. Database of KPIs for Decision Support methodology (adapted from Longo et al., 2019)*

| KPI | Stage description | KPI units | Average | St. Dev. | P90 | P10 | WWTP observed |
|---|---|---|---|---|---|---|---|
| **S1** | Pre-treatment | $kWh/m^3$ | 0.048 | 0.039 | 0.101 | 0.009 | 97 |
| **S2** | Primary treatment | kWh/kg $TSS_{rem}$ | 0.028 | 0.03 | 0.055 | 0.007 | 64 |
| **S3** | Secondary treatment | kWh/kg $TPE_{rem}$ | 0.289 | 0.246 | 0.519 | 0.108 | 87 |
| **S4** | Sludge treatment | kWh/kg TSE | 0.308 | 0.4 | 0.577 | 0.055 | 89 |

For the primary treatment stage (S2), the KPI units provided in the methodology are kWh/kg $TSS_{rem}$, which need to be converted into $kWh/m^3$. To do this, we must understand that kWh/kg $TSS_{rem}$ refers to the energy used to remove suspended solids during primary treatment. With an initial value of 292 mg SS/L and an elimination percentage of 60%, the converted value is 0.175 $kgSS/m^3$. This value is then multiplied by 0.028, which is the KPI for the given stage.

Due to the varying influent conditions, the pollution load requiring treatment fluctuates, impacting the energy and chemical requirements accordingly (Revollar et al., 2017). This is particularly relevant for the secondary treatment phase, where the KPI units are expressed in kWh/kg $TPE_{rem}$, reflecting the energy required to remove Total Pollution Equivalent (TPE). The equation below outlines how this parameter is calculated:

*Equation 1. Calculation of TPE (Longo et al., 2019)*

$$TPE = COD\ (kg_{COD}) + 20\ TN\ (kg_{TN}) + 100\ TP\ (kg_{TP})$$

To estimate these values accurately for stage S3 (secondary treatment), we analyse the total pollutants (COD, TN, and TP) removed from the system, in order to determine the total pollution equivalent removed according to Benedetti et al. (2008). For example, to determine the COD removal efficiency, we subtract the COD concentration at the end of the water treatment process from the COD concentration in the secondary treatment stage. This calculation reveals the actual pollutants removed during this stage.

From the water treatment simulation at the current stage, we derive values for COD, TN and TP, they are represented in the table below:

*Table 16. Values for TPE calculation for Scenario 0*

| Parameter | Values S3 | Discharge values | Difference | Units |
|---|---|---|---|---|
| **DQO** | 329.7 | 79 | 250.7 | mg $O_2$/L |
| **TN** | 33.9 | 9.33 | 24.6 | mg N/L |
| **TP** | 4.71 | 1.46 | 3.25 | mg P/L |

Calculating the value of TPE a value of 23356.3 $kgTPE_{rem}$ is obtained, which will be used to calculate the specific energy consumption for the whole WWTP.

Converting these values to their respective units allows us to calculate the TPE which is then multiplied by the KPI specific to the third stage to achieve the desired result.

For the fourth phase (sludge treatment), we analysed two parameters: the removal of generated sludge and dewatered sludge. The sludge under consideration is a combination of primary and secondary sludge. According to Andreoli, 2007, untreated sludge typically contains about 75% water, resulting in a dry mass content of 25%. The formula for Total Solid Equivalent (TSE) is provided below:

*Equation 2. Calculation of TPE (Longo et al., 2019)*

$$TSE = TS_{removed}(kg_{TS}) + 2TS_{dewatered}\,(kg_{TS})$$

The initial values for Scenario 0 for calculation TSE are reflected in the table 17.

*Table 17. Values for TSE calculation for Scenario 0*

| TSE calculation | | |
|---|---|---|
| **$TS_{removed}$** | $kg_{TS}$/d | 13132 |
| **Dry mass percentage** | 25 | % |
| **$TS_{dewatered}$** | $kg_{TS}$/d | 3283 |
| **TSE** | $kg_{TS}$/d | 19698 |

Taking into account the values for the average KPI and previously calculated parameters, the following data obtained. It helps us estimate the total daily plant consumption for the scenario 0.

*Table 18. Daily energy consumption values according to DS ENERWATER methodology for Scenario 0*

| Daily energy consumption according to DS ENERWATER for Scenario 0 | | |
|---|---|---|
| **S1** | 1051.0 | kWh/d |
| **S2** | 179.0 | kWh/d |
| **S3** | 6750.0 | kWh/d |
| **S4** | 6067.0 | kWh/d |
| **Total consumption WWTP** | 14046.9 | kWh/d |

In a study conducted by the Institute for Energy Diversification and Saving (IDEA, 2010) across 617 WWTPs throughout Spain, it was found that the energy consumption for treating urban wastewater accounts for 1% of the country's total energy use. The study reports that the national average power required for this treatment is 5.6 W/h.e., translating to an energy consumption of 49 kWh per h.e. per year, or 0.67 kWh per cubic meter.

The Global Water Research Coalition, consisting of 12 leading water research organizations, launched a program in 2008 aimed at achieving an energy and carbon-neutral urban water cycle by 2030. Initial estimates, based on limited data, suggest that the energy consumption for potable water treatment and supply ranges from 0.4 to 1 kWh/m$^3$. Similarly, the energy footprint for wastewater management, which includes collection and treatment, is estimated to be between 0.5 and 0.7 kWh/m$^3$. According to this data, our obtained value of 0.64 kWh/m$^3$ falls well within this estimated range.

Another energy source to consider is biogas production from anaerobic digestion (AD) of mixed sludge. It is assumed that the primary sludge exhibits approximately 95% moisture content and possesses a specific gravity of 1.02 kg/L. Other essential design parameters include:

- The digester operates under a complete-mix hydraulic regime;
- The Solids Retention Time (SRT) is 20 days at a temperature of 35°C (mesophilic conditions);
- Waste utilization efficiency (solids conversion) is estimated at E = 0.70;
- The sludge contains sufficient nitrogen and phosphorus for biological growth.
- Y = 0.08 kg VSS/kg bCOD utilized and b = 0.03 $d^{-1}$ are the yield and decay coefficients respectively, applicable at 35°C;
- The digester gas is composed of 65% methane.

Not all the produced electricity can be utilized for energy consumption due to inefficiencies in the conversion process. Specifically, the conversion factor, which represents the efficiency of transforming biogas into usable electricity, is not 100%. In our case, based on the guidelines provided by Metcalf & Eddy, 2014, the conversion efficiency is estimated to be 35%. This means that only 35% of the energy contained in the biogas can be effectively converted into electrical power, with the remainder being lost as heat or other forms of energy dissipation. Therefore, when calculating the actual electricity available for consumption, this conversion factor must be taken into account to provide a realistic assessment of energy production capabilities.

*Table 19. Biogas production data for Scenario 0*

| **Biogas production** | | |
|---|---|---|
| **Px** | 160.5 | kg/d |
| **$Q_{CH4}$ (35ºC)** | 1192.5 | $m^3/d$ |
| **$Q_{biogas}$ (35ºC)** | 1834.6 | $m^3/d$ |
| **Recovery from Biogas** | | |
| **$Q_{CH4}$ (25ºC)** | 1153.7 | $m^3/d$ |
| **Unit conversion** | 47.2 | kmol/d |
| **$E_{produced}$** | 10056820.0 | Kcal/d |
| **Unit conversion** | 42238.6 | MJ/d |
| **Electricity** | 14783.5 | MJ/d |
| **Unit conversion** | 4106.6 | kWh/d |

We also need to convert units to make sure we can accurately estimate energy production and compare the values properly. This step is essential for keeping our analysis consistent and reliable, ensuring all energy measurements are in compatible units for easy evaluation and comparison. The unit conversion for electricity produced from biogas is represented in the table 20 below.

*Table 20. Unit conversion for electricity produced from biogas for Scenario 0*

| Parameter | Value | Units |
|---|---|---|
| **Electricity produced from biogas** | 14783.5 | MJ/d |
| **1 MJ** | 0.28 | kWh |
| **Electricity produced from biogas** | 4106.6 | kWh/d |

### 4.2.2. Scenario 1

Since one fifth of the initial flow is redirected to the parallel plant, the estimated sludge and biogas production will have smaller values (table 21).

*Table 21. Sludge production data from Scenario 1*

| | | |
|---|---|---|
| **Primary sludge production** | | |
| **SST** | 5098.3 | kgTSS/d |
| **SST** | 99.97 | $m^3/d$ |
| **Secondary sludge production** | | |
| **SST** | 4363.0 | kgTSS/d |
| **SST** | 545.3 | $m^3/d$ |
| **Mixed sludge** | | |
| **Mix 1º y 2º** | 9461.3 | kgTSS/d |
| **Mix 1º y 2º** | 645.30 | $m^3/d$ |
| **Mix 1º y 2º** | 14661.9 | $gTSS/m^3$ |
| **AD Volume** | 12906 | $m^3$ |
| **SRT** | 20 | d |
| **Anaerobic digestion** | | |
| **bCOD load,1** | 2482.4 | KgbBOD/d |
| **bCOD load,2** | 1023.0 | KgbBOD/d |
| **Mix** | 3505.4 | KgbBOD/d |
| **Volumetric loading factor** | 0.57 | $KgVSS/m^3d$ |
| **Sludge production (thickener)** | | |
| **TSS,eff** | 46000 | mgTSS/L |
| **Q,thick** | 205.7 | $m^3/d$ |
| **AD Volume** | 3085.1 | $m^3$ |
| **Volumetric loading factor** | 2.39 | $KgVSS/m^3 \cdot d$ |

The assumptions regarding biogas production remain consistent with Scenario 0. The main difference lies in the estimation of sludge production, which affects subsequent calculations automatically.

*Table 22. Biogas production data for Scenario 1*

| Biogas production | | |
|---|---|---|
| **Px** | 122.7 | kg/d |
| **$Q_{CH4}$ (35ºC)** | 911.9 | $m^3/d$ |
| **$Q_{biogas}$ (35ºC)** | 1402.8 | $m^3/d$ |
| **Recovery from Biogas** | | |
| **$Q_{CH4}$ (25ºC)** | 882.3 | $m^3/d$ |
| **Unit conversion** | 36.1 | kmol/d |
| **$E_{produced}$** | 7690402.9 | Kcal/d |
| **Unit conversion** | 32299.7 | MJ/d |
| **Electricity** | 11304.9 | MJ/d |
| **Unit conversion** | 3165.4 | kWh/d |

Research indicates that HRAPs require about 0.25 kWh per cubic meter of treated wastewater (Garfí et al., 2017). The energy costs for HRAPs are generally lower than those for conventional wastewater treatment methods, such as activated sludge systems, due to a reduced need for aeration.

In table 23 below, the key parameters for energy consumption in HRAP systems are presented.

*Table 23. Calculation of HRAP operation consumption*

| Parameter | Value | Unit |
|---|---|---|
| **SEC HRAP** | 0.25 | $kWh/m^3$ |
| **Flow to HRAP** | 4432 | $m^3/d$ |
| **Daily consumption** | 1108 | kWh/d |

When considering the operation values for the Conventional Activated Sludge (CAS) system, it is important to note that the wastewater flow is reduced to 80% of its original volume. This reduction in flow subsequently lowers the energy consumption, as less wastewater requires treatment.

The calculation process is similar to the one described in Scenario 0, the results are presented in the following table 24 below:

*Table 24. Daily energy consumption values according to DS ENERWATER methodology for Scenario 1*

| **Daily energy consumption according to DS ENERWATER** | | |
|---|---|---|
| **S1** | 838 | kWh/d |
| **S2** | 143 | kWh/d |
| **S3** | 5155 | kWh/d |
| **S4** | 4371 | kWh/d |
| **Total consumption WWTP** | 10506.6 | kWh/d |

The average Key Performance Indicator (KPI) for each stage was multiplied by the corresponding value for each stage to ensure unit consistency. These stages include Suspended Solids (SS) from the primary settler, the previously calculated TPE and TSE, respectively. By applying these values to the daily flow rate of 17,463 cubic meters per day, the total daily energy consumption is determined.

### 4.2.3. Comparison

In Scenario 0, the entire daily flow of 21,985 $m^3/d$ is treated using conventional methods. This process results in the production of 4,106.6 kWh/d of energy from biogas.

This scenario does not provide any additional benefits beyond energy production. Scenario 1 splits the daily flow into two parts:

- Conventional Treatment: 17,463 $m^3$ daily, producing 3,140.3 kWh/d from biogas.
- HRAP: 4,432 $m^3$ daily, which does not produce energy directly but offers significant environmental benefits.

In Scenario 1 (CAS+HRAP), there is a noted decrease in energy production from biogas compared to Scenario 0 (CAS only). Specifically, Scenario 0 produces 4,106.6 kWh/d of energy from biogas, while Scenario 1 produces 3,140.3 kWh/d, marking a decrease of 966.3 kWh/d.

However, despite this reduction in energy output, Scenario 1 offers additional benefits that enhance the sustainability of the cycle:

1. Reclaimed water: The HRAP process in Scenario 1 generates reclaimed water, which can be utilized for irrigation purposes.

2. Biofertilizers: Additionally, biofertilizers rich in nutrients are produced through the HRAP process and can be used to meet the agricultural requirements of the crop.

Furthermore, redirecting a portion of the flow to the HRAP in Scenario 1 results in lower energy consumption costs compared to Scenario 0. In Scenario 0, there is no water reuse, leading to the necessity of groundwater pumping and treatment, which incurs additional expenses. The energy consumption for the CAS system (without HRAP) for scenario 1 is 10506.6 kWh/, which is 25% lower than for the scenario 0, making it more efficient. The similar values for energy production and overall net consumption are calculated for an agricultural community of 65 ha and equal to 24% and 34%, respectively.

This data can be view in the table 25 below.

*Table 25. Energy consumption and production data compared in both scenarios for 65 ha of tomatoes for both scenarios*

| Energy | | | | |
|---|---|---|---|---|
| **Parameter** | **Scenario 0** | **Scenario 1** | **Units** | **Comparison** |
| **Energy consumption CAS** | 14046.9 | 10506.6 | kWh/d | 25% |
| **Energy consumption HRAP** | - | 1108.0 | kWh/d | - |
| **Energy consumption groundwater pumping (65 ha)** | 2917.2 | - | kWh/d | - |
| **Energy production** | 4106.6 | 3140.3 | kWh/d | 24% |
| **Net consumption** | 12857.5 | 8474.3 | kWh/d | 34% |

Since the outflow is 4432 m³/d and 1 ha of tomatoes only requires 66 m³/d, the remaining water can be used for other farming areas within the farming community. Assuming each hectare consumes the same amount of water (66 m³/d), we can irrigate approximately 65 ha.

We need to estimate not only the energy consumption per hectare but also the total energy consumption for the entire agricultural community. This will help us evaluate the feasibility and efficiency of using reclaimed water compared to using groundwater for larger surfaces.

The results are presented in table 26, demonstrating a significant energy savings of approximately 63% for both the 1-hectare and 65-hectare gardens when using HRAP compared to groundwater.

*Table 26. Energy consumption for drop irrigation of 1 ha and 65 ha for both scenarios*

| Parameter | Type and surface | Scenario 0 | Scenario 1 | Units | Comparison |
|---|---|---|---|---|---|
| **Energy consumption** | Single unit (1 ha) | 44.9 | 16.8 | kWh/d | 63% |
| | Agricultural community (65 ha) | 2917.2 | 1072.5 | kWh/d | 63% |

## 4.3. Food

### 4.3.1. Scenario 0

As established earlier, drip irrigation has an efficiency loss of 10%. Therefore, we need to recalculate the amount of water applied to our crops to account for this loss (table 27).

*Table 27. General input data for 1 ha of tomato crop*

| Parameter | Value | Unit |
|---|---|---|
| **Water demand** | 5400 | $m^3$/ha |
| **Drip irrigation efficiency** | 90 | % |
| **Recalculated water demand** | 5940 | $m^3$/d |

Additionally, we need to consider the life cycle duration and the number of waterings required for tomatoes to grow and bear fruit. The life cycle of a tomato plant varies depending on the variety and growing conditions, but it generally consists of the following stages, which rounds up to 90 days on average:

- Germination and seedling: 7 days
- Vegetative development: 23 days
- Flowering: 20 days
- Fruit set and maturation: 40 days

On average, a tomato plant needs to be watered approximately 40 times during its life cycle. Since our flow rates are calculated on a daily basis, we need to estimate the daily water usage to match the units of measurement. The data related to the water usage requirements for a tomato plant are outlined in the table 28 below.

*Table 28. Water requirements of a tomato plant*

| Parameter | Value | Unit |
|---|---|---|
| **Life cycle** | 90 | days |
| **Average water frequency (over life cycle)** | 40 | times |
| **Average amount of water per 1 watering** | 148.5 | $m^3$/ha·d |
| **Average amount of water per 1 watering (daily)** | 66 | $m^3$/day |

To estimate the amount of fertilizer required, we first need to assess the available nutrients for plant use. For phosphorus, we begin with the P Olsen value, such as 20 mg P/kg soil for

Italian soils on average. P Olsen is a method used to estimate phosphorus availability in soil, critical for supporting plant growth. This method evaluates both agronomic factors, which pertain to plant uptake, and environmental considerations, including potential runoff or leaching. By determining the accessible phosphorus levels in soil, it helps optimize fertilizer application strategies and mitigate environmental effects.

Given these data, including an average sampling depth of 20 centimetres, a known area of 1 hectare, and a soil apparent density of 1300 kg/m³, we calculate the amount of available phosphorus in the given area. The results are provided in the table 29.

*Table 29. Calculation of the amount of phosphorus available for plants in soil in 1 ha*

| Parameter | Value | Unit |
|---|---|---|
| **P Olsen** | 20 | mgP/kg soil |
| **Sampling depth** | 0.2 | m |
| **Area** | 10000 | $m^2$ |
| **Volume** | 2000 | $m^3$ |
| **Apparent density of soil** | 1300 | $kg/m^3$ |
| **Mass of soil in the area** | 2600000 | kg/ha |
| **Amount of P in the soil** | 52000000 | mg P/ha |
| **Amount of P in the soil (unit conversion)** | 52 | kg P/ha |

Determining the phosphorus (P) content in both irrigation water and soil is crucial for accurately estimating the appropriate amount of P fertilizer to apply. This information establishes a baseline for existing nutrient levels, which is essential for preventing both over- and under-fertilization. Phosphorus available to plants is derived from multiple sources, including the soil, irrigation water, and applied fertilizers. A comprehensive understanding of the contributions from each of these sources enables precise calculation of the total P availability, thereby ensuring optimal nutrient management.

*Table 30. Calculation of phosphorus fertilizer requirements for Scenario 0*

| Parameter | Value | Unit |
|---|---|---|
| **Phosphorus crop requirement** | 65 | kgP/ha |
| **Total P effluent** | 1 | mgP/L |
| **Total P effluent** | 0.001 | $kgP/m^3$ |
| **P irrigation water** | 0.066 | kgP/ha |

| P available in soil | 52.0 | kg P/ha |
|---|---|---|
| P fertilizer requirement (P to add) | 12.9 | kgP/ha |

In case of nitrogen the crop requirements are described in the following equation 3 (Ramos et al., 2017).

*Equation 3. Nitrogen fertilizer requirement for 1 ha of tomatoes*

$$N_{to\ add} = N_{crop\ requirement} - N_{\min soil} - N_{mineralization} - N_{water\ irrigation}$$

In horticultural crops, the mineral N in the soil (primarily nitrate) is one of the most important factors, usually mineral nitrogen is the sum of nitrate N and ammonium N. According to a study carried out in the Valencian Community by Instituto Valenciano de Investigaciones Agrarias this value is equal to approximately 24 kgN/ha.

In this region, agricultural soils typically contain approximately 0.10 to 0.15 percent nitrogen in the top 20 cm layer (Horneck et al., 2011). Sampling follows the same procedure as for phosphorus analysis. Considering the amount of $N_{min}$ to be 2% of all nitrogen in soil, the value of 78 $kgN_{min}$ is obtained.

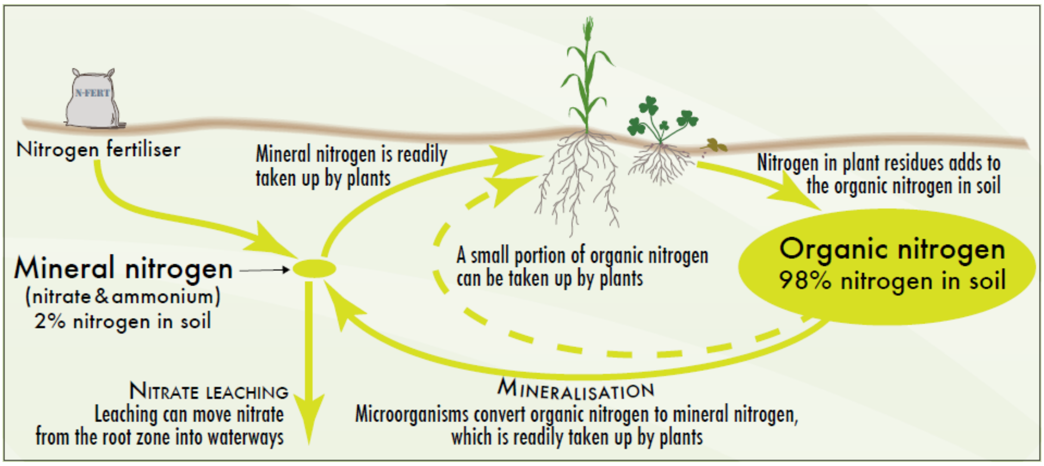


*Fig. 8. The soil nitrogen cycle and mineralisation (Carson et al.)*

By compiling all the data, the resulting table reveals that an additional 147.7 kg of nitrogen per hectare needs to be applied. This calculation integrates various factors to determine the optimal nitrogen application for agricultural purposes.

*Table 31. Calculation of phosphorus fertilizer requirements for Scenario 0*

| Parameter | Value | Unit |
|---|---|---|
| Nitrogen crop requirement | 250 | kgN/ha |
| Total N effluent | 5 | mgN/L·d |

| | | |
|---|---|---|
| **Total N effluent** | 0.005 | $kgN/m^3 \cdot d$ |
| **$N_{min}$ soil** | 24 | kgN/ha |
| **N mineralization** | 78 | kgN/ha |
| **N irrigation water** | 0.33 | kgN/ha |
| **N fertilizer requirement (N to add)** | 147.7 | kgN/ha |

In agricultural production, food loss is an unavoidable reality, and achieving a 100% yield efficiency is not possible due to several factors. Research by Boiteau et al., 2022 highlights that tomatoes, for instance, experience a significant food loss rate of 13.9%. This loss occurs throughout the growing, production and distribution chain, impacting overall yield outcomes. Furthermore, substantial investments in water and fertilizers are made during cultivation. However, a portion of these resources inevitably becomes wasted and unusable, contributing to nutrient losses. These losses not only affect agricultural productivity but also underscore the importance of efficient resource management practices to minimize environmental impact and enhance sustainability in farming. Those losses along with other information are represented in the table 32.

*Table 32. Calculation of crop, water and nutrients loss for Scenario 0*

| Parameter | Value | Unit |
|---|---|---|
| **Total crop** | 100000 | kg |
| **% loss** | 13.9 | % |
| **Loss amount** | 13900 | kg |
| **Yielded crop amount** | 86100 | kg |
| **Drip irrigation efficiency** | 0.9 | |
| **Water loss (due to drip irrigation efficiency)** | 540 | $m^3/ha$ |
| **Recalculated amount of water needed** | 5940 | $m^3/ha$ |
| **Water loss (due to food waste)** | 750.6 | $m^3/ha$ |
| **N loss** | 20.5 | kgN/ha |
| **P loss** | 1.8 | kgP/ha |

To sum up, this concludes the calculation for our agricultural component, taking into account factors such as nutrient requirements, crop losses, and resource utilization in our analysis.

### 4.3.2. Scenario 1

Taking into account the considerations mentioned in the methodology of the present study, certain adjustments must be made. With that in mind, there is a need to recalculate the amount of nutrients that should be added to the system. Here, we have to remember about the nutrient absorption, because plants can only absorb a certain portion of the fertilizers applied. The aforementioned data is outlined in the table 33.

*Table 33. Calculation of phosphorus fertilizer requirements for Scenario 1*

| Parameter | Value | Unit |
|---|---|---|
| **Phosphorus crop requirement** | 65 | kgP/ha |
| **Total P effluent** | 1.61 | mgP/L |
| **Total P effluent** | 0.00161 | kgP/m$^3$ |
| **P irrigation water** | 0.10626 | kgP/ha |
| **P available in soil** | 52 | kg P/ha |
| **P provided by HRAP biomass** | 0.225 | kg P/ha |
| **P fertilizer requirement (P to add)** | 12.7 | kgP/ha |

Since the crop demands remain constant and the amount of fertilizers will be balanced in both scenarios, the productivity and amount of water used will stay the same. What changes is the amount of nitrogen (N) and phosphorus (P) provided to the plants through water and fertilizers. Therefore, there is no need to repeat calculations for food and water losses. However, we must account for nutrient loss, as it will vary. The corresponding data is represented in the table 34.

*Table 34. Recalculated amount of nutrient loss for Scenario 1*

| Parameter | Value | Unit |
|---|---|---|
| **N loss** | 20.18 | kgN/ha |
| **P loss** | 1.76 | kgP/ha |

The calculations were conducted for a single hectare. However, if we consider a farming community with 65 hectares, for instance, the daily irrigation requirement would be 66 m$^3$ of water per hectare * 65 hectares = 4290 m$^3$ per day. This demand can be met by the HRAP output without any additional cost. In contrast, irrigating with groundwater would incur a daily energy cost of 0.68 kWh/m³ * 4290 m³ = 3141.6 kWh for groundwater extraction and treatment.

### 4.3.3. Comparison

The results calculated for both 1 ha and 65 ha areas, since it is convenient when it comes to estimation of both small and large surfaces. The results are depicted in the table 35.

*Table 35. N and P requirements for both 1-ha and 65-ha areas*

| Parameter | Area | Scenario 0 | Scenario 1 | Units | Compa-rison | Observations |
|---|---|---|---|---|---|---|
| **Nitrogen crop requirement** | - | 250 | 250 | kgN/ha | | |
| **Phosphorus crop requirement** | - | 65 | 65 | kgP/ha | | |
| **Biomass produced (biofertilizer)** | - | - | 450 | kgVSS/d | | |
| **N from biofertilizer produced by HRAP** | - | - | 2.25 | kgN/ha | | |
| **P from biofertilizer produced by HRAP** | - | - | 0.225 | kgP/ha | | |
| **Total P effluent** | Single unit (1 ha) | 0.001 | 0.11 | kgP/ha | | |
| | Agricultural community (65 ha) | 0.065 | 6.91 | | | |
| **P available in soil** | Single unit (1 ha) | 52 | 52 | kg P/ha | | |
| | Agricultural community (65 ha) | 3380 | 3380 | | | |
| **P fertilizer requirement (P to add)** | Single unit (1 ha) | 13.0 | 12.7 | kg P/ha | 3% | |
| | Agricultural community (65 ha) | 844.9 | 823.5 | | 3% | |
| **Nmin soil** | Single unit (1 ha) | 24 | 24 | kgN/ha | | |
| | Agricultural community (65 ha) | 1560 | 1560 | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **N mineralization** | Single unit (1 ha) | 78 | 78 | kgN/ha | | |
| | Agricultural community (65 ha) | 5070 | 5070 | | | |
| **N in water (groundwater)** | | 0.005 | - | kgN/ha | | Concentration in water flow which is then multiplied by liters of water to estimate the amount of nutrients per watering |
| **N in water (reclaimed water)** | | - | 0.00858 | | | |
| **N irrigation water** | Single unit (1 ha) | 0.33 | 0.6 | kgN/ha | | |
| | Agricultural community (65 ha) | 21.5 | 36.8 | | | |
| **N fertilizer requirement (P to add)** | Single unit (1 ha) | 147.7 | 145.2 | kgN/ha | 2% | |
| | Agricultural community (65 ha) | 9598.6 | 9436.9 | | 2% | |

The data indicates a slight reduction in the consumption of both N and P in Scenario 1 compared to the baseline. Specifically, the use of nitrogen decreases by 2%, while phosphorus usage drops by 3%.

Although our calculations suggest that nutrient recovery may appear insignificant from an agricultural perspective, it is important to emphasize the broader benefits of implementing this system. By integrating this approach, we are able to "close" the loop in the circular economy, ensuring that resources are reused and recycled rather than wasted. This system not only promotes sustainability but also leads to a significant reduction in energy consumption, enhancing overall efficiency. The combination of these factors makes the adoption of this system highly beneficial despite the seemingly modest impact on nutrient recovery for agriculture.

# 5. Conclusions

In conclusion, our study focused on the dynamics of the WEF nexus within a real-world WWTP. Key aspects including energy consumption and production, biofertilizer production, microalgal and nutrient valorization, and sludge management were analyzed. Implementing the WEF nexus framework has proven useful in facilitating a smoother and more integrated approach to these interconnected systems.

In terms of energy dynamics, he combined HRAP + CAS system consumes less energy than CAS-only methods, making it more attractive for saving energy and utilizing biomass. Scenario 1 demonstrated a notable 34% reduction in net energy consumption compared to Scenario 0, while energy production saw a 24% decrease, indicating a promising trend towards energy efficiency. Moreover, applying HRAP-reclaimed water for drip irrigation across both 1-ha and 65-ha areas resulted in significant energy savings of approximately 63%.

The reuse of reclaimed water has not only mitigated the reliance on groundwater but also reduced the risks associated with aquifer depletion and water quality degradation.

In agriculture, although the results show modest improvements (2% for Nitrogen and 3% for Phosphorus in nutrient recovery), our findings highlight the continued potential for further research and optimization. This includes maximizing agricultural productivity and enhancing resource efficiency within the WEF nexus framework.

Overall, our study underscores the potential of integrating WEF nexus principles in wastewater treatment and reuse systems, paving the way for sustainable resource management practices and emphasizing the importance of continued exploration and innovation in this field.

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