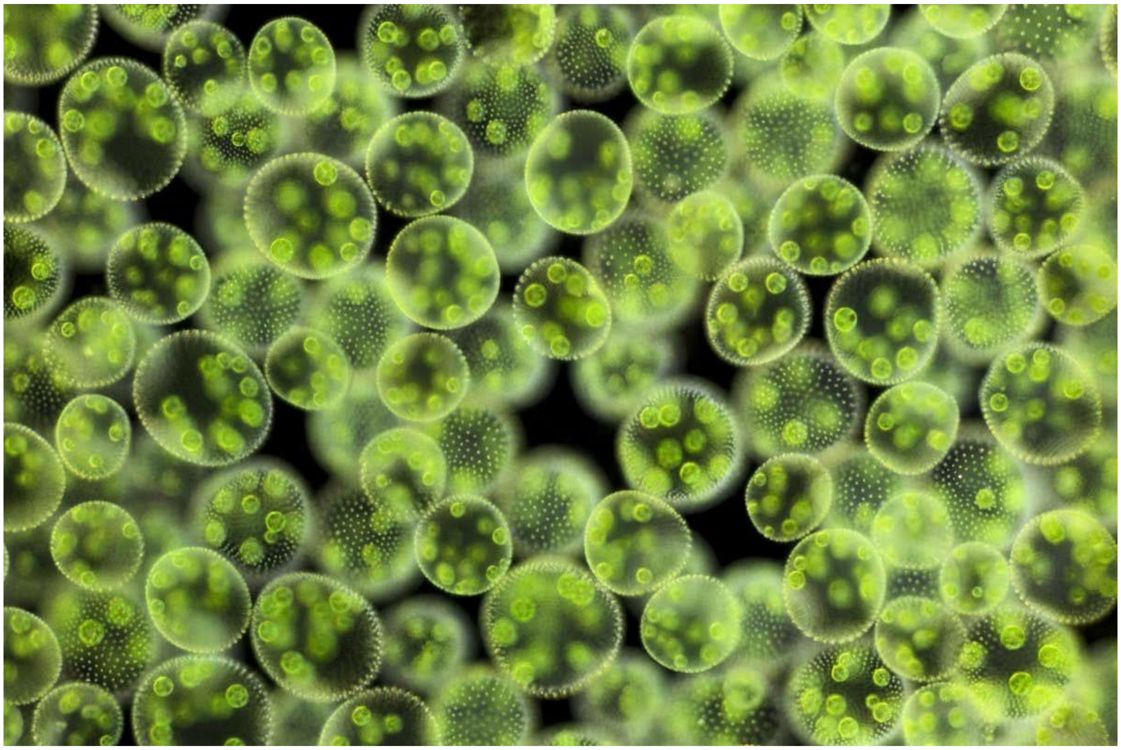
MASTER THESIS



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Integrating algae-based systems in urban metabolism as a means of mitigating its metabolic challenges. A SWOT analysis and strategic recommendations

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ABSTRACT

This thesis explores an alternative approach to promote sustainability in urban metabolism by addressing its three key challenges. With the increasing urbanization, there is a continuous need to reconceptualize urban systems for more efficient resource management. The three metabolic challenges of water supply, sewage disposal, and air pollution control hinder the optimal functioning of urban metabolism. The integration of algae-based systems within the urban infrastructure is proposed to overcome these challenges. This research focuses mainly on wastewater treatment plants. The main question that is examined is "How alga-based systems can tackle the three metabolic challenges in urban metabolism, considering the principles of circular economy". In order to answer this main question, three sub-questions have occurred. The first one examines the internal urban system, where algae can be integrated. The second one is based on a SWOT analysis, aiming to gain insights on algae in WWTPs, and the last one is focusing on strategic recommendations to scale-up the model of algae in WWTPs. Algae demonstrate the potential to create circular urban metabolism by closing resource loops and mitigating the identified challenges. By incorporating algae into wastewater treatment plants, nutrients can be efficiently removed, improving water quality and availability. Placing these plants near industrial areas allows for the capture of CO_2 emissions, enhancing air quality and reducing pollution. Additionally, algae biomass can be utilized as biofuel, bioplastic, or fertilizer, promoting circular economy principles, and closing material and energy loops.

However, large-scale commercialization and practical implementation of algae-based systems face technical, economic, and regulatory limitations. To address these limitations, a SWOT analysis was conducted, alongside three interviews, to identify key advantages and disadvantages. The SWOT analysis showed several strengths of this model, including sustainability benefits through nutrient utilization and CO2 absorption, as well as revenue generation and job creation. On the other hand, sensitivity to environmental conditions, pathogen interference, and the need for costly infrastructure and technical expertise were considered as weaknesses, whereas economic barriers, lack of public acceptance, and a fragmented framework as threats. Based on the SWOT analysis, strategic recommendations for scaling-up the algae-based systems in WWTPs were proposed, focusing mainly on leveraging strengths and opportunities through revenue generation, collaboration with academic institutions, and partnering with private investors. Strategies to address weaknesses and threats involve raising public awareness, monitoring environmental conditions, implementing government policies, fostering research and development, and establishing collaborations.

Overall, this thesis provides valuable insights into the potential of algae-based systems to enhance sustainable urban metabolism and offers recommendations for their effective implementation on a larger scale.

Key words: algae, circular economy, wastewater treatment plants, SWOT analysis, sustainability, urban metabolism

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABREVIATIONS

C	Carbon
CE	Circular economy
CO_2	Carbon Dioxide
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
N	Nitrogen
P	Phosphorus
SGDs	Sustainable Development Goals
SWOT	Strengths, Weaknesses, Opportunities, Threats
WWTP	Wastewater treatment plants

Chapter 1: Introduction

This section of the thesis provides an introductory overview of the research, including an explanation of the research problem, objectives as well as the main question and sub questions.

1.1 Background

The Anthropocene epoch is negatively influencing the Earth's balance, equilibrium that exists between the planet's various systems, whereas industrialization was the beginning of climate destruction (Steffen et al., 2007). Until today, human activity and its dominant power are still present (Dijst et al., 2018), contributing to global warming and harming the ecosystems (IPCC et al., 2007). This human activity is mainly concentrated in urban areas, leaving less space not only for the Earth to breathe but also for the citizens themselves (Rockström et al., 2009). In numbers, 56% of the global population lives in cities, a figure that is expected to rise up to 70% by 2050 (UNEP et al., 2013). In Europe, that number will reach 80 % by 2050 (EEA, 2021a). The citizens of urban areas, through their direct and indirect actions, are accountable for breaching the planetary boundaries [1](Rockström et al., 2009), starting with greenhouse gas (GHG) emissions. Urban activities contribute to 60-80% of GHG emissions (UNEP et al., 2013), while the Nitrogen (N) and Phosphorus (P) cycles, also considered planetary boundaries that are interrupted by human activities (Rockström et al., 2009) .

Therefore, there is a necessity to reconceptualize the ways in which urban systems work, in order to render their structural patterns of resource use more sustainable. An urban system can be defined as a network of cities within a region that interact with each other and the surrounding environment (Pumain, 2018). Within a single city, the urban system refers to the interconnected physical, social, and economic components that shape the city's functioning. This includes the built environment, transportation networks, energy and water systems, waste management, and social networks (Pumain, 2018). This research project focuses on the internal system of a city, as a critical component of urban metabolism(Kennedy et al., 2007), aiming to improve its sustainability. Urban metabolism examines the flow of resources, including energy, materials, and water (Wolman, 1965). It looks at the inputs, outputs, and internal processes of cities, and aims to understand the urban systems and their interactions with the environment (Wolman, 1965). The goal of urban metabolism is to promote sustainable development and reduce the environmental footprint of cities and its metabolic challenges (Dijst et al., 2018). In the context of urban metabolism, a metabolic challenge can be defined as a condition that hinders the efficient performance of metabolic flows and processes in an urban system (Kennedy et al., 2011). According to Wolman, the urban system faces three "metabolic challenges", that is, challenges related to: "the adequate water supply, the effective disposal of sewage and the control of air pollution" (Wolman, 1965).

[1] Planetary Boundaries are a set of nine environmental boundaries proposed in scientific research to help identify and quantify the limits within which human activities can safely operate to maintain Earth's essential life-support systems (Rockström et al., 2009).

As these flow streams are most of the time linear, a more circular concept would enhance this goal, making more efficient and effective resource use systems, by reducing pollution, and emissions and minimizing waste. In order to achieve this goal, a promising concept that uses algae can be introduced and implemented. Algae, these tiny microorganisms, have the ability to close loops, create a circular urban metabolism, and minimize the impact of metabolic challenges (Ji et al., 2013). Its potential beneficial effects are in the following paragraphs explained.

Introducing algae to the internal urban system is a potential innovation, especially in mitigating the three metabolic challenges. The proposed model starts with the integration of algae in Wastewater treatment plants (WWTP)(Chen et al., 2022; Ji et al., 2013). Algae need three key nutrients to grow: Nitrogen, Phosphorus, and Carbon (C) (Barsanti L. & Gualtieri P., 2014). Nitrogen and Phosphorus can be obtained when algae are added to wastewater, removing nutrients and chemicals (Zabochnicka et al., 2022). The treated water can be used for various purposes such as for landscape irrigation and industrial processes. The use of treated water from WWTP for non-potable purposes not only conserves freshwater resources but also reduces the discharge of treated wastewater into the environment (Zabochnicka et al., 2022), ensuring the first two metabolic challenges; adequate water supply and effective disposal of sewage. The third nutrient, Carbon, can be obtained in the form of CO_2, removing significant amounts of CO_2 and improving air quality (Razzak et al., 2017). However, the CO_2 in the atmosphere is not sufficient for algae, hence, this model proposes to place the WWTP next to heavy industries that emit flue gases, resolving the third metabolic challenge; control of air pollution (Ji et al., 2013; Razzak et al., 2017). The remained biomass can be used as a biofuel, enhancing circular economy and closing the material and energy loop (Zabochnicka et al., 2022).

Besides all these, algae have been identified as a promising solution to achieve several Sustainable Development Goals (SDGs) (Olabi et al., 2023), and this model can contribute to some of them. The production of biofuels from algae can improve Goal 7 (Affordable and Clean Energy) by providing a renewable and sustainable source of energy(Sutherland et al., 2021). Algae when used in wastewater treatment, support Goal 6 (Clean Water and Sanitation) by removing pollutants from water sources(Sutherland et al., 2021). SDG 3 (Good Health and Well-being) can be connected with the use of algae for CO_2 sequestration, as it can lead to improved air quality (Sutherland et al., 2021). Finally, by incorporating algae-based solutions into urban systems, cities can become more sustainable and resilient, contributing to the achievement of SDG 11 (Sustainable Cities and Communities) (Sutherland et al., 2021).

Nevertheless, all these methods have challenges, threats, and limitations, which will be analyzed further below, to understand the reasons that algae are not already commercialized on a large scale in urban areas and to develop strategic recommendations for their further utilization.

1.2 Problem statement

Climate change and urban pollution have become increasingly pressing issues that pose a threat to both the environment and human health (Rockström et al., 2009). This situation impedes cities to cope with the three metabolic challenges effectively, creating an unbearable environment for citizens (Rockström et al., 2009).

To begin, the adequate water supply is essential for the health and well-being of city residents (EEA, 2018). However, in many urban areas, the water supply is scarce or contaminated, hence the importance of wastewater treatment plants is crucial to avoid waterborne diseases, as well as other health problems related to poor hygiene and sanitation (EEA, 2018). Implementing the concept of circular economy combined with algae in WWTP, nutrients, and chemicals can be removed and then the treated water can be reused (Zabochnicka et al., 2022). This reduces the burden of water scarcity, ensuring the effective disposal of sewage back to the environment (Rockström et al., 2009). Hence, the first two metabolic challenges have been resolved, maintaining a healthy and livable city.

Air pollution is another critical environmental problem, well connected with the third metabolic challenge (UNEP, 2022). It is primarily caused by transportation and heavy industries, which are located close to the cities (UNEP, 2022). The micro-particulate matter that comes mainly from exhausting pipes has a significant impact on human health, causing respiratory and cardiovascular diseases, as well as cancer (UNEP, 2022). This type of pollution is contributing also to climate change, through the emission of greenhouse gases such as CO_2 (UNEP, 2022). To intergrade circular economy in order to reduce air pollution and GHG emissions, renewable sources of energy should be introduced. In this study, the circularity starts with the absorption of CO_2 when alga-based systems are placed next to polluting industries, improving the third metabolic challenge (Razzak et al., 2017). As a next step, the remained biomass is transformed into biofuel, closing the energy loop (Demirbas, 2010).

By implementing these circular solutions in the urban system, resource flows towards more sustainable patterns can be improved. As mentioned before, algae-based systems have the potential to play a significant role in addressing the three metabolic challenges of urban metabolism. However, another challenge lies in finding effective ways to utilize algae systems in a larger scale (Morais et al., 2021). The purpose of this research is to analyze the strengths, weaknesses, opportunities and threats (SWOT analysis) of algae systems when they are integrated in wastewater treatment plants, and to subsequently propose strategic recommendations for their upscaling in urban systems.

1.3 Research Objective

The main focus of this research is on wastewater treatment plants and the use of algae-based systems for nutrient removal. Then, when these systems are located next to heavy industries, they can contribute to CO_2 capture, hence to the improvement of air quality and subsequently human health. Finally, the utilization of the remained biomass as a biofuel can boost circular economy, by eliminating the remaining waste from this model (Chen et al., 2022; Ji et al., 2013). By implementing alga-based systems in these three domains, the three metabolic challenges can be tackled effectively.

Notwithstanding the promising potential of alga-based systems, their practical implementation has remained constrained by various technical and economic limitations, thereby primarily restricting their application to small-scale settings (Li et al., 2019; Morais et al., 2021). Moreover, there is limited research that has examined the interaction between alga-based systems and the principles of circular economy (Chen et al., 2022). As such, the present study seeks to fill this gap in the literature by conducting an in-depth analysis of this intersection and proposing a set of strategic solutions to scale-up alga-based systems.

1.4 Research Questions

In order to achieve the research objective, this study aims to answer the below research questions.

Main research question:

How alga-based systems can tackle the three metabolic challenges: "the adequate water supply, the effective disposal of sewage and the control of air pollution", in urban metabolism, considering the principles of circular economy?

Sub questions:

i. In which internal urban systems can algae-based systems be integrated?
ii. What are the Strengths, Weaknesses, Opportunities and Threats (SWOT) of algae-based systems in WWTPs?
iii. What specific strategic recommendations can be made to facilitate the scaling up of algae-based systems in WWTPs from an environmental planning perspective?

The first sub-question aims to produce knowledge about the different systems, such as WWTPs or heavy industries, that algae can be integrated in urban metabolism in order to improve its sustainability. The second sub-question focuses on the SWOT analysis on algae-based systems in WWTPs, whereas the last one will develop strategic recommendations, based on the SWOT analysis.

Chapter 2: Literature Review

This chapter illustrates the preliminary research and the analytical framework that this thesis is consisted of. At the beginning, various concepts are analyzed, starting with the concept of circular economy and then of urban metabolism. Later, it elaborates what algae are and how they can be incorporated in urban metabolism to create a more circular one, especially when integrated in WWTPs. Parallel to this, algae can sequestrate CO_2, while the remaining biomass can be transformed into biofuel. Finally, the analytical framework is explained, alongside with its method. The framework is SWOT analysis, which considers Strengths, Weaknesses, Opportunities and Threats of the model, based on the TOWS matrix.

2.1 Circular Economy

2.1.1 The concept of Circular Economy

The concept of circular economy (CE) is based on the idea of mimicking nature's closed-loop systems, where the waste from one organism becomes a resource for another (Kirchherr et al., 2017). However, that modern concept began to emerge by the end of the 1960s in response to the growing awareness of the negative impact that industrialization has on the environment, and the need to find more sustainable ways to manage resources (Reike et al., 2018). The next decade in 1970s, circular economy gained even more attention as the first energy crisis hit, embracing more the idea of recycling and reusing resources (Reike et al., 2018). By the end of 1980s, the term circular economy became more prominent, as the environmental and social challenges have been increasing due to climate change, depletion of natural resources and waste generation (Velenturf & Purnell, 2021). Since then, the concept has been evolving constantly, gaining more attention among businesses, governments and scholars, as they strive to reduce the environmental impact and create more sustainable models for economic growth (Reike et al., 2018).

This economic model targets to replace the traditional linear model of production and consumption, based on the principles of waste reduction, resource efficiency, and sustainable use of materials (Velenturf & Purnell, 2021). Under the concept of circular economy, waste and its by-products are seen as valuable resources that can be reused, recycled, or recovered, instead of being discarded as waste, following "closed loop" processes, which aim to eliminate waste generation. This leads to a more sustainable use of resources and reduces the environmental impacts that are interconnected with the extraction, production, and disposal of raw materials (Lieder & Rashid, 2016). It is worth mentioning, that by minimizing the demand for raw materials, the dependency on imports is decreased, enhancing resource security in the European Union (EU) (Reichel A. et al., 2016). CE is also deeply intertwined with social concerns, as it strives to mitigate the environmental footprint of human activities while promoting economic growth (MacArthur, 2020). On the one hand, by reducing the pollution generated by anthropogenic activities, CE can ameliorate the urban environment, while on the other hand, it can provide opportunities for employment and technological advancements (Reichel A. et al., 2016)

The European Union is a front-runner of CE, has already acknowledged the benefits of such a model, having incorporated it into its goals. EU's aim is to achieve climate neutrality by 2050, exploiting the environmental and economic benefits of such a model (European Commission, 2020). CE integration could increase EU's GDP by 0.5% by 2030, alongside 700.000 new job opportunities (European Commission, 2020). Additionally, the benefits are expanded to both individual companies and citizens. On average, manufacturing companies in the European Union spend 40% of their costs on materials, making the adoption of closed-loop models a profitable move that protects them from fluctuations in resource prices. From the perspective of citizens, circular economy offers a range of products that are not only affordable and efficient but also safe and functional (European Commission, 2020).

The European Commission recently adopted “The Circular Economy Action Plan”, a vital component of the European Green Deal and a key feature of Europe's latest plan for sustainable development (European Commission, 2020). The comprehensive new plan includes measures that span the entire product life cycle, such as product design initiatives, promotion of circular economy processes, support for sustainable consumption, and strategies to maximize the retention of resources within the EU economy (European Commission, 2020). These initiatives will help to support Europe's commitment to environmental sustainability and contribute to its long-term economic growth, considering the considers the planetary boundaries, alongside with the Sustainable Development Goals (European Commission, 2020).

The goal of this strategy is to establish a resilient and eco-friendly economy in the EU. Taking into consideration the global trend regarding the continuous consumption of biomass, fossil fuels, and water, coupled with the accumulation of all forms of waste, the need for such a plan is pivotal (OECD, 2019). The objective is to reduce waste and enhance the quality of secondary raw materials. A key component of this framework is the "Integrated Nutrient Management Plan," which promotes nutrient recovery via sustainable processes. Furthermore, the Commission aims to evaluate natural approaches for nutrient removal, such as algae, and potentially revise directives on wastewater treatment and sewage sludge (European Commission, 2020).

2.1.2 Cities and circular economy

As the global population continues to grow, cities face an increasing pressure to find sustainable solutions for resource consumption, waste generation, and greenhouse gas emissions (United Nations, 2015). Cities play a crucial role, as they are major contributors to resource consumption, consuming 60-80% of natural resources, are responsible for 50% of waste generation and emitting 75% of the global GHG emissions (Camaren & Swilling, 2012). All these actions, alongside with population growth, will result to the triplication of the urban footprint by 2030 (Seto et al., 2012).

One crucial challenge that cities are facing, is resource security (Richter et al., 2013). As cities grow continuously, their resource demand is increasingly constantly in order to meet the needs of their inhabitants, especially regarding water, energy, and food (Richter et al., 2013). This situation leads to the increased flow of goods and services in and out of the city, creating a strain on the infrastructure and resources of other surrounding areas (Richter et al., 2013). Rural areas are mainly responsible for providing food, water, and other resources to support urban growth (Hoff H., 2011). This requires the development of efficient systems for transportation, storage, and distribution, which can involve significant investment in infrastructure and technology. At the same time, rural areas are facing the negative side of the increased demand for urban development, leaving them not only with less resources, but also with negative impacts on the local ecosystem and agriculture, alongside to biodiversity loss (Hoff H., 2011).

On the other side, cities are dealing with a linear model based on inputs and outputs. These inputs would be the resources and materials that flow into the city from outside sources (fossil fuels, food, water, raw materials) (Wielemaker et al., 2018). Outputs are considered waste and emissions that flow out to the surrounding environment (air pollution, solid waste, wastewater, and sewage, GHG emissions) (Wielemaker et al., 2018).

Water scarcity is an emerging issue that more cities will have to deal with it in the future, alongside with the dependency on fossil fuels from incumbent regimes (International Energy Agency, 2008). Therefore, finding ways to recycle and reuse water is of a significant importance. Another challenge is the proper management and treatment of wastewater, ensuring that the system is operating efficiently and that the quality of the discharged water is safe for the environment (EEA, 2018). To achieve this goal, WWTPs use mainly chemical treatments, however, it is not the most sustainable option. Biological treatments are gaining popularity as a circular way to boost urban sustainability (Muga & Mihelcic, 2008). However, algae-based systems that are intergraded into existing WWTP infrastructure and can provide a more sustainable and cost-effective alternative to already existing biological treatments. Algae-based systems also have the potential to address multiple environmental challenges simultaneously, including nutrient removal, carbon sequestration, and the production of renewable energy (Muga & Mihelcic, 2008). Finally, controlling air pollution and GHG emissions is essential to improve citizens' well-being and decrease the outputs of a city.

These patterns have resulted in an abnormal lifestyle, but cities have also the potential to become hubs of circular economy innovation and sustainability (Rees & Wackernagel, 1996), minimizing waste and optimizing the use of resources by creating closed-loop systems and following a "take-make-dispose" mentality (Pearce & Turner, 1991). By adopting circular economy principles, their urban metabolism can be improved, alongside with the environmental sustainability, economic resilience, and social well-being (Velenturf & Purnell, 2021).

2.1.3 Circular economy and Urban Metabolism

Wolman (1965) was the first that introduced the concept of urban metabolism, explaining that a hypothetical model of a city is characterized by inputs and outputs. It is a concept that aims to understand the flow of resources in urban areas and the impacts of urbanization on the environment (Wolman, 1965). The urban metabolism framework consists of four components: inputs, stocks, outputs, and feedback loops (Dijst et al., 2018). Inputs are the resources that enter the city, such as food, water, and energy, whereas outputs are waste and emissions that leave the city, such as sewage, greenhouse gases, and solid waste (Dijst et al., 2018). Stocks are the resources that are stored in the city, for example, buildings, infrastructure, people and finally, feedback loops are the interactions between these components that can affect the overall functioning of the urban system (Dijst et al., 2018).

Today, most cities are following a linear urban metabolism, making them more vulnerable to external and internal shocks, as they are always dependent on material and energy supply (Brunner, 2007). Beside these dependencies, the current model follows overconsumption patterns, which are interconnected with overproduction (Wielemaker et al., 2018). Therefore, a huge amount of material and energy flows are imported in and exported out in urban cities.

Additionally, these patterns are connected with resource depletion, for instance, regarding water or fossil fuels and pollution of the environment, such as air pollution or disposal of waste (Wielemaker et al., 2018).

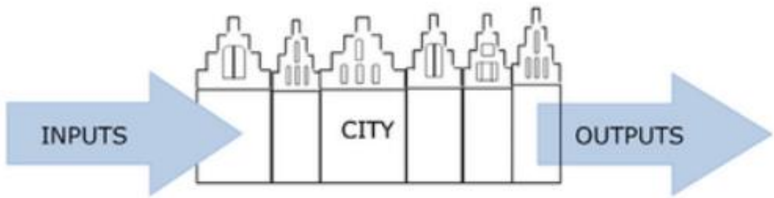

Figure 1: Linear model of urban metabolism , Wielemaker et al., 2018

Nevertheless, this linear model can be transformed into a circular one, which incorporates recycling and reuse of various urban flows. The circular urban metabolism tries to imitate the function of natural ecosystems (Broto et al., 2012), converting waste into valuable resources and reducing the need for additional extraction of raw materials (Agudelo-Vera et al., 2012) . The incorporation of circular principles can also minimize the environmental impact of urbanization, (Fernandez John & Ferrão Paulo, 2013) and of the three metabolic challenges.

Urban metabolism consists of four principal cycles; water, materials, energy, and nutrients and from these cycles, water is the primary component in terms of its mass, whereas the majority of this output is released as wastewater (Kennedy et al., 2007). Hence, it is closely connected with wastewater treatment plants as they are responsible for managing the organic and inorganic waste generated by cities(Kennedy et al., 2011), while proper management of wastewater is critical for urban metabolism as it helps to reduce the environmental impact of cities and promotes sustainable resource use (Kennedy et al., 2007).

To integrate a circular economy in the wastewater treatment sector, it is necessary to shift from linear pollutant removal to resource recovery. However, the recycled elements should be determined, ways to do it sustainably, and how to incorporate the resources in the market of circular economy (Zabochnicka et al., 2022). Algae present a viable wastewater processing alternative that can capture nutrients before they reach water bodies (Chen et al., 2022). Additionally, they can upcycle nutrients and atmospheric carbon dioxide into biomass, which can be used as a biofuel. Integrating nutrient removal, CO_2 sequestration (Chen et al., 2022), and biofuel production through microalgae systems could tackle the challenges of the linear economy around waste management and fossil-based resource dependence (Alami et al., 2021), beside the three metabolic challenges of urban metabolism.

2.2 Algae

Algae are aquatic organisms that evolved over three billion years ago and were among the first photosynthetic life forms, producing oxygen that helped make the Earth habitable for other forms of life. Until today, almost 50% of the oxygen that is produced on Earth is coming from algae (Chapman, 2013). They are photosynthetic eukaryotic organisms and are divided into uni-cellular and pluri-cellular. The uni-cellular ones are about 80% of the species and are called microalgae, while the pluri-cellular ones are the remaining percentage and are called macroalgae or seaweeds (Barsanti L. & Gualtieri P., 2014). Throughout history, algae have been used in various ways, such as the production of animal feed, fertilizers, biofuel, biomaterials, cosmetics, and pharmaceuticals (Vazqyuez Calderon, 2020).

2.2.1 Cultivation of algae

Algae can be cultivated in salty and fresh water, as well as in wastewater (Zabochnicka-Świątek et al., 2019). Microalgae can be farmed either in open ponds or closed systems, each with its own set of advantages and disadvantages (Leite et al., 2013). Open ponds are the simplest and most common method of algae cultivation. They are large, shallow ponds that are exposed to sunlight, which provides the energy required for photosynthesis. Open ponds have less complicated and less expensive construction processes, require little maintenance, and they are suitable for large-scale production (Leite et al., 2013). However, this type of cultivation is more prone susceptible to extreme weather events and water losses, due to evaporation. Open ponds typically have lower biomass productivity compared to closed systems due to their exposure to environmental variables such as temperature, light intensity, and contamination (Li et al., 2019). Additionally, the harvesting process in open ponds can be more challenging and expensive since it involves separating the algae from the water and other contaminants (Acién et al., 2017)

Figure 2: Open ponds for algae cultivation, Archimede Ricerche, 2023

Closed systems, on the other hand, are a more controlled method of algae cultivation. Photobioreactors (PBRs) are the most common closed system and can be found in different applications, such as flat panel, column or the most common one on an industrial scale, tubular PBRs (Vo et al., 2019). They are typically indoor systems that use artificial lightings and controlled conditions, such as temperature and pH, and nutrient levels to maximize growth and productivity

(Leite et al., 2013). They are less prone to contamination and weather conditions than open ponds, and they can also be used in urban areas where space is limited. Another advantage is the year-round production, compared to open systems, which is limited by seasonal variations in sunlight and temperature (Li et al., 2019). Nevertheless, closed systems are more expensive in construction, requiring high maintenance and monitoring to ensure optimal growth conditions (Leite et al., 2013).

Figure 3:Tubular PHRs, Abdel-Raouf et al., 2012

2.2.2 Properties of algae

One of the most significant properties they have is the absorption of nutrients, such as N and P, which are necessary for their growth, alongside with C. Microalgae have also a very rapid growth rate, requiring these nutrients and sunlight for photosynthesis (Zabochnicka-Świątek et al., 2019). Additionally, their energy efficiency is 20 times higher compared to the biomass of other common energy crops, such as maize. And the fact that they can be cultivated in an arid land, makes them non-competitive with food production crops or other land crops (Zabochnicka-Świątek et al., 2019). Besides these facts, algae are suitable for CO2 sequestration, in order to obtain carbon, which is also necessary for their growth (Zabochnicka et al., 2022).

2.3 Urban metabolism and algae

As mentioned before, one of the key principles of a circular urban metabolism is the closure of material and energy flows, the recycling of resources, as well as to address the three metabolic challenges (Brunner, 2007). Algae can have a significant role in this process, as they have various potentials since their integration in urban metabolism will provide several benefits and can reduce the dependency on external resources, such as water and energy (Leong & Chang, 2022). Additionally, when algae are used in a circular model, they can reduce raw material usage, as well as water and energy consumption. All of these make algae suitable for CE and for achieving Sustainable Development Goals (Zabochnicka et al., 2022).

To contribute to a more sustainable urban metabolism, this study aims to focus on the integration of algae in the wastewater treatment system, tackling the three metabolic challenges (Wolman, 1965). Algae have been proposed as a potential solution for wastewater treatment (Cai et al., 2013), as they are effective in removing nutrients from wastewater and can also be used to produce biofuels and sequester carbon dioxide from the atmosphere(Razzak et al., 2017). Algae's capacity to remove nutrients and pollutants can tackle the first two metabolic challenges; "the adequate water supply" and the "effective disposal of sewage" (Morais et al., 2021). The water demand will be reduced as the treated water can be reused for agricultural purposes or industrial procedures, while the remaining algae biomass can be used as a biofuel (Zabochnicka et al., 2022). The third challenge, regarding air pollution, can be mitigated when algae systems are incorporated in WWTPs and located next to heavy industries that emit fuel gas and GHG (Razzak et al., 2017).

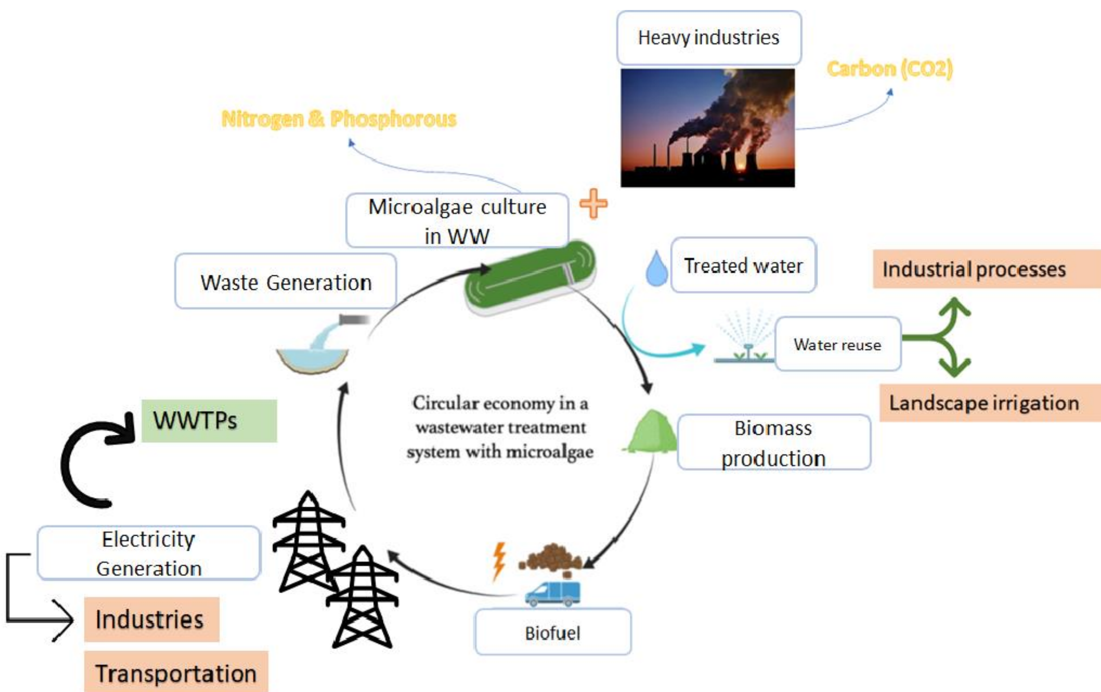

Figure 4: The circular model in a picture, Chen et al., 2022; Morais et al., 2021

2.3.1 Algae and Wastewater treatment plants

Wastewater treatment plants are crucial infrastructure for a modern society, ensuring that cities can dispose of their wastewater safely and efficiently, being as a resource of re-suppliers instead of resource end points. The history of WWTPs can be traced back to ancient civilizations, where rudimentary systems were used to manage wastewater. However, it was not until the Industrial

Revolution that the development of centralized, modern wastewater treatment began (Lofrano & Brown, 2010). Focusing on WWTP is of significant importance, as 80% of the wastewater is discharged without any treatment, while just a small percentage of treated water is eventually reused (EEA, 2021b). These numbers indicate a great potential to transform this process into a more circular and sustainable one (UNESCO, 2012).

Wastewater treatment plants have a fundamental role in managing urban waste and protecting the environment by removing pollutants and contaminants from wastewater before it is released into natural waterways. However, WWTPs are high energy consumers, which leads to increased GHG emissions. Traditional methods that remove nutrients are far from the sustainable concept and have plenty of disadvantages such as high energy consumption, CO2 emissions, waste of recyclable water and other resources (Tian et al., 2022).

Composition of wastewater

Wastewater contains organic and inorganic substances, human and animal waste, chemicals, pharmaceuticals, oils, greases, food particles, as well as heavy metals, pathogens, and other pollutants (Acién et al., 2016). Algae need three main substances in order to ensure their growth; Phosphorus, Carbon, and Nitrogen. Inorganic phosphorus and nitrogen can be found in huge quantities in wastewater, but carbon is in low concentration. Hence, it is suggested that algae can absorb the necessary carbon from CO_2 emissions coming from heavy industries and flue gases (Morais et al., 2021).

The wastewater can be divided in municipal, agricultural, and industrial (Li et al., 2019). Municipal water is considered the most suitable for algae systems, due to the high concentration of nutrients. Additionally, by increasing the concentration of CO_2 in the algae system – from 5-15%- the lipid content and productivity could also be increased, which would enhance the potential of algae to be used as biofuel, along with the nutrient removal(Ji et al., 2013b).

On the other hand, agricultural wastewater even if it contains a high concentration of nutrients, other chemical substances such as chroma, suspended solids and ammonia create an unsuitable environmental for microalgae application (Li et al., 2019). Similar to agricultural wastewater, industrial one is highly toxic, hence there is no implemented treatment procedure (Li et al., 2019).

To address these issues, researchers are exploring the potential of algae as a way to improve the sustainability of WWTPs. Algae can be considered a solution and close the nutrient loop and mitigate the first two metabolic challenges, when used in wastewater treatment plants, removing harmful pollutants and excess nutrients (Morais et al., 2021). After the removal of nutrients, the purified water can then be reused, reducing the amount of freshwater that needs to be taken from natural resources, ensuring adequate water supplies (1st metabolic challenge) (Abdel-Raouf et al., 2012). Microalgae can remove nutrients and pollutants from water through a process known as phytoremediation. In this process, microalgae absorb the pollutants and excess nutrients from the water and convert them into biomass (Marella et al., 2019). This biomass can then be harvested and processed to produce various products, such as biofuels

(Marella et al., 2019). The nutrients and pollutants that have been absorbed by the algae are taken out of the water and prevented from causing further harm. This helps to improve the quality of the water that is released back into the aquifer, securing safe disposal of sewage (2nd metabolic challenge). Moreover, it contributes to close the nutrient loop, as the nutrients and pollutants are recycled and put back into the system, rather than being released into the environment(Cai et al., 2013).

Besides phosphorus and nitrogen, algae require a source of carbon to support their growth, and CO_2 is a major carbon source for microalgae. This means that microalgae can be cultivated using flue gas emissions from industrial processes, including power plants and cement industries that produce significant amounts of CO_2 (Iglina et al., 2022). By capturing and utilizing this CO_2, microalgae cultivation can contribute to the CO_2 loop, helping to reduce greenhouse gas emissions.

However, there are three main factors that can influence nutrient removal and recovery from wastewater (Li et al., 2019). To begin, wastewater characteristics, such as pH, temperature, and concentration of heavy metals, can have a significant impact on algae's growth, nutrient removal and biomass productivity (Cai et al., 2013). Then, the light intensity and light dark cycle, followed by the CO2 concentration (Li et al., 2019). Biotic factors affect algae's growth, and the most significant factor is the alga density, where the higher it is the faster the growth and the removal of nutrients (Lau et al., 1995).

By integrating algae into WWTPs, internal urban systems can move towards a more circular and sustainable approach. In this context, the benefits and challenges of using algae in WWTPs will be explored and analyzed in this study, as well as how this approach can contribute to the development of a sustainable urban metabolism. The utilization of microalgae in wastewater treatment can aid in creating a circular economy, which involves connecting all stages of a process to reuse and enhance the value of waste and raw materials(Morais et al., 2021).

2.3.2 Algae and Carbon capture

Cities are accounting for more than 70% of the world's greenhouse gas emissions, whereas, with rapid urbanization and industrialization, the energy demand in cities has been increasing (World Bank, 2022). This has led to a significant rise in the consumption of fossil fuels, which is one of the primary sources of CO_2 emissions (World Bank, 2022). To mitigate the negative impact of urbanization, cities are exploring alternative sources of energy, finding innovative ways to reduce their carbon footprint (Kamal-Chaoui & Robert, 2009). Algae systems have emerged as a promising solution for capturing CO_2 emissions in cities, improving air quality (3rd metabolic challenge), while simultaneously treating wastewater (Chen et al., 2022).

Algae can close the carbon loop, as they need Carbon for their growth, which can be in the form of CO_2. The biomass, which has absorbed nutrients from the WWTP and CO_2 from the atmosphere, can be used as a source of energy (Alami et al., 2021). Algae-based systems can be based next to heavy industries that emit flue gas, capturing CO_2 (Iglina et al., 2022). This could reduce the amount of carbon dioxide in the atmosphere, mitigating its harmful effects on the environment and contributing to the third metabolic challenge (Morais et al., 2021).

The sequestration of CO_2 through photosynthesis by microalgae has gained significant interest as an alternative strategy to reduce carbon emissions. Compared to chemical methods, this process is less capital and energy-intensive, making it a more feasible and sustainable (Seth & Wangikar, 2015). One of the main advantages of using microalgae for carbon sequestration is that the captured CO_2 can be converted into organic carbon, which can be used as a raw material for the production of biofuels (Seth & Wangikar, 2015).

The injection of flue gases, or other residual gases, is a potential strategy to utilize CO2 emissions from various sources in microalgae cultivation. However, the effectiveness of this approach relies heavily on proper execution to avoid any inadvertent release of CO2 into the atmosphere, which could hinder any carbon capture benefits (Seth & Wangikar, 2015). Studies have shown that careful management of the injection process is critical to ensure that the captured CO2 is effectively sequestered by microalgae and not released back into the environment (Acién et al., 2016). Therefore, it is important to develop efficient and sustainable methods for utilizing CO2 emissions in microalgae cultivation to maximize the benefits of carbon capture and reduce the overall carbon footprint of industrial processes (Acién et al., 2016).

2.3.3. Algae and Biofuels

Fossil fuels are our primary source of energy, which has resulted in severe environmental and health consequences, such as air and water pollution and climate change (Perera, 2018). Biofuels have emerged as an alternative and promising solution, with advantages such as reduced greenhouse gas emissions, increased energy security, and economic opportunities for rural communities (UNCTAD, 2005). Depending on the raw material, biomass can produce first, second and third generation of biofuels (Lee & Lavoie, 2013). The first generation is produced from food crops such as corn, sugarcane, and vegetable oils, while the second from non-food crops such as switchgrass, jatropha, and woody biomass (Lee & Lavoie, 2013). Algae used in WWTP can be used to generate biofuels, making use of a previously wasted resource, and creating a closed-loop system (Morais et al., 2021).

Algae biomass is considered a successful third generation, more sustainable and environmentally friendly because it deals better with the main challenges that occur in biofuels' first and second generations (Morais et al., 2021). The third generation of biofuels is considered more promising and advantageous due to several reasons. One significant advantage is that they are produced from non-food sources, such as microalgae, which do not compete with food crops for arable land, thus minimizing the potential food and land-use conflicts and enhancing food security (Walls et al., 2019). Moreover, microalgae can be grown in non-potable water, wastewater, and other non-agricultural areas, further reducing the pressure on limited resources (Walls et al., 2019). When they are cultivated in closed systems under specific conditions, their cultivation can take place throughout the whole year (Leite et al., 2013). Third-generation biofuels also have higher energy yields and higher lipid content than first and second-generation biofuels, making them more efficient and cost-effective (Abbasi et al., 2021).

It is worth mentioning that different kinds of biofuels can be obtained from algae; biodiesel, biohydrogen, biogas and bioethanol (Morais et al., 2021). Additionally, hazardous contaminants in wastewater and hence in biomass do not affect the production of biofuel (Morais et al., 2021), compared to the production of bioplastics that the biomass and the final product should be examined for remnants of contaminants (Leite et al., 2013).

Biofuels coming from algae can be used either as transport fuels or to generate electricity for the WWTP (Zabochnicka et al., 2022). This situation can reduce the dependency on fossil fuels and enhance energy security in Europe, reducing GHG emissions (Alam et al., 2015). Moreover, the use of algae for biofuel production can contribute to the circular economy and sustainable resource management (Alam et al., 2015).

Nevertheless, the usage of algae biomass as a biofuel has a few challenges and barriers that need to be overcome (Leite et al., 2013). To begin, in many cases the technology is still limited, as well as the knowledge of markets and consumers (Vassilev & Vassileva, 2016). High capital costs are required for implementing algae-based biofuel production systems (Demirbas, 2010). Algae cultivation can be sensitive to environmental factors such as temperature, light, and pH, which can affect production and consistency, fluctuating the final price (Alam et al., 2015). Until today there are technical problems that are connected to the cultivation of algae and then their transformation to biofuels (Singh et al., 2011). Algae biofuel production requires specific processing methods and infrastructure, regarding separation of the biomass from wastewater (Slade & Bauen, 2013). Finally, there are no adequate policy frameworks and regulations for the use of algae as a biofuel (Singh et al., 2011). Many European countries have yet to establish clear guidelines and regulations for the production and use of these biofuels, which can create uncertainty for investors and businesses (European Commission, 2022). However, the EU has already goals for using algae as biofuel by 2030, aiming to minimize the fragmented governance framework, reduce the knowledge gap and enhance social awareness (European Commission, 2022).

2.4 Analytical framework

2.4.1 SWOT analysis

SWOT analysis is a widely used tool in business and strategic planning, but its origins can be traced back to the 50s and 60s, at Harvard Business school, developed by George Albert Smith Jr. and C. Roland Christensen (Hill & Westbrook, 1997). Later, the concept was introduced again by Albert Humphrey, a management consultant who led a research project at Stanford University (Hill & Westbrook, 1997). The goal of his project was to identify the reasons of success and failure of businesses. Humphrey and his team developed a framework that assessed a company's internal strengths and weaknesses, as well as external opportunities and threats (Puyt et al., 2023). This framework became known as SWOT analysis, and it quickly gained popularity as a useful tool for strategic planning in a variety of industries and organizations, as well as among scholars (Hill & Westbrook, 1997). Today, SWOT analysis remains a valuable tool for businesses and organizations to evaluate their position in the market and make robust decisions about their future direction (Gürel, 2017).

A SWOT analysis is considered as a strategic planning framework, which is used to identify and analyze the internal strengths and weaknesses of an organization, as well as external opportunities and threats. There are different SWOT analysis methods, which examine both internal and external factors that may impact the ability of any business or organization to achieve its objectives. On the one side, strengths and weaknesses are connected to internal factors such as the organization's resources, capabilities, and limitations, whereas opportunities and threats refer to external factors such as market trends, competition, and regulatory changes(Gürel, 2017). The purpose of a SWOT analysis is to identify areas where academics, organizations and businesses can improve and develop a strategic plan to take advantage of its strengths and opportunities, address its weaknesses, and mitigate existing threats (Gürel, 2017).

In a similar study, SWOT analysis was used as an analytical tool to evaluate and identify municipal WWTPs regarding their current environmental management and one based on international standards. The research was carried out in Mexico, and SWOT analysis was utilized as a complementary analysis tool for identifying the internal and external factors that aid in identifying challenges and opportunities, ultimately leading to decision-making in environmental initiatives (Herrera-Navarrete et al., 2022).

2.4.2 SWOT analysis methods

There are several SWOT analysis methods, with their advantages and disadvantages, and each one can be used depending on their specific circumstances. However, all of them are strategic planning tools that help the identification of strengths, weaknesses, opportunities, and threats of a model or system (Gürel, 2017).

To begin, the TOWS Matrix can develop strategies that use their strengths to take advantage on external opportunities while mitigating threats, while it provides a more structured framework for developing specific strategies (Weihrich, 1982). In other words, the TOWS matrix starts with the external aspects (threats and opportunities) and then moves to the internal ones (strengths and weaknesses), while the traditional SWOT matrix starts with the internal aspects (Gürel, 2017).

SWOT combined with SMART (Specific, Measurable, Achievable, Relevant, and Time-bound) sets specific, measurable, achievable, relevant, and time-bound goals (Gürel, 2017). SWOT combined with MADM (Multiple Attribute Decision Making) uses a “multi-attribute decision-making” approach to evaluate and prioritize strategic options (Gürel, 2017). Fuzzy SWOT analysis is a mathematical framework that also considers the uncertainty of data (Ghazinoory, 2007). Spatial SWOT analysis considers geographical factors “across time and space” that may affect a business (Øivind Madsen, 2016).

Quantitative and qualitative SWOT analysis combines both types of data to provide a more comprehensive evaluation of the business environment (Gürel, 2017). The SWOT analysis combined with legal (PESTEL) framework evaluates the external political, economic, social, technological, environmental, and legal factors that impact the organization's operations and strategies (Benzaghta et al., 2021). Finally, SWOT ANP (analytic network process) is another decision-making tool that evaluates strategic options based on a network of interdependent factors (Benzaghta et al., 2021).

This research has followed the TOWS Matrix method, as it can create robust strategic recommendations, by focusing on the external and internal factors. It is further elaborated under the sub-chapter “3.1 Research Framework”.

2.4.3 Urban planning methods

Urban planning has a significant role in shaping the construction of cities, aiming to create resilient communities that meet the needs of their inhabitants, both today and in the future, while it is responsible for increasing their sustainability and livability (Huxley & Inch, 2020). The regulation of the built environment and urban design are part of urban planning, alongside with social, economic, and environmental factors (Mohanty & Kumar, 2021). The main challenges that urban planners are facing are connected with transportation, land use, housing and finding the balance between all these, combined with environmental sustainability and livability(Mohanty & Kumar, 2021). These challenges are combated with various urban planning methods, depending on the circumstances (Sailus, 2023).

- Strategic urban planning focuses on a long-term approach and seeks to develop a comprehensive vision for the entire urban area, identifying all necessary actions and policies. It should involve different stakeholders, including government officials, community groups, as well as the private sector (Halla, 2007; Sailus, 2023).
- Land use planning is focusing on the regulation of land use in specific a given area, including zoning laws, policies, and legislations (Barton, 2009; Sailus, 2023).
- Economic development planning: Economic development planning aims on the promotion and management of economic growth, including the creation of new businesses and job opportunities (Cowell, 2013).
- Environmental planning is characterized by the management of natural resources and the protection of the environment in the urban areas, including water resources, air quality, and green spaces(Mersal, 2016; Sailus, 2023).
- Infrastructure planning is the process of designing the physical structures and systems necessary to support the development in an efficient way (Adshead et al., 2019; Sailus, 2023).
- Urban revitalization refers to the process of renewing and improving urban areas, which experience a decline (Ramlee et al., 2015).
- Master planning is method for developing new projects on untouched land, starting from the beginning (Halla, 2007; Sailus, 2023).

Chapter 3: Methodology

This chapter describes the steps that were taken in order to answer the main and sub questions. It illustrates the research framework, research strategy, data collection and data analysis.

3.1 Research Framework

A research framework is a visualization used in research to structure the research process and achieve the research objective (Verschuren & Doorewaard, 2010). In this study the research objective was to define the threats and weaknesses of scaling up the integration of algae in WWTP and then suggest strategic recommendations. The research evaluated this model through SWOT analysis, examining its Strengths, Weaknesses, Opportunities and Threats. The most suitable method for conducting SWOT analysis was the TOWS matrix because it can create strategic recommendations for the company or the proposed model, which aligns with the research objective of this study (Weihrich, 1982). As mentioned before, the SWOT matrix starts analyzing Strengths and Weaknesses (internal aspects), whereas the TOWS starts from the external aspects. This reversed approach identifies potential threats and opportunities and then focuses on how internal strengths and weaknesses can be used to address these factors (Weihrich, 1982).

A SWOT analysis was conducted by following a structured methodology (Gürel, 2017). Firstly, the internal and external factors were identified. As a next step, these factors were categorized into strengths, weaknesses, opportunities, and threats. After analyzing and assessing them, strategies based on the analysis were developed (Gürel, 2017). The analysis was conducted using literature review and interviews with companies and experts, as it is important to involve key stakeholders in the process to ensure a comprehensive and accurate analysis and results (Gürel, 2017).

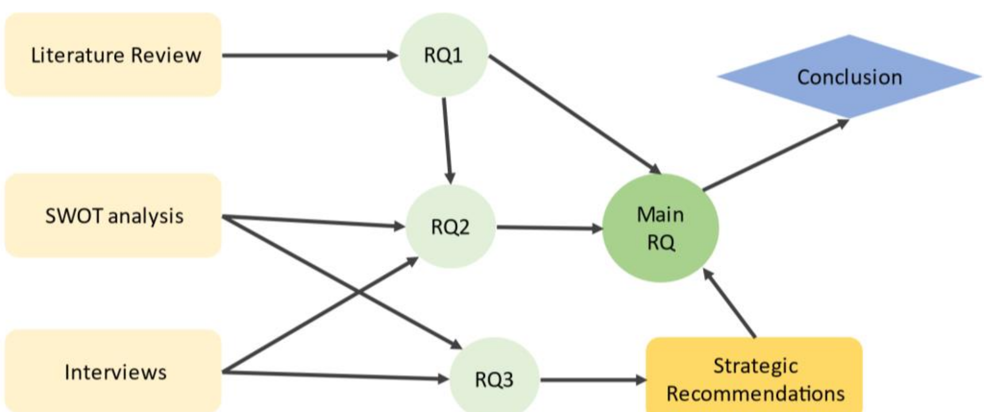

Figure 5: Workflow of Research Strategy, Own elaboration

Furthermore, after analyzing and comparing the various types of urban planning, the domain of environmental planning was considered the most appropriate for this research. Environmental urban planning is an important factor in sustainable development in urban areas. This method seeks to promote environmentally responsible practices in urban design, construction, and management, in order to reduce the negative impact of urban development on the natural environment, improving the quality of life for residents (Mersal, 2016). One overarching principle is the conservation and protection of natural resources. In this study, this can be ensured with the safe disposal of treated water back into the environment, tacking the 2nd metabolic challenge. Additionally, environmental urban planning is connected with the improvement of air quality (Mersal, 2016), which can be achieved by CO_2 capture from algae-based systems, mitigating the 3rd metabolic challenge. Finally, it promotes waste reduction and renewable energy recourses (Mersal, 2016). This goal is accomplished when algae biomass is transformed into biofuel and with the reuse of wastewater, achieving the 1st metabolic challenge.

3.2 Research Strategy

The aim of this research was to propose strategic recommendations on WWTPs for scaling up algae-based systems, in order to improve the sustainability of urban metabolism. To achieve this goal, a comprehensive and robust research strategy is essential.

The first step to reach this goal was to find ways to answer the research sub-questions. To begin, the first sub-question "In which internal urban systems can alga-based systems be integrated? " was answered through literature review of past research in the domains of WWTPs, heavy industries and algae, as well as CO_2 sequestration. Preliminary keywords for the literature review are provided in section 3.3. Regarding the second sub-question, "What are the Strengths, Weaknesses, Opportunities and Threats (SWOT) of alga-based systems in WWTPs?, a combination of literature review and interviewing relevant companies or algae projects was conducted, to enhance the validity of the SWOT analysis. The SWOT analysis, which is based on the TOWS matrix, led this research to strategic recommendations, which, in conjunction with the scope of environmental urban planning outlined previously, provided the answer to the third sub-question "What specific strategic recommendations can be made to facilitate the scaling up of algae-based systems in WWTPs from an environmental planning perspective?". To propose these recommendations, the main focus was on threats and weaknesses, considering the possible opportunities and strengths as a solution, if applicable. These strategic recommendations were based on literature review and interviews with companies and alga projects.

Finally, the main research question "How alga-based systems can tackle the three metabolic challenges in urban metabolism, considering the principles of circular economy? ", was answered after considering the literature review, SWOT analysis and interviews.

Research (Sub)-Question	Data/Information required to answer question	Sources of data
In which internal urban systems can algae-based systems be integrated?	Various domains that algae-based systems can be integrated.	Literature review: Secondary data, published articles, books, reports
What are the Strengths, Weaknesses, Opportunities and Threats (SWOT) of algae-based systems in WWTPs?	Strengths, Opportunities, Weaknesses and Threats of algae-based systems, when integrated in WWTPs	Secondary data; Literature Review Primary Data; Interviews with companies & algae projects
What specific strategic recommendations can be made to facilitate the scaling up of algae-based systems in WWTPs from an environmental planning perspective?	Based on SWOT analysis, recommendations will be proposed	Using answers from previous questions Secondary data; Literature Review Primary Data; Interviews with companies & algae projects

Table 1: Methods per research sub-question, Own elaboration

In this research study, the selected research unit is WWTPs, whereas the geographical borders of this study are the European Union. Beside these, the focus is municipal wastewater from cities, setting aside other types of water, as well as other spatial units. Moreover, the mentioned industries and sectors, such as heavy industries that capture CO2 and the biofuel sector, were not examined, and analyzed in detail.

Nevertheless, this research had a few limitations, as not all companies that are working on wastewater with algae were contacted or answered. This might led to an incomplete collection of data, as the sample size of the companies and alga-projects might not be sufficient. Avoiding bias was also an obstacle, as some companies are focusing on marketing their products and give information aiming to abuse the market.

3.3 Data collection

In this section the data collection process will be analyzed. The principal component of this research entailed the collection of secondary data through a comprehensive review of existing literature, using Google Scholar, Scopus, and scientific magazines as databases, and considering only articles in English. At the beginning of this research and to comprehend the concept of circular economy, algae and urban metabolism, the next key words were used: “circular economy”, “urban metabolism”, “algae and circular economy”, “algae in closing the loops”. Then, the keywords became more targeted, such as “algae and urban metabolism”, “algae in WWTP”, “algae and biofuels”, “algae and CO_2 capture”. Secondary data collection and analysis aimed to answer the first and partially the second and third sub-question.

To answer in a more precise and scientific way the second and third sub-question, primary data were collected by interviewing companies. More specifically, the primary data were collected through semi-structured interviews with representatives from selected companies and algae projects that have experience in WWTPs, as well as in biofuel generation from algae and CO_2 capture. Below are stated the people that were interviewed. The selection criteria for the interviewees in this study were carefully considered to ensure a comprehensive and diverse perspective on algae-based systems in wastewater treatment, whereas experts and professionals from the academia and industry were contacted, while they should be based in Europe.

Name of Interviewee	**Role in the Industry**
Bernard Willems	Manager at InnoLab[2]
Alla Silkina	Senior Researcher at Swansea University
Marcel Janssen	Assistant Professor at Wageningen University and Member of AlgaePARC

Table 2: List of Interviewee’s names, Own elaboration

The interviews were conducted online, via Teams. The questions aimed to create a more detailed understanding on the Strengths, Weaknesses, Opportunities and Threats that the integration of algae-based systems might have in WWTPs. Additionally to this, open questions were included for strategic recommendation on scaling-up the proposed model. The interviews were recorded, with participants' consent, and then were transcribed for analysis, always following a transparent procedure. Below are mentioned the questions for the interview.

Questions:

1. Where do you use algae and how can they contribute to sustainability?
2. What would you consider as an internal Strength and external Opportunity of your model?
3. What would you consider as internal Weakness and external Threat of this model?
4. If the model is in an experimental phase, how are you aiming to scale it up? Which could be the limitations in the future?

Overall, the combination of primary and secondary data provided a holistic and robust understanding of the SWOT analysis, which led eventually to the strategic recommendations.

3.4 Data analysis

The data analysis in this research was carried out in two phases to achieve the research objective. The first phase involved the analysis of secondary data collected from literature review, while the

[2] InnoLab: European Laboratory Expert in Biomass Valorization

second phase focused on the analysis of data collected through semi-structured interviews with companies and projects. The collected data both from literature review and interviews was analyzed by using qualitative data analysis method.

On the first phase, literature review was conducted to collect data for the all research questions. Regarding the second sub- question, the secondary collected data were examined and analyzed in a way that created a comprehensive SWOT analysis, considering all four aspects (Strengths, Weaknesses, Opportunities, Threats). The creation of the TOWS matrix was the fundamental basis to answer the third sub-question, regarding strategic recommendations.

On the second phase and parallel to the first one, interviews were conducted. The data collected from the interviews was analyzed using content analysis to identify the Strengths, Weaknesses, Opportunities, and Threats associated with algae-based systems in WWTPs. Content analysis was used for the interviews, since it involved analyzing verbal language, in order to identify common patterns with the literature review.

Considering all the previous actions, the main research question was answered, alongside with proposing strategic recommendations for scaling-up the algae-based systems in WWTP and drawing, finally, a conclusion.

Figure 6: Steps for data analysis, Own elaboration

3.5 Ethical Considerations

For the purpose of this research information from interviewers was gathered. Therefore, a form of consent for the participants was sent in prior the interview, emphasizing to be read carefully and signed when needed. The information of voluntary participation was highlighted, as well as their right to withdraw from the interview or decline the interview without giving any explanation or having any consequences. All information was kept in confidentiality and anonymity, upon request. On Appendix I, the form of consent can be found.

Chapter 4: Findings

This chapter presents the findings of the SWOT analysis, as well as the data that were collected by the interviews. The findings of the SWOT analysis and the interviews are collected to answer the second and subsequently the third sub question. The required data for the first sub question were collected under the chapter “Literature Review”. All (sub)- questions are answered in detail under the chapter 5 “Discussion”.

4.1 SWOT Analysis

This section is analyzing SWOT analysis, which is targeting on algae-systems in WWTPs. More specifically, this analysis is using the TOWS matrix, starting from the external factors (Threats and Opportunities) and moving to the internal factors (Weaknesses and Strengths). Algae-based systems can improve the sustainability of urban metabolism in various ways. They can effectively remove nutrients, particularly nitrogen and phosphorus from wastewater plants (Cai et al., 2013), while they can capture the CO2, as they need the carbon for their growth (Razzak et al., 2017). Then, algae biomass can be used to produce biofuels, closing the material and energy loop in the urban systems (Leite et al., 2013). All these factors are crucial to tackle the three metabolic challenges and create a more circular urban metabolism. Nevertheless, this research is using the TOWS matrix, which is focusing on algae-based systems in WWTPs, in order to explore the limitations of such a system and ways that the algae systems can be scaled-up.

Regarding the classification process as external or internal, as well as their categorization under the different elements of SWOT analysis, several criteria were considered. On the one hand, factors beyond the control of the company or project were classified as external, such as economic barriers related to different and competitive markets, legal factors, social issues, and technological advancements. On the other hand, various elements within the influence of the organization were classified as internal, including profit generation, weaknesses and strengths related to processes, technology, and technical expertise.

The table below presents the TOWS matrix in summary.

Threats	Opportunities	Weaknesses	Strengths
Competition	Circular economy	Sensitivity to environmental factors	Sustainability
Economic barriers	Water reuse	Risk of contamination	Efficiency
Public acceptance	Economic opportunities	Harvesting challenges	High growth rate
Environmental risks	Regulations	Technological barriers	Potential revenue
Regulations	Research and development	Technical expertise	

Table 3: TOWS matrix, Own elaboration

Threats

- **Competition**: Algae-based systems face competition from other wastewater treatment methods, such as traditional activated sludge systems. If algae-based treatment is not cost-competitive or does not receive sufficient support, it may struggle to succeed in the market or to compete with more established technologies (Acién et al., 2016; Morais et al., 2021).
- **Economic barriers:** These systems may require significant initial investment, which can be a barrier to their adoption (Mohsenpour et al., 2021), as they are still in their early stages of development, and therefore, the technology may not be cost-competitive which makes it difficult to attract investors(Shams Forruque et al., 2022). The initial investment may include the cost of setting up the necessary infrastructure, such as cultivation ponds, photobioreactors, and processing equipment, as well as research and development costs for developing and optimizing the technology (Shams Forruque et al., 2022). Overall, the financial resources needed may deter potential, external investors or organizations from investing and hence embracing algae-based systems, especially if they already have established a cost-effective traditional treatment method, alongside with a more safe and secure technology.
- **Public acceptance**: Lack of public awareness and understanding could hinder their adoption (European Commission, 2022). Many people may not be familiar with the concept of using algae for wastewater treatment, making them hesitant to support it, having also negative perceptions of the technology (European Commission, 2022).
- **Environmental risks:** Potential release of algae into surrounding water bodies can lead to eutrophication and other environmental risks if not properly managed (Abdul Latif et al., 2022).
- **Regulations:** Implementation of algae in wastewater may face regulatory barriers or challenges related to permitting and land use (Acién et al., 2016). According to the European Commission, there is also a fragmented framework on algae cultivations, which needs to be improved (European Commission, 2022).

Opportunities

- **Circular economy**: The use of algae in wastewater treatment aligns with the circular economy principles of resource, recovery, and reuse (Mohsenpour et al., 2021). As algae remove nutrients from the wastewater, the treated, water can be reused for other purposes, such as agriculture (Cai et al., 2013), while the remaining biomass can be used as a resource of energy, since it can be transformed into biofuel. Hence, this new source of energy can be used by the WWPTs closing the energy loop (Leite et al., 2013).
- **Water reuse**: Following the circular model, algae can be used to treat wastewater to a high standard, allowing it to be reused for non-potable purposes, such as irrigation or industrial processes (Cai et al., 2013).

- **Economic opportunities:** Algae can be used to produce a range of high-value byproducts, creating economic opportunities for businesses and communities (European Commission, 2022). As mentioned before, the biomass can be transformed into other products, such as biofuel or even fertilizers, creating a new product market (Leite et al., 2013). However, other forms of economic opportunities could be developed, related to job creation for the operation and maintenance of algae-based wastewater treatment systems (European Commission, 2022).
- **Regulations:** Regulations and policies that promote the use of sustainable wastewater treatment methods, such as algae-based systems, can create opportunities for their wider adoption (European Commission, 2022). One potential benefit of such policies is that they can address some of the economic barriers, especially when governmental bodies are implementing policies that provide financial incentives for businesses to invest in these systems (European Commission, 2022). Additionally, regulations and policies could address some of the environmental risks, such as the restriction of certain chemicals in wastewater treatment (European Commission, 2022).
- **Research and development:** There is an opportunity for further research and development, including the optimization of system design, algae selection, and nutrient recovery (European Commission, 2022). This can boost other innovations or improve the current technology, making the system more efficient and effective (European Commission, 2022).

Weaknesses

- **Sensitivity:** Algae can be sensitive to variations in temperature, pH, and nutrient levels, which could affect their effectiveness in nutrient removal in WWTPs (Li et al., 2019). Low light transmissivity is another limitation that WWTPs have to deal with, as light is essential for photosynthesis. Light transmissivity can occur when there is limited sunlight in the area that the WWTP is located, or when the water is blear (Nguyen et al., 2022). Pathogens that are in the wastewater can negatively influence the treatment process (Acién et al., 2016).
- **Risk of contamination:** These systems can be vulnerable to contamination by pathogens or pollutants, which can affect the quality of the algae and its biomass and pose a risk to human health (Nguyen et al., 2022). The causes of contamination could be improper storage, environmental conditions, or failure of the equipment (Nguyen et al., 2022). Finally, any type of contamination could lead to the loss of valuable biomass and reduce the efficiency of the treatment process, negatively affecting the revenue (Nguyen et al., 2022).
- **Harvesting challenges:** Algae are tiny microorganisms that when they are used in WWTPs are hard to be separated from water and hence to collect the biomass for further uses (Nguyen et al., 2022). The process of harvesting requires specialized equipment, such as

centrifuges, filters, and dewatering technologies (Christenson & Sims, 2011). These technologies are expensive to implement, making the whole system less economically effective, considering a larger scale. Finally, the current limitations in cultivation technology, such as photobioreactors and open ponds, restrict the scalability of these systems, because they still require significant amounts of land, water, and energy (Christenson & Sims, 2011).

- **Technological barriers:** As there is lack of advanced technology in order to scale -up the algae-based system, most of the implemented alga systems are on a pilot phase or on laboratory research (Morais et al., 2021). There may be challenges in designing and implementing efficient harvesting systems to collect the algae biomass. In addition, the lack of appropriate monitoring and control technologies makes it difficult to optimize the treatment process and ensure consistent performance (Morais et al., 2021). Furthermore, the equipment and infrastructure required to support the growth and harvesting of algae may be costly, limiting the feasibility of larger-scale model. However, the economic barriers are well connected with the ability to scale-up these systems (Li et al., 2019).
- **Technical expertise:** The design and operation of algae-based systems requires technical expertise in areas such as biology, engineering, and chemistry. This means that wastewater treatment plants should seek advanced expertise(Nguyen et al., 2022). In addition, the lack of technical expertise can lead to poor performance, which can undermine public trust in their effectiveness (Nguyen et al., 2022).

Strengths

- **Sustainability:** Algae integrated in WWTPs can be considered as a sustainable way to treat wastewater, since they can absorb nutrients, especially nitrogen and phosphorus, as well as CO_2 to grow, alongside with sunlight (Cai et al., 2013). Additionally, algae do not require fertilizers or other supplements, as they get all they need from the wastewater (Mohsenpour et al., 2021).
- **Efficiency:** Algae-based systems can be more efficient than traditional wastewater treatment methods, because they can remove more nutrients, such as nitrogen and phosphorus, from the wastewater (Acién et al., 2016). Parallel to nutrients, algae absorb other pollutants from wastewater, such as heavy metals, organic compounds, and pharmaceuticals (Acién et al., 2016).
- **High growth rate:** Algae can grow at a rapid rate, which means they can treat large volumes of wastewater in a relatively short amount of time, creating also larger amounts of biomass (Yadav et al., 2021).
- **Potential Revenue**: Algae have gained significant attention in recent years due to their various commercial applications (European Commission, 2022). Their biomass has the potential to be transformed to biofuels, such as biodiesel and biogas, and later on sold, providing not only a renewable source of energy but also a source of income for the

facility (Leite et al., 2013). Beside biofuels, there are other commercial applications of algae biomass, for instance, fertilizers, pharmaceuticals, or bio-plastics (European Commission, 2022). Nevertheless, strict regulations are required when biomass is used for the later uses, as it might contain other chemicals, heavy metals and toxic substances that could be transmitted to people and cause harm (Morais et al., 2021).

4.2 Interview findings

This sub-chapter is presenting the main key parts of the interview discussion and the necessary information, which will be analyzed in the discussion chapter.

Interview with Bernard Willems, manager at InnoLab:

In the first interview Bernard Willems (B. Willems, personal interview, 17 May, 2023) mentioned that algae can contribute to produce food or feed additives but not as a protein replacement for soybean for example, because for that the production cost is 10 to 20 times to high. As a strength of the model, when algae are used in wastewater in the CO2 sequestration, which has a high potential to create a clearer atmosphere. Additionally, algae can have a rather low-cost input material to produce high value end products, such as fertilizers. A crucial notice is that they need to be cultivated in a closed building that is well isolated and not in greenhouses which have too many variations due to the weather. On the other hand, as a weakness, he considered the large surface that is required in order to cultivate algae. The already competitive market is considered as a threat for the end-product and in most cases not enough product is produced to deliver to the consumer. Hence, it is unknown quite how much biomass the company will produce in order to have a stable market and customers. Finally, to scale-up the model, investors and funding need to be placed on these systems.

Interview with Alla Silkina, Senior Researcher at Swansea University

The second interview with Alla Silkina (A. Silkina, personal interview, 23 May, 2023) had a more detailed perspective of algae in wastewater. According to her, as a strong point, algae can grow in different types of water, such as waste or marine, and it can cope efficiently with waste material. This means that algae can remove nutrients from waste streams and later on can be used as fertilizers. Furthermore, one significant point is regarding the carbon neutrality. To continue, she explained that fertilizers is a more vital option for the biomass, compared to biofuels, since other existing fuels are cheaper and cannot compete with biofuels coming from algae biomass. Additionally, the biomass is full of nutrients and it would be more valuable to convert it into something more useful. Regulations and social acceptance were the two main limitations that she mentioned, in order to scale-up this model. Finally, she proposed that a closer look to the process in order to achieve a better understanding on the needed technology and cost is required to scale-up the system, alongside with people with more applied and technical skills.

Interview with Janssen Marcel, Assistant Professor at Wageningen University and member of AlgaePARC

The third interview with Janssen Marcel (M. Janssen, personal interview, 9 June, 2023) started by mentioning that the scale-up should be done by companies, as they have the capital. Again, he agreed that the algae biomass should be transformed into fertilizer, instead of biofuel, as the current fuels are very cheap. As a weak point he mentioned that algae cultivation required large surface to treat the wastewater, which means also high construction and equipment cost. Lack of funding, stability and technical skills are the hurdles regarding the bigger scale, whereas building a system that can last long term, e.g. 50 years instead of ten, can improve the economics drastically.

Chapter 5: Discussion

This chapter answers the main research question and sub-questions, considering all the collected, secondary and primary, data. Each question is discussed in a different sub-category, also having interconnections between each (sub)-question and answer. The main research question is answered in the end, after considering all previous questions.

5.1 Internal urban systems and algae-based systems

As mentioned in the previous chapter of "Literature Review", algae-based systems can be integrated in various internal urban systems, such as wastewater treatment plants, CO_2-intensive industries, and biofuel industries (Acién et al., 2016). These algae systems have emerged as a promising technology for integration into various internal urban systems, offering potential benefits in terms of sustainability, resource utilization, regarding water and fuels, and a less polluted atmosphere (Cai et al., 2013). This research focuses mainly on a key internal urban system where algae-based systems can be effectively integrated: wastewater treatment plants, where the other two forementioned systems are incorporated though circular economy.

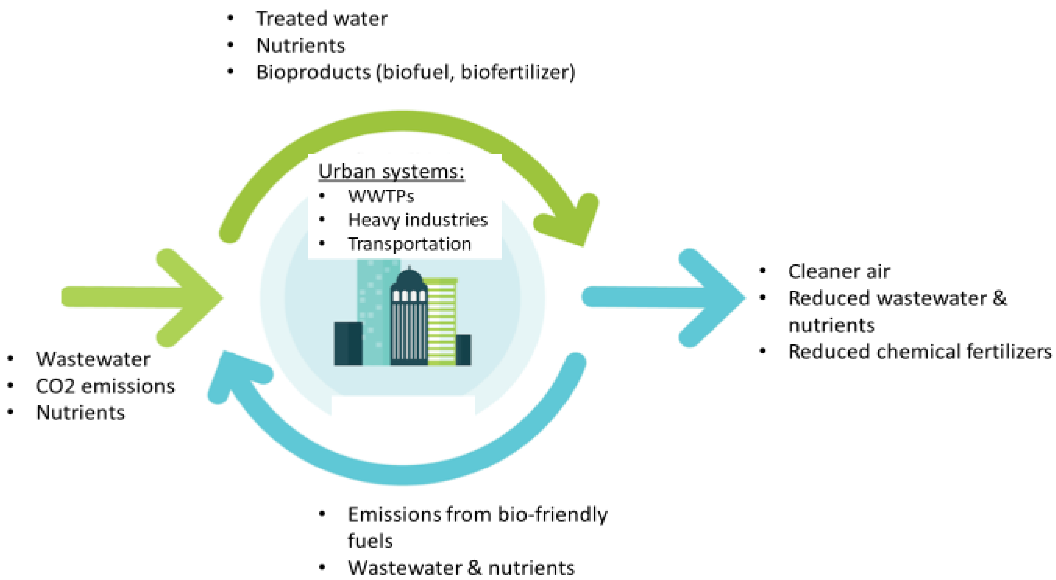

Figure 7: Inputs and outputs in a more circular urban metabolism, where algae are integrated, Own elaboration

To begin, algae-based systems can be integrated into WWTPs as a component of the nutrient removal process. By utilizing algae in the final stages of treatment, residual nutrients, such as nitrogen and phosphorus, can be efficiently removed from the treated wastewater(Nguyen et al., 2022). The treated water can be reused for agricultural purposes, improving the water supply and distribution system, or even for industries that generate energy, in order to cool down their processes (Mohsenpour et al., 2021). At this point the first two metabolic challenges have been mitigated. The first one regarding the adequate water supply, as the treated water is reused for other non-potable purposes. The second challenge refers to the safe and effective disposal of sewage, as not only nutrients but also other chemicals can be removed from the wastewater with the use of algae, enhancing the wastewater management system of a city (Wolman, 1965).

Algae assimilate these nutrients, contributing to improved water quality and reduced environmental impact. The remaining biomass can be used when it is transformed into a useful material (Zabochnicka et al., 2022). The product that was discussed in this research was biofuel, in order to generate electricity to the WWTP or even for other commercial uses. However, according to the interviews, converting algae biomass into biofuel is insufficient for a few reasons, which will be analyzed further below.

Besides biofuels, the biomass can also be used as fertilizers, but at this point strict regulations should be enacted, as the biomass might contain pathogens that might be transmitted into the growing plants. Nevertheless, in case that the algae cultivation contains pathogens, the latter will kill all the reproduction, making impossible the biomass generation (Acién et al., 2016).

To continue, algae beside nitrogen and phosphorus need carbon to grow. This carbon can also be obtained in the form of CO_2, which comes from heavy industries, such as power plants or cement factories, which release substantial quantities of CO_2 into the atmosphere (Razzak et al., 2017). This integration of algae can effectively mitigate the CO2 emissions, tackling the third metabolic challenge regarding air pollution in urban areas, and improving the environmental performance, contributing to the goal of carbon neutrality (Chen et al., 2022).

Finally, algae-based systems hold a significant potential for integration into the biofuel industry, hence the transportation urban system. Algae can be cultivated to produce biomass rich in oils, which can be converted into various forms of biofuels (Leite et al., 2013). However, this concept is not embraced by everyone for couple of reasons. First of all, the market is not ready for biofuels, which are made of algae biomass, as it is hard to compete the current fuel market. On the one hand, the cheap, traditional fuels are hard to be replaced and on the other hand, Marcel Janssen (M. Janssen, personal interview, 9 June, 2023) mentioned, "the alternative option for more sustainable options lies on electric vehicles". Another important point was raised by Alla Silkina (A. Silkina, personal interview, 23 May, 2023), saying that "this biomass is full of valuable nutrients, that should be converted into something more useful, like fertilizers".

In each of these internal urban systems, algae-based systems offer unique advantages, especially in WWTPs and CO_2 capture, as the biofuel industry is becoming uncertain. However, challenges such as scaling up production, optimizing cultivation methods, and developing cost-effective harvesting and processing techniques need to be addressed to fully realize the potential of algae-based systems in these contexts. Through the SWOT analysis, this research will continue discussing strong points and limitations of this model, reasons that it is still in a small scale and finally, strategic recommendations to overcome the challenges and achieve the larger scale.

5.2 Discussion on SWOT analysis

Algae-based systems exhibit several strengths when integrated into wastewater treatment plants and other internal urban systems (Abdel-Raouf et al., 2012). In this research, the SWOT analysis presented some key strengths and opportunities, as well as weaknesses and threats of this model, which are discussed in this sub-chapter.

Aspect	Strengths	Weaknesses	Opportunities	Threats
Sustainability	- Utilizes nutrients (nitrogen, phosphorus) and absorbs CO2 from the atmosphere for growth	- Heavy metals and toxic compounds from wastewater could be transmitted into the food chain	- CO2 sequestration can support carbon neutrality in urban areas	- Strict regulations required to prevent health problems
Nutrient removal efficiency	- Algae obtain necessary nutrients from wastewater, reducing the need for additional fertilizers/supplements	- Sensitivity to variations in temperature, pH, and nutrient levels	- Improved water quality due to assimilation of heavy metals, organic compounds, and pharmaceuticals	- Pathogens in wastewater can interfere with treatment process
High growth rate	- Treats large volumes of wastewater in a short time	- Low light transmissivity, limiting effectiveness in locations with limited sunlight	- Algae biomass can be used for biofuels, fertilizers, or bioplastics	- Limited funding for algae-based projects
Economic viability	- Production of high-value byproducts like lipids for biofuels	- Expensive infrastructure and equipment	- Favorable regulations and policies can promote adoption	- Competition from other wastewater treatment methods
Technical expertise	- Can create economic prospects, job opportunities, and increased revenue through biomass and byproduct sales	- Limited technical expertise in natural sciences and engineering	- Incentives can stimulate innovation and research in algae-based systems	- Economic barriers and high upfront costs
Public acceptance		- Lack of awareness and understanding may lead to skepticism		- Environmental risks, potential negative impacts on ecosystems
Scalability		- Most projects/facilities are in small-scale or experimental phase		

Table 4: Summary of key points of the SWOT analysis, Own elaboration

Firstly, these systems offer sustainability benefits as they utilize nutrients, such as nitrogen and phosphorus, and absorb CO_2 from the atmosphere to grow (Cai et al., 2013). According to the interviews, the CO_2 sequestration is considered a great advantage of algae, as it can be a support to reach the carbon neutrality in urban areas (Chen et al., 2022). Moreover, algae obtain all their necessary nutrients from the wastewater itself, eliminating the need for additional fertilizers or supplements (Mohsenpour et al., 2021). They can assimilate not only nitrogen and phosphorus but also heavy metals, organic compounds, and pharmaceuticals, leading to improved water quality (Acién et al., 2016). However, at this point strict regulations are essential as those heavy metals and other toxic compounds can be transmitted into the food chain and eventually to human bodies, causing health problems (Morais et al., 2021).

The high growth rate of algae is another strength, enabling the treatment of large volumes of wastewater in a short amount of time (Yadav et al., 2021). Rapid growth indicates adaptability and the ability to utilize more nutrients from the wastewater, which is crucial for effective treatment and for the water reuse (Yadav et al., 2021). Having accomplished these two goals- the reuse of threated water and the safe disposal of wastewater- the first two metabolic challenges have been also achieved (Wolman, 1965), leading eventually to a more sustainable and circular urban metabolism. Finally, to enhance the circularity and close the energy or the material loop, the algae biomass can be used in the energy sector as a form of biofuel or in the creation of fertilizers or bioplastics (Demirbas, 2010). However, even if biofuels are necessary in today's world, biofuel from algae biomass might not be competitive enough with the current fuel market (Leite et al., 2013). Hence, the main focus regarding the biomass should be on other forms, starting with fertilizers as the most widely common, as algae are rich in nutrients, enriching the soil (Wielemaker et al., 2018).

Despite their strengths, algae-based systems face certain weaknesses that need to be addressed. Sensitivity to variations in temperature, pH, and nutrient levels can affect their nutrient removal effectiveness in WWTPs (Li et al., 2019). Low light transmissivity poses another challenge, particularly in locations with limited sunlight, as light is essential for photosynthesis (Nguyen et al., 2022). Pathogens present in the wastewater can also interfere with the treatment process, by wiping out the algae population or jeopardizing the quality of the algae biomass (Nguyen et al., 2022). This can have a negative result in the amount of biomass that is produced, according to Bernard Willems (B. Willems, personal interview, 17 May, 2023), creating an unstable market as the company has not managed to cultivate the willing amount of biomass, making unsatisfied customers. Additionally, based on the interview with Alla Silkina (A. Silkina, personal interview, 23 May, 2023) and Janssen Marcel (M. Janssen, personal interview, 9 June, 2023), "the large surface that is required in another disadvantage, as this is also connected with the high cost of infrastructure and the land use".

Another part of the infrastructure is the required equipment, which can be expensive to implement and operate, making large-scale adoption economically less viable, parallel with the limited funding that exists in the European Union for algae-based projects (Acién et al., 2016; Mohsenpour et al., 2021). As the interviewers also mentioned, technical expertise in natural sciences and engineering is limited but necessary for the design and operation of these systems, which may require additional personnel or external expertise for implementation and maintenance (Nguyen et al., 2022).

Economically, algae-based systems offer multiple opportunities. The production of high-value byproducts from algae, such as lipids for biofuels, can create economic prospects for businesses and communities, job creation, and increased revenue through the sale of excess biomass and byproducts (European Commission, 2022). Furthermore, favorable regulations and policies can promote the adoption of algae-based systems by providing financial incentives, addressing economic barriers, and mitigating environmental risks associated with traditional treatment methods (European Commission, 2022). These policies can also stimulate innovation and research in algae-based systems, optimizing their design, algae selection, and nutrient recovery processes (European Commission, 2022). Nevertheless, these regulations are most of the times neglected, as algae are not quite widespread and do not return a high revenue, as they are still in a small scale.

On the other hand, beside their potential, these systems face certain threats that could impede their adoption. To begin, competition from other wastewater treatment methods, including traditional systems and newer technologies, poses a challenge (Acién et al., 2016; Morais et al., 2021). If algae-based treatment is not cost-competitive, it may struggle to establish itself in the market against more established alternatives (Acién et al., 2016; Morais et al., 2021). Economic barriers, such as significant initial investments and lack of cost-competitiveness, can hinder their adoption, (Mohsenpour et al., 2021; Shams Forruque et al., 2022), whereas the high upfront costs associated with infrastructure and research and development may discourage investment (Shams Forruque et al., 2022). However, as Janssen Marcel (M. Janssen, personal interview, 9 June, 2023) explained, "building a system that can last for a long term, can actually reduce the cost", while Alla Silkina (A. Silkina, personal interview, 23 May, 2023) claimed that "better understanding of the technology that is needed is necessary in order to minimize the infrastructure's expenses".

Public acceptance can also be a threat, a topic that Alla Silkina (A. Silkina, personal interview, 23 May, 2023) referred to, as "the lack of awareness and understanding may lead to skepticism". Environmental risks, such as the potential release of algae into water bodies, need to be effectively managed to avoid unintended consequences and negative impacts on ecosystems (Abdul Latif et al., 2022). Additionally, regulatory barriers, permitting challenges, and fragmented frameworks related to algae cultivation can pose obstacles to implementation (Acién et al., 2016; European Commission, 2022).

Beside all the advantages and disadvantages of algae-based systems in urban metabolism, especially in WWTPs, one main limitation is the small scale of these systems (Morais et al., 2021). Most of the projects and facilities are in a small scale or even experimental phase, making it hard to embrace all the opportunities and strengths they offer. In the next sub-chapter, strategic recommendations will be examined in order to scale up the algae-based systems, considering the environmental planning.

5.3 Strategic recommendations

Based on the TOWS matrix and on the environmental planning, strategic recommendations are discussed and analyzed, in order to facilitate the scaling up of algae-based wastewater treatment plants. As mentioned before, environmental planning involves the effective management of natural resources and the preservation of the environment within urban areas. It encompasses various aspects such as the sustainable utilization of water resources and ensuring good air quality. This entails implementing strategies and policies that aim to minimize the negative impact of urbanization on the environment, while maximizing the benefits and services that natural resources provide to the urban population (Mersal, 2016; Sailus, 2023).

- ➔ SO (Strengths-Opportunities) Strategies:

Algae biomass offers the potential for generating revenue and by utilizing the by-products of the algae biomass, wastewater treatment plants can have an additional income (Zabochnicka et al., 2022). The most profitable and suitable products for the market must be considered, and after this research biofuel might not be the one, since the fuel market is already competitive. Fertilizers seem to be quite appropriate, as the biomass contains valuable nutrients (Zabochnicka-Świątek et al., 2019). The treated water can also be used as a commodity and create extra profit, as it can be reused for irrigation and in industries (Zabochnicka et al., 2022). The production and sale of these products derived from algae can serve as a sustainable solution, reducing reliance on raw materials, for fertilizers and water, and mitigating environmental impact. This revenue generation can further support the long-term viability and economic feasibility of algae-based wastewater treatment plants and support the new technologies and equipment that is needed (Zabochnicka et al., 2022).

Collaboration with academic and research institutions holds significant potential in advancing the development and testing of new technologies aimed at enhancing the technical expertise for the efficiency and effectiveness of algae systems (Nguyen et al., 2022). By fostering partnerships with institutions, universities and companies' wastewater treatment plants can access the expertise and resources necessary to optimize the performance of algae-based systems. This collaboration can involve joint research and development projects to address key challenges related to system design, nutrient recovery, scalability, and cost-effectiveness (Nguyen et al., 2022).

Finally, considering the opinion of interviewers, funding is a key problem of not scaling up, hence, partnering with private investors can play a crucial role. Private investment can provide the necessary funds to support the infrastructure development and operational costs associated with larger-scale implementation (European Commission, 2022). These partnerships can also bring valuable market knowledge, aiding in the commercialization and wider adoption of algae-based technologies and systems (European Commission, 2022).

Nevertheless, environmental urban planners should incorporate these strategies, in order to create a sustainable city, starting with the context of urban agriculture. By integrating algae-based wastewater treatment systems with urban farming practices, cities can create a balanced relationship between food production and sustainable wastewater management. As a first step, the treated water can be provided and used by citizens that cultivate urban farms and urban gardens or even urban roofs, providing a reliable and sustainable water source. The second step would be to transform the biomass into a nutrient-rich fertilizer on the same plantations, promoting healthy and sustainable plant growth and reducing the need for synthetic fertilizers. Therefore, urban planners could turn their focus into expanding urban gardens and roofs in buildings, where algae biomass and the treated water can be utilized, enhancing the sustainability of urban agriculture.

Furthermore, these systems can be implemented in the development of eco-industrial parks or sustainable industrial zones. Hence, the treated water can be utilized for industrial processes, reducing the demand for freshwater resources and minimizing the environmental impact of industrial activities. The by-products derived from the algae biomass can be utilized within the industrial park, as a biofuel, creating a closed-loop system where waste from one industry becomes a valuable resource for another. This promotes resource efficiency, economic growth, and environmental sustainability within the industrial sector.

Another possible implementation for urban planners could be in urban planning and projects focused on water capture and water management. Since these systems can be integrated into the design of stormwater management infrastructure, firstly, treated water can be reused for irrigation, or even groundwater recharge, mitigating simultaneously the risk of urban flooding.

- ➔ ST (Strengths-Threats) Strategies:

Regarding the strengths and threats of this matrix, there are more recommendations. Firstly, it is essential to highlight the sustainability and efficiency of algae systems in comparison to traditional treatment methods(Muga & Mihelcic, 2008). By emphasizing these advantages, public awareness can be raised, leading to increased acceptance of the utilization of such a model. This can be achieved through targeted educational campaigns, public outreach programs, and the dissemination of research findings that present the positive environmental and economic outcomes associated with algae systems (European Commission, 2022).

Furthermore, monitoring and adapting to weather conditions is crucial to mitigate potential challenges that may arise in relation to algae growth and harvesting, due to algae's sensitivity on external conditions (temperature, pH levels, nutrient availability). Therefore, continuous monitoring of environmental factors and the implementation of adaptive strategies can optimize algae growth and ensure efficient harvesting. This may involve utilizing more advanced equipment to keep the conditions stable, implementing control measures to regulate environmental conditions (Morais et al., 2021).

Regarding the direct implementation for urban planners, aiming to raise public awareness, algae systems could be placed in green infrastructure. By integrating algae systems into the design of green spaces, parks, and urban water bodies, cities can showcase the sustainability and efficiency of this approach to the public. These spaces can serve as demonstration sites and educational platforms, providing opportunities for community engagement and raising public awareness about the benefits of algae systems. Additionally, the integration of algae systems with other green infrastructure components, such as rain gardens or bioswales, can enhance the water treatment capacity and ecological value of these systems.

- ➔ WO (Weaknesses-Opportunities) Strategies:

To maximize the utilization of algae systems in wastewater treatment plants, it is crucial to implement a multifaceted approach that encompasses government policies and regulations. This approach aims to overcome economic and technological barriers and optimize the performance of algae-based systems (European Commission, 2022).

First of all, seeking government incentives and regulations is crucial, as governments can provide financial support, tax benefits, or grants to encourage industries to invest in algae-based technologies (European Commission, 2022). Additionally, implementing regulations that mandate the use of algae systems can foster the development and integration of these systems into existing wastewater treatment infrastructure.

Secondly, the understanding and development of advanced technologies, that enhance the scalability and efficiency of these systems, is an essential point (Abdul Latif et al., 2022). Therefore, research and development should be focused towards improving the cultivation techniques, optimizing the design of photobioreactors, and enhancing the harvesting and processing methods of algal biomass (European Commission, 2022).

Lastly, increasing technical expertise in relevant fields such as biology, engineering, and chemistry is of a significant importance (Nguyen et al., 2022). Encouraging research collaborations and educational programs can foster a deeper understanding of algae biology, bioengineering principles, and chemical processes involved in wastewater treatment (Nguyen et al., 2022). This expertise can lead to the development of innovative solutions and improved system designs.

However, in order to achieve robust regulations and incentives, government bodies should corporate with environmental urban planners, discussing which technologies are most suitable for financial support, as well as easy to be handles by citizens or even companies.

- ➔ WT (Weaknesses-Threats) Strategies:

The development of contingency strategies to prevent and manage contamination of algae-based systems is essential to reduce the risk of potential public health concerns. This involves implementing robust monitoring and quality control measures throughout the entire process, from cultivation to harvesting, to ensure the integrity of the algae biomass and minimize the presence of pathogens or pollutants (European Commission, 2022).

Co-operation with other organizations plays a significant role in overcoming technological barriers (European Commission, 2022). By establishing partnerships and knowledge-sharing networks with academic and research institutions, private companies, and government agencies, valuable resources and expertise can be combined (European Commission, 2022). This collaboration can facilitate the development and testing of new technologies, the optimization of system design, and the identification of innovative solutions,

Overall, considering the strategic recommendations and by taking action to implement them, algae-based systems in WWTPs can become successful in the future. Hence, urban metabolism has the potential to be transformed in to a sustainable one, mitigating the three metabolic challenges and closing the energy and material loops.

5.4 Tackling the three metabolic challenges

Urban metabolism refers to the flow of resources, energy, and waste within urban systems (Kennedy et al., 2011). As cities continue to grow, they face three significant metabolic challenges; the adequate water supply, air pollution and the effective disposal of sewage (Wolman, 1965). Algae-based systems offer a promising solution to tackle these challenges while aligning with the principles of the circular economy and environmental planning (Zabochnicka et al., 2022). By integrating algae into urban metabolism, cities can achieve resource efficiency, reduce environmental impact, and foster sustainable development.

To begin, resource scarcity, especially water scarcity, is a major concern in urban metabolism, particularly regarding water and nutrients (International Energy Agency, 2008). By integrating algae-based systems into wastewater treatment plants, cities can recover these valuable nutrients, which can be reused in various applications, such as fertilizers or bio-based products (Zabochnicka et al., 2022). Additionally, instead of treating wastewater solely for disposal, these systems harness the potential of nutrients present in the wastewater (Nguyen et al., 2022). Algae assimilate and remove nitrogen and phosphorus from the wastewater, effectively converting them into biomass. This biomass can be harvested and processed to recover these nutrients, closing the nutrient and material loop and reducing reliance on external inputs (Muga & Mihelcic, 2008). By incorporating nutrient recovery from wastewater, cities can alleviate the pressure on conventional fertilizer production, reduce nutrient pollution in water bodies, and mitigate the second metabolic challenge, regarding the safe disposal of sewage(Wolman, 1965). Parallel to nutrient recovery, algae-based systems facilitate water reuse, another essential aspect of circular urban metabolism. By effectively treating wastewater, algae-based systems produce treated water that can be reused for non-potable purposes, such as irrigation, industrial processes, or urban green spaces (Morais et al., 2021). Furthermore, the reuse of treated water contributes to the conservation of natural ecosystems and helps create a closed-loop system within the urban environment.

To continue, urban metabolism is also linked to the environmental and air pollution (UNEP, 2022). Algae can play a crucial role in carbon sequestration by utilizing CO_2 from various sources, including flue gases from industries or power plants (Razzak et al., 2017). Algae-based systems offer a sustainable approach to mitigate these forms of pollution through, regarding CO_2 sequestration. As algae need carbon to grow, they have the ability to absorb CO_2 and hence reduce the levels of CO2 (Chen et al., 2022), mitigating the third metabolic challenges, regarding air pollution (Wolman, 1965), aligning with the environmental planning aspect, which aims to create an atmosphere of good quality.

To conclude, algae hold great promise for addressing metabolic challenges in urban metabolism through the principles of the circular economy. By integrating algae into urban systems, cities can tackle resource scarcity, mitigate environmental pollution, and improve waste management. However, to utilize the full potential of algae-based systems, it is essential to address the aforementioned limitations, such as economic barriers, public acceptance and fragmented policies and regulations. Through strategic planning, collaboration, and innovation, algae-based systems can contribute to building sustainable and resilient cities. In the future, the implementation of these strategies should be evaluated based on specific criteria, and assess whether or not these systems contributed to the sustainability of urban metabolism. For example, the air and water quality can be measured, however the results might have been affected by other factors as well. Further research is required upon these criteria.

Chapter 6: Conclusions and Recommendations

6.1. Conclusion

This thesis examined a different way of making urban metabolism more sustainable, tackling the three metabolic challenges, by integrating algae-based systems. Today, there is an urgency of addressing the negative impacts of human activity on the Earth's balance and ecosystems, particularly in the context of the Anthropocene epoch, as the increased urbanization has intensified the struggles linked to sustainable resource management and environmental degradation (Steffen et al., 2007). Consequently, there is a continuous necessity to reconceptualize urban systems, enhancing their resource utilization patterns and fostering sustainability.

As mentioned under the introduction chapter, the concept of urban metabolism has been introduced as a key framework for understanding the flow of resources within cities (Kennedy et al., 2007). By examining the inputs, outputs, and internal processes of urban systems, urban metabolism provides valuable insights into the interactions between cities and their environment (Kennedy et al., 2007). The three metabolic challenges identified by Wolman – adequate water supply, effective sewage disposal, and air pollution control – are considered as critical issues that hinder the efficient performance of metabolic flows in urban areas (Wolman, 1965).

To address these challenges, the integration of algae-based systems within the internal urban system has been proposed as a promising solution. Algae have demonstrated the ability to close resource loops, create circular urban metabolism, and most importantly mitigating the three metabolic challenges. Therefore, the main question that this research aimed to answer is "how algae can tackle these three metabolic challenges in urban metabolism". This study showed that algae have the potential to be integrated in various systems, such as heavy industries that emit CO2, however, its main focus was on WWTPs, where algae present a great potential to improve urban metabolism's sustainability. By integrating algae into wastewater treatment plants, nutrients can be efficiently removed, improving water quality and availability, whereas the treated water can be used for agricultural purposes or for the process of other industries (Zabochnicka et al., 2022). Moreover, placing WWTPs near heavy industries allows for the capture of CO2emissions, thus enhancing air quality and mitigating the impact of air pollution (Razzak et al., 2017). The utilization of algae biomass as a biofuel, bioplastic or fertilizer further promotes circular economy principles by closing the material and energy loops (Demirbas, 2010). To continue with the first sub question, algae and their by-products can be integrated in various urban systems, such the transportation sector, the WWTPs, and the urban irrigation sector.

However, despite the potential benefits of algae-based systems, their large-scale commercialization and practical implementation face various technical, economic, and regulatory limitations (Morais et al., 2021). For that reason, a SWOT analysis, which is connected to the second sub question, was conducted on algae in WWTPs, alongside with interviews, in order to identify key points and limitations of this model and develop strategic recommendations for their successful upscaling and utilization within urban metabolism. According to the SWOT analysis, Strengths were considered the CO_2 sequestration, the nutrient removal, the reuse of water and of biomass, overall, following a circular model, increasing the sustainability of the system. At this point, it is worth mentioning that the production of biofuel was not considered economically feasible, as the current fuel market is already competitive. Nevertheless, other products can be created by algae biomass, equally valuable to biofuels, (fertilizers, bioplastics), creating another potential source of revenue. Moreover, the main weaknesses were the capital investment, the technological barriers and technical expertise, while the most common threat is the public acceptance, alongside with the fragmented regulations. Nevertheless, there are plenty opportunities that can tackle these challenges, such as investing in long term infrastructure, creating a new market for the bioproducts and involving institutions into the research. By following these, this model can have a higher rate of success when it is integrated into urban metabolism.

Finally, regarding the strategic recommendations and hence the last sub question, the collaboration of the academia, the private sector, as well as the government bodies is of great importance, in order to enhance the technical expertise, advance the required technology and improve the fragmented regulatory framework. Raising public awareness towards algae and the environmental protection could build a more empowered society, which is ready to take action and accept new initiatives and innovations.

In other words, a futuristic metabolic city where the recommendations for integrating algae-based systems into wastewater treatment have been embraced could be perceived more sustainable and circular, offering a more efficient and environmentally friendly approach. These systems would be in various areas of the city, in order to maximize the benefits, they can provide. On the one side of the city, the urban planners could place these systems next to heavy industries, in order to improve the air quality for the citizens. On the other side, algae systems would be incorporated into the WWTPs, harnessing the natural power of sunlight, allowing algae to thrive and absorb nutrients, such as nitrogen and phosphorus, from the wastewater. This threated water and biomass could be utilized by companies, the municipality, agriculture, and citizens. Companies could use the treated water for their processes, whereas the remaining sectors for agricultural and irrigation purposes. Having a city with communal gardens, or roof grades, even citizens could take part in this recreational space, and learn about the benefits of circular economy, algae, and the value of saving the water, promoting a more sustainable water cycle.

But the benefits wouldn't stop there. The algae biomass itself would become a valuable resource, with multiple applications. Biofertilizer production would be one of the key outputs, as it could be used in the same urban gardens and parks, mitigating the use of chemical ones. Algae biomass also offers the option to be transformed into biofuels, however it might not be vital, due to the competitive market of the current fuels and electrical vehicles. Nevertheless, community engagement is a cornerstone to a successful metabolic city. Residents actively participate in algae cultivation projects, maintaining green spaces, and contributing to the circular economy.

Upon all, collaboration and knowledge-sharing would be at the heart of this transformation. Partnerships between research institutions, private companies, and government agencies would drive continuous innovation and improvement in algae-based systems, having as a goal the protection of the environment, beside the profits. Scientists and engineers would work together to optimize the design of the equipment alongside with the procedures, aiming to develop advanced monitoring and control technologies, while urban planners and government bodies would corporate to find the most suitable locations and systems to implement these systems, creating a sustainable urban metabolism. Educational campaigns towards citizens should be on the top of the agenda for the government, raising public awareness towards algae and the necessity of the environmental protection, in nowadays.

As a result of these advancements, the metabolic city of the future would be characterized by clean, efficient, and resourceful wastewater management, while the residents would enjoy the benefits of cleaner water, reduced pollution, and a sense of belonging in their community, since they would have the chance to contribute to a greener and more sustainable future.

6.2 Limitations and recommendations for future research

During this research there were several limitations that occurred and could be also a future, new research topic. The biggest limitation is that the desired number of interviews was not achieved. This can result in limited data, as diverse input from the industries is significantly important and gives a different perspective compared to literature. Biased interviewers are considered as another limitation, as their perspective is linked either to their personal research or to the products of their company, leading to one-sided opinion. Additionally, the results are generalized to all Europe, even if the interviewers where from three European countries; the UK, Netherlands, Belgium. However, in order to achieve this large scale implementation of algae systems in wastewater treatment plants, strong economies with advanced technologies are needed, a situation which does not apply in the whole part of Europe equally.

As further research, I would include more interviews with different sectors that are not only related to wastewater treatment plants. To begin, I would interview representatives from the wastewater treatment industry, such as Aqualia, in Spain, as well as traditional treatment industries, to comprehend their biases and barriers, in case they have a negative opinion about algae in that sector. Moreover, due to the fragmented regulations on algae, I would consider crucial interviews with government representatives, to understand the reasons that the framework is limited and ways that can promote policy initiatives on algae in WWTPs. Finally, interviews with the private sector as the perspective of private investors is of a significant importance and could influence the initial capital investments.

Therefore, three main research topics could be conducted in the future. The first one can focus on collecting more primary data from companies and projects regarding algae in wastewater, in order to gain more personal and practical insights. Parallel to this, local citizens could be interviewed in order to examine the public acceptance of the community and comprehend their opinions and suggestions towards the new algae-systems. The second one could focus on algae and CO2 sequestration, based on a SWOT analysis, in order to scale-up also this procedure. Finally, the third one should be focus on algae’s biomass and its transformation into fertilizers, as well as their challenges and limitations.

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APPENDIX I

CONSENT FORM TO PARTICIPATE IN A RESEARCH INTERVIEW

A brief explanation of the research topic

This research (*Integrating algae-based systems in urban metabolism as a means of mitigating its metabolic challenges. A SWOT analysis and strategic recommendations*) focuses on how algae-based systems can tackle the three metabolic challenges in cities, considering the principles of circular economy. The three metabolic challenges are adequate water supply, effective disposal of sewage, and control of air pollution. The model that is examined starts with algae-based systems that are integrated into wastewater treatment plants. The algae absorb nutrients (nitrogen and phosphorus), creating treated water that can be used in other, non-potable facilities. Additionally, algae need carbon, which can be acquired if the algae systems are based next to heavy industries that emit CO2, mitigating air pollution. Finally, the biomass can be transformed into biofuel. This study will be based on the SWOT (Strengths, Weaknesses, Opportunities, Threats) analytical framework, focusing mainly on wastewater treatment plants. However, the algae-based systems are integrated into wastewater treatment plants, either on a small or an experimental scale. Therefore, this interview aims to collect further information about the limitations that this model faces, as well as recommendations that could enhance its scaling-up.

Taking part in the study

By participating in this interview, I hereby provide my voluntary consent to be a participant in the study. I am aware that I have the right to decline to answer any questions and to withdraw from the interview or the study at any time without providing any explanation.

I understand that, by participating in the interview, I will have to answer questions, while the researcher will be taking notes, and will record the audio of the interview session, which will be transcribed as a text for effective data analysis. (All documents will be deleted when the research is complete.)

I acknowledge that my full name will appear in the report of the research unless I prefer full anonymity, which will be kept by the researcher.

I understand that I can request and have access to the information that I have provided after the interview and I have the right to requestion modification clarification, or any other changes.

I am aware that I have the right to contact the researcher for further clarification and questions.

Use of the information in the study

I understand that the information I provide will be treated confidentially and used strictly for research purposes.

Consent to be Audio Recorded

I also agree to be audio recorded.

The participant **Signature** **Date**

_______________ _________________ _______

The researcher **Signature** **Date**

APPENDIX II: Interviews' questions

Questions with Bernard Willems (B. Willems,personal interview, 17 May, 2023)

1. Where do you use algae and how can algae-based systems contribute to sustainability?
2. What would you consider as a Strength and Opportunity of your model?
3. What would you consider as Weakness and Threat of this model?
4. If the model is in an experimental phase, how are you aiming to scale it up?

Questions with Alla Silkina (A. Silkina, personal interview, 23 May, 2023)

1. What do you think are the main strengths of algae in wastewater?
2. The algae biomass can be used as a fertilizer but also as a a biofuel. Which option you consider the most viable?
3. What are the limitations of algae in wastewater, especially for scaling up the system?
4. What do you think it should change in the future in order overcome the limitations?

Questions with Janssen Marcel (M. Janssen, personal interview, 9 June, 2023)

1. According to you, which are the strong points of using algae in the circular model?
2. Are the regulations strict regarding using the biomass as fertilizer, since algae might have absorbed toxic substances and heavy metals?
3. What do you think is the weak point of algae in wastewater treatment plants?
4. How can we overcome these limitations and weak points in the future, in order to create a larger scale of these systems?