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Exploring Sustainable Pathways For Wastewater Treatment: A Comprehensive Investigation Of Various Routes

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Abstract
Water treatment is essential in guaranteeing the accessibility of uncontaminated and secure water for diverse societal requirements. This paper examines the importance of sustainable wastewater treatment, providing a detailed analysis of various methods and strategies to tackle the urgent issues related to wastewater management. This study seeks to examine various treatment methods and technologies to gain valuable insights into their feasibility, efficiency, and environmental impact. The study also explores in depth the pressing environmental concerns presented by textile dyeing wastewater, which contains dangerous dyes and compounds that are not easily treated using conventional procedures. In addition to that, the textile industry's carbon dioxide (CO_2) emissions contribute to global climate change. One proposed solution is to utilize microalgae-based systems for wastewater treatment in a sustainable manner, with a specific focus on properly treating textile dye effluent and simultaneously capturing CO_2 emissions. The integration of wastewater bioremediation and carbon sequestration offers an eco-technological solution that addresses both the issues of wastewater treatment and carbon reduction in a synergistic manner. The outcomes of this study are anticipated to aid in the advancement of an eco-friendly and sustainable method for treating wastewater and minimizing carbon emissions in the textile sector. This will promote the industry's overall sustainability and decrease its negative impact on the environment.

Keywords
Wastewater, Treatment Methods, Carbon Reduction, Textiles Dyes, Microalgae-based systems.

I. INTRODUCTION

The last century has seen tremendous amount of textile production which obviously stimulates water pollution and furthermore has a devastating impact on the aquatic ecosystems [1]. The textile industry is a major contributor to water pollution, as a significant portion of the wastewater it produces is released into neighboring rivers, lakes, and other natural water bodies [2]. The dye is an indispensable component in textile and fabric production, but it is also a major contributor to the hazardous wastewater generated by the textile industry, posing significant harm to the ecology [2]. Even the World Bank has estimated that as much as 17–20% of the industrial water pollution problem originates from the dyeing and fabric finishing treatment process [3]. The annual global discharge of textile effluents as waste are approximately 280,000 tons of textile dyes [4]. The mainly synthetic dyes are azo dyes, which are a group of synthetic dyes having one or more nitro groups (N=N-) [5]. These dyes are known for their ability to dissolve, and they are economical, stable, and color as well, which makes them desired and applied in different applications [6], [7]. Approximately 10% - 15% of dye substances that are discharged into water bodies become dissolved in the aquatic ecosystem, resulting in a hazardous exposure of marine organisms to poisonous concentrations[5]. Various azo dyes and their degradation by-products have been proven to be carcinogenic, mutagenic, and have other undesirable effects on living organisms. These dyes cause allergic reactions, reproductive difficulties, skin dermatomes, also impact the lungs, liver, vascular-intestinal, immunological, and reproductive systems in animals and humans [5].

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An improvement in the living conditions of the global population leads to a rise in worldwide energy consumption. The utilization of fossil fuels for energy production leads to an upsurge in the emission of carbon dioxide (CO_2) [8], [9]. The global scientific community is concerned about the increasing concentration of CO_2 in the atmosphere due to its status as the most prevalent greenhouse gas, which contributes to global warming [10], [11]. There is a loss of atmospheric oxygen due to the activities of the industries that release CO_2.The intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) assesses that there is more than half a chance that temperature 'll exceed the 1.5°C between 2021 and 2040 in most assessed scenarios [12].

The current implementation of renewable energy technologies, such as wind, solar, and hydropower, is anticipated to be insufficient to supply existing power requirements and transition away from fossil fuels [13]. Consequently, biomass may get more and more popular as green fuel in the global effort to burden the environment with minimum environmental impact [14]. While biomass holds considerable untapped potential, the current CO_2 sequestration in plants through photosynthesis is insufficient to fully address the atmospheric CO_2 problem. This is primarily due to various factors, including limited land availability for tree planting [9]. Microalgae exhibit a unique method of producing useful products and sequestering CO_2 [15]. As efficient as carbon dioxide fixation and the manufacturing of multi-purpose products. Microalgae have significantly faster development rates compared to typical forest, agricultural crop, and other aquatic plants [15]. Microalgal culture has the potential to recycle CO_2 by storing it in biomass through photosynthesis, which can then be converted into fuels using other methods [16]. Microalgae possess other advantages beyond biofuel generation, including their potential applications in human and animal food production, pharmaceutical and personal care sectors, cosmetics industry, and wastewater remediation [14].

Microorganisms have been utilized for bioremediation since 1980. They are a promising option due to their ability to rapidly and efficiently grow, especially in challenging environments with limited nutrient resources, industrial effluents, and other types of wastewater [17], [18]. They are a single cell organism that can up take CO_2 and encage the sun rays to synthesize their own food during photosynthesis. By these ways their cellular structure resembles that of higher plants. usually, they have 80,000-100,000 mg/L of chemical oxygen demand (COD) and 40,000–50,000 mg/L of biological oxygen demand (BOD) [19]. Also, they can adsorb and absorb toxic heavy metals (Cd, AR, Hg and Cu) and toxic chemical compounds from industrial effluents for the growth [20]. It is one of the main sources to produce valuable economical products, for example biofuels, biodiesel, biohydrogen, bioplastics, and other products [21]. Microalgae-derived biofuel offers numerous advantages [22],including low water consumption, cost-effectiveness, minimal land usage, the capacity to absorb atmospheric CO_2, utilization of inexpensive nitrogen sources, reduced nitrogen oxide emissions during combustion, and rapid growth potential [17], [23], [24],. The cultivation of microalgal biomass that is convenient generally needs inorganic nutrients such as carbon, nitrogen and phosphorous along with external growth factors, such as climatic factors and biological factors [25], [26]. Microalgae can be harvested in various methods including sedimentation, flocculation, flotation, filtration, and centrifugation [27], [28].

Microalgal lipids can be extracted using many methods, including solvent extraction, ultrasonic and microwave extraction, hydrothermal agitation, osmotic shock, enzymatic disruption, oxidative stress, and electricity [27], [29]. Microalgae may be effectively grown and used to treat various types of wastewater, including those from dairy and food production, industrial waste, and municipal waste [30]. On the contrary, certain types of microalgae strains thrive based on the specific physical-chemical properties of the wastewater, such as the composition of nutrients, the lack of trace elements, and the presence of inhibitory or poisonous substances [31], [32]. Utilizing algae for the rehabilitation of industrial effluents presents numerous obstacles, particularly when accounting for external environmental conditions. Typically, this process requires three primary components: water, CO_2, and high levels of light intensity. Conversely, the presence of disease-causing microorganisms in the culture hinders the growth of microalgae, while several environmental elements such as climate change, light intensity, cultivation area, pH, insects, and other microorganisms operate as barriers in the process of phytoremediation [33].

Industries that specialize in synthetic materials are a significant contributor to environmental pollution. They dispose of large quantities of wastewater that contain dangerous and harmful dyes, which directly contributes to the release of greenhouse gases through the wasteful use of fossil fuel-based energy. Conventional wastewater treatment methods typically prove ineffective in removing persistent colored molecules, while utilizing modern carbon capture systems is prohibitively expensive and energy intensive. Hence, it is imperative to address the need for a cost-effective and efficient approach to tackle wastewater treatment and carbon dioxide (CO_2) reduction in the textile sector. This study introduces a pragmatic and effective solution: a collaborative eco-technological method that combines the treatment of textile dye waste and the capture of CO_2 using microalgae.

Wastewater treatment is an essential procedure for safeguarding public health and the environment, but it can also entail substantial financial expenditure for municipalities and companies. The economic variables to consider while assessing the viability of establishing a large-scale wastewater treatment system include:

Capital Costs refer to the initial expenditure needed to build the wastewater treatment facility, encompassing expenses such as site acquisition, equipment procurement, and infrastructure development. Variables such as the magnitude of the establishment, the intricacy of the treatment procedures, and the geographical position can have a substantial effect on capital expenses.

Furthermore, Operating and Maintenance Costs refer to the continuous expenditures involved in operating the wastewater treatment plant, including energy use, chemical usage, labor, and routine maintenance. The costs can fluctuate based on the treatment methods utilized, the size of the operation, and the prevailing labor and utility rates in the area.

In addition to that Wastewater treatment facilities are obligated to adhere to stringent regulatory criteria regarding the quality of their effluent. This sometimes necessitates making further investments in advanced treatment technologies. Adhering to environmental rules can influence both the initial investment and ongoing expenses [34]–[36].

Potential Cost Savings should be considered, efficiently designed and managed wastewater treatment systems can save costs by extracting and reutilizing valuable resources, such as water, energy, and nutrients, from the waste stream. The potential income generated from the sale of these reclaimed materials can counterbalance the total expenses of the treatment system.

Economies of scale refer to the cost advantages that larger wastewater treatment facilities experience as their capacity increases. In these facilities, the per-unit cost of treatment lowers as the facility's size grows. This can enhance the economic feasibility of large-scale adoption in contrast to smaller, decentralized treatment systems.

Possibilities for obtaining funds and financial resources could help, the presence of government subsidies, low-interest loans, or public-private partnerships can have a substantial impact on the financial viability of large-scale wastewater treatment projects. Investigating these financial options can assist in mitigating the substantial initial investment expenses. Through meticulous examination of these economic elements, decision-makers can more effectively assess the overall cost-efficiency and enduring viability of implementing extensive wastewater treatment solutions. Conducting a thorough economic evaluation is essential to ensure the practicality and effective execution of these vital infrastructure initiatives [37], [38]

II. ENVIRONMENTAL IMPACT OF INDUSTRIAL WASTEWATER

The contamination and discharge of water is the most critical concern we face today due to the activities related to industry and urbanization [39]. Industries depend on fresh water as their main raw resource to conduct their operations and procedures. Consequently, the availability of freshwater resources on Earth is restricted. A significant proportion of environmental water contamination is attributed to the discharge of industrial effluent. Throughout the past century, a substantial quantity of waste from industrial operations was released into water bodies, including rivers, lakes, and coastal regions. Consequently, this resulted in significant pollution issues in the aquatic environment, which subsequently had adverse impacts on the ecology and human well-being [40]. Each sector produces a unique combination of pollutants due to variations in wastewater composition resulting from specific industrial processes and the presence of different toxins. Appropriate adaptation of wastewater treatment for industrial processes is necessary to account for the specific properties of the effluent it includes [41]. Furthermore, as industrial technologies continue to advance, the amount of wastewater will progressively diminish [42]. The volume of wastewater is contingent upon the level of technical innovation exhibited by each industry sector. Researchers and engineers are discovering new techniques of recycling and treating this industrial wastewater since the untreated contaminated wastewater discharge into environment brings diseases such as cancer, mutagenic changes, nervous system response, etc. [43].

III. CHARACTERISTICS OF INDUSTRIAL WASTEWATER

The composition or the amount of wastewater varies depending on the type of enterprise and the toxins present. Every sector generates a unique blend of contaminants. Industrial wastewaters are categorized based on their physical properties (such as Total solid, Suspended solid, Dissolved Solid, odor, color and pH), chemical properties (both organic & inorganic), and biological properties deliberated on (Table 3-1). [42], [44].

Table 3-1 Characteristics of industrial WW.

Chemical characteristics:	**Physical characteristics:**	**Biological characteristics**
Organic constituents:	Color	Animals
Carbohydrates	Odor	Plants
Fats, and oils	Turbidity	Eubacteria
VOC	Temperature	Archaebacteria
Priority pollutants	Solids	
Proteins	pH	
Surfactants		
Phenols		
Pesticides		
Inorganic components:		
Gases		
HMs		
P		
N		
S		
O_2		
CH_4		
H_2S		
Chlorides		
Alkalinity		

Industrial effluent contains a range of impurities, with organic pollutants being the most significant component. Industrial wastewater contains a wide range of organic substances, including aliphatic and heterocyclic compounds, PAHs, PCBs, pesticides, herbicides, and phenols [44]. Industrial wastewater contains a variety of inorganic chemicals such as phosphates, nitrates, and sulphates, as well as heavy metals like Cd, Cr, Ni, and Pb. The presence of a significant quantity of contaminants in water bodies leads to an elevation in BOD, COD, total suspended solids (TSS) and total dissolved solids (TDS). BOD and COD denote the total quantities of organic material and its components contained in wastewater (Figure 1) [44]. The contaminants emitted from the effluents are directly correlated with the characteristics of the industry [44]. As an example, the wastewater discharged from the textile sector contains elevated levels of BOD ,COD, and color, while the wastewater released from the tannery industry has a high concentration of metals such as Cd, Cr [44].

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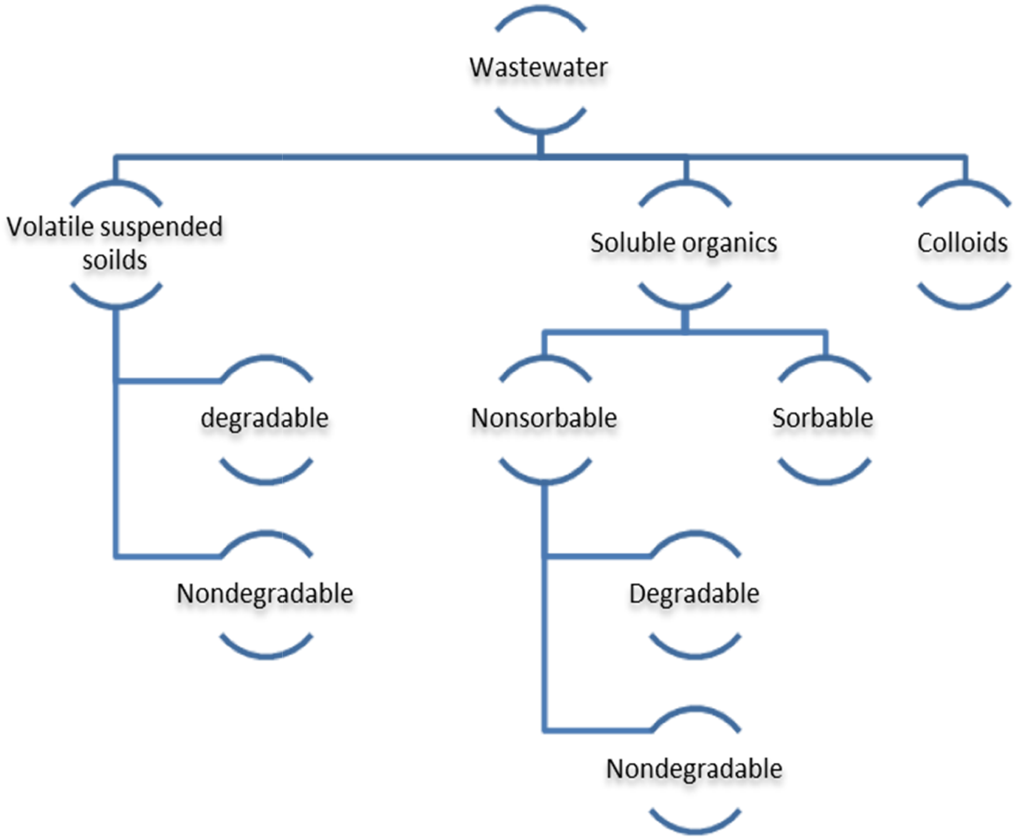

Figure 1. Constituents of WW.

IV. WASTE WATER TREATMENT TECHNIQUES

The conventional techniques of wastewater treatment aim to enhance its quality prior to its discharge into the environment, with the goal of preventing contaminated water from contaminating nearby cleaner water sources. Industrial wastewater treatment is categorized based on primary, secondary, and tertiary stages, as shown in figure (2) [44]. The initial or the primary stage of treatment involves the pre-treatment of wastewater using grit chambers and sedimentation tanks. Additionally, various methods such as precipitation, coagulation, sand filtration, and activated carbon adsorption are employed to effectively eliminate bigger and suspended solid particles [40]. The secondary treatment of wastewater involves the application of chemical and biological treatments, utilizing either aerobic or anaerobic processes. Its purpose is to eliminate dissolved organic materials, as well as nitrogen and phosphorus-based nutrients [44]. Secondary treatment techniques are dependent on the organic matter content of the wastewaters, and biological approaches are preferable. Wastewater with low levels of organic matter can be effectively treated utilizing aerobic technologies such as activated sludge, trickling filters, and rotating biological contactors. Wastewater containing larger concentrations of organic matter requires increased degrees of biodegradation and necessitates the use of more effective anaerobic bioprocesses for treatment [44]. The wastewater treatment procedures consist of unit operations figure (2):

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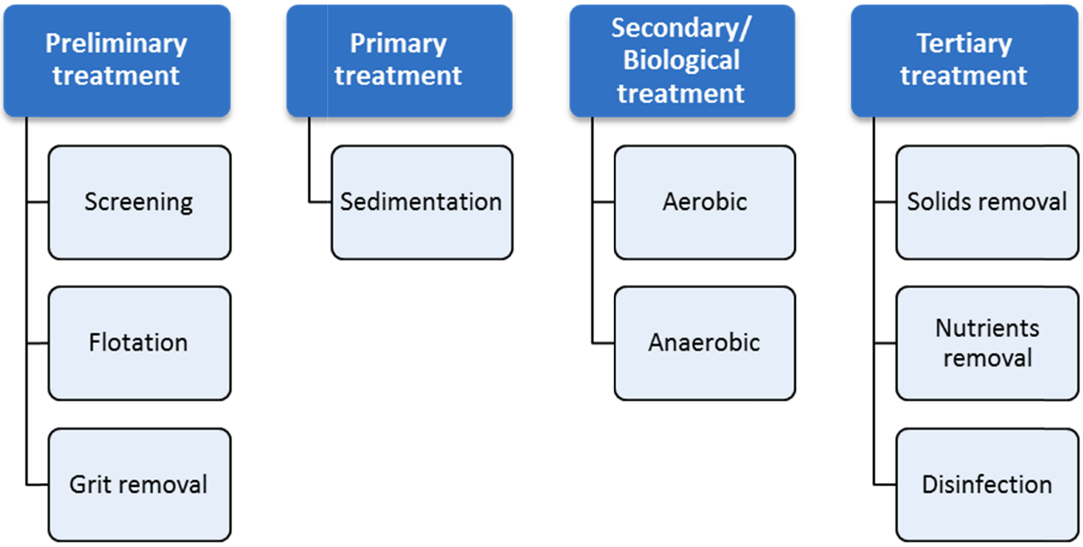

Figure 2. Classification of Industrial WW treatment.

Furthermore, a systematic pre-treatment of water effluents is conducted to develop treatment methods that enhance the efficiency of removing and disposing of pollutants. This ensures that the pollutants can either be directed to a sewage water treatment plant or be repurposed for other uses [45]. However, the existing technologies for treating water with pollutants are insufficient to fully resolve the situation [46]. Various approaches are examined in the literature for the treatment of wastewater. Typically, these treatments encompass physical, chemical, and biological processes that effectively treat and disinfect water. Figure (3) below provides a conceptual representation of these processes. The choice between methods is affected by factors like dye concentration, composition of sewage, cost of the process or additional waste that might be present in sewage [47]. Each treatment technique has its unique merits, but some of these benefits can, unfortunately, also be limited. Techniques that need high maintenance and running costs, longer processing time, less output, and produce poisonous waste after treatment do not commonly satisfy industrial applications [48]. Therefore, it is critical to find an alternative treatment system that can fully remove pollutants [49].

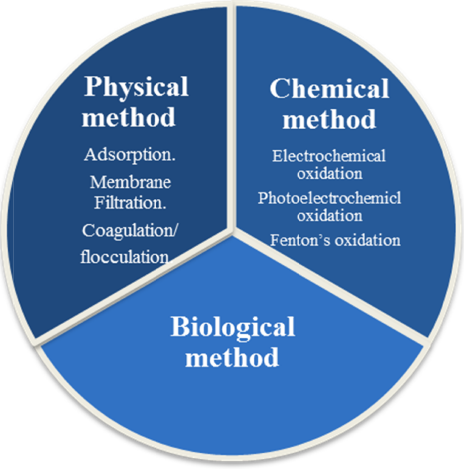

Figure 3. Methods of WW treatment.

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A. Physical Methods

Mass transfer strategy provides the physical pollutant removal methods with the basis [50]. It would be used more due to its simplicity, flexibility, high efficiency, and pollutant recyclability [48], [51]. It is another benefit, too, that chemical requirements are few in this approach. Physical treatment is more reliable than the other kinds because it does not depend on living organisms [50]. Among the physical methods, adsorption is a method that has been adopted in the recent period due to its high capacity and lower cost [51].

i. Adsorption

Adsorption is typically considered as an economical and reliable approach which is used for wastewater treatment [52]. Adsorption can be called the phenomenon of mass transfer which means that the solute substance is removed from a fluid phase and stays adsorbed on the solid adsorbent surface. Physicochemical interactions are occurring during adsorption that leads to binding off the gaseous species to a solid surface [53]. The adsorption efficiency can span up to 99.9%, by removing the contaminants. USEPA (The United States Environmental Protection Agency) rated the adsorption technique as the most advanced and the best method in the field of wastewater treatment, as compared to other treatments [54].The adsorption technique is thought to be a well-established process for the removal of dyes from the wastewater due to its simplicity and more cost-effective than the other approaches. In this process, generally, adsorbate migration occurs in three sequential steps: (1) adsorption of adsorbate at the interface, (2) diffusion inside the pores, and (3), adsorption and desorption of solute [55]. Adsorbate, Adsorbent, and Matrix properties control the rate of all these steps. To find out the adsorption capacity, isotherms of adsorption are employed. Adsorption isotherms are constructed based on the adsorbed molecules vs the interface area and the equilibrium pressure of the gas or the concentration of the solution of the liquid. Isotherms of Langmuir and Freundlich are the most common models being use for pollutant adsorption evaluation [48].

ii. Membrane Filtration

Membrane filtration technology has developed into a significant separation technique during the past 20 years, emerging as a prominent method for wastewater treatment. The water industry has been actively seeking innovative solutions in response to evolving regulatory standards and aesthetic preferences for ensuring the quality of consumer water [55]. Membrane technology exemplifies an innovative technological advancement. Membranes are utilized as filters in separation procedures throughout a wide range of applications in this field of technology [55]. Adsorption, ion exchangers and sand filters are among the technologies that can be substituted. Water filtration, including purification and desalination of wastewater and groundwater are significant applications of this technology. Additionally, sectors such as biotechnology and food & beverage also utilize this technology. including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis [55]. Table (4-1) shows the ranges of separation pore sizes for various membrane technologies. The mechanism of membrane filtration is shown in Figure (4) [44].

Table 4-1. Membrane technology ranges

Process	Forces	Size range	Examples
Microfiltration	Hydraulic pressure	0.1 to 10 μm	Bacteria and microorganisms Yeast cells Denatured proteins Algae
Ultrafiltration	Hydraulic pressure	1 nm to 0.1 μm	Viruses Protein molecules Large molecules like sugars Dyes and colorants Colloids
Nanofiltration	Hydraulic pressure	0.0001 to 0.001 μm (1-100 nm)	Multivalent ions Organic contaminants
Reverse osmosis	Hydraulic pressure	Below 2 nm	Monovalent ions Dissolved salts Micro solutes

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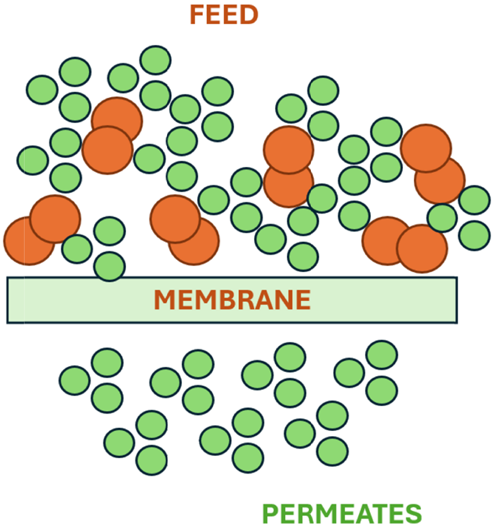

Figure 4. Mechanism of membrane filtration technology.

iii. Coagulation/flocculation

The coagulation-flocculation methods being used for the discoloration of disperse dye-containing wastewater are suitable. They have low dye removal efficiency for reactive and vat types of dye wastewater [55]. These procedures are very limited because they fail to remove dyeing color and excessive sludge formation. Coagulation is the process by which dye solution systems are inexpediently destabilized to make flocs and agglomerates [56]. Flocculation refers to the process of destabilizing the suspended particle and creating large settling masses of flocs by the action of gravity, as seen in Figure (5). The coagulation-flocculation process is for compensating charges by bridging or trapping the suspended particles that form the gelatinous agglomerates, big enough to get restricted in the filter or settle down because of gravity [57], [58].

Coagulation-Flocculation is the process of choice in textile industries concerning the wastewater treatment as this process is economically convenient, easy to set up & operate, and has short detection time. In this method, these coagulants which include lime, ferric chloride, ferric sulfate, and aluminum sulfate can bind with the pollutants and other dyes, thereby promoting the process of sorption, electrostatic force and bridging to remove [55]. This process helps dyes and pollutants get rid of their suspended state through sorption and bridging due to the protonated amine groups and polymer (in high molecular weight), respectively [55]. Coagulation-flocculation decreases dissolved substances, suspended matter, colloidal particles, non-settling particulate and discoloring agents from the effluent [59].

B. Chemical Methods

Multiple chemical oxidation systems have been reported for a series of catalysis applications. Moreover, advanced oxidation process has been found to be one of the critical applications of wastewater treatment [60], [61]. AOPs is an abbreviation for all processes used during wastewater treatment that operate on the same principles, in the creation of oxidizing species, such as hydroxyl radicals (•OH) [50]. Oxidation methods include galvanic oxidation, photoelectrochemical oxidation, UV-Fenton's oxidation and ozonation. The oxidation result is highly sensitive to the pH and regularly used catalysts [62].

i. Electrochemical oxidation

The electrochemical advanced oxidation processes (EAOPs) have become a significant method in the field of wastewater treatment (dye removal) as an advanced technique. On the contrary to the fact that many chemical products are utilized during yarn dying process, however this EAOPs do not contain any added chemicals and they can curb the formation of dye sludge. Hence, the EAOPs can be considered as environment friendly as they have the inherently clean electrons with no extra steps required for sludge [55]. It also includes high efficiency in removing pollutants, easy operation, and ease in handling. The major and the primary difficulty that hinders energy-assisted applications is the increased energy expenses with the corresponding lower oxidation effectiveness [55]. Recently, the stability of electrode materials and catalytic activity improvement has been getting consideration by manufacturing various metal oxides into electrodes and doping. Electrooxidation using pulse current supply can be as efficient as traditional methods to meet the world's energy needs [55].

C. Biological Methods

Treatment methods involve the elimination of pollutants by biological processes that take place throughout aerobic and anaerobic conditions [42]. The biological methods for total degradation of textile wastewater have their benefits (a) eco-friendly, (b) cost competitive, (c) lesser sludge production, (d) bio treatment giving nonhazardous metabolites or complete mineralization, and (e) water reuse (higher concentration or less dilution requirement) in comparison with the physical/oxidation method of treatment [55]. The degradation efficiency of biological processes crucially relies on the ability of selected microbes to adapt, and on the activity of their enzymes. Hence, countless microorganisms and enzymes are isolated and evaluated for the destruction of various dyes [55]. The microorganisms with degradation power when isolated and used, is an interesting biological aspect of textile wastewater treatment. There exist various microorganisms like bacteria, fungi, and algae that can spin-off different dyes present in the textile wastewater [63].

i. Aerobic Treatment

Facultative bacteria and Aerobic decompose or breakdown the biodegradable organic matter through aerobic respiration in the presence of freely available oxygen or air in dissolved form within wastewater [64], [65]. The process is limited by factors such as temperature, retention duration, available of O_2, and the activity of the bacteria. Moreover, the inclusion of chemicals that are crucial for bacterial growth may enhance the speed at which organic contaminants are physiologically converted into oxides. This method can eliminate COD, BOD, phosphates, nitrates, VOC, dissolved and suspended organic matter, and other contaminants [65]. It is feasible to decrease the quantity of biodegradable organic substances in the environment by as much as 90%. An inherent drawback of the approach is the generation of a substantial quantity of bio-solids, thereby requiring further expensive measures for treatment and handling. Activated sludge and aeration lagoons technologies are employed to facilitate the aerobic process [64]. Equation (1) provides a concise representation of aerobic breakdown.

Equation 1. Depiction of aerobic decomposition.

$$\text{Organic matter} + \text{Bacteria} + O_2 \rightarrow \text{Bacteria} + \text{By Product} + H_2O + CO_2$$

ii. Activated Sludge Process

Activated sludge technology operates by maintaining a significant bacterial population in wastewater through a process of suspension, while ensuring the presence of oxygen. Unlimited nutrition and oxygen can lead to increased bacterial growth and metabolism, causing the breakdown of organic molecules into oxidized byproducts or the production of new microorganisms [65]. The active sludge system consists of 5 interrelated components: activated sludge bioreactor, mixing and aeration system, returned sludge and sedimentation tank. The activated sludge process is a commonly used biological mechanism for treating wastewater, known for its cost-effectiveness [42], [45].

iii. Anaerobic Treatment

Anaerobic waste treatment is a biological process where microorganisms break down organic contaminants in the absence of oxygen. In the absence of free dissolved oxygen in the wastewater, anaerobic decomposition or putrefaction occurs, during which facultative bacteria and anaerobic breakdown complex organic compounds into S, C, and N_2. This biochemical process described results in the production of biogas, specifically CH_4, H_2S,

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N_2, and ammonia. This technique reduces the bacterial population in wastewater [66]–[68]. Anaerobic treatment is typically employed as a preliminary step to aerobic treatment in cases when streams have elevated levels of organic matter, as indicated by high measurements of BOD, TSS, or COD. Anaerobic treatment is an established and energy-efficient method for treating the wastewater of industry. The equation (2) provided below depicts the anaerobic process.

Equation 2 Anaerobic process.

$$\text{Organic matter} + \text{Bacteria} \rightarrow \text{Bacteria} + \text{ByProduct} + CH_4 + CO_2$$

The anaerobic digestion (AD) method is attractive due to its ability to cleanse wastewater, provide renewable energy, and generate byproducts that may be used as fertilizers on farms, making it an environmentally friendly process [69]. The AD method has the following advantages in comparison to the aerobic wastewater treatment procedure: Reduced nutrient need and the production of minimal biological sludge, which can be easily treated by drying [70]. Additionally, it requires a low reactor capacity and absence of oxygen, which decreases the energy required for oxygen delivery in the aerobic method. Moreover, the organic loading on the system is not limited to an oxygen source [65]. Therefore, in AD, it is possible to employ a greater loading rate, which enables a quicker reaction to the introduction of substrate after extended periods of no feeding, as well as semi-feed strategies over several months[69]. This enhances the functionality of the process, rendering AD a feasible choice for treating wastewater and eliminating OFF-GAS emissions that contribute to air pollution [70]. Some examples of anaerobic treatment systems are the anaerobic filter reactors, anaerobic lagoons, UASB, EGSB, and ABR.

iv. Bioremediation

It is a biological treatment strategy that transforms environmental contaminants into less dangerous forms by using biological resources for instance, the natural capacity of bacteria, fungi, plants, algae, and microorganisms to endure, and flourish in incredibly harsh environments had been used to treat the contaminated soils and water bodies [71]. Bioremediation is preferable because it doesn't require solvents or a lot of energy, just like any other biological treatment method. It is possible to use this technology both in-situ and ex-situ. Environments that are either aerobic or anaerobic can support bioremediation [65]. In aerobic environments, ambient oxygen is necessary for living organisms to flourish. In anaerobic environments, there is no oxygen. To obtain the necessary energy in this scenario, microbes break down chemical molecules or ions such as sulfates in the wastewater [71].

V. LIMITATIONS OF CONVENTIONAL TEXTILE WASTEWATER TREATMENT

Traditional biological techniques such as activated sludge are not effective in removing stubborn colors, heavy metals, surfactants, and other synthetic compounds often present in textile effluents. These contaminants can traverse without undergoing any changes [72], [73].
The generation of substantial quantities of dangerous sludge that necessitate specialized disposal, contributing to the overall environmental impact. The lack of ability to retrieve nutrients such as nitrogen and phosphorus for reuse, resulting in a linear waste disposal paradigm. Physic-chemical treatment procedures such as coagulation, adsorption, or advanced oxidation have high operational costs and require a significant amount of energy. Conventional treatment technologies in the textile industry do not effectively reduce greenhouse gas emissions, resulting in a large carbon footprint.

VI. TEXTILE DYEING WASTEWATER

A suggested approach is to employ microalgae-based systems for sustainable wastewater treatment, specifically targeting the effective treatment of textile dye effluent while concurrently absorbing CO_2 emissions. The combination of wastewater bioremediation and carbon sequestration provides an eco-technological approach that effectively tackles the problems of wastewater treatment and carbon reduction in a mutually beneficial way. The depletion of non-renewable resources is occurring due to their heightened utilization in response to the growing energy demand. The objective of biological wastewater treatment is to provide a system that allows for the collection and proper disposal of decomposition products [74]. The combination of wastewater treatment and microalgal cultivation can effectively decrease and fulfil the needs for nutrients and water. In order to enhance the production of value-added products utilizing microalgae, it is necessary to enhance and optimize the combination of wastewater treatment and microalgal biomass production [74].

Agricultural, municipal, and industrial wastewaters are among the many wastewater types that contain algae, which are photosynthetic organisms that evolve oxygen [75]. By absorbing organic nutrients and converting them into biomass, microalgae thrive in nutrient-rich wastewater. Because microalgae may simultaneously use nitrogen, organic and inorganic carbon, and phosphorus while building biomass and decreasing COD, they are used in wastewater treatment [74]. Since they need a lot of nitrogen and phosphorus in addition to carbon dioxide and sunlight as a carbon source for the biosynthesis of proteins, phospholipids, and carbohydrates, microalgae are well known for their ability to grow and utilize nutrients from wastewaters [74]. Microalgae need nutrients like phosphates and urea, as well as metals like arsenic, cadmium, lead, and zinc, to grow. As a result, the BOD has decreased [74]. These qualities of microalgae allow for the benefits of a green and circular economy in wastewater treatment processes based on microalgae [76].

VII. REMEDIATION MECHANISMS AND INFLUENCING FACTORS

Microalgae employ bio-adsorption, bioaccumulation, and biodegradation mechanisms to eliminate textile effluents as deliberated in figure(6) [43] .

A. Bio Adsorption

Precipitation, absorption, absorption, ion exchange, surface complexation, and electrostatic interaction are some of the mechanisms supporting the physical, chemical, and metabolically independent processes that make up biosorption [77]. This phenomenon's mechanisms necessitate the dissolution or dispersion of a target sorbate in water together with a biosorbent. The biomaterial in question may consist of living or deceased microorganisms, or even individual parts of them [43]. Until the concentration of the substance that the biosorbent has adsorbed and the remaining concentration in the liquid reaches equilibrium, the process is repeated. Furthermore, the distribution of a particular sorbate between the liquid and solid phases is dictated by the degree of biosorbent affinity for that sorbate [78].

Microalgae's cell wall is directly in charge of biosorption, and the mechanism by which this phenomenon takes place is determined by its chemical makeup, which also plays a critical role during the process as shown in Figure (6). Furthermore, the surfaces of microalgae have pores, and the surface charge promotes biosorption [43]. A variety of chemical groups, including (—OH), COOH, and S, are present in the microalgae's cell walls and serve as binding sites as well as efficient ion exchangers that support organic material adsorption from contaminated water and metal ion complexation [79]. Although they are primarily found in the plasma and cytoplasm membrane, other molecules like lipids, proteins, and nucleic acids may also be deposited on the surface of cells [43]. These molecules could attach to metal cations through a variety of functional groups, including aminic, COOH, Thiol, imidazole, thioester, N, and oxygen in peptide bonds [80]. Microalgae's cell wall structure is generally composed of a fibril matrix that offers high mechanical strength, while the amorphous fraction is responsible for its flexibility. Both fractions, as well as the intercellular spaces on the cell wall, may facilitate the biosorption process [81].

B. Bioaccumulation

It is challenging to quantify pollutants that have been bio-sorbed and accumulated because the processes of bioaccumulation and biosorption are fundamentally different, but they also interact dynamically. In addition to accumulating nutrients and microelements, microalgae also gather various pollutants [82]. Because microalgae can adapt to their surroundings, they can withstand pollutants even at low concentrations. Moreover, microalgae exhibit remarkable resilience against an extensive range of pollutants originating from industrial, agricultural, and residential domains, thereby augmenting their capacity for bioremediation [83], [84].

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Pollutants flow along a concentration gradient, moving from a high to a low concentration region without the need for energy [85]. Low-molecular-weight substances that are nonpolar and lipid-soluble could most likely pass through the cell membrane by passive diffusion due to the hydrophobicity of the membrane.

C. Biodegradation

The basic processes of biodegradation fall into two categories: (i) metabolic degradation, where pollutants serve as a source of carbon and a donor or acceptor of carbon for microalgae and (ii) cometabolism, where pollutants serve as a carbon source and an electron donor for non-living matter [86]. Extracellular breakdown is followed by intracellular breakdown of the breakdown intermediates in microalgae-mediated biodegradation, which can occur either alone, in combination with one another, or both [86]. Extracellular polymeric substances (EPS), which are primarily expelled by microalgae, are the foundation of extracellular degradation. It stays confined to the outer walls of the cells, enabling microalgae to act as an external digestive system and mineralize contaminants when they are dissolved [43]. Additionally, EPS functions as an emulsifier in the shape of bio surfactants to raise the availability of pollutants in the environment, facilitating the bioaccumulation of pollutants by microalgae in the future [43].

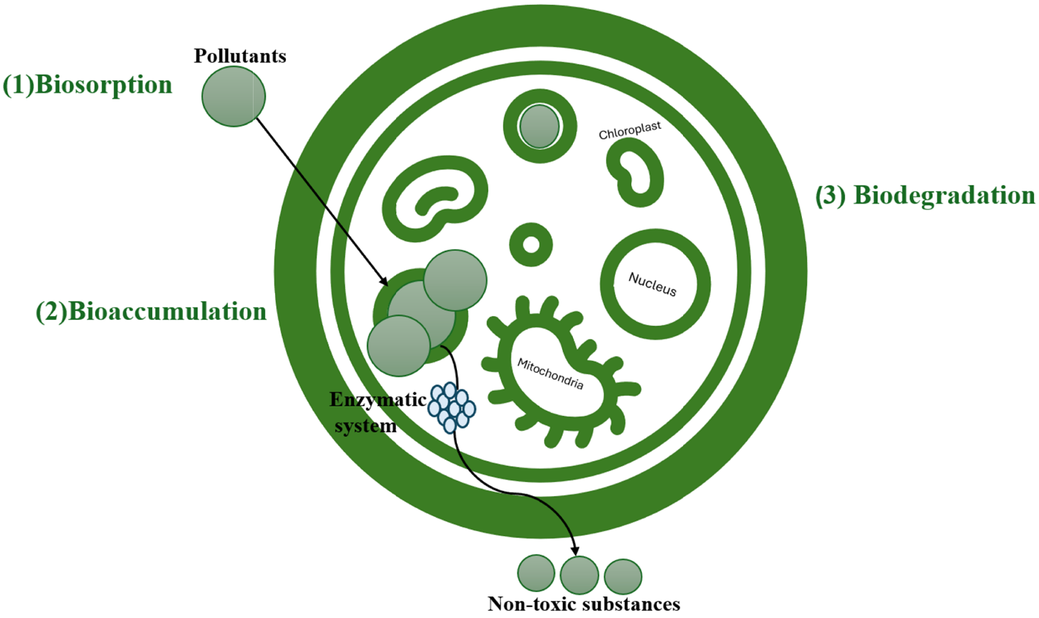

Figure 5.Bioremediation mechanisms of pollutants.

VIII. Benefits of Using Microalgae

Microalgae effectively remove pollutants by a combination of biosorption, bioaccumulation, and biodegradation pathways.

The microalgae can recover nutrients by using nitrogen, phosphorus, and carbon from the wastewater as nutrients to facilitate their growth. The production of microalgal biomass with the potential to be transformed into lucrative bioproducts such as biofuels, animal feed, or biofertilizers, thereby establishing a circular economic model [43], [87].

- This process involves treating wastewater and capturing carbon dioxide at the same time using photosynthesis, which helps to counterbalance the greenhouse gas emissions produced by the textile sector.
- The microalgae-based system offers significant cost savings compared to traditional physic-chemical treatment approaches, since it can be mostly self-sustaining.
- Reduced environmental impact by preventing the need for hazardous sludge disposal.

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IX. NUTRIENT RECOVERY BY MICROALGAE

Using various biochemical processes, such as fixation, assimilation, precipitation, and bio-adsorption accumulation, microalgal-based wastewater treatment directly consumes nearby contaminants or nutrient loads [88]. An essential component for the growth of microorganisms is nitrogen. Many different biological materials, such as energy transfer molecules, genetic materials, proteins, peptides, and enzymes, and structural elements require nitrogen [89]. Wastewater contains a variety of nitrogen sources, including organic nitrogen sources and ammonium and nitrate. Although inorganic nitrogen can be assimilated by microalgae [90], [91], inorganic nitrogen forms must first be reduced to ammonium in order to be incorporated as amino acids into the intracellular membrane.

But for the cultivation of microalgae, NO_3^- is the most stable, oxidized form of N_2 [91].The proton-motive force produced by H^+-ATPases and nitrite transporter proteins preserves NO_3^-, which is typically taken up by microalgae through active transport utilizing NO_3^-/H^+ co-transporters (Figure 7) [91]–[93].Another nutrient that is necessary for living things is phosphorus. In the synthesis of energy transfer, nucleic acids, phospholipids, lipids, proteins, and the metabolism of carbohydrates, P is essential. For growth and metabolism of microalgae, inorganic phosphorus is the favored form of P [94], [95].

High concentrations of P are found in wastewater; the most prevalent forms are polyphosphate, organic phosphate, H_2PO_4 (dihydrogen phosphate), and HPO_4 (mono hydrogen phosphate) [91], [93], [94]. Orthophosphate is the most prevalent type of phosphate that microalgae absorb through active transport across the plasma membrane. The process of phosphorylation involves the incorporation of inorganic phosphate into organic compounds and involves the production of ATP from ADP along with an energy input (Figure 7). The mitochondrial electron transport chain, light energy conversion, and substrate oxidation can all provide the necessary energy [90], [93], [95].

Furthermore, one of the benefits of microalgae is that they can store excess phosphate in their cellular granules, which maximizes their ability to absorb P from wastewater with high P concentrations [92], [93], [96]. According to S. Gupta, this indicates improved wastewater remediation and phosphorus recovery. Microalgae are photosynthetic microorganisms that produce biomass by using CO_2 as a carbon source [92]. When exposed to light, microalgae use autotrophic processes to fix CO_2 from the atmosphere and heterotrophic mechanisms to absorb organic loadings from wastewater.

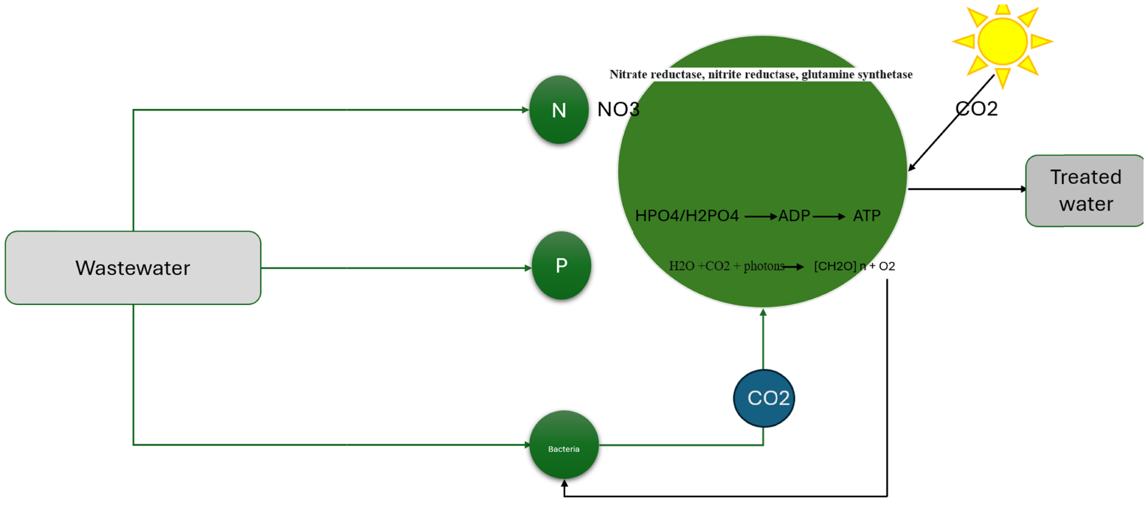

Figure 6. Nutrients recovery using microalgae.

Although previous studies have shown that using microalgae-based systems for treating textile wastewater is technically feasible and environmentally beneficial, it is crucial to conduct further study on the economic viability of these technologies. Future research should prioritize completing thorough cost-benefit assessments and comprehensive economic feasibility studies to evaluate the practical possibility more accurately for implementing new practices in the textile sector [97], [98].

Assessing the overall economic feasibility is essential for the general acceptance and expansion of microalgae-based wastewater treatment systems. Conducting a thorough cost-benefit analysis can assist in quantifying the possible operating cost reductions, income generated from resource recovery, and environmental advantages, thereby presenting a comprehensive economic justification. Performing comprehensive economic feasibility studies can determine the primary factors influencing costs, the points at which revenue equals expenses, and the return on investment to evaluate the commercial appeal of these systems in comparison to traditional wastewater treatment technologies.

Future research in this field should prioritize conducting a comprehensive evaluation of the financial expenses involved in establishing and operating a microalgae-based wastewater treatment system. This would entail examining the original capital outlays as well as the continuous operational expenses, encompassing energy, labor, maintenance, and disposal. By comparing these expenses to those of other wastewater treatment methods, we can illustrate the possible economic benefits of using the microalgae-based approach.

Furthermore, it is imperative for researchers to accurately measure the monetary value that may be obtained from the retrieval and utilization of resources such as biofuels, animal feed, and biofertilizers that are derived from the grown microalgal biomass. Examining the market demand and pricing of these items derived from microalgae might assist in determining the potential extra sources of income that can be generated to counterbalance the expenses of treatment [99].

Moreover, it is essential to do a thorough life cycle cost-benefit analysis to evaluate the environmental, social, and economic consequences across the whole lifespan of the microalgae-based system. This would entail converting the advantages, such as decreased usage of freshwater, reduction of greenhouse gas emissions, and minimization of waste, into monetary value. Then, the overall costs and benefits of the entire life cycle would be compared to conventional solutions for wastewater treatment.

Ultimately, creating techno-economic models that can accurately simulate the performance and costs of large-scale microalgae-based systems, along with conducting sensitivity analyses to determine the most crucial cost factors, can assist in optimizing the design and operation of the system to achieve the most advantageous cost-benefit ratio. This information can offer useful insights to direct the practical application of these technologies in the textile sector [100].

X. CONCLUSION

In conclusion, this study provides an overview of the current state of textile wastewater treatment, focusing on a novel technique using microalgal systems that might be considered as an environmentally benign solution. The textile production process produces hazardous wastewater that is contaminated with chemically dyed substances, which pose challenges for conventional treatment procedures. The textile industry is a big emitter of greenhouse gases (GHG) and generates substantial quantities of hazardous waste. This study demonstrated the potential to achieve both water cleanup and CO_2 reduction by cultivating microalgae. Microalgae possess a notable capacity for biosorption, bioaccumulation, and biodegradation, making them suitable for the purification of textile effluents containing diverse pollutants. The cell wall possesses many functional groups that enable the binding of pollutants, contributing to its structural properties. Moreover, these microalgae thrive in streams abundant with textile waste, utilizing nitrogen, phosphorous, and carbon as a readily available source of fuel for their rapid growth and reproduction. Through the process of photosynthesis, plants efficiently reduce parameters such as COD, BOD, and other water quality indicators. Combining wastewater treatment with algae growth gives a circular economy notion of several opportunities. It serves as a nutrient source for the organisms that feed on the algae and cleanses the water. Furthermore, microalgae capture CO_2 through photosynthesis, hence options like carbon credit or offsets are provided. This carbon is being stored in the collected algae biomass because of this process. Value chains expansion through the manufacture of non-food products like biofuels, chemicals and nutraceuticals is also possible from the biomass.

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