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Assessment of algae-based domestic wastewater treatment resource recovery, effluent quality, cost analysis and life cycle: a review

Aira Muzammal*, Iqra Zahoor

Department of Chemistry, University of Agriculture, Faisalabad-38040-Pakistan.

Abstract

The impact on water supplies and the amount of wastewater produced at the same time have both greatly grown because of the constantly growing population. The need to upgrade the traditional wastewater treatment process is driven by the shortage of water resources and worries about environmental degradation. This review will highlight the use of microalgae in domestic wastewater treatment. Algae-based domestic wastewater treatment systems have advantages such as adapting to different environmental conditions. They are effective, economical, and environmentally friendly methods to remove nutrients, pollutants and improve water quality. Microalgae species such as *Chlorella vulgaris* and *Scenedesmus obliquus* have shown excellent results in treating domestic sewage and have the potential to produce biofuel. Algae-based solutions for rural wastewater treatment offer affordability, nutrient removal, water reuse and environmental sustainability. Algae-based wastewater treatment effectively removes micro-plastics, provides high biomass yields and productivity. Life cycle analysis (LCA) of algae-based municipal wastewater treatment looks at energy use and environmental impacts. By reducing waste and producing useful by-products such as fertilizers and biofuels, algae processing systems can support the circular economy. The "All-Gas Project", the Algae-based Factory, "Algae Discovery Centre" and the "Algal Septic Tank" are all successful examples of algae-based wastewater treatment in developed and developing countries. Optimizing processing methods, improving algae, maximizing growth conditions, integrating with other processing methods, and scaling up for commercial applications are some future research opportunities. Although there are still challenges in process optimization, algae-based municipal wastewater treatment is an inexpensive and environmentally friendly option with advantages in terms of nitrogen removal, biomass utilization, energy efficiency, and resource recovery.

Keywords: micro-algae, wastewater treatment, nutrient recovery, life cycle analysis, micro-plastic, circular economy.

Full length review article
*Corresponding Author, e-mail: airamuzammal2511@gmail.com

1. Introduction

A key component of environmental preservation is the treatment of domestic wastewater. According to estimates by various scientists more than 85% of the wastewater produced worldwide is released into the environment untreated. As a result, water supplies get contaminated, illnesses that are transmitted through water are disseminated, and aquatic ecosystems are harmed. To solve this issue, several home wastewater treatment techniques, including physical, chemical, and biological ones, have been developed. These techniques need for a lot of energy and are frequently pricey. As a result, scientists have started looking into less expensive, more environmentally friendly alternatives for treating home wastewater. Domestic wastewater treatment systems based on algae are one such approach [1]. Domestic wastewater can be treated using a technique called algae-based domestic wastewater treatment. Microorganisms that use photosynthetic energy to develop quickly and ingest nutrients like nitrogen and phosphorus are known as algae. Domestic wastewater frequently contains these nutrients, which when dumped into aquatic bodies without treatment can pollute them. The ability of algae to assimilate certain nutrients allows for the removal of these nutrients from wastewater in algal-based home wastewater treatment systems. Algae provides several benefits when used to remediate domestic wastewater. High nutrient concentrations, low light levels, and hot temperatures are just a few of the environmental conditions that algae can thrive in. They are therefore perfect for use in home wastewater treatment systems, where environmental conditions are frequently variable. In addition, compared to other treatment techniques, algae-based systems are relatively inexpensive and need little energy input. Domestic wastewater treatment systems using algae have been created in a variety of configurations, including open ponds, closed photo-bioreactors, and hybrid systems. The most popular kind of algae-based system, open ponds involve the development of algae in ponds that are not covered. These ponds come in a variety of sizes, from modest backyard setups to enormous industrial setups. On the other hand, closed photo-bioreactors are enclosed devices that offer more environmental control. Applications for research and development frequently employ these platforms. Open ponds and closed photo-bioreactors are combined in hybrid systems to maximize their respective benefits. Numerous studies have shown that algae-based domestic wastewater treatment systems are efficient at removing nutrients from wastewater. For instance, a study found that an open pond system using the algae species *Chlorella vulgaris* was able to remove up to 97% of nitrogen and 98% of phosphorus from domestic wastewater. Algae-based systems have also been found to be successful in removing additional pollutants from wastewater, such as organic pollutants and heavy metals. During photosynthesis, algae may also create oxygen, raising the dissolved oxygen level of wastewater and improving its suitability for aquatic life [2].

2. Importance and background of the topic:

Due to its many advantages, algae-based home wastewater treatment has attracted a lot of interest lately. The significance of treating residential wastewater with algae might be cost-effective and treated effectively and economically using algae. It has a minimal energy need and is inexpensive to run. Algae are capable of absorbing nutrients from wastewater, which is the main cause of water pollution, including nitrogen and phosphorus. This aids in preserving the water's quality and lowering eutrophication danger. Algae may be utilized as a source for the generation of biofuels [3]. It is possible to create biogas, bioethanol, or biodiesel from the gathered algae. Algae take up CO_2 from the atmosphere when photosynthesis is taking place. This aids in lowering the wastewater treatment process' carbon footprint. Both urban and rural locations can use algae-based wastewater treatment. It may be used in closed systems and doesn't need any more land or resources. Numerous research has been done to determine how well home wastewater may be treated using algae. For instance, research by Wang et al. discovered that adding microalgae to a wastewater treatment system significantly reduced the levels of nitrogen and phosphate and raised the levels of dissolved oxygen. Wu et al.'s hybrid system that combines microalgae and bacteria was successful in removing phosphate, nitrogen, and organic matter from home wastewater, according to a different research they conducted [4]. Algae-based wastewater treatment contributes to better water quality and lower risk of waterborne illnesses. Reusing the treated water is possible for non-potable uses like irrigation or commercial use. In conclusion, the treatment of household wastewater using algae is a novel and environmentally friendly approach that has numerous advantages for both the environment and society. It might help address the challenge of rising water contamination and advance the creation of a circular economy [5].

3. Objectives and scope of the report:

Microalgae are used in a developing technique called algae-based residential wastewater treatment to remove contaminants from wastewater. Due to its low cost, great efficiency, and promise for sustainable wastewater treatment, this technology is growing in popularity. Home wastewater may be treated using algae-based systems to remove up to 93% of the nutrients and organic materials. The researchers also mentioned the possibility of producing beneficial byproducts like biofuels and fertilizer through the use of algae in wastewater treatment [6].

Another research examined the viability of utilizing algae for wastewater treatment in a decentralized context, such as a home or community-scale system. According to the study, algae-based treatment is a good choice and has the potential to be less expensive and energy-intensive than traditional wastewater treatment techniques. There is also a possibility of producing beneficial byproducts like biofuels and fertilizer using algae in wastewater treatment. Microalgae are used in a developing technique called algae-based residential wastewater treatment to remove contaminants from wastewater. Due to its low cost, great efficiency, and promise for sustainable wastewater treatment, this technology is growing in popularity [7].

4. Algae Species used in domestic wastewater treatment.

4.1. Chlorella vulgaris:

Microalgae of the species *Chlorella vulgaris* have been investigated for their ability to cleanse residential wastewater. Research that was published in the Journal of Environmental Science and Health assessed *Chlorella vulgaris* efficacy in treating home wastewater under various circumstances. The initial biomass concentration and the hydraulic retention duration were shown to have a substantial impact on the removal efficiency of nitrogen and phosphorus by *Chlorella vulgaris*. Using *Chlorella vulgaris* to treat septic tank effluent, a typical kind of residential wastewater in rural regions. It was discovered that *Chlorella vulgaris* could remove up to 95.6% of the total phosphorus and up to 87.5% of the total nitrogen from the wastewater from septic tanks [8-9]. *Chlorella vulgaris* has also been researched for its ability to turn home wastewater into biofuels and other high-value goods. *Chlorella vulgaris* cultured on home wastewater was able to create lipids with a high potential for producing biodiesel, according to a study published in the Journal of Applied Phycology. Overall, *Chlorella vulgaris* has demonstrated good outcomes in the treatment of household wastewater and has the potential to be employed as a long-term and affordable wastewater treatment solution [9-10].

4.2. Scenedesmus obliquus:

Another microalgae species that has been investigated for its potential in the treatment of household wastewater is *Scenedesmus obliquus*. The effectiveness of *Scenedesmus obliquus* in cleaning residential wastewater under various circumstances was assessed in one research that was published in the Journal of Environmental Management. The scientists discovered that *Scenedesmus obliquus* could remove up to 89% of the wastewater's total nitrogen and up to 96% of its total phosphorus. Another research examined *Scenedesmus obliquus* application in a system that integrated wastewater treatment and biofuel generation. The scientists discovered that *Scenedesmus obliquus* could produce lipids that might be utilized to make biodiesel while also removing nutrients from the wastewater [11]. The ability of *Scenedesmus obliquus* to remove heavy metals from wastewater has also been investigated. *Scenedesmus obliquus* was shown to be capable of removing up to 91% of cadmium and lead from simulated wastewater.

Overall, *Scenedesmus obliquus* has demonstrated encouraging results in the treatment of household wastewater and has the potential to be employed as a long-term and affordable wastewater treatment solution. The efficacy of two different species of algae *Chlorella vulgaris* and *Scenedesmus obliquus* in cleaning home wastewater was assessed in research that was published in the Journal of Environmental Management. *Chlorella vulgaris* demonstrated the best removal effectiveness of the three species tested by the researchers in the removal of nitrogen and phosphorus from wastewater [12] {Javed, 2022 #9}.profuv

5. Types of Algae and their usage in wastewater treatment:

5.1. Micro algae:

A wide variety of small organisms known as microalgae may be found in freshwater and marine habitats. They are generally unicellular or colonial in nature. They are a crucial component of the aquatic food chain and are generally referred to as phytoplankton. They are the main source of nutrition for tiny aquatic species like zooplankton. Microalgae are photosynthetic creatures, which means they use sunlight to carry out the process of photosynthesis to create their own food and oxygen. They may produce a multitude of substances, including lipids, carbohydrates, proteins, and pigments, all of which have different industrial uses. Microalgae are being investigated for their possible application in a range of sectors, including biofuels, food, and medicine, due to their quick growth rate and capacity to create high-value chemicals.

5.2. Macro algae:

A wide variety of small organisms known as microalgae may be found in freshwater and marine habitats. They are generally unicellular or colonial in nature. They are a crucial component of the aquatic food chain and are generally referred to as phytoplankton. They are the main source of nutrition for tiny aquatic species like zooplankton. Microalgae are photosynthetic creatures, which means they use sunlight to carry out the process of photosynthesis to create their own food and oxygen. They may produce a multitude of substances, including lipids, carbohydrates, proteins, and pigments, all of which have different industrial uses. Microalgae are being investigated for their possible application in a range of sectors, including biofuels, food, and medicine, due to their quick growth rate and capacity to create high-value chemicals [13]

5.3. Blue Green Algae:

By using both organic and inorganic photosynthesis processes, BGA can produce biomass and biofuel with amazing flexibility when using large-scale chemicals as energy sources. BGA also inhibits the development of pathogenic coliforms and other microbes that use dissolved oxygen to oxidize organic and inorganic materials, which lowers the biological oxygen demand (BOD) and chemical oxygen demand (COD) of aquatic ecosystems. BGA is often utilized as a water quality indicator, for animal and aquaculture feeding, composting, and the creation of valuable compounds like methane. However, during the last several decades, BGA has begun to become more widely used for the treatment of wastewater [14].

6. Selection Criteria for Algae Species:

To remove nutrients naturally and sustainably from water, such as nitrogen and phosphorus, algae can be utilized in wastewater treatment. It should be possible for the algae species to effectively take nutrients from the wastewater. Some types of algae have a stronger preference for nitrogen, whereas others have a stronger preference for phosphorus. To guarantee effective nutrient removal, the algae species should have a rapid growth rate. Some types of algae may increase their biomass by a factor of two in just a few hours. The algae species should be able to develop and flourish in the challenging circumstances of wastewater, such as low light, high nutrient, and high organic content levels. The algae species should be immune to contamination by bacteria and fungus that could compete with them for nutrients. The algal species should generate biomass that can be harvested and processed further, such as into biofuels or other goods. The algae species should be widely distributed and simple to grow [15]

7. Algae-based wastewater treatment system design and operation:

Algae species, wastewater properties, and cultivation system design are just a few of the many variables that must be carefully considered while designing and running algae-based wastewater treatment systems. Analyzing the wastewater's properties, such as its nutritional content, pH, temperature, and organic load, comes first. The right algae species and culture conditions are chosen using this information. The algae species is chosen based on how well it can handle the wastewater conditions, how productive its biomass is, and how well it can remove nutrients. *Chlorella vulgaris*, and *Scenedesmus obliquus* are a few examples of popular algae species utilized in wastewater treatment [16]. Depending on the available area, the environmental factors, and the required biomass yield, the culture system may be constructed as open ponds or closed photo-bioreactors. While closed photo-bioreactors offer more control over the cultivation conditions but are more expensive, open ponds are less expensive to build and maintain but are prone to contamination. Controlling the culture parameters, such as light intensity, temperature, pH, and fertilizer delivery, helps optimize the growth of the algae. Algae biomass may be collected and processed for use in a variety of applications, including the generation of biofuel, animal feed, and fertilizer, after it reaches its peak productivity. To avoid contamination and guarantee optimal algae development, the culture system must undergo routine maintenance. This entails maintaining the culture system's cleanliness and disinfection, checking the water's quality, and changing the growing medium as necessary [17].

8. Design and operation of an Open Pond system:

The process of treating wastewater in shallow, open-air ponds using photosynthetic microorganisms—typically microalgae—involves an open pond system. The device works by exposing the wastewater to sunlight, allowing the microalgae to ingest nutrients and impurities from the water, and then using photosynthesis to transform those substances into biomass and oxygen. After that, the treated water can be released or utilized again for irrigation. To guarantee that the pond water is uniform and doesn't stagnate, open ponds should be situated in places with the most sunshine, adequate drainage, and level terrain. The amount of wastewater to be treated and the intended hydraulic retention time (HRT) should be taken into consideration when determining the pond's size. The HRT, which ranges between five and fifteen days, is the amount of time wastewater stays in the pond. To allow enough sunlight penetration and to stop the growth of anaerobic bacteria, the pond's depth should be kept between 15 and 35 cm. To avoid soil pollution, the pond should be built with a non-toxic liner or with natural clay. To guarantee consistent fertilizer distribution and to avoid the development of scum or algae mats on the surface, the wastewater should be continually mixed. To encourage algae development and remove these nutrients from wastewater, nutrients like nitrogen and phosphorus should be introduced to the pond [18]. To start algal development, the pond should be infected with a starting culture of microalgae. To guarantee ideal growth circumstances, the pH, temperature, dissolved oxygen, and algal biomass content should be routinely checked. To maintain ideal growth conditions and prevent nutrient depletion, algal biomass needs to be periodically collected. The gathered biomass can be used into animal feed or utilized to make biofuels. Before being released, the effluent from the pond needs to be cleaned to make sure it complies with legal requirements [19].

9. Design and operation of Photo-bioreactors:

There are several PBR types, including bubble column reactors, flat-panel PBRs, and tubular PBRs. The wastewater treatment needs, the available area, and the required biomass productivity all influence the PBR type that is chosen. Glass, plastic, and stainless steel are just a few of the materials that may be used to build PBRs. The choice of material is determined by the type of microorganisms being cultivated, the cost, and the intended system lifetime. To supply energy for photosynthesis, the PBR needs a light source. With a wavelength and intensity that encourages optimal growth and biomass productivity, the light source should be tailored to the microalgae being employed. The wastewater in the PBR must be continuously mixed to ensure uniform nutrient distribution and to prevent sedimentation of the microalgae. Nutrient addition: The wastewater must be supplemented with nutrients, such as nitrogen and phosphorus, to promote algal growth and to remove these nutrients from the wastewater. The pH of the wastewater must be maintained within a narrow range to optimize algal growth [20]. To start algal development, the PBR must be infected with a starting culture of microalgae. To guarantee ideal growth circumstances, it's important to keep a close eye on the pH, temperature, dissolved oxygen, and algal biomass concentration. To maintain ideal growth conditions and prevent nutrient depletion, algal biomass must be regularly harvested. The gathered biomass can be used into animal feed or utilized to make biofuels. Before being released, the effluent from the PBR must be disinfected to make sure it complies with legal requirements management of wastewater treatment systems based on algae [21].

10. Design and operation of Hybrid Systems:

To profit from the advantages of both methods, a hybrid system for the use of algae in wastewater treatment combines open pond systems with photo-bioreactors. A hybrid system's design and operation are more intricate than those of a single system, but it provides better treatment effectiveness and uses less energy. Considering the amount of space that is available, the nature of the wastewater, and the required effluent quality, the hybrid system should be set up to maximize treatment efficiency. Integration is necessary to get the best nutrient removal and algal growth from the open pond and photo-bioreactor systems. In order to minimize nutrient depletion and maintain ideal growth conditions, algal biomass from both open pond and photo-bioreactor systems need be taken out at regular intervals [22]. To guarantee ideal growth circumstances, it is important to frequently check the pH, temperature, dissolved oxygen, and algal biomass concentration. To achieve consistent nutrient distribution in the open pond, wastewater should be mixed continually. Meanwhile, wastewater in the photo-bioreactor must be mixed to avoid microalgae sedimentation. To start algal development, a starting culture of microalgae should be added to the open pond and photo-bioreactor systems. Before being discharged, the effluent from the hybrid system needs to be disinfected to make sure it complies with legal requirements [23].

11. Algae-based technologies for wastewater treatment in rural areas:

Algae ponds, sometimes referred to as the stabilization ponds or lagoons, are small, artificial basins used to clean wastewater using natural algae growth. These ponds may be built inexpensively in rural locations, using sunshine, nutrients, and naturally existing algae to filter toxins from wastewater. Algal ponds efficiently remove organic debris, nutrients, and pathogens while also providing the possibility of reusing water for irrigation or agriculture. To clean wastewater, wetlands are manmade systems that resemble natural wetland ecosystems. By using algae's capacity to absorb nutrients and organic contaminants, integrating algae into artificial wetlands increases their effectiveness. Algae assist in the removal of pollutants through procedures including filtration, adsorption, and biological degradation, together with wetland plants and microbes. To improve wastewater treatment in rural regions, integrated systems combine different treatment processes, including technology based on algae. For instance, a comprehensive and effective wastewater treatment solution can be created by combining primary treatment (such as septic tanks), secondary treatment based on algae (such as algal ponds or artificial wetlands with algae), and tertiary treatment (such as sand filters or disinfection). Algae-based methods in rural areas have some advantages. They need comparatively low startup and ongoing expenses to traditional treatment approaches. Algae serving as natural nutrient predators to recover nutrients. Reusability of water in non-potable or agricultural uses. Environmental sustainability, as systems based on algae help collect carbon and use less energy [24]. However, there are some challenges and considerations that needs attention. For example, it might be challenging to design and construct algae-based systems that specifically address the wastewater treatment requirements of rural areas. To accomplish effective treatment, the systems must be correctly scaled and constructed while considering aspects including hydraulic retention duration, loading rates, and nutrient removal needs. In rural locations, access to adequate design and engineering knowledge may be restricted. For algae-based systems to operate at their best, correct nutrient balance and algal growth management must be maintained. It can be difficult to maintain the right nutrient levels for algal development in rural wastewater without contributing to excessive algal biomass buildup or imbalances.

Algae-based systems must be regularly monitored, operated, and maintained to function at their best. Resources and technical know-how for system operation and maintenance may be scarce in rural locations. To solve these issues and guarantee the long-term viability of algae-based treatment systems, adequate training and capacity building are required. Seasonal fluctuations in sun radiation, temperature, and wastewater flow rates are common in rural locations and can affect algal growth and treatment effectiveness. Algal-based systems may work poorly in cold areas and during specific seasons of restricted solar availability, necessitating system modifications or alternate treatment methods. In rural locations, it might be difficult to get community approval and manage social issues such opinions on odor, aesthetics, and possible health hazards related to algae-based systems. Programs for educating the public are crucial to promoting acceptance and knowledge of the advantages of algae-based wastewater treatment [25].

12. Algae-based technologies for wastewater treatment in urban areas:

Because of the high population density and industrial activity in urban areas, nutrient contamination in wastewater is a frequent problem. Algae-based solutions offer a practical and long-lasting way to remove nutrients, enhance water quality, and lessen the impact on receiving water bodies. Technologies based on algae have the potential to provide renewable energy while treating wastewater. Algae may be grown to provide biomass, which can then be broken down into biogas to produce energy and heat. Algae also actively absorb and store carbon dioxide during photosynthesis, helping to increase carbon sequestration and lower greenhouse gas emissions. Algae-based systems are excellent for urban settings with limited space since they may be constructed to be small and flexible. Without needing major land expansion, these systems may be installed in already-existing infrastructure, such wastewater treatment plants or industrial areas. They are scalable because to their modular design, allowing treatment capacity to be changed to meet the demands of expanding metropolitan populations [4]. Reusing treated wastewater is essential due to the growing water shortage in metropolitan areas. Using technology based on algae, wastewater may be safely reused for non-potable uses including irrigation, industrial operations, and urban landscaping. This method is dependable and economical. As a result, less demand is placed on freshwater resources and sustainable water management practices are supported. Technologies based on algae offer chances for environmental awareness campaigns and public participation. Algae-based wastewater treatment systems may be used as teaching tools to spread knowledge of water pollution, resource recovery, and sustainable urban development. Urban areas are centers of community engagement and activism [10]. There are some major issues that algae-based systems for wastewater treatment in metropolitan settings face. It might be difficult to provide land for the development of algae growing systems or treatment facilities in urban settings since there is sometimes a shortage of accessible space. Algae-based systems require enough room for algae development and growth, which might necessitate creative design strategies. Due to the enormous amounts of wastewater produced in urban areas, nutrient and hydraulic loads on wastewater treatment systems are frequently significant. Algae-based solutions must be developed to handle these heavy loads effectively and efficiently. To avoid excessive algal growth, biomass buildup, and system imbalances, nutrient control is essential. Temperature, light availability, pH, and nutrient concentrations are a few environmental elements that have an impact on algae growth. Maintaining ideal development conditions for algae in urban environments may be difficult, especially in places with little sunshine or where the temperature fluctuates. It may be necessary to use unconventional design and operating techniques to provide appropriate light exposure and regulate environmental factors [26].

13. Comparison of algae-based wastewater treatment with conventional methods:

Algae-based treatment methods, such algal ponds, or photo-bioreactors, are very good at removing nutrients from wastewater, especially nitrogen and phosphorus. During photosynthesis, algae naturally absorb and store these nutrients, which results in effective nutrient removal. Contrarily, conventional techniques like drip filters or active sludge may need extra steps or substances to achieve comparable rates of nutrient removal. Systems based on algae have the potential to be more energy-efficient than traditional techniques. Algae use sunlight as their main energy source for photosynthesis, which minimizes their reliance on outside energy sources. Conversely, traditional approaches frequently rely on mechanical aeration, mixing, or pumping, which can use a lot of power [10]. Algae can be harvested and used for various purposes, such as biofuel production, feed for livestock, or fertilizers, which provides an opportunity for resource recovery and contributes to the circular economy. In conventional methods, sludge generated during the treatment process typically requires separate management and removal, which can be expensive and ecologically burdensome. Systems based on algae have the potential to lessen the environmental impact of treating wastewater. Algae serve as a natural carbon sink by consuming carbon dioxide during photosynthesis. This adds to carbon capture and lessens greenhouse gas emissions. When using conventional techniques, the treatment procedure may result in the production of greenhouse gases such nitrous oxide (NO). Water might potentially be reused in algae-based treatment systems because of their effective nutrient removal and disinfection capabilities. Possible non-potable uses for the treated water produced by algae-based systems include irrigation and industrial activities. To reach the needed water quality for reuse using conventional techniques, extra treatment processes are frequently necessary. Algae are known to adapt to changing conditions and can tolerate higher organic loads or toxic substances, providing more stability in treatment performance. Conventional methods may require adjustments or additional treatment steps to handle such fluctuations effectively. Algae-based systems can demonstrate better resilience to variations in wastewater composition and flow rates than traditional techniques [27].

14. Efficiency Assessment of Algae Based domestic wastewater treatment:

Domestic wastewater treatment systems based on algae are gaining popularity as a more environmentally friendly option to conventional wastewater treatment techniques. There are numerous approaches to evaluate these systems' effectiveness. Algae are effective in removing nutrients from wastewater, including nitrogen and phosphorus, which are important causes of water pollution. Monitoring the amounts of these nutrients in the influent (incoming wastewater) and effluent (treated wastewater) can be used to gauge the effectiveness of nutrient removal. COD is a gauge of how much organic stuff is present in wastewater. Algae can successfully lower wastewater's COD levels. By keeping an eye on the COD levels in the influent and effluent, the effectiveness of COD reduction may be evaluated. Algae may be collected to provide biomass for use in the production of biofuels, animal feed, and other products. The amount of algal biomass generated per unit of wastewater treated may be used to gauge how effectively biomass is produced. Monitoring the quantity of energy used throughout the treatment process will allow you to gauge the effectiveness of an algae-based wastewater treatment system. This might refer to the power utilized for lighting, mixing, and pumping [28]

15. Factors Affecting treatment efficiency:

For development and metabolic functions, algae need minerals like nitrogen and phosphorus. The productivity and growth rate of algae can be affected by the presence of certain nutrients in wastewater. Algal blooms brought on by an excess of nutrients may potentially have a detrimental effect on the effectiveness of therapy. Photosynthesis, the process by which algae convert carbon dioxide and water into organic matter and oxygen, depends on light. The rate of photosynthesis and the growth rate of algae can both be influenced by the amount and quality of light. Reduced treatment effectiveness might result from excessive or insufficient lighting. Algae can only grow at a certain range of temperatures. The rate of development and production of algae can be influenced by the temperature of wastewater. A too-low temperature may cause algae development to slacken or halt entirely. A temperature that is too high might harm cells and lessen the effectiveness of the treatment. Algae are susceptible to pH fluctuations. Typically, a pH range of 8 to 9 is ideal for the development of algae [29]. The growth rate and productivity of algae may be significantly impacted if the pH of wastewater is outside of this range. The effectiveness of treatment using algae might vary depending on the wastewater quality. Algal growth and production may be adversely affected by high concentrations of pollutants or poisons. The effectiveness of treatment can also be impacted by the presence of heavy metals or other impurities in wastewater. The susceptibility of various strains of algae to environmental elements including temperature, light, and nutrition availability varies. The effectiveness of therapy and overall system performance can be affected by the choice of a suitable algal strain [30].

16. Nutrient removal from domestic wastewater using Algae:

Since algae needs these nutrients for development, algae can extract nitrogen and phosphorus from wastewater. They can remove up to 91% of nitrogen and 98% of phosphorus from wastewater. The removal efficiencies of nitrogen and phosphorus from household wastewater utilizing microalgae were found to be 75–95% and 80–90%, respectively. The removal efficiency of nitrogen and phosphorus from household wastewater using algae-based wastewater treatment systems have been demonstrated to reach up to 98% and 73%, respectively. Removal efficiencies of up to 97.5% for total nitrogen and 96.4% for total phosphorus were attained in a study of home wastewater treatment utilizing microalgae [29-31]{Nadeem, 2022 #3}.

17. Mechanism of nutrient removal:

Algae use a mix of physical, chemical, and biological mechanisms to remove nutrients from wastewater. For their development and reproduction, algae have a high requirement for nutrients like nitrogen and phosphorus. These nutrients can be found in wastewater as organic and inorganic components including phosphate, ammonia, nitrate, and nitrite. Algae absorb these nutrients through a process known as assimilation when exposed to wastewater. The algae take the nutrients during absorption and transform them into organic matter, which is subsequently used for growth and reproduction. Adsorption is another method through which algae remove nutrients. Algae may absorb nutrients onto their cell surfaces due to their large surface area. This procedure aids in depleting the wastewater's concentration of nutrients by removing them from the water column [32]. Algal nutrient removal is facilitated by sedimentation, which is one of the functions of algae in addition to absorption and adsorption. Algae spread out and develop into thick mats on the water's surface or sink to the bottom of the treatment tank. This procedure enhances water clarity while also removing nutrients and other organic materials from the water column. In a nutshell, a complicated interplay between physical, chemical, and biological processes leads to the absorption, adsorption, and sedimentation of nutrients by the algae, which is the mechanism for nutrient removal by algae from wastewater [33].

18. Removal of micro-plastic from domestic wastewater using algae:

The effectiveness of several algae species at removing micro-plastic was investigated in research. According to the findings, several species, including *Chlorella vulgaris* and *Scenedesmus obliquus*, had high micro-plastic removal rates with efficiencies ranging from 75% to 95%. Another investigation into the impact of micro-plastic removal on algal growth conditions. They discovered that optimizing elements like light intensity, nutrition availability, and pH can improve the effectiveness of algae-based systems in removing micro-plastic. Micro-plastics can be successfully trapped and removed by algal biofilms, which are created when algae collect on surfaces. Research showed that biofilms produced by mixed algal cultures were capable of removing micro-plastic with up to 96% efficiency [34]. Algal-bacterial collaborations, in which bacteria and algae collaborate well, have demonstrated potential in the removal of micro-plastic. In contrast to algae alone, bacteria and algae combined in a biofilm-based system improved micro-plastic removal, attaining removal rates of over 92%. Algae-based systems have the capacity to remove micro-plastic, as shown by laboratory-scale investigations, however expanding these systems to bigger treatment facilities presents difficulties. For efficient micro-plastic removal at a broader scale, research from the year 2022 underlined the significance of optimizing system design, hydrodynamic conditions, and operating factors [34].

19. Biomass production and harvesting in algae-based wastewater treatment:

An economical and environmentally favorable method of treating wastewater is algae-based treatment. Utilizing algae to absorb and remove nutrients from wastewater, such as nitrogen and phosphorus, helps to reduce the quantity of contaminants in the water. Algae are grown under controlled settings, such as in photo-bioreactors or open ponds, for biomass generation in algae-based wastewater treatment. Algae may be cultivated under artificial or natural lighting, and the growth parameters can be optimized to produce the most biomass. The wastewater treatment system may be used to collect the algae once they have achieved their maximal biomass output. Depending on the species of algae, the growing circumstances, and the intended use of the collected biomass, several harvesting techniques may be used. Filtration, centrifugation, and sedimentation are frequently used harvesting techniques. After being harvested, the algal biomass may be further processed to extract useful substances like lipids, proteins, and pigments that can be utilized in a variety of products, including biofuels, animal feed, and cosmetics. Overall, wastewater treatment with algae is effective and sustainable, and it yields useful biomass [35].

20. Biomass yield and productivity:

To treat wastewater using algae effectively and efficiently, it is crucial to consider biomass production and productivity. While biomass productivity relates to the pace at which the algal biomass is generated, biomass yield describes how much algae biomass is produced per unit of volume or area. The species of algae, the growing conditions, and the wastewater quality are only a few of the variables that affect the biomass output and productivity in algae-based wastewater treatment. Increasing nutrient concentrations in the wastewater can increase biomass yields and productivity, but too many nutrients can also promote the growth of undesirable algae and lower the system's overall efficiency. The yield and productivity of biomass may also be increased by optimizing the growing parameters, such as temperature, light intensity, pH, and carbon dioxide concentration. For instance, boosting light intensity can improve photosynthesis and boost biomass output, while regulating pH can stop undesirable algae from growing and guarantee the survival of good ones. The productivity and production of biomass can also be impacted by the harvesting technique. For instance, centrifugation can produce better productivity but lower biomass yield whereas sedimentation can produce higher biomass yield but lower productivity. Overall, in order to ensure effective nitrogen removal and to maximize the potential of the algal biomass for further processing and utilization, high biomass yield and productivity are essential in algae-based wastewater treatment [32-36-37] {Chauhdary, 2022 #13}.

21. Harvesting techniques and challenges:

Depending on the species of algae, the growth circumstances, and the planned use of the collected biomass, several algae harvesting techniques can be used in wastewater treatment. In typical harvesting method the first step is sedimentation that entails letting the algae accumulate at the bottom of the purification system, where it is simple to collect them. Then to separate the algae from the water, the algae are spun at a high speed in a centrifuge. Next comes filtration that includes separating the algae from the water using filters, such as membranes or screens. Flocculation is the process of introducing a chemical, such as aluminum sulfate, to wastewater in order to cause the algae to group and settle more readily [38].

22. Resource recovery from algae-based wastewater treatment:

In addition to assisting in the removal of contaminants and nutrients from wastewater, algae-based wastewater treatment also offers the chance to recover resources from the harvested algal biomass. Lipids, proteins, pigments, and biofuels are some of the resources that may be recovered from wastewater treatment using algae. Lipids are abundant in algae biomass and may be removed and utilized to make biofuels like biodiesel, bioethanol, and bio-jet fuel. Different methods, including solvent extraction, supercritical fluid extraction, and wet lipid extraction, can be used to extract lipids. The biomass produced from algae is a rich source of proteins that may be utilized in the production of bioplastics, animal feed, and other industrial products. There are several methods for extracting proteins, including solvent extraction, aqueous extraction, and enzymatic extraction [39].

Algae biomass also includes a variety of pigments that can be exploited as natural colorants in the food, cosmetic, and pharmaceutical sectors. These pigments include chlorophyll, carotenoids, and phycobili proteins. Different methods, including solvent extraction, supercritical fluid extraction, and ultrasound-assisted extraction, can be used to extract pigment. Algae biomass may be utilized as a source of nutrients and organic matter for agriculture in bio-fertilizers. To improve soil fertility and agricultural productivity, the collected algal biomass can be composted and utilized as a bio-fertilizer. Through anaerobic digestion, algae biomass may also be utilized to create biogas. The resulting biogas can be utilized to fuel automobiles or as a source of renewable energy to produce electricity. Overall, resource recovery from wastewater treatment using algae can support the circular economy [40].

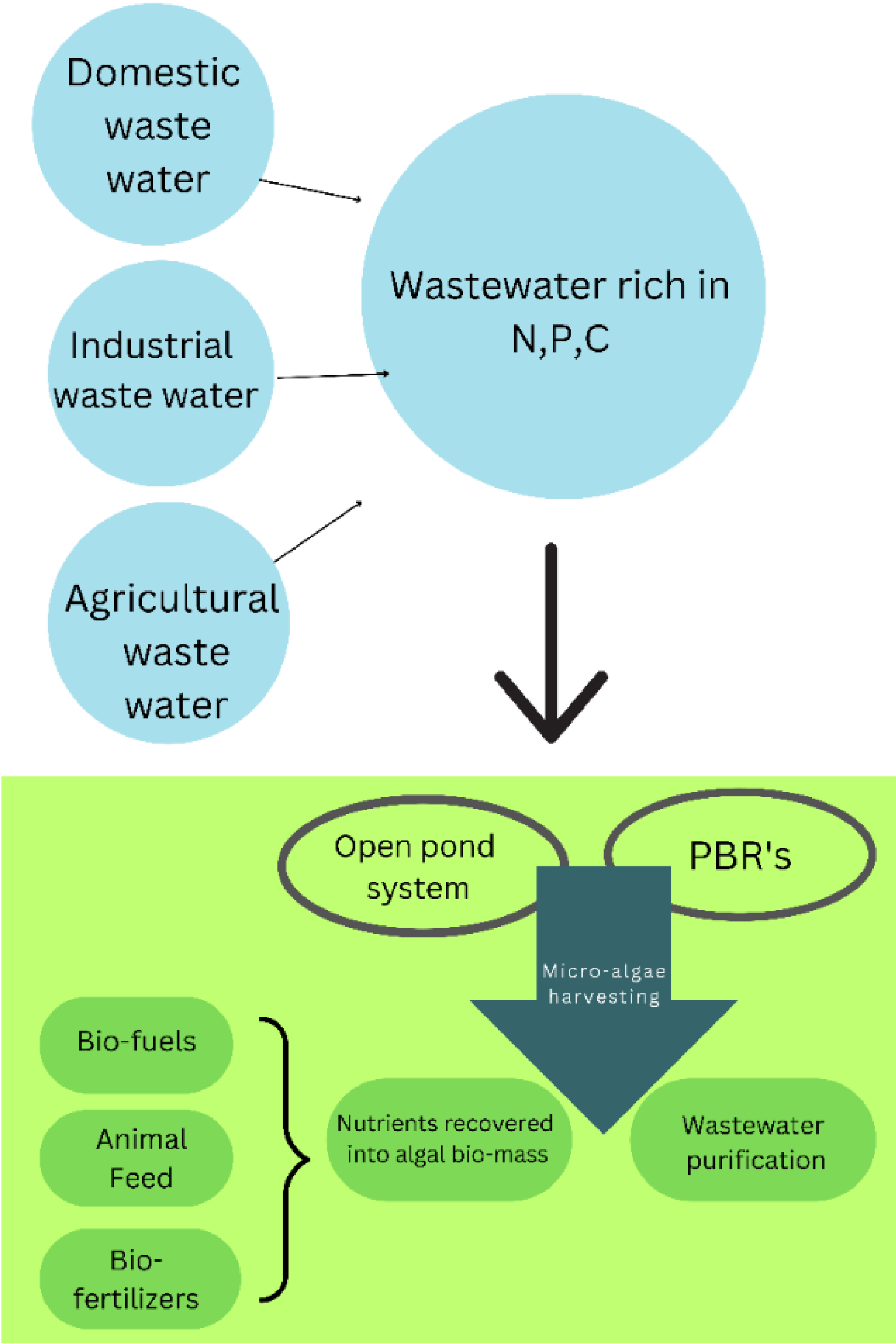

Figure 1: Summary of how water is treated and nutrients are recovered with open pond system & PBR's

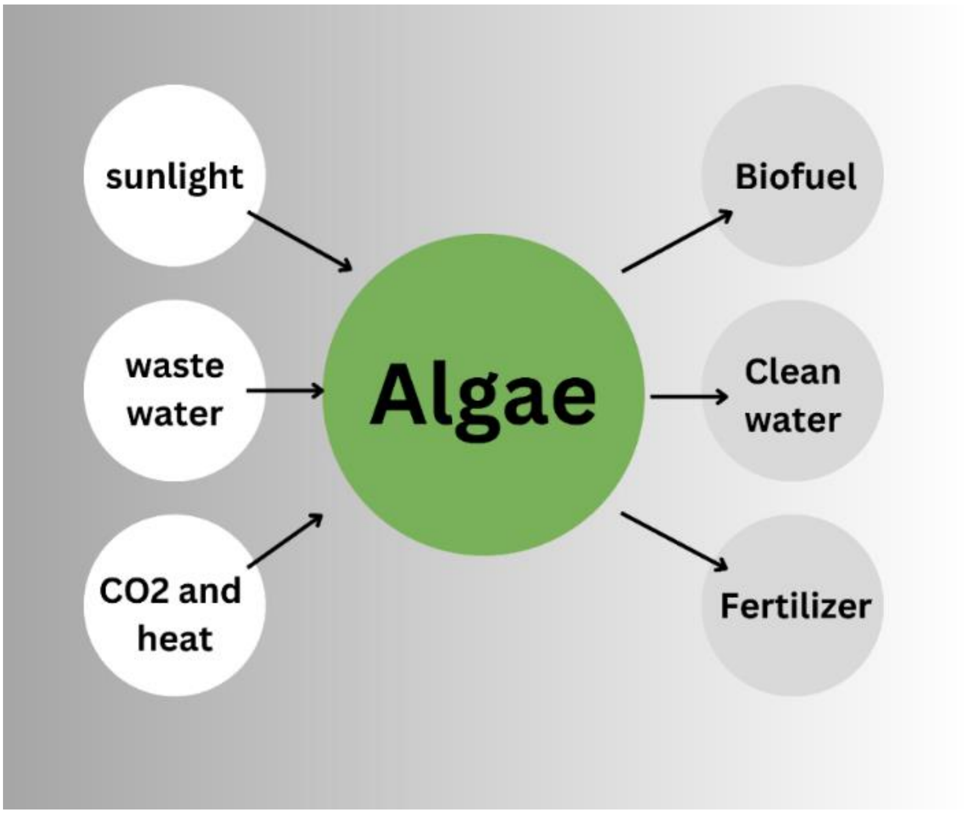

Figure 2. Algae uses Sunlight, nutrients from wastewater, heat and carbon dioxide to produce biofuel and other useful products

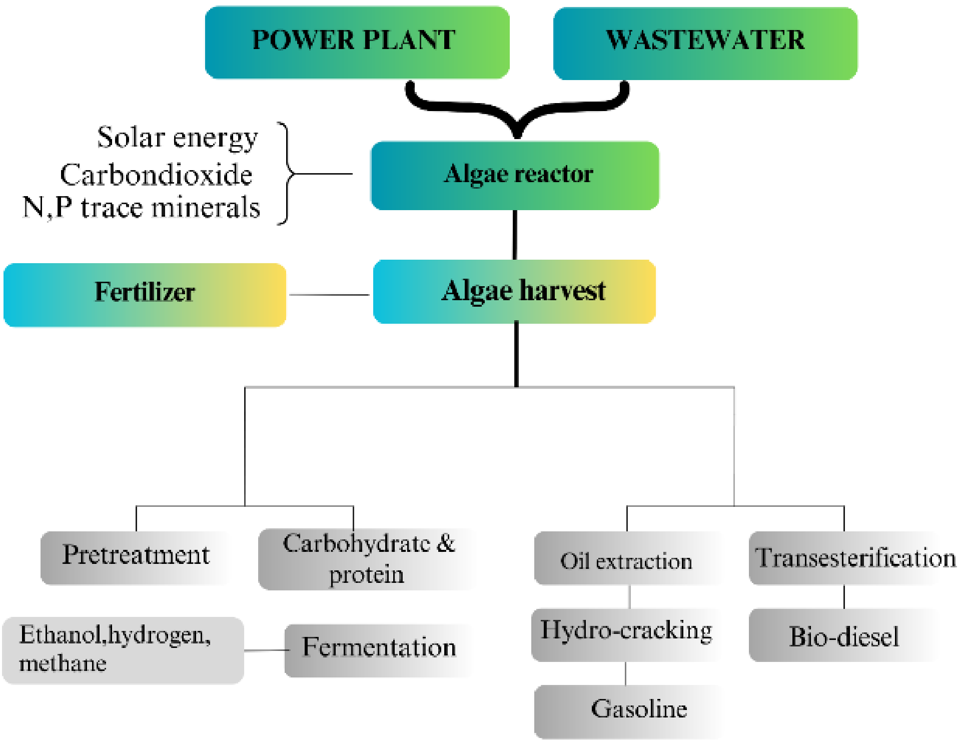

Figure 3. Mechanism of resource recovery from wastewater treatment from algae

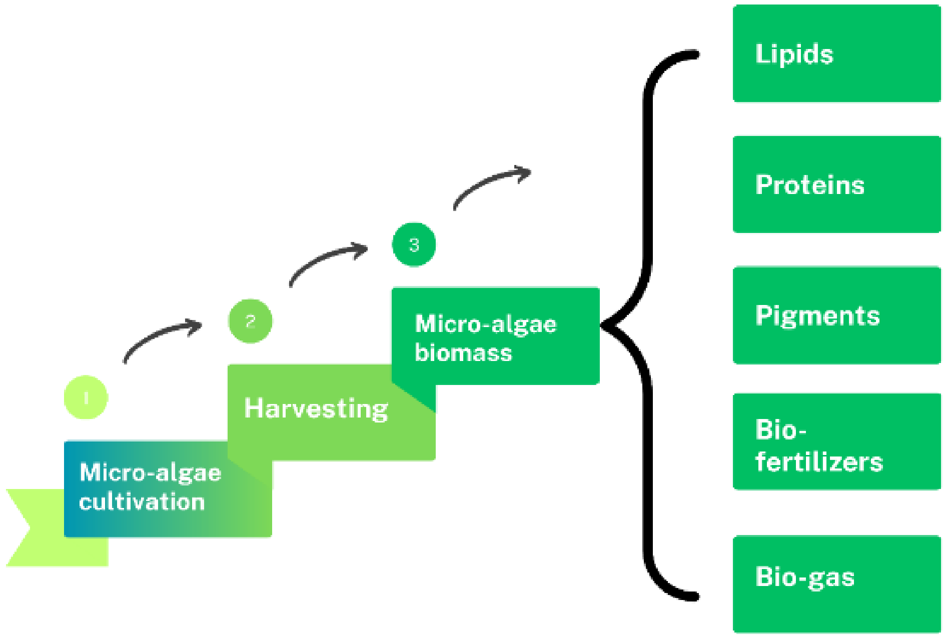

Figure 4. Nutrients recovery from algae-based domestic wastewater treatment

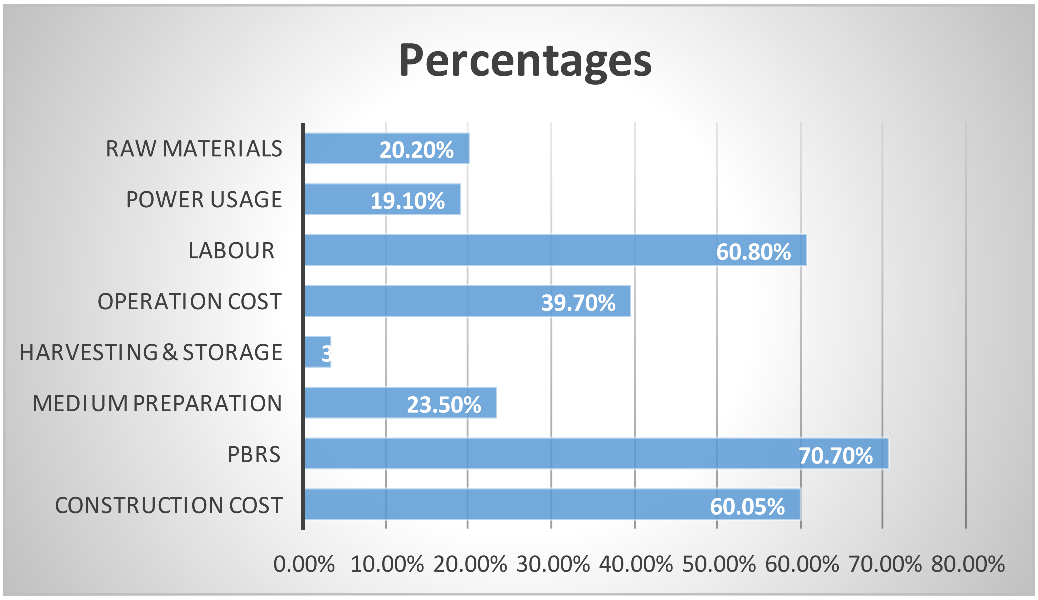

Figure 5. Analysis of cost for typical micro-algae cultivation using tubular PBRs.

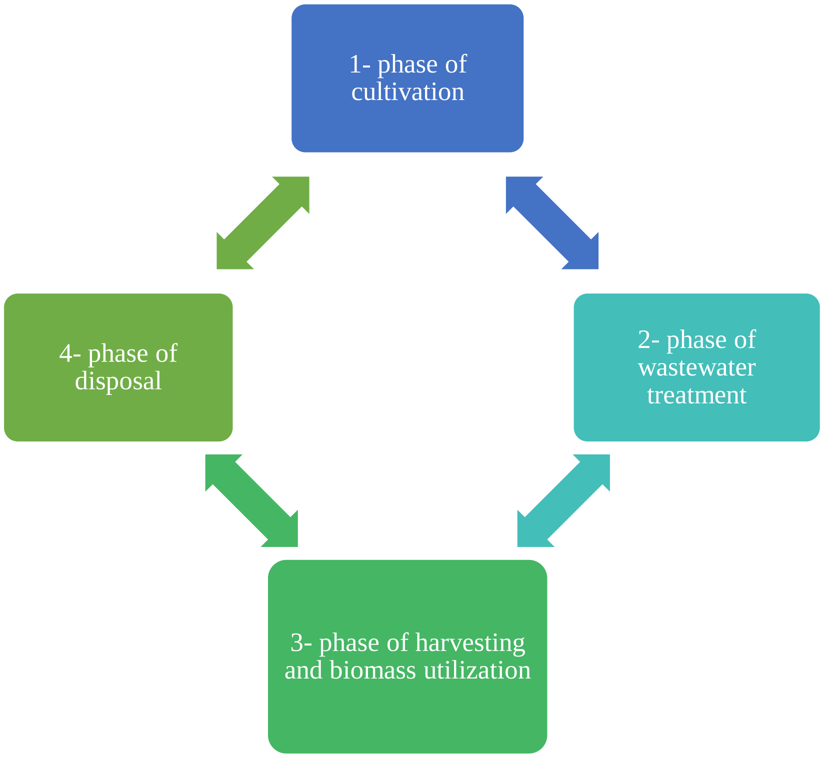

Figure 6. Phases involve in the LCA of algae-based domestic wastewater treatment

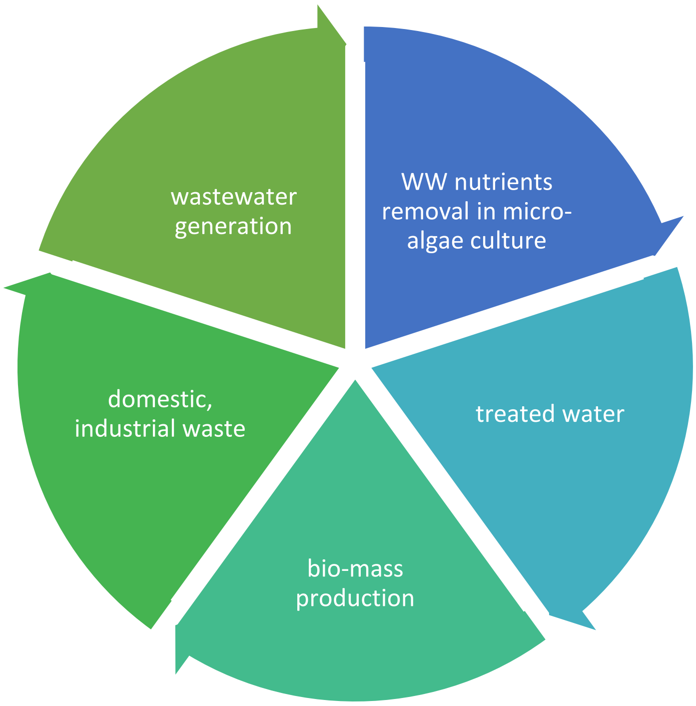

Figure 7. Cycle showing circular economy in wastewater treatment using micro-algae

23. Nutrient Recovery from algae-based wastewater treatment:

The process of recovering nutrients from wastewater treated with algae entails taking nutrients like nitrogen, phosphorus, and potassium out of the harvested algae biomass. The nutrients that are extracted can subsequently be applied industrially or as fertilizers. There are several techniques for recovering nutrients from wastewater treated with algae. Wastewater can be used to recover crystalline magnesium, ammonium, and phosphate chemical known as struvite. Struvite precipitation can be utilized to recover phosphorus from the harvested algal biomass in wastewater treatment processes based on algae. To encourage the production of struvite crystals, which can be isolated from the liquid phase and used as a slow-release fertilizer, the procedure requires adding magnesium and ammonium to the wastewater. Ammonia stripping is the process of turning ammonium ions into ammonia gas, which is subsequently recovered and used as a concentrated supply of nitrogen. Ammonia stripping can be used to recover nitrogen from the harvested algal biomass during the treatment of wastewater using algae. To raise the pH and encourage the transformation of ammonium into ammonia gas, wastewater is treated by adding a strong base, such as sodium hydroxide. Following capture, the gas is condensed into a concentrated liquid state. Ashing is a technique in which harvested algal biomass is burned to create an ash residue that contains inorganic nutrients like phosphate and potassium. The leftover ash might be applied as fertilizer [29-31-41]. Therefore, nitrogen recovery from wastewater treatment based on algae may support the circular economy by lowering waste and supplying sustainable supplies of industrial materials like fertilizers.

24. Cost Analysis of Algae-based domestic wastewater treatment:

Due to the requirement for specialized infrastructure and equipment, algae-based treatment systems may have greater capital costs than traditional treatment systems. However, as technology advances, the capital costs of systems based on algae are getting lower. Because they use less energy and chemicals, algae-based treatment systems often have lower running costs than traditional treatment systems. But the price of growing, harvesting, and dewatering algae can be high. Due to the requirement for specialized infrastructure and equipment, maintenance costs for algae-based treatment systems may be greater than for conventional treatment systems. Algae-based treatment systems use less land than traditional treatment systems, which might be crucial in metropolitan settings with a shortage of available space [24-42-45]. In terms of nutrient removal, organic matter removal, energy consumption, and land utilization, algae-based treatment systems may be more efficient and sustainable than traditional treatment systems. Algae-based systems may have larger initial outlays, though, and the price of growing, collecting, and dewatering the algae may be expensive.

25. Advantages and Disadvantages of algae-based wastewater treatment:

Algae-based treatment systems are very good at getting rid of nutrients like nitrogen and phosphorus from wastewater. Algae-based treatment systems can remove up to 97% of nitrogen and 98% of phosphorus from wastewater, according to a study that was published in the journal Bio-resource Technology. The collected algal biomass from algae-based treatment systems may be used to produce bioenergy in the form of biogas or biodiesel. Algae-based systems can produce up to 27 times more energy than is necessary to run the system, according to research published in the journal Renewable and Sustainable Energy Reviews. When compared to traditional treatment methods, algae-based treatment systems have a low carbon impact. According to research in the journal Algal Research, systems based on algae can have a carbon footprint up to 92% lower than those of traditional systems [46-48]. Due to the requirement for specialized infrastructure and equipment, algae-based treatment systems may have greater capital costs than traditional treatment systems. The capital expenses of algae-based systems might be as much as three times greater than those of conventional systems, according to a study that was published in the journal Water Research. Algae-based treatment systems include considerable operational expenses associated with the growing, harvesting, and dewatering of the algae. According to research in the journal Bio-resource Technology, an algae-based treatment system's operating costs can be up to four times greater than those of a traditional system. Because specialized infrastructure and equipment are required for algae-based treatment systems, maintenance costs may be greater than for conventional treatment systems. According to research in the journal Water Research, an algae-based treatment system's maintenance costs can be as much as threefold greater than those of a traditional system [46-48-50]{Nadeem, 2022 #4}.

26. Life Cycle Assessment of Algae-based domestic wastewater treatment:

A life cycle assessment (LCA) of an algae-based domestic wastewater treatment system is a thorough method that measures the environmental costs and gains of the treatment process while considering all the various stages, including algae cultivation, the treatment of wastewater, mud management, and energy consumption. (i) phase of cultivation: Algal biomass production occurs during this phase. LCA would evaluate the energy and resource inputs necessary for growing algae, including the usage of land, water, electricity for lighting, aeration, and fertilizer augmentation. We would also consider the effects of manufacturing and shipping cultivation tools and supplies. (ii) phase of wastewater treatment: LCA would assess the environmental and energy effects associated with running the algae-based wastewater treatment system. Energy used for mixing, pumping, and upholding favorable environmental conditions for the growth of algae are included in this. Additionally, evaluated would be the usage of chemicals, if any, in pH correction or algal biomass harvesting. (iii) phase of harvesting and biomass utilization: The LCA would consider the energy, substances, and tools needed for gathering, removing water from, and processing algal biomass. The following use of algal biomass, such as the creation of value-added goods or the manufacturing of biofuels, would also be assessed. (iv) phase of disposal: Any remaining biomass or byproducts are treated and disposed of at this stage of the life cycle. Assessments would be made on the environmental effects of various waste management practices, such as burying and fire suppression [51-52].

27. Circular Economy in wastewater treatment system with micro-algae:

By lowering waste and creating useful byproducts, algae-based home wastewater treatment has the potential to make a substantial contribution to the circular economy. The generation of biofuels, fertilizers, and other products from the use of algae in wastewater treatment can be utilized to offset the expense of wastewater treatment. Algae may create oxygen during photosynthesis, which can increase the quantity of dissolved oxygen in the water, which can further aid to lower the amount of energy needed for treatment. The potential for an integrated circular economy and bio-refinery approach to algae-based wastewater treatment was shown in one research [32-53]. According to the study, converting the algal biomass produced during wastewater treatment into biofuels and other useful bio-products might be an affordable and long-term wastewater treatment option. Another research conducted by the European Commission in 2019 shown the potential for algae-based wastewater treatment to support the circular economy by decreasing waste and generating useful byproducts like biofuels and fertilizers. By decreasing waste and creating useful byproducts, algae-based home wastewater treatment has the potential to greatly contribute to the circular economy. As study in this field goes forward, it's conceivable that more people will use this in more situations [54].

28. Social and Economic implications of Algae-based domestic wastewater treatment:

The social and financial issues posed by conventional wastewater treatment technologies have drawn attention to algae-based wastewater treatment as a viable and affordable option. Water pollution and eutrophication in receiving bodies of water may be prevented by using algae-based systems to efficiently extract nutrients like nitrogen and phosphorus from wastewater. In addition to removing additional impurities including heavy metals, organic pollutants, and medicines, this method also helps to improve the general condition of the water. Algae absorb carbon dioxide as they develop, offering a possible possibility for carbon storage and aiding in the fight against global warming. Comparing algae-based treatment systems to traditional wastewater treatment methods, operational expenses may be reduced. Wastewater and sunshine may be used to develop algae, doing away with the requirement for energy-consuming aeration and chemical dosing. The collected algal biomass may be used to produce fertilizer, biofuels, bioplastics, animal feed, and other products with added value, generating extra income [4-55]. Algae-based systems can recover priceless materials from wastewater, such as metals and phosphorus, which may then be sold or used again, further lowering treatment costs. By opening new job possibilities in industries including algae cultivation, harvesting, processing, and product development, the adoption of algae-based wastewater treatment can promote economic growth. Particularly in places with plenty of water resources and favorable climatic conditions for algae growth, algae-based enterprises, including biofuels and bio-products, can draw investments and support regional development. Since they may be incorporated into urban settings, parks, or even building facades, algae-based systems provide a more aesthetically pleasing alternative to traditional wastewater treatment facilities. This increases public acceptability and lessens "never in my backyard" (NIMBY) resistance. Communities close to establishments using algae as a treatment method may gain from cleaner water supplies, less odors, and possible recreational opportunities linked to aesthetically beautiful algae ponds [56].

29. Market opportunities and incentives for algae-based wastewater treatment:

The use of algae-based wastewater treatment is encouraged by several commercial prospects. Due to rising population, urbanization, and industrialization, the desire for effective and sustainable treatment methods is driving the growth of the worldwide wastewater treatment market. Systems based on algae provide a possible alternative to established practices. Algae-based systems can recover nutrients from wastewater, including nitrogen and phosphorus, which are important inputs for farming and fertilizer manufacture. Economic potential presented by this nitrogen recovery, which also lessens the need for pricey chemical fertilizers. Biofuels including ethanol, biodiesel, and biogas may be made from algae. Algae-based biofuels provide a sustainable and possibly carbon-neutral alternative to fossil fuels as the need for renewable energy sources rises. Algae biomass may be processed to create a variety of products with added value. For making valuable substances like pigments, omega-3 fatty acids, antioxidants, and specialized chemicals, as an example. These goods' expanding markets provide financial incentives for systems based on algae [57]. By storing carbon dioxide, wastewater treatment systems based on algae can reduce greenhouse gas emissions. Their capacity to store carbon might qualify them for carbon credits and offer financial incentives for their adoption. Algae-based systems may also benefit from environmental rules and policies that support sustainable wastewater treatment. Incentives, grants, and financing programs are frequently offered by governments and regulatory organizations to encourage the creation and use of sustainable technology, such as wastewater treatment using algae. These monetary rewards might lower the initial investment and encourage market adoption. As part of their corporate social responsibility (CSR) activities, several sectors of business and businesses are implementing sustainable practices. Wastewater treatment with algae is in line with sustainability objectives and improves businesses' social and environmental impact [58].

30. Examples demonstrating the successful implementation of algae-based wastewater treatment plants around the world:

In most of the developed countries a system based on algae was deployed at the wastewater treatment facility, for example "The All-Gas Project", "Algae Discovery Centre", and "Algal Septic Tank. In "The All-Gas Project" the initiative, wastewater is utilized to grow microalgae, which are subsequently used to make biogas. The produced biogas is then used to create energy and heat. Success has been achieved in the project's wastewater treatment and renewable energy production. To combat water pollution and lake eutrophication, China has established an algae-based wastewater treatment facility. Floating algae mats that naturally develop and absorb nutrients from home wastewater are used in the project. The gathered algae are subsequently used in agriculture as bio-fertilizer. The initiative has contributed to a decrease in the negative effects of wastewater discharge on aquatic ecosystems and an improvement in water quality [59]. The revolutionary "Algae Discovery Centre" grows algae from home wastewater, which is then collected and used to make biofuel. The goal of the study is to show that algae-based wastewater treatment is feasible, and that sustained biofuel generation is possible. In a residential complex dubbed "Algal Septic Tank" conducted an algae-based household wastewater treatment scheme. The idea makes use of an algae-based unit coupled with a septic tank system. Algae aids in enhancing the quality of wastewater by removing nutrients and organic contaminants. Reusing the treated water for irrigation reduces the need for freshwater. Within the residential complex, the initiative has been effective in delivering sustainable wastewater treatment [60-61].

31. Future research directions in Algae-based domestic wastewater treatment and challenges/limitations:

Investigations and further studies are still required to address the problems associated with the complexity of sewage characteristics and adaption of algae species, as well as the difficulties with developing and optimizing treatment procedures to obtain better removal efficiencies at lower costs. The high energy needs of some processes, including centrifugation, and the demand for expensive processing facilities to manage the volume of wastewater are some of the difficulties in algae harvesting for wastewater treatment. Additionally, certain methods can be expensive to use and may lead to reduced biomass recovery rates. Algal strains with high rates of nitrogen absorption and suitability for wastewater treatment must be found and chosen. This will increase the effectiveness of the healing process and lower total costs. Researchers have proposed using selective breeding and genetic engineering to create algae strains with enhanced wastewater treatment capability [62]. Algae's growth and nutrient absorption rates must be maximized by optimizing the growing circumstances. To promote optimal development, factors including light intensity, temperature, pH, and nutrient concentrations must be properly regulated. In research, the effects of various light intensities on the growth and nutrient removal effectiveness of microalgae in wastewater treatment were examined. It was discovered that high light intensity can increase the microalgae's ability to remove nutrients [63]. To increase its effectiveness, algae-based wastewater treatment can be combined with additional processes such anaerobic digestion, coagulation, and flocculation. To determine the best treatment combinations for various types of wastewaters, more investigation is required. In research, the effectiveness of a hybrid system for treating residential wastewater that combines microalgae and anaerobic digestion was examined. The system was shown to be successful in eliminating organic debris and nutrients. While laboratory and small-scale tests of algae-based wastewater treatment have shown promise, the technology still must be scaled up to a commercial level. Further investigation into the construction and operation of large-scale wastewater treatment systems using algae will be necessary [64].

32. Conclusions:

According to scientific research, treating home wastewater using an algae-based system is a viable and long-term solution. Nutrients like nitrogen and phosphorus may be successfully removed from wastewater using algae-based treatment, which also yields useful biomass that can be used in a variety of ways. Experts have shown that home wastewater treatment based on algae has the potential to be a more economical and efficient use of energy than conventional wastewater treatment techniques. The algae-based domestic wastewater treatment shown substantial advantages over the traditional wastewater treatment method, and it also complies with emerging trends in wastewater treatment. In a nutshell algae-based home wastewater treatment provides a practical and affordable answer to the problems posed by conventional wastewater treatment techniques. These systems may efficiently remove fertilizers, pollutants, and toxins from home wastewater, improving water quality and minimizing environmental consequences. They achieve this by utilizing algae's inherent powers. The use of systems based on algae has several positive social and economic effects. By limiting water pollution, minimizing eutrophication, and assisting with carbon sequestration, it helps to safeguard the environment [59]. It provides chances for resource recovery, including the repurposing of nutrients and the creation of value-added goods from biomass gathered from algae. In some developed countries successful algae-based household wastewater treatment plants have been established that shows the practicality and efficacy of these systems. These initiatives have made notable advancements in the generation of renewable energy, the use of sustainable resources, and water quality [65]. In a nutshell, the treatment of household wastewater using algae shows considerable potential as a sustainable and ecologically responsible method. To maximize the effectiveness and sustainability of algae-based wastewater treatment, however, a few issues and restrictions still need to be resolved.

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