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Development of a sustainable phytoremediation-bioenergy model for wastewater treatment using high-biomass species

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Abstract

Water crisis and energy deficit in the world have become critical issues that need innovative solutions that will not only ameliorate the environment but also produce renewable energy. The paper is a review article that analyzes the construction of an integrated phytoremediation- bioenergy model that utilizes high-biomass plant species to treat wastewater and convert it to renewable energy. The paper has summarized the recent studies on phytoremediation processes, the selection criteria of species to be used in biomass, and bioenergy conversion technology with specific reference being water hyacinth (*Eichhornia crassipes*), vetiver grass (*Chrysopogon zizanioides*), Napier grass (*Pennisetum purpureum*), and microalgal systems. This review shows that high-biomass phytoremediation systems can be used to recover pollutant removal efficiencies of greater than 90 percent with simultaneous production of high concentrations of biomass to produce bioethanol, biodiesel, biogas, and bioelectricity. Combined systems of constructed wetlands and microbial fuel cells with modern bioconversion technologies are promising options to cheaper and environmentally friendly wastewater treatment. Nonetheless, there are still several issues concerning fatness of heavy metals in the biomass, optimization of the process of conversion, and the scaling between pilot and commercial processes. The paper gives important policy development, technology innovation and implementation recommendations to develop bioeconomic potential of phytoremediation- bioenergy systems in developing and developed countries.

Keywords: Phytoremediation, bioenergy production, wastewater treatment, high-biomass species, sustainable development, bioeconomy, constructed wetlands, renewable energ

Introduction

Background and Rationale

The intersection of rapidly growing urbanization and industrialization and population growth has triggered the unprecedented stresses on the world water resources and energy infrastructures. The amount of wastewater produced across the globe is greater than 380 billion cubic meters per year, and a significant part of it is not treated, or not properly treated, especially in the developing world (Sharma *et al*., 2024) [14]. At the same time, the needs of climate change mitigation and energy security presuppose the replacement of fossil fuels by renewable energy sources. The twofold task is a challenge that requires new solutions that will harmoniously solve the task of environmental cleaning and produce sustainable energy.

The conventional approaches to wastewater treatment such as chemical precipitation, ion exchange, membrane filtration, and activated sludge techniques have serious constraints such as high operational expenses, power intensity, formation of secondary pollutants, and massive infrastructure needs (Khan *et al*., 2022) [8]. These limitations make traditional methods especially inappropriate in the case of resource-constrained environments and decentralized treatment objectives. Moreover, traditional systems do not take advantage of the intrinsic resource worth in the wastewater streams but treat the pollutants as wastes instead of a possible feedstock.

Phytoremediation is a new paradigm that uses growing plants and related microorganisms to extract, sequester, degrade or stabilize soil and water matrix contaminants. The benefits of this green technology are strong such as cost-effectiveness, low energy needs, beautiful appearance, rehabilitation of the ecosystem, and acceptance by people (Ahmed *et al*., 2025) [1]. Phytoremediation is value-generating bioeconomic platform and not merely a pollution mitigation strategy when it is implemented strategically in combination with the systems of bioenergy production.

The Dual-Purpose Concept

Combining phytoremediation and bioenergy generation is an embodiment of the idea of circular economy because it turns environmental burdens into renewable energy resources. The high-biomass species of plants have a dual purpose: With its extensive root system and metabolic processes, it is able to remove contaminants and with its high aboveground biomass, it serves as a rich source of feedstock to be used in a wide range of biofuel conversion routes (Wijekoon *et al*., 2025) [15]. This combined solution is a solution to the important problem of biomass disposal after the phytoremediation, which in the past was a limitation to the overall use, because of the presence of contaminated plant material which had to be dealt with specifically and it was to be disposed.

Recent innovations show that the well-designed phytoremediation systems can attain impressive pollutant removal rates as well as produce bioproducts that are economically valuable. Research reports on heavy metal elimination of over 95, nutrient reduction of more than 90, and organic contaminate destruction of up to 98 and biomass of bioethanol, biodiesel, biogas, biohydrogen, and bioelectricity production (Sharma *et al*., 2024; Ahmed *et al*., 2025) [1, 14]. This two-fold model can be attributed to Sustainable Development Goal 7, which is about affordable and clean energy, Goal 6, which is about water quality and sanitation, and Goal 13, which is about a climate action.

Objectives and Scope

The paper is a review article that provides an organized study of the scientific basis, technology, plans of implementation, and future of the sustainable phytoremediation- bioenergy systems using high-biomass species. The individual objectives are: First, to understand the underlying mechanisms of the process of phytoremediation and its efficiency in the removal of various types of contaminants. Second, comparing appropriate plant species with high-biomass on the basis of phytoremediation potential, growth, environmental and bio-energy capabilities. Third, evaluation of bioconversion technologies which convert contaminated biomass to different energy products without causing a large amount of transfer of pollutants. Fourth, analyzing successful implementation case studies that illustrate viable practicality and performance measures. Fifth, defining enduring issues, knowledge gaps and research priorities that would be critical to commercial advancement.

It includes both aquatic and terrestrial systems of phytotransformation and has specifically concentrated on constructed wetlands, floating treatment wetlands and integrated cultivation systems. The contaminants dealt with are heavy metals, nutrients, organic and emerging contaminants through municipal, agricultural and industrial wastewater. Energy pathways that have been considered include first, second, and third generation biofuels such as bioethanol, biodiesel, biogas, biohydrogen, and direct combustion of biofuels to heat and produce electricity.

Phytoremediation Mechanisms and Principles

Fundamental Processes

Phytoremediation involves a complex of interdependent processes in which plants and their microbial communities decontaminate polluted ecosystems. Knowledge of these processes can be optimized to select species and design systems to meet the requirements of certain contaminant profiles and environments.

Phytoextraction is the main process of heavy metal cleaning, where hyperaccumulator plants absorb the contaminants by hyperaccumulating the contaminants through the root and relocating it to the harvestable aboveground tissue (Sharma *et al*., 2024) [14]. The process needs plants with a bioconcentration factor that is greater than unity and a high translocation factor which shows an effective transportation of metals between roots and shoots. It should also possess several or more harvesting cycles during the growing season, a large biomass production and a high rate of growth. The biomass collected is further recovered as energy in terms of proper thermochemical or biochemical transformations.

Rhizofiltration is the process where the contaminants are absorbed, concentrated and also precipitated by the aqueous solution using the structure of plant roots and is especially efficient in handling wastewater streams with high levels of heavy metal (Khan *et al*., 2022) [8]. Water hyacinth, duckweed, and water lettuce exhibit extraordinary rhizofiltration performance since they have vast fibrous root systems with a large surface area of interaction with contaminants. Rhizosphere environment has a wide variety of microbial communities that enable the transformation of contaminants by enzyme activities and biochemical processes.

Phytostabilization bonds up the contaminants to the soil structure or root zone so that the contaminants cannot move to the groundwater or be taken up by the organisms of the food chain, but the contaminants are not eliminated (Sharma *et al*., 2024) [14]. This method can be useful on the sites where total remediation is not feasible or where the prevention of contaminant propagation is the main goal. Some species with high biomass can also act to stabilize the soil by the production of root exudates which also changes soil chemistry and make the metals less available to the soil.

The enzymatic degradation of organic pollutants in the plant tissues occurs through phytodegradation and transforms the complex pollutants into simpler and less toxic substances by a series of metabolic reactions (Khan *et al*., 2022) [8]. Plants make numerous different enzymes such as dehalogenases, nitro-reductases, and peroxidases, which are used to transform herbicides, pesticides, petroleum hydrocarbons and herbicides, chlorinated solvents, and pharmaceutical residues. The mechanism is especially applicable in the treatment of agricultural runoff as well as industrial effluents that have organic pollution.

The processes involved in phytovolatilization allow absorbing and emitting volatile contaminants using foliage and converting them to gaseous substances emitted into the air (Sharma *et al*., 2024) [14]. Although it is applicable in some cases with metals and organic compounds, this mechanism should take an extensive consideration on the possible atmospheric contamination and subsequent environmental effects down the line. The main potential candidates to phytovolatilization are selenium, mercury, and volatile organic compounds.

Rhizosphere Dynamics and Interactions between microbes

The rhizosphere is the slender layer of soil that has been impacted by the root secretions along with related microbial action, which is the main place of contaminant transformation in phytoremediation systems. The root of plants secretes large amounts of organic compounds such as sugars, amino acids, organic acids, and enzymes that form good environments to different microbial communities (Sharma *et al*., 2023) [13]. These microorganisms improve phytoremediation in a variety of ways; solubilizing precipitated metals to augment plant uptake, biosurfactants to improve the bioavailability of organic contaminants, complex pollutants due to enzymatic action, and withholding plants to contaminant toxicity by sequestration.

Plant-rhizosphere microorganisms’ symbiosis is known as rhizo-degradation, which is an important aspect of organic contaminant remediation. Pseudomonas, Bacillus, Arthrobacter, and Rhodococcus are genera of bacteria with great potential in the degradation of petroleum hydrocarbons, polycyclic aromatic hydrocarbons, and chlorinated compounds (Khan *et al*., 2022) [8]. Mycorrhizal fungi also play a role in improved nutrient uptake, tolerance to stress and sequestration of contaminants in the fungal biomass.

Factors that affect Remediation Efficiency

Phytoremediation performance is controlled by various environmental, physiological and management conditions which need to be streamlined to ensure a successful application process. The first limiting factor is contaminant bioavailability, which depends on the soil or water chemistry, pH, the content of organic matter, the competing ions, and the speciation (Sharma *et al*., 2024) [14].

Bioavailability of the metal can be improved by the use of chelating agents and surfactants, but caution is taken to ensure that they are not used to excessively increase their mobility and thus cause groundwater pollution.

Remediation capacity is directly affected by plant physiological traits such as growth rate, biomass yield, root morphology and translocation efficiency, and stress tolerance (Ahmed *et al*., 2025) [1]. Environmental factors that include temperature, availability of moisture, sunlight, nutrient level, and oxygen concentration have great influence on the performance of plants and the rate of transforming contaminants. Management activities such as the frequency of harvesting, hydraulic retention time, density of planting and nutrient supplementation must be optimized depending on the conditions in a given site and the remediation goals.

High-Biomass Species for Phytoremediation-Bioenergy Systems

Selection Criteria and Characteristics

A successful execution of phytoremediation- bioenergy dual-purpose systems needs the proper selection of species according to various criteria. The target species will have a high contaminant accumulation capacity and high growth rates with massive biomass production, environmental stress resistance, low nutritional needs, easy cultivation and harvesting, not invaded, and bias biochemical structure to transform into bioenergy (Wijekoon *et al*., 2025) [15]. Also, the species are required to be tolerant to the toxicity of contaminants, have a huge root system to have maximum rhizosphere interactions and adjust to the local climatic conditions.

Aquatic Species

One of the most thoroughly examined and actively used species in the field of aquatic phytoremediation and bioenergy generation is Water Hyacinth (*Eichhornia crassipes*). This perennial which is free floating exhibits great growth rates that doubles biomass in just two weeks under favorable conditions and it can also grow in various climatic zones (Idrees *et al*., 2013) [6]. Water hyacinth is also very effective in removing heavy metals such as chromium, lead, cadmium, mercury, nickel among others, with its root and shoot bioaccumulation efficiency of over 90 percent in several contaminants. The species also shows impressive abilities in terms of nutrient absorption and lowers nitrogen and phosphorous levels by 80-95% in municipal and agricultural wastes (Bhatt *et al*., 2014) [3].

Water hyacinth has an extensive fibrous root system that can be more than one meter in length and has a huge surface to receive the contaminant and harbors extensive microbial communities that promote the breakdown of organic contaminants (Nagi *et al*., 2020) [10]. Effective treatment of tannery waterborne waste, textile effluent, domestic sewage, and agricultural run off have been reported in the literature with considerable enhancements in the parameters of biochemical oxygen demand, chemical oxygen demand, and turbidity.

In the case of bioenergy uses, the water hyacinth biomass has been found to have about 10-15% cellulose, 25-30% hemicellulose, and 5-10% lignin on a dry weight basis which is suitable to use in production of bioethanol using enzymatic hydrolysis and fermentation (Idrees *et al*., 2013) [6]. Optimization experiments show that with the right pretreatment technique such as enzymatic saccharification and dilute acid hydrolysis, ethanol yields can be up to 95 percent of theoretical maximum. Also, water hyacinth is good feedstock to produce biogas by anaerobic digestion with a concentration of 55-65% of methane in a biogas mixture. The moisture content is high which supports the process of anaerobic digestion and the relative low content of lignin increases digestibility in comparison to lignocellulosic terrestrial biomass.

The key issues to be considered when deploying water hyacinth are that it is an invasive species in many areas, should be grown under controlled cultivation systems, and that it needs to have contaminated biomass managed to avoid heavy metal re-release during the bioconversion (Alam *et al*., 2021) [2]. They ensure that the pollutants are not transferred to biofuel products through proper pretreatment and choice of conversion pathway, and most of the heavy metals are retained in solid residues after thermochemical or biochemical conversion.

Another group of organisms that have a high potential in wastewater treatment and the production of bioenergy include microalgae and Cyanobacteria. Some of such species are *Chlorella vulgaris, Scenedesmus obliquus, Spirulina platensis,* and *Chlamydomonas reinhardtii*, which have dual functionality in regard to nutrient remediation and lipid accumulation to produce biodiesel (Gupta *et al*., 2024) [5]. Microalgae are more efficient than terrestrial plants in photosynthesis with light conversion efficiencies of 10-20 percent as compared to 1-2 percent in conventional crops and can rapidly accumulate biomass.

The phycoremediation processes include the biosorption of heavy metals to cell wall constituents, bioaccumulation of the metals in the intracellular space and assimilation of nutrients into cellular biomass. Microalgae are an effective means of eliminating nitrogen, phosphorus, and heavy metals in the municipal wastewater, industrial effluents, and agricultural runoff, and the removal rates of major nutrients are above 90% (Rawat *et al*., 2011) [12]. Small cellular structure and high growth rates allow small cultivation areas to serve large volumes of wastewater in comparison to traditional systems.

Microalgal biomass has a lipid content of 20-50%, a protein content of 30-60% and a carbohydrate content of 10-40% on a dry weight basis of species and growth conditions and serves as a source of biodiesel feedstock by undergoing transesterification, bioethanol feedstock by undergoing fermentation, biogas feedstock by undergoing anaerobic digestion and biohydrogen feedstock by undergoing dark fermentation or photofermentation processes (Bhatt Nutrient stress conditions result in an increased lipid build-up, but to the cost of the overall biomass productivity, requiring compromise between growth and product accumulation periods.

The latest developments show better performance based on co-cultivation mechanisms, as mixtures between complementary species have better biomass productivity and enhanced harvesting performance than monocultures (Gupta *et al*., 2024) [5]. The flocculation of the filamentous species and high-lipid unicellular species enables the biomass to be efficiently recovered at low costs, and still achieve high levels of wastewater treatment.

Terrestrial and Emergent Species

The Vetiver Grass (*Chrysopogon zizanoides*) is a superior phytoremediation species with very deep and dense root systems extending depths of over three meters in favorable conditions. It is a perennial grass that is highly resistant to heavy metals, extreme pH conditions, drought, floods, and temperature fluctuations, allowing it to be used in a wide range of conditions (Nugroho *et al*., 2021) [11]. Vetiver has a high bioaccumulation of chromium, nickel, lead, cadmium, zinc, and arsenic with removal efficiencies of 85-95 percent of contaminated waters.

The literature of phytoremediation records the efficiency of vetiver to treat electroplating wastewater with a 61% chromium removal rate and 96% nickel removal rate in four-week treatments (Nugroho *et al*., 2021) [11]. The widespread root system contains numerous microbial communities, which increase the contaminant degradation and transformation. More than that, vetiver exhibits high water uptake rates of more than 7.5 times of the high-water uptake rates of conventional wetland plants, increasing the hydraulic throughput within treatment systems.

In the case of bioenergy, vetiver can offer large amounts of above ground biomass of up to 50-100 tonnes per hectare per year under ideal conditions. The biomass structure of the grass is ordinary grasses having moderate levels of cellulose and hemicellulose that can be converted to bioethanol either by thermochemical treatment or by enzymes. Also, Vetiver can be used as biogas feedstock via anaerobic digestion, and studies have reported the same level of methane production as from intentionally grown energy crops. The biomass that is harvested also offers livestock fodder after proper heavy metal testing, which generates more streams of economic value.

Another high-biomass terrestrial species, Napier Grass (*Pennisetum purpureum*), has high phytoremediation potential and great bioenergy potential. The tropical perennial grass not only has an exceptional high rate of growth and biomass yield of up to 80-120 tonnes fresh weight per hectare per year but is also one of the highest-yielding herbaceous energy crops (MR *et al*., 2021) [9]. Napier grass has shown good efficiency in eliminating nutrients and organic matter, as well as heavy metallic components of various wastewater, such as dairy effluents, palm oil mill wastewater, and domestic sewage.

The root system is very extensive and penetrative, which helps in efficient uptake of contaminants and also it forms good rhizosphere environments to degrade microorganisms. The studies performed using Napier grass as the constructed wetland show the biochemical oxygen demand removal in the range of 80-85, chemical oxygen demand removal in the range of 85-90 and the removal of the nutrients above 80% (MR *et al*., 2021) [9]. The high rate of growth permits the harvesting period to often take place allowing faster removal of contaminants by the repeated extraction of biomass.

The biomass of Napier grass has desirable properties of bioenergy transformation which included high carbohydrate, moderate lignin, and high combustion properties. Its uses include bioethanol production by enzymatic hydrolysis and fermentation, generation of biogas by anaerobic digestion and direct combustion to produce heat and electricity. The fresh biomass has a high moisture content, which is specifically conducive to anaerobic digestion processes, whereas drying permits pathways of thermochemical conversion.

Hyperaccumulator Species in removal of heavy metals

In addition to the large biomass-producing species, there are many hyperaccumulator plants that are especially regarded as having a strong ability of heavy metals accumulation, which exceed by 100-1000 times that of non-accumulator species (Ahmed *et al*., 2025) [1]. Pteris vittata species that deal with arsenic, Thlaspi caerulescens deal with zinc and cadmium, and Brassica juncea deal with lead have potential of combined remediation and bioenergy uses. The relatively low biomass production of most hyperaccumulators in comparison to high-biomass species, however, requires the consideration of trade-offs between the efficiency of contaminant removal and bioenergy production.

Combination methods of hyperaccumulators to extract contaminants intensively with high-biomass species to treat and generate energy are presented as promising methods of complex remediation contexts. Sequential treatment systems, in which high biomass systems treat effluents with hyperaccumulators, allow not only effluent contaminants to be eliminated effectively but also a significant amount of bioenergy to be produced.

Bioenergy Conversion Technologies and Pathways

Biochemical Conversion Processes

The conversion of phytoremediation biomass to useful energy products uses a variety of conversion technologies, and these can be broadly grouped into biochemical and thermochemical conversion processes. The choice of suitable conversion pathways is based on the nature of biomass, contaminants, required energy products, and cost-efficiency (Wijekoon *et al*., 2025) [15].

Anaerobic Digestion is the commonest biochemical conversion process of the high-moisture biomass, which involves decomposition of the organic materials in anaerobic surroundings to generate the biogas that contains methane and other gases. It takes place in stages; hydrolysis to the breakdown of complex polymers to simple sugars and amino acids, acidogenesis to the conversion of these substances to volatile fatty acids, acetogenesis to the production of acetic acid and hydrogen, and methanogenesis to produce methane (Ahmed *et al*., 2025) [1]. Methane, carbon dioxide and trace elements of hydrogen sulfide, ammonia and others are the typical components of biogas (55-70% methane, 30-45% carbon dioxide).

Anaerobic digestion is especially found to be viable with aquatic phytoremediation biomass such as water hyacinth and microalgae because of the high moisture content that does away with energy-demanding drying processes. Experiments show that methane production using water hyacinth biomass yields 200-350 liters of methane per kilogram of volatile solids with the yield improved when co-digestion is done with other organic wastes (Bhatt *et al*., 2014) [3]. Heavy metals that are accumulated in the course of phytoremediation are mostly left in the solid digestates, and therefore, the transfer to biogas is low, though high concentrations may inhibit the methanogenic bacteria necessitating process optimization.

The biogas residue after manufacturing of the digestate has stabilized organic material and condensed nutrients that can be used as either soil amendment or as fertilizer as long as the concentration of the heavy metals is released to meet some regulatory requirements of land application. Additional work involves vermicomposting, thermal treatment or safe disposal of the material, based on the content of contaminants.

Enzymatic hydrolysis and fermentation process of phytoremediation biomass converts cellulosic and hemicellulosic parts to produce alcohol fuel. It involves pretreatment to destroy lignin structures and increase accessibility of enzymes, enzymatic hydrolysis to release fermentable sugars and fermentation of sugars with yeast to produce ethanol (Idrees *et al.*, 2013) [6]. The pretreatment processes such as dilute acid hydrolysis, alkaline treatment, steam explosion and organosolv processes have their merits and drawbacks on the basis of cost, efficiency and environmental impact.

It has been shown that water hyacinth biomass can be used to produce bioethanol, with ethanol concentrations of 35-45 grams per liter and yields of 90-95 percent of theoretical maximum achieved under optimal pretreatment and hydrolysis conditions (Idrees *et al.*, 2013) [6]. The comparatively low lignin of aquatic biomass makes it simple to pretreat than woody feedstocks; this means that it consumes less chemicals and energy. Nevertheless, the existence of heavy metals in the contaminated biomass also requires a thorough designing of the process to reduce the metal transfer into the ethanol products and to handle the concentrated residues.

The second-generation bioethanol processes that use consolidated bioprocessing, involving the production of cellulolytic enzymes and fermenting released sugars by engineered microorganisms, can potentially be more efficient and less expensive. Further, sequential extraction approach to extraction of value-added products prior to conversion into ethanol can further increase the overall economic viability of biorefinery systems.

Thermochemical Conversion Processes

Combustion and Co-firing are the simplest thermochemical conversion method where the dried biomass is directly burned to produce heat that can be used to produce electricity or industry. Favorable combustion properties of the high-biomass phytoremediation species such as Napier grass and vetiver have heating values of 15-18 mega joule per kilogram dry matter, which match with traditional biomass fuels (Ahmed *et al.*, 2025) [1]. The co-firing of phytoremediation biomass with coal in the current power plants allows the gradual replacement of renewable energy with the use of the already developed infrastructure.

Important issues to be considered during combustion of contaminated biomass are volatilization of heavy metals during combustion and their concentration in ash products. Some metals such as mercury, cadmium and lead can partially evaporate at combustion temperatures and therefore an atmospheric emission must be avoided by the use of flue gas treatment system. The concentrated ash must be handled with caution by encapsulating, vitrifying or disposing it safely to avoid the release of the accumulated contaminants to the environment. Various superior combustion technologies such as fluidized bed systems have better efficiency and control of emissions as opposed to the traditional grate-fired systems.

Pyrolysis and Gasification utilize the biomass by decomposing it thermally under oxygen-restricted conditions to yield biochar, bio-oil, and syngas products which have various uses. At temperatures of 400-600 degrees Celsius, Oxfatal pyrolysis in the absence of oxygen produces liquid bio-oil (40-60% by weight), solid biochar (15-30%), and non-condensable gases (15-25%). The bio-oil may be used as an alternative to petroleum-based fuels in stationary combustion functions or subjected to upgrading to transportation fuels with hydro-processing (Wijekoon *et al.*, 2025) [15].

Gasification is a process that is done at a higher temperature (800-1000 degrees Celsius) under controlled introduction of oxygen where the gas formed is mostly composed of carbon monoxide, hydrogen, methane and carbon dioxide. The syngas can be used as gas turbines/engines to produce electricity, or it can be catalytically transformed into liquid fuels by Fischer-Tropsch synthesis. Syngas can also be used as feedstock to produce methanol, ammonia and hydrogen.

The heavy metals accumulated in phytoremediation biomass are largely immobilized in a pyrolysis and gasification solid char and ash fraction, with little being transferred to liquid or gaseous products. Experiments record heavy metal trapping of more than 95 percent in biochar matrices, in which the metals are trapped in carbonaceous frameworks (Ahmed *et al.*, 2025) [1]. The property allows possible utilization of polluted biomass as sources of energy recovery and storage of pollutants in solid forms that are easy to handle.

There are other value opportunities of the biochar product of pyrolysis of phytoremediation biomass. Provided that the levels of heavy metal are low enough or metals are sufficiently stabilized in the char matrix, the use of biochar in the form of soil amendment can be effective in improving the soil quality, sequestration of carbon, and improving the agricultural productivity. Nevertheless, biochar made using highly polluted biomass needs other management such as; adsorbing the biomass in order to get highly insoluble wastewater, activation of the biomass to get high-quality activated carbon, or safe waste disposal.

New Technology and Innovations

Bioelectricity Generation using Microbial Fuel Cells is a new technology that combines phytoremediation and direct electricity generation. Wetland-microbial fuel cells are hybrid systems that build upon traditional phytoremediation systems and bioelectrochemical subunits, in which exoelectrogenic bacteria oxidize organic matter to produce electrons released by anode to produce electrical current, which is collected by external circuits and sent to cathodes to treat wastewater at the same time (Jacobs *et al.*, 2024) [7]. The technology has two advantages as it can treat wastewater and generate power without conversion to intermediates biomass.

Recent research is showing power densities of 10 to 100 milliwatts per square meter of electrode surface area in built-in wetland-microbial fuel cell systems, and efficiencies of wastewater treatment similar to those of conventional built-in wetlands (Jacobs *et al.*, 2024) [7]. Although the present power output is still too low to use in large-scale generation of electricity, the technology is promising in decentralized uses such as sensors, monitoring devices, and off-grid communities. The current research is aimed at the optimization of electrode material, the optimization of microbe's communities, and the scaling to show good performance and economic feasibility.

Hydrothermal Processing uses reactions carried out under high-temperature and high-pressure in wet biomass to transform biomass into energy products, and thus removes the intensive requirement to dry biomass. Hydrochar is made by hydrothermal carbonization at temperatures of 180-250 degrees Celsius to produce coal-like hydrochar and bio-crude oil is obtained by hydrothermal liquefaction at temperatures of 280-370 degrees Celsius which can be refined into transportation fuels. These are processes that are especially beneficial with high-moisture aquatic biomass such as algae and water hyacinth that need lots of drying.

Research shows that microalgal biomass is capable of producing bio-crude oil yields of 25-40% on dry weight basis under the process of hydrothermal liquefaction to produce bio-crude oil with heating values close to petroleum crude oil (Wijekoon *et al*., 2025) [15]. The heavy metals are distributed mainly in solid forms and water phases, and can be recovered and managed to generate relatively clean products of bio-oil. Nevertheless, economics needs to be developed in order to decrease capital expenditures and enhance energy saving.

Case Studies and Implementation Examples

Bangladesh: Integrated Phytoremediation-Bioenergy for Heavy Metal Contamination

Industrial activities, agricultural practices, and natural occurrence of arsenic are severe challenges to Bangladesh that end up polluting soil and water resources through heavy metals. In-depth research revealed 36 native hyperaccumulator species having phytoremediation and bioenergy capabilities (16 species with potential to generate second-generation bioethanol, biodiesel and bioelectricity) (Ahmed *et al*., 2025) [1]. The species has successfully accumulated arsenic, chromium, lead, cadmium, and other priority pollutants of contaminated locations.

The implementation strategies focus on the species such as water hyacinth to treat aquatic contamination, jute to treat textile wastewater and a range of hyperaccumulating crops to treat agricultural soils. According to the degree of contamination and the characteristics of biomass, the harvested biomass is subjected to suitable conversion procedures. Mediocre contaminated biomass facilitates anaerobic digestion in the generation of biogas, and heavy metals are condensed in digestible volumes of digestate. Biomass with a high contamination is pyrolyzed and the metals can be captured in biochar where energy can be salvaged.

Economic models indicate that there is a possibility of phytoremediation-bioenergy systems to accrue to positive returns based on combined benefits of pollution removal, biofuel revenue generation and opportunities of carbon credits. Nevertheless, this would not be successfully implemented without the support of policies, monetary encouragement, capacity building in technical matters and awareness programs by the population. The government targets to generate 15 percent of renewable electricity by 2041 and the phytoremediation- bioenergy systems would be part of this target as well as satisfying the environmental remediation requirements.

India: High-Biomass Species Constructed Wetlands to treat Domestic Wastewater

Several studies conducted in India assess constructed wetlands systems to treat and use high-biomass species to treat decentralized domestic wastewater. Comparative evaluation of the Napier grass, vetiver and Equisetum in box-type horizontal subsurface flow-built wetlands showed outstanding performance on treatment in all the species (MR *et al*., 2021) [9]. Napier grass recorded average removal efficiencies of 91.3, 86.8, 82.1 and 88.7 percent on turbidity, acidity, biochemical oxygen demand and chemical oxygen demand respectively. Vetiver was slightly better in terms of removing 92.5% turbidity, 88.4% acidity, 83.2% biochemical oxygen demand, and 90.1% chemical oxygen demand. In Equisetum, the turbidity, acidity, biochemical oxygen demand, and chemical oxygen demand removal were 94.6, 91.4, 80.0 and 88.1, respectively.

All the systems had their treated effluent meeting national standards of irrigation water use, which allowed productive reuse of water and reduced the freshwater demand. The high amount of biomass, which is produced in Napier grass and vetiver, can be used as the feedstock in the creation of biogas using anaerobic digesters of the community scale, and it can be used as the household energy source. Econometric studies have shown that the payback period of box-type constructed wetlands are 3-5 years based on water savings, fertilizer value of treated water and biogas generation.

The systems show specific appropriateness to rural and peripheral communities without centralized wastewater treatment systems. The easily serviceable, low-technology systems allow implementation by the members of the community with very little technical training. Nevertheless, to be optimally performed, periodic harvesting, proper management of hydraulic loading, and seasonal changes to meet different wastewater properties are necessary.

Wastewater Treatment at the Municipal Scope and using Microalgae

Pilot studies combining the use of microalgae with the use of conventional constructed wetlands indicate increased treatment performance and bio-mass generation. A system by which Typha latifolia in built wetlands was then followed by Chlorella cultivation produced comprehensive elimination of nutrients and biomass that can be used in biofuel production (Giri *et al*., 2023) [4]. The wetland constructed offered primary treatment that depressed organic contents and suspended solids and the remaining nutrients in the effluent supported the growth of healthy micro algae.

The biomass productivity of the cultivation conditions was better than those of purely autotrophic or heterotrophic cultivation conditions obtained using more energetic light sources coupled with the remaining organic carbon in the cultivation. The combined system eliminated 95 percent of the nitrogen, 92 percent of the phosphorus and 98 percent of the biochemical oxygen demand in the sewage of the municipality, and had final effluent that met high discharge requirements. The Chlorella biomass obtained had 35-40% lipids that could be used to produce biodiesel and 40-45% proteins that could be used as animal feed supplement after proper safety test.

This strategy is a best example of synergistic integration in which every element contributes positively to the system as a whole. The built wetland mitigates the loading of contaminants that can perhaps suppress the growth of algae and the growth of algae purifies the effluent to meet tough discharge standards. The hybrid system utilizes less land as compared to normal treatment plants and produces two sources of revenue i.e. biofuel and protein products.

Applications in industrial Wastewater

Phytoremediation- bioenergy schemes demonstrate potential in a wide range of industrial effluents such as tannery effluent, textile dyeing effluent, and palm oil mill effluent as well as dairy processing effluent. Microalgae treatment of tannery wastewater is shown to be effective in removing chromium, organic matter, and nutrients and generating biomass to make biogas fuel (Nagi *et al*., 2020) [10]. The great tolerance of some algal species to high levels of chromium allows the treatment of wastes that are hard to treat using conventional biological systems.

Napier grass as a Palm oil mill effluent treatment in built wetlands makes 85-90 percentage chemical oxygen demand reduction, significant removal of nutrients and the harvested biomass contributes to the generation of biogas (MR *et al*., 2021) [9]. The use of palm oil effluent has a high organic content that increases the productivity of biomass treatment as compared to the household wastewater treatment. Nevertheless, the high biochemical demand of oxygen must be closely hydraulically controlled to avoid oxygen loss and system breakdown.

Another area of application is textile wastewater that contains synthetic dyes and the species involved include water hyacinth and some species of microalgae that have the ability to decolorize dyes via enzymatic degradation and biosorption. After decolorization and removal of the contaminants, the biomass is subjected to recovery of energy using suitable conversion processes depending on the profiles of the accrued contaminants.

Challenges and Limitations

Contaminant Transfer and Product Safety

The inherent issue of phytoremediation-bioenergy systems is not letting the contaminants be passed to biofuel products in the biomass that has been remedied so that the products are safe and readily acceptable in the market. Phytoremediation creates heavy metals that need to be kept sequestered in the conversion processes or be eliminated by means of relevant treatment procedures. The contaminants partitioning in the different conversion pathways vary, so that the choice of the pathway should be taken with care aiming at the selection of the least contaminated biomass (Wijekoon *et al*., 2025) [15].

The anaerobic digestion research indicates that heavy metals are mainly retained in the solid fractions of digestate and that there is little movement of metals to biogas, but large quantities of metals can suppress the activity of methanogenic bacteria, decreasing the effectiveness of the process (Ahmed *et al*., 2025) [1]. Biochemical oxygen demand inhibition takes place in the cases of metal concentration that is higher than the specific levels which cause species to degrade, and thus requires dilution or pre-treatment of highly contaminated biomass.

It is also with respect to fermentation of bioethanol that the transfer of heavy metals to ethanol products is not very heavy because of the aqueous nature and solid nature of metals. Nevertheless, fermentation of yeasts to metal toxicity necessitates that the biomass be pre-treated and the metal eliminated in feedstocks that contain metals in large amounts. The metals are concentrated in stillage residues that must be managed through proper means.

Pyrolysis and gasification are thermochemical conversion methods that demonstrate good heavy metal sequestration in the char and ash fractions and the concentration of heavy metals in bio-oil and syngas is normally less than 5 percent (Wijekoon *et al*., 2025) [15]. This property allows energy recovery of moderately polluted biomass with the contaminants concentrated in solid residues that are manageable. Nonetheless, unstable metals such as mercury, cadmium, and selenium have to be curbed in their emissions to avoid being released to the atmosphere.

Economic Viability/Scale-Up Problems

The financial viability of phytoremediation-bioenergy systems over traditional wastewater treatment and dedicated energy crops is a major consideration that dictates the extensive implementation. Although phytoremediation is far less expensive in capital and operation expenses than traditional treatment technologies, the economical feasibility relies on various sources of revenue such as avoided treatment expenses, biofuel sales, carbon credits, and even nutrient recovery (Ahmed *et al*., 2025) [1].

Technoeconomic studies reveal good economics in large systems that treat large volumes of wastewater flows in areas where land and biomass conversion facilities are available. But, small-scale and decentralized systems are challenged by increased per-unit costs and small biomass volumes that restrict the choice of conversion technology. The ability to co-process contaminated biomass with other organic wastes in centralized conversion facilities provides possible solutions that would allow economies of scale.

The technical issues associated with scale-up of laboratory and pilot demonstrations to commercial operations include seasonality of biomass productivity and composition, the fluctuating nature of wastewater properties to treatment efficiency, storage and transportation of biomass in year-round operation of a conversion facility, and compatibility with existing energy infrastructure. These challenges need to be mitigated by using proper system design, operational mechanisms, and supportive policy structures to ensure successful commercial implementation.

Capital requirements of bio-mass conversion plants are extremely inhibiting, especially in anaerobic digestion and advanced thermochemical conversion that consume particular equipment and a fine group of professionals. Scalable conversion technology that can be distributed and scaled would lead to an improvement in economic viability into different scale applications.

Environmental and Ecological Support

Although phytoremediation systems have significant positive impacts on environmental conditions in contrast to traditional methods, there are possible ecological issues that need to be considered. Invasiveness an issue of the use of non-native species such as water hyacinth that requires containment cultivation systems which avoid escape to the natural waterways. Lots of areas label water hyacinth as noxious invasive species, which limits cultivation even when it demonstrates favourable phytoremediation and bioenergy properties.

In cases of the availability of suitable candidates, the selection of native species reduces ecological hazards and offers habitat and biodiversity advantages. Nonetheless, the tolerance to contaminants and biomass productivity of native species is lower than that of cosmopolitan invaders and trade-offs must be evaluated. Enclosed systems such as lined created wetlands or controlled canals allow high-performance non-native species to be used and do not release into the environment.

The use of land in terrestrial phytoremediation systems attracts land use considerations, especially when it comes to food production and preservation of the natural ecosystem.

Nevertheless, phytoremediation systems may also make use of degraded, contaminated or marginal lands that cannot be used as agricultural lands hence the environmental restoration advantages. At the time of integration with wastewater treatment facility, the efficiency of land use is maximized because it offers two functions of treatment and energy generation.

The impacts of biodiversity need to be evaluated since monoculture-based phytoremediation systems offer a low value of habitat in comparison to biodiverse wetlands. The added value of adding several complementary species increases the Biodiversity and may also increase the treatment performance by niche differentiation. Constructed wetlands created with habitat attributes such as diverse water depths, vegetation areas and structural complexity can offer wildlife advantages together with treatment purposes.

Technical and Knowledge Gaps

More work is still required on how to maximize phytoremediation-bioenergy systems and to allow their use across large scale commercial applications. The key knowledge gaps involve the long-term system performance under diverse environmental conditions, optimization of multi-species systems to achieve improved treatment and biomass production, the creation of low-cost technologies to convert biomass, management of the contaminated residues of biomass conversion, and the life cycle analysis to estimate the environmental benefits and impacts (Wijekoon *et al*., 2025) [15].

Poor knowledge of microbial community interactions in phytoremediation system limits optimization of rhizosphere processes involved in contaminant transformation. The use of advanced molecular methodologies such as metagenomics and metabolomics may clarify functional capacity of microbial communities and hence functional improvements can be done using bioaugmentation or environmental manipulation.

The design of engineering principles of integrated phytoremediation-energy systems are still underdeveloped, and most of the available knowledge is based on research-level demonstrations and not on commercial processes. The standard design methodology, performance prediction models and best management practices would be developed and help in its wider acceptance by practitioners and regulators.

Most jurisdiction regulators have no particular provisions on phytoremediation- bioenergy systems which makes it difficult to know what is required in order to be permitted, product standards, and disposal of the residues. Formulation of proper rules that can facilitate innovation and at the same time take care of the environment and the safety of the products is a key policy agenda.

Future Directions and Research Priories.

Technological Innovations

There is a chance of using emerging technologies to improve the performance and economic feasibility of the phytoremediation-bioenergy system. Genetic engineering and targeted breeding initiatives can create better varieties of plants which are more resistant to contaminants, more biomass productive, better biochemical make-up to target biofuel pathways, and less invasive nature (Wijekoon *et al*., 2025) [15]. Nonetheless, the introduction of genetically modified organisms should be supported by a rigorous risk analysis and regulation.

Sensors networks and automated control systems facilitates real time monitoring and optimization of phytoremediation system to adjust hydraulic retention times, harvesting periods and nutrient supplementation depending on treatment performance and biomass quality parameters. Remote sensing such as satellite imagery and unmanned aerial navigation is used to track the overall systems and identify the presence of stress before it becomes evident and can be addressed.

The economic feasibility can be improved by more sophisticated ideas of biorefinery that extract most of the value streams out of phytoremediation biomass sequentially, followed by the ultimate transformation of the energy. In example, the removal of high-value pharmaceutical, pigment or specialty chemicals and preceding lipid recovery in microalgal biomass to make biodiesel generates more income to offset system economics in general. Likewise, animal feeds that use algae or aquatic plants as a source of protein and then undergo anaerobic digestion of the remaining biomass use up the maximum resource.

Hybrid systems using phytoremediation in combination with complementary treatment technologies can be developed to provide an improvement in performance and broader applicability. Combination with membrane filtration, advanced oxidation processes or electrochemical treatment can be used to achieve high standards of effluents to be used in direct potable reuse. The integrated physical-biological-chemical methods offer redundant treatment layers and maximize each phase to a certain contaminant.

Policy and Institutional Development

Enabling policy systems are fundamental towards the extensive implementation of phytoremediation- bioenergy systems. The suggested policy tools would consist of financial incentives, including capital subsidies or tax credits or preferential loans on system installation, feed-in tariffs and renewable energy credits in favor of biofuel production, carbon prices mechanisms in reward of the reduction in emissions, and ecosystem service payments based on the benefits of improving water quality (Ahmed *et al*., 2025) [1].

To achieve deployment Regulatory reforms may be used to deploy phytoremediation systems by streamlining permitting of systems that meet specific performance standards, by providing guidance in the management and conversion product requirements of contaminated biomass, in phytoremediation as part of watershed management planning and by supporting demonstration projects and technology transfer programs.

Capacity building activities such as technical training to design, operate, and maintain systems, educational programs that inculcate phytoremediation concepts and practices, extension services that link researchers to practitioners and communities, and platforms of exchanging knowledge bases and practices that enable exchange of experiences and best practices are some of the capacity building activities that reinforce institutional bases supporting the adoption of technology.

International collaboration allows transfer of technology between developed and developing countries, joint research on common problems, the standardization and regulation of standards and regulations that help in the development of markets and financial systems that help in implementing the same in resource-constrained environments where they are often needed most.

Research Priorities

Important knowledge gaps limiting the development of technology should be filled through strategic research investments. The most urgent research topics are: the overall evaluation of various species combinations in specific cases of wastewater and climate, the optimization of pretreatment operations that reduce the transfer of heavy metals during the conversion of biomass, effective harvesting and processing technologies at low costs and how to implement them in distributed demands, the life cycle analysis and technoeconomic evaluations that support making reliable decisions, and the long-term field research that reports the performance stability under real-world conditions (Wijekoon *et al*., 2025) [15].

Basic studies that explain the process of contaminant absorption, conversion and tolerance can inform the creation of superior types of plants and management practices. Research of plant-microbe interactions and rhizosphere behavior allows to selectively improve by positive microbial inoculation or environmental control in support of preferred microbial communities.

Research in biomass conversion needs to focus on technologies that can be deployed on a distributed basis such as low-cost anaerobic digesters, small-scale pyrolysis units, and on-site ethanol production of bioethanol. Creation of well-developed, user friendly systems with reduced technical expertise needs would be critical in application to resource constrained environments.

Social science studies on community acceptance, stakeholder involvement and implementation barriers are essential findings that lead to successful implementation. The knowledge of the user perspective, culture, and institutional processes help in designing implementation strategies and support mechanisms that improve the adoption and continued functionality.

Table 1: Comparison of High-Biomass Species for Phytoremediation-Bioenergy Applications

Species	Annual Biomass Yield (tonnes/ha)	Primary Contaminants Removed	Removal Efficiency (%)	Bioenergy Products	Key Advantages	Major Limitations
Water Hyacinth (*Eichhornia crassipes*)	150-200 (fresh weight)	Heavy metals, nutrients, organic matter	85-95	Bioethanol, biogas, direct combustion	Rapid growth, high nutrient removal, aquatic habitat	Invasive species, high moisture content, seasonal variation
Microalgae (*Chlorella, Scenedesmus*)	50-100 (dry weight)	Nutrients, heavy metals, CO_2	90-98	Biodiesel, bioethanol, biogas, biohydrogen	High lipid content, rapid growth, compact footprint	Harvesting challenges, contamination risks, light requirements
Vetiver Grass (*Chrysopogon zizanioides*)	50-100 (dry weight)	Heavy metals, organic pollutants	85-96	Bioethanol, biogas, direct combustion	Deep roots, extreme tolerance, non-invasive	Slower establishment, moderate biomass yield
Napier Grass (*Pennisetum purpureum*)	80-120 (fresh weight)	Nutrients, organic matter, heavy metals	80-90	Bioethanol, biogas, direct combustion	Very high biomass yield, rapid growth	Moderate heavy metal tolerance, tropical climate preference

Conclusion

Phytoremediation integrated with bioenergy production is a disruptive solution to the twin issues of water pollution and energy deficit that offers systemic solutions to each problem, using the concept of the circular economy. High-biomass species such as water hyacinth, microalgae, vetiver grass, and Napier grass have been shown to have both high capacities to effectively treat wastewater with pollutant removal efficiencies of over 90 and high biomass capacity that can be used as various bioenergy pathways. The synthesis of the recent studies indicates that correctly designed and operated phytoremediation- bioenergy systems have several outcomes: efficient removal of municipal, agricultural, and industrial wastewaters; production of transportation fuel renewable, biogas, and electricity; less emission of greenhouse gases than the fossil fuels; creation of employment and economic growth of the area; and recovery of degraded ecosystems and improvement of the biodiversity.

Key parameters that should be in place to ensure a successful implementation are proper selection of the species used based on contaminant profile, the environment and bioenergy goals; proper selection of bioconversion technology that will minimize the transfer of contaminants to products; complements with exo-wastewater treatment and energy facilities; favorable policy frameworks that offer incentives and effective regulatory policies; and community involvement that will ensure social acceptance and long-term operation.

There are still major issues in terms of economic competitiveness on large commercial levels, handling of biomass residues contamination, the propagation of an invader species by non-native phyto-remediation plants, and the establishment of effective technologies that can be distributed to work in resource-constrained environments. To solve these challenges, a long-term research investment, technology development and policy formulation and capacity building on technical, institutional and community levels are necessary.

The way ahead requires concerted efforts that require innovation in plant science, environmental engineering, transformation technology and implementation policies. Genetic enhancement of phytoremediation species to be more tolerant of contaminants and have a higher biomass, creation of cost-effective distributed conversion technologies, creation of enabling policy and financing mechanisms and demonstration project showing successful models are all key priorities in the near-term.

With respect to future application, phytoremediation-bioenergy systems have specific potential in developing world, where acute water pollution problems and the lack of energy access are a major challenge. The minimal capital requirements, low complexity of operation, and utilisation of locally available resources of the technology are in line with the development priorities and resource limitations. Nevertheless, to be deployed successfully, it must be context relevant to the local conditions and needs with context appropriate designs, capacity building and institutional support.

In case of the developed countries, phytoremediation-bioenergy systems provide rural and peri-urban wastewater treatment opportunities, contaminated site pollution mitigation, renewable energy portfolio diversification, and greenhouse gas emissions reduction to fulfill climate commitments. Value creation and reduction of environmental impact can be achieved through integration with precision agriculture, smart grid technologies and circular economy initiatives.

Phyto-energy systems have more than direct benefits of wastewater treatment and energy generation in terms of bioeconomic potential. These systems reflect key tenets of sustainable development through turning environmental liabilities into economic resources, resource loops, ecosystem services, and viable directions on the way towards regenerative resources management. With the maturation of technologies, their decreased costs and enhancing conditions, phytoremediation-bioenergy systems may be shifted to mainstream by becoming a highly-prospective practice that could be of significant impact to the overall global sustainability goals.

Combining environmental need, technological potential, and economic potential leads to good terms in the fast uptake of combined phytoremediation- bioenergy systems. To achieve this possibility, concerted efforts on the part of researchers who push the boundaries of knowledge, engineers who create viable technology, policymakers that formulate enabling structures, investors that provide funds, and communities that establish and run systems are required. With these types of collaborative work, the idea of sustainable wastewater treatment as the source of clean energy and a means of regaining environmental quality can turn into a dream and a reality of the entire world, enhancing the wellbeing of people of our time and the health of the planet in the present and in the future.

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