Sustainability Project - Final Report

Wastewater Treatment in the Crocodile River: An Impact Analysis of Technological Interventions

Adina Tărbăşanu (i6275390)
Evangelia Georgiou (i6295301)
Mia Coupard (i6292304)

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Course coordinators: Andrew Oringer, Bram Fleuren and Serdar Turkeli

University: Maastricht university

Faculty: School of Business and Economics (SBE)

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1. Introduction

Clean water, sanitation, and hygiene, recognized as fundamental human rights by the United Nations (2022), remain inaccessible to over 5.5 billion people globally in 2022 (United Nations, n.d). Water pollution, largely from inadequately treated wastewater, claims 14000 lives daily and depletes freshwater sources (Fn & Mf, 2017; U.S. Environmental Protection Agency, 2023). Only 11% of estimated domestic and industrial wastewater is repurposed, highlighting the urgent need for proficient wastewater treatment plants (WWTPs) (United Nations, 2023).

South Africa, among the world's most water-stressed regions, grapples with providing only about 1200m3 of fresh water annually per person (Chertock, n.d.; Iloms et al., 2020). Climate change and rapid urbanization worsen the situation, leading to more frequent droughts and increasing need of fresh water for a growing urban population (UNU-WIDER, n.d.; Parliament of the Republic of South Africa, n.d.). Inadequate infrastructure and funding contribute to insufficient wastewater treatment (WWT), with various provinces failing to deliver good water quality (Department of Water and Sanitation, 2022).

Figure 1:Map of the Crocodile River, South Africa (Deksissa, 2004)

The Crocodile River, an important water resource in Mpumalanga, South Africa, spanning 320 kilometers with a drainage area of 10,450 square kilometers, is vital for activities like fishery, forestry, agriculture, and spiritual practices (Phungela et al., 2022b; Hassan, 2003). Furthermore, it serves as a significant biodiversity hub. Despite its importance, however, the river faces heightened water pollution, especially in its lower reaches, reflecting the broader challenge of pollution in South Africa (Phungela et al., 2022b).

In this report, therefore, our primary focus is to address the challenge of *optimizing WWTPS along the Crocodile River in Mpumalanga, South Africa*. We aim to answer key questions such as *how to enhance WWTP cleaning processes, implement measures for energy self-reliance, and operate in a cost-efficient manner.* We initially conducted a literature review to gain a deeper understanding of the case's context. Then, we proposed three technologies — microalgae, solar power, and hydrogen power that we analyzed individually followed by an impact analysis where we assessed their suitability synergistically. The report concludes by acknowledging limitations and offering recommendations for future studies.

2. Literature Review

2.1 General Literature Review

The Crocodile River in South Africa is a significant water resource that faces challenges related to water quality and sustainability. According to Phungela et al. (2022), the Crocodile River is generally classified as Class C in regard to ecological status, which is intended to support farming, commercial, and sustenance fishing. However, its water quality has been deteriorating due to increased anthropogenic land use and land cover changes, as well as excessive discharge of poorly treated effluent from WWTPs (Samuel et al., 2022).

The area around the Crocodile River hosts a number of manufacturing industries, steel and iron smelting, mining, and intensive commercial and subsistence agriculture (Samuel et al., 2022). Particularly, the southern portion of the Crocodile River sub-catchment is highly developed, with large industrial, urban, and semi-urban sprawls in northern Johannesburg, Mid-Rand, and southern Tshwane (Tshivhase, 2019). As a result, large wastewater return flows are generated from these areas, which represents the second most prevalent cause of pollution in water bodies due to chemical and microbiological pollution (Edokpayi et al., 2017). According to DW News (2023), South Africa's coal power plants supply most of the country's energy, but these power stations are not functioning at full capacity due to aging infrastructure. Therefore, they fail to eliminate non-biodegradable waste and heavy metals, leading to their discharge into surface water bodies, exacerbating the issue of persistent and toxic pollutants in wastewater (Koivunen et al., 2003; Iloms et al., 2020).

There are already several improvement initiatives and projects dedicated to mitigating this issue. The Blue Deal Crocodile River project aims to improve the river's health and ensure safe drinking water for local communities (Berghuis, 2023). Partner municipalities including Mbombela, Emakhazeni, and Nkomazi are actively developing and implementing their Green Drop Improvement Plans as part of this project, focusing on enhancing water quality and sustainability, benefiting the region's economy and local communities (Berghuis, 2023). Additionally, the Crocodile River Partnership involves stakeholders such as the Dutch Water Authorities, IUCMA, DWS, COGTA, MISA, and local municipalities, aiming to improve the operation of six WWTPs and elevate water quality in the Crocodile River, seeking Green Drop Certification for all six participating WWT Works (Chakuya, 2018).

2.2. Why address this problem

The need to address the WWT problem in the Crocodile River arises from various environmental, public health, and socio-economic concerns (Phungela et al., 2022). Firstly, waterborne diseases pose significant risks to both human health as well as the natural equilibrium of the aquatic ecosystem. The presence of harmful bacteria and viruses, such as E. coli, in wastewater not only jeopardizes human consumption but also affects the integrity of water resources that are essential for basic needs such as drinking, irrigation, and recreational activities. The health of local communities is further at risk due to limited access to clean water as a result of poor quality of water used for agricultural purposes, causing adverse health impediments from consuming contaminated crops. (Phungela et al., 2022).

Secondly, climate change exacerbates these challenges through emissions of methane and eutrophication as a direct result of the disposal of industrial and domestic waste into the river. Such pollutants contribute to the salinization, eutrophication, and microbiological pollution of water (Phungela et al., 2022). Furthermore, biodiversity in aquatic ecosystems faces a fair share of risks due to the presence of toxic substances and high pathogen levels in water. On the one hand, discharge from wastewater significantly disrupts the equilibrium of aquatic systems, including nutrient uptake efficiency, organic carbon content and bacterial levels. On the other hand, excessive nitrogen and phosphorus in water trigger algae overgrowth, which deplete the overall oxygen levels and increase production of toxins, harming aquatic life, and causing unpleasant odors in lakes and reservoirs (Phungela et al., 2022).

2.3. What is needed to address this problem

Addressing this issue requires the implementation of several key factors. First, establishing partnerships such as the Crocodile River Partnership emerges as a crucial step and facilitates the exchange of invaluable knowledge and the sharing of various resources. To witness change however, funding will need to be obtained through grants or private investments. In addition, investing in new advanced technological infrastructures, such as more efficient filtration systems and new biological treatment methods, and introducing new renewable energy sources, proves crucial in improving the environmental impact of the WWTP as well as the quality of the WWT. Moreover, to implement these technologies, it is necessary to maintain skilled and qualified employees acquainted with both new and old technologies. Finally, robust security measures such as cybersecurity need to be enforced to prevent crime and theft.

3. Methodology

This study was based on secondary data collection from scholarly papers found on databases such google scholar and various governmental websites. Preliminary research first allowed for the identification of 3 techniques relevant to WWTPs in South Africa, namely microalgae, solar power and hydrogen energy. The aim of this research paper was to investigate their potential for improving WWT and achieving energy self-sufficiency.

To achieve this goal, a thorough analysis of each technology was conducted, assessing both benefits and limitations. Afterwards, this study investigated all potential combinations and synergies between techniques. Following the data collection phase, an assessment framework was crafted employing three key metrics, categorised as either low, medium or high: WWT effectiveness, energy self-sufficiency and cost-efficiency. WWT effectiveness measured how effective the technique was at cleaning, disinfecting and improving the overall quality of the water exiting the WWTPs. On the other hand, energy self-sufficiency assessed how successful the technique was at providing energy to the WWTPs. The last metric, cost efficiency, examined the overall cost of the technologies as well as potential revenue streams generated by the technologies for the WWTPs. Finally, the cumulative effect of these three metrics was compiled into one final variable named the expected impact. The results of this study are intended to benefit municipalities along the Crocodile River in South Africa and provide them with a comprehensive analysis of various technologies and their associations as well as provide them with content to make more informed decisions on the optimisation of their WWTPs.

4. Assesment

4.1. *Microalgae*

Microalgae, comprising microscopic unicellular organisms, are utilized in WWT, particularly in tertiary treatment for efficient nitrogen and phosphorus removal, reaching up to 90% effectiveness (Tan et al., 2023). Furthermore, according to Arashiro (n.d.) the use of microalgae in the activated sludge phase, meaning the phase where microorganisms such as bacteria break down organic pollutants, can be immensely beneficial by providing the microorganisms with oxygen, leading to a reduction in energy requirements from aeration up to 60% (Alami et al., 2021). Additionally, accessible algae species make them suitable for regions lacking wastewater infrastructure. Microalgae has also been found to aid CO2 sequestration, tackling climate change (Alami et al., 2021)

In terms of by-products, microalgae biomass can be converted into fertilizers, supplements, dyes, and lucrative biofuels like biohydrogen and biomethane (Srimongkol et al., 2022). Furthermore, these by-products may also possess valuable anti-inflammatory and antioxidant properties.

Microalgae's climatic suitability requires high solar radiance and temperatures between 15 to 35 degrees Celsius, fitting the climatic profile of South Africa (Nwoba et al., 2020). Overall, their accessibility, cost efficiency, and pollutant removal capabilities makes them a promising technology for the Crocodile River context.

However, microalgae use also displays certain limitations and in their work Anand et al. (2023) explore some of them. Firstly, extracting microalgae from wastewater is challenging due to their small size and tendency to form clusters, hindering settling and filtration. Secondly, operational factors like temperature, pH, and light intensity complicate harvesting efficiency and cost. Thirdly, modulating quality and quantity in cultivation is challenging due to diverse characteristics across microalgae types, adding complexity to the process. Lastly, finding the optimal balance of co-cultivated microalgae and bacteria in wastewater is hindered by synergistic or antagonistic interactions, leading to potential competition for nutrients and light and undermining micro-pollutant treatment.

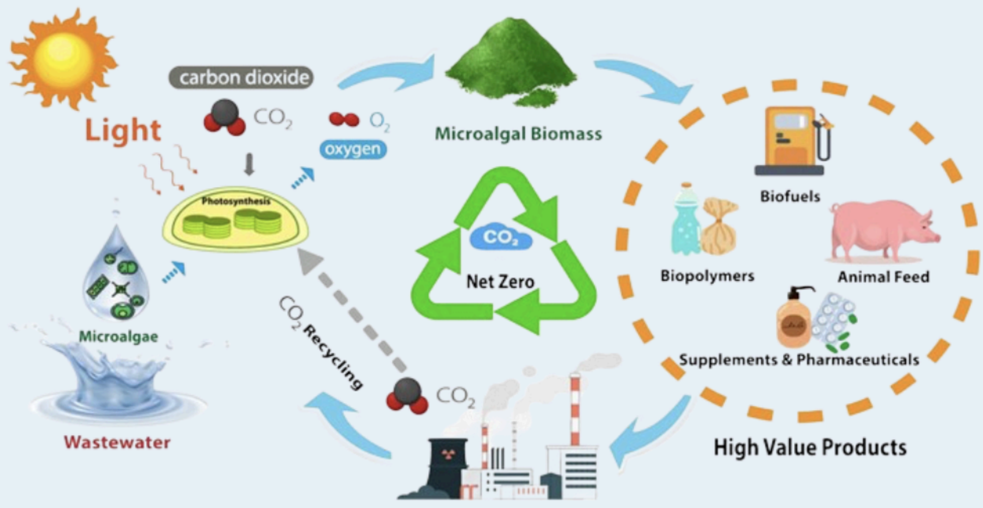

Figure 2 : Microalgae wastewater treatment and biomass production (Srimongkol et al., 2022)

4.2. Solar Power

The second technology considered is solar power, as it is a viable option for WWTPs due to the high energy consumption required to operate these facilities. WWTPs are among the most suitable sites for photovoltaic module installation and utilization, and solar energy can be used to power process controls and reduce energy costs (Siwulec, 2023). For instance, solar panels have the potential to aid WWTPs' in several ways. Solar cells - also known as photovoltaic (PV) - can be used as Auxiliary and Supplemental Power Sources (ASPSs), and are great at powering process controls during anaerobic processes and reducing energy costs (Pandey et al., 2021). Solar energy can also be used to power aerators in WWTPs, which can improve biochemical oxygen demand and sludge reductions, control odor and reduce total ammonia concentrations in the effluent (United States Environmental Protection Agency, 2013).

Next, we found heterogeneous solar photocatalysis, a catalysis technology which is used to speed up light-relevant chemical reactions (Pandey et al., 2021). During the disinfection stage of the WWTP, a special substance, like titanium dioxide, is added into wastewater. When the substance gets hit by the light, it becomes highly energetic and starts a powerful reaction that creates special molecules called reactive oxygen species (ROS), which act as cleaning agents that break down pollutants and contaminants in wastewater. As a result of this reaction, the pollutants are broken down into smaller, less harmful pieces, making the water cleaner and suitable for non-drinking purposes.

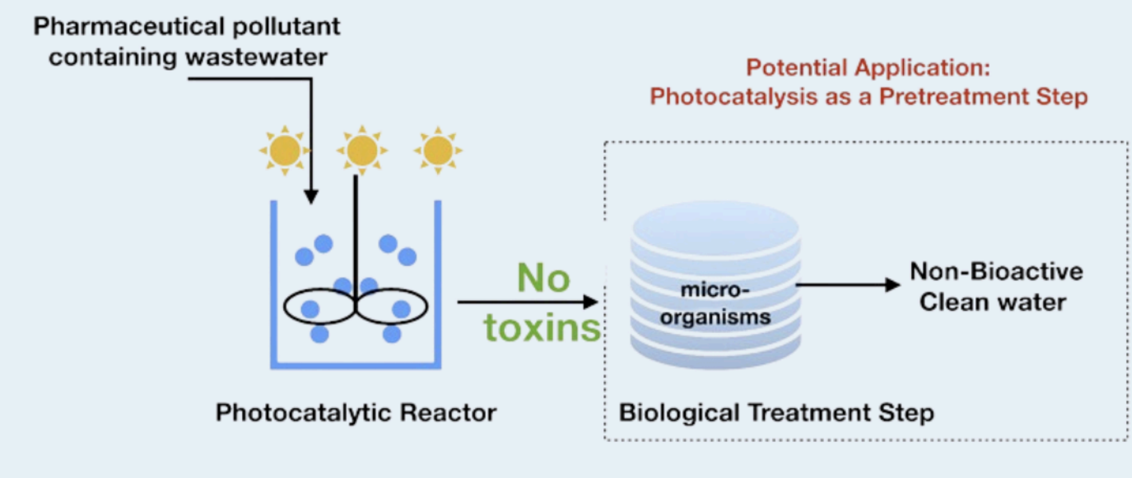

Figure 3: Solar Photocatalysis (Rana & Rana, 2023)

Lastly, we chose a solar desalination method called vacuum technique - a process where a vacuum, which is an empty space without air, is created to help with the desalination. This process uses the power of the sun to create conditions where water turns into vapor (evaporation) and then back into liquid (condensation). This solar-assisted desalination system was found to produce up to 30% higher levels of fresh water compared to traditional methods (Pandey et al., 2021).

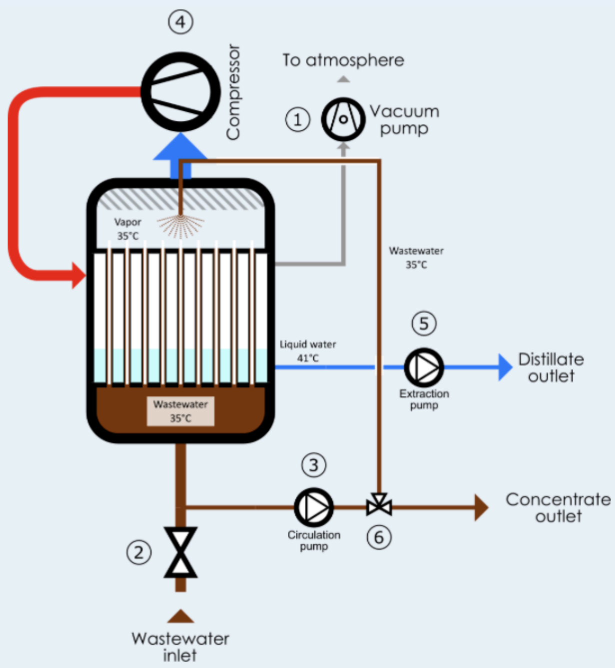

Figure 4: Solar Desalination - The Vacuum Technique (*Leviathan Dynamics*, n.d.)

Efficient energy use and resource valorization are some advantages of using solar power as an energy source for WWTPs. Milani & Bidhendi (2023) argue that integrating renewable energy sources, particularly solar energy, could provide a significant portion of the annual energy requirements of WWTPs, up to 88% in some cases. Also, according to Siwulec (2023), cost savings can be achieved thanks to the low-cost nature of solar energy and long-term cost predictability facilitated by power purchase agreements (Siwulec, 2023b). Additionally, solar-powered WWTPs are not only easy to maintain (NuWater, 2023), but also render environmental benefits by curbing GHGs and reducing the reliance on non-renewable energy sources (Pandey et al., 2021). These properties are especially fitting for regions where access to energy is limited and uncertain, such as in South Africa.

On the downside, solar power generation is dependent on sunlight, which is intermittent. This can lead to fluctuations in energy supply, requiring backup power sources or energy storage systems to ensure a consistent energy supply (Sansaniwal, 2019). Also, despite the long-term reduction in overall energy costs, the upfront investment for installing solar panels and associated equipment can be high (Pandey et al., 2021). Lastly, the installation of solar panels requires significant land or roof space, which may not be readily available at some WWTP sites (Sansaniwal, 2019).

4.3. Hydrogen energy

The third and final technology considered was hydrogen power. Hydrogen, the most abundant chemical element contained in all living things, emerges as an important future clean energy source. Notably, it is already being used to power vehicles and generate electricity, demonstrating its high potential for diverse applications as a renewable energy source. Hydrogen can be classified as green, blue or grey, depending on the source from which it is produced. While blue and grey hydrogen are derived from natural gasses such as methane and emit carbon dioxide as a byproduct, green hydrogen is produced from water by a process called electrolysis (National Grid, s.d.). In this process, water will enter an electrolyser, powered by renewable energy such as wind or solar power, which will split the water molecules into hydrogen and oxygen (fig.5) (Energy, s.d.) To generate energy, this hydrogen will react with oxygen across a hydrogen fuel cell to produce electricity, minimal heat and water (fig.6) (EIA, s.d.).

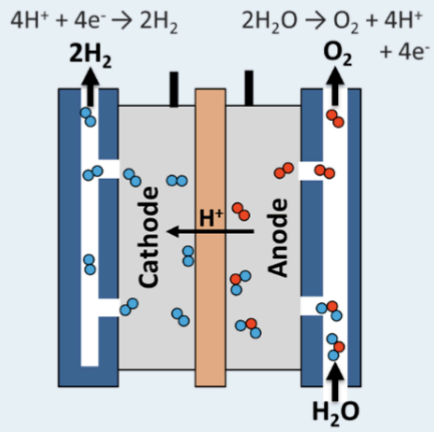

Figure 5 : Hydrogen production by electrolysis (Energy, s.d.)

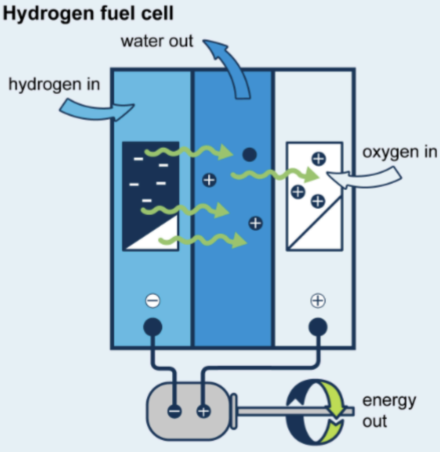

Figure 6: Electricity production by hydrogen fuel cell (EIA, s.d.)

Projections suggest that by 2050, hydrogen could meet 24% of the global energy needs. However, green hydrogen production requiring a significant amount of water reserves, led scientists to explore more unconventional sources. A company named Scottish water in the UK decided to investigate other possibilities and the preliminary results from their study suggested that hydrogen production from wastewater might now be possible (Aquatechtrade, s.d.).

Examining the advantages of using hydrogen as an energy source for South African WWTPs in the Crocodile river reveals several benefits. First, hydrogen produced from waste water could be an opportunity for implementation of a circular economy in WWTPs. Indeed, they would be capable of producing their own energy and therefore no longer be subject to frequent blackout events. Furthermore, producing green hydrogen from wastewater ensures the local freshwater supply stays untouched and additionally, the water released in the consumption process meets nearly all of WHO’s drinking water requirements (Allen, 2022). Using green hydrogen also improves the overall environmental impact of the wastewater industry as this type of hydrogen does not release carbon dioxide when produced or consumed and instead produces oxygen as a byproduct (Arriaga et al., 2007). Finally, the use of electricity for hydrogen production offers the possibility to redirect any excess electricity from solar power that cannot be stored to electrolysis which produces easily stored hydrogen for future energy needs (National grid, s.d.; Arriaga et all., 2007).

Nevertheless, hydrogen power is not without its limitations. Storing hydrogen is a challenge as it has a high density and a low volume, therefore, containers need to be big, heavy, high pressure and sturdy. If it stocked improperly, it could lead to leaks which would increase the risk for explosion and endanger the employees and the material. In addition, the material required for this hydrogen production is expensive and requires in-depth knowledge and trained employees.

5. Impact analysis

5.1. Microalgae/Solar Power

The first synergy we explored was microalgae with solar power and the results were very promising. Specifically, in terms of WWT effectiveness, we ranked it as high, due to the symbiotic relationship between microalgae and solar power. Microalgae's proficiency in pollutant removal aligns with the disinfecting capabilities of solar photocatalysis, collectively enhancing water quality and treatment outcomes. Regarding energy self-sufficiency, the collaboration between microalgae and solar power earns a high rank. Solar power significantly addresses the energy demands of WWTPs, while microalgae's role in aeration energy reduction further amplifies the overall energy self-sufficiency, mitigating dependence on conventional energy sources. Furthermore, the synergy is sufficiently cost-efficient, with a medium rank, acknowledging the combined high upfront infrastructure costs, while including the long-term benefits, such as reduced dependency on conventional energy from solar power and revenue generation through the by-products of microalgae.

Lastly, the cumulative impact is assessed as medium-high, which is the average ranking across the previously mentioned categories. Therefore, this integrated approach of combining microalgae and solar power in WWTPs along the Crocodile River can be regarded as one of the most advantageous alternatives explored in our study.

5.2. Solar Power/Hydrogen Energy

Solar-hydrogen systems have been proposed by many research centers and universities as they allow for the storage of excess energy from solar panels by means of hydrogen generation. Indeed, as previously mentioned, excess energy from solar panels could be used to power the electrolyser needed for hydrogen production from wastewater (Arriaga et al., 2007; National Grid, s.d.). In addition to being easily stored compared to electrical energy, hydrogen also presents the great advantage of retaining its energy content as long as it is unused, which means this energy storage method could have less energetic losses than common battery systems (Arriaga et al., 2007; National Grid, s.d.). These characteristics reveal a great synergy between these two methods as they are able to work together to produce and store energy. Concerning WWT, solar power acts as an essential addition to hydrogen energy as it is able to clean and disinfect the wastewater effectively. However, cost efficiency is considered low for this combination as both techniques are expensive and would be too costly together.

5.3. Hydrogen Energy/Microalgae

The combination of microalgae and hydrogen power does not reveal a synergy as observed in other combinations but rather showcases an effective association. While microalgae may fall short in energy production, hydrogen energy excels in this aspect, ranking this combination as high in energy self sufficiency. On the other hand, microalgae addresses the WWT aspect and renders it highly effective where hydrogen energy falls short. Furthermore, when considering cost-efficiency, the initial elevated cost of hydrogen production material proves to be less problematic due to the lower cost of microalgae. Therefore, despite lacking a direct synergy in their combination, it can be concluded that their association proves highly advantageous and can be considered one of our study’s most beneficial alternatives.

5.4.Microalgae/Hydrogen Energy/Solar Power

The synergy of microalgae, hydrogen energy, and solar power demonstrates high effectiveness in WWT and energy self-sufficiency. Microalgae and solar power synergize to enhance pollutant removal, while hydrogen energy addresses energy production. Despite the upfront costs, the collaboration proves transformative and sustainable, especially for wastewater treatment along the Crocodile River. However, the low rank in cost efficiency was given due to the initial infrastructure expenses that surpasses all the previously mentioned combinations. The overall impact, therefore, is considered medium due to the great potential for energy-sufficiency and water treatment but also great upfront costs,especially for the south african context.

Technology	Energy Self-Sufficiency	Water Treatment	Cost-Efficient	Expected Impact
Microalgae	Low	High	Medium	Medium
Solar Power	Medium	High	Low	Medium
Hydrogen Energy	High	Low	Medium	Medium
Microalgae + Solar Power	High	High	Medium	Medium-High
Microalgae + Hydrogen Energy	High	High	Medium	Medium-High
Solar Power + Hydrogen Energy	High	High	Low	Medium
Microalgae+Solar Power +Hydrogen Energy	High	High	Low	Medium

Table 1: Impact analysis table of the technologies and their combinations

6. Discussion

Our analysis points to the most advantageous combinations for WWTPs along the Crocodile River being microalgae with either solar power or hydrogen. These combinations ranked medium-high, the highest among the evaluated synergies.

The collaboration between microalgae and solar power demonstrated a symbiotic relationship, enhancing WWT effectiveness and achieving energy self-sufficiency. Microalgae's proficiency in pollutant removal combined with the disinfecting capabilities of solar photocatalysis showed potential for significant water quality improvement. Despite initial infrastructure costs, the long-term benefits, including reduced energy dependency and revenue from valuable microalgae by-products, making this combination a cost-efficient and transformative solution.

Similarly, the synergy between microalgae and hydrogen power revealed an effective association, balancing WWT and energy self-sufficiency. Microalgae's competence in WWT complemented hydrogen energy's capability for addressing energy production needs. The initial costs associated with hydrogen production materials were offset by the lower cost of microalgae, rendering this combination economically viable. This synergy presented a beneficial alternative for optimizing WWTPs.

It is important to note that the most appropriate technological combination to be implemented will depend on the local context along the Crocodile River in South Africa. For instance, municipalities experiencing higher water flow conditions might find the combination of hydrogen and microalgae more beneficial. In contrast, municipalities with more prolonged periods of high solar radiance might find the synergy of microalgae and solar power more advantageous.

7. Limitations and Implications for Future Research

Throughout our research process, we encountered several bottlenecks. The most prevalent one is lack of information including, but not limited to studies conducted on the WWTPs on the Crocodile River as well as information about the Crocodile River Partnership. We researched the Crocodile River and found valuable papers discussing its general characteristics. Also, we spent plenty of time understanding the general functionality of WWTPs. However, when we looked into the specific context of the six WWTPs spread along the Crocodile River, we found little to no information. The limited amount of research papers and websites that we gathered were either strictly touching upon issues with the river, lacking specific plans of action, or required us to pay a substantial amount to be able to access their content. Moreover, although we understood how WWTPs operate and are designed, we found no specific information on WWTPs in South Africa, which also limited our potential solutions from a technical point of view.

Furthermore, the available information about the Crocodile River Partnership was not that helpful either because, despite their mission, vision and stakeholders involved, everything else about them was too vague or unmentioned. In efforts to collect primary data, we reached out to Guido van de Ven, a knowledgeable stakeholder. However, this approach also turned out to be unsuccessful as his availability did not fit our time frame.

Future research efforts should prioritize addressing the significant gaps in information encountered during this study. Specifically, there is a need for comprehensive studies and data collection focusing on WWTPs along the Crocodile River. Furthermore, there is a need for more transparency and accessibility regarding information about the Crocodile River Partnership, including its objectives and activities. Future research endeavors should explore alternative methods for obtaining primary data, such as conducting interviews with relevant stakeholders, to supplement existing information and address these knowledge gaps.

8. Conclusion

Our research revealed that microalgae, solar power, and hydrogen energy individually offer substantial benefits in WWT and energy production. Furthermore, our impact analysis highlighted the synergies between these technologies for an effective and sustainable solution.

The collaboration between microalgae and solar power stood out as a symbiotic relationship, addressing both WWT effectiveness and energy self-sufficiency. Similarly, the association between microalgae and hydrogen power proved effective, balancing WWT and energy production needs. Despite initial infrastructure costs, the synergies between microalgae and solar power, as well as microalgae and hydrogen power, presented cost-efficient solutions. The long-term benefits, including reduced energy dependency and revenue from valuable microalgae by-products, mitigated the initial expenses.

In conclusion, while each technology has its advantages, the most suitable solution for optimizing WWTPs along the Crocodile River depends on the local context and specific requirements of each municipality. Our study provides a foundation for further exploration and emphasizes the need for tailored solutions that consider the social-ecological systems, environmental impact, and stakeholders involved. By addressing these challenges, municipalities can make informed decisions to enhance WWT and contribute to sustainable development along the Crocodile River.

9. References

Acién, F., Gómez-Serrano, C., Morales-Amaral, M. M., Sevilla, J. M. F., & Molina-Grima, E. (2016). Wastewater treatment using microalgae: how realistic a contribution might it be to significant urban wastewater treatment? Applied Microbiology and Biotechnology, 100(21), 9013–9022. https://doi.org/10.1007/s00253-016-7835-7

Alami, A. H., Alasad, S., Ali, M., & Alshamsi, M. (2021). Investigating algae for CO2 capture and accumulation and simultaneous production of biomass for biodiesel production. Science of the Total Environment, 759, 143529. https://doi.org/10.1016/j.scitotenv.2020.143529

Allen, C. (2022, 29 novembre). Is a hydrogen-powered future hiding in our wastewater ? - Valuing Water Initiative. Valuing Water Initiative. https://valuingwaterinitiative.org/is-a-hydrogen-powered-future-hiding-in-our-wastewater/

Anand, U., Dey, S., Parial, D., Federici, S., Ducoli, S., Bolan, N., Dey, A., & Bontempi, E. (2023). Algae and bacteria consortia for wastewater decontamination and transformation into biodiesel, bioethanol, biohydrogen, biofertilizers and animal feed: a review. Environmental Chemistry Letters, 21(3), 1585–1609. https://doi.org/10.1007/s10311-023-01562-w

Aquatech. (s. d.). Wastewater to hydrogen : the fuel of the future ? Aquatech. https://www.aquatechtrade.com/news/wastewater/wastewater-to-hydrogen-fuel-of-the-future

Arashiro, L. (n.d.). Microalgae as a sustainable alternative for wastewater treatment. International Water Association. https://iwa-network.org/microalgae-sustainable-alternative-wastewater-treatment/

Arriaga, L., Martínez, W., Cano, U., & Blud, H. (2007). Direct coupling of a solar-hydrogen system in Mexico. International Journal of Hydrogen Energy, 32(13), 2247‑2252. https://doi.org/10.1016/j.ijhydene.2006.10.067

Berghuis, H. (2023, August 30). Green Drop Improvement Plans for a better water quality in the Blue Deal Crocodile River project - Dutch Water Authorities. Dutch Water Authorities. https://dutchwaterauthorities.com/news/green-drop-improvement-plans-south-africa

Biggs, H., Du Toit, D., Étienne, M., Jones, N., Leitch, A., Lynam, T., Pollard, S., & Stone-Jovicich, S. (2008). A preliminary exploration of two approaches for documenting “mental models” held by stakeholders in the crocodile catchment, South africa. In HAL (Le Centre Pour La Communication Scientifique Directe). https://hal.inrae.fr/hal-02821875

Centers for Disease Control and Prevention. (2024, February 1). Presentation on The Safe Water System. https://www.cdc.gov/presentations/unagb

Chakuya, J. (2018). The Human Crocodile Conflicts and the Sustainable Conflict Resolutions Review. International Journal of Environmental Sciences & Natural Resources, 13(2). https://doi.org/10.19080/ijesnr.2018.13.555856

Chertock, S. K. L. S. M. (n.d.). 25 countries, housing one-quarter of the population, face extremely high water stress. World Resources Institute. https://www.wri.org/insights/highest-water-stressed-countries

Deksissa, T. (2004). Dynamic integrated modelling of basic water quality and fate and effect of organic contaminants in rivers

https://www.researchgate.net/publication/292609830_

Department of Water and Sanitation. (2022). Annual Report 2021/22.Government of South Africa. https://www.gov.za/sites/default/files/gcis_document/202210/dws2021-22annualreport.pdf

DW News. (2023, January 20). 10-hour blackouts: What is behind the South Africa’s energy crisis? | DW News [Video]. YouTube. https://www.youtube.com/watch?v=OaOjRGOJlOU

Fn, C., & Mf, M. (2017). Factors affecting water pollution: a review. Journal of Ecosystem & Ecography, 07(01). https://doi.org/10.4172/2157-7625.1000225

Hassan, R. M. (2003). Economy-wide benefits from water-intensive industries in South Africa: Quasi-input-output analysis of the contribution of irrigation agriculture and cultivated plantations in the Crocodile River catchment. Development Southern Africa, 20(2), 171–195. https://doi.org/10.1080/03768350302953

Hydrogen production : electrolysis. (s. d.). Energy.gov. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis#:~:text=Electrolysis%20is%20the%20process%20of,water%20into%20%20hydrogen%20and%20%20oxygen

Leviathan Dynamics. (n.d.). https://www.leviathan-dynamics.com/en/technology-watertreatment

Magome, M. (2023, March 6). South African leader grapples with ever-worsening power cuts | AP News. AP News. https://apnews.com/article/south-africa-power-cuts-electricity-corruption-c86b3db8bce962cd8b0fa672310d95aa

Milani, S. J., & Bidhendi, G. N. (2023). Biogas and photovoltaic solar energy as renewable energy in wastewater treatment plants: A focus on energy recovery and greenhouse gas emission mitigation. Water Science and Engineering. https://doi.org/10.1016/j.wse.2023.11.003

NuWater. (2023, November 15). The advantages of solar powered water treatment solutions. NuWater Water Treatment Solutions South Africa. https://nuwater.com/advantages-of-solar-powered-water-treatment-solutions/

Nwoba, E. G., Vadiveloo, A., Ogbonna, C. N., Ubi, B. E., Ogbonna, J. C., & Moheimani, N. R. (2020). Algal cultivation for treating wastewater in African Developing countries: a review. CLEAN - Soil, Air, Water, 48(3). https://doi.org/10.1002/clen.202000052

Pandey, A., Kumar, R., Kalidasan, B., Laghari, I. A., Samykano, M., Kothari, R., Abusorrah, A., Sharma, K., & Tyagi, V. (2021). Utilization of solar energy for wastewater treatment: Challenges and progressive research trends. Journal of Environmental Management, 297, 113300. https://doi.org/10.1016/j.jenvman.2021.113300

Parliament of the Republic of South Africa. (n.d.). Urbanisation. https://pmg.org.za/page/Urbanisation#:~:text=South%20Africa%20is%20urbanising%20rapidly,demand%20on%20basic%20infrastructure%20requirements.

Phungela, T. T., Maphanga, T., Chidi, B. S., Madonsela, B. S., & Shale, K. (2022). The impact of wastewater treatment effluent on Crocodile River quality in Ehlanzeni District, Mpumalanga Province, South Africa. South African Journal of Science, 118(7/8). https://doi.org/10.17159/sajs.2022/12575

Rana, A. Y., & Rana, A. Y. (2023, November 23). Tsinghua University leads breakthrough in wastewater treatment using organic photocatalysts. BNN Breaking. https://bnnbreaking.com/world/china/tsinghua-university-leads-breakthrough-in-wastewater-treatment-using-organic-photocatalysts/

Samuel, N., Bett, S. K., Okpara, E. C., Olagbaju, P. O., Fayemi, O. E., & Mathuthu, M. (2022). An Assessment of Land Use and Land Cover Changes and Its Impact on the Surface Water Quality of the Crocodile River Catchment, South Africa. In River Deltas Research - Recent Advances. https://doi.org/10.5772/intechopen.95753

Sansaniwal, S. K. (2019). Advances and challenges in solar-powered wastewater treatment technologies for sustainable development: a comprehensive review. International Journal of Ambient Energy, 43(1), 958–991. https://doi.org/10.1080/01430750.2019.1682038

Singh, G., & Thomas, P. B. (2012). Nutrient removal from membrane bioreactor permeate using microalgae and in a microalgae membrane photoreactor. Bioresource Technology, 117, 80–85. https://doi.org/10.1016/j.biortech.2012.03.125

Siwulec, C. (2023, January 12). Why solar for water and wastewater treatment facilities? Sol Systems. https://www.solsystems.com/why-solar-for-water-and-wastewater-treatment-facilities/

Sources and solutions: Wastewater | US EPA. (2023, November 29). US EPA. https://www.epa.gov/nutrientpollution/sources-and-solutions-wastewater#:~:text=Wastewater%20contains%20nitrogen%20and%20phosphorus,of%20nitrogen%20and%20phosphorus%20pollution.

Srimongkol, P., Sangtanoo, P., Songserm, P., Watsuntorn, W., & Karnchanatat, A. (2022). Microalgae-based wastewater treatment for developing economic and environmental sustainability: Current status and future prospects. Frontiers in Bioengineering and Biotechnology, 10. https://doi.org/10.3389/fbioe.2022.904046

Tan, Y. H., Chai, M. K., Na, J. Y., & Wong, L. S. (2023). Microalgal growth and nutrient removal efficiency in Non-Sterilised Primary domestic wastewater. Sustainability, 15(8), 6601. https://doi.org/10.3390/su15086601

Torres-Tiji, Y., Fields, F. J., & Mayfield, S. P. (2020). Microalgae as a future food source. Biotechnology Advances, 41, 107536. https://doi.org/10.1016/j.biotechadv.2020.107536

Tshivhase, N. S. (2019). Assesement of river health using "in situ" water quality parameters and mini-sass biomonitoring tool in the Marico and Crocodile Rivers, Northern Province, SouthAfrica.https://repository.up.ac.za/bitstream/handle/2263/77891/Tshivhase_Assessment_2019.pdf?sequence=1&isAllowed=y

U.S. Environmental Protection Agency. (2023). Sources and Solutions: Wastewater. Retrieved, from https://www.epa.gov/nutrientpollution/sources-and-solutions-wastewater#:~:text=Wastewater%20contains%20nitrogen%20and%20phosphorus,of%20nitrogen%20and%20phosphorus%20pollution.

United Nations University World Institute for Development Economics Research (UNU-WIDER). (n.d.). Potential impacts of climate change on national water supply in South Africa. https://www.wider.unu.edu/publication/potential-impacts-climate-change-national-water-supply-south-africa#:~:text=By%202050%2C%20climate%20change%20is,small%20water%20resource%20management%20systems.

United Nations. (2023). Water Quality and Wastewater. UN Water. https://www.unwater.org/water-facts/water-quality-and-wastewater

United Nations.(2024), Water and Sanitation.https://www.un.org/sustainabledevelopment/water-and-sanitation/

United States Environmental Protection Agency. (2013, August). Renewable Energy Fact Sheet: Solar Cells [Slide show]. https://www.epa.gov/sites/default/files/2019-08/documents/solar_cells_fact_sheet_p100il8r.pdf

Use of hydrogen - U.S. Energy Information Administration (EIA). (s. d.). https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php

What is hydrogen ? (s. d.). National Grid. https://www.nationalgrid.com/stories/energy-explained/what-is-hydrogen#